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A Unified Theory on the Effects of
Auger Recombination in GaInAsP/InP Lasers and LEDs

K.D. Chik

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Doctor of Philosophy
in Electronic Engineering

Ottawa-Carleton Institute for Electrical Engineering
Department of Electronics
Carleton University
Ottawa, Ontario, Canada

1987

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Auger Recombination in GaInAsP/InP Lasers and LEDs

submitted by Kiu-chi Daw-kung Chik in partial fulfillment of
the requirements for the degree of Doctor of Philosophy.

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ABSTRACT

An Auger recombination-induced energetic carrier leakage theory is developed, which in conjunction with the Auger recombination mechanism, forms a unified model to account for the fundamental differences in device characteristics of GaInAsP/InP light emitting devices in comparison to their AlGaAs/GaAs counterparts. Unlike many of the existing models, this unified model allows the properties of the GaInAsP/InP light emitting diodes and injection lasers to be derived consistently without the need of invoking different mechanisms for each type of device or for specific properties and observed phenomena.

Using this unified model, the carrier leakage observed in various GaInAsP/InP light emitting devices over wide ranges of operating conditions, and the effects of Auger recombination and its induced energetic carrier leakage on the relevant static and dynamic properties of light emitting diodes and injection lasers can be calculated directly from the material and design parameters of the devices. Analytic and experimental results are found to be in excellent agreement.

It is found that the energetic electron leakage dominates the carrier leakage in GaInAsP/InP light emitting devices.

By properly designing the light emitting diodes such that the energetic carrier leakage becomes diffusion limited, the carrier leakage becomes only a small fraction of the total injection current, and Auger recombination theory alone is capable of explaining the device behavior in a wide range of operating conditions without significant error. However, energetic carrier leakage becomes significant in devices where the carrier leakage is drift limited, and in devices such as injection lasers where the active layer thickness is reduced to be comparable to the effective diffusion length of the energetic carriers. Under such conditions, the effect of Auger recombination induced energetic carrier leakage must be incorporated into the theoretical model. This is a principal finding of the present thesis research and is the key factor in developing the unified theoretical model. For the first time, it has been possible to reconcile the discrepancies between experimental and theoretical results based upon the Auger recombination model alone.

The thesis will demonstrate that the effects of device temperature, active and confinement layer doping concentration and thickness on the efficiency and non-linearity of light output of LEDs, as well as the temperature and stripe width dependence of threshold behavior of stripe geometry gain guided lasers, are all well explained by the new unified model.

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1. INTRODUCTION

Double heterojunction light emitting diodes (LEDs) and injection lasers, with quaternary semiconductor GaInAsP active layers and InP optical and charge carrier confinement layers, emitting in the wavelength range of 1.1-1.6 μm , are very attractive light sources in fiber optical communication systems. However, two basic characteristics of these devices, that is, the linearity of the LEDs and the temperature sensitivity of threshold current of lasers are substantially different from similar devices made from AlGaAs/GaAs materials. The rapid increase of threshold current with temperature of lasers and the decrease of efficiency with excitation of LEDs from GaInAsP/InP materials are serious concerns for their applications. There has been considerable interest in determining the basic mechanisms responsible for this behavior which deviates from the behavior observed in their AlGaAs/GaAs counterparts.

Several physical mechanisms have been proposed to account for these basic characteristics and associated phenomena. These include:

- (1) loss of injected carriers by non-radiative Auger recombination for both LEDs and lasers⁽¹⁻¹²⁾;

- (2) loss of injected carriers to in-plane superluminescence in surface emitting LEDs⁽¹³⁾;
- (3) internal optical loss by intervalence band absorption in lasers⁽¹⁴⁻¹⁶⁾;
- (4) loss of injected carriers by non-radiative recombination through defects in the active layers and/or at the active and confinement layer interfaces in lasers⁽¹⁷⁻²¹⁾;
- (5) carrier heating effects where carrier temperature rises several tens of degrees above lattice temperature in the active layer of LEDs and lasers⁽²²⁻²⁵⁾; and
- (6) carrier leakage over the heterojunction barrier into the InP confinement layer, arising from carriers whose energies exceed the heterojunction barrier height, either as a result of normal injection⁽²⁶⁻³⁰⁾, or an enhancement by carrier heating⁽³¹⁻³²⁾.

It has been found that more than one mechanism can often be used to explain a particular characteristic. On the other hand, no one mechanism described above alone is capable of accounting for all of the observed phenomena in both LEDs and lasers. The lack of theoretical understanding of the mechanism(s) governing the fundamental properties of the devices under study have complicated the development progress in device design optimization.

Several attempts have been made^(1,2,3), to date, to combine more than one mechanism to form a complete model. However, such approaches are usually aimed at a particular type of device or a specific characteristic under some operating conditions. Thus the aim of this work is to explore the possibility of developing a unified theoretical model, based on the fundamental material properties and device structures, to clarify the basic mechanism(s) responsible for those characteristics of GaInAsP/InP light emitting devices which significantly deviate from similar structures of AlGaAs/GaAs materials. This unified model would then form the basis for design optimization as well as the understanding of various relevant properties of such devices. In order to achieve this goal, experimental measurements performed on suitable device structures, under various operating conditions are necessary to verify the validity of the theoretical model.

In chapter 2, the various mechanisms proposed to account for the basic properties of GaInAsP/InP light emitting devices deviating from devices on AlGaAs/GaAs materials are examined in sufficient detail. Emphasis is placed both on the area of applicability of each of the models on specific devices and properties, and on the area of weaknesses of each model as compared to experimentally measured results. These analyses then form a foundation for the development of the unified model of this work through identifying the necessary

features that a unified model has to possess in order to provide full consistency with the device properties experimentally observed to date.

The unified model is derived in chapters 3 and 4. This model possesses two separated but interrelated mechanisms: the loss of injected electrons and holes through non-radiative Auger recombination processes, and the loss of Auger recombination induced energetic charge carriers over the heterojunction barrier.

In chapter 3, the relevant Auger recombination processes, as well as methods of deriving the Auger recombination rate in GaInAsP quaternary semiconductor, both experimentally and theoretically, are briefly described. The problems of determining the Auger recombination coefficients through experimental measurements or by theoretical calculations are discussed in some detail. Continued efforts in these areas are needed.

In chapter 4, the relaxation of Auger recombination induced energetic charge carriers is analysed and the energy loss rate is calculated. An effective energy relaxation time related to the heterojunction barrier height of the GaInAsP active layer and the InP confinement layers is estimated, which is used in the rate equations of Auger recombination induced energetic carriers and injected carriers. This is

then followed by the derivation of a theoretical model of Auger recombination-induced energetic carriers leaking across the heterojunction barrier of the GaInAsP/InP light emitting devices. The Auger recombination induced energetic carrier leakages are examined in both diffusion and drift-limited cases, where each case may represent a class of structure design of devices with some special device characteristics.

Chapter 5 contains the analytic results obtained from the unified model regarding the properties of GaInAsP/InP light emitting diodes. The nonlinearity of the light output power versus the injection current density (L-I) characteristics of the LEDs are first calculated under various situations. These are then compared to the characteristics of similar devices without the non-radiative Auger recombinations and/or the Auger recombination induced energetic carrier leakage mechanisms. The temperature sensitivity of the light output power, and the effects of device design on the dynamic and static properties of the LEDs are also analysed. Some of the theoretically simulated results are also compared with the experimentally measured characteristics of devices on both GaInAsP/InP and AlGaAs/GaAs materials.

In chapter 6, the effects of Auger recombination and Auger recombination induced carrier leakage on the properties of lasers are analysed. Special emphasis is placed on the

temperature sensitivity of threshold current density of broad area lasers. The theoretical results are then compared to experimentally measured data to show the validity of the unified model. The application of the unified model to the design optimization of double heterostructure stripe geometry laser diodes is illustrated by the threshold current dependence on the stripe width of the devices. The dependence of static and dynamic properties of the laser diodes above the threshold current (such as kinks, relaxation oscillations and self-sustained pulsations) on Auger recombination and its induced leakage is discussed without simulated results. This is mainly due to the excessively large cost associated with such calculations.

Finally, some of the unsolved problems that require further studies in understanding both device and material properties, as well as some suggestions and recommendations are summarised in chapter 7.

2. ANALYSIS OF THE EXISTING MODELS

Since the demonstration of the possibility of realising light emitting devices from the quaternary semiconductor GaInAsP on InP substrate materials^(1,2,3), extensive research and development studies have been carried out aimed at understanding the material and device properties, and at achieving high performance devices. These activities are basically driven by the fact that the capability of fiber optical communications could be substantially enhanced from the 0.8 μm wavelength regime offered by the first generation AlGaAs/GaAs light emitting devices to the 1.3 μm wavelength region where the material dispersion of silica fibers can be made to be zero and the transmission loss relatively low (less than 0.5 dB/km as compared to about 2 dB/km at 0.8 μm)^(4,5).

However, it has been widely recognized even at the early stage of studies that the GaInAsP/InP light emitting devices possess some characteristics which are substantially different from similar AlGaAs/GaAs devices. Two of the important properties, which have attracted most of the attention, are the non-linearity of the light emitting diodes and the strong temperature sensitivity of the threshold current of lasers. Fig. 2-1 shows measured light output power versus injection current characteristics of

surface emitting LEDs and Fig. 2-2 shows measured temperature variation of threshold current of stripe geometry gain guided lasers from GaInAsP/InP material at 1.3 μm wavelength. Also shown for comparison on these figures are the corresponding characteristics of similar structures from the AlGaAs/GaAs system at 0.8 μm . It is clearly shown that the efficiency of the GaInAsP/InP LED drops severely as the injection current increases and the threshold current of GaInAsP/InP lasers increases more rapidly as temperature increases, especially at higher temperatures. The temperature change of lasing threshold current of semiconductor injection lasers is usually well described by an empirical relation

$$I_{th}(T_j) = I_0 \exp(T_j/T_0) \quad (2.1)$$

where T_0 is called the characteristic temperature of the laser. Fig. 2-3 shows that the characteristic temperature is about 145°K for the entire temperature range illustrated in the case of AlGaAs/GaAs laser measured. The characteristic temperature of GaInAsP/InP laser at 1.3 μm wavelength is about 100°K for temperature below 250°K and reduces to about 65°K around room temperature for the laser characterised.

Fig. 2-1 Measured light output power versus injection current characteristics of surface emitting GaInAsP/InP and AlGaAs/GaAs LEDs at 1.3 and 0.8 μm wavelength, respectively.

Fig. 2-2 Measured temperature variation of threshold current of stripe geometry gain guided lasers.

(a) GaInAsP/InP laser at 1.3 μm wavelength;

(b) AlGaAs/GaAs laser at 0.84 μm wavelength.

Fig. 2-3 Temperature dependence of threshold currents for GaInAsP/InP and AlGaAs/GaAs lasers emitting at 1.3 and 0.8 μm wavelength, respectively. The characteristic temperature is calculated from the measurement results as $T_o = \frac{T_2 - T_1}{\ln\left(\frac{I_{th}(T_2)}{I_{th}(T_1)}\right)}$,

where T_1 and T_2 are the junction temperatures such that $T_2 > T_1$, and $I_{th}(T_2)$ and $I_{th}(T_1)$ are the threshold currents at the corresponding temperatures.

It should be emphasized that results obtained from laboratories around the world have been in essential agreement, even though different crystal growth and processing techniques as well as device structures in both material systems have been utilized. This indicates that these characteristics arise mainly from intrinsic mechanism(s) rather than being caused entirely by extrinsic effects or device design.

These phenomena, to date, have attracted intensive studies, experimentally as well as theoretically, and numerous models based on various mechanisms have been proposed. Even though some of these models are developed for a specific phenomenon in nature, many are intended to identify the mechanism(s) dominating the properties of the GaInAsP/InP light emitting devices.

In this chapter, these proposed mechanisms are analysed and compared with experimentally observed properties and phenomena. Through these analyses, the basic aspects of a unified model have been established. The unified model is derived from a fundamental hypothesis that properties of semiconductor devices are interrelated, i.e., device properties should not be independently treated and isolated from each other. This means that a mechanism which governs some properties of a device should not be allowed to violate or contradict other characteristics of the same device. That,

is, any mechanisms which affect a specific property of a device should be consistent with other properties. This basic assumption has been used in many previous studies as a powerful means in the advancing of the understanding and modelling of semiconductor devices by assuming that any proposed mechanism(s) used to explain some phenomena but violating other properties or contradicting experimental results is(are) invalid. This hypothesis is further extended in this study that the behavior of different types of devices which physically share common operating principles should be determined by the same basic mechanism(s). For example, if we consider devices such as lasers and LEDs at injection levels up to the lasing threshold, where the stimulated emissions in lasers are relatively weak as compared with the spontaneous emissions, it is certainly questionable that completely different mechanisms have to be invoked for each type of device. This principle is also applied to devices from different materials where the proposed mechanism does not involve any difference in material properties.

2.1. Injected Carrier Loss Through Non-radiative Auger Recombination

2.1.1. Non-linearity of LEDs

The behavior of injected charge carriers in a light emitting diode can be described approximately by the charge control equation⁽¹⁾, which states that the rate of change of charge carriers in the active layer is equal to the charge injection rate minus the charge recombination rate. In a double heterojunction where the injection efficiency is nearly unity⁽²⁾, under steady state conditions, the recombination rate is then equal to the charge injection rate. Thus, the average injected electron density in a p-type active layer, with layer thickness much less than the electron diffusion length, can be approximated by

$$\Delta n \approx \frac{J}{ed} \tau_n \quad (2.2)$$

where e is the electron charge, d is the active layer thickness, J is the injection current density, and τ_n is the minority carrier lifetime in the active layer. The internal photon generation rate per unit volume is then given by

$$R_r = \frac{\Delta n}{\tau_r} = \frac{\tau_n}{\tau_r} \frac{J}{ed} = \eta_i \frac{J}{ed} \quad (2.3)$$

where τ_r is the radiative recombination lifetime; the ratio τ_n / τ_r determines the internal radiative quantum efficiency η_i .

Equation (2.3) implies that the internal photon generation rate would be linearly proportional to the injection current density if η_i is constant. Thus, the intrinsic non-linearity of the light output power versus injection current of GaInAsP/InP light emitting diodes, as shown in Fig. 2-1, implies that the internal radiative quantum efficiency η_i is not constant, but decreases as the injection current increases.

In the Auger recombination model, it is assumed that the non-radiative Auger recombination process co-exists with the radiative recombination process, and the injected carrier loss through the non-radiative Auger recombinations is responsible for the observed non-linearity in the light versus current characteristics. The effects of this assumption are shown by expressing the minority carrier lifetime τ_n in terms of the radiative and non-radiative components:

$$\frac{1}{\tau_n} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \quad (2.4)$$

In equation (2.4), τ_r determines the radiative recombination rate R_r , and τ_{nr} the non-radiative recombination rate R_{nr} .

Assuming τ_{nr} is determined by the non-radiative surface recombination rate R_s and Auger recombination rate R_A , respectively, and applying the following relationships⁽⁴⁾

$$R_s = \frac{\Delta n}{\tau_s} = \frac{2s}{d} n \quad (2.5a)$$

$$R_A = \frac{\Delta n}{\tau_A} = Cnp \quad (2.5b)$$

$$R_r = \frac{\Delta n}{\tau_r} = B_r np \quad (2.5c)$$

where B_r is the effective radiative recombination coefficient, s is the surface recombination velocity due to recombination centres at the heterojunction interfaces, C is the Auger recombination coefficient, and n and p represent the electron and hole densities in the active layer, respectively, which are n_0 and p_0 at thermal equilibrium but increase to $n_0 + \Delta n$ and $p_0 + \Delta n$ with an injected excess electron density Δn , then the internal quantum efficiency η_i can be expressed as

$$\eta_i = \frac{B_r np}{B_r np + \frac{2s}{d} n + Cnp^2} \quad (2.6)$$

From equation (2.6), it is concluded that surface recombination due to traps at the heterojunction interfaces would not contribute to the observed decrease of internal quantum efficiency as the charge injection rate increases, because it has a weaker carrier density dependence than

radiative recombination. Rather, it is responsible for the often observed superlinearity at low injection level of LEDs. This applies also to the non-radiative recombination through defects in the active layer. In contrast to this behavior, Auger recombination would continuously reduce the internal quantum efficiency with increasing injection rate due to its stronger dependence on carrier density than radiative recombination. This is, in fact, consistent with the experimentally measured light output power versus injection current characteristics of GaInAsP/InP LEDs in the 1.3 μm wavelength. A typical comparison of analytic and experimental results are shown in Fig. 2-4. The deviation between calculated and measured results at high injection current may vary from structure to structure, depending on device design parameters. Almost identical results have also been obtained by Su et al⁽¹¹⁾, Dutta and Nelson⁽¹²⁾, and Uji et al⁽¹³⁾ in other laboratories on similar surface emitting and edge emitting LEDs and lasers at below threshold current.

Fig. 2-4 Comparison of calculated and measured light output power versus injection current characteristics of a GaInAsP/InP LED emitting at 1.3 μm wavelength. The LED has 1 μm thick active layer and 1.5 μm thick p-type InP confinement layer with $2\text{--}3 \times 10^{17} \text{ cm}^{-3}$ doping concentration.

2.1.2. Temperature Sensitivity of Threshold Current of Lasers

In broad area double heterojunction lasers where current spreading effects and charge out-diffusion effects can be neglected, the cavity gain can be considered uniform across the entire width of the structure. If the optical mode is not propagating completely within the active layer, the threshold mode gain g_{th} achieved through injected charge carriers is then given by,

$$\Gamma g_{th} = \alpha + \frac{1}{L} \ln \frac{1}{R} \quad (2.7)$$

where α is the total internal loss, consisting of free carrier absorption in the active layer and surrounding confinement layers and scattering loss of the optical waveguide; R is the cavity facet power reflectance and thus the term $(1/L)\ln(1/R)$ represents the optical power emitted from both facets of the cavity with cavity length L ; and Γ is the optical confinement factor defined by

$$\Gamma = \frac{\int_{-d/2}^{d/2} |E(x)|^2 dx}{\int_{-\infty}^{\infty} |E(x)|^2 dx} \quad (2.8)$$

where d is the active layer thickness and $E(x)$ is the electromagnetic field across the slab waveguide of the double heterostructure.

It has been shown that in semiconductor lasers⁽¹¹⁾, the current dependence of gain in a wide range of injection can be described by a linear approximation

$$g_{\max} = m(J_{\text{nom}} - J_0) \quad (2.9)$$

where $g_{\max}$ is the maximum gain at a given excitation, J_0 is the nominal current density required for the band-to-band absorption to be reduced to zero in the case of the linear approximation used, and m is a gain coefficient. The nominal current density J_{nom} is the current density necessary to maintain the total spontaneous radiative recombination at unity quantum efficiency in a one micrometer thick layer⁽¹¹⁾. In case of no leakage current, the actual current density J in a laser is then related to the nominal current density by

$$J = J_{\text{nom}} d / \eta_i \quad (2.10)$$

where d is the active layer thickness in micrometers and η_i is the internal quantum efficiency.

From the above equations, the threshold current density of a broad area laser can be approximated by

$$J_{th} = \frac{1}{\eta_i} \left\{ J_o d + \frac{d}{\Gamma_m} \left(\alpha + \frac{1}{L} \ln \frac{1}{R} \right) \right\} \quad (2.11)$$

The temperature dependence of the lasing threshold current can be related to the temperature sensitivities of J_o , m , η_i and α .

In the Auger recombination model, the excess temperature sensitivity of the threshold current of the GaInAsP/InP lasers compared to AlGaAs/GaAs devices is attributed to the temperature sensitivity of the internal quantum efficiency. In analogy to the case of light emitting diodes, the internal quantum efficiency is given by

$$\eta_i = \frac{R_r}{R_r + R_{nr}} = \frac{1}{1 + \frac{R_A}{R_r}} \quad (2.12)$$

Thus, the decrease of η_i arising from the increasing of non-radiative Auger recombination rate with temperature in the GaInAsP active layer will cause a stronger temperature sensitivity of threshold current in comparison with AlGaAs/GaAs lasers where the Auger recombination coefficient is an order of magnitude smaller⁽¹¹⁾. Since Auger recombination at low temperature is significantly reduced, the Auger model also predicts that the temperature sensitivity of threshold current of GaInAsP/InP lasers would

be reduced at low temperature. These two conclusions are, in fact, consistent with experimental measurements⁽¹⁾ as shown in Fig. 2-5, where the relative spontaneous emission efficiency at lasing threshold of GaInAsP/InP lasers emitting at 1.3 μm wavelength is clearly a decreasing function of temperature, in contrast with AlGaAs/GaAs lasers. Also shown in Fig. 2-5 is the temperature variation of threshold currents of GaInAsP/InP lasers whose characteristic temperature approaches the values commonly observed in AlGaAs/GaAs lasers if the threshold current is normalised by the change of internal quantum efficiency η/η_0 , where η_0 is the internal quantum efficiency of GaInAsP/InP lasers at low temperature.

Fig. 2-5 Temperature dependence of threshold current, I_{th} , and normalised threshold current by the internal quantum efficiency of spontaneous emission at low temperature, $I_{th}(\eta/\eta_0)$, in 1.3 μ m GaInAsP/InP lasers.

After Thompson et al⁽¹⁾

2.1.3 Discussions and conclusions

(i) The non-radiative Auger recombination mechanism can successfully account for the excess non-linearity of light emitting diodes and temperature sensitivity of threshold current of lasers from the GaInAsP/InP materials. The analytic results are generally consistent with experimental measured device characteristics. The Auger recombination coefficient in GaInAsP is larger than in GaAs by an order of magnitude due to differences in band structure parameters; and thus could well explain the observed properties of the GaInAsP/InP light emitting devices that deviate significantly from the AlGaAs/GaAs counterparts.

Although the leakage phenomenon observed in many device structures has not been integrated well into the Auger recombination model, no measured properties or observed phenomena at present are in contradiction with the Auger recombination mechanism.

(ii) However, the effects of Auger recombination critically depend on the magnitude of the coefficients of the Auger recombination processes. Although various techniques have been developed to date and numerous attempts made to calculate the Auger recombination coefficients and to determine the dominant recombination processes, conclusive results have not been obtained.

(iii) The assumption that the recombination rate is approximately equal to the charge injection rate used in early models involving Auger recombination is not valid if charge leakage is considered, especially in some device designs where leakage could be greatly enhanced by lowering the doping level in the confinement layers. Since leakage has been observed directly, the leakage mechanisms have to be incorporated in any realistic model.

2.2. Injected Carrier Loss to In-plane Superluminescence in LEDs

2.2.1. The In-plane Superluminescence Mechanism

In the in-plane superluminescence model, the non-linearity of surface emitting LEDs arises from the enhanced emission in the plane of the active layer through stimulated emission processes⁽¹⁾. This enhanced emission in the plane of the active layer takes place at the expense of emissions in other directions because all of the emissions originate from recombinations in the same reservoir of injected carriers.

Assuming the injected carrier density is uniform in the active volume of a surface emitting LED by ignoring the effects of current spreading and charge carrier out-diffusion, the light intensity emitted by a LED can be

divided simply into the light intensity emitted in the plane of the active layer and the emission in other directions. Assuming the thickness of the active layer is much smaller than the diameter of injection of the LED, then the current component for light intensity emitted in directions other than the plane of the active layer, I_s , is proportional to the spontaneous emission rate. On the other hand, the stimulated emission in the plane of the active layer depends exponentially on the single pass gain (in-plane superluminescence). Assuming the current component for stimulated emission in the plane of the active layer is I_{st} , the total rate of carrier injection into the active layer will be the sum of I_s and I_{st} . This implies that the efficiency of radiative emission observed from a surface emitting LED in directions other than in the plane of the active layer would be reduced as injection level increases.

