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OPTOELECTRONIC SWITCHING WITH GaAs PHOTOCONDUCTORS

by

Dennis Kwok Wah Lam B.Eng., M.Eng.

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

Doctor of Philosophy

Department of Electronics
Faculty of Engineering
Carleton University
Ottawa, Canada
April 1986
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ABSTRACT

Optoelectronic switching and signal processing using GaAs photoconductors are studied in this thesis. Optoelectronic switching has many significant advantages over other forms of switching. The foremost one is that the signal is introduced into the switch optically. Optical signals in waveguiding media are immune to electromagnetic interference. Consequently, the crosstalk between adjacent channels carried by different waveguiding elements is extremely low. Also, optical signals in optical waveguiding media are inherently broadband. A proper design of the switch can give fast response time and gigahertz bandwidth. A single chip broadband switching matrix is therefore possible using optoelectronic switching.

The approach that is taken in this thesis is as follows. The individual switching element is first examined. Photoconductors are chosen as the switching elements because of their superior performance in comparison with other semiconductor devices. A new type of photoconductor that uses the surface depletion effect is introduced. Its noise performance is superior to that of conventional photoconductors and close to that of photodiodes. A study of a novel optoelectronic switching matrix (OSM) making use of an array of crosspoint switches and lasers, and an optical distribution network (ODN) is then examined. Crosstalk between devices is the major concern here. A monolithically integrated photoconductive detector array (ICDA) that exhibits a -44 dB crosstalk between devices at 100 μ m separation over >1 GHz bandwidth is demonstrated. This confirms the feasibility of a monolithic OSM. The introduction of feedback elements into an OSM resulted in a reflex OSM (ROSM) capable of performing various signal processing functions.

Finally, solutions to a couple of problems encountered in realizing

monolithic OSM or KOSM are proposed. The first one concerns the OLN in a large scale OSM. A novel integrated optics approach using in-diffused optical waveguides in a glass substrate which also has the electrical mating pattern to the array of crosspoint switches is demonstrated. Secondly, electronic amplification is required when the signal derived from the switch is weak due to low light level. The planar fabrication process and the material requirement in photoconductors(PC) allow a monolithic integration of a PC with a field effect transistor(FET). Such an optoelectronic integrated circuit(OEIC) would provide the many advantages that are available in electronic integrated circuits. A one stage PC-FET integration is attempted and a 6 dB gain in a 1 GHz bandwidth is achieved. It is believed that the successful full scale implementation of these two proposed structures will lead to large scale monolithic OSM, KOSM and other forms of OEIC such as optical receivers and repeaters.

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LIST OF SYMBOLS

A	Cross section area of the photoconductor ($W \times D$)
b	Bandwidth
C	Capacitance
D, L, W	Depth, length and width of the photoconductor
e	electronic charge
E	Energy, electric field
E _g	bandgap energy
g	Photoconductive gain
G	Conductance
h	Planck's constant
I	Photocurrent
I ₀	Primary photocurrent
I ₁	Optical power at various point of an optical waveguide
J	Photocurrent density
m	Modulation index
NEP	Noise equivalent power
n, p	Electron and hole density
P	Optical power
r	LC to RF responsivity
SNR	Signal to noise ratio
t _r	Transit time
v	Drift velocity
V	Voltage
α	Propagation loss per length
η	Quantum efficiency
η _c	Waveguide coupling efficiency
θ	Coupling efficiency
λ	Wavelength
μ	Mobility
ν	Frequency
σ	Conductivity
τ	Carrier lifetime
τ _{rel}	Dielectric relaxation time

CHAPTER 1

INTRODUCTION

1.1 An Historical Review of Photoconductors

The photoconductivity phenomenon was first observed in an experiment with the element Selenium in 1873 by W. Smith [1]. Following this initial discovery, much interest was generated and various groups proceeded to search for other photoconductive materials and at the same time tried to understand the physical processes involved. Various theories were quickly proposed but it was not until some years later that it was acknowledged that photoconductivity is an electronic rather than a chemical or ionic transport process. A comprehensive summary of the early work on photoconductivity from 1900 to 1960 can be found in a book by Bube [2].

A photoconductor in action can be visualized to consist of three processes. The first one is the generation of electronic carriers by the incident light. This is the excitation of electrons from the valence band to the conduction band thereby creating electron-hole pairs and reducing the device resistivity. The second process is the transport of carriers under a driving field present to produce the photocurrent. The last process is the interaction of the photocurrent with the external circuit to provide the output signal. Theoretically speaking, all materials are photoconductive as they all react to light to a certain extent. However, it may sometimes be difficult if not impossible to observe the infinitesimal effect in the highly insensitive material.

When light impinges on a photoconductive device, the photogenerated extra free carriers constitute a photocurrent. The resistivity of the device also changes as a result of this photocurrent. This phenomenon

has been observed in materials with resistivity ranging from less than 1 ohm-cm to more than 10^{18} ohm-cm. Furthermore the lifetime of the free carriers, which is an approximate measure of the device response time, ranges from picoseconds to seconds. The availability of this large working range of resistivity and response time in photoconductors indicates that they can be used in many different applications.

The early photoconductors were limited to applications where the device was large and the response time was slow. This is because microelectronics technology was simply non-existent then. The device sizes were measured in centimetres or inches. Also, the material purity was poor and this led to trapping phenomena and other anomalous effects detrimental to high speed processes.

Typical applications of photoconductive devices in the early days were for sensing operations. For example, they can be used to control street lights which turn on at dusk and turn off at dawn. They can also be used to measure the illumination level, as in exposure meters, for still and motion cameras. Also, they can be used in conjunction with a light source to form a moving object counter in production lines.

1.2

Recent Status of Photoconductors

Two major technological advances in the last two decades have changed the status of photoconductors. They are (1) ultra-pure material growth methods and (2) microelectronic fabrication processes. Various growth methods such as Molecular Beam Epitaxy (MBE), Liquid Phase Epitaxy (LPE), Vapour Phase Epitaxy (VPE) and Metallorganic Chemical Vapour Deposition (MOCVD) have been developed and are capable of producing ultra pure materials. With these developments, the device performance is based on an intrinsic process rather than on an extrinsic process arising from surface and bulk defects. Also the MBE method is

capable of producing thin films with thickness of the order of atomic layers. Therefore the thickness of the device can be well controlled or tailored. The many undesirable bulk effects can thus be eliminated. In the device processing area, it is now possible to achieve sub-micron structures by UV-photolithography, Electron Beam Etching, Laser Assisted Chemical Etching, and other optical methods. The result is that very small devices can be made and closely packed device patterns as in VLSI are attainable.

The technological advances in material growth and device fabrication coupled with the maturity of Optical Communication Systems(OCS) in the last decade have created new roles for photoconductors. In an OCS an electrical signal is used to modulate a light source such as a laser or a light emitting diode(LED). The optical signal is then transmitted through an optical medium such as an optical fibre to its destination. As the bandwidth of the optical fibre is effectively infinite, it is therefore possible and desirable to send very high frequency signals by using a fast laser or multiplexing several LEDs. The optical signal at the receiving end has to be modulated and converted back to its electrical form. With the high frequency signal it is therefore necessary to use a fast photodetector. Some of the choices are p-n, p-i-n and avalanche photodiodes, and photoconductors. Depending on the power level of the incoming signal and the availability of a low noise front end amplifier, any of the above photodetectors may be the most suitable device. Although p-n and p-i-n photodiodes have in general lower noise, this factor may not suffice in some circumstances when detector internal gain is necessary and a low noise front end amplifier is not available. In these cases, avalanche photodiodes and photoconductors become the better choices.

Another recent application of photoconductors is as a sampling gate as reported by Auston[3]. The idea basically consists of a broken microstripline where the gap is filled in by a photoconductor. The electrical signal to be sampled is sent in from one end of the stripline and the other end is connected to the measurement system. Without any

incident light to the photoconductor the stripline is in the open-circuited condition and there is no signal to the measurement system. With the application of an ultra short picosecond light pulse, as generated from a mode-locked synchronously pumped dye laser, the stripline is made to conduct momentarily with a duration approximately equal to the lifetime of the photogenerated carriers. The photoconductor thus acts as a sampling window of the electrical signal. By using several of these photoconductive sampling gates in certain special configurations, it is also possible to achieve auto- and cross-correlation functions.

Finally, a photoconductor can also be used as an optoelectronic switch. This operation is the inverse of the sampling gate just described above. The incoming signal is optical and it is switched into or out of a circuit by turning the bias on or off, respectively, in the photoconductive switch. The operating principle can be understood by recalling that a photoconductor in action requires three constituents: (i) an incident light, (ii) a driving field, and (iii) an external circuit. In the case here, electron-hole pairs are generated when the optical signal is present. But with no applied bias, these carriers recombine before they reach the contact electrodes of the photoconductors. Hence there is no photocurrent to the external circuit. When the bias is on, these carriers drift to the electrodes and give rise to a signal to the external circuit. It will be shown later in the work reported here that photoconductors are the best optoelectronic switches.

1.3 Application of Optoelectronic Switching in a Matrix

Optoelectronic switching can be applied to form a matrix capable of routing and broadcasting broadband signals. Such a matrix can be used in time domain multiple access systems and local area networks. The structure of an optoelectronic switching matrix (OSM) consists of a

2-dimensional array of crosspoint switches, a 1-dimensional array of light sources and an optical distribution network (ODN). Photoconductors are chosen as the crosspoint switches here because of their superior performance in switching. Semiconductor lasers are used as the light sources because of their gigahertz bandwidth and generally better optical coupling efficiency compared with LED's. The simplest ODN is made of a number of fused optical fibre couplers. There are N of 1-to- N such couplers in a $N \times N$ matrix. Fig.1.1 depicts a very simple 2×2 OSM. Since $N=2$ there are two of 1-to-2 couplers in this example.

At any input or output port of an OSM, the signal is in electrical form. Internally, an incoming signal at the input is used to modulate a laser. This modulated light is then distributed to a column of the 2-dimensional array of crosspoint switches through one of the couplers (see Fig.1.1). Each input signal is hence available to all the output ports. This arrangement permits a broadcasting mode in the OSM. The use of an ODN in a OSM has some very important advantages. One is that optical signals in optical waveguides are immune to electromagnetic interference (EMI). A high density array as can be achieved in monolithic integration is therefore possible provided that the crosstalk level between devices on the chip is within the design limit. A second advantage is that optical coupling to a crosspoint switch is a unidirectional process. There is no reflection and there is no impedance matching problem. Lastly the bandwidth in an optical medium is practically infinite. These important properties facilitate the realization of a monolithic broadband OSM.

The switching of the signal from a given input port to a given output port in an OSM is achieved by applying bias to the appropriate crosspoint switches. When the bias is applied, the photoconductor becomes sensitive to the optical signal and a signal is generated at the output. Referring to Fig.1.1, applying bias to the bottom left photoconductor will present a routing path from input 1 to output 2. And if the bias is applied to the top left photoconductor as well, the OSM is in the broadcasting mode and all the output ports (1 and 2 here) are

Fig.1.1.1. SCHEMATIC OF A 2 × 2 OPTOELECTRONIC SWITCHING MATRIX

receiving the signal from input 1. In the normal operation, only one switch along each output port can be on. In the absence of a bias the photoconductor is rendered insensitive to the optical signal. The residual signal level is related to the isolation value from the switch and the crosstalk from the adjacent switches that are on.

1.4 Objectives of the Present Work

The present work attempts to provide a detailed investigation on optoelectronic switching and an introduction to signal processing with photoconductors. Gallium Arsenide (GaAs) is chosen as the material because of its importance in Optical Communication Systems (OCS) and Monolithic Microwave Integrated Circuits (MMIC). It should however be noted that most of the results for GaAs can be applied to other III-IV compounds such as Indium Phosphide (InP), or even ternary or quaternary compounds such as GaInAs or InGaAsP respectively. Almost all of the work reported here is original and has been published in journals or presented in conferences [4-18].

The approach taken in the present work can be divided into four sections. They are: (i) photoconductor theory, (ii) device level study, (iii) system level study, and (iv) advanced level study. The basic broadband optoelectronic properties of GaAs photoconductors are first investigated. They form the foundations for the device, system and advanced level studies. Important parameters such as responsivity, bandwidth, electrical switching time, isolation and noise performance pertinent to the functions of the photoconductors are each examined. Three functions of great importance are identified and they are each discussed in detail in the device level study. They are photodetection, optoelectronic switching and optoelectronic mixing. The optimum design of a photoconductor depends on the function that it is going to perform. For instance, whereas photodetection in an OCS need not have

fast electrical switching time since the detector bias is permanently on, this is not true in optoelectronic switching. An ohmic contact is therefore an important criterion in designing a switch. This is because a non-ohmic contact has charge storage effects and subsequently a longer switching time. High isolation is also important in a switch. Therefore care must be taken to avoid forming any undesired junction that gives a photovoltaic potential. In optoelectronic mixing operation it is desirable to operate the mixer in a bilinear mode with respect to the incoming RF signal and the local oscillator(LO) signal.

In the system level study, the operation of an array of photoconductors in conjunction with an array of optical sources and an optical distribution network(ODN) is examined. The photoconductors operate in the optoelectronic switching mode. The optical sources are semiconductor lasers. These components are configured into a broadband Optoelectronic Switching Matrix(OSM). High frequency electrical signals at the input of the OSM are used to modulate the lasers. The optically modulated signals are then directed to the array of photoconductors via the ODN made of optical fibres. Optical signals in optical waveguides such as optical fibres are insensitive to crosstalk regardless of their proximity to each other. Therefore very low crosstalk between different channels and output lines can be obtained. Furthermore the photoconductive switches themselves have very good isolation values. Hence crosspoints that are common in a given output line will not suffer from background interference. That is, the output carries only the signal from the "on" switch as all the "off" switches have very low background level.

Another important topic in the system level study is the Reflex Optoelectronic Switching Matrix(ROSM). It is an extension of the OSM with the provision of a set of variable delay feedback paths. This delay feedback feature allows the ROSM to perform many useful signal processing functions. For instance, sequential recirculating and sampling of an incoming signal can be performed. This operation is analogous to transversal filtering in surface acoustic wave(SAW)

devices. The advantage here is that the photoconductive switches have very fast electrical switching time and therefore the delay can be tuned quickly. This results in a programmable and real-time filtering process. Other important signal processing functions in a KOSM include digital to analogue conversion, integration, word generation and correlation.