2.2.2. Discussions and Conclusions

(i) The effects of the in-plane superluminescence mechanism on the device behavior depend critically on the magnitude of the net single path gain, g , which is determined by the carrier density and the absorption and scattering losses in the active layer. If f is the fraction of spontaneous emission that travels the distance L , the single pass gain becomes important only if $fe^{gL} > 1$. For typical surface emitting LEDs with diameters of 20 to 100 μm and active

layer thickness of 1 μm , the value of f is in the range of 0.1 to 0.02; the required single pass gain, g , would be in the order of 800 to 2000 cm^{-1} . Using the gain-current dependence value of $dg/dI = 32 \text{ cm}^{-1}/\text{kA-cm}^{-2}\text{-}\mu\text{m}^{-1}$ at 300°K , the current density required is from 25 to 60 kA/cm^2 , which is many times higher than the current densities where substantial non-linearity of the LED is observed as shown in Fig. 2-1. Thus, the in-plane superluminescence could not be an important factor in surface emitting LEDs under typical operating conditions where the injection current densities do not exceed about 10 kA/cm^2 . This is also confirmed by measurement of radiative side-emission from typical surface emitting LEDs. Within the accuracy of the measurements, no deviation from the surface emission has been detected. Even at very high injection level, the in-plane superluminescence has also to compete with charge carrier leakage mechanisms as described in section 2.6.

(ii) The effect of in-plane superluminescence is expected to be stronger at lower temperature due to the higher single pass gain. This implies that the non-linearity of the surface emitting LEDs would be more severe at low temperature. This is clearly in contradiction with experimental measurements.

(iii) The effects of in-plane superluminescence on AlGaAs/GaAs surface emitting LEDs should be expected to be

similar to GaInAsP/InP devices, unless the dependence of gain on current density is substantially lower in GaAs. However, measured dg/dI values in AlGaAs/GaAs lasers are even higher than in GaInAsP/InP devices. This is then not consistent with the stronger non-linearity of GaInAsP/InP surface emitting LEDs as compared to AlGaAs/GaAs devices.

(iv) The charge leakage phenomenon observed in both lasers and LEDs could not be accounted for by the in-plane superluminescence mechanism.

(v) The excess temperature sensitivity of the threshold current of the GaInAsP/InP lasers as compared to AlGaAs/GaAs lasers could not be explained by the in-plane superluminescence. New mechanisms have to be invoked for such characteristics.

Therefore, it is concluded that the in-plane superluminescence is not a dominant mechanism for explaining either the excess non-linearity of LEDs or the temperature sensitivity of the threshold current of lasers observed in GaInAsP/InP materials.

2.3. Internal Optical Loss by Intervalence Band Absorption in Lasers

2.3.1. The Mechanisms of Intervalence Band Absorption

The excess temperature sensitivity of threshold current of GaInAsP/InP lasers has also been proposed to be caused by the optical loss due to intervalence band absorptions, i.e., the temperature dependence of the reabsorptions of the emitted photons by transitions from the split-off band into the heavy hole band and into the acceptor level⁽¹⁴⁾.

The model for intervalence band absorptions in the active layer is schematically illustrated in Fig. 2-6(a). In this model, the absorption by transition from the split-off band into the heavy hole band at energy level E_1 is assumed to depend directly on the hole density available at E_1 ⁽¹⁴⁾, i.e.

$$\alpha_1 = B_1 \{ 1 + \exp(E_1 - E_F)/kT \}^{-1} \quad (2.13)$$

where E_F is the hole Fermi level and B_1 is a proportionality constant related to the band parameters of the split-off and the heavy hole bands.

Similarly, the absorption by transition from the split-off band into the acceptor level is assumed to be given by⁽¹⁴⁾

$$\alpha_2 = B_2 \{ 1 + \frac{1}{2} \exp(E_A - E_F)/kT \}^{-1} \quad (2.14)$$

where B_2 is also a proportional constant and E_A is the energy of the acceptor level.

Since $E_A - E_F$ is very small, α_2 is not strongly temperature dependent. By contrast, if $E_1 - E_F$ is of many kT s, α_1 would increase significantly with temperature.

Adams et al.⁽¹⁴⁾ have used $B_1 = 3.7 \times 10^5 \text{ cm}^{-1}$ and $B_2 = 63 \text{ cm}^{-1}$ to demonstrate that the absorption in the active layer of lasers at 1.6 μm wavelength is dominated by the intervalence band absorption. Taking $\alpha = \alpha_1 + \alpha_2$, such effects are illustrated in Fig. 2-6(b). The change of the total absorptions is then consistent with the temperature variation of threshold current of GaInAsP/InP lasers.

Fig. 2-6 (a) Schematic diagram of the band structure of p-type GaInAsP indicating photon emission across the band gap and its reabsorption by transitions from the split-off band into the heavy hole band at energy E_1 and into the acceptor level at energy E_A . These are designated α_1 and α_2 respectively.

(b) Temperature dependence of the absorption coefficient in the active region showing experimental points together with the theoretical variation, solid curve, which is the sum of α_1 and α_2 .

after Adams et al⁽¹¹⁾

2.3.2. Discussions and Conclusions

(i) Direct measurement of the intervalence band absorption in GaInAsP is limited by the thickness of the quaternary material grown by the traditional liquid phase epitaxial technique. Henry et al⁽¹²⁾ have measured the intervalence band absorptions in $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ and InP, as well as in GaAs, at wavelengths of 1.3 μm and 1.6 μm . As shown in Table 2-1, the coefficients of intervalence band absorptions are in the range of 12-13 cm^{-1} and 24-26 cm^{-1} at wavelengths of 1.3 μm and 1.6 μm , respectively, for hole concentration of $1 \times 10^{18} \text{ cm}^{-3}$. This is also consistent with the measurements of Casey et al⁽¹³⁾ on p-type InP, where intervalence band absorption coefficients of $14(p/10^{18} \text{ cm}^{-3}) \text{ cm}^{-1}$ at wavelength of 1.3 μm and $20(p/10^{18} \text{ cm}^{-3}) \text{ cm}^{-1}$ at 1.5 μm are obtained. Since the intervalence band absorption coefficients of InP and $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$ are very similar, and these two compositions form the two end points of the quaternary GaInAsP lattice matched to InP, it is reasonable to expect that these absorption coefficients would apply approximately throughout the entire range of quaternary materials for the light emitting devices considered here. In case of the low coefficient value, it is concluded that the intervalence band absorption only plays a minor role in determining the properties of GaInAsP/InP lasers. That is, the intervalence band absorption contributes somewhat to the total cavity loss. However, GaAs has an almost identical coefficient of

— intervalence band absorption. This implies that the excess temperature sensitivity of the GaInAsP/InP lasers as compared to AlGaAs/GaAs devices could not be caused by such absorption mechanisms. This conclusion is further supported by the extremely low temperature dependence of the intervalence band absorption coefficients of $\text{Ga}_{0.47}\text{In}_{0.53}\text{As}$, InP and GaAs.

(ii) The intervalence band absorption, if dominant, would cause a rapid increment of threshold current with temperature as well as a reduction of differential quantum efficiency of lasers above threshold. This is in contradiction to the measured results showing that the differential quantum efficiency remained essentially constant as the temperature of the lasers increased from 20 to 70°C, whereas the threshold current increased by 2.5 times⁽²¹⁾. This is also shown in Fig. 2-2(a), where the efficiency dropped by <35% as temperature increased from -20°C to +60°C, whereas the threshold current increased more than 4 times.

(iii) Due to the low photon densities in the active layer of light emitting diodes, the effects of intervalence band absorption would be even lower in LEDs than in lasers. In order to account for the non-linearity of the GaInAsP/InP LEDs, a different mechanism has to be used.

(iv) The intervalence band absorption would not be consistent with the carrier leakage observed in GaInAsP/InP lasers and LEDs. The intervalence band absorption produces energetic holes, whereas the leakage has been determined to be mainly of electrons.

However, the above conclusions do not exclude intervalence band absorption entirely, even though such absorption is not a dominant mechanism for the properties concerned.

	$\text{Ga}_{0.47}\text{In}_{0.53}\text{P}$	InP	GaAs
β at 1.3 μm	12 cm^{-1}	14 cm^{-1}	13 cm^{-1}
T_c at 1.3 μm	390°K	340°K	180°K
β at 1.6 μm	25 cm^{-1}	24 cm^{-1}	26 cm^{-1}
T_c at 1.6 μm	1600°K	540°K	340°K

Table 2-1 Measured intervalence band absorption coefficient β and its characteristic temperature T_c at 1.3 μm and 1.6 μm wavelength. The characteristic temperature is defined as $T_c = \frac{\beta}{d\beta/dT}$ after Henry et al^(1,2)

2.4. Loss of Injected Carriers by Non-radiative Recombination through Defects

2.4.1. Recombination at Defects

The temperature sensitivity of threshold current in GaInAsP/InP lasers could also be caused by non-radiative recombination through defects in the active layer^(11,12) and/or at the interfaces of the active and confinement layers⁽¹³⁾, if the recombination rate increases with temperature.

(1) Horikoshi and Furukawa⁽¹¹⁾ proposed that recombination centers in the active layer with activation energy of 0.25 to 0.3 eV caused the excess temperature dependence of threshold current of GaInAsP/InP lasers. The non-radiative recombination rate of these defects depends on the activation energy E_a as $R_{nr} \propto \exp(-E_a/kT)$. At sufficiently high temperature, the recombination rate at defects becomes comparable to the radiative recombination rate, and causes a rapid increase of threshold current.

(2) Multi-phonon recombination through deep level traps has been used by Wang and Shui⁽¹²⁾, where the non-radiative recombination rate is given by⁽¹⁴⁾

$$R_{mp} = N_t B_p \quad (2.15)$$

where N_t is the density of the deep level traps and B_p is the multi-phonon recombination coefficient given by

$$B_p = B_{po} \left(1 + \frac{1}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1} \right)^p \exp\left(-\frac{2H}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1}\right) \quad (2.16)$$

where B_{po} is a proportionality constant, $\hbar\omega$ is the phonon energy, p is the multi-phonon number, and H the Huang-Rhys factor. The increase of threshold current with temperature is then a consequence of the increased multi-phonon recombination rate with temperature. The temperature dependence of threshold current of GaInAsP/InP lasers at wavelengths of 1.1, 1.27 and 1.48 μm are calculated to fit the experimental results by choosing suitable densities of the deep level traps of 0.6, 1.4, and $1.5 \times 10^{14} \text{ cm}^{-3}$, respectively.

(3) Recombination centers with large recombination velocity at the Heterojunction interfaces have been proposed by Yano et al.⁽¹¹⁾ to be responsible for the excess temperature sensitivity of threshold current in GaInAsP/InP lasers. In this model, the non-radiative recombination at the heterojunction interfaces between the active layer and the confinement layers is given by

$$R_{nr} = \frac{S_1 + S_2}{d} n \quad (2.17)$$

where S_1 and S_2 are the interfacial recombination velocities, d is the active layer thickness and n is the density of injected carriers in the active layer. Assuming that S_1 and S_2 are relatively large and would increase from 500 - 1000 cm/sec at 20°C to 1500 - 2700 cm/sec at 70°C, this non-radiative recombination then could affect the threshold current similarly to recombination centers in the active layer.

2.4.2. Discussions and Conclusions

(i) The defect model is difficult to accept because of the fact that devices fabricated through completely different crystal growth and processing techniques have shown similar characteristic temperature. In addition, despite the great reduction of threshold current density through material and processing improvements, the temperature sensitivity of GaInAsP/InP lasers remains essentially the same.

(ii) The temperature variation of threshold current of multiple quantum well GaInAsP/InP lasers has been shown to be similar to that of ordinary devices, even though large numbers of interfaces exist in the multiple quantum well structures⁽¹¹⁾. It is then reasonable to conclude that the recombination at the heterojunction interfaces is not the dominant mechanism of the temperature sensitivity of GaInAsP/InP lasers.

This conclusion is further supported by recent measurements of carrier lifetime. Henry et al⁽¹¹⁾ have determined that the surface recombination velocity at the GaInAsP - InP interface is less than 50 cm/sec, which is much smaller than the 500 - 1000 cm/sec required to account for the observed effects in the GaInAsP/InP lasers. More importantly, this value is about an order of magnitude less than that found in the AlGaAs/GaAs double heterojunctions⁽¹²⁾.

(iii) The non-radiative recombination through defects could not be used to account for the non-linearity characteristics of the LEDs. As shown in section 2.1.1, the non-radiative recombinations through defects at interfaces or in the active layer would cause superlinearity in the light output power versus current characteristics of the LEDs due to their weaker carrier density dependence than radiative recombinations.

(iv) Carrier leakage phenomenon in GaInAsP/InP light emitting devices could not be explained by the non-radiative recombination via defect model.

2.5. Carrier Heating Effect

2.5.1. The Carrier Heating Model

In the carrier heating model, the carrier temperature in the active layer is assumed to be substantially higher than the lattice temperature: depending on the injection current densities, the carrier temperature could be several tens of degrees, or even 30% higher than the lattice temperature⁽²²⁾. The source of carrier heating could be the result of non-radiative Auger recombinations and/or intervalence band absorptions, where in both cases, energetic carriers are generated. Assuming these mechanisms are stronger in GaInAsP than in GaAs, the differences observed between GaInAsP/InP and AlGaAs/GaAs₂ devices are then explained.

Thus, the non-linearity of the LEDs is attributed to the increased carrier temperature with injection current. Similarly, the temperature dependence of threshold current is caused by the higher current required to reach the lasing condition at increased temperature. That is, at low temperature, carrier temperature is approximately equal to lattice temperature; when device temperature increases, the difference between carrier temperature and lattice temperature increases. Such effect is well illustrated in Fig. 2-7.

Fig. 2-7 Variation of carrier temperature deduced from the electroluminescence spectra as a function of drive current. The insert shows the variation of total luminescence output over the same current range.

after Shah et al⁽²²⁾

2.5.2. Discussions and Conclusions

(i) The carrier heating effect has to be accompanied by other mechanism(s), such as Auger recombination and intervalence band absorption. It is, therefore, an induced effect and its validity depends on other model(s).

(ii) Henry et al⁽¹¹⁾ studied an LED and three different types of lasers and found no evidence of increase in carrier temperature from a low level of excitation to the lasing threshold or to an injection current of 400 mA in the LED. The carrier heating is not observed at lattice temperature from 300 to 343°K. Etienne et al⁽¹²⁾ who observed substantial difference in carrier and lattice temperatures also measured very little carrier heating in devices they have characterized later. However, in all devices where carrier heating is negligible, the usual non-linearity in LEDs and excess temperature sensitivity of threshold current remained, indicating that carrier heating is not a fundamental cause of the properties concerned.

(iii) The degree of carrier heating is determined by the difference between the rate of energy put into the carrier system and the rate of energy loss from carriers to the lattice. The energy input to the carrier system could be the result of non-radiative Auger recombination and/or intervalence band absorption. Since the coefficient of

intervalence band absorption in GaInAsP is relatively small (about 14 cm^{-1}), the generation rate of energetic carriers in LEDs from such absorption would be extremely low due to the low photon density in the active layer. Assuming Auger recombination is responsible, then the source of energy input to the carrier system can be estimated by Cn^3E , where C is the coefficient of the relevant Auger recombination, n is the carrier density, E is the energy supplied to the carriers by the Auger processes and is approximately equal to the band gap of the material where the recombinations take place. At lasing threshold, n is about $2 \times 10^{18} / \text{cm}^3$ and using $C = 5 \times 10^{-32} \text{ cm}^3 / \text{sec}$, the rate of energy input to the carrier system is about $6 \times 10^7 \text{ W/cm}^3$. Using the value of energy relaxation rate of energetic carriers of the order of 10^{11} eV/sec (see chapter 4 for details), the rate of energy loss from the carriers to the lattice is greater than $3 \times 10^{10} \text{ W/cm}^3$, which is more than 500 times higher than the rate of energy input to the carrier system. Thus, carriers should not be heated in the active layer of the devices, which is consistent with the observations of Henry et al⁽¹¹⁾.

In order to heat up the carriers by 40°C above lattice temperature, the energy relaxation time should be longer than $50 \times 10^{-12} \text{ sec}$. Such a long relaxation time is more than an order of magnitude larger than the measured energy relaxation times of $2.5\text{--}5.6 \times 10^{-12} \text{ sec}$ in GaAs and $1.7\text{--}2.7 \times 10^{-12} \text{ sec}$ in InP⁽¹²⁾.

2.6. Carrier Leakage over Heterojunction Barrier

2.6.1. Carrier leakage Mechanisms

Carrier leakage over the heterojunction barrier has been studied in AlGaAs/GaAs lasers and LEDs^(1,2,3). Such leakage has been attributed to carriers in the active layer with energies exceeding the band discontinuities between the active layer and the confinement layer materials. A similar approach has then been extended to the GaInAsP/InP lasers and LEDs^(4,5). However, the observation of carriers leaking over a GaInAsP/InP heterojunction barrier directly in various specially designed devices^(6,7,8,9,10), as well as conventional devices^(11,12,13) has stimulated studies for additional leakage mechanism(s) to account for the anomalous properties of the GaInAsP/InP devices.

(1) One leakage model attributes charge carrier leakage over the heterojunction barrier to normally injected carriers whose energies exceed the band discontinuities. The densities of such carriers in the active layer can be estimated from the Fermi level, the density of states in the band and the band discontinuity. For example, the distribution of injected electrons in the conduction band can be determined by the products of the Fermi distribution function and the density of states in the conduction band. Using the parabolic band approximation and ignoring

contributions from the indirect bands, the electron density at energy E is given by

$$n(E) = \frac{1}{2\pi^2} \left(\frac{2m_e}{\hbar^2} \right)^{3/2} (E - E_c)^{1/2} \left(1 + \exp \frac{E - F_n}{kT} \right)^{-1} \quad (2.18)$$

where $E - E_c$ is the energy above the band edge, F_n is the quasi-Fermi level which can be determined from the total injected electron density

$$n = \frac{1}{2\pi^2} \left(\frac{2m_e}{\hbar^2} \right)^{3/2} \int_0^\infty (E - E_c)^{1/2} \left(1 + \exp \frac{E - F_n}{kT} \right)^{-1} dE \quad (2.19)$$

Thus, the density of electrons whose energies exceed the conduction band discontinuity of the active and the confinement layers can be calculated as

$$n_e = \frac{1}{2\pi^2} \left(\frac{2m_e}{\hbar^2} \right)^{3/2} \int_{\Delta E_c}^\infty (E - E_c)^{1/2} \left(1 + \exp \frac{E - F_n}{kT} \right)^{-1} dE \quad (2.20)$$

Figure 2-8 shows schematically the energy distributions of electrons and holes, and the portion of electrons and holes whose energies exceed the band discontinuities.

The leakage currents are then limited by the rates at which these carriers drift and diffuse into the confinement layers. Since the concentration of the carriers with energies exceeding the band discontinuity is strongly temperature dependent, the leakage thus increases with

temperature. This is consistent with the temperature sensitivity of the threshold current.

Yano et al⁽¹¹⁾ used the diffusion model to derive an activation energy of 0.3 eV for the electron leakage and concluded that below room temperature the leakage is negligible, but that it exhibits a fast increase above room temperature. Olshansky et al⁽¹²⁾ used the drift model for devices with lightly doped InP confinement layer and concluded that although carrier leakage may contribute to the excess temperature sensitivity of the threshold current, it is not the major factor for the GaInAsP/InP devices.

(2) The carrier leakage over the heterojunction barrier has also been proposed to be enhanced by the carrier heating effect, where the carrier temperature is assumed to be substantially higher than the lattice temperature. Under this condition, the concentration of carriers with energies exceeding the band discontinuity would be increased and thus the leakage current would also be increased. Using this effect, Chiu et al⁽¹³⁾ have concluded that the electron leakage current increases from 11, 3, 0.4 percent of the total injection current without hot carriers to 22, 11, 4 percent with carrier heating effect at lattice temperature of 290°K for lasers of 1.2, 1.3, and 1.5 μm wavelength, respectively.

Fig. 2-8 Schematic diagrams of energy distributions of electrons and holes at 25°C and 70°C. F_n & F_p are the quasi-Fermi levels, E_{c2} , E_{v2} , E_{c3} , & E_{v1} are the band edges of GaInAsP and InP, respectively. after Yano et al.⁽²⁰⁾

2.6.2. Discussions and Conclusions

(i) Carrier leakage through GaInAsP/InP and AlGaAs/GaAs heterojunction barriers has been directly observed. The effect on device characteristics should be incorporated into any realistic device models.

(ii) All direct observations indicate that the leakage is dominated by electrons, rather than holes. Therefore, energetic holes arising either from intervalence band absorptions or from valence band Auger recombinations are not the major source of leakage.

(iii) An increment of leakage current with injection current, has been observed in a special surface emitting LED structure by Yamakoshi et al⁽¹¹⁾ as shown in Fig. 2-9. Using different area LEDs, they have demonstrated that the electron leakage is uniquely determined by the carrier density in the active layer.

A similar increment of leakage current with injection current and with temperature has also been directly measured by Chen et al⁽¹²⁾ on a unique laser/bipolar transistor structure, with similarly lightly doped p-type InP confinement layer as the LED of Yamakoshi et al⁽¹¹⁾. Both experimental results implied that in devices with lightly doped p-type InP confinement layers, drift electron leakage

current is significant. This is also consistent with the carrier lifetime and spontaneous emission measurement in lasers with lightly doped p-type confinement layers⁽¹¹⁾.

(iv) However, measuring the electrical derivative characteristics of GaInAsP/InP laser diodes, Dutta et al⁽¹²⁾ and Pollack et al⁽¹³⁾ have concluded that although drift leakage current is not important in their devices, the lasers exhibit the usual threshold current dependence on temperature. Thus, drift leakage current alone could not be responsible for the temperature sensitivity of threshold current in GaInAsP/InP lasers.

(v) Calculation of leakage current using a model based on normal injected electrons whose energies exceed the conduction band discontinuity predicts negligible leakage in GaInAsP/InP lasers emitting at 1.55 μm wavelength, even at temperatures around 100°C, due to increased heterojunction barrier height. This is clearly in contradiction with experimentally measured higher temperature dependence of threshold current in GaInAsP/InP lasers emitting at 1.5 μm wavelength than for these emitting at 1.3 μm .

(a)

(b)

Fig. 2-9 (a) Emission spectra observed at room temperature for different dc currents (10–200 mA, roughly correspond to current densities of 0.8–16 kA/cm²)

(b) Peak intensities of two emissions at λ_2 and λ_4 , represented in (a), plotted as a function of operating current.

after Yamakoshi et al⁽¹¹⁾

(vi) Since carrier heating has been determined not to be an intrinsic mechanism in GaInAsP/InP light emitting devices as discussed in section 2.5.2, it is then reasonable to conclude that carrier leakage enhanced by the carrier heating effect is not a necessary mechanism for determining the properties of GaInAsP/InP lasers and LEDs. On the other hand, even if carrier heating exists, the decrease of leakage current from 11% to 4% as wavelength increases from 1.3 μm to 1.5 μm , as obtained by Chiu et al⁽¹¹⁾, would contradict the higher temperature sensitivity of threshold current of 1.5 μm lasers as compared to 1.3 μm devices.

2.7. Development of Unified Model

Various attempts have been made, to date, to develop a unified model to account for the observed characteristics of the GaInAsP/InP double heterojunction light emitting devices. Dutta and Nelson⁽¹²⁾ have used Auger recombination in conjunction with in-plane superluminescence in surface emitting LEDs. Mozer et al⁽¹³⁾ suggested that Auger recombination and intervalence band absorption contributed to additional threshold current increments of 50% and 23%, respectively, relative to the "ideal" case, in lasers. Su et al⁽¹⁴⁾ combined Auger recombination with electron leakage over the heterojunction barrier due to injected electrons whose energies exceed the conduction band discontinuity of the GaInAsP active and the InP confinement layers. Chiu et

al⁽¹⁾ combined Auger recombination and electron leakage enhanced by the carrier heating effect induced by the Auger recombination.