In the advanced level study, a couple of issues that were encountered in the course of this work are examined. The solutions to them are proposed and implemented. The first issue concerns the fact that in an OSM and a KOSM the switches have very small dimensions and inter-spacing. Therefore as the matrix size increases, the OSM using optical fibres becomes very complicated if not impossible. A different approach has to be used. A possible solution is to apply Integrated Optics (IO). Indiffused optical waveguides are made on a dielectric substrate on which the semiconductor chips containing the switches are bonded upside down to make the necessary optical contacts. The dielectric substrate also carries the necessary metallic contact electrode pattern for bias supplies and signal outputs. Very large OSM and KOSM can be accommodated using this approach. Furthermore, more than one semiconductor chip can be laid down on the dielectric substrate. These chips can be made to couple with each other through both the indiffused optical waveguides and the metallic pattern on the surface. Complex optoelectronic integrated circuits (OEIC) and totally integrated functional blocks such as an optical repeater can be envisaged. Redundancy circuits for reliability purposes and space division multiplexing can be achieved as well.

The second issue concerns the fact that when the incoming optical signal is very weak, the electrical signal generated by the photoconductor is correspondingly weak. It may have to be amplified to some standard level prior to any signal processing. The conventional approach is to couple the photoconductor to a discrete low noise front end amplifier followed by perhaps more amplifiers. A better approach is to directly integrate the photoconductor with the amplifying

element. Photoconductors are especially suitable for monolithic integration with GaAs field-effect-transistors(FETs) due to their compatibility in the material and the fabrication process. Both devices are made using a planar fabrication process. They also both have GHz bandwidth. It is therefore possible to obtain a fully integrated broadband optical receiver.

In summary, the present work first attempts to provide a detailed study of the broadband optoelectronic properties of GaAs photoconductors. The three operating modes of the photoconductors are identified in the device level study and they are photodetection, optoelectronic switching and optoelectronic mixing. The switching operation is especially important. It identifies photoconductors as the most suitable crosspoint switching elements. This represents the major issue in this thesis. Optoelectronic switching and signal processing in a switching matrix using photoconductors are discussed in detail in the system level study. A couple of practical problems encountered in the course of this work are addressed in the advanced level study. Proposed solutions to them are examined. They indicate that it is possible to achieve large scale monolithic OSM and other optoelectronic integrated circuits(OEIC).

The photoconductor theory, the device, system and advanced level experimental studies are presented in sequence in the following chapters.

CHAPTER 2

THEORY AND DISCUSSION OF PHOTOCONDUCTORS2.1 A Review of Basic Photoconductor Theory

A photoconductor(PC) in its simplest form consists of a slab of photoconductive material with ohmic contacts deposited on both ends as shown in Fig.2.1a. This configuration is known as the axial structure. A more practical photoconductor, the kind used in the work reported here, employs a planar structure instead. It consists of an epi-layer grown on a semiconductor substrate or a thin photoconductive film deposited on a semiconductor or other suitable substrate. Ohmic contacts are then deposited on top of this thin layer at both ends as shown in Fig.2.1b. The area not covered by the ohmic contacts forms the active region or channel. The active region can be further identified or isolated by a mesa structure.

A photoconductor employing a planar structure is especially important because it is very suitable for monolithic integration. This is not true for the more common p-n, p-i-n and avalanche photodiodes as they all employ the axial structure. Only very recently have there been attempts to use the planar structure for the photodiodes[19-20]. An axial structure not only complicates monolithic integration, it also requires a thin transparent front layer to be used in order to receive the incident light efficiently. One important application of monolithic integration is the fabrication of a photoconductive detector array. The latter can be used for optical scanning, optical fourier transform and image processing. Another important application of monolithic integration is the direct integration of a photodetector with an amplifying element such as a FET. This allows a totally integrated optical receiver to be made.

(a)

(b)

Fig.2.1. Photoconductor using (a) axial and (b) planar structure.

When incident light impinges on the active region of the photoconductor, excess free carriers are generated through either direct band-to-band transition or trapping states in the forbidden gap. Direct band-to-band transition is preferred because it is more efficient. Transitions through trapping states usually involve a loss of free carriers and may exhibit a longer response time characteristic of the trap lifetime. Also, a direct bandgap material is preferred because it conserves momentum without any phonon production in the transition process. This results in better quantum efficiency, i.e. photon-to-electron-hole pair conversion efficiency. GaAs material is used exclusively in the work reported here because it has a direct bandgap and it can be grown relatively free of traps. Also it is widely used in the fabrication of high frequency FETs. This facilitates the photoconductor and field effect transistor(PC-FET) integration work.

A review of basic photoconductor theory is presented here. The assumption of no trapping states is made. Although trapping phenomena were observed in a few of the early devices used in the experiments, their effects were reduced by an optical method. By increasing the LC light level incident on the active channel of the photoconductor, the traps became saturated. Their effects on the performance of the photoconductor were hence reduced to an insignificant level.

For the photoconductor to be responsive, the incident light wavelength must have corresponding energy E greater than or equal to the bandgap E_g . The wavelength(λ) and energy(E) are related by the formula:

$$E(\text{eV})\lambda(\mu\text{m})=1.24 \quad (1)$$

however, in practice, it is better to have the energy E within a few kT of the bandgap E_g for efficient operation. For light of longer wavelength, the material behaves as if it is transparent unless it is extremely thick, or contains a lot of trapping states so as to allow successive transition from level to level. For light of shorter

wavelength, surface absorption dominates and this usually results in a reduction of the signal. Therefore, suitable material should be chosen to match the wavelength of the incident light.

There are three operation modes in a photoconductor, namely photodetection, optoelectronic switching and optoelectronic mixing. Their performances are measured with respect to different parameters, as described below.

4.2 Photodetection

The performance of a photoconductor in the photodetection mode can in general be measured by three important parameters: (i) quantum efficiency (η) with or without internal gain, (ii) response time and bandwidth(B), and (iii) sensitivity and noise performance. In the steady state condition, carrier generation(gen) must equal carrier recombination(rec). Therefore, assuming an n-type material is used so that electrons are the majority carriers,

$$\text{gen} = \text{rec}$$

$$\frac{\eta(P\theta/(h\nu))}{WLD} = \frac{n}{\tau} \quad (2)$$

where P = optical power

θ = coupling efficiency

= (fraction of total power absorbed in volume $W \times L \times D$)

h = Planck's constant

ν = frequency

τ = carrier lifetime

W, L, D = width, length and depth of the photoconductor

n = excess carrier density

The photocurrent generated (1) is:

$$I = ne\mu EA \quad (3)$$

where e = electronic charge

μ = electron mobility

E = electric field

A = cross sectional area

$=W \times D$

Substituting n from Eq. (2) into Eq. (3) gives

$$I = \frac{ne(P\theta/(h\nu)) \tau \mu E}{L} \quad (4)$$

However, μE = drift velocity (v), and L/v = transit time (t_r), therefore

Eq. (4) can be re-written as,

$$I = ne(P\theta/(h\nu)) \tau \frac{\mu E}{t_r} \quad (5)$$

The primary photocurrent (I_0) is equal to,

$$I_0 = ne(P\theta/(h\nu)) \quad (6)$$

Eqs. (5) and (6) gives the photoconductive gain (g) as,

$$g = \frac{I}{I_0} = \frac{\tau}{t_r} \quad \text{or} \quad I = g I_0 \quad (7)$$

This photoconductive gain mechanism can be visualized as follows. When the excess free carriers are generated by the incident light, they drift towards the electrodes under the influence of the applied field. When

they reach the electrodes and there is a charge imbalance in the active region, another carrier will be injected into the channel. This process continues until the excess carriers recombine according to their lifetime. The photoconductive gain is therefore equal to the lifetime divided by the transit time of the excess carriers. It is a measure of how many times the carriers can travel across the channel in a lifetime duration. Photoconductive gain is therefore only possible when the contact electrodes are ohmic. Contacts with a potential barrier as in a Schottky diode or a heterojunction diode do not freely allow the injection of charges.

The gain expression in Eq.(7) is a simple but important result. It indicates that a photoconductor using material of long lifetime and employing small structure to achieve short transit time will have very high gain. However this may not be desirable for high speed operation since the bandwidth will suffer from the long lifetime ($B \propto 1/\tau$). The gain-bandwidth product is equal to the inverse of the transit time.

$$g \cdot B = 1/\tau_t \quad (8)$$

A high speed photoconductor requires a short carrier lifetime and the gain suffers correspondingly. In a photoconductor with a significant density of traps, its response time may not be equal to the lifetime but the time involved in the trapping and re-emission processes between the traps and the bands [21]. Typical GaAs photoconductors can have a gain of 2-4 and a gain-bandwidth product of 6-12 GHz.

A final comment on Eq.(7) is that the gain will not increase indefinitely with respect to an increasing electric field which is supposed to increase the drift velocity and decrease the transit time ($v = \mu E$, $\tau_t = L/v$). This is because the mobility becomes nonlinear and actually decreases at high field. Therefore velocity saturation takes

place. Also, when a voltage is reached such that

$$VC = ne \quad (9)$$

where C = parallel plate capacitance of the electrode/area
a space charge of electrons equal in number to the photogenerated
electrons(n) is forced into the photoconductor by the applied field. At
and above this voltage, the transit time becomes equal to the dielectric
relaxation time of the photoconductor. This space charge effect imposes
a fundamental limit to the maximum attainable gain[21]. Eqs.(7) and (8)
can be written as follows for the space charge limited condition:

$$g = \frac{\tau}{\tau_{rel}} \quad (10)$$

$$g^*B = \frac{1}{\tau_{rel}} \quad (11)$$

where τ_{rel} = dielectric relaxation time

So far the discussion has been centred on the DC condition. For AC
analysis, a photoconductor operating at the frequency of interest can
usually be represented by its shunt conductance. The AC photocurrent is
equal to[22],

$$I_S = \frac{ne(P\theta/(hu)) \tau}{t_T (1+j\omega\tau)} \quad (12)$$

For the DC condition, $\omega=0$ and Eq.(12) becomes Eq.(4) as expected.

There are two dominant noise sources in a photoconductor. One is the Thermal or Johnson noise related to the shunt conductance G and it is equal to [22],

$$i_{th}^2 = 4kTBG \quad (13)$$

The other is the generation-recombination noise given by [22],

$$i_{gr}^2 = 4eIB \frac{\tau}{t_r} \frac{1}{(1+a^2\tau^2)} \quad (14)$$

Since the noise currents are uncorrelated, the total noise content is,

$$i_n^2 = i_{th}^2 + i_{gr}^2 \quad (15)$$

When the thermal noise component dominates, the noise content becomes frequency independent. When the generation-recombination noise dominates, the noise content becomes frequency sensitive. There are other noise sources in the photoconductor but they are usually either much smaller or out of the frequency band of interest. For instance the $1/f$ noise is significant only in the very low frequency region.

The signal to noise ratio (SNR) in a photoconductor can be computed by using Eqs. (12)-(15). Assuming a modulation index equal to m and an AC power equal to $mP/2$, this gives,

$$SNR = \frac{i_s^2}{i_{th}^2 + i_{gr}^2} = \frac{1}{8B} \frac{m^2 P_0}{h\nu} \frac{1}{e} \left(\frac{1}{1 + kT(1 + a^2\tau^2) \frac{t_r}{\tau} G} \right)^{-1} \quad (16)$$

An important figure of merit is the noise equivalent power (NEP). It corresponds to the incident rms signal power required to produce a SNR of one in a 1 Hz bandwidth. This is calculated by setting $SNR=1$ and $B=1$ in Eq. (16) and finding the corresponding value of $nP/\sqrt{2}$.

A NEP of $10E-11$ to $10E-10$ Watt/Hz is attainable for a typical photoconductor. This assumes a quantum efficiency of 0.5-0.8, a carrier lifetime of one to a few hundred picoseconds and a shunt resistance in the kilo-ohm region. The NEP increases with respect to the conductance, the dark current and the photocurrent. High resistivity materials therefore have a better noise performance. It will be shown in the next chapter that a special type of photoconductor can have a NEP as low as $10E-13$ Watt/Hz. Although it is true in general that p-n and p-i-n photodiodes have better NEP values ($10E-14$ to $10E-13$ Watt/Hz), they usually require a pre-amplifier to bring the signal level up and in doing so the noise performance may become dictated by the amplifier. In this circumstance it may be better to use a detector with internal gain. Another important point is that the photoconductor high frequency circuit model is a fairly frequency insensitive shunt conductance. This contrasts with the shunt capacitance, which is highly frequency sensitive, in a p-n or p-i-n photodiode high frequency circuit model. It is therefore conceivably easier to broadband match a photoconductor to the circuit load. Other advantages are the low operating voltage and the ease of fabrication.

To recapitulate, the parameters that have been discussed are gain, bandwidth and noise performance. They are especially important when the photoconductor is operating in the photodetection mode. There are other

parameters that are important when the photoconductor is operating in the optoelectronic switching and mixing modes. They are discussed below.

2.3 Optoelectronic Switching Mode

In optoelectronic switching, the incoming signal is again optical and the DC bias control to the photoconductor is used as the switching mechanism. This operation mode finds many applications in high frequency switching or broadcasting networks. A couple of examples are the Satellite Switched Time domain Multiple Access (SS-TDMA) system and the optical local area network (LOC) [23,24]. Fast access time and low crosstalk interference are important criteria in these systems. Photoconductors can offer these qualities because of their extremely fast electrical switching time and high isolation values.

The electrical switching time in a switch is a measure of how fast the latter can change from the on to the off state and vice versa. In a photoconductor the off state is simply the no bias condition. In this condition there are photogenerated carriers but there is no external driving field. The carriers therefore recombine according to their lifetime and there is no signal delivered to the external circuit. In the on condition the external field drives the photogenerated carriers to the contact electrodes and hence there is a photocurrent. One factor that affects the electrical switching time in a photoconductor is therefore the transit time across the active channel. This transit time can be very small by using a small device structure. For instance, a device channel length of $10\text{ }\mu\text{m}$ has a transit time of 170 picoseconds at the saturation velocity condition ($6 \times 10^6\text{ cm/sec}$). Switching time of this order has been observed in the experimental studies here.

The isolation value in a switch is a measure of the ratio of the on state response to the off state response. In a photoconductor the on

state response is taken as the response at saturation condition. The off state response is the residual response due to photovoltaic or self-biasing potential from undesired junction effects. With a good ohmic contact the residual response becomes extremely small. An isolation value of 65 dB in a 1GHz bandwidth is possible and has been observed experimentally here.

The situation in a p-n or a p-i-n photodiode for switching operation is less attractive. In order to achieve a high isolation value, a forward bias is actually necessary to turn the photodiode fully off. This forward bias creates charge storage. These charges have to be removed when the photodiode is being turned on. Therefore the switching time of a p-n or a p-i-n photodiode is inferior to that of a photoconductor. The switching time can be improved by not operating the photodiode in the fully off condition. This will however result in a low isolation value. Therefore, in a photodiode, the switching time and the isolation value work against each other, whereas in a photoconductor these two parameters are independent of each other. Some of the best photodiode switches exhibit a switching time of a few nanoseconds. This contrasts with the subnanosecond switching time in photoconductors. Photoconductors are the best optoelectronic switches currently available.

2.4 Optoelectronic Mixing Mode

In optoelectronic mixing, the incoming optical signal represents the RF content and the LO bias control to the photoconductor is replaced by a local oscillator (LO). The output is at an intermediate frequency (IF) from the RF and LO mixing interaction. The application of a LO to a photoconductor is equivalent to switching it on and off very fast. The switching result discussed above indicates that the photoconductor is capable of handling a high LO frequency. One immediate consequence is that the RF signal can be simultaneously detected and downconverted to a

moderate IF band so that all post-detection signal processing can be done using standard electronic circuits. Also, a frequency division multiplexing scheme can be realized.

Another significance of optoelectronic mixing is that, whereas ohmic contacts are imperative in order to achieve photoconductive gain, high isolation and fast electrical switching time under the DC bias condition, this is not true under the mixing condition. This is because the LO driving field is capacitively coupled into the active channel of the photoconductor. Ohmic contact problems that may be encountered in high resistivity material can therefore be circumvented by using this technique.

A further significance in the mixing operation is that there may be an enhanced RF gain to be secured. The photoconductive gain under the DC bias condition was given by Eq. (7) as $g = \tau/t_r$. It was also indicated that this gain will be limited by both velocity saturation and space charge effects. In a mixing operation where the applied LO frequency is sufficiently high such that the carriers travel less than the active channel length during half of the LO cycle, the carriers are effectively trapped and shuttled back and forth in the channel. In this case the gain is independent of the transit time. It is now a measure of how many times the carriers can oscillate in the active channel in one photoconductive lifetime. The RF photoconductive gain is given by:

$$g_{rf} = \frac{\tau}{1/f_{lo}} \quad (17)$$

where f_{lo} = LO frequency

The gain bandwidth product now becomes,

$$g_{rf} * B = f_{lo} \quad (18)$$

and it is independent of any material parameter.

To recapitulate, replacing the DC bias control by a LO eliminates the necessity to have ohmic contact in order to have gain, high isolation value and fast electrical switching time. The mixing operation also provides the possibility of obtaining enhanced RF gain.

Finally it is important to note that the efficiency of a mixer should also be measured against its bilinearity. This is a measure of how linear the IF signal is with respect to the variation in the RF and LO signal levels. The fact that a photoconductor is basically a photoresistor assures good linearity. Over 30dB bilinearity has been observed in the experiment.

2.5 Summary

In summary the theoretical study presented in this section has examined the important parameters of a photoconductor pertinent to a given application. The gain mechanism, bandwidth, noise performance, electrical switching time, isolation value, mixing mode enhanced gain and bilinearity have all been discussed. The significance of ohmic contacts and dielectric relaxation have also been addressed. The study here revealed that a photoconductor has three important operating modes which are photodetection, optoelectronic switching and optoelectronic mixing. Depending on the operating mode the various parameters and properties have different significance. It is indicated that a photoconductor in the photodetection mode has commensurate performance with a p-n or a p-i-n photodiode. Typical NEP of $10E-11$ to $10E-10$ Watt/Hz is attainable. This can be improved by a special type of

photoconductor to be discussed in the next chapter. Its capability to provide internal gain is especially attractive when the incoming signal is weak. In switching operation, it has the best performance in comparison with all other competitors. It possesses sub-nanosecond electrical switching time and over 65dB isolation. In mixing operation it is capable of handling a high LO frequency so that the post-detection signal processing can be done at a low IF band. It also gives enhanced RF gain and good bilinearity.

CHAPTER 3

DEVICE LEVEL EXPERIMENTAL STUDY3.1 Introduction

GaAs semiconductor wafers made of single and multi-epi layers on semi-insulating (SI) substrates have been primarily used in the work here. The epi layers have a dopant concentration range from $\sim 10^{14}$ to $\sim 10^{16}/\text{cc}$ and a thickness range from 0.3 to 4.0 μm . Recalling that ohmic contact is an important criterion in achieving good photoconductive properties, special care must therefore be taken in the deposition of the metallic contact electrodes. The single-epi layer wafer with low dopant concentration requires a special Au-Ge-Ni alloy and a proper annealing temperature. The multi-epi layer wafer with progressively higher dopant concentration from the SI substrate provides a graded effect to assist the formation of an ohmic contact. This is however done at the expense of a more complex etching process. The different layers have different etching rates. Proper calibration of the etching time is required so as to avoid over- or under-cutting.

In order to obtain the intrinsic behaviour of the photoconductors which are known to have GHz bandwidth, they have to be carefully mounted and tested. Microstripline circuits are used to preserve their broadband characteristics. Fast semiconductor lasers mounted on microstripline circuits and broadband amplifiers are used as well. Other necessary instruments include multi-GHz RF generators, sweep oscillators, network analyzers and spectrum analyzers for frequency domain measurements, and sub-nanosecond impulse response generators and a sampling oscilloscope for time domain measurements.

The three operating modes of a photoconductor are photodetection, optoelectronic switching and optoelectronic mixing. They are each individually described below.

3.2 Photodetection Mode

In photodetection the function of the photoconductor is to convert the incoming optical signal as efficiently as possible into its electrical equivalent. The ability to collect all the incoming light is important. A large detector will certainly satisfy this requirement. However a large detector inevitably has a sluggish time response and therefore is limited to low frequency operation. It can be visualized that in a large detector the photogenerated carriers have to travel a long distance to reach the electrode to generate the signal.

Two basic detector structures are employed in the experiment and they are shown in Fig.3.1. Both of them use the planar processing method. This is important for monolithic integration. The active region of the detector can be either a simple single channel(SC) or an area overlaid with interdigitated fingers(IDF). The SC structure is easy to fabricate and control. The transit time is determined by the separation between the two electrodes. They have to be very close together in high frequency operation and therefore the light collection efficiency decreases. The IDF structure offers a large active area and at the same time permits high frequency operation. This is because the transit time is now determined by the separation between the interdigitated fingers which can be very small. The drawback in the IDF structure is that it takes more current as its channel resistance is lower. This results in a higher thermal noise current and possibly a power dissipation problem when it is integrated on a large scale.

3.2.1 Conventional photoconductor

A photodetector can be characterized using both frequency and time domain analyses(FDA,TDA). The results from these two measurements can be compared. Fig.3.2. shows the frequency domain experimental set up. A GaAlAs semiconductor laser(0.8-0.88 μm) mounted in a microstripline circuit capable of handling multi-GHz signals is used as the optical

(a) SINGLE

(b) DIGITATED

Fig. 3.1. Photoconductor using (a) single channel and (b) interdigitated structure. The active area in (a) is 20 micron square and (b) is 100 micron square interdigitated with a finger spacing of 5 micron.

Fig.3.2. Experimental set up of frequency domain measurement.

source. Fig.3.3 shows a typical circuit used for the laser. The circuit provides an AC coupled RF path and a DC bias input with an RF choke. A chip capacitor and a chip resistor are used to facilitate the high frequency operation. A sweep generator and a network analyzer are used to modulate the laser. The modulated light from the laser is coupled to the photoconductor via an optical fibre. The detected signal from the photodetector is displayed on a network analyzer and on a spectrum analyzer. From the measured incident optical power and the optical modulation index, the responsivity, that is, the optical to electrical conversion factor measured in ampere/watt(A/W), can be deduced. Responsivity ranging from 0.1 to 0.6 A/W has been observed in the experiment. The responsivity is found to be dependent on the electric field or the applied bias, the channel length and thickness, the laser wavelength and to a lesser degree the dopant concentration. The electric field and the channel length determine the drift velocity and the transit time respectively. The transit time is related to the photoconductive gain as indicated in Eq.(7). At very low fields, loss can actually occur due to premature and partial recombination of the photogenerated carriers prior to them reaching the electrodes. The channel thickness and the laser wavelength determine the absorption efficiency in the photoconductor. A thin channel does not absorb all the incoming radiation and hence the responsivity suffers. As the signal wavelength increases, the penetration depth increases accordingly and a thicker channel is required to maintain the same responsivity. On the other hand, too short a signal wavelength will result in heavy surface absorption. This is usually not a desirable condition because of surface traps. The dopant concentration has an effect on the carrier lifetime and the carrier mobility. However no definite trend was observed in the experiment. The experimental results here indicate that the optimum condition with respect to the responsivity and the bandwidth is at a signal wavelength of 0.8-0.84 μm , a channel thickness of 1-2 microns, a channel length of 20 microns or less, and an electric field of a few kV/cm. A photoconductive gain of 1.5-2.5 is obtainable with the 5-10 μm devices. The observed responsivity of 0.6 A/W compares well with that of photodiodes. The frequency response of a typical photoconductor using an IDT structure with 10 μm finger spacing is shown in Fig.3.4. The

Fig.3.3. Microstrip line circuit used for the laser(D.U.T).
A chip capacitor(C) and a chip resistor(R) are used in the circuit.

PHOTOCONDUCTOR RESPONSE

Fig.3.4a. Frequency response of a photoconductor using an interdigitated structure with 10 micron finger spacing. Observation from the network analyzer.

Fig. 3.4b. Frequency response of a photoconductor using an interdigitated structure with 10 micron finger spacing. Observation from the spectrum analyzer.

frequency response is flat to 1.3 GHz as monitored by a network analyzer and shown in Fig 3.4a. The upper 3 dB point is measured at 1.75 GHz in a spectrum analyzer and shown in Fig 3.4b. The low frequency roll-off is due to the high pass network used to modulate the laser. Even higher bandwidth has been observed in smaller devices and 1D1 structures using 5 μm finger spacing. The bandwidth follows a fairly linear relationship with respect to decreasing channel length. The high frequency response at longer wavelength operation ($> 0.87 \mu\text{m}$) was observed to deteriorate somewhat. This is because at this wavelength, the penetration depth is much deeper than the channel thickness. Carriers that are generated outside the active channel experience a weaker electric field and they require a longer time to diffuse to the active channel and then drift to the electrodes.

The impulse response of a photodetector is measured using a time domain analysis. Fig.3.5 shows the experimental set up. A sub-nanosecond electrical impulse generator is applied to a semiconductor laser biased at its threshold current. The laser under this condition produces a train of pulses corresponding to the generator duty cycle. Each optical pulse is about 100 picoseconds in duration as monitored by a calibrated p-i-n photodiode and shown in Fig.3.6. This train of pulses is coupled to the photodetector under test via an optical fibre and the detected signal is displayed on a sampling scope with a 25 picoseconds risetime. A detected pulse for a photoconductor using an interdigitated structure with 10 μm finger spacing is shown in Fig.3.7. The photodetector true impulse response can be obtained by deconvolving Fig.3.7 with Fig.3.6. The bandwidth can be obtained by performing a Fast Fourier Transform on the deconvolved impulse response. Correlation between the results from the frequency and the time domain measurements can therefore be done. The relationship between the full-width-half-maximum interval ($\Delta\tau$) in the time domain measurement and the 3dB bandwidth (B) in the frequency domain measurement can be approximated [25] by $B \cdot \Delta\tau \approx 1.38/\pi$. This formula assumes a Gaussian or at least a Gaussian-like symmetric pulse profile which is applicable here. The observed $\Delta\tau \approx 200\text{ps}$ in Fig.3.7. indicates a bandwidth of 2.2 GHz according to this formula. This is in reasonable agreement with the frequency domain result of 1.75 GHz given Fig.3.4b.

Fig.3.5. Experimental set up of time domain measurement.

100ps / DIV

2mV / DIV

10. Optical impulse from the laser is monitored by a photodiode.

Horizontal: 100ps/div
Vertical : <2mV/div

Fig.3.7. Impulse response of a photoconductor using an interdigitated structure with 10 micron finger spacing.

The noise measurement can be done at RF frequency in the frequency domain set up if the device under test has higher noise content than the measurement system. Currently available spectrum analyzers and network analyzers set a limit of measurable NEP in the range of $10E-11$ to $10E-10$ Watt/Hz. It is in theory possible to use a transimpedance amplifier followed by perhaps a chain of amplifiers to increase the sensitivity. However in doing so, the measurement bandwidth suffers accordingly due to the high input impedance. Proper equalization is necessary. The introduction of all these elements complicates the measurement procedure and causes uncertainties in the measurement. DC measurement using a picoammeter is a better alternative for low noise devices. Since the noise content is either frequency independent or decreasing with respect to the frequency as discussed in Chapter 2, a DC measurement would provide a conservative estimate of the noise performance.

The early devices that were used in the experiment exhibit at best a NEP of $\approx 10E-11$ Watt/Hz. Their noise content can therefore be measured in the frequency domain set up using the following procedure. The modulation on the optical signal is removed and a measurement is taken at the network analyzer (NA). This measurement is valid if it is higher than the noise floor of the NA. Otherwise it only represents an upper bound value. This noise level corresponds to the total noise which consists of the thermal and the generation-recombination noise. If the incident light is now entirely removed and a measurement is taken again, this corresponds to the thermal noise content. The experimental results indicate that the generation-recombination noise dominates.

In general, the NEP increases with respect to the dopant concentration. This is because the resistivity decreases and the current flowing through the channel increases. Also, the NEP increases with respect to the applied bias. Devices that were made of an epi-layer with $5 \times 10E15/cc$ dopant concentration and employed 5-10 microns channel length showed a NEP of $2-7 \times 10E-11$ Watt/Hz. These values agree with those indicated in section 2.2. They are about three orders of magnitude higher than that of p-i-n photodiodes. Such high NEP values in photoconductors are due to the high bias current which is usually in the μA and mA range. This contrasts with the nA bias current in photodiodes.

3.2.2 Surface depleted photoconductor (SDPC)

A novel type of photoconductor with much lower noise characteristic is described here. It makes use of the surface depletion effect in the active channel due to surface traps which create an electric field to drive the carriers away. It is thus called the surface depleted photoconductor (SDPC). It has a dark current in the nA range and a NEP of the order of 10^{-13} Watt/Hz. It has a more uniform frequency response and it also preserves all the desirable characteristics of the conventional photoconductor.

The surface depleted photoconductors used in the experiment are made by the MOCVD process on undoped LEC GaAs substrates with the following specification: a top layer of $n^+ : 2 \times 10^{18}/\text{cc}$, $\approx 0.2 \mu\text{m}$ thick; and a bottom layer of $n^- : 5 \times 10^{14}/\text{cc}$, $\approx 1 \mu\text{m}$ thick. The n^+ layer was used to form a good ohmic contact with evaporated and annealed Au-Ge-Ni alloy. The n^+ layer was etched away in selective regions to expose the n^- layer which formed the active channel. A device structure of $20 \mu\text{m} \times 20 \mu\text{m}$ was used in the experiment.

The surface depletion thickness for the n^- layer is estimated to be a few microns. The n^- layer being only $1 \mu\text{m}$ thick resulted in a totally depleted channel. The resistance of the devices was monitored at 30 sec intervals as the n^+ layer was being etched using a calibrated etchant (NH_4OH 2%, H_2O_2 0.7% and H_2O 97.3%, 1500 A/min at 23°C). The etching was stopped when the resistance increased from a few hundred ohms into the mega-ohm region, which occurred when the etchant punctured the n^+ layer, according to the calibration. Since the n^- layer is intact in these devices, and would ordinarily result in a resistance in the kilo-ohm region, the observed very high resistance indicates that the channel is entirely depleted by surface effects. The dark current is in the nA range under the bias condition.