In view of the conclusions from the various mechanisms, each of these models has serious limitations; either in the sense of applicability to only certain types of devices, or in the sense of consistency with experimental results.

However, in the analysis of temperature dependence of threshold current of GaInAsP/InP lasers, Casey⁽²⁾ has pointed out that Auger recombination induced leakage must be included to account for the observed characteristic temperature of these devices, and even though without analytic analysis, discussed the general approach for modelling such leakage.

In this work, a unified analytic model is proposed. This model is based on the Auger recombination mechanism in conjunction with the Auger recombination induced energetic carrier leakage. In contrast with the electron leakage enhanced by the carrier heating, the leakage is a direct consequence of the Auger induced energetic carriers. By calculating the energy relaxation behavior of these energetic carriers, a rate equation governing the density of the energetic carriers is derived, which, in combination with the rate equation of the injected carriers, determines

the properties of the GaInAsP/InP light emitting devices that are substantially different from the characteristics of devices using AlGaAs/GaAs materials.

It is found that this unified model not only can account well for the difference between devices made on GaInAsP/InP and AlGaAs/GaAs materials, but also it is applicable for both lasers and LEDs. Carrier leakage results calculated from this model agree excellently with the experimental results, both in terms of temperature effect and wavelength dependence. The analytic results of this unified model on other properties of the lasers and LEDs are also consistent with observed properties and phenomena.

High energy emission caused by carrier leakage over the heterojunction barrier into the InP confinement layers was first observed by Moser et al⁽¹⁴⁾. Chen et al⁽¹⁵⁾ have measured the spatial distribution of the high energy emissions. Recent results of Zhuang et al⁽¹⁶⁾ through lateral photoluminescence studies have revealed that the integrated intensity of the 950 nm emission has a different dependence on the active layer injected carrier density than the 1.3 μ m wavelength emission. As shown in Fig. 2-10, the integrated intensity of the 950 nm emission, I_{950} , as a result of leakage of carriers from the active layer into the InP confinement layers showed a dependence on the carrier

density of $I_{950} \propto n^{2.4-3.0}$; whereas the integrated intensity of the 1.3 μm emission, $I_{1.3}$, arising from radiative recombination in the GaInAsP active layer, showed a relation of $I_{1.3} \propto n^2$. Using spatially resolved 950 nm emission measurement, they also found that the 950 nm emissions exist in both the p-InP and the n-InP confinement layers. This provides direct evidence that carrier leakage from the GaInAsP active layer into the InP confinement layers is associated with non-radiative Auger recombination in the active layer and supports strongly the model of this work.

In the next two chapters, the Auger recombination processes and the Auger induced leakage are discussed, and then the unified model is described.

Fig. 2-10 Injection carrier concentration dependence of integrated intensity of 1.3 μm (●) and 950 nm (○) band for three laser diodes.

after Zhuang et al.⁽²²⁾

3. AUGER RECOMBINATION

This chapter begins the development of a unified model for GaInAsP/InP lasers and LEDs based on Auger recombination effects. In the unified model, the properties of the light emitting devices on GaInAsP/InP materials are affected by the non-radiative Auger recombinations through two effects: the loss of injected carriers through the non-radiative recombination processes and through the leakage of Auger recombination induced energetic carriers over the heterojunction barriers. Both of these effects will depend on the Auger recombination rates under the operating conditions of the devices. In this chapter, various relevant Auger recombination processes are first described, and then experimental and theoretical methods for determining the Auger recombination coefficients are described as well as the limitations.

3.1. Direct Band to Band Auger Recombination Processes

Direct or phonon-less band to band Auger recombinations have been extensively studied in recent years since the early work of Beattie and Landsberg⁽¹⁾. Some of the relevant processes that are concerned in this work are schematically illustrated in Fig. 3-1. These Auger recombinations are labeled as CHCC, CHLH, and CHSH, by using the nomenclature based on the actual electron transitions in the processes.

radiative

Auger recombinations

Fig. 3-1 Schematic diagrams of radiative and various direct band to band Auger recombination processes.

The CHHH process is not shown due to its insignificance as compared with other processes.

The Auger recombination rate per unit volume through the two-carrier scattering process with initial and final energies and wavevectors $E_1, E_2, \bar{k}_1, \bar{k}_2$, and $E'_1, E'_2, \bar{k}'_1, \bar{k}'_2$, respectively, can be expressed as (**)

$$R = \frac{2\pi}{h} \left(\frac{1}{8\pi^3} \right)^3 \int T(1,1',2,2') P(1,1',2,2') d\bar{k}_1 d\bar{k}'_1 d\bar{k}_2 d\bar{k}'_2 \quad (3.1)$$

where $P(1,1',2,2')$ is the product of the occupancy probability of the various states involved in the Auger process, and $T(1,1',2,2')$ is the transition probability of the two-carrier scattering process.

The product of the occupancy probability $P(1,1',2,2')$ of the four states involved in the Auger process can be viewed as the difference between the probabilities of the Auger recombination process of a charge carrier pair and the reverse process of creating a pair. Basically, a particular Auger recombination could take place only if the four states involved are in their appropriate occupancy states.

For example, the direct band to band CHCC Auger process as shown in Fig. 3-1 could occur only if states $|1\rangle$ and $|2\rangle$ are occupied by electrons, while state $|1'\rangle$ is occupied by a hole and state $|2'\rangle$ is not occupied by an electron. As the

occupancy probabilities of the states are described by the Fermi-Dirac distribution statistics, the product of the occupancy probability of the states involved in the CHCC Auger process is given by

$$P(1,1',2,2') = f_c(1)f_v(1')f_c(2)\{1-f_c(2')\} \\ - \{1-f_c(1)\}\{1-f_v(1')\}\{1-f_c(2)\}f_c(2') \quad (3.2)$$

where $f_c(1) = \left(1 + \exp \frac{E_1 - F_n}{kT}\right)^{-1}$

$$f_v(1') = \left(1 + \exp \frac{E'_1 - F_p}{kT}\right)^{-1}$$

$$f_c(2) = \left(1 + \exp \frac{E_2 - F_n}{kT}\right)^{-1}$$

$$f_c(2') = \left(1 + \exp \frac{E'_2 - F_n}{kT}\right)^{-1}$$

The quantities F_n and F_p are the quasi-Fermi levels for the electrons and holes measured from the conduction band and the valence band edge, respectively, where F_p is positive as measured downward into the valence band. Thus f_c and f_v are the occupancy probabilities for electrons or holes at the states denoted. Therefore, unless the carrier density is very high, $f_c(2')$ could be approximated to be zero.

In analogy, the product of the occupancy probability of the states involved in other direct band to band Auger recombination processes can also be derived.

The transition probability of the two-carrier scattering process $T(1,1',2,2')$ can be expressed as^(*)

$$T(1,1',2,2') = |M_{if}|^2 \delta(\bar{k}_1 - \bar{k}_f) \delta(E_1 - E_f) \quad (3.3)$$

where $\bar{k}_1 = \bar{k}_1 + \bar{k}_2$, $\bar{k}_f = \bar{k}_1' + \bar{k}_2'$, $E_1 = E_1 + E_2$, $E_f = E_1' + E_2'$, respectively. M_{if} is the matrix element of the interaction potential, determined by the position of the interacting carriers. Beattie and Landsberg^(**) used the hypothesis that the interaction Hamiltonian for any of the Auger processes could be represented by the screened carrier-carrier Coulomb interaction, i.e.,

$$\bar{H} = \frac{e^2}{\epsilon \bar{r}} e^{-\lambda \bar{r}} \quad (3.4)$$

where $\bar{r}$ is the relative distance between the two interacting carriers, λ is the screening factor describing the influence which is exerted on the two interacting carriers by other carriers due to excitation and/or doping, ϵ is the effective dielectric constant representing the effect of the inner electrons, particularly of the valence electrons. They then derived the expression for the quantity $|M_{if}|^2$ as

$$\begin{aligned} |M_{if}|^2 = & \left| \frac{4\pi e^2}{\epsilon} \right|^2 \left| \left| \frac{F(1,1')F(2,2')}{\lambda^2 + g^2} \right|^2 + \left| \frac{F(1,2')F(2,1')}{\lambda^2 + h^2} \right|^2 \right. \\ & \left. + \left| \frac{F(1,1')F(2,2')}{\lambda^2 + g^2} - \frac{F(1,2')F(2,1')}{\lambda^2 + h^2} \right|^2 \right| \quad (3.5) \end{aligned}$$

where $g^2 = |\bar{k}_1 - \bar{k}_1'|^2 = |\bar{k}_2' - \bar{k}_2|^2$, $h^2 = |\bar{k}_1 - \bar{k}_2'|^2 = |\bar{k}_1' - \bar{k}_2|^2$. The $F(i,j)$'s are the overlap integrals of the periodic parts of the Bloch functions and their magnitudes depend on the interatomic spacing and potential in the semiconductor.

It should be emphasized that the wavevector and energy conservation must be observed for the four states involved in each direct band to band Auger process. As shown by Beattie and Landsberg(''), this momentum and energy conservation leads to a minimum or threshold energy E_{th} for the excited Auger state to participate in each of the Auger processes. Consequently, the recombination rate is proportional to an Arrhenius factor $\exp(-E_{th}/kT)$, which implies a strong temperature sensitivity of direct band to band Auger processes, unless the threshold energy is very low.

3.2. Phonon-Assisted Band to Band Auger Recombination Processes

In analogy to the direct band to band Auger processes, the relevant phonon-assisted band to band Auger recombinations are schematically illustrated in Fig. 3-2. These processes are labeled as phonon-assisted CHCC, CHLH, and CHSH, respectively, where the phonon scattering is assumed to occur in the heavy hole band because this process gives the

largest Auger recombination rate amongst the phonon-assisted processes.

The phonon-assisted Auger recombination is a second order process, and the recombination rate per unit volume is given by (3.5)

$$R = \frac{2\pi}{n^2} \left(\frac{1}{8\pi^3} \right)^4 \int T(1,1',2,2',\bar{q}) P(1,1',2,2') d\bar{k}_1 d\bar{k}_1' d\bar{k}_2 d\bar{k}_2' d\bar{q} \quad (3.6)$$

where $P(1,1',2,2')$ is the product of the occupancy probability of the various states involved in the Auger process and is given by equation (3.2). $T(1,1',2,2',\bar{q})$ is the transition probability of the phonon-assisted two-carrier scattering process and is expressed by Lochmann (3.1) as

$$T(1,1',2,2',\bar{q}) = \frac{|M_{if}|^2 |M_{cp}|^2}{|E_m - E_1|^2} \delta(\bar{k}_1 - \bar{k}_f \pm \bar{q}) \delta(E_1 - E_f \pm \hbar\omega) \quad (3.7)$$

where $\bar{k}_1 = \bar{k}_1 + \bar{k}_2$, $\bar{k}_f = \bar{k}_1' + \bar{k}_2'$, $E_1 = E_1 + E_2$, $E_f = E_1' + E_2'$, and $\bar{q}$ and $\hbar\omega$ are the wavevector and energy of the phonon involved in the process, and

$|E_m - E_1| = |E_H(\bar{k}_1 - \bar{q}) - E_H(\bar{k}_1') \pm \hbar\omega| = |E_H(\bar{k}_1 + \bar{k}_2 - \bar{k}_2') - E_H(\bar{k}_1') \pm \hbar\omega|$, where $E_H(\bar{k})$'s are energies in the heavy hole band at wavevector $\bar{k}$.

Phonon-Assisted

CHCC-

CHLH

CHSH

Fig. 3-2 Schematic diagrams of phonon-assisted Auger recombination processes. The phonon scattering is indicated by a wavevector $\vec{q}$ in the heavy hole band.

M_{if} is the matrix element of the interaction potential, determined by the position of the interacting carriers as described in section 3.1. The quantity $|M_{cp}|^2$, which represents the carrier-phonon interaction, is derived by Lochmann⁽¹¹⁾ as

$$|M_{cp}|^2 = |M(\bar{q})|^2 (1 + 2N_{\bar{q}}) \quad (3.8)$$

where $N_{\bar{q}}$ denotes the number of phonons of wavevector $\bar{q}$, and $M(\bar{q})$, which depends on the type of phonon scattering processes, is the strength of the interaction for the emission or absorption of a phonon of wavevector $\bar{q}$.

The phonon scattering can be classified into acoustic and optical scattering mechanisms. The quantity $|M(\bar{q})|^2$ has been derived by Lochmann⁽¹¹⁾ for various scattering processes. In the case of acoustic phonons, if the scattering is caused by acoustic waves shifting the atoms at lattice sites (acoustic deformation potential phonon scattering),

$$|M(\bar{q})|^2 = D^2 \hbar \omega / 2c_l \quad (3.9a)$$

where D is the deformation potential and c_l is the spherically averaged longitudinal elastic constant. Note that since $\hbar \omega \ll kT$ for acoustic phonons, the Bose statistics $N_{\bar{q}} = (\exp(\hbar \omega / kT) - 1)^{-1}$ for acoustic phonons can be approximated by $N_{\bar{q}} = kT / \hbar \omega$. Therefore, for acoustic

deformation potential phonon scattering, $|M_{cp}|^2 = D^2 kT/c_l$, which is independent of the wavevector $\bar{q}$ of the phonons.

In the case of scattering caused by acoustic wave induced electric field in the direction of propagation of the acoustic waves (piezoelectric potential scattering),

$$|M(\bar{q})|^2 = e^2 P^2 \hbar \omega / 2 q^2 \quad (3.9b)$$

where P is the isotropic piezoelectric coefficient, e is the electron charge.

In the case of optical phonons, if the scattering is caused by relative displacement of two sublattices (nonpolar optical deformation potential phonon scattering),

$$|M(\bar{q})|^2 = E^2 \hbar \omega / 2 \bar{c} \quad (3.9c)$$

where E is the optical mode deformation potential, $\bar{c}$ is the averaged elastic constant, determined by the spherically averaged elastic constants for the longitudinal and transverse modes c_l and c_t as $\bar{c} = c_l/3 + 2c_t/3$.

Finally, in the case that the scattering is caused by differently charged ions vibrating in opposite directions (polar optical phonon scattering),

$$|M(\bar{q})|^2 = \frac{2\pi e^2 \hbar \omega}{\epsilon_0 q^2} \left(\frac{1}{k_0} - \frac{1}{k_\infty} \right) \quad (3.9d)$$

where k_0 and k_∞ are the static and high frequency relative dielectric constants, respectively, and ϵ_0 is the permittivity of free space.

It should be mentioned here that, in contrast to direct band to band Auger processes, for the phonon-assisted band to band Auger processes, the momentum (wavevector) conservation requirements for the four states in the process is relaxed from the phonon scattering process, i.e., $\bar{k}_1 + \bar{k}_2 = \bar{k}'_1 + \bar{k}'_2 \pm \bar{q}$, where the plus and minus signs correspond to phonon absorption and emission, respectively. Therefore, there is no threshold energy requirement for the excited Auger states to participate in each of the Auger processes, and hence the phonon-assisted Auger processes do not have strong temperature dependence.

3.3. Evaluation of the Auger Recombination Rate

Since Auger recombination was proposed in the early 1980's⁽¹⁻⁴⁾ as one of the potential mechanisms determining the non-linearity of the light output power versus current characteristics of light emitting diodes and the temperature sensitivity of threshold current of lasers employing GaInAsP lattice matched to InP, considerable efforts have been devoted to the determination of the Auger recombination

rates in the quaternary semiconductor material GaInAsP, both experimentally and theoretically. To date, although uncertainty still remains in the absolute values of the Auger recombination coefficients and controversy exists even in the conclusion of which Auger recombination mechanism will be dominant in the material, there is an increasing trend towards accepting the fact that Auger recombination and related processes are the determining, and perhaps the only, factor which account for the differences between GaInAsP/InP light emitting devices and their AlGaAs/GaAs counterparts.

In this section, methods of determination of Auger recombination rates experimentally are first briefly described and the resultant Auger recombination coefficients compared. Theoretical approaches for calculating the Auger recombination rates are then discussed, especially the uncertainties involved in the calculations. The main aim here is to point out that theoretical and experimental work in this area of understanding the Auger recombination processes on the GaInAsP/InP devices is lagging behind the technology advancement in developing such devices, and is a subject of future research.

3.3.1. Experimental Methods for Determining Auger Recombination Rates

Auger recombination rates in GaInAsP lattice matched to InP have been evaluated through analysing device characteristics^(2-4,7,11), as well as the dynamic behavior of photoexcited carriers in GaInAsP layers^(7,11) and heterostructure layers⁽¹¹⁾. In both approaches, experimental data were fitted to theoretical models using a prior assumption.

The early method of deriving the Auger recombination coefficient using devices involved the measurement of the intensity of the spontaneously emitted light in a GaInAsP/InP surface emitting LED as a function of injection current. A curve fitting procedure, based on the principle that Auger recombination rate and spontaneous radiative recombination rate have different carrier density dependences, as shown in equation (2.5), is used to obtain the Auger recombination coefficients⁽²⁻⁴⁾. A similar fitting technique involving the measuring of the rise and decay of the spontaneously emitted light in LEDs as a function of drive current is based on the same assumption⁽¹¹⁾. However, in this case, the device capacitance effect has to be separated. An improved technique, which reduces the capacitance effect, measures the carrier lifetime as a function of device current by

observing the optical risetime produced by a small signal pulse⁽⁴⁾.

In the optical excitation method, the time resolved decay of photoexcited carrier induced luminescence is measured. Since nonlinear carrier dynamics are involved, the temporal development of the carrier density and photon absorption and the spatial averaging of the bleaching have to be taken into consideration. †

Table 3-1 lists the Auger recombination coefficients of GaInAsP with compositions corresponding to wavelength of 1.3 μm , at room temperature, derived from experimental results in various laboratories.

As mentioned before, the Auger recombination coefficients listed in Table 3-1 are obtained through data fitting. Without a proven theoretical model, such approaches face a serious risk that a satisfactory model is not unique and that a relatively good fit to the experimental data can be obtained over a range of values by compensating the effect of one coefficient against the others. For example, Thompson⁽⁵⁾ demonstrated that using the data of Su et al⁽⁶⁾, he could obtain an Auger recombination coefficient three times larger than the value obtained by Su et al⁽⁶⁾. The only difference is that a different model was used by Thompson⁽⁵⁾. However, in each case, almost perfect fitting

was obtained. This is also seen by assuming a carrier dependent radiative recombination⁽¹¹⁾ in the results of Chik et al⁽¹²⁾, where the Auger recombination coefficient would then be about 7.5×10^{-22} cm³/sec instead of 1×10^{-22} cm³/sec. The value could be even lower if a correct leakage model is applied.

The large difference in Auger recombination coefficients obtained by Su et al^(13,14), as shown in Table 3-1, has been explained by the dependence of the Auger recombination coefficient on the doping concentration of the GaInAsP active layer, i.e., with doping increased from $1-2 \times 10^{17}$ cm⁻³ to $1-2 \times 10^{18}$ cm⁻³, the Auger recombination coefficient increases from 0.1×10^{-22} cm³/sec to 0.9×10^{-22} cm³/sec. But recent photoexcited carrier induced photoluminescence measurements on undoped (7×10^{15} cm⁻³) and heavily zinc doped (2×10^{18} cm⁻³) materials by Mottos et al⁽¹⁵⁾ did not reveal such a doping concentration dependence.

	Auger Coefficient (cm ⁶ /sec)	Radiative Coefficient (cm ⁶ /sec)
Chik et al ⁽²⁾	1×10^{-22}	1.2×10^{-10}
Su et al ⁽⁷⁸⁾	0.9×10^{-22}	0.8×10^{-10}
Dutta & Nelson ⁽³³⁾	$1.2 \pm 0.4 \times 10^{-22}$	1.2×10^{-10}
Uji et al ⁽⁴⁾	$0.3 - 0.8 \times 10^{-22}$	$0.7 - 1.5 \times 10^{-10}$
Mozer et al ⁽³⁴⁾	0.5×10^{-22}	0.8×10^{-10}
Su et al ⁽⁶³⁾	0.1×10^{-22}	$0.7 - 0.8 \times 10^{-10}$
Heinen et al ⁽⁷³⁾	0.15×10^{-22}	5×10^{-10}
Sermage et al ⁽⁷⁴⁾	$0.3 \pm 0.1 \times 10^{-22}$	
Winter & Ippen ⁽⁷⁵⁾	0.15×10^{-22}	1.2×10^{-10}
Garbuzov et al ⁽⁷⁷⁾	0.07×10^{-22}	$1.2 - 1.7 \times 10^{-10}$
Mottos et al ⁽⁷⁶⁾	0.43×10^{-22}	0.79×10^{-10}

Table 3-1 Experimentally determined Auger recombination coefficient in 1.3 μ m GaInAsP at room temperature.

3.3.2. Theoretical Calculation of Auger Recombination Rate

The determination of Auger recombination rates using equations (3.1) and (3.6) critically depends on the band structure and the wavefunction overlap integrals.

For the band structure, the most readily available one is the four-band Kane model, where the conduction, light hole and split-off bands are modified to include the effects of the bands other than the four bands with parameters A' , M , and L' as (**)

$$\begin{aligned} E_c &= \frac{\hbar^2 k^2}{2m_0} + E'_c + (a_c^2 A' + b_c^2 M + c_c^2 L') k^2 \\ E_l &= \frac{\hbar^2 k^2}{2m_0} + E'_l + (a_l^2 A' + b_l^2 M + c_l^2 L') k^2 \\ E_s &= \frac{\hbar^2 k^2}{2m_0} + E'_s + (a_s^2 A' + b_s^2 M + c_s^2 L') k^2 \end{aligned} \quad (3.10)$$

where m_0 is the free electron mass, and $E'_c > E'_l > E'_s$ are the solutions of the following equation

$$E'(E' - E_g)(E' + \Delta) - \frac{\hbar^2 k^2}{2m_0} E_p (E' + \frac{2}{3} \Delta) = 0 \quad (3.11)$$

where E_g is the band gap, Δ is the split off band separation, and E_p is the energy equivalent of the principal interband matrix element, representing the coupling between the valence and the conduction bands. The quantities a_c , b_c , c_c are given by

$$a_c^2 = \frac{\hbar^2 k^2}{2m_0} E_p (E'_c + \frac{2}{3} \Delta)^{-2} N \quad (3.12)$$

$$b_c^2 = \frac{2}{9} \Delta^2 (E'_c - E_g)^2 N$$

$$c_c^2 = (E'_c - E_g)^2 (E'_c + \frac{2}{3} \Delta)^2 N$$

where the normalizing coefficient N is determined from

$a_c^2 + b_c^2 + c_c^2 = 1$. The quantities a_l , b_l , c_l and a_s , b_s , c_s are given by similar expressions with E'_l and E'_s in place of E'_c .

The values of E_p , A' , M , L' have been calculated by Lawaetz⁽¹¹⁾ for the binary of InP, GaAs, InAs and GaP, which can be used to estimate for the quaternary GaInAsP.