The noise performance of the surface depleted photoconductor was

measured using a ~~picoammeter~~. In this method, the DC dark current of the photoconductor was measured as a function of the applied bias by means of a Keithley picoammeter. This measurement is consistent with the fact the dark current dominates in the noise performance of photoconductors under low level illumination. This low level condition is applicable in a large switching matrix, where the power division is large, and in a long optical communication link.

Fig. 3.8 shows the experimental results of the dark current and the NEP as a function of the applied bias. The dark current and the NEP at 4 volts bias are 17 nA and 2.3×10^{-13} Watt/Hz respectively. At this bias, the dark resistance is about 240 MΩ. These values are much better than those of the conventional photoconductors. They approach the photodiode performances. Operation beyond 4 volts showed instability and a larger rate of increase in the dark current and the NEP. This may be attributed to a high field effect such as impact ionization.

The bandwidth of the surface depleted photoconductor was measured to be 1.3 GHz. The isolation value is over 60 dB across this entire bandwidth. The responsivity at DC and RF frequency are 0.47 A/W and 0.22 A/W respectively. This very low ratio of the responsivity at DC to that at RF ($r=2.4$) is another distinctive characteristic of the surface depleted photoconductor. Conventional photoconductors have very high gain at DC due to mechanisms such as optical backgating or parasitic transistor action from the optical modulation of the depletion width. DC gain as high as 300 has been reported [26]. A large DC and low frequency responsivity is undesirable because it necessitates AC coupling to sensitive devices to avoid damage and frequency compensation for flat response from DC to RF frequency. The SDPC does not have these problems. Since its channel is always depleted, the optical backgating and the parasitic transistor effects are reduced.

In summary the experimental work on the photodetection mode of the photoconductor has confirmed multi-GHz bandwidth, responsivity as high

Fig.3.8. Dark current and noise-equivalent-power(NEP) of a surface depleted photoconductor(SDPC) using single channel structure of 20 micron square.

as 0.6 A/W and a NEP of 2.7×10^{-11} Watt/√Hz for the conventional photoconductor. A novel type of photoconductor that employs the surface depletion layer as the active channel is also discussed. It has a dark resistance of 200 MΩ and a dark current of 17 nA under the bias condition. The NEP is 2.3×10^{-13} Watt/√Hz. These values represent a significant improvement over those of conventional photoconductors. A 1.3 GHz bandwidth and over 60 dB isolation over this bandwidth are achieved. In addition the DC to RF responsivity is only a factor of 2.4. This facilitates the direct coupling to sensitive devices and eliminates the need for excessive frequency compensation. This novel type of photoconductor can find important uses in large switching matrices or long optical communication links where the available signal level is low and the noise performance is an important criterion.

3.3 Optoelectronic Switching Mode

Switching operation is basically the same as photodetection except that the bias control is allowed to change states. Two types of photoconductive optoelectronic switches, which are not well distinguished by the terminology, are available. The one introduced by Auston[3] is of the type in which the switching signal is introduced optically and the signal to be gated is introduced electrically. The light serves to complete the electrical path through an interrupted stripline on a semiconductor substrate by means of photogenerated carriers. Such optoelectronic switches are used for high speed sampling of electrical signals and rapid switching of high voltages. Photoconductive switches of this type are referred to as optically gated(OG). The photoconductive switch reported here is an optoelectronic crosspoint switch of a type especially suitable in switching matrices for very broadband signals. The signal to be gated is introduced optically and the switching is accomplished by varying the bias on the photoconductor. When the bias voltage is sufficiently low or absent the

transit time exceeds the recombination time and there is no detected signal. Since the optical introduction of the incoming signals gives excellent isolation, very low cross talk interference can be obtained in such a switching matrix. Optoelectronic switches of this type are referred to as electrically gated (EG).

The properties of the photoconductor in the photodetection mode still apply here. There are two additional parameters in the switching mode. They are the isolation value and the electrical switching time. The isolation value is a measure of the on state to the off state response. The on state response is taken as the detected signal at saturation condition. The off state response is the residual signal from photovoltaic and self-biasing effects. When good ohmic contact is achieved this residual response is very small. The isolation value can be most easily measured using the frequency domain set up. The detected optical signals with the bias on and off are compared. Fig. 3.9 shows the isolation measurement for a photoconductor with interdigitated structure with 10 μm finger spacing. More than 60dB isolation over a 1.3GHz band has been achieved.

The electrical switching time is a measure of how fast the switch can change states. A photoconductive switch is superior to all other optoelectronic switches. A photodiode requires forward bias in the off state to achieve high isolation. It consequently has long turn-on time because of the charge storage in the junction. The best photodiode switches have a switching time of a few nanoseconds. An avalanche photodiode has good isolation without the use of forward bias in the off state. It however requires a very large voltage in the on state (50-300 volts). The switching of this large bias voltage can itself be a problem and a time limiting process. A photoconductive switch does not have either of these problems. It has sub-nanosecond switching time and requires only a few volts for switching. This is even less than the bias requirement for a photodiode.

Fig. 3.10 shows the experimental apparatus used to measure the

Fig. 3.9. Isolation value of a photoconductor using an interdigitated structure with 10 micron finger spacing. The bias is 4 V.

Fig. 3.10. Experimental set up for electrical switching time measurement.

electrical switching time [17]. The reference pulser generates a train of fast impulses to pulse the semiconductor laser. Optical pulses of 80 picoseconds duration at a peak power of 0.5 watt were obtained. The trigger signal from the reference pulser was divided into two separate paths. One was used to trigger the oscilloscope whereas the other was applied to the external trigger input of a dual pulser which has variable delay, pulsewidth, amplitude, and dc offset controls. One of the dual pulser outputs was connected to the high frequency stripline bias network of the photoconductor whereas the other output was set to be identical in shape, coincident in time with the first one, and displayed on the oscilloscope. The fast optical pulses from the laser were coupled into a 1 to 2 optical fibre power splitter having equal lengths of fibre at the output ports. The latter were coupled to an avalanche photodiode (APD) and the photoconductor in the experiment and both signals were displayed on the oscilloscope. The signal from the APD was used to monitor the arrival of the optical pulses at the photoconductor. All electrical delay differences between the bias pulse and the optical pulses due to cable, splitter, attenuation, and other items were properly compensated by a suitable delay line. The only variable delay was that from the dual pulser.

A constant dc bias was supplied to the APD so that it was always photosensitive to the incoming optical signal, whereas a pulse bias with variable time delay with respect to the timing of the optical pulses was applied to the photoconductor. A response signal from the photoconductor, therefore, only occurred when the laser pulse and the bias voltage pulse were coincident. This was achieved by varying the delay such that the laser pulse occurs within the bias pulse. To perform the measurement the delay was adjusted from the point when the laser pulse was ahead of the bias pulse to that when it was after. Fig. 3.11 shows the response of the switch with respect to the time delay between the laser and the bias pulses. The photoconductor has an interdigitated structure with 10 μm finger spacing. By taking into account the bias pulse shape, the turn-on and turn-off times were determined. Fig. 3.12 shows the switching response normalized with respect to the peak

Fig.3.11. Electrical switching response of a photoconductor using an interdigitated structure with 10 micron finger spacing when:

- (a) (ii) is ahead of (i), off condition
- (b) (ii) is within (i), on condition
- (c) (ii) is after (i), off condition
- (f) bias pulse monitor: 1V/div, 1ns/div
- (ii) laser pulse monitor: 5mV/div, 1ns/div
- (iii) photoconductor response: 2mV/div, 50ps/div

Note: The photoconductor response (iii) is deliberately offset to the right for clarity.

Fig.3.12. Electrical switching time of a photoconductor using an interdigitated structure with 10 micron finger spacing. The rise and fall times are 0.6 and 1.1 ns respectively.

amplitude of the detected pulse. The rise and fall times were measured to be 0.6 and 1.1 ns respectively. Optoelectronic switching at this speed is much faster than that offered by photodiodes.

It should be mentioned that the rise and fall times measured here are really upper bound values since the adjustable delay in the dual pulser has a resolution of 0.5 ns. The observed rise time of 0.6 ns is a factor of 3.7 from the estimated transit time (≈ 170 ps) for the device under test.

In summary, the experimental measurement of the isolation value and the electrical switching time of the photoconductors have been performed. A 60 dB isolation value in a 1.3 GHz bandwidth and an upper bound switching time of 0.6 ns were observed. These values confirm that photoconductors are the best choice for optoelectronic switching.

3.4 Optoelectronic Mixing Mode

The mixing operation is an extension of the switching operation in that the DC bias control is replaced by a LO. The incoming optical signal is the RF and it is mixed with the LO to produce the IF output. Photoconductive mixing has significant advantages over a conventional direct detection scheme. Optical signals on very high frequency subcarriers can be simultaneously detected and mixed down to a moderate frequency range such that the following signal processing can be done with standard electronic equipment. The heterodyne detection of frequency division multiplexed signals on an optical carrier is an obvious application. Heterodyne detection would permit the very high frequencies possible with present optical transmission systems to be employed without incurring the expense of a broadband amplifier in the receiver, since all post-detection processing can be done at as low an IF frequency as the stability of the LO allows. Also the availability of

the enhanced RF gain in the mixing operation is of value when the incident signal is weak.

Fig. 3.13 shows the block diagram of the experimental set up [12,13]. The optical signal is generated by a semiconductor laser (Mitsubishi 5308) mounted on a microstripline circuit designed and tested to have a relatively flat response from 0.5 to 4.5 GHz. The initial modulation frequency setting for the laser and the mixer were 1.0 and 0.5 GHz and they were incremented in steps of 100 MHz to 4.5 and 4.0 GHz respectively. The RF and LO power level were set at 0 dBm and 10 dBm respectively. The photoconductive mixer employs an interdigitated structure with 10 μ m finger spacing. It was mounted on a microstripline circuit. Fig. 3.14 shows the frequency response of the mixer. The 3dB frequency is about 4.0 GHz. The signal-to-noise ratio of the mixer was 54dB and the estimated NEP is of the order of $10E-11$ Watt/Hz which is similar to values obtained in the DC biased condition. The frequency stability of the experimental system was 10 kHz as limited by the RF generators. This means that quasi-biased operation is possible with appropriate equipment.

A gain of 17 dB was observed in the mixing operation in comparison to the direct detection scheme whereby the photoconductor was DC biased at a voltage equivalent to the rms voltage applied to the photoconductor in the mixing operation. This observation apparently relates to the relatively high resistivity GaAs. Since Schottky barriers are formed at these contacts, the photoresponse voltage is necessarily divided between the load and the Schottky barrier that is reversed biased, so that there is a parasitic loss of signal. Under RF bias condition, the bias voltage is coupled to the photoconductor through the capacitance of the Schottky barriers, which at high frequencies, may never complete forward recovery. The voltage drop at the contacts is thus significantly reduced.

This gain is also related to the RF gain effect discussed in

Fig.3.13. Experimental set up of optoelectronic mixing. A Mitsubishi (MIT) 5308 laser mounted on a microstripline circuit was used.

NORMALIZED RESPONSE vs RF

Fig.3.14. Frequency response of an optoelectronic mixer using an interdigitated structure with 10 micron finger spacing.

Chapter 2. The 10 dBm LO setting corresponds to only 1 volt rms across the device. DC operation at this bias has a transit time longer than the lifetime. Therefore there is actually a photoconductive loss. In a mixing operation the RF gain depends on the LO frequency in the high frequency region. The gain therefore does not suffer. Also the 3 dB bandwidth may increase since the gain is proportional to the LO frequency. This enhanced bandwidth was indeed observed in the experiment. Previous measurement of a similar device operating in the DC condition indicates a bandwidth of ≈ 2 GHz. The bandwidth measured in the mixing condition is 4 GHz.

Finally the linearity of the device was investigated by varying the LO and RF power levels and observing the corresponding change in the IF signal. A linear power level relationship between the LO and the IF, and the RF and the IF was observed over a 30dB dynamic range. Saturation effects take place in the mixer at higher RF and LO power.

In summary the use of a photoconductive mixer for broadband downconversion has been demonstrated. Significant gain in signal is available and system stability of 10kHz as limited by the RF sources is achieved. A frequency response enhancement is also observed. A 30 dB bilinearity with respect to the RF and the LO is available. Heterodyne detection of frequency division multiplexed signals in optical communication systems is one of the many possible applications. The significance of these results for broadband optoelectronic crosspoint switching is noteworthy. The mixing efficiency is constant up to about 4 GHz, which indicates that the switching time of the device is of the order of 0.25 ns. A direct measurement (section 3.3) has established only an upper bound limit of 0.6 ns on this value.

3.5 Summary

In this chapter the characteristics of a photoconductor operating in its photodetection, optoelectronic switching and optoelectronic mixing modes have all been examined. A photoconductor with an active channel length of 5 to 20 μm has a bandwidth that ranges from one to a few GHz and a responsivity from 0.3 to 0.6 A/W. These are satisfactory performances in comparison with other photodetectors. The noise performance of a conventional photoconductor is inferior to that of a p-i-n photodiode due to its large dark current under the biased condition. A novel type of photoconductor that employs the surface depletion layer as the active channel is introduced. This SDPC has very low dark current. Its NEP is $\approx 2.5 \times 10^{-15}$ watt/Hz. This is a significant improvement over that of the conventional photoconductor and is within an order of magnitude to that of the photodiode. In addition, this SDPC has a more uniform frequency response from DC to RF. It does not exhibit the undesirable high LC gain common in conventional photoconductors due to optical backgating and parasitic transistor action. Its active channel being always depleted avoids any optical modulation of the depletion width. This facilitates LC coupling to sensitive devices and alleviates the need for sophisticated frequency compensation circuits. This SDPC also preserves the desirable characteristics, namely bandwidth, responsivity, isolation value and switching time, available in conventional photoconductors.

In the optoelectronic switching mode, the isolation value and the electrical switching time are the two key parameters. Photoconductors are the best optoelectronic switches. This is because the two key parameters are independent of each other. This contrasts with the situation in photodiodes when the two parameters are related in a conflicting manner. The experimental study has shown > 60 db isolation

value in at least a 1.3 GHz bandwidth and an electrical switching time of 0.25 ns. Currently, the best photodiodes have a switching time of a few ns at a comparable isolation value.

In the optoelectronic mixing operation the switching DC bias is replaced by a LO. The fast electrical switching time available means that a high LO frequency can be used. This allows the mixing down of a very high RF signal to a moderate IF band, so that all post-detection signal processing can be done without incurring expensive broadband instruments. A 4 GHz mixer bandwidth and a frequency stability of 10 kHz, as limited by the RF generators, have been observed. These are accompanied by an enhancement in both the gain and the frequency response. A bilinearity of 30 dB in the IF signal with respect to the LO and RF power levels has also been demonstrated by experiment. These performances of the optoelectronic mixer are unprecedented.

SYSTEM LEVEL EXPERIMENTAL STUDY4.1 Introduction

There are two systems to be discussed here. They are the optoelectronic switching matrix(OSM) and the reflex optoelectronic switching matrix(ROSM). Both employ the optoelectronic switching principle in photoconductors. They are constructed with a 2 dimensional array of photoconductive crosspoint switches, a 1-dimensional array of optical sources and an optical distribution network(ODN) that directs the optical signal from the sources to the switches. In a ROSM a set of delay lines, either optical or electrical, is introduced as well.

In an OSM, broadband signals are routed or broadcast from any input to any output of the network. In a ROSM these signals can in addition be processed through sequential recirculation and sampling. This is analogous to transversal filtering in surface-acoustic-wave(SAW) devices. Various optoelectronic signal processing functions can be realized. The experimental studies of a 3x3 OSM and ROSM are discussed in the following two sections.

4.2 Optoelectronic Switching Matrix(OSM)

The device level experimental study has shown that photoconductive switches have good responsivity, GHz bandwidth, high isolation and fast electrical switching time. These properties make them especially suitable to be used as crosspoint elements in a broadband switching matrix for directing and broadcasting high frequency signals. Fig.4.1 illustrates a 3x3 OSM. The signals to be switched are used to modulate the semiconductor lasers. The optical signals are then directed to the

Fig.4.1. A 3 x 3 optoelectronic switching matrix.

crosspoint elements in the switching matrix via optical waveguides. A common optical distribution network (ODN) makes use of 1-to-3 (or 1-to-4 for an $N \times N$ matrix) optical fibre couplers. The excellent isolation between optical waveguide signal paths gives the basis for the immunity of the array to crosstalk between ports. The crosspoint elements are rendered sensitive or insensitive via the bias control. For a photoconductive switch the off state is simply no bias as discussed earlier. The electrical signals from the detectors along any given output port can be summed together by simply providing a common connection for one of the terminals. (This common connection can be achieved as an integrated part of a monolithic array of photoconductors as shown in Fig. 4.2.) Furthermore, since the physical spacing of the photoconductors is very much smaller than the signal wavelength, the actual layout of the common connection is not critical and the summing function is easily achieved. An OSM finds many uses in broadband switching networks such as the Satellite Switched Time Domain Multiple Access (SS-TDMA) system and the optical Local Area Network (LAN).

The performance of an OSM is dictated by how well each crosspoint element behaves and how well the crosspoint elements behave together. The former can be answered from the results in the device level study. That is, responsivity as high as 0.6 A/W , greater than 1.0 GHz bandwidth, subnanosecond electrical switching time and over 65 dB isolation value. How well the crosspoint elements behave together is a question of how they affect each other. This is basically a measure of the crosstalk interference between them. There are three sources of crosstalk in an OSM and they are the crosstalk between (i) crosspoint elements along the same output port, (ii) crosspoint elements from different output ports, and (iii) optical signals in different optical waveguides. The last crosstalk source can be ignored since optical waveguides have extremely low light leakage and no electromagnetic coupling. The only possible way to crosstalk is at the actual coupling points. This can however be very small when the coupling is directional or has a small numerical aperture (NA). An example where this is true is with optical fibres when the NA is 0.1 - 0.2 . Also, when the physical spacing at the coupling point between the end of the optical waveguide and the crosspoint element is small, and the size of the crosspoint element is greater than or equal

Fig.4.2. Integrated array of GaAs photoconductive crosspoint with a common terminal.

to that of the end of the optical waveguide, the crosspoint element then effectively acts as an aperture stop. The crosstalk at the coupling points in this case is again very small. An example is when the optical fibre is end-buttet into the crosspoint element.

The crosstalk between crosspoint elements from different output ports can in principle be made arbitrarily small by physically separating the crosspoint arrays serving different ports. For instance, placing them on different semiconductor chips and mounting the latter in distant circuit mounts. This discrete element approach however makes the matrix quite large in size and not easily packagable. Fig.4.3 shows a 3x3 OAM using this discrete element approach and clearly illustrates its drawback. Also shown there are the 1 to 3 optical fibre couplers used as the OAM. The fibre ends were end-buttet and UV-cpoixed to the crosspoint elements. Monolithic integration of the whole matrix is a much better approach as it offers very significant advantages in size, efficiency, compactness and cost.

Initial experimental results on the crosstalk level of a monolithically integrated photoconductive array indicated that proper circuits for the array are necessary. This is because the crosspoint element spacing is of the order of $100\mu\text{m}$ and therefore the electrical lines connected to them are in very close proximity. Direct coupling between the electrical lines becomes very significant at frequency greater than 100MHz. Proper circuits have to be used to overcome this direct coupling. Having identified and solved this problem the true on-chip crosstalk level between the crosspoint elements can be measured.

In order to minimize the crosstalk level between detectors from adjacent output ports, a monolithically integrated ground plane(GP) isolating the neighbour detectors is employed. This ground plane is very effective in reducing the crosstalk between two adjacent detectors at $100\mu\text{m}$ spacing to, at least -44 dB across a 1.3 GHz bandwidth. Figs. 4.4 and 4.5 show respectively the monolithically integrated photoconductive detector array(PCDA) with an integrated ground plane and the experimental set up used to measure the crosstalk levels.

1 to 3 optical
fibre couplers
as the optical
distribution
network

INPUT

OUTPUT

Fig.4.3. A fully assembled 3 x 3 optoelectronic switching matrix using discrete element approach.

Fig.4.4. A monolithic photoconductive detector array with a ground plane. The finger spacing is 10 micron.

Fig.4.5. Experimental set up for crosstalk measurement.

The material used for the PCDA was a commercially grown GaAs vapour phase epitaxial n^+-n-n^- structure with $n^+ = 2 \times 10^{18}/\text{cc}$, $0.3 \mu\text{m}$; $n = 4 \times 10^{15}/\text{cc}$, $0.5 \mu\text{m}$; and $n^- = 10^{14}/\text{cc}$, $3 \mu\text{m}$. Each individual detector had an overall dimension of $100 \mu\text{m}$ wide $\times$ $300 \mu\text{m}$ long and an active area of $100 \mu\text{m} \times 100 \mu\text{m}$ interdigitated at $10 \mu\text{m}$ finger spacing. The detectors were mesa isolated. Each detector's area was etched to the n^- layer whereas the contact pads were formed with evaporated and annealed Au-Ge-Ni on the n^+ layer in order to achieve good ohmic contact. The shielding plane that surrounds the detectors was also formed by the metallized n^+ layer. The separation between the adjacent detectors was $100 \mu\text{m}$. The detector array was mounted on a microstripline circuit fabricated on alumina substrate. The circuit provided both the bias tee and the ac decoupling networks. The alumina substrate was permanently bonded to the circuit mount to ensure good grounding.

The network analyzer shown in Fig. 4.5 has an RF signal output and it was used to modulate the laser from 250MHz to 1.3GHz. The signal from the laser was coupled via an optical fibre to one of the detectors on the extreme end of the detector array. This procedure allowed measurement of the maximum variation of the crosstalk level from one detector to the other as a function of physical separation. A bias sufficient for current saturation (3 volts) was applied to the illuminated detector. The rest of the detectors were turned off by short circuiting them to ground. (The measured crosstalk level was not affected whether the unilluminated detectors were biased, grounded or in an open circuit). The outputs from the on detector and one of the off detectors were monitored at the network analyzer. By progressively choosing the off detector to be at the adjacent positions out to the farthest position (i.e. device separation by 2 detectors), the crosstalk level as a function of distance was determined. The initial measurement was taken between the on detector and the adjacent off detector with the ground plane grounded via bond wires to the circuit ground. After the measurement was taken with the ground plane grounded, the ground plane was made ineffective by physically removing the grounding wires. This procedure served to examine the effect of the ground plane. When this was done, the entire procedure was repeated for the next nearest off detector.

Table 1 summarizes the experimental results for isolation between the on detector and its first, second and third nearest neighbours. The crosstalk levels across the 1.3 GHz frequency range as monitored on the network analyzer are shown in Figs. 4.6a and 4.6b for the case of the first and the third nearest detectors respectively. It can be seen from Table 1 and Fig. 4.6 that uniform crosstalk level as low as -50dB across the 1.3GHz frequency range has been achieved by the monolithically integrated photoconductive detector array with a ground plane provision. Also shown in Fig. 4.6b is the effectiveness of the ground plane. The lower two traces indicate that the effect of the ground plane is a 6dB reduction in the crosstalk level. The observed crosstalk level is mainly due to the on-chip direct coupling. Other sources of crosstalk were each carefully examined and found to be at a much lower level. Scattered light from the fibre to the nearby detectors was minimized by blackening the fibre jacket. Applying bias to the normally off detector did not increase the crosstalk level indicating that there is no photoconductive response and hence no significant scattered light present. Different circuit mounts were tested and found to have no effect on the crosstalk as long as they provided proper launching conditions. The crosstalk that originated from the circuit due to direct coupling between the microstriplines was also investigated. By removing the bond wire connected to the off detectors, crosstalk due to coupling on the chip was eliminated. The crosstalk that remained was due to direct coupling between the microstriplines. This crosstalk is 10 dB lower than that on the chip. Several slightly different circuits providing the bias tees and ac decoupling network were also tested and found to have similar performance.

The above crosstalk measurement is for crosspoint elements from different output ports. The crosstalk level between crosspoint elements along the same output port can be deduced directly from the individual device's isolation value. This is because there is only one "on" detector along each output port at any time. The crosstalk level from the other "off" detectors along the same output port is therefore the summation of their off state response. This is just a measure of the

TABLE 1

CROSSTALK LEVEL BETWEEN THE ON DETECTOR
AND ITS Nth NEAREST DETECTOR

N	1	2	3
Crosstalk	-44dB	-46dB	-50dB

(a)

(b)

Fig.4.6. Crosstalk measurement between the on detector and its (a) adjacent detector (100 micron spacing) and (b) third nearest neighbour (500 micron spacing). In (b) crosstalk* represents the crosstalk when the ground plane is removed.

isolation value. The device level study has shown this value to be over 60 dB. This is much lower than the crosstalk interference from detectors on the adjacent output ports. It can therefore be concluded that in an OSM the crosstalk is dominated by the interference between the crosspoint elements on adjacent output ports.

The experimental result of this crosstalk level at -44dB at a detector spacing of 100 μm in a 1.3GHz bandwidth is a very significant one. It demonstrates successfully the monolithically integrated photoconductive detector array. This signifies the certain possibility of a single chip handling broadband signal switching. The problem that remains now is an efficient and stable way of coupling light to this tiny chip. An optical distribution network employing optical fibre couplers is not likely to fulfil this function. Its size and method of bonding to the chip present definite difficulties (see Fig.4.3). A new approach using Integrated Optics should be used instead. This is described in detail in the next chapter.

Although the experimental results here demonstrated the array performance out to 1.3 GHz only, there are reasons to believe that the frequency of operation can actually be higher. The crosstalk level shown in Fig.4.6 shows no sign of deterioration towards the high frequency end. In fact, the crosstalk in the detectors used in the experiment was -40 dB at 2 GHz.

Possible applications of broadband optoelectronic switching matrices include large scale switching in proposed broadband subscriber networks, for which beam directing switches are already under consideration [24]. It is also reported elsewhere [27] on the promise of the optoelectronic technique for very large scale switching of high rate digital data. On the basis of the present results, large portions of the switches for a digital subscriber network operating at rates above 1GB/s could be constructed as a simple monolithic optoelectronic circuit.

4.3 Reflex Optoelectronic Switching Matrix (ROSM)

A ROSM is an extension of an OSM by introducing a set of delay lines between the input and the output ports. The introduction of the delay lines results in many useful signal processing functions. Fig. 4.7 illustrates a 3X3 ROSM [15]. Here all but one of the output ports of the array are connected back to corresponding input ports through delay lines of various lengths. These delay lines can be either electrical or optical, depending on whether they are inserted before or after the laser sources. Optical waveguide delay lines are particularly suitable for precision, stability, and wideband operation. As is evident from Fig. 4.7, it is possible to insert a delay in the propagation of the input signal through the switch array by arranging to have it pass through one or more of the delay lines on the way. For example, rendering photodetectors A and I sensitive will cause a delay of t_1 ; similarly, rendering A, F, and H sensitive will result in a delay $t_1 + t_2$. In general, an $N \times N$ crosspoint matrix provided with $N-1$ reflex connections with different lengths can provide $2^{(N-1)}$ different delays, including no delay. If each delay is twice as long as the previous one, and the shortest is t , the systematic provision of any delay up to $t \cdot (2^{(N-1)} - 1)$ is possible, in increments of t . Delay lines can also be selected in parallel to give simultaneous multiple delays of the input signal.

Since both the photoconductive switches and the optical delay lines have very wide bandwidths, a ROSM can serve as a variable delay generator for such wide band signals as are encountered in radar antenna phasing and similar applications. In addition, the switches are known to have sub-nanosecond switching time, so that the delays can be altered quickly. Application in high speed digital multiplexing and word generation can be foreseen because of this property.

Fig.4.7. A 3 x 3 reflex optoelectronic switching matrix.

The optical signal distribution employed in a ROSM also gives a feature that would not be available in a purely electronic switching matrix with reflex connections. The optical to electronic conversion at the crosspoint imposes a directionality that permits recirculation of the signal in the loops, so that a ring resonator can be constructed. For example, rendering crosspoints A, C, and I photosensitive in Fig.4.7 gives recirculation through loop t_1 . The inclusion of an amplifier in the delay path to offset the loop loss results in a ring resonator with the Q-value controllable by the amplifier. This ring resonator functions as a comb filter and behaves very much like a transversal filter in surface acoustic wave (SAW) devices. The ease and speed with which the loop can be altered in the switching matrix give very significant advantages in tuning the filter.

The frequency response of a comb filter synthesized by a broadband ROSM employing fast lasers, optical fibre delay lines, and photoconductive switches is shown in Fig.4.8. A 26dB loop amplifier was included to control the loop loss. The filter envelope extends to above 1GHz and the measured Q-value at 600 MHz is over 300. The dynamic range is about 26 dB. The upper limit of the dynamic range is set by the saturation in the photoconductive detector; the lower limit is set by the amplifier noise. There thus seems to be scope for improvement with improved detectors and amplifiers.