For the overlap integrals, Antoncik and Landsberg⁽¹²⁾, and Beattie and Smith⁽¹³⁾ showed that $|F(i,j)|^2 = 1$ when i,j are in the same band, and $|F(i,j)|^2 = \frac{n^2 \alpha_{ij}}{2m_0 |E_i - E_j|} |\bar{k}_i - \bar{k}_j|^2$ when i,j are in different bands. Taking into consideration the most probable transition, Beattie and Smith⁽¹³⁾ approximated α_{ij} 's by α_{CH} , α_{SH} and α_{LH} according to the bands involved, and their values depend entirely on the band structures. Using the band model of Kane, they approximated α_{CH} , α_{SH} and α_{LH} by

$$\alpha_{CH} = \frac{E_p}{3E_g} \quad (3.13)$$

$$\alpha_{SH} = \frac{E_p}{3|E'_s|} \frac{(\frac{n^2 k^2}{2m_0}) E_p (E'_s + \frac{2}{3} \Delta)^2}{(\frac{n^2 k^2}{2m_0}) E_p (E'_s + \frac{2}{3} \Delta)^2 + \frac{2}{9} \Delta^2 (E'_s - E_g)^2 + (E'_s - E_g)^2 (E'_s + \frac{2}{3} \Delta)}$$

$$\alpha_{LH} = \frac{2E_p}{9(E'_l - \frac{n^2 k^2}{2m_0})} \frac{E'_l (E'_l + \Delta) (E'_l + \frac{2}{3} \Delta)}{2E_l^3 + (3\Delta - E_g)E_l^2 + \frac{4}{3} \Delta(\Delta - E_g)E'_l - \frac{2}{3} \Delta^2 E_g}$$

For the GaInAsP with composition corresponding to 1.3 μm wavelength, using Boltzmann degenerate statistics, Sugimura⁽¹⁾ concluded that the direct band to band CHSH Auger process is dominant with a coefficient of about 1.1×10^{-22} cm^3/sec . On the other hand, applying Fermi non-degenerate statistics, Dutta and Nelson⁽²⁾ calculated that the direct band to band CHCC process with a coefficient of 1×10^{-22} cm^3/sec is most important.

Garbuzov et al⁽³⁾ and Gelmont et al⁽⁴⁾ adopted accurate expressions of the overlap integrals and found that the direct band to band CHSH Auger process is dominant. The coefficients that they obtained are 7.1×10^{-22} cm^3/sec and 3.3×10^{-22} cm^3/sec , respectively. This approach was recently used by Bardyszewski and Yevick⁽⁵⁾, who further incorporated in their calculations a method for determining the Fermi levels as a function of carrier concentration by numerically integrating the four-band Kane model density of states, and obtained a total Auger recombination coefficient of 3.5×10^{-22} cm^3/sec with 2.6×10^{-22} , 0.6×10^{-22} and 0.3×10^{-22} cm^3/sec for direct band to band CHSH, phonon-assisted CHCC and direct band to band CHCC processes, respectively.

In all of the above approaches, a fundamental question concerns the validity of the four-band Kane model at the threshold momentum of the Auger excited state with large k values. Parabolic bands may be a relatively good

approximation for the initial states which are close to the band edges, but may become questionable for the highly excited states with energy larger than the band gap. The conduction band and split-off band non-parabolicity has been partially taken into account by the introduction of energy dependent effective mass for the highly excited states using the k.p perturbation theory. However, Haug⁽¹¹⁾ has demonstrated that this modification is not sufficient to fully account for the real band structure effects, especially for relatively large band gap semiconductors such as GaInAsP lattice matched to InP with compositions corresponding to wavelength of 1.3 and 1.5 μm , where a difference of four orders of magnitudes in Auger coefficient of the direct band to band CHCC process is obtained by employing a realistic band structure in place of the parabolic approximation. Using a "realistic" band structure of Chelikowsky and Cohen⁽¹²⁾ derived from nonlocal pseudopotential methods, Haug⁽¹¹⁾ concluded that the phonon-assisted CHCC Auger process dominates at room temperature. The Auger recombination coefficients are 0.001, 3.96, 1.40, and 0.56×10^{-11} cm^3/sec for direct band to band CHCC, phonon-assisted CHCC, direct band to band CHSH and phonon-assisted-CHSH processes, respectively. Unfortunately, the "realistic" band structure of GaInAsP that Haug relied upon in his calculations is not available. In his calculations, the "realistic" band structure of GaInAsP is determined from the binary band structure diagrams evaluated

by Chelikowsky and Cohen⁽¹¹⁾ and the threshold energy of the related Auger process is obtained by a graphical analysis. Considering the alloying effects, such an approach may not be realistic after all.

Table 3-2 summarizes the coefficients of Auger recombinations calculated using various approaches. It should be emphasized that the uncertainty in the conclusions and especially in the coefficient values arises not only from the band model employed. Large uncertainty also comes from other assumptions and the unavailability of accurate values of band structure parameters and the relevant material parameters. For example, the screened Coulomb potential of equation (3.4) uses a screening factor to approximate the influence exerted onto the two interacting electrons by other electrons. Haug and Ekardt⁽¹²⁾ have shown that calculations based on the assumption of equation (3.4) may lead to an error of two orders of magnitude. Furthermore, the uncertainty associated with band structure parameter values can be appreciated from the error estimations of Bardyszewski and Yevick⁽¹³⁾, where they have concluded that a 10% error in effective mass would cause 50% error in the value of the Auger recombination coefficient. The possible error in this aspect can be felt by the experimental values of the effective mass of electrons in the conduction band of 0.043⁽¹⁴⁾ and 0.055⁽¹⁵⁾ for GaInAsP with composition corresponding to 1.3 μm . Other significant

errors could also result from uncertainty of many material parameters.

The wide spread of the calculated values shows that the determination of the Auger recombination coefficients theoretically is as difficult as experimentally. Comparing the values in Tables 3-1 and 3-2, one can only state that the theoretical and experimental results are comparable. Therefore, any preference for a value of the Auger recombination coefficient is rather arbitrary in nature, at least up to now. The question of adopting the values in analytic studies of device properties should be guided by the results of experiments. This approach is in fact used in most calculated work. For example, in Haug's calculation⁽¹¹⁾ there is a multiplication factor β of the Auger recombination coefficient, where $1 < \beta < 2$. The value of $\beta = 1$ is selected to have the total coefficient of Auger recombinations of 5.9×10^{-22} cm³/sec which matched best to most experimental values. This is the main reason for applying the results of Haug's⁽¹¹⁾ in this work, besides the fact that his calculations provide the most complete set of values to date.

	Auger Coefficient (cm ⁶ /sec)	Dominant Process
Sugimura (84)	$1-1.1 \times 10^{-22}$	direct CHSH
Dutta & Nelson (85)	1×10^{-22}	direct CHCC
Garbuzov et al (86)	0.71×10^{-22}	direct CHSH
Gelmont et al (87)	0.36×10^{-22}	direct CHSH
Haug (11)	0.59×10^{-22}	phonon CHCC
Bardyszewski & Yevick (88)	0.35×10^{-22}	direct CHSH

Table 3-2 Theoretically calculated Auger recombination coefficients in GaInAsP with composition corresponding to 1.3 um wavelength, at 300°K.

4. AUGER RECOMBINATION INDUCED LEAKAGE

This chapter deals with the second feature of the unified model, that is, the effects of Auger recombination induced leakage.

Non-radiative Auger recombination processes produce excited charge carriers with excess energies greater than or equal to the band gap of the material. Unless the energy loss rate of the energetic carriers is extremely high, there may exist a significant concentration of energetic carriers, at steady state, in the active layer of the devices, which could lead to excess leakages. Such leakages, therefore, would depend on the generation rate of the energetic carriers through Auger recombination processes, the energy loss rate of the energetic carriers, and the heterojunction barriers that provide carrier confinements. In this chapter, the relaxation of Auger recombination induced energetic carriers is first examined. Since many scattering mechanisms exist in the semiconductor materials, we limit ourselves to the dominant scattering process, although a similar approach could be extended to other scattering processes. By applying the generation and relaxation rates of energetic carriers, a rate equation governing the rate of change of energetic carriers in the active layer of the devices is established, which in conjunction with the leakage mechanisms, determines the leakage current of the devices.

4.1. Relaxation of Auger Recombination Induced Energetic Carriers

In polar crystals, the polarization of the crystal arising from the vibrations of the longitudinal optical (LO) phonon branch results in an additional electron - lattice interaction: the polar optical scattering. In the studies of carrier transport properties, it has been shown that the polar optical scattering is the dominant electron - phonon interaction in such crystals except at very low temperature. Thus, in polar crystals, the energetic carriers relax to the band minimum by emitting successive longitudinal optical (LO) phonons. One of these processes is schematically shown in Fig. 4-1.

The rate of change of energy of the energetic carriers due to polar optical scattering can be estimated by the product of the LO phonon energy and the difference between the probability per unit time for phonon absorption and the probability per unit time for phonon emission. Thus, the energy relaxation rate of the Auger recombination excited electrons can be expressed as

$$\left(\frac{dE}{dt} \right)_{op} = \frac{2eE_0 \hbar \omega_0}{(2m_e E)^{1/2}} \left\{ N_q \sinh^{-1} \left(\frac{E}{\hbar \omega_0} \right)^{1/2} - (N_q + 1) \sinh^{-1} \left(\frac{E - \hbar \omega_0}{\hbar \omega_0} \right)^{1/2} \right\} \quad (4.1)$$

where E is the energy of the Auger recombination excited electrons, m_e is the effective mass of electrons, N_q is the

occupation number of phonons of wavevector q interacting with the electron, $\hbar\omega_0$ is the LO phonon energy and E_0 is an effective coupling electric polarization field associated with the longitudinal optical modes and is given by

$$E_0 = \frac{e m \hbar \omega_0}{4 \pi \hbar^2 \epsilon_0} \left(\frac{1}{k_\infty} - \frac{1}{k_0} \right) \quad (4.2)$$

where k_∞ and k_0 are the high frequency (optical) and static relative dielectric constants of the material, and ϵ_0 is the permittivity of free space.

For a quaternary semiconductor such as GaInAsP in which more than one type of LO phonons exist, the energetic carriers are assumed to interact with each type of LO phonons independently. In this case, the overall energy loss rate can then be estimated as the sum of the rates from each individual type of LO phonon weighted by the corresponding mole fraction of the binary pair, i.e.

$$\begin{aligned} \left(\frac{dE}{dt} \right)_{op} = & xy \left(\frac{dE}{dt} \right)_{xy} + x(1-y) \left(\frac{dE}{dt} \right)_{x(1-y)} \\ & + (1-x)y \left(\frac{dE}{dt} \right)_{(1-x)y} + (1-x)(1-y) \left(\frac{dE}{dt} \right)_{(1-x)(1-y)} \end{aligned} \quad (4.3)$$

Assume that the four phonon energy values are as follows: the InAs - like phonon energy of 28.8 meV, the GaAs - like phonon energy of 31.6 meV, the InP - like phonon energy of 40.0 meV and the GaP - like phonon energy of 43.4

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meV. Then Fig. 4-2(a) shows the total energy loss rate of the Auger recombination excited electrons in quaternary compound of GaInAsP with composition corresponding to the lasing wavelength of 1.3 μm .

Similar calculations have also been done for the Auger recombination excited holes, as shown in Fig. 4-2(b). Since the effective mass of holes is an order of magnitude higher than the effective mass of electrons, the energy relaxation rate of energetic holes is more than three times higher than the energy loss rate of energetic electrons. The higher energy loss rate of energetic holes combined with the low mobility of holes in InP and GaInAsP thus results in a much reduced Auger recombination induced energetic hole leakage as compared with Auger recombination induced energetic electron leakage. As a consequence, in typical laser and LED structures designed on GaInAsP/InP materials, electron leakage current should be dominant, if it exists, a fact consistent with experimental observations (.....).

In the calculation, it is assumed that the phonon temperature is the same as the lattice temperature. Under this condition, the injected electron gas in the active layer of the device would not be heated up by the Auger recombination processes. This is consistent with the observations of Henry et al (..) that the carrier temperature

Fig. 4-1 Schematic diagram of relaxation processes of CHCC Auger recombination induced energetic electrons. E is the excess energy of the Auger recombination excited electron, E_g is the band gap, ΔE_c is the conduction band discontinuity of GaInAsP and InP, and $\hbar\omega_0$ is the longitudinal optical phonon energy.

Fig. 4-2(a) Energy relaxation rate of energetic electrons at 300°K in GaInAsP with composition corresponding to 1.3 μm wavelength. τ_{op} is the statistical average of relaxation time of Auger excited energetic carriers in the energy interval of $E_g - \Delta E$ as discussed in the text.

Fig. 4-2(b) Energy relaxation rate of energetic holes at 300°K in GaInAsP with composition corresponding to 1.3 μm wavelength.

is the same as the lattice temperature from a low level of excitation to lasing threshold current density or higher, over a wide range of lattice temperatures.

As indicated from Fig. 4-2, the energy relaxation rate of the energetic carriers is energy dependent. Thus, an effective energy relaxation time τ_{op} is used in this work as a phenomenological parameter to relate the energy relaxation rate of Auger recombination excited energetic carriers to the carrier leakage current. That is, τ_{op} is defined as the statistical average of the relaxation times of Auger excited energetic carriers in the energy interval of $E_g - \Delta E$, where E_g is the bandgap of the quaternary GaInAsP active layer material involved, and ΔE is the energy discontinuity in the conduction or valence bands between the active layer and the InP confinement materials. Using the value of $\Delta E_c = \Delta E_g/3$, the effective energy relaxation times of 5.2×10^{-11} second and 1.6×10^{-11} second have been determined for Auger recombination induced energetic electrons and holes, respectively, in GaInAsP with composition corresponding to 1.3 μm wavelength. This value is comparable to the experimentally determined energy relaxation times of energetic electrons in GaAs and InP, measured to be $2.5 - 5.6 \times 10^{-11}$ second and $1.7 - 2.7 \times 10^{-11}$ second, respectively, by Glover⁽¹⁰⁾, and 4.8×10^{-11} second for GaAs by Xu and Tang⁽¹¹⁾. However, it should be pointed out that the effective energy relaxation time defined in this work is not

exactly the same as the energy relaxation time used elsewhere. It is generally assumed that the energetic electron relaxes primarily by successive LO phonon emissions until it has relaxed close to the bottom of the band, and then loses its energy to the low energy injected electron gas in the case where the electron - electron collisions are more frequent than collisions with acoustic phonons. Therefore, the effective energy relaxation time defined here is solely determined by the energy loss rate through carrier - phonon interactions due to the fact that ΔE is many times greater than the LO phonon energy.

4.2. The Auger Recombination Induced Leakage Model

From the previous section, it has been noted that Auger recombinations produce energetic carriers which relax to the band bottom by successive longitudinal optical phonon emissions. Therefore, in cases where conduction band discontinuity or valence band discontinuity is comparable to or smaller than the excess energy of the Auger recombination excited energetic carriers, it is expected that some of these energetic carriers in the GaInAsP active layer would leak over the heterojunction barrier into the higher band gap InP confinement layers. In this section, this type of Auger recombination induced leakage current is analysed.

4.2.1. The Rate Equations of Auger Recombination Excited Energetic Carriers

A schematic diagram of the n-type InP / p-type GaInAsP / p-type InP heterostructure of typical light emitting devices is shown in Fig. 4-3, where the conduction band discontinuity and the valence band discontinuity provide the carrier confinement barriers for electrons and holes injected into the active layer, respectively. The density of electron and hole currents injected into the active layer are represented by J_e and J_h , respectively, and J_r is the density of recombination current in the active layer, and J_{eL} and J_{hL} are the density of electron and hole leakage currents, respectively. Since the hole leakage current is insignificant as compared with the electron leakage current (as discussed in previous section, and as shown in section 4.3.1), J_{hL} can be assumed to be zero to simplify the calculations. In this case, the recombination current density in the active layer is equal to the density of the hole injection current.

Leakage of electrons over the heterojunction barrier has been attributed previously to electrons in the active layer whose energies exceed the barrier height provided by the conduction band discontinuity of the GaInAsP active material and the InP confinement material. As discussed in chapter 2, such electrons have been assumed to arise from the higher

Fig. 4-3 Schematic energy band diagram of N-p-P double heterojunctions, where F_n and F_p are the Fermi levels for electrons and holes, ΔE_c and ΔE_v are the conduction and valence band discontinuities, J_e and J_h , J_{eL} and J_{hL} are the injected and leakage current densities of electrons and holes, respectively, and J_r is the recombination current density in the active layer.

energy tail of the energy distribution of the normally injected electrons⁽³⁾ or enhanced by the carrier heating effect of the Auger recombination with the assumption that the average carrier temperature is substantially higher than the lattice temperature⁽³⁾. In view of the discrepancies between experimental results and these previous models, an Auger recombination induced energetic carrier leakage model is proposed in this work.

In the Auger recombination induced energetic carrier leakage model, the concentration of the carriers whose energies exceed the barrier height is determined by the generation rate of the energetic carriers, the heterojunction barrier height, and the relaxation rate of the energetic carriers through carrier - phonon interactions. The generation rate of the Auger recombination excited energetic electrons n_{ex} is related to the conduction band Auger recombination processes, i.e.

$$G_{n_{ex}} = (C_n + C_n^{ph}) n^2 (n + p_a) \quad (4.4a)$$

where C_n and C_n^{ph} are the coefficients of the direct and phonon-assisted band to band CHCC Auger recombinations, n and p_a are the injected electron density and the acceptor concentration in the active layer, respectively.

Similarly, the generation rate of the energetic hole concentration p_{ex} can be expressed by the valence band Auger processes

$$G_{p_{ex}} = (C_p + C_p^{ph}) n (n + p_a)^2 \quad (4.4b)$$

where C_p and C_p^{ph} are the coefficients of the direct and phonon-assisted band to band CHSH Auger recombinations, respectively.

The Auger recombination excited energetic carriers lose their energy through successive LO phonon emissions as discussed in section 4.1, and the relaxation rate of the Auger recombination induced energetic carriers involved in the leakage processes is then determined by the effective energy relaxation times of energetic electrons and holes, respectively,

$$R_{n_{ex}} = \frac{n_{ex}}{\tau_{op}^n} \quad R_{p_{ex}} = \frac{p_{ex}}{\tau_{op}^p} \quad (4.5)$$

Since only those Auger recombination induced energetic carriers whose energies exceed the corresponding band discontinuity when they have reached the GaInAsP-InP heterojunction interfaces are available for leaking out of the active layer, it is evident that Auger recombination induced energetic carriers away from the heterojunction interfaces would have less chance to leak over the

heterojunction barrier heights. Thus, if we define a quantity $L_{op}^n = (D_n \tau_{op}^n)^{1/2}$ and $L_{op}^p = (D_p \tau_{op}^p)^{1/2}$ as the effective diffusion length of the energetic electrons and holes, respectively, where D_n and D_p are the electron and hole diffusion coefficients in the GaInAsP active layer, respectively, then only those Auger recombination induced energetic electrons and holes whose energies exceed the conduction and valence band discontinuities within their corresponding effective diffusion lengths have the possibility of leaking out of the active layer. Therefore, the rate of change of the Auger recombination induced energetic electrons and holes in the active layer can be approximated as

$$\begin{aligned} \frac{dn_{ex}}{dt} &= (C_n + C_n^{ph}) n^2 (n + p_a) - \frac{n_{ex}}{\tau_{op}^n} - \frac{J_{eL}}{eL_{op}^n \tanh(\frac{d}{L_{op}^n})} \\ \frac{dp_{ex}}{dt} &= (C_p + C_p^{ph}) n (n + p_a)^2 - \frac{p_{ex}}{\tau_{op}^p} - \frac{J_{hL}}{eL_{op}^p \tanh(\frac{d}{L_{op}^p})} \end{aligned} \quad (4.6)$$

where d is the thickness of the active layer, and J_{eL} and J_{hL} are the energetic electron and hole leakage current densities, respectively.

In the case of negligible leakage, the steady state densities of energetic electrons and holes whose energies exceed the corresponding heterojunction barrier heights have their maximum values, and are given by

$$n_{ex} = \tau_{op}^n (C_n + C_n^{ph}) n^2 (n + p_a) \quad (4.7)$$

$$p_{ex} = \tau_{op}^p (C_p + C_p^{ph}) n (n + p_a)^2$$

Using typical doping concentration of $p_a < 10^{17} \text{ cm}^{-3}$ in the active layer, and $5.2 \times 10^{-12} \text{ sec}$ and $1.6 \times 10^{-12} \text{ sec}$ as the values of the effective energy relaxation times of energetic electrons and holes, and the values of the relevant Auger recombination coefficients, it is concluded that the Auger recombination induced energetic electrons and holes are orders of magnitudes less than the injected electron density for injection levels up to 10^{17} cm^{-3} . Therefore, under normal excitation conditions for light emitting devices where the injected carrier density is less than $5 \times 10^{16} \text{ cm}^{-3}$, it is justified to decouple the rate equations of the energetic carriers from the rate equations of the injected carriers.

4.2.2. The Leakage Current

The rate of leakage of the Auger recombination induced energetic carriers, depending on the device parameters, can be limited by either drift^(1.1-1.2) or diffusion^(1.3) mechanisms.

4.2.2.1. Diffusion Limited Leakage

In well designed devices, the energetic carrier leakage is assumed to be diffusion current dominated. That is, the

Auger recombination induced energetic electrons and holes which reach the corresponding heterojunction interfaces with energies exceeding the barrier heights would diffuse away from the interfaces into the InP confinement layers, where they would recombine either radiatively or non-radiatively with majority carriers, or they would recombine at the lower bandgap capping layer or at the semiconductor - metal contacts. In this case, the Auger recombination induced energetic electron and hole leakage current densities are given by

$$J_{diff}^n = \frac{eD_n n_{ex} w_n}{L_n \tanh(\frac{w_n}{L_n})}$$

(4.8)

$$J_{diff}^p = \frac{eD_p p_{ex} w_p}{L_p \tanh(\frac{w_p}{L_p})}$$

where D_n , D_p , L_n , L_p are the diffusion constants and diffusion lengths of electrons and holes, respectively, of the InP confinement layers, and w_n and w_p are the thicknesses of the corresponding n- and p-type InP layers.

Thus, the densities of the energetic electrons and holes in the active layer with sufficient energies to leak over the heterojunction barriers, at steady state, can be determined by

$$\begin{aligned}
 n_{ex} &= \frac{\tau_{op}^n L_{op}^n \tanh\left(\frac{d}{L_n}\right) (C_n + C_n^{ph}) n^2 (n+p_a)}{L_{op}^n \tanh\left(\frac{d}{L_n}\right) + \frac{\tau_{op}^n D_n}{L_n \tanh\left(\frac{p}{L_n}\right)}} \\
 p_{ex} &= \frac{\tau_{op}^p L_{op}^p \tanh\left(\frac{d}{L_p}\right) (C_p + C_p^{ph}) n(n+p_a)^2}{L_{op}^p \tanh\left(\frac{d}{L_p}\right) + \frac{\tau_{op}^p D_p}{L_p \tanh\left(\frac{n}{L_p}\right)}}
 \end{aligned} \tag{4.9}$$

Thus, for well designed devices where the leakage is diffusion limited, the Auger recombination induced energetic carrier leakage currents are related to the Auger recombination rates and the effective energy relaxation times,

$$\begin{aligned}
 J_{diff}^n &= \frac{e D_n \tau_{op}^n L_{op}^n \tanh\left(\frac{d}{L_n}\right) (C_n + C_n^{ph}) n^2 (n+p_a)}{D_n \tau_{op}^n + L_{op}^n \tanh\left(\frac{d}{L_n}\right) \frac{W}{L_n \tanh\left(\frac{p}{L_n}\right)}} \\
 J_{diff}^p &= \frac{e D_p \tau_{op}^p L_{op}^p \tanh\left(\frac{d}{L_p}\right) (C_p + C_p^{ph}) n(n+p_a)^2}{D_p \tau_{op}^p + L_{op}^p \tanh\left(\frac{d}{L_p}\right) \frac{W}{L_p \tanh\left(\frac{n}{L_p}\right)}}
 \end{aligned} \tag{4.10}$$

4.2.2.2. Drift Limited Carrier Leakage

It has been shown by Anthony and Schumaker^(1.1) that some light emitting devices may exhibit anomalous electrical characteristics arising from excess drift leakage current. The main characteristic of these devices is that the doping level of the p-type confinement layer is relatively low.