These results demonstrate the use of a ROSM as a discretely tunable ring resonator filter. Other important applications arise in processing digital signals. Owing to the high speed with which the photoconductive switches can be reset, it is possible to employ the delays to generate digital words from a single input pulse, yielding a high rate multiplexer or word generator. For a $N \times N$ matrix which has $N-1$ discrete delay lines with linearly related lengths, it is possible to produce from a single input pulse any combination of $N-1$ equi-spaced pulses following it. Thus by reconfiguring the state of the switching matrix properly,

Fig.4.8. Frequency response of a comb filter made of optical fibre ring resonator in a ROADM. The filter envelope exceeds 1 GHz and the Q is over 300 at 600 MHz.

any digital word of length N can be generated and the driving pulse can be eliminated if required. Since the crosspoint switches have subnanosecond switching time, very high rate word pattern generation can be achieved. Furthermore, since the matrix reconfiguration rate need only be $1/N$ of the output pulse rate, the latter will be limited by the bandwidth of the matrix and not by the properties of the external digital driving circuits. It is also possible to use the ROSH as a correlator or matched filter for optimizing the signal to noise ratio in digital signal processing. This is done by prebiasing the crosspoint matrix such that upon the arrival of the desired signal, a maximum impulse response will be detected at the output. The advantage of the ROSH is that adaptive matched filtering application can be achieved by real-time programming of the bias configuration to allow for different signal identification or other changing conditions.

In summary, the feasibility of using wide band reflex optoelectronic switching matrices to generate discretely programmable precise delays and discretely tunable comb filters of good dynamic range and Q have been demonstrated. Complex filter responses can be realized as well by making use of serial and parallel combinations of the delay lines. These ROSHs are very versatile in that they can be used to perform various signal processing functions and can be programmed at a very high rate. Many applications in processing analog and digital signals are foreseen.

4.4 Summary

The application of optoelectronic switching in a network to route, broadcast and process broadband signals is demonstrated in this chapter. An OSM consists of a 2-dimensional array of crosspoint switches addressed by a 1-dimensional array of semiconductor laser via an optical distribution network. An electrical signal that is present at the input is converted into its optical equivalent via the semiconductor laser.

This is then distributed to the crosspoint switches via the OLN. By applying bias to one or more of the crosspoint switches, any input signal can be made to appear at any one, any combination or all of the output ports.

The performance of such a switching matrix is assessed against the interference level that exists amongst the crosspoint switches. The usage of an OLN assures very high isolation between optical waveguide signal paths. The high isolation value in a photoconductor provides a ~ 60 dB interference amongst crosspoint switches along the same output port since only one switch is on at any time along a given output port. Crosstalk between crosspoint switches in adjacent output ports turns out to be the major interference source. Using an integrated ground plane in a monolithic photoconductive detective array (PCDA), the crosstalk level is reduced to -44 dB across 1.3 GHz at a detector spacing of only 100 μ m. At 2 GHz, the crosstalk level is still very low at -40 dB. These experimental results clearly demonstrate the feasibility of a single chip handling broadband signal switching. In the course of constructing the 3×3 OSM using the monolithic PCDA, it became apparent that an OLN using optical fibre is not a good choice for a large scale OSM. This is because of the large size of the optical fibre and the lack of an efficient way of attaching and packaging them permanently to the PCDA. The identification of this problem leads to an alternative approach using integrated optics to be discussed in the next chapter.

Signal processing can be achieved in an OSM when a set of delay lines are introduced between the input and the output ports. Such a matrix is called a reflex OSM or RSM. A RSM has many significant features. It is inherently a broadband system since all its elements are capable of handling broadband signals. The electrical switching time being very fast facilitates the rapid tuning of the delay lines. Real time programming of the RSM is possible. Tunable delay line generation, digital word generation, multiplexing and demultiplexing, and correlation are some of the available functions. The optical to electrical conversion at the crosspoint switch imposes a directionality

that permits recirculation of the signal in the delay lines. This results in additional signal processing functions. Comb filter generation is an example and is demonstrated experimentally. A filter envelope of ≈ 1 GHz and a Q of over 300 at 600 MHz have been observed. Again, fast tuning of the filter is possible. This allows the operation of a real time matched filter or correlator. Many other applications are possible.

CHAPTER 5

ADVANCED LEVEL EXPERIMENTAL STUDY5.1 Introduction

The last two chapters have studied respectively, the device performance of GaAs photoconductors, and the system performance of an optoelectronic switching matrix using an array of photoconductors as the crosspoint switching elements. A reflex optoelectronic switching matrix capable of performing various signal processing functions was also discussed in the last chapter. It is the purpose of this chapter to address some of the problems that were encountered in the course of this work and to attempt to provide solutions to these problems.

An experimental 3X3 optoelectronic switching matrix(OSM) using the discrete element approach, that is, 3 discrete detector arrays mounted on their respective circuits, was shown in Fig.4.3. Optical fibre couplers(1 to 3) were used as the optical distribution network(OLN) to direct the light to the crosspoint switches. The ends of the fibres were end-buttet and then UV-epoxy bonded to the switches. Long term aging effects of the epoxy have been observed in this experimental 3X3 OSM. This results in less than optimum and uneven coupling of light to the switches. This epoxy method is therefore not very practical. Furthermore, as can be seen in Fig.4.3, this method does not lend itself to portability. It was demonstrated in the section 4.2 that monolithically integrated photoconductive detector arrays have low enough on-chip crosstalk level to handle broadband switching. These facts indicate that a better OSM should make use of a single switching chip and a new approach to the OLN. Successful implementation of this idea will result in large scale monolithic optoelectronic integrated circuits(OEIC). This OEIC approach is expected to yield similar advantages in optoelectronics to those associated with integrated

electronic circuits. Superior performances in speed, power consumption, compactness and mass integration are anticipated.

The problem of achieving an efficient OLN between laser sources, detectors and other signal processing devices in the development of OLC can be managed by the Integrated Optics (IO) approach. This approach consists of direct deposition of dielectric planar optical waveguides between the semiconductor devices on the semiconductor substrate. Direct deposition of optical waveguides on a semiconductor substrate has problems of its own. The requirements for material and processing steps for the dielectric waveguides and the semiconductor devices are not very compatible. For instance, dielectric waveguide deposition requires a temperature in excess of the temperature where moderate decomposition of GaAs and other similar III-V compounds begins. The two materials also have different thermal expansion coefficients. Aging effects will cause optical misalignment and possibly damage the devices. Considerable efforts in process development and materials research are required to ensure that different processing steps in fabricating the dielectric waveguides and various semiconductor devices on the same chip do not interfere with or perturb earlier and/or later steps.

A new approach still using IO aimed at solving both the mass integration and process compatibility problem is proposed here [9]. The idea is to fabricate both an optical waveguide pattern and an electrical layout contact pattern on the surface of a single dielectric substrate. Optoelectronic elements fabricated on a second substrate of semiconductor material are positioned upside down on the first and make proper contact with the metallic electrodes and also with the optical waveguide pattern. (See Fig. 5.1 for illustration). Connection between optoelectronic devices and optical waveguides can be by means of evanescent couplers, or simple absorption, since the refractive index of the semiconductor substrate is higher than that of the dielectric waveguide and will cause the modes to become unbound in regions where the two touch. A low index cladding layer such as air separates the two substrates elsewhere. The slab waveguide therefore acts as a buffer medium which allows ease of large scale optical connection. By

Fig.5.1. Hybrid integration of a dielectric substrate with a semiconductor substrate. The semiconductor devices mate electrically with the metallic electrodes and optically with the optical waveguide.

fabricating the waveguide and the optoelectronic devices separately, conflict in material and processing steps is avoided. The advantage of using this so-called Flip-Chip technique is that very large scale integration can be achieved. Multi-switching can also be achieved by fabricating different optical waveguide patterns and altering the contact position of the detector array automatically by precision stepping motors. An uncommitted array of detectors can be used to mate with different optical waveguide patterns to achieve different functions. This will save cost since dielectric material is much cheaper than semiconductor material. Also, the electro-optic effect in optical waveguide can be used to achieve switching of the optical signal paths.

The technical procedures required to implement this Flip-Chip approach should not be very difficult. This is because the approach makes use of already existing technologies such as vacuum deposition of dielectric and metal, photolithography, etching and other material processing steps. It is basically a hybrid-monolithic approach to integrated optoelectronics by exploiting two established technologies.

Another issue that needs to be addressed here concerns the situation when the incident light to the photodetector may be very weak as in the case of a long optical communication link, or a very large switching matrix. The signal coming from the photodetector will therefore need amplification prior to any signal processing. Also, comb filtering in a ROADM requires an amplifier in the ring resonator to control the loop loss and the Q-value. Though it is true that a discrete amplifier can be used, monolithic integration of the photodetector with the amplifying elements is a much better approach in terms of cost, efficiency, compactness and feasibility of mass integration. A fully integrated optical receiver can also be envisaged using this approach.

Photoconductors are especially suitable for this monolithic integration idea with FETs. This is because both devices use the planar processing method. This is not true for p-n and p-i-n photodiodes. They use an axial structure which is less compatible with the planar

structure of a FET. In terms of material choices, photoconductors and FETs can be fabricated together on a common semiconductor substrate, such as GaAs.

A proposed structure for the photoconductor-FET(PC-FET) integration is shown in Fig.5.2. The top layer is the active layer for the FET channel. A notch can be introduced to adjust the drain current. This layer is however too heavily doped to be suitable for the photoconductor. It is therefore etched away on the photoconductor side. The photoconductor uses the layer below this layer which is very lightly doped and can actually be the buffer layer of the semi-insulating semiconductor substrate. Any further necessary isolation between the photoconductor and the FET can be achieved by a mesa etch. The photocurrent from the photoconductor is connected to the gate of the FET. The FET not only acts as an amplifier, it can also be made to act as a buffer to any following amplifiers for further gain. A totally integrated optical receiver is conceivable using this approach.

The Flip-Chip and PC-FET approaches together signify the possibility of many useful optoelectronic integrated circuits. For instance, integrating the output of a PC-FET to the input of a laser results in an optical repeater. Incorporating an optical delay path between the laser output and the PC-FET input and connecting the PC-FET output to the laser input result in a comb filter. The wide bandwidth available in all the individual optoelectronic devices allows many broadband signal processing functions to be realized.

5.2

Integrated Optics Approach to ODN in a Large Scale OSM

The experimental result of a hybrid integration of an optical waveguide to a photoconductive detector array (PCDA) is presented here. The result serves to demonstrate that this integrated optics approach is a suitable solution to the ODN in a large scale, especially monolithic, OSM. This approach can also be used in other optoelectronics integrated

Fig. 5.2.2. Photocoupled-field effect transistor (PC-FET) integration structure.

circuits(OEIC) where both electrical and optical interconnections are desired. The procedures that were taken consisted of (1)the fabrication of the PCDA, (2)the fabrication of the optical waveguide, and (3)the coupling of the signal from the waveguide to the PCDA. They are discussed below. The detailed fabrication processes are described in the Appendix.

5.2.1 Fabrication of the PCDA

The PCDA used in this experiment has a very similar geometric structure to the one used in the crosstalk measurement described in the last chapter. Each detector has an overall dimension of $300\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ and an active dimension of $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$. The active area is interdigitated with 10 μm fingers. The detector separation is $100\text{ }\mu\text{m}$ edge to edge. The differences here are that the ground plane is not employed and that an array of five rather than four detectors is used. The material used was a $3\text{ }\mu\text{m}$ thick undoped epi-layer grown by organometallic pyrolysis on semi-insulating LEC grown substrate. A very thin and highly doped cap layer was used to make the ohmic contacts. This cap layer was etched away in areas where the active channel was desired. The PCDA's were cleaved from the wafers into chips having a $1\text{ mm} \times 1\text{ mm}$ dimension. The average responsivity of the detectors was measured to be 0.3 A/W .

5.2.2 Fabrication of the optical waveguide

The optical waveguides were made by electric field aided in-diffusion of silver ions into a soda lime glass slide. Ionic replacement of sodium with silver ions results in a small perturbation of the refractive index in the positive direction. The dimension of the glass slide is about one inch square. Graphite electrodes were deposited on both sides of the glass slide. Electrolysis of $0.2\text{ }\mu\text{m}$ of evaporated

silver at an electric field of 0.3 kV/cm through an aluminum mask aligned with a Karl-Suss photolithography machine was used to define the 2-dimensional waveguide pattern. The electric field aided pre-diffusion was carried out at a temperature of 250°C for 2 hours. The diffused depth at the end of the process was about 10 μm deep. A post-diffusion was later carried out at 480°C for 1/2 hour. The final diffused depth is between 60-80 μm deep. The waveguide width is about 100 μm wide as defined by the aluminum mask in the first step. The waveguide substrate was polished at the edges to facilitate the end-fire coupling from the end-buttet optical fibre in the characterization procedure. Alumina powders from 30 μm down to 0.1 μm size were progressively used in the polishing.

The optical waveguides were characterized in terms of their overall throughput coupling efficiency ($\eta_c = 10 \cdot \log(I_1/I_0)$) and the propagation loss (α). The former is a measure of the total insertion loss. Fig. 5.3 illustrates the measurement procedure. The output power I_1 coupled from the end-buttet optical fibre at the output end is compared with the input power I_0 coming out from the optical fibre at the input end. This measurement accounts for the input and output coupling loss, and the propagation loss due to absorption and scattering. A value of ≈ 10 dB was measured in the experiment for a 2.5 cm long waveguide. The loss apparently occurred mainly at the input coupling. This is due to a mismatch in the size and shape of the optical fibre and the in-diffused waveguide. This results in a mismatch in the intensity profile distribution. This can be improved by altering the diffusion profile by controlling the diffusion temperature and duration. Insertion loss as low as 1 dB has been reported when mode matching is done [28].

The propagation loss was measured by monitoring the scattered light as a function of distance with a television camera. Absorption and scattering loss have a one to one relationship. The experimental set up and data analysis are shown in Fig. 5.4. A pair of opaque markers made of very thin wire were placed at a known separation across the optical waveguide perpendicular to the propagation direction. They registered as

2 OF/DE 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Fig.5.3. Experimental set up for total insertion loss or throughput coupling efficiency measurement

Fig.5.4. Experimental set up for propagation loss measurement.

nodes in the scattered intensity versus distance plot as shown in Fig. 5.4. The extrapolated intensity at these two points together with the known distance (L) give the propagation loss $\alpha = 1/L(10 \log(I_a/I_b))$. A propagation loss of $\approx 1 \text{ dB/cm}$ was measured in the experiment. This compares very well with other types of optical waveguide.

5.2.3 Coupling of light from the optical waveguide to the PCIA.

The key demonstration in this integrated optics approach to the OLN in a large scale OSM and perhaps other OEIC as well is how efficient the light can be coupled from the optical waveguide to the semiconductor devices (the PCIA here). Directional coupling is not necessary because the detectors are relatively large in size and can be located in close proximity to the optical waveguides. Isotropic scattering is sufficient if the loss of half of the scattered light through the substrate can be tolerated. An added advantage in isotropic scattering is that only a small portion of the light will be coupled at each location. This makes it especially suitable for a large scale OSM where there are a large number of coupling points.