To model the drift limited case of the Auger recombination induced energetic carriers, we limit the case to electrons only, since the energetic hole leakage is relatively low. Under this condition, the Auger recombination induced energetic carrier drift leakage current density is given by

$$J_{\text{drift}} = e\mu_n n_{\text{ex}} E \quad (4.11)$$

where μ_n and E are the mobility of electrons and electric field in the p-type InP confinement layer, respectively. Charge neutrality requires that the total density of holes in the confinement layer be $\Delta n + p_0$, where p_0 is the acceptor level, and Δn is the minority carrier density. In case of $p_0 > 1 \times 10^{17} \text{ cm}^{-3}$, $\Delta n \approx n_{\text{ex}}$. This means that the hole (majority carriers) drift current can be expressed as

$$J_h = e\mu_p (n_{\text{ex}} + p_0) E \quad (4.12)$$

where μ_p is the hole mobility of the p-type InP confinement layer. Since n_{ex} is usually much smaller than p_o , thus $J_h = e \mu_p p_o E$. Hence the Auger recombination induced energetic electron drift leakage current density is related to the hole injection current density by

$$J_{drift} = \frac{\mu_n n_{ex}}{\mu_p p_o} J_h \quad (4.13)$$

As mentioned in section 4.2.1, the hole injection current density can be taken as the recombination current density in the active layer if the hole leakage current density is negligible. Thus

$$J_{drift} = \frac{\mu_n n_{ex}}{\mu_p p_o} J_r \quad (4.14)$$

The density of Auger recombination induced energetic electrons in the active layer, at steady state, can then be determined as

$$n_{ex} = \frac{\tau_{op}^n L_{op}^n \tanh\left(\frac{d}{L_{op}^n}\right) (C_n + C_n^{ph}) n^2 (n + p_a)}{L_{op}^n \tanh\left(\frac{d}{L_{op}^n}\right) + \frac{\tau_{op}^n \mu_n J_r}{e \mu_p p_o}} \quad (4.15)$$

In typical devices $p_o > 1 \times 10^{17} \text{ cm}^{-3}$, thus at normal levels of injection, $n_{ex} = \tau_{op}^n (C_n + C_n^{ph}) n^2 (n + p_a)$, and the drift leakage density of the Auger recombination induced energetic electrons is given by

$$J_{\text{drift}} \approx \frac{\mu_n \tau_{\text{op}}^n (C_n + C_n^{\text{ph}}) n^2 (n + p_a)}{\mu_p p_o f_i} J_r$$

However, as the injection increases, n_{ex} may approach

$$\frac{L_{\text{op}}^n \tanh\left(\frac{d}{L_{\text{op}}^n}\right) (C_n + C_n^{\text{ph}}) n^2 (n + p_a)}{\left(\frac{\mu_n J_r}{e \mu_p p_o}\right)}$$

and the drift current density of the Auger recombination induced energetic electron leakage approaches

$$\frac{L_{\text{op}}^n \tanh\left(\frac{d}{L_{\text{op}}^n}\right) (C_n + C_n^{\text{ph}}) n^2 (n + p_a)}{L_{\text{op}}^n}$$

That is, it asymptotically approaches the value such that all of the Auger recombination induced energetic electrons whose energies exceed the heterojunction barrier within the effective diffusion length would leak out.

4.2.2.3. Drift and Diffusion Limited leakage

For theoretical interest, it is also necessary to consider a general case where both drift and diffusion mechanisms are included. In this case, by ignoring the leakage of energetic holes, the Auger recombination induced energetic electron leakage current density in the confinement layer is given by

$$j_l(x) = -eD_n \frac{dn_{\text{ex}}(x)}{dx} + e n_{\text{ex}}(x) \mu_n E \quad (4.16)$$

where $n_{\text{ex}}(x)$ is the distribution of the energetic electrons within the confinement layer along the x-direction. Using

the continuity equation and the boundary conditions that $n_{ex}(x) = n_{ex}$ at the heterojunction interface and $n_{ex}(x) = 0$ at the edge of the confinement layer, the total leakage current density can be solved (10.4).

$$J_L = eD_n n_{ex} \frac{\left(\frac{eE}{kT} - \lambda_1\right) e^{\lambda_2 W_p} + \left(\lambda_2 - \frac{eE}{kT}\right) e^{\lambda_1 W_p}}{e^{\lambda_2 W_p} - e^{\lambda_1 W_p}} \quad (4.17)$$

where $\lambda_{1,2} = \frac{\frac{eE}{kT} \pm \left\{ \left(\frac{eE}{kT}\right)^2 + 4/L_n^2 \right\}^{1/2}}{2}$

In deriving the above solution, it has been assumed that the electric field is constant throughout the confinement layer, which is only valid if the energetic electron leakage current density is relatively small as compared to the hole injection current density. Under this condition, the electric field can be approximated by $E = J_r / e\mu_p p_0$.

In well designed devices, $E=0$, equation (4.17) then reduces to $J_L = \frac{eD_n n_{ex}}{L_n \tanh(W_p/L_n)}$, i.e., the diffusion limited leakage case. However, if the doping level of the confinement layer is relatively low, such that substantially high electric field exists in the confinement layer, then equation (4.17) approaches the form of $J_L = e\mu_n n_{ex} E = \frac{\mu_n n_{ex}}{\mu_p p_0} J_r$, which is the case of drift limited leakage.

4.2.3. The Rate Equation of Injected Carriers

Since the energetic carriers are induced by the Auger recombination processes, the analysis of the energetic carrier leakage requires that the injected carriers in the active layer of the devices be accurately determined. In surface emitting LEDs, this can be achieved by solving the rate equation for the injected electrons in the active layer. A similar approach can be used for the stripe geometry lasers by including stimulated emission. However, below or even at threshold current, the stimulated emission in a laser is usually quite low as compared to spontaneous emission. Thus, for simplicity, the stimulated emission at injection levels below or up to the lasing threshold could be ignored in studying the Auger recombination induced leakage current. For currents greater than the threshold value, the injected carrier density in the active layer is almost clamped at the threshold level, and hence the Auger recombination induced energetic carrier leakage current is also clamped at the threshold value. Therefore, the analysis can be applied even above threshold current in lasers provided that carrier density saturation is obtained.

The rate equation of the injected electrons in the active layer, according to the unified model, in a light emitting device is given by

$$\frac{dn}{dt} = \frac{J}{ed} - R_r - R_{nr} - \frac{J_L}{ed} \quad (4.18)$$

where J is the injection current density and J_L is the Auger recombination induced energetic carrier leakage current density as derived from previous sections under various leakage conditions. R_r and R_{nr} are the radiative and non-radiative recombination rates, respectively.

The non-radiative recombination rate in the active layer is assumed to be dominated by the Auger recombinations, i.e.

$$R_{nr} = (C_n + C_n^{ph}) n^2 (n + p_a) + (C_p + C_p^{ph}) n (n + p_a)^2 \quad (4.19)$$

where C_n , C_n^{ph} , C_p and C_p^{ph} are the coefficients of the related Auger recombination processes. In this model, the non-radiative recombinations through traps in the bulk of the active layer and at the heterojunction interfaces are ignored for simplicity. This is justified if one considers that recombination through defects does not relate to the leakage properties of the devices of interest here.

The radiative recombination rate is dominated by the bimolecular spontaneous emissions,

$$R_r = Bn(n + p_a) \quad (4.20)$$

where the radiative recombination coefficient, B , depends on temperature as well as on carrier density.

The rate equation of injected carriers in combination with the rate equation of the Auger recombination-induced energetic carriers thus describes completely the charge carriers injected into the active layer of the light emitting diodes and, approximately, of lasers up to lasing threshold, especially as the leakage is concerned. The leakage current as a function of injection current, at steady state, can then be obtained by setting the rate of change of injected carriers and the rate of change of Auger recombination induced energetic carriers to zero.

4.3. Analysis

In this section, the analytic results of solving the appropriate equations derived in previous sections are presented. The calculations, as all of the calculations throughout this work, are performed on an IBM 370 computer using numerical analysis techniques.

4.3.1. Diffusion Limited Leakage

Fig. 4-4 shows the analytic results of injected electron density and Auger recombination induced energetic electron density in the active layer of an ordinary LED, where the p-type InP confinement layer is 1.5 μm thick and the 1 μm thick active layer is relatively large as compared to the effective diffusion length of the energetic carriers. Even at $10\text{kA}/\text{cm}^2$ injection, the energetic electron density is three orders of magnitude lower than the injected carrier density. This shows that the decoupling of the rate equation of energetic carriers from the rate equation of injected carriers in the active layer as discussed in section 4.2.1 is justifiable.

The superlinear dependence of the energetic electron density on injection current density shown in Fig. 4-4(b) means that the energetic carrier leakage current density would be greatly increased at high injection current. This is shown

in Fig. 4-5, where both energetic electron and hole leakages are calculated. The energetic hole leakage is less than 0.01% of the total injection current, and is less than 1% of the energetic electron leakage current. This is consistent with the result of Chen et al.⁽¹⁰⁾ that within the accuracy of 0.1% of the total injection current, no hole leakage was observed in a specially designed laser-transistor structure. Therefore, in the following calculations of this work, the effect of energetic hole leakage is not included.

With a 1 μm thick active layer, even the energetic electron leakage is relatively small, accounting for only about 1.3% of the total current at an injection level of 10 kA/cm^2 . Thus, a well designed surface emitting LED is an almost ideal structure in determining Auger recombination coefficients as discussed in chapter 2. Furthermore, as seen from equation (4-10), in the case of diffusion limited energetic carrier leakage, the leakage current is directly proportional to the Auger recombination rate in the active layer. Thus, the leakage effect could not be separated from the Auger recombination rate by measuring either the carrier lifetime or the spontaneous emission rate as a function of injection current. This explains why Su et al.⁽¹¹⁾ did not need to invoke leakage in zinc diffused LEDs in their data fitting procedures for both carrier lifetime and spontaneous emission measurement results.

Fig. 4-4(a) Calculated injected electron density in the active layer of a LED as a function of the injection current density. The active layer thickness is 1 μm and the energetic carrier leakage is assumed to be diffusion limited.

Fig. 4-4(b) Auger recombination induced energetic electron density in the active layer of a LED as a function of the injection current density. The active layer thickness is of 1 μm and the energetic carrier leakage is assumed to be diffusion limited.

Fig. 4-5 The Auger recombination induced energetic electron and hole leakage current density as a function of injection current density. The active layer of the device is 1 μm and the energetic carrier leakage is assumed to be diffusion limited.

Recent measurements of Zhuang et al⁽¹⁰⁾ indicated that the carrier leakage induced 950 nm emission in the InP confinement layer has a $n^{2.1-2.3}$ dependence on the carrier density in the active layer, over a wide range of carrier density values from $3 \times 10^{17} < n < 1.5 \times 10^{18} \text{ cm}^{-3}$. The prediction of equation (4-10) is that the energetic electron leakage has a $n^2(n+p_g)$ dependence. Although the exact value of doping in their undoped GaInAsP active layer is not known in the work of Zhuang et al⁽¹⁰⁾, the out-diffusion of zinc from the p-type InP confinement layer during the liquid phase epitaxial growth could cause the impurity level in the active layer to be $1-2 \times 10^{17} \text{ cm}^{-3}$. Thus, the experimental results are indeed in excellent agreement with the theoretical prediction.

Furthermore, in the work of Zhuang et al⁽¹⁰⁾, the integrated intensities of 1.3 μm and the 950 nm emissions showed a relationship of

$$\frac{I_{1.3}}{I_{950}} = \frac{\tau_{\text{Auger}}}{K \tau_r} \quad (4.21)$$

with K remaining constant over the wide range of injected carrier concentrations mentioned above. Since the ratio $\tau_{\text{Auger}} / \tau_r$ represents the internal ratio of radiative recombination rate to the rate of Auger recombination relevant to leakage, such a relationship not only provides clear evidence for Auger recombination in the active layer

and the physical cause of the leakage, but also indicates that only a fraction of the Auger recombination induced energetic carriers contributes to the leakage; which is consistent with the leakage theory of the unified model of this work.

In fact, from the Auger recombination induced energetic carrier leakage model, the ratio of the radiative emission from the active layer and the 950 nm emission from the InP confinement layer could be estimated as

$$\frac{I_{1.3}}{I_{950}} = \frac{f_{1.3} A d R_r}{f_{950} A J_L} \quad (4.22)$$

where A is the injection area of the device and d is the thickness of the active layer, R_r is the radiative recombination rate (assumed uniform throughout the active layer), J_L is the Auger recombination induced energetic carrier leakage current density, and the f 's are the external efficiencies of the 1.3 μm and 950 nm emissions, respectively. Substituting R_r from equation (4.20) and J_L from equation (4.10) we obtain the relationship of (4.21), with

$\tau_{\text{Auger}} = \{(C_n + C_n^{\text{ph}})n(n+p_a)\}^{-1}$ as the lifetime of Auger recombination associated with energetic carrier leakage related 950 nm emission, and $\tau_r = \{B(n+p_a)\}^{-1}$ as the lifetime of radiative recombination.

The quantity K is the fraction of externally observed Auger recombination induced energetic carriers that leak over the heterojunction barrier, and is given by

$$K = \frac{f_{950} D_n \tau_{op}^n L_{op}^n \tanh\left(\frac{d}{L_n}\right)}{f_{1.3} d L_n \tanh\left(\frac{W}{L_n}\right) \left\{ L_{op}^n \tanh\left(\frac{d}{L_n}\right) + \frac{\tau_{op}^n D_n}{L_n \tanh\left(\frac{W}{L_n}\right)} \right\}} \quad (4.23)$$

External efficiencies at 1.3 μm and 950 nm are smaller than internal efficiencies due to absorptions and detection efficiency.

Note that the unified model predicts that the value of K is independent of injected carrier density in the active layer. Also the K value would decrease as the active layer thickness increases. Both of these agree with the experimental results of Zhuang et al⁽²²⁾. In their work, the K values are 6×10^{-4} and 1.5×10^{-3} for devices with active layer thickness of 0.5 μm and 0.2 μm , respectively.

The low leakage current in ordinary LEDs with thick active layers as discussed above would not be found in lasers where the active layer thickness is about 0.2 μm . Fig. 4-6 shows that at such thickness, the leakage current would increase substantially. Thus, the Auger recombination induced energetic carrier leakage affects lasers more severely than ordinary LEDs. Yamakoshi et al⁽²³⁾ determined

experimentally that the electron leakage current is slightly more than 10% of the total injection current at 3kA/cm^2 in a special structure with active layer thickness of $0.15\text{ }\mu\text{m}$. The theoretically calculated energetic carrier leakage current from the unified model is about 10.5% of the total injection current under such conditions.

4.3.2. Drift Limited Leakage

In devices with lightly doped p-type InP confinement layers where significant electric field exists, the energetic carrier leakage is drift limited. Fig. 4-7 shows the calculated energetic electron leakage at various doping concentrations of the p-type InP confinement layer. The leakage current increases as the doping level decreases. Comparing with the diffusion limited case, the energetic carrier leakage has much stronger dependence on the injection current density, hence the injected carrier density in the active layer. From the analysis of section 4.2.2.2, it can be shown that the drift leakage current density of the Auger recombination induced energetic electrons, at injected carrier density $n > p_a$, can be expressed as

$$J_{\text{drift}} = ed \frac{\mu_n \tau_{\text{op}}^n}{\mu_p p_0} (C_n + C_n^{\text{ph}}) \{ B_0 n^5 + (B_1 + C_n + C_n^{\text{ph}} + C_p + C_p^{\text{ph}}) n^6 \} \quad (4.24)$$

i.e., the drift limited energetic carrier leakage has a functional dependence on the injected carrier density in the active layer between n^s and n^d , as compared to n^s in the diffusion limited case as shown in previous section. This is consistent with the experimental results of Olshansky et al⁽¹¹⁾, where a $n^{1.5}$ dependence is obtained.

Substituting equation (4.24) into the rate equation of injected carriers and defining an effective carrier leakage rate in the active layer of $Dn^{1.5}$ as in the work of Olshansky et al⁽¹¹⁾, it can be shown that

$$D = \frac{\mu_n \tau_{op}^n}{\mu_p p_o} (C_n + C_n^{ph}) \{ B_o (n)^{-1/2} + (B_1 + C_n + C_n^{ph} + C_p + C_p^{ph}) (n)^{1/2} \} \quad (4.25)$$

Using a data fitting procedure, Olshansky et al⁽¹¹⁾ obtained a D value of $1.2-2.1 \times 10^{-11}$ cm²/sec for the estimated doping concentration in the p-type InP confinement layer of $2.5-4 \times 10^{17}$ cm⁻³. This compares with $2-4 \times 10^{-11}$ cm²/sec calculated from equation (4.25). Considering the accuracy of data fitting with four unknown parameters in the work of Olshansky et al⁽¹¹⁾, the approximation in deriving equation (4.25), as well as the method of obtaining the doping concentrations of the devices, the agreement between calculated and data fitted values is excellent. Furthermore, there are no free parameters in the calculation, and in actual devices, there exists both drift and diffusion leakages as shown in next section.

Fig. 4-6 The dependence of energetic carrier leakage current on the active layer thickness. The calculation is based on diffusion limited leakage. Similar dependence is obtained for the drift limited condition.

Fig. 4-7 The dependence of drift limited energetic carrier leakage current on the doping concentration of the p-type InP confinement layer. The active layer thickness is 1 μm and the thickness of the p-type InP confinement layer is 1.5 μm .

4.3.3. General Case

In actual devices, both diffusion and drift leakages of the energetic carriers exist. Fig. 4-8 shows the calculated energetic electron leakage current at various doping concentrations of the p-type InP confinement layer. Fig. 4-8(a) shows that with 1 μm thick active layer, the total leakage current dropped from 6% to 3% of total injection current as doping increased from $2 \times 10^{17} \text{ cm}^{-3}$ to $1 \times 10^{18} \text{ cm}^{-3}$. Comparing with Fig. 4-7, the diffusion leakage portion could be obtained. At doping level of $2 \times 10^{17} \text{ cm}^{-3}$, the diffusion leakage is less than 8% of the total leakage current, and it increases to 30% at $1 \times 10^{18} \text{ cm}^{-3}$, with total injection current density of 10 kA/cm^2 .

It should also be emphasized that the leakage current can be greatly enhanced by device design. Fig. 4-8(b) shows that with low doped InP confinement layer and a thin active layer, the leakage current could be more than 24% of total injection current.

In order to approach the diffusion limited leakage situation, the doping level of the p-type InP confinement layer of the devices should be more than $5 \times 10^{18} \text{ cm}^{-3}$. This level may not be suitable for lasers with thin active layer, fabricated by the liquid phase epitaxial technique using zinc as dopant.

Fig. 4-8(a) Calculated energetic electron leakage including both diffusion and drift mechanisms. The active layer is of 1 μm thick and the p-type InP confinement layer is 1.5 μm thick with doping concentration as shown.

Fig. 4-8(b) Calculated energetic electron leakage including both diffusion and drift mechanisms. The active layer is of 0.2 μm thick and the p-type InP confinement layer is 1.5 μm thick with doping concentration as shown.

4.3.4. Discussions and Conclusions

The analytic results of the energetic carrier leakages from the unified model are consistent with leakages observed in various types of devices and over a wide range of operating conditions as discussed in previous sections.

However, a most important phenomenon lies in the wavelength dependence of leakages. Carrier leakage models have been proposed by Yano et al⁽²²⁾, with carrier leakage resulting from normal injected electrons whose energies exceed the heterojunction barrier height in the energy distribution, and by Chiu et al⁽²³⁾ with a carrier heating effect such that the average carrier temperature is substantially higher than lattice temperature. These models predict a substantial reduction of leakages as wavelength increases to 1.5 μm from 1.3 μm , due to the increased heterojunction barrier height as wavelength increases. For example, using the model of Yano et al⁽²²⁾, the leakage current would be two orders of magnitude smaller in 1.55 μm devices as compared with 1.3 μm devices. Contradicting such a prediction from these leakage models, 950 nm emission, hence carrier leakage, has been measured to be 3.6 to 6 times higher in 1.55 μm than in 1.3 μm devices^(1,2,3).

The theoretically estimated Auger recombination coefficient is about 2.8 to 4.4 times higher in GaInAsP with composition

corresponding to 1.55 μm than 1.3 μm (.....), while an experimentally determined value is 5 times higher ('). Unless the energy relaxation rate is more than two orders of magnitude higher in 1.55 μm material, the energetic carrier leakage model of this work would predict a higher leakage in 1.55 μm than in 1.3 μm devices. Fig. 4-9 shows the calculated energy relaxation rate of the energetic electrons in GaInAsP with composition corresponding to 1.55 μm wavelength. The effective energy relaxation time for the Auger recombination excited electrons is 8.35×10^{-12} second as compared to 5.2×10^{-12} second for the 1.3 μm material. Thus, the estimated energetic carrier leakage in the 1.55 μm devices from the unified model would be in the order of 4.5 to 8 times higher than in 1.3 μm devices, depending on the Auger recombination coefficient used. Therefore, it is concluded that the leakage theory derived from the unified model is a more satisfactory one and is in close agreement with experimental results.

Fig. 4-9 Energy relaxation rate of energetic electrons in GaInAsP at 300°K with composition corresponding to 1.55 μm wavelength.

5. ANALYTIC RESULTS OF THE UNIFIED MODEL ON THE PROPERTIES OF LEDS

The effects of Auger recombination and its induced energetic carrier leakage on the properties of LEDs are analysed and compared with experimental results. The implications of the unified model on the design optimization of LEDs are also described.

5.1. The Light Output Power versus Injection Current (L-I) Characteristics

In normal LEDs, the active layer is relatively thick. If the device structure is designed such that the energetic carrier leakage is diffusion limited, then the leakage current would be relatively low as compared to the total injection current. Under this condition, the L-I characteristics of the LEDs are determined mainly by the recombination mechanisms in the active layer. Fig. 5-1 shows the calculated L-I characteristics of such a LED, where curve(a) contains both the Auger recombination and the Auger recombination induced energetic carrier leakage, curve(b) includes only the effect of Auger recombination without leakage, and curve(c) reduces the Auger recombination rate by an order of magnitude, i.e., approaching the Auger recombination rate in GaAs. The energetic carrier leakage

contributes only an additional 0.3% light output power reduction at 10 kA/cm² of injection current. This is consistent with the results of Chik et al⁽¹⁾ and Su et al⁽²⁾ that, in zinc diffused LEDs, the Auger recombination model could be applied to account for the full characteristics of the LEDs. Furthermore, since the diffusion limited energetic carrier leakage has a n^2 dependence on the injected carrier density in the active layer, data fitting on both L-I characteristics and carrier lifetimes would not be able to separate the carrier leakage effect from the Auger recombination effect. The measurement of 950 nm emission, however, would be useful in analysing the energetic carrier leakage effect as discussed in section 4.3.1.

The effect of Auger recombination on the GaInAsP/InP LEDs is revealed by the much more severe saturation of the L-I characteristics shown in curve(b) as compared with curve(c), where a 43% power reduction at 10 kA/cm² injection current density is obtained.

Fig. 5-1 Calculated L-I characteristics of LED with 1 μm thick active layer. The energetic carrier leakage is assumed to be diffusion limited. Curve(a) includes the effects of both Auger recombination and energetic carrier leakage, curve(b) has only the effect of Auger recombination without leakage, and curve(c) shows the effect of reducing the Auger recombination to a rate as in GaAs.

The effect of Auger recombination induced energetic carrier leakage could be greatly enhanced in LEDs where the energetic carrier leakage is drift limited as shown in Fig. 5-2. With a doping concentration of $2 \times 10^{17} \text{ cm}^{-3}$ in the p-type InP confinement layer, the energetic carrier leakage contribution on the saturation of the light output power increased to 4% at 10 kA/cm^2 injection current density as compared to 0.3% in the diffusion limited case. Thus, the combined light output power reduction by Auger recombination and energetic carrier leakage could be more than 47%, i.e., at 10 kA/cm^2 injection current density, the GaInAsP/InP LEDs emitting at $1.3 \text{ }\mu\text{m}$ would have only 53% power emission as compared to devices with Auger recombination coefficient reduced by an order magnitude. Experimentally, Temkin et al.⁽²³⁾ measured the output powers of AlGaAs/GaAs and GaInAsP/InP LEDs emitting at 0.87 and $1.3 \text{ }\mu\text{m}$ wavelength, respectively, and found that at 40 kA/cm^2 injection current density, the light output power of the GaInAsP/InP LED is 47% of the AlGaAs/GaAs devices.

Fig. 5-2 Calculated L-I characteristics of LED with 1 μm thick active layer. The energetic carrier leakage is assumed to be drift limited. Curve(a) includes the effects of both Auger recombination and energetic carrier leakage, curve(b) has only the effect of Auger recombination without leakage.

The effect of Auger recombination induced energetic carrier leakage could also be enhanced in LEDs and lasers with thin active layers. For example, Fig. 5-3 shows that by reducing the active layer thickness from 1 μm as for Fig. 5-2, to 0.2 μm , the drift limited energetic carrier leakage contribution increased by an additional 10% light output power saturation at $3\text{kA}/\text{cm}^2$ which is about the threshold current density required for lasers at room temperature. Thus, in analysing the temperature sensitivity of threshold current in lasers, the Auger recombination induced energetic carrier leakage should not be ignored.

The theoretically calculated L-I characteristics using the unified model are compared with the experimentally measured results in Fig. 5-4. Excellent agreement has been obtained. The consistency of the analytic results with the experimental measurement is further revealed by harmonic distortion measurements as shown in section 5.2.

Fig. 5-3 Calculated L-I characteristics of LED with 0.2 μm thick active layer. The energetic carrier leakage is assumed to be drift limited. Curve (a) includes the effects of both Auger recombination and energetic carrier leakage, curve (b) has only the effect of Auger recombination without leakage.

Fig. 5-4 Comparison of analytic and measured L-I characteristics of GaInAsP/InP LEDs emitting at 1.3 μm wavelength.

5.2. Harmonic Distortion

For analog applications, the harmonic distortion of the L-I characteristics of the LEDs is one of the important properties to be considered. Fig. 5-5(a) shows the measured second and third harmonic contents of a typical LED modulated with a 80 mA peak to peak current of sinusoidal waveform. The second and third harmonics are up to 30 dB and 60 dB, respectively, below the fundamental in the GaInAsP/InP LED emitting at 1.3 μ m wavelength. This is to be compared to 36 dB and 67 dB, respectively, measured on AlGaAs/GaAs devices at similar operating conditions^(11,12).

The calculated harmonic distortions of the GaInAsP/InP LEDs using the unified model are shown in Fig. 5-5(b). They agree very well with the measured results, where the second harmonic is within one decibel in a wide range of operating current. Since the harmonic content could be measured accurately in LEDs, the harmonic distortion measurements then provides a good means in verifying the accuracy of the proposed unified model.

Fig. 5-5(a) Measured harmonic distortions of a GaInAsP/InP LED emitting at 1.3 μm wavelength.

Fig. 5-5(b) Comparison of calculated and measured harmonic distortions of GaInAsP/InP LED emitting at 1.3 μm wavelength.

5.3. Temperature Sensitivity of Light Output Power

One of the advantages of LEDs over injection lasers is their capability of high temperature operation. Since the Auger recombination rate is temperature dependent, both the energetic carrier leakage and the light output power of the LEDs should also be temperature dependent. Fig. 5-6 shows the calculated L-I characteristics of the GaInAsP/InP LEDs at temperatures of 100, 200, 300 and 400°K. At 5 kA/cm² injection current density, the output power dropped 30% when temperature increased from 200°K to 300°K. This is to be compared to measured results under similar conditions where light output power reduction of 0.3-0.5%/°K from 253 to 323°K of typical LEDs. The light output power reduction measured by Olshansky et al⁽¹¹⁾ on broad area lasers with 0.2 μ m thick active layer is about 32% as temperature increases from 193°K to 292°K at injection current density of 0.5 kA/cm², which is consistent with higher carrier density in the active layer as well as higher energetic carrier leakage associated with thin active layer as shown in next section.

Fig. 5-6 Calculated L-I characteristics of GaInAsP/InP LEDs at various temperatures.

5.4. Effect of Active Layer Thickness

Fig. 5-7 shows that the light output power saturation of the GaInAsP/InP LEDs becomes more severe and the internal quantum efficiency decreases as the active layer thickness decreases. The main cause comes from the higher carrier density in the active layer. However, the increased energetic carrier leakage as shown in chapter 4 causes further reduction in light output power with magnitude depending on the device design, i.e., device dimensions, doping concentration of the layers and energetic carrier leakage mechanisms. In Fig. 5-7, the minimum effect of energetic carrier leakage is illustrated, as the diffusion limited leakage is applied. The effect would be greatly enhanced in the drift limited leakage situation.

To illustrate the effect of active layer thickness on the L-I characteristics of LEDs, the light output power of the 1.05 μm and 1.3 μm wavelength emissions of a special LED structure designed by Yamakoshi et al.⁽¹¹⁾ are calculated using the unified model, as shown in Fig. 5-8, where the 1.05 μm wavelength emission is a consequence of carrier leakage over the heterojunction barrier between the GaInAsP active layer and the InP confinement layer. In the calculation, the active layer is assumed to be of 0.15 μm , and the p-type InP confinement layer 0.3 μm . The measured results are shown in the insert of Fig. 5-8. In the actual

devices measured, the active layer is approximately 0.15 μm and the p-type InP confinement layer is 0.3 μm thick. In addition to the excellent agreement between calculated and measured results, it is to be noted that the carrier leakage is extremely high in this structure, as shown by both the calculated and measured 1.05 μm emissions.

It should be emphasized here that Auger recombination model alone without energetic carrier leakage would have difficulties in explaining the above experimental results.

Fig. 5-7(a) Calculated L-I characteristics of LEDs at various active layer thicknesses.

Fig. 5-7(b) Calculated internal quantum efficiency of LEDs at various active layer thicknesses.

Fig. 5-8 Calculated intensities of 1.05 μm and 1.3 μm emissions as a function of injection current of the LED structure of Yamakoshi et al⁽³³⁾ using the unified model. Insert at the upper corner shows the measured results of Yamakoshi et al⁽³³⁾.

5.5. The Effect of Doping in InP Confinement Layer

In device modelling, it is necessary to compare analytic and experimental results to verify the validity of the proposed model. Such comparison is sometimes difficult due to the parameter variations between devices. For example, in Fig. 2-4 of chapter 2; Auger recombination theory alone may well fit the measured characteristics in a wide range of operating conditions, except at injection current above 150 mA. In zinc diffused LEDs, the Auger recombination theory alone could fit the measured characteristics in an even wider range of injection current. The differences between measured device characteristics can be well explained by the effect of device parameters. Fig. 5-9 shows the effect of the doping concentration in the p-type InP confinement layer on the L-I characteristics of the GaInAsP/InP LEDs. In the calculation, both diffusion and drift energetic carrier leakages are included. It shows that, for low doping concentration, where the energetic carrier leakage is high, the exclusion of the carrier leakage in the model would produce a discrepancy between theoretical and experimental results as shown in Fig. 2-4. In practice, the energetic carrier leakage should be minimized to obtain higher efficiency..

Fig. 5-9(a) Effect of doping concentration in the p-type InP confinement layer on the L-I characteristics of GaInAsP/InP LEDs. The active layer is 1 μm and the InP layer is 1.5 μm . In the calculation, both diffusion and drift energetic carrier leakages are included.

Fig. 5-9(b) Effect of doping concentration in the p-type InP confinement layer on the L-I characteristics of GaInAsP/InP LEDs. The active layer is 0.2 μm and the InP layer is 1.5 μm . In the calculation, both diffusion and drift energetic carrier leakages are included.

5.6. Dynamic Properties and Design Optimization

In the application of LEDs in fiber optical communication systems, optimizing the device design to meet specific system requirements is often necessary. In this regard, the efficiency and the bandwidth of the devices become the major concerns. It is well known that the rise time of the LEDs can be significantly reduced by increasing the injection current, i.e., by reducing the minority carrier lifetime. However, in such an approach, the fall time of the devices may become the limiting factor in determining the speed of the LEDs to be operated. This is illustrated in Fig. 5-10, where the light output waveform of a GaInAsP/InP LED subjected to a 20 nsec, 5 kA/cm² current pulse is calculated from the unified model. The rise time is less than 5 nsec, while the fall time is more than 8 nsec. A practical method for reducing the fall time is to increase the doping concentration in the active layer. Fig. 5-11(a) shows the rise and fall times of GaInAsP/InP LEDs as a function of the doping concentration, where the rise and fall times become comparable only for doping concentrations higher than 8×10^{18} cm⁻³. The increased bandwidth of the devices is obtained, in fact, at the expense of the device efficiency, as shown in Fig. 5-12. At doping level of 8×10^{18} cm⁻³, the bandwidth increased to 350 MHz from 40 MHz at 1×10^{18} cm⁻³, while the efficiency, however, dropped by more than 30%. In practice,

the unified model can be applied to model such device designs for optimization.

The effects of Auger recombination and its induced energetic carrier leakage on the dynamic properties of GaInAsP/InP LEDs are illustrated by comparing Fig. 5-11(a) and (b). In Fig. 5-11(b), the rise and fall times of the same LED structure with Auger recombination reduced to a rate in GaAs are shown. The Auger recombination and its induced energetic carrier leakage increase substantially the speed of the GaInAsP/InP LEDs. However, Fig. 5-12(a) and (b) show that the internal quantum efficiency is reduced by 35-55%, depending on the active layer doping concentrations.

Fig. 5-10 Calculated pulse response of GaInAsP/InP LEDs.
The active layer doping is assumed to be $1 \times 10^{18} \text{ cm}^{-3}$.

Fig. 5-11(a) Calculated rise and fall times of GaInAsP/InP LEDs as a function of active layer doping concentration.

Fig. 5-11(b) Calculated rise and fall times of LEDs as a function of active layer doping concentration with Auger recombination reduced to a rate of GaAs.

Fig. 5-12 Calculated internal quantum efficiency of GaInAsP/InP LEDs as a function of active layer doping concentration.

(a) using the unified model;

(b) by reducing Auger recombination to a rate of GaAs.

6. ANALYTIC RESULTS OF THE UNIFIED MODEL ON THE PROPERTIES OF LASERS

The effects of Auger recombination and its induced energetic carrier leakage on the properties of stripe geometry lasers are analysed and compared with experimental results. Emphasis is put on the threshold current behavior of the devices, such as the temperature sensitivity of threshold current density and threshold current dependence on device design. This is due to the fact that Auger recombination and its induced energetic carrier leakage affect the lasers most severely at current levels below threshold where the stimulated emission is relatively weak as compared to spontaneous emission. Since in ideal lasers, the mode gain and hence carrier density is clamped to the threshold value at above lasing threshold⁽¹⁰⁾, the Auger recombination and the energetic carrier leakage are also nearly clamped. However, the Auger recombination and its induced energetic carrier leakage do affect the properties of the lasers above threshold. This is mainly through the modification of the gain profile of stripe geometry lasers, especially gain guided structures, where the gain profile determines, to a large extent, the device's static and dynamic characteristics⁽¹¹⁾ such as kinks⁽¹²⁾, relaxation oscillations⁽¹³⁾ and self-sustained pulsations⁽¹⁴⁾. Several attempts⁽¹⁵⁾ have been made to obtain analytical

results for such characteristics. In most cases, however, a constant carrier lifetime has been assumed from below to above threshold current. This simplification was needed to reduce the complexity of the calculations, although it excluded the possibility of determining the effects of recombination processes on the device properties. This approach is especially crude in the GaInAsP/InP gain guided lasers if one considers the effects of Auger recombination and its induced energetic carrier leakage on the carrier lifetime and hence the gain profile in the laser cavity.

6.1. The Rate Equations

Fig. 6-1 shows a schematic diagram of the cross section of a typical gain guided GaInAsP/InP laser employed in the experimental study of this work. The active GaInAsP region of the laser with thickness of d and length of L is bounded by the InP confinement layers in the direction perpendicular to the junction plane (x -direction), and by two cleaved facets along the direction of optical field propagation (z -direction). The current injection along the junction plane (y -direction) is limited by a stripe width of w at the semiconductor and metal contact.

Fig. 6-1 Schematic diagram of cross section of a typical GaInAsP/InP gain guided laser. The z -axis is perpendicular to this cross section.

In such a double heterojunction stripe geometry laser, perpendicular to the junction plane, mode confinement is mainly accomplished by the dielectric slab waveguide created by the refractive index discontinuity between the GaInAsP active and the InP confinement layers. Along the junction plane, the mode confinement is mainly due to gain guiding. Gain guiding occurs in the narrow region under the stripe contact where the injected carrier density is high as compared to the side regions which exhibit loss because injected carrier density is low. Marcattili⁽¹¹⁾ has shown that such waveguides can be analysed by considering the guiding conditions in the x and y directions separately.

In studying the properties of such a laser, it is generally also assumed that the carrier density and injection current density in the x and z directions are uniform and the relative field distribution in the y direction remains unchanged. Under these assumptions, the one dimensional rate equations could be readily analysed⁽¹¹⁾. However, a constant carrier lifetime is often assumed in such analyses, which excludes the study of the effects of recombination processes on the device properties.

In this work, Auger recombination and its induced energetic carrier leakage effects are included in the analysis. In this case, the rate equations of the injected carrier

density along the y-direction $n(y,t)$ and the photon density of the pth mode s_p are given by

$$\begin{aligned} \frac{\partial n(y,t)}{\partial t} = & \frac{J(y,t)}{ed} - \{ B_0 + B_1 n(y,t) \} n(y,t) \{ n(y,t) + p_a \} \\ & - (C_n + C_n^{ph}) n(y,t)^2 \{ n(y,t) + p_a \} - (C_p + C_p^{ph}) n(y,t) \{ n(y,t) + p_a \}^2 \\ & + D \frac{\partial^2 n(y,t)}{\partial y^2} - \frac{J_L(y,t)}{ed} - \bar{c} g(n(y,t)) \Gamma \sum_p I_p(y,t) S_p(t) \quad (6.1) \end{aligned}$$

$$\frac{dS_p(t)}{dt} = \bar{c} \{ G_p(t) - \alpha \} S_p(t) + B \{ B_0 + B_1 \bar{n}_p \} \bar{n}_p (\bar{n}_p + p_a) \quad (6.2)$$

In the injected carrier rate equation (6.1), $J(y,t)$ is the injected current density, e is the electron charge. The second term on the right-hand side of equation (6.1) represents the bimolecular spontaneous emission, and the Auger recombinations are given by the third and fourth terms. The carrier diffusion in the active layer and the Auger recombination induced energetic carrier leakage are expressed by the next two terms, respectively, where D is the diffusion constant and $J_L(y,t)$ is the leakage current density of the energetic carriers as described in chapter 4. The last term is the stimulated emission, where $\bar{c}$ is the speed of light in the laser cavity and $g(n(y,t))$ is the carrier induced gain. The optical confinement factor Γ expresses the fraction of optical intensity contained in the active layer, and is determined by the active layer thickness and the refractive indices of the active layer and the confinement layers. $I_p(y,t)$ is the normalized intensity

distribution for the pth lateral mode, and s_p the corresponding magnitude.

In equation (6.2), the first term represents the net rate of generation of photons by stimulated emission and the second term is the fraction of spontaneous emissions coupled into the lasing mode. Thus, $G_p(t)$ is the net mode gain and α the total optical loss of the cavity, β is the coefficient of spontaneous emission coupling into the lasing mode and $\bar{n}_p$ is the average carrier density in the active layer, i.e.,

$$\bar{n}_p = \frac{1}{s} \int_{-\infty}^{\infty} n(y,t) I_p(y,t) dy \quad (6.3)$$

The mode gain $G_p(t)$ is determined by the local carrier gain by

$$G_p(t) = \frac{1}{s} \int_{-\infty}^{\infty} \Gamma g(n(y,t)) I_p(y,t) dy \quad (6.4)$$

and the total optical loss of the cavity can be approximated by

$$\alpha = \Gamma \alpha_a + (1-\Gamma) \alpha_c + \alpha_s + \frac{1}{L} \ln\left(\frac{1}{R}\right) \quad (6.5)$$

where α_a and α_c are the free carrier absorption loss in the active and confinement layers, α_s is the scattering loss and $(1/L)\ln(1/R)$ represents the facet loss. In most laser analysis, the dependence of gain on carrier density is

assumed to be linear, i.e., $g(n(y,t))=an-b$, where a and b are constants, determined by the properties of the active layer material.

The normalized intensity distribution $I_p(y,t)$ is given by

$$I_p(y,t) = \frac{|E_p(y,t)|^2}{\frac{1}{s} \int_{-\infty}^{\infty} |E_p(y,t)|^2 dy} \quad (6.6)$$

where s is a scaling width which could be set equal to the stripe width w . The field $E_p(y,t)$ is a solution of the wave equation

$$\frac{d^2 E_p(y,t)}{dy^2} + \{ \epsilon(y,t) k^2 - \beta_{z_p}^2(t) \} E_p(y,t) = 0 \quad (6.7)$$

where $k=2\pi/\lambda$ is the wavenumber, β_{z_p} is the propagation constant, and $\epsilon(y,t)$ is the complex dielectric constant. The latter can be approximated by

$$\epsilon(y,t) = \epsilon_0 - A n(y,t) \quad (6.8)$$

where ϵ_0 is the complex dielectric constant without injected carriers in the active layer and $A = A_r + A_i$ is a complex parameter, with A_r and A_i representing the variation rates of real refractive index and gain with carrier density, respectively.

Equations (6.1) to (6.8) describe a gain guided stripe geometry GaInAsP/InP laser approximately, and the properties of the device could be analysed by solving those equations. However, in certain cases, such as in broad area lasers as described in the next three sections, simplifications can be made to reduce the complexity of the calculations.

6.2. The Temperature Sensitivity of Threshold Current

In broad area lasers, the effects of current spreading in the confinement layer and charge out-diffusion in the active layer on the optical field distribution are minimized. The temperature sensitivity of the laser is then related more closely to the properties of the material. Therefore, for clearly showing the effects of Auger recombination and its induced leakage on the temperature dependence of threshold current of GaInAsP/InP lasers, the threshold current densities at various device temperatures are calculated and compared with experimental results.

Under this condition, the rate equations of (6.1) and (6.2) can be reduced to

$$\begin{aligned} \frac{dn}{dt} = & \frac{J}{ed} - (B_0 + B_1 n) n(n+p_a) - (C_n + C_n^{ph}) n^2(n+p_a) \\ & - (C_p + C_p^{ph}) n(n+p_a)^2 - \bar{\alpha} \Gamma g(n-n_0) S - \frac{J_L}{ed} \end{aligned} \quad (6.9a)$$

$$\frac{dS}{dt} = \bar{c}g(n-n_0)S - \bar{c}\alpha S + \beta(B_0 + B_1 n) n(n+p_a) \quad (6.9b)$$

At threshold condition, the optical gain through carrier injection into the laser cavity of length L can be expressed by the total loss,

$$\Gamma g_{th} = \Gamma \alpha_a + (1 - \Gamma) \alpha_c + \alpha_s + \frac{1}{L} \ln\left(\frac{1}{R}\right) \quad (6.10)$$

Using a Kane-model⁽¹¹⁴⁾ extrapolation to the Halperin-Lax band tails⁽¹¹⁵⁾ and Stern's matrix element⁽¹¹⁶⁾, Dutta and Nelson have calculated the gain as a function of injected carrier density at various temperatures⁽¹¹⁷⁾. With these values of threshold carrier density, the effect of Auger recombination and its induced energetic carrier leakage on the threshold current density of broad area GaInAsP/InP lasers emitting at 1.3 μ m wavelength is then calculated. The results are shown in Fig. 6-2, where curve(a) shows the variation of threshold current density when both Auger recombination and its induced energetic carrier leakage are included, while in curve(b) only the Auger recombination is used. Curve(c) is obtained by reducing the Auger recombination coefficient by an order of magnitude to approach the condition for AlGaAs/GaAs devices.

Fig. 6-2 shows that the Auger recombination is the dominant cause of the high temperature sensitivity of threshold current of GaInAsP/InP lasers at temperature $>250^\circ\text{K}$.

Calculations show that Auger recombination reduces the characteristic temperature from about 145°K down to about 83°K. The Auger recombination induced energetic carrier leakage accounts for a 10°K further reduction in the characteristic temperature to about 70°K, which is comparable with measured values of 65-70°K at temperatures above 250°K.

At low temperature, the effects of Auger recombination and its induced energetic carrier leakage are much reduced, and the characteristic temperature of GaInAsP/InP lasers emitting at 1.3 μm wavelength approaches the characteristic temperature of AlGaAs/GaAs lasers of 0.8 μm wavelength.

The characteristic temperatures obtained from Fig. 6-2 are summarised in Table 6-1., together with experimentally determined results. Considering the complexity of these calculations and without any free parameters, the agreement between the calculated and measured results is excellent.

It should be mentioned that the characteristic temperature depends also on device design parameters. For example, Fig. 6-3 shows the characteristic temperature as a function of laser stripe width of GaInAsP/InP gain guided lasers obtained on devices from the same wafer. The decreasing of the characteristic temperature at narrow stripe width is consistent with the increased mode loss at the stripe edges.

In comparing calculated and measured results, however, such effects should be taken into consideration.

Fig. 6-2 Calculated temperature dependence of threshold current of GaInAsP/InP broad area laser emitting at 1.3 μm wavelength.

- (a) using the unified model;
- (b) including Auger recombination only; and
- (c) with Auger recombination rate reduced by an order of magnitude to simulate AlGaAs/GaAs laser devices.

Junction Temperature	$T_j < 250^\circ\text{K}$	$T_j > 250^\circ\text{K}$
GaAs Like Model	145°K	145-190°K
Auger Model	99°K	83-85°K
Unified Model	92°K	70-72°K
Measured Results	90-120°K	65-70°K

Table 6-1 Analytically and experimentally determined characteristic temperature of GaInAsP/InP lasers at junction temperatures below and above 250°K.

Fig. 6-3 Effect of stripe width on the characteristic temperature of gain guided GaInAsP/InP lasers

6.3. The Light-Current Characteristics

The effect of Auger recombination and its induced energetic carrier leakage on the light output versus injection current characteristics of broad area GaInAsP/InP lasers can be estimated by solving equations (6.9a) and (6.9b) under steady state conditions. Fig. 6-4 shows the calculated results, where curve(a) contains both the effect of Auger recombination and the effect of Auger recombination induced energetic carrier leakage, whereas curve(b) includes only Auger recombination but without leakage. In curve(c), the Auger recombination coefficient is reduced by an order of magnitude to resemble the rate in AlGaAs/GaAs devices. As indicated from these calculated results, the Auger recombination alone could account for a 73% (640 A/cm²) increment of threshold current density for GaInAsP/InP lasers at 300°K, and the Auger recombination induced energetic carrier leakage by an additional 16% (140 A/cm²). Although the absolute value of threshold current density depends critically on the loss and gain parameters used and comparison to experimental data is also limited by theoretical and experimental assumptions for broad area lasers, the calculated values compare favourably with the best experimental value of threshold current density of 1.7 kA/cm² for GaInAsP/InP lasers at 1.3 μm wavelength, and 900 A/cm² for AlGaAs/GaAs lasers at 0.8 μm wavelength.