Isotropic scattering can be achieved in a number of ways. The refractive index can be perturbed so as to cause the waves to become unbound at the coupling points. A second diffusion of a different kind of ions, which has the effect of lowering the refractive index, after the post diffusion of the Ag ions, was tried. It however altered the waveguide profile more than desired and this resulted in a significant propagation loss. Application of an index matching fluid (IMF) of slightly higher index on the waveguide surface can also cause unbound waves. It was however difficult to confine the fluid to the desired location. Any spill-over translates into propagation loss. Direct contact of the semiconductor chip to the waveguide surface would also cause unbound waves since semiconductors have much higher index than glasses. However the combined thickness of the cap layer and the

metallization on the semiconductor chip, and the metallic electrodes on the glass slide presented too large a distance for efficient coupling. Refractive index perturbation did not prove to be a good approach for the coupling of light from the waveguide to the PCA.

Geometric perturbation of the waveguide in the form of surface indentation is the approach that proved to be successful. Different ways of producing geometric indentation in the waveguide were tried in the experiment. Chemical wet etching using HF was unsuccessful because glass is severely undercut by HF. The waves remained bound in the perturbed area or suffered reflection at the undercut surface and exited through the substrate. Dry etching with oxygen, and argon ions in a plasma chamber were both slow and inefficient. A mechanical technique using micro-particle bombardment through an appropriate protective mask was found to be most successful.

The procedure used for micro-particle bombardment is as follows. A thick protective multi-layer coating made of aluminum and photoresist was deposited on the waveguide surface. Photolithography was then used to define $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ openings where the detectors will be located. The etching process is sensitive to the size of the micro-particles used. Alumina powders were used. Particles that are $1\text{ }\mu\text{m}$ or larger tend to cause too much damage and poor uniformity amongst the perturbations. Particles that are smaller than $0.2\text{ }\mu\text{m}$ give very slow and minor etching. Particles that are between 0.3 to $0.6\text{ }\mu\text{m}$ produce the optimum result. In general the smaller particles give smoother and more uniform perturbation. The etching was done by scanning the particle beam at a pressure of $\sim 100\text{ psi}$ 10-20 times across the waveguide with alternate scans perpendicular to each other. Afterward, surface damage was alleviated by rinsing the waveguide in a diluted HF solution. The smoothness achieved is closely related to the size of the micro-particles used.

The electrical contact pattern for the PCA was then deposited on the waveguide surface. It was done by etching a sputtered film of Ti-Au. The alignment of the PCA with respect to the contact pattern was

facilitated visually by observing the process through the back side of the waveguide substrate. The PCDA was affixed in the desired location with conductive epoxy. The final assembly of the hybrid integration of the optical waveguide to the PCDA is shown in Fig.5.5.

The performance of this hybrid device was measured in two steps. Prior to bonding the PCDA chip to the waveguide surface, a 100 μm core optical fibre was used to monitor the power that was scattered from the perturbations. With a 1 mW input power (I_0 in Fig.5.3), three perturbations at an interspacing of 300 μm registered an output power of 2.5, 2.5, and 2.0 μW . It is estimated that the coupling efficiency from the perturbation to the fibre is about 80%, or -1dB coupling loss is incurred. The waveguide was earlier measured to have a 10dB total insertion loss and a propagation loss of 1 dB/cm. The perturbations are near the centre of the one inch square glass slide. Therefore there is roughly 1 cm travel from the edge to the perturbations. The actual coupling efficiency of the propagating signal in the waveguide to the perturbation is calculated as follows.

Total loss from input (I_0) to coupling point:

$$10 \log(2.5 \mu\text{W}/1\text{mW}) = -26 \text{ dB}$$

Various losses incurred:

(i) Coupling from monitor fibre = 1dB

(ii) Waveguide insertion loss with 1 cm travel

From total insertion loss with 2.5 cm travel = 10 dB

propagation loss = 1dB/cm, the waveguide insertion

loss with 1 cm travel = $10 - (2.5 - 1) * 1 = 8.5 \text{ dB}$

Coupling loss from the waveguide to the perturbation is

$$(-26 + 1 + 8.5) \text{ dB} = -16.5 \text{ dB}$$

The uniformity in the coupling efficiency is within 20% from the three measurements of 2.5, 2.5 and 2.0 μW .

After the PCDA chip was bonded to the waveguide surface, the

METALLIC
ELECTRODE

IN-DIFFUSED
OPTICAL
WAVEGUIDE

PHOTOCONDUCTIVE
DETECTOR
ARRAY

Fig. 1. (a) Integration of the optical waveguide to the photoconductive detector array (PDWA). Each detector has an active area of 100 micron $\times$ 400 micron (area defined at 10 micron line spacing). The detector spacing is 100 micron edge to edge. The PDWA is silver sisted onto the metallic electrode. The optical waveguide can be seen running across the PDWA horizontally. The coupling is realized at the perturbation through partial evaporation of the photoconductive film into the detector.

coupling efficiency was again measured by comparing the direct responsivity when coupling the signal through the back side of the substrate with that when coupling from the waveguide. Direct responsivity was measured at 0.3 A/W . Responsivity via coupling from the waveguide was measured at $0.5 \times 10^{-4} \text{ A/W}$ or a -28 dB total loss from the input to the coupling point. The extra 2 dB loss (recall -26 dB loss when using a monitor fibre) is attributed to the alignment between the PCIA and the waveguide, and the physical separation between them. The monitor fibre used was endbutted into the perturbations. The frequency response of the PCIA via the in-diffused waveguide is shown in Fig.5.6. The response is less smooth than when the PCIA is mounted on a micro-stripline circuit. This is because the metallic contact pattern used on the waveguide substrate does not have a 50Ω characteristic impedance. Fig.5.6 indicates a bandwidth of close to 1 GHz even under this condition.

The weak coupling of -16.5 dB achieved in the experiment here is suitable for an OLN in a very large scale OSM where there are a large number of coupling points. Improvement on the throughput coupling efficiency can be made by better matching at the input. Better coupling from the waveguide perturbation to the PCIA can be achieved by finding a suitable chemical etchant that does not undercut glass significantly. Chemical wet etching produces a much smoother perturbed surface than what mechanical abrasion can produce. The coupling efficiency for chemical etching can thus be expected to be higher.

The experimental results here demonstrate the feasibility of the integrated optics approach to the OLN in a large scale OSM. The approach can also be applied to other optoelectronics integrated circuit (OEIC) assemblies where both optical and electrical interconnections are necessary. The advantage of this hybrid approach is that the processing steps for the dielectric and the semiconductor substrates are separated from each other. No conflicting steps were encountered in the experiment. This approach also allows the attachment of several semiconductor chips on a single dielectric substrate. The dielectric substrate thus acts as an OEIC breadboard. This eliminates the need for

Fig.5.6. Frequency response of the PCDA via the optical waveguide coupling.

a large semiconductor substrate which is much more expensive than a dielectric substrate. Finally, electro-optic and acousto-optic effects can be introduced as well by using the appropriate substrate, say lithium niobate or quartz. Complex and modular OELCs as in an optical repeater, an optical modulator and optoelectronic signal processors can be realized.

5.3 Monolithic Integration of a Photoconductor and a Field Effect Transistor

A one stage photoconductor-field effect transistor(PC-FET) monolithic integration was attempted in the experiment. The material was grown by the VPE process on chromium doped semi-insulating(SI) GaAs substrate with the following specification; a top layer of $n = 2 \times 10^{17}/\text{cc}$, $\approx 0.3 \mu\text{m}$ thick and a buffer layer of $n^- = 5 \times 10^{14}/\text{cc}$, $\approx 3-4 \mu\text{m}$ thick. It is similar to the structure shown in Fig.5.2. The only difference is the absence of the buffer layer. The PC-FET layout as it appeared in the composite photolithography mask is shown in Fig.5.7.

The n layer is used for the FET active channel. This layer is too heavily doped for the photoconductor. It is etched away on the photoconductor side. The photoconductor uses the n^- layer as the active channel. A tandem photoconductor configuration as shown in Fig.5.7 is employed. The common connection from it is connected to the gate of the FET. This tandem configuration facilitates bipolar biasing so that the gate potential can be made to operate at near zero voltage. The FET has a gate length and width of $2 \mu\text{m}$ and 1 mm respectively. The photoconductor has an active area of $100 \mu\text{m} \times 100 \mu\text{m}$ interdigitated with $10 \mu\text{m}$ fingers. The ohmic contacts to the photoconductors and the source and drain of the FET are evaporated and annealed Au-Ge-Ni alloy. The interconnection from the photoconductor to the gate of the FET is made of Ti-Au.

Fig.5.7. Photoconductor-field effect transistor(PC-FET) layout as it appeared in the composite photolithography mask.

The characterization of the PC-FET was done in three steps. The FET and the PC were first individually examined. Their performance as a unit was then investigated. The DC characteristic I-V curves of the FET are shown in Fig.5.8. At a gate bias (V_g) of ≈ 0 V and a drain bias (V_d) of ≈ 2 V, the transconductance (g_m) is about 70 mS. The corresponding drain current (I_d) is about 20 mA. A reverse gate bias of less than 0.5 V is sufficient to turn the FET off.

The photoconductor has a responsivity of 0.3 A/W. Its dark current is about 3 μ A at 3 V bias. This gives a dark resistance of ≈ 1 M Ω . The isolation value is about 60 dB across a ≈ 1 GHz bandwidth. These values are in close agreement with those of similar devices discussed in Chapter 3.

The performance of the PC-FET as a unit was measured as follows. The experimental set up is shown in Fig.5.9. The V_g was established by applying a bipolar power supply to the tandem PC pair. The photoconductors were illuminated by a 1 to 2 optical fibre coupler. A V_g of near zero volts was used in the experiment since it gave the optimum gain. The V_d is applied to the FET via a broadband bias tee. The RF output from the bias tee was connected to a dual input network analyzer. The input of the PC-FET, the connection between the PC pair and the gate of the FET, was either left in open circuit condition or connected to a second broadband bias tee. The V_g bias can be monitored via the DC port of this bias tee. When the RF port of this bias tee is connected to the other input of the network analyzer, a 50 Ω input load is established. This allows a direct comparison between the signals at the input and the output of the PC-FET, and between the output signals from a PC alone and a PC-FET, both 50 Ω terminated at the input.

When the input of the PC-FET is left in the open circuit condition, the parallel resistance of the tandem PC pair forms the input impedance. The PC-FET in this condition has a significant gain at the expense of a reduced bandwidth due to the large RC time constant at the input. This reduced bandwidth can however be compensated by proper equalization. It is common practice in an optical receiver to have a

Fig.5.8. DC characteristic of the FET used in the PC-FET integration.

Fig.5.9. Experimental set up for measuring the PC-FET performance.

high impedance front end followed by an equalizer stage [29-30].

The experimental result of the PC-FET under a 50 Ω input condition is shown in Fig. 5.10. The V_d and V_g are 2 V and ≈ 0 V respectively. A midband gain of 6 dB was obtained. The bandwidth is about 1.1 GHz. A slight "auto" high frequency enhancement was also observed. This is illustrated in Fig. 5.11 where the output and the input are made to coincide in the midband by the offset control in the network analyzer. The high frequency response is better in the output trace. The 3 dB point for the input and the output are 0.97 and 1.1 GHz, respectively. The low frequency roll off is not due to the PC-FET but is due to the laser transmitter which has a 200 MHz roll-off point.

The gain characteristics of the PC-FET as a function of V_d and V_g are shown in Fig. 5.12. At $V_g \approx 0$ V, a gain saturation of 6 dB was observed at $V_d = 2$ V. At $V_d = 2$ V, the FET was observed to be completely turned off at $V_g \approx -0.3$ V. These low voltage operations facilitate large scale integration where power dissipation can be a concern.

The experimental observation of a 6 dB gain is somewhat inferior to the maximum gain that can be achieved with the FET used. The S-parameters of the FET from 4 MHz to 1.3 GHz are shown in Fig. 5.13. The V_d and V_g are 2 V and 0 V respectively. The S_{22} parameter indicates a reasonably good match to 50 Ω at the output. The S_{11} parameter on the other hand indicates proper matching at the input is required in order to realize the maximum available gain in the FET. The S_{21} parameter indicates a transducer gain ($|S_{21}|^2$) of 9.5 dB at midband. The maximum available gain (MAG) at midband, assuming unilateral condition ($S_{12} \approx 0$), can be estimated using the following formula [31].

$$MAG = |S_{21}|^2 \cdot \frac{1}{|1 - S_{11}|^2} \cdot \frac{1}{|1 - S_{22}|^2}$$

S_{11} , S_{22} and S_{21} at midband are respectively 0.8, 0.1 and 3. These values imply a MAG of 14 dB at midband. A comparison of this value with

Fig.5.10. Frequency response of the PC-FET, and the PC. A 2 V bias is applied across the photoconductor. V_g and V_d are 0 and 2 V respectively. A midband gain of 6 dB is obtained. The low frequency rolloff is due to the laser transmitter.

Fig. 5.11. "Auto" high frequency enhancement in the PC-FET.
The PC-FET response is offset 6 dB to coincide
with the PC response.

Fig.5.12. Gain characteristic of the PC-FET with respect to (a) V_d at $V_g = 0$ V and (b) V_g at $V_d = 2$ V. Gain saturation at $V_d = 2$ V and turn-off at $V_g = -0.3$ V were observed.

• Fig.5.13. Measured S-parameters of the FET. $V_{ds} = 2$ V and $V_g = 0$ V.

the experimentally observed gain of 6 dB indicate a further gain of 8 dB can be harnessed by properly matching the input and output condition of the FET. Passive LC elements or buffered stages between the PC and the FET, and between the FET and the external load can be introduced to provide the matching condition. The PC resistance is in the $k\Omega$ region whereas the FET's is about $10\ \Omega$. An impedance transformation ratio of ~ 100 is therefore required. This ratio can be reduced by using a more heavily doped layer for the PC. This is, however, done at the expense of a higher noise level in the PC. Therefore some optimization will be necessary in the matching process.

5.4 Summary

A couple of key problems that were encountered in the course of the work have been examined here and solutions to them have been attempted. A compact OLN using a hybrid integration of a dielectric and a semiconductor substrate suitable for use in a large scale OSM is demonstrated. This approach makes use of in-diffused optical waveguide in a glass substrate which also has the metallic contact pattern on the front surface. The semiconductor substrate is bonded upside down to mate with the contact pattern and the waveguide paths. This hybrid integration scheme has the important advantage of separating the processing procedures on the dielectric and the semiconductor substrates. This eliminates any conflicting factor and avoids any undesired perturbation due to process incompatibility. Also, the dielectric substrate can be used as a breadboard to accommodate more than one semiconductor substrate. The latter can be related via both the metallic contact pattern and the waveguide paths. Complex optoelectronic integrated circuits(OEIC) can be achieved this way.