Perhaps the most important result of these calculations of Fig. 6-4 is the demonstration that the quantum efficiency of the GaInAsP/InP laser does not depend on the Auger recombination and its induced energetic carrier leakage. Thus, as temperature increases, the laser quantum efficiency does not decrease greatly as the threshold current increases. This is in contrast to the intervalence band absorption model⁽¹⁴⁾ but agrees well with experimental results as shown in Fig. 2-2.

Fig. 6-4 Calculated L-I characteristics of GaInAsP/InP broad area laser at 300°K.
 (a) using the unified model;
 (b) including Auger recombination only; and
 (c) with Auger recombination rate reduced by an order of magnitude to simulate AlGaAs/GaAs laser devices.

6.4. Transient Response

In fiber optical communication systems, the information is usually carried in the form of on-off pulse modulation. The transient response of the laser that generates the optical output pulse from the current input pulse is one of the major concerns. This is especially important at bit rates comparable to the transient oscillatory output frequency of a laser subjected to current input pulses. The transient oscillatory behavior of laser diodes has been studied theoretically in AlGaAs/GaAs lasers^(11,12), where the Auger recombination effect is negligible. In GaInAsP/InP lasers, such effects should not be overlooked, especially insofar as the damping characteristic of the transient oscillation is concerned. Fig. 6-5(a) shows the calculated transient response of GaInAsP/InP broad area lasers from the unified model. The effect of Auger recombination on the transient oscillatory behavior is shown by comparing Fig. 6-5(a) with Fig. 6-5(b) where the transient response is calculated by reducing the Auger recombination rate by an order of magnitude. In both calculations, the lasers are pre-biased at 10% below threshold current and then a 23 nsec current pulse is applied to drive the lasers above the threshold value. In order to reveal the effect of Auger recombination, the height of the current pulse is made to be the same as indicated by the identical steady state photon density in the laser cavity in both cases. Fig. 6-5(a) and

(b) indicate that Auger recombination reduces the settling time of the transient oscillation by 50%. This result is expected from the unified model since the minority carrier lifetime is shortened by the Auger recombination. Calculation of transient response without Auger recombination induced energetic carrier leakage shows that the effect from the leakage is minor as compared to the Auger recombination.

Fig. 6-5(a) Calculated transient response of GaInAsP/InP broad area lasers from the unified model.

Fig. 6-5(b) Calculated transient response of broad area lasers with Auger recombination rate reduced by an order of magnitude to simulate AlGaAs/GaAs laser devices.

6.5. Effect of Stripe Width

In studying the properties of GaInAsP/InP lasers, Auger recombination and its induced energetic carrier leakage should not be neglected, which has been the case in most theoretical work on AlGaAs/GaAs lasers. This is especially important for the temperature dependence of threshold current of GaInAsP/InP lasers as demonstrated in previous sections.

The Auger recombination and its induced energetic carrier leakage also affect the device characteristics through device design, especially for gain guided lasers where the optical and spectral properties are determined mainly by the gain profile. One of the simplest design parameters of stripe geometry gain guided lasers is the stripe width of current injection. In section 6.2, it has been shown that the characteristic temperature of GaInAsP/InP lasers decreases by narrowing the stripe width. Fig. 6-6 shows the effect of stripe width on the threshold current. These effects can be well explained by the unified model. The narrowing of the stripe to a certain width would eventually cause extra mode loss when a significant portion of the optical field is outside the gain region. This will cause a higher cavity loss and hence higher carrier density to reach lasing threshold, similar to AlGaAs/GaAs lasers. However, in GaInAsP/InP laser, higher carrier density implies an extra

increase of threshold current due to the increased Auger recombination rate and the increased energetic carrier leakage as compared to AlGaAs/GaAs lasers. Evidence of carrier density increase at threshold as stripe width narrows is provided by the measured lasing wavelength dependence on stripe width of GaInAsP/InP lasers from the same wafer, as shown in Fig. 6-7.

However, to quantify the effects of recombination processes in GaInAsP/InP stripe geometry gain guided lasers, the complicated equations described in section 6.1 must be solved. As mentioned before, such an analysis has not been accomplished to date, except by assuming a constant carrier lifetime in AlGaAs/GaAs lasers^(1,2). Such an approach excludes the possibility of studying the effects of recombination processes on the properties of lasers. This, to a certain extent, hindered the advancement in understanding of the observed differences between GaInAsP/InP and AlGaAs/GaAs lasers in many aspects. In the following, analytic results on the threshold behavior, gain profile and optical intensity distribution in stripe geometry lasers are presented by including both Auger recombination and its induced energetic carrier leakage. These results are obtained by solving all of the equations of section 6.1 in a self-consistent manner to satisfy all the conditions simultaneously.

Fig. 6-6 Dependence of threshold current on stripe width
for GaInAsP/InP lasers (measured)

Fig. 6-7 Dependence of lasing wavelength on stripe width
for GaInAsP/InP lasers (measured)

Fig. 6-8(a) shows the calculated light output power versus injection current for a 12 μm wide stripe geometry gain guided GaInAsP/InP laser emitting at 1.3 μm wavelength using the unified model. It should be emphasized that no attempt has been made to vary the parameter values involved in the calculation to match the experimental data as shown in Fig. 6-6. All parameter values used are typical ones cited in the literature. Nevertheless, the calculated threshold current agrees reasonably well with measured results. Also, it should be mentioned that the calculated differential efficiency of 0.25 mW/ma agrees excellently with experimentally measured values, indicating that no extraordinary assumptions and parameters have been incorporated into the analysis.

Fig. 6-9 shows the calculated electron density distribution and optical intensity profile in the laser cavity at slightly above lasing threshold of the 12 μm laser of Fig. 6-8. In Fig. 6-10, the calculated results of similar laser with Auger recombination reduced to a rate corresponding to GaAs are shown. A comparison of Fig. 6-9(a) and 6-10(a) reveals that Auger recombination and energetic carrier leakage have significantly modified the carrier density distribution, hence gain profile, in the laser cavity. Notable gain flattening has occurred in the case of 6-9(a) when compared to the case in 6-10(a). Also, the carrier density drops much faster outside the stripe region in the

case of 6-9(a). As a result of higher loss suffered, the optical intensity distribution in Fig. 6-9(b) becomes narrower as compared to Fig. 6-10(b). The full width at half maximum (FWHM) of the optical intensity distributions reduces from 9.25 μm in Fig. 6-10(b) to 8.7 μm in Fig. 6-9(b). Furthermore, Auger recombination and energetic carrier leakage increases the threshold current from 52 mA in the case of Fig. 6-10 to 90 mA in the case of Fig. 6-9.

From the above results, it is also expected that the stripe width dependence of threshold current in GaInAsP/InP gain guided lasers would be considerably different from AlGaAs/GaAs lasers. The calculated results of threshold behavior are shown in Fig. 6-11, where curve (a) shows the stripe width dependence of threshold current of GaInAsP/InP lasers of 1.3 μm wavelength using the unified model, while curve (b) shows the dependence by reducing the Auger recombination to a rate corresponding to GaAs. As mentioned previously, no attempt has been made in the calculations to match the experimental results. Nevertheless, the analytic and the experimental results of the threshold dependence on stripe width agree remarkably well. Furthermore, the difference of threshold current dependence on stripe width between GaInAsP/InP and AlGaAs/GaAs lasers is well explained by the results shown in Fig. 6-11(a) and (b).

Fig. 6-8 Calculated L-I characteristics of a 12 μm stripe width GaInAsP/InP gain guided laser of 1.3 μm wavelength.

Fig. 6-9(a) Calculated electron density distribution of the laser shown in Fig. 6-8 at light output power of 0.6 mW, using the unified model.

Fig. 6-9(b). Calculated normalized optical intensity profile of the laser shown in Fig. 6-8 at output power of 0.6 mW, using the unified model.

Fig. 6-10(a) Calculated electron density distribution of a 12 μm stripe width gain-guided laser by reducing Auger recombination to a rate corresponding to GaAs.

Fig. 6-10(b) Calculated optical intensity distribution of a 12 μm stripe width gain guided laser by reducing Auger recombination to a rate corresponding to GaAs.

Fig. 6-11 Calculated stripe width dependence of threshold current of gain guided lasers using the unified model:

- (a) GaInAsP/InP lasers;
- (b) lasers assuming a reduced Auger recombination rate corresponding to GaAs.
- are experimental results of GaInAsP/InP lasers from Fig. 6-6 for comparison.

To provide an insight into the results of Fig. 6-11, in Fig. 6-12, the electron density distribution and optical intensity profile for a few stripe widths calculated from the unified model at slightly above threshold are shown. These analytic results reveal that at wide stripe width, say 14 μm , the optical intensity profile is relatively narrow as compared to the electron density distribution. Optical loss outside the stripe is then very small. As the stripe width decreases, so does the optical intensity profile. However, as stripe width narrows to a certain extent, optical loss outside the stripe region becomes significant. To reach mode gain threshold, the local gain and hence carrier density within the stripe region has to be increased substantially. The high carrier density within the stripe decreases the refractive index with respect to outside of the stripe, thus increasing the strength of anti-guiding. This is clearly shown in Fig. 6-12(c) where the stripe width is reduced to 4 μm . In this case, the strength of gain guiding is substantially weakened by the anti-guiding caused by the carrier induced refractive index decreasing within the stripe. As a consequence, the optical intensity profile widens significantly. However, in GaInAsP/InP lasers, higher carrier density means an extra penalty in threshold current density due to increased Auger recombination and energetic carrier leakage, as indicated by the results of Fig. 6-6 and 6-11(a). However, this effect should be greatly reduced by reducing the Auger recombination rate. This is illustrated

by the stripe width dependence of threshold current of Fig. 6-11(b).

To show that the large increase of threshold current at narrow stripe width is indeed due to Auger recombination and energetic carrier leakage, the calculated full width at half maximum of the optical intensity distribution as a function of stripe width is shown in Fig. 6-13. Curve (a) of Fig. 6-13 corresponds to GaInAsP/InP laser, while curve (b) corresponds to the case that the Auger recombination being reduced to a rate of GaAs. Note that the FWHM of optical intensity profile of curve (b) is larger than curve (a).

It is also interest to see that the minimum FWHM of the optical intensity profile is at about 8 μm stripe width, which is also the stripe width of minimum threshold current of GaInAsP/InP gain guided lasers of 1.3 μm wavelength, as shown by experimental results in Fig. 6-8 and by the computed results of Fig. 6-11(a).

The observed lasing wavelength dependence on stripe width of GaInAsP/InP gain guided lasers shown in Fig. 6-7 is also consistent with these theoretical results. Fig. 6-14 shows the calculated peak carrier density as a function of stripe width. The sharp increase of peak carrier density at about 4 μm stripe width corresponds well to the sharp drop of lasing wavelength. Thus, the observed lasing wavelength dependence

of GaInAsP/InP lasers could be explained simply by the band filling effect.

Fig. 6-12 Calculated electron density distribution and optical intensity profile of gain guided stripe geometry lasers at various stripe widths. The output power is 0.1mW (slightly above threshold).

Fig.6-13 Calculated full width at half maximum of intensity distribution as a function of stripe width using the unified model:

(a) GaInAsP/InP lasers;

(b) lasers assuming a reduced Auger recombination rate corresponding to GaAs.

Fig.6-14 Peak carrier density as a function of stripe width at 0.1 mW output power (slightly above threshold).

6.6 Discussions and Conclusions

In the previous sections, the effects of Auger recombination and its induced energetic carrier leakage on the properties of stripe geometry gain guided lasers have been analysed. It is believed that this is the first time that the modification of gain profile by recombination processes and carrier leakage on stripe geometry gain guided lasers has been addressed properly.

In the study of stripe geometry lasers, temporal instability (self-sustained pulsation) has also attracted much attention. At present, no unique model has been established for the phenomenon of self-sustained pulsations. In AlGaAs/GaAs gain guided lasers, we have experimentally determined a relationship between stripe width and the probability of occurrence of self-sustained pulsations: by reducing the stripe width from 5-10 μm to 2.5 μm , the occurrence of self-sustained pulsations is greatly reduced⁽¹¹⁾. The development of self-sustained pulsations through device aging⁽¹²⁾ points to the extrinsic nature of most observed self-sustained pulsations in AlGaAs/GaAs lasers⁽¹¹⁾. In GaInAsP/InP gain guided lasers, two important phenomena on self-sustained pulsations could not be explained by the theory developed for AlGaAs/GaAs lasers: first, the behavior of self-sustained pulsations, in most

cases, does not change with aging; most importantly, we have also observed that by reducing stripe width from 5-10 μm to 2-3 μm , strong self-sustained pulsations occur on all devices tested at light output level slightly above threshold⁽¹¹¹⁾.

In this section, qualitative discussions of the effect of Auger recombination and energetic carrier leakage on self-sustained pulsations are made.

In the analysis of stripe width dependence of threshold current of lasers, it has been observed that at stripe width of 2 μm and 3 μm , stable photon density could not be obtained at light output power levels above 0.15 mW and 0.4 mW, respectively, if Auger recombination rates corresponding to those in GaInAsP/InP lasers at 1.3 μm wavelength are applied. However, after reducing the Auger recombination to the rate of GaAs, stable photon density is obtainable for such stripe widths. It seems, then, there may exist a correlation between the instability of photon density as calculated, and experimentally observed self-sustained pulsations in narrow stripe GaInAsP/InP lasers.

Fig. 6-15 shows the carrier density distribution and relative optical intensity profile of a 3 μm stripe width laser calculated from the unified model at a current level just before stable photon density could not be obtained. It

shows that the large spread of the optical field into the absorbing regions outside the stripe edges causes excessive optical loss. This is also indicated by the excess peak carrier density at the stripe centre (10% higher than the case where Auger recombination is reduced to the rate of GaAs). The widening of the intensity profile indicates that the anti-guiding caused by carrier induced refractive index reduction within the stripe is strongly competing with the guiding provided by carrier induced gain (the width of the gain region is 8% narrower than the case when Auger recombination is reduced to the rate of GaAs). Stable solutions would be obtained only if the relative strength of guiding and anti-guiding could be maintained. A further increase of injection current, however, could change this situation. For example, if the reduction of the strength of anti-guiding becomes larger than the reduction of the strength of gain guiding by a slight increase of photon density, the laser would have a stronger guiding. This would then cause a reduction of the spreading of the optical field, which means a decrease of optical loss and an increase of net mode gain in the laser cavity. Thus, the photon density would increase further. Therefore, the criterion of instability given by Basov⁽¹²⁾, i.e., $dG/dS > 0$, where G is the net mode gain and S the photon density, is satisfied. Detailed analysis of such instability involves, however, excessively large computer costs. In the study of self-sustained pulsations, Arnold and Petermann⁽¹³⁾ have

proposed that such temporal instability of laser output power could be related to self-focusing effects induced by spatial hole burning. Fig. 6-16 shows the progress of spatial hole-burning calculated using the unified model. Shown in Fig. 6-17 is the full width at half maximum of the optical intensity distribution. Self-focusing effects are clearly indicated. It is worth noting that stable solutions could be found in all of the above cases.

Fig. 6-15(a) Calculated carrier density distribution of 3 μm wide gain guided laser at optical output just before stable photon density could not be obtained.

Fig. 6-15(b) Calculated optical intensity distribution of 3 μm wide gain guided laser at optical output just before stable photon density could not be obtained.

Fig. 6-16 Progress of spatial hole burning calculated in a 14 μm wide stripe geometry gain guided laser using the unified model.

Fig. 6-17 Full width at half maximum (FWHM) of optical intensity distribution at various output power levels, showing self-focusing effect.

7. CONCLUSIONS.

This thesis has described a unified model developed to account for the fundamental differences in device characteristics of light emitting diodes and injection lasers from GaInAsP/InP and AlGaAs/GaAs material systems. Through this unified model, it is possible to predict correctly the light output power versus injection current characteristics of light emitting diodes, temperature dependence of threshold current of lasers, and other properties of interest, directly from the material and device design parameters.

The unified model consists of two separate but interrelated mechanisms: the Auger recombination of injected carriers in the active layer of the devices (which is studied in the early phase of this thesis research), and the Auger recombination induced energetic carriers leaking over heterojunction barriers between the GaInAsP active and the InP confinement layers.

In the Auger recombination model, the excess non-linearity of light output power versus injection current characteristics of light emitting diodes and the excess temperature sensitivity of threshold current of lasers arise from the non-radiative Auger recombination processes which

compete with the radiative recombination processes; furthermore, the Auger recombination rate increases with temperature.

The Auger recombination model can account successfully for the characteristics of GaInAsP/InP light emitting devices over a wide range of operating conditions, especially in zinc diffused surface-emitting LEDs. Discrepancies do exist, however, between theoretical and experimental results in some designs of light emitting devices, as well as in some ranges of operating conditions. Direct observation of carrier leakages with certain characteristics, therefore, pointed out the need to incorporate a realistic carrier leakage model into the theory for the analysis of device properties.

An Auger recombination induced energetic carrier leakage theory was developed during the latter phase of this work, which in conjunction with the Auger recombination mechanism, forms the unified model. In developing the Auger recombination induced energetic carrier leakage model, a rate equation describing the rate of change of densities of energetic carriers is derived, which takes into consideration the rate of generation of energetic carriers through Auger recombination processes, the rate of energy relaxation of the energetic carriers through electron-phonon interactions, and the leakage of energetic carriers over

heterojunction barriers limited by diffusion and drift mechanisms. The rate equation of energetic carriers including leakage coupling with the rate equations of injected carriers and photon densities could then be used to describe the behavior of the light emitting devices of interest.

The unified model has been applied to different designs of light emitting diode and laser structures, and gives excellent agreement between theoretical and experimental results.

Specifically, in the analysis of device leakage, it is found that the energetic electron leakage dominates. In light emitting diodes with thick active layer and with proper confinement layer doping such that the leakage becomes diffusion limited, the device leakage is then negligibly small compared to total injection current. Under such conditions, the Auger recombination model alone can account well for the observed device characteristics over a wide range of operating conditions. The discrepancy between analytic and experimental results widens as the active layer thickness reduces from 1 μm in ordinary light emitting diodes to about 0.2 μm as found in ordinary lasers, and as the leakage becomes drift limited, if the Auger recombination model is used alone under such conditions. However, by including the Auger recombination induced

energetic carrier leakage in the analysis, the light output saturation behavior of light emitting diodes and the temperature dependence of the threshold current of lasers are found to be in excellent agreement with experimental measurements. Thus the unified model can be used in the design optimization of light emitting devices in this aspect.

Carrier leakage can be greatly enhanced in some special device structures specifically designed for studying carrier leakage. The unified model is fully capable of calculating the effects of the enhanced leakage in such devices.

In the analysis, it is found that the leakage current density has an n^2 dependence on the carrier density in the active layer for the diffusion limited case. In the drift limited case, the dependence is between n^2 and n^3 . These dependencies are confirmed by studying either carrier lifetimes or high energy emission caused by carrier leakage.

Unsolved problems still remain in many areas. First, the values of Auger recombination coefficients, which are important in theoretical simulations, are still uncertain, despite intensive experimental and theoretical studies. As a matter of fact, even the dominant Auger recombination process in GaInAsP is undetermined. Detailed measurements and data fitting by applying the unified model in a wide

variety of device design parameters and operating conditions perhaps may provide a solution. Secondly, detailed study of electron - electron and electron - phonon interactions, which are important in calculating carrier leakage effects, is lacking. For example, in studying the effective energy relaxation times of the energetic carriers, alloy scattering, carrier scattering and other phonon scattering, except polar optical phonon scattering, are not included. Also not included in the calculations are the effects of carrier screening. Although the calculated effective energy relaxation time of energetic electrons is found consistent with measured results, it is questionable to rule out the contributions from other scattering mechanisms entirely. The carrier screening effect, compensating the effects of other scattering mechanisms, is one of the possibilities for such good agreement being obtained. It is believed that, even though the development of the model does not depend on the absolute values of Auger recombination coefficients and the effective energy relaxation times, detailed analysis of device characteristics critically depends on them.

Detailed study of the effects of Auger recombination and its induced energetic carrier leakage on the static and dynamic properties of lasers through various device design parameters has not been carried out, mainly due to the large computer costs of such calculations. Neither has the effect of energetic carrier leakage on the reliability of the light

emitting devices been determined. The energy released through non-radiative recombination by the leaked carriers in the wide band gap InP material at the vicinity of the active and confinement layer interfaces is approaching the value of GaAs. This is especially of concern in buried heterostructure index guided lasers where defects may exist at the interfaces between the active layer and the regrown InP-burying materials.

8. REFERENCES

(1) G.H.B. Thompson and G.D. Henshall, "Nonradiative carrier loss and temperature sensitivity of threshold in 1.27 μm (GaIn)(AsP)/InP D.H. lasers," Electron. Lett., vol.16, pp.42-44, 1980.

(2) K.D. Chik, A.J. SpringThorpe, T.F. Devenyi, and B.A. Richardson, "Effects of Auger recombination on double heterojunction 1.3 μm GaInAsP/InP light-emitting diodes," Technical Digest, IEEE international Electron Devices Meetings, pp.374-377, 1980.

(3) N.K. Dutta and R.J. Nelson, "Temperature dependence of threshold of InGaAsP/InP double-heterostructure lasers and Auger recombination," Appl. Phys. Lett., vol.38, pp.407-409, 1981.

(4) T. Uji, K. Iwamoto, and R. Lang, "Non-radiative recombination in InGaAsP/InP light sources causing light emitting diode output saturation and strong laser-threshold-current temperature sensitivity," Appl. Phys. Lett., vol.38, pp.193-195, 1981.

(5) A. Sugimura, "Band-to-band Auger effect on the output power saturation in InGaAsP LED's," IEEE J. Quantum Electron., vol.QE-17, pp.441-443, 1981.

(6) A. Sugimura, "Band-to-band Auger recombination effect on InGaAsP laser threshold," IEEE J. Quantum Electron., vol.QE-17, pp.627-635, 1981.

(7) G.H.B. Thompson, "Temperature dependence of threshold current in (GaIn)(AsP) DH lasers at 1.3 and 1.5 μm wavelength," IEE Proc., vol.128, pt.1, pp.37-43, 1981.

(8) N.K. Dutta and R.J. Nelson, "Temperature dependence of the lasing characteristics of the 1.3 μm InGaAsP-InP and GaAs-AlGaAs DH lasers," IEEE J. Quantum Electron., vol.QE-18, pp.871-878, 1982.

(9) T. Uji, K. Iwamoto, and R. Lang, "Dominance of Auger recombination in InGaAsP light emitting diode current-power characteristics," IEEE Trans. Electron Devices, vol.ED-30, pp.316-320, 1983.

(10) R.J. Nelson and N.K. Dutta, "Calculated Auger rates and temperature dependence of threshold for semiconductor lasers emitting at 1.3 μm and 1.55 μm ," J. Appl. Phys., vol.54, pp.2923-2929, 1983.

(11) A. Haug, "Evidence of the importance of Auger recombination for InGaAsP lasers," Electron. Lett., vol.20, pp.85-86, 1984.

(12) A. Haug, "Theory of the temperature dependence of the threshold current of an InGaAsP laser," IEEE J. Quantum Electron., vol.QE-21, pp.716-718, 1985.

(13) R.C. Goodfellow, A.C. Carter, G.J. Rees, and R. Davis, "Radiance saturation in small-area GaInAsP/InP and GaAlAs/GaAs LED's," IEEE Trans. Electron. Devices, vol.ED-28, pp.365-371, 1981.

(14) A.R. Adams, M. Asada, Y. Suematsu, and S. Arai, "The temperature dependence of the efficiency and threshold current of InGaAsP lasers related to intervalence band absorption," Japan. J. Appl. Phys., vol.19, pp.L621-624, 1980.

(15) M. Asada, A.R. Adams, K.E. Stubkjaer, Y. Suematsu, Y. Itaya, And S. Arai, "The temperature dependence of the threshold current of GaInAsP/InP DH lasers," IEEE J. Quantum Electron., vol.QE-17, pp.611-619, 1981.

(16) M. Asada and Y. Suematsu, "The effects of loss and nonradiative recombination on the temperature dependence of

threshold current in 1.5-1.6 μm GaInAsP/InP lasers," IEEE J. Quantum Electron., vol.QE-19, pp.917-923, 1983.

(17) Y. Horikoshi and Y. Furukawa, "Temperature sensitive threshold current of InGaAsP-InP double heterostructure lasers," Japan. J. Appl. Phys., vol.18, pp.809-815, 1979.

(18) R.E. Nahory, M.A. Pollock, and J.C. DeWinter, "Temperature dependence of InGaAsP double heterostructure laser characteristics," Electron. Lett., vol.15, pp.695-696, 1979.

(19) N.K. Dutta, R.J. Nelson, and P.A. Barnes, "Temperature dependence of threshold and electrical characteristics of InGaAsP-InP D.H. lasers," Electron. Lett., vol.16, pp.653-654, 1980.

(20) D. Wang and H. Shui, "Multi-phonon recombination (MPR) effect on GaInAsP/InP laser threshold," Proc., IEEE International Semiconductor Laser Conference, pp.64-65, 1982.

(21) M. Yano, H. Nishi, and M. Takusagawa, "Influence of interfacial recombination on oscillation characteristics of InGaAsP/InP DH lasers," IEEE J. Quantum Electron., vol.QE-16, pp.661-667, 1980.

(22) J. Shah, R.F. Leheny, and R.E. Nahory, "Hot-carrier effect in 1.3 μ m InGaAsP light emitting diodes," Appl. Phys. Lett., vol.39, pp.618-620, 1981.

(23) H. Temkin, A.K. Chin, M.A. DiGiuseppe, and V.G. Keramidas, "Light-current characteristics of InGaAsP light emitting diodes," Appl. Phys. Lett., vol.39, pp.405-407, 1981.

(24) O. Wada, S. Yamakoshi, and T. Sakurai, "Band-gap enhanced carrier heating in InGaAsP/InP double heterostructure light-emitting diodes," Appl. Phys. Lett., vol.41, pp.981-983, 1982.

(25) B. Etienne, J. Shah, R.F. Leheny, and R.E. Nahory, "Influence of hot carriers on the temperature dependence of threshold in 1.3- μ m InGaAsP lasers," Appl. Phys. Lett., vol.41, pp.1018-1020, 1982.

(26) M. Yano, H. Nishi, and M. Takusagawa, "Temperature characteristics of threshold current in InGaAsP/InP double heterostructure lasers," J. Appl. Phys., vol.51, pp.4022-4028, 1980.

(27) M. Yano, H. Imai, and M. Takusagawa, "Analysis of threshold temperature characteristics of InGaAsP/InP double

heterojunction lasers," J. Appl. Phys., vol.52, pp.3172-3175, 1981.

(28) M. Yano, H. Imai, and M. Takusagawa, "Analysis of electrical, threshold, and temperature characteristics of InGaAsP/InP double-heterojunction lasers," IEEE J. Quantum Electron., vol.QE-17, pp.1954-1963, 1981.

(29) S. Yamakoshi, T. Sanada, O. Wada, I. Umebu, and T. Sakurai, "Effects of carrier leakage on InGaAsP/InP double-heterostructure light emitters," Proc., International Symp. GaAs and Related Compounds, pp.485-490, 1981.

(30) T.R. Chen, B. Chang, L.C. Chiu, K.L. Yu, S. Margalit, and A. Yariv, "Carrier leakage and temperature dependence of InGaAsP lasers," Appl. Phys. Lett., vol.43, pp.217-218, 1983.

(31) R. Lang, M. Sugimoto, T. Uji, K. Kasahara, and A. Suzuki, "Auger recombination, carrier heating and enhanced carrier leakage in InGaAsP/InP DH-light sources," Proc., IEEE International Semiconductor Laser Conference, pp.60-61, 1982.

(32) L.C. Chiu, K.L. Yu, S. Margalit, T.R. Chen, U. Koren, A. Hasson, and A. Yariv, "Field and hot carrier enhanced

leakage in InGaAsP/InP heterojunctions," IEEE J. Quantum Electron., vol.QE-19, pp.1335-1338, 1983.

(33) N.K. Dutta and R.J. Nelson, "Light saturation of InGaAsP-InP LED's," IEEE J. Quantum Electron., vol.QE-18, pp.375-381, 1982.

(34) A. Mozer, K.M. Romanek, W. Schmid, and M.H. Pilkuhn, "Evidence for Auger and free-carrier losses in GaInAsP/InP lasers: Spectroscopy of a short wavelength emission," Appl. Phys. Lett., vol.41, pp.964-966, 1982.

(35) A. Mozer, K.M. Romanek, O. Hildebrand, W. Schmid, and M.H. Pilkuhn, "Losses in GaInAs(P)/InP and GaAlSb(As)/GaSb lasers-the influence of the split-off valence band," IEEE J. Quantum Electron., vol.QE-19, pp.913-916, 1983.

(36) C.B. Su, R. Olshansky, J. Manning, and W. Powazinik, "Temperature dependence of threshold current in III-V semiconductor lasers," Appl. Phys. Lett., vol.44, pp.1030-1032, 1984.

(37) H.C. Casey, Jr., "Temperature dependence of the threshold current density in GaInAsP (1.3 μ m) double heterostructure lasers," J. Appl. Phys., vol.56, pp.1959-1964, 1984.

(38) W. Zhuang, B. Zheng, J. Xu, Y. Li, J. Xu, and P. Chen, "Carrier loss resulting from Auger recombination in InGaAsP/InP double heterojunction laser diodes: spectroscopy of 950 nm high energy emission," IEEE J. Quantum Electron., vol. QE-21, pp. 712-715, 1985.

(39) A.P. Bogatov, L.M. Dolginov, L.V. Druzhinina, P.G. Eliseev, B.N. Sverdlov, and E.G. Shevchenko, "Heterojunction lasers made of GaInAsP and AlGaSbAs solid solutions," Soviet J. Quantum Electron., vol. 4, p. 1281, 1975.

(40) J.J. Hsieh, "Room-temperature operation of GaInAsP/InP double-heterostructure diode lasers emitting at 1.1 μm ," Appl. Phys. Lett., vol. 28, pp. 283-285, 1976.

(41) J.J. Hsieh, J.A. Rossi, and J.P. Donnelly, "Room-temperature CW operation of GaInAsP/InP double-heterostructure diode lasers emitting at 1.1 μm ," Appl. Phys. Lett., vol. 28, pp. 709-711, 1976.

(42) D.N. Payne and W.A. Gambling, "Zero material dispersion in optical fibers," Electron. Lett., vol. 11, pp. 176-178, 1975.

(43) M. Horiguchi and H. Osanai, "Spectral losses of low-OH-content optical fibers," Electron. Lett., vol. 12, pp. 310-312, 1976.

(44) C. Hu, "LED charge-control model and speed at high current," Proc. IEEE, vol.66, pp.599-601, 1978.

(45) T.P. Lee, "The nonlinearity of double-heterostructure LED's for optical communications," Proc. IEEE, vol.65, pp.1408-1410, 1977.

(46) H. Kressel and J.K Butler, "Semiconductor lasers and heterojunction LED's," Academic Press, N.Y., 1977.

(47) C.B. Su and R. Olshansky, "Carrier lifetime measurement for determination of recombination rates and doping levels of III-V semiconductor light sources," Appl. Phys. Lett., vol.41, pp.833-835, 1982.

(48) H.C. Casey, Jr., "Room-temperature threshold-current dependence of GaAs/AlGaAs double-heterostructure lasers on x and active-layer thickness," J. Appl. Phys., vol.49, pp.3684-3692, 1978.

(49) F. Stern, "Calculated spectral dependence of gain in excited GaAs," J. Appl. Phys., vol.47, pp.5382-5386, 1976.

(50) W. Bardyszewski and D. Yevick, "A numerical analysis of Auger processes in p-type GaAs," J. Appl. Phys., vol.57, pp.4820-4822, 1985.

(51) N.K. Dutta and R.J. Nelson, "Gain measurements in 1.3 μm InGaAsP-InP DH lasers," IEEE J. Quantum Electron., vol.QE-18, pp.44-49, 1982.

(52) C.H. Henry, R.A. Logan, F.R. Merritt, and J.P. Luongo, "The effect of intervalence band absorption on the thermal behavior of InGaAsP lasers," IEEE J. Quantum Electron., vol.QE-19, pp.947-952, 1983.

(53) H.C. Casey, Jr., and P.L. Carter, "Variation of intervalence band absorption with hole concentration in p-type InP," Appl. Phys. Lett., vol.44, pp.82-83, 1984.

(54) B.K. Ridley, "On the multiphonon capture rate in semiconductors," Solid State Electron., vol.21, pp.1319-1323, 1978.

(55) E.A. Rezek, N. Holonyak, Jr., and B.K. Fuller, "Temperature dependence of threshold current for coupled multiple quantum-well InGaPAs-InP heterostructure laser diodes," J. Appl. Phys., vol.51, pp.2402-2405, 1980.

(56) C.H. Henry, B.F. Levine, R.A. Logan, and C.G. Bethea, "Minority carrier lifetime and luminescence efficiency of 1.3 μm InGaAsP-InP double heterostructure layers," IEEE J. Quantum Electron., vol.QE-19, pp.905-912, 1983.

(57) R.J. Nelson and R.G. Sobers, "Interfacial recombination velocity in GaAlAs/GaAs heterostructures," Appl. Phys. Lett., vol.32, pp.761-763, 1978.

(58) C.H. Henry, R.A. Logan, H. Temkin, and F.R. Merritt, "Absorption, emission, and gain spectra of 1.3 μm InGaAsP quaternary lasers," IEEE J. Quantum Electron., vol.QE-19, pp.941-946, 1983.

(59) G.H. Glover, "Electron energy relaxation times in GaAs and InP," Appl.Phys. Lett., vol.21, pp.409-411, 1972.

(60) D.L. Rode, "How much Al in the AlGaAs-GaAs laser?," J. Appl. Phys., vol.45, pp.3887-3891, 1974.

(61) H.C. Casey, Jr. and M.B. Panish, "Heterostructure Lasers", Academic Press, N.Y., 1978.

(62) N. Kameta, T. Kamiya, and H. Yanai, "Direct observation of carrier leakage through hetero-barriers in a highly excited AlGaAs DH LED," Proc. Int. Symp. GaAs and Related Compounds, pp.497-502, 1981.

(63) C.B. Su, J. Schlafer, J. Manning, and R. Olshansky, "Measurement of radiative recombination coefficient and

carrier leakage in 1.3 μm InGaAsP lasers with lightly doped active layers," Electron. Lett., vol.18, pp.1108-1110, 1982.

(64) S. Yamakoshi, T. Sanada, O. Wada, I. Umebu, and T. Sakurai, "Direct observation of electron leakage in InGaAsP/InP double heterostucture," Appl. Phys. Lett., vol.40, pp.144-146, 1982.

(65) T.R. Chen, S. Margalit, U. Koren, K.L. Yu, L.C. Chiu, A. Hasson, and A. Yariv, "Direct measurement of the carrier leakage in an InGaAsP/InP laser," Appl. Phys. Lett., vol.42, pp.1000-1002, 1983.

(66) L. Chen, J.C.V. Mattos, F.C. Prince, and N.B. Patel, "Spatially resolved observation of carrier leakage in 1.3 μm InGaAsP lasers," Appl. Phys. Lett., vol.44, pp.520-522, 1984.

(67) R. Olshansky, C.B. Su, J. Manning, and W. Powazinik, "Measurement of radiative and nonradiative recombination rates in InGaAsP and AlGaAs light sources," IEEE J. Quantum Electron., vol.QE-20, pp.838-854, 1984.

(68) M.A. Pollack, J.R. Pawlik, R.E. Nahory, and P.J. Anthony, "Comparison of the electrical characteristics and threshold temperature dependences of 1.3 μm and 1.6 μm

stripe geometry InGaAsP DH lasers," IEEE J. Quantum Electron., vol.QE-17, pp.450-453, 1981.

(69) A.R. Beattie and P.T. Landsberg, "Auger effect in semiconductors," Proc. Phys. Soc. A, vol.249, pp.16-29, 1959.

(70) D.M. Eagles, "The phonon assisted Auger effect in semiconductors," Proc. Phys. Soc., vol.78, pp.204-252, 1961.

(71) W. Lochmann, "Phonon-assisted Auger recombination in semiconductors," Phys. Stat. Sol. (a), vol.40, pp.285-292, 1977.

(72) W. Lochmann, "Scattering mechanisms in phonon-assisted Auger recombination," Phys. Stat. Sol. (a), vol.42, pp.181-185, 1977.

(73) J. Heinen, H. Albrecht, and C. Weyrich, "Determination of the recombination coefficients in undoped (In,Ga)(As,P) from transient optical output analysis of (In,Ga)(As,P)-InP double heterostructure LEDs," J. Appl. Phys., vol.53, pp.1800-1803, 1982.

(74) B. Sermage, H.J. Eichler, J.P. Heritage, R.J. Nelson, and N.K. Dutta, "Photoexcited carrier lifetime and Auger

recombination in 1.3 μm InGaAsP," Appl. Phys. Lett., vol.42, pp.259-261, 1983.

(75) E. Winter and E.P. Ippen, "Nonlinear carrier dynamics in GaInAsP compounds," Appl. Phys. Lett., vol.44, pp.999-1001, 1984.

(76) J.C.V. Mattos, E.O. Gobel, and A. Mozer, "Picosecond luminescence studies of the recombination kinetics of GaInAsP," Solid State Communications, vol.55, pp.811-816, 1985.

(77) D.Z. Garbuzov, V.V. Agaev, V.B. Khalfin, and V.P. Chalyi, "Radiative and Auger processes in a photoexcited electron-hole plasma in InGaAsP/InP double heterostructures (1.3 μm)," Soviet Phys. Semiconductor, vol.17, pp.992-995, 1983.

(78) C.B. Su, J. Schlafer, J. Manning, and R. Olshansky, "Measurement of radiative and Auger recombination rates in p-type InGaAsP diode lasers," Electron. Lett., vol.18, pp.595-596, 1982.

(79) G.H.B. Thompson, "Analysis of radiative and nonradiative recombination law in lightly doped InGaAsP lasers," Electron. Lett., vol.19, pp.154-155, 1983.

(80) E.O. Kane, "The $k \cdot p$ method," Semiconductors and Semimetals, vol.1, Academic Press, N.Y., 1966.

(81) P. Lawaetz, "Valence-band parameters in cubic semiconductors," Phys. Rev. B, vol.4, pp.3460-3467, 1971.

(82) E. Antoncik and P.T. Landsberg, "Overlap integrals for Bloch electrons," Proc. Phys. Soc., vol.82, pp.337-342, 1963.

(83) A.R. Beattie and G. Smith, "Recombination in semiconductors by a light hole Auger transition," Phys. Stat. Sol., vol.19, pp.577-586, 1967.

(84) A. Sugimura, "Band to band Auger recombination in InGaAsP lasers," Appl. Phys. Lett., vol.39, pp.21-23, 1981.

(85) N.K. Dutta and R.J. Nelson, "The case of Auger recombination in InGaAsP," J. Appl. Phys., vol.53, pp.74-92, 1982.

(86) D.Z. Garbuzov, Z.N. Sokolova, and V.B. Khalfin, "Calculation of Auger process times for p-type InGaAsP solid solutions," Soviet Phys. Semicond., vol.16, pp.707-708, 1982.

(87) B.L. Gelmont, Z.N. Sokolova, and V.B. Khalfin, "Auger recombination in a degenerate electron-hole plasma in InGaAsP solid solutions," Soviet Phys. Semicond., vol.17, pp.280-283, 1983.

(88) W. Bardyszewski and D. Yevick, "Compositional dependence of the Auger coefficient for InGaAsP lattice matched to InP," J. Appl. Phys., vol.58, pp.2713-2723, 1985.

(89) A. Haug, "Auger recombination in direct gap semiconductors: band structure effects," J. Phys. C, vol.16, pp.4159-4172, 1983.

(90) J.R. Chelikowsky and M.L. Cohen, "Nonlocal pseudopotential calculations for the electronic structure of eleven diamond and zinc-blende semiconductors," Phys. Rev. B, vol.14, pp.556-582, 1976.

(91) A. Haug and W. Ekardt, "The influence of screening effects on the Auger recombination in semiconductors," Solid State Communications., vol.17, pp.267-268, 1975.

(92) H. Brendecke, H.L. Stormer, and R.J. Nelson, "Cyclotron resonance in n-type InGaAsP," Appl. Phys. Lett., vol.35, pp.772-774, 1979.

(93) R.J. Nicholas, J.C. Portal, C. Honlbert, P. Perrier, and T.P. Pearsall, "An experimental determination of the effective masses for GaInAsP alloys grown on InP," Appl. Phys. Lett., vol.34, pp.492-494, 1979.

(94) E.M. Conwell, "High field transport in semiconductors," Solid State Phys. Suppl. 9, Academic Press, N.Y., 1967.

(95) Y. Takeda, M.A. Littlejohn, R.J. Trew, and J.A. Hutchby, "Effects of two longitudinal optical phonon modes on electron distribution in GaInAsP," Appl. Phys. Lett., vol.40, pp.836-838, 1982.

(96) R.M. Amirtharaj, G.D. Holah, and S. Perkowitz, "Far-infrared spectroscopic study of InGaAsP," Phys. Rev. B, vol.21, pp.5656-5661, 1980.

(97) D.L. Rode, "Low-field electron transport," Semiconductors and Semimetals, vol.10, Academic Press, N.Y., 1975.

(98) J.D. Wiley, "Mobility of Holes in III-V compounds," Semiconductors and Semimetals, vol.10, Academic Press, N.Y., 1975.

(99) R. Chin, N. Holonyak, Jr., S.W. Kirchoeffer, R.M. Kolbas, and E.A. Rezek, "Determination of the valence-band discontinuity of InP-InGaPAs($x=0.13, z=0.29$) by quantum-well luminescence," Appl. Phys. Lett., vol.34, pp.862-864, 1979.

(100) Z.Y. Xu and C.L. Tang, "Picosecond relaxation of hot carriers in highly photoexcited bulk GaAs and GaAs-AlGaAs multiple quantum well," Appl. Phys. Lett., vol.44, pp.692-694, 1984.

(101) P.J. Anthony and N.E. Schumaker, "Ambipolar transport in double heterostructure injection lasers," IEEE Electron Device Lett., vol.EDL-1, pp.58-59, 1980.

(102) P.J. Anthony and N.E. Schumaker, "Temperature dependence of the lasing threshold current of double heterostructure injection lasers due to drift current loss," J. Appl. Phys., vol.51, pp.5038-5040, 1980.

(103) A.R. Goodwin, J.R. Peters, M. Pion, G.H.B. Thompson, and J.E.A. Whiteaway, "Threshold temperature characteristics of double heterostructure GaAlAs lasers," J. Appl. Phys., vol.46, pp.3126-3131, 1975.

(104) G.F.D. Duff and D. Naylor, "Differential equations of applied mathematics," John Wiley & Sons, N.Y., 1966.

(105) B.A. Richardson, to be published.

(106) J. Straus, "The nonlinearity of high radiance light emitting diodes," IEEE J. Quantum Electron., vol.QE-14, pp.813-819, 1978.

(107) W.B. Joyce and R.W. Dixon, "Electrical characterization of heterostructure lasers," J. Appl. Phys., vol.49, pp.3712-3728, 1978.

(108) B.W. Hakki, "GaAs double heterostructure lasing behaviour along the junction plane," J. Appl. Phys., vol.46, pp.292-302, 1975.

(109) T.L. Paoli, "Nonlinearities in the emission characteristics of stripe geometry (AlGa)As double heterostructure junction lasers," IEEE J. Quantum Electron., vol.QE-12, pp.770-776, 1976.

(110) T. Ikegami, K. Kobayashi, and Y. Suematsu, "Transient behaviour of semiconductor injection lasers," Electr. & Commun. Jap., vol.53B, pp.82-89, 1970.

(111) K.D. Chik, J.C. Dymont, and B.A. Richardson, "Self-sustained pulsations in semiconductor laser: experimental results and theoretical confirmation," J. Appl.

Phys., vol.51, pp.4029-4039, 1980, and references cited therein.

(112) J. Buus, "Principles of semiconductor laser modelling," IEE Proc., vol.132, pt.J, pp.42-51, 1985, and references cited therein.

(113) E.A.J. Marcatili, "Dielectric rectangular waveguide and directional coupler for integrated optics," Bell Syst. Tech. J., vol.48, pp.2071-2102, 1969.

(114) E.O. Kane, "Thomas-Fermi approach to impure semiconductor band structure," Phys. Rev., vol.131, pp.79-88, 1963.

(115) R.I. Halperin and M. Lax, "Impurity-band tails in the high density limit I: minimum counting methods," Phys. Rev., vol.148, pp.722-740, 1966.

(116) F. Stern, "Band-tail model for optical absorption and for the mobility edge in amorphous silicon," Phys. Rev. B, vol.3, pp.2636-2645, 1971.

(117) J.C. Dymont, F.R. Nash, C.J. Hwang, G.A. Rozgonyi, R.L. Hartman, H.M. Marcus, and S.E. Haszko, "Threshold reduction by the addition of P to the ternary layers of

double heterostructure GaAs lasers," Appl. Phys. Lett., vol.24, pp.481-484, 1974.

(118) M.J. Adams, "Rate equations and transient phenomena in semiconductor lasers," Opto-Electron., vol.5, pp.201-215, 1973.

(119) P.M. Boers, M.T. Vlaardingerbroek, and M. Danielsen, "Dynamic behaviour of semiconductor lasers," Electron. Lett., vol.11, pp.206-208, 1975.

(120) T.L. Paoli, "Changes in the optical properties of CW (AlGa)As junction lasers during accelerated aging," IEEE J. Quantum Electron., vol.QE-13, pp.351-359, 1977.

(121) K.D. Chik and J.C. Dymont, unpublished results.

(122) N.G. Basov, "Dynamics of injection lasers," IEEE J. Quantum Electron., vol.QE-4, pp.855-864, 1968.

(123) G. Arnold and K. Petermann, "Self-pulsing phenomena in (Ga,Al)As double heterostructure injection lasers," Opt. Quantum Electron., vol.10, pp.311-322, 1978.

APPENDIX

The properties of GaInAsP/InP lasers can be determined from equations (6.1) to (6.8) which are formulated according to the unified model. Solving these equations is a rather complex problem even by numerical methods. The approach taken to obtain the solutions of such a system of equations is through multiple numerical iteration processes, where decisions are made at various points to determine whether the calculated results are physically meaningful. For example, since negative photon densities are physically impossible, it is checked after each time the gain profile is calculated to decide whether such a gain profile would lead to negative photon densities. In case that the gain profile would not lead to negative photon densities, the calculation will continue. However, if the gain profile obtained would produce negative photon densities, a new set of photon density values is substituted in and the calculation will be returned to the previous iteration step. The flow chart of such a multiple iteration scheme for the static properties of the stripe geometry gain guided GaInAsP/InP lasers is outlined in Fig. A-1. Similar flow charts are used for the dynamic properties of lasers and for the static and dynamic properties of LEDs.

Fig. A-1 Flow chart for calculating the static properties of stripe geometry gain guided GaInAsP/InP lasers

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