The experimental demonstration of an in-diffused optical waveguide integrated to a PCDA is done here. It shows the coupling efficiency of the light from the waveguide to the PCDA to be $-16.5\ \text{dB}$. The uniformity

of the coupling is about 20%. This loose coupling is especially suitable for usage in a large scale OSM or other complex OEICs where a large number of coupling points are required.

The monolithic integration of a PC to a FET is also demonstrated here. This finds application in situations where the incoming light level is low and hence the signal derived from the detector requires amplification prior to any further signal processing. The material requirement and the planar fabrication process in PCs make them suitable for monolithic integration with FETs. A one stage PC-FET integration is implemented. A 6 dB gain and a 1.1 GHz bandwidth are achieved. The PC-FET operates at near zero gate voltage and 2 volts drain voltage. The experimental results also indicate that higher gain can be attained by proper matching. The hybrid integration of a dielectric and one or more semiconductor substrates, and the monolithic integration of PCs to FETs can be applied together to implement many important optoelectronic integrated circuits(OEIC).

CHAPTER 6

SUMMARY AND SUGGESTIONS FOR FURTHER RESEARCH

In this final chapter, the summary of the results obtained in the course of this thesis work is presented. Suggestions for further research aimed at realizing the potential of optoelectronic processes in photoconductors and integration of them with other optoelectronic devices are made.

A photoconductor basically consists of a piece of semiconductor with two ohmic contact terminals. It reacts to an optical signal by generation of electron-hole(e-h) pairs. In the presence of an electric field these e-h pairs drift towards and are collected at the respective terminals and a signal is generated. In the absence of such an electric field they recombine according to their lifetime and hence there is no signal. Although GaAs has been exclusively used in the work reported here, similar results can be expected with other III-V binary, ternary and quaternary materials.

The operating mode of a photoconductor is determined by the bias scheme. The photodetection mode uses a constant DC bias so that the photoconductor is always sensitive to the incoming optical signal. In optoelectronic switching the DC bias is toggled to render the photoconductor either sensitive or insensitive to the optical signal. Finally, optoelectronic mixing is achieved by replacing the DC bias by a local oscillator(LO) so that the output is in an intermediate frequency(IF) band.

The experimental studies have indicated that photoconductors used in the photodetection mode have commensurate performance with respect to photodiodes in both the responsivity and the bandwidth. A responsivity of 0.6 A/W and a bandwidth of 3 GHz have been observed. Conventional photoconductors do exhibit a significantly higher noise-equivalent-power (NEP) of 10^{-11} - 10^{-10} Watt/Hz in comparison to that of $\approx 10^{-14}$

Watt/Hz in photodiodes. This is due to the large dark current under the bias condition in the photoconductor. A novel type of photoconductor that utilizes the surface depletion layer as the active channel shows considerable improvement in the noise performance. Its NEP of $\sim 2 \times 10^{-13}$ Watt/Hz is within an order of magnitude to that of photodiodes. This surface depleted photoconductor (SDPC) also does not possess a huge LC gain which is due to backgating and parasitic transistor effects common in conventional photoconductors. The result is a fairly flat LC to RF frequency response. This facilitates direct coupling to other devices and alleviates the need for sophisticated frequency compensation circuits. Furthermore, the SDPC maintains the good responsivity and bandwidth that are available in the conventional photoconductors. Its low noise characteristic is a bonus that can find important application in situations where the incoming signal is weak and the noise performance is critical. As the operation of the SDPC depends on the presence of traps on the surface of the active layer to create an electric field which depletes the layer, the surface condition is therefore very important. The trap density may be altered with respect to time due to humidity or other environmental conditions. Therefore in order to have a long lifetime, proper packaging such as hermetically sealed mounts should be used. Alternatively, proper surface passivation to control and maintain the desired trap density that would produce the surface depletion effect should be investigated.

The experimental studies confirm that photoconductors are the best candidate for optoelectronic switching. This is because the key factors of isolation and electrical switching time in a photoconductor are independent variables. This contrasts with the situation in a photodiode when the two are related in a conflicting manner. When good ohmic contacts are formed in a photoconductor, an isolation value of over 60 dB across at least a 1.3 GHz bandwidth has been observed. An electrical switching time of 0.25 ns has also been observed. This is of the order of transit time limited switching. Optoelectronic switching is the focus of this thesis.

The experimental studies on optoelectronic mixing have revealed a

number of important characteristics. A frequency stability of 10 kHz in the mixer, as limited by the RF generator, has been achieved. This stability coupled with the GHz bandwidth that is available in the mixer imply that quasi-baseband operation is possible. High RF signals can be mixed down to a moderate IF band so that all post-detection signal processing can be performed without the need for broadband equipment. An enhanced gain of 17 dB and frequency response of 4GHz have been attained. This mixing operation allows the usage of high resistivity materials where good ohmic contacts are difficult to achieve. The electric field is capacitively coupled into the active channel. A bilinearity of 30 dB has also been achieved.

The SDPC was also tested under the optoelectronic switching and mixing operations. In both instances it preserves the desirable characteristics that are available in the conventional photoconductors. It can therefore be concluded here that the SDPC should be used for all the operation modes available in a photoconductor.

The application of optoelectronic switching in a network for routing and broadcasting broadband signals was demonstrated in Chapter 4. This kind of network is called an optoelectronic switching matrix (OSM). It consists of a two-dimensional crosspoint switch array, a one-dimensional laser array and an optical distribution network (OLN) to direct the optical signals from the laser array to the crosspoint array. The performance in an OSM is dictated by the interference level amongst the crosspoint switches. Experimental studies show that the major source of crosstalk is between crosspoint switches in adjacent channels. Other sources of crosstalk are well below 60 dB in a 1.3 GHz bandwidth. A monolithic integration of a ground plane to a photoconductive detector array (PCDA) gives a crosstalk level of -44 dB at 100 μ m spacing in the same bandwidth. At 2 GHz the crosstalk is -40 dB. These results confirm the feasibility of a single chip OSM. In order to take advantage of this single chip OSM, a more compact OLN is necessary. Optical fibre couplers are too large for integration purposes and are also difficult to be permanently packaged. The integrated optics approach was later introduced in Chapter 5 as the solution.

The introduction of a set of delay lines to an OSM results in a reflex OSM or ROSM capable of performing various signal processing functions. The simplest function is a tunable delay line. The fact that each crosspoint switch has sub-nanosecond response time means that real time operation for GHz signals is possible. The imposed directionality at the crosspoint switch where optical to electrical conversion takes place permits recirculation of the signal through the delay loop. This allows the construction of a ring resonator with variable round trip delay. A comb filter utilizing this recirculation property was demonstrated in the experiment. The filter exhibits a 1 GHz envelope and a Q value of over 300 at 600 MHz. Many other important digital and analog signal processing functions are foreseen in a ROSM. The significant advantage here is that real time operation can be achieved by re-configuring the switching condition to accommodate the changing environment.

The OSM and ROSM demonstrated in chapter 4 used the discrete element approach. This approach is massive in size even for a 3×3 matrix as shown in Fig.4.3. The experimental results on the monolithically integrated PCIA with a ground plane indicate that very low crosstalk at 100 μm spacing is possible. A single chip OSM or ROSM is therefore readily available. The key to realizing such an integrated version is the provision of a more compact OLN. Integrated optics using in-diffused optical waveguides was found to be a suitable choice.

The integrated optics approach used here is different from the conventional approach. The latter always involves the direct deposition of the optical waveguides onto the semiconductor substrate where the devices are fabricated. This approach has several drawbacks. It necessitates a large expensive substrate to be used. It does not lend itself readily to versatility. The fabrication processes of the dielectric and the semiconductor devices are usually conflicting. The approach that is taken here is a hybrid integration method whereby the dielectric and semiconductor devices are fabricated separately on their respective substrates. Electric field aided in-diffused waveguides are first fabricated in a glass substrate. The metallic electrode pattern

for the semiconductor devices is then deposited on the surface of the glass substrate. The semiconductor substrate with the devices fabricated is then bonded upside down onto the glass substrate to mate with the contact pattern. The semiconductor devices can be related both optically and electrically. This approach eliminates any conflict and incompatibility in the fabrication process. The added advantage in this hybrid integration approach is that the dielectric substrate is cheap and its large size can be used as a motherboard to accommodate more than one semiconductor chip. These chips can again be related both optically and electrically. Complex functional blocks can be realized using this approach.

The feasibility of this hybrid integration approach was illustrated experimentally in the coupling of light from an in-diffused waveguide to a PCDA. The coupled power is about -16.5 dB with respect to the propagating power in the waveguide. The coupling uniformity at different coupling points is about 20%. The weak coupling of -16.5 dB is especially suitable for large scale operation where the number of coupling points is large. For small scale operation, the coupling will have to be stronger for an efficient operation. Chemical etching rather than the mechanical abrasion used here should be employed. This is because chemical etching is known to provide a smoother surface. It also has the tendency of giving more uniform results amongst different coupling points. The mechanical abrasion method used here can produce strong coupling by using larger particles for bombardment. However the uniformity amongst the different coupling points tends to deteriorate with respect to the particle size. Chemical etching using HF was tried in the experiment but it was found to produce severe undercutting. Consequently the propagating waves remained bound. The search for a suitable chemical etchant that does not undercut is necessary for achieving strong coupling and good uniformity.

The crosstalk at the coupling points in the hybrid integration approach demonstrated here requires special attention. The coupling process induced by the perturbation in the form of a square-well indentation in the waveguide is not directional. In fact, it is an

isotropic scattering process. Therefore, in order to minimize the crosstalk at the coupling points, the physical spacing between the perturbation in the waveguide and the semiconductor device must be minimized as well. Also, the size of the perturbation should be smaller than that of the semiconductor device. In this case, the latter acts effectively as an aperture stop. Alternatively, directional coupling can be introduced in the perturbation to reduce the crosstalk. This can be achieved by a surface with the proper angle or coated with a reflective film, or by a tailoring of the refractive index profile.

The comb filter synthesis in the RUSI identified another practical problem. In order to control the loop loss and hence the Q of the filter, an amplifier was needed. A discrete amplifier was used in the experiment. This has two major drawbacks. The first is the large physical size involved and the second is the typical long propagation delay of the amplifier, connectors and cables. This propagation delay will be interpreted as the minimum time delay in the delay loop that is being used. A monolithic integration of the crosspoint switch with an amplifying element such as a FET is a better solution. A photoconductor is especially suitable for monolithic integration with a FET because of its compatible planar fabrication process and material requirement. A one stage photoconductor-FET (PC-FET) integration was demonstrated in the experiment. It employed a tandem PC configuration at the input. Bipolar biasing was used for the tandem PC so that the gate voltage was maintained at near zero volts for optimum operation. The FET has very low operating voltage: V_d saturation ≈ 2 V and V_g turn off ≈ -0.3 V. The PC-FET exhibits a midband gain of 6 dB and a bandwidth of 1.1 GHz. The S-parameter measurements indicate that higher gain can be attained if proper matching is performed. This can perhaps be achieved by a passive LC network or a buffer stage using another FET.

The monolithic integration of the one stage PC-FET can be extended to include other electronic and optoelectronic elements to realize certain functional blocks. For instance, cascading a series of FETs to the output of the PC-FET gives a basic optical receiver. The connection

of a laser to the end of this basic receiver, after some pulse cleaning and synchronization, gives an optical repeater. The combined application of the hybrid integration approach discussed earlier and this monolithic integration of optoelectronic and electronic devices can result in even more diversified and complex functional blocks. Electro-optic and acousto-optic effects in the dielectric substrate are further dimensions that can be explored. Various totally integrated optoelectronic modules such as an optical transceiver, a multiplexer and other signal processing units are foreseen.

In conclusion, it is hoped that the work presented here has served to identify and confirm photoconductors as important optoelectronic elements, to introduce the significance of optoelectronic technology in broadband switching and signal processing, and to enhance the research and development in monolithic optoelectronic circuits(OEIC).

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APPENDIX

Hybrid Integration Fabrication Process

This appendix provides a detailed description of the fabrication process of the hybrid integration of the electric field aided in-diffused optical waveguide to the photoconductive detector array. The dielectric substrates used were 2.5 cm x 2.5 cm, 0.16 cm thick soda-lime glass slides. Cleanliness throughout the entire fabrication process must be maintained in order to obtain low loss optical waveguides. Ultrasonic cleaning and keeping most of the processing steps in a laminar flow fumehood were found to be important. Also, flushing the furnaces with clean air or nitrogen prior to the pre- and post-diffusion processes was helpful.

Substrate Preparation

- 1) Clean the glass substrate in ultrasonic bath with trichloroethylene, followed by acetone, and then absolute methanol. Blow dry with clean dry nitrogen.

Optical Waveguide Definition

- 2) Apply photoresist AZ1350 onto the glass substrate and soak it in chlorobenzene briefly.
- 3) Expose the waveguide mask and develop.
- 4) Evaporate Al onto the substrate in a vacuum deposition chamber.
- 5) Perform Al liftoff process by 1 minute ultrasonic bath in acetone.
- 6) Clean the substrate by dipping it into absolute methanol and blow dry with dry nitrogen.

- 7) Evaporate Ag onto the substrate in the vacuum deposition chamber.
- 8) Deposit graphite electrodes on both sides of the substrate for the electric field aided diffusion.
- 9) Carry the pre-diffusion at 250 C for 2 hours at 50 V.
- 10) Remove the graphite electrodes by 5 minute ultrasonic methanol bath.
- 11) Clean the substrate by dipping it into absolute methanol and blow dry with dry nitrogen.

Perturbation Definition

- 12) Apply photoresist AZ1350 onto the substrate and soak it in chlorobenzene briefly.
- 13) Expose the perturbation mask and develop.
- 14) Evaporate Al onto the substrate in the vacuum deposition chamber.
- 15) Perform Al liftoff process by 1 minute ultrasonic acetone bath.
- 16) Apply a thick AZ1375 coating onto the substrate.
- 17) Reverse expose from the back and develop.
- 18) Mechanical bombardment with Alumina micro-particles.
Size=0.3-0.6 μ m. Pressure 100psi. 10-20 scannings.
- 19) Remove the protective coating of AZ1375 and Al.

- 20) A quick rinse in diluted HF to smooth out the mechanical damages.

Post Diffusion, Metallization and Bonding

- 21) Perform post-diffusion at 480°C for $\frac{1}{2}$ hour.
- 22) Evaporate Au onto the substrate.
- 23) Apply photoresist AZ1350.
- 24) Expose the metallization mask and develop.
- 25) Polish the substrate edges with alumina powders from 50 μm down to 0.1 μm size to facilitate end-buttet coupling.
- 26) Align the photoconductive detector array with respect to the perturbations on the glass substrate using a photolithography machine modified with a plane mirror in the lower platform. This modification allows visual observation of the alignment process.
- 27) Bond the photoconductive detector array onto the substrate with conductive epoxy.

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