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**A Study of
Resonant Tunnelling Diodes
and their Application to
Hybrid Oscillators**

by

Matthias Roschke, B.Sc.

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

Ottawa-Carleton Institute for Electrical Engineering

Department of Electronics

Carleton University

Ottawa, Ontario

September, 1995

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"A Study of Resonant Tunnelling Diodes
and their Application to Hybrid Oscillators"

submitted by Matthias Roschke, B.Sc.
in partial fulfilment of the requirements for
the degree of Master of Engineering

Thesis Supervisor

Thesis Co-Supervisor

Chair, Department of Electronics

Carleton University

Abstract

In order to study the behaviour of Resonant Tunnelling Diodes (RTDs) and their application to low power oscillator circuits, a variety of AlGaAs/GaAs/AlGaAs RTDs have been fabricated. After careful characterization (both dc and RF), three of these devices were installed in simple hybrid oscillator circuits, which were found to oscillate at 1.77 GHz (18 μ W), 16 GHz (60 nW) and 37 GHz (3.2 μ W) respectively. The circuits were evaluated in terms of short term stability (5 ppm/s) as well as the effects of bias and temperature changes on the output. It was found that the frequency drift with temperature for at least one of the circuits (the 16 GHz oscillator) was highly dependant on the bias setting and could be reduced to near zero. It might be possible to use this property to design temperature compensated circuits. All three circuits were bias tunable, which would allow the use of phase locking techniques to stabilize the circuits. It was concluded that RTDs could be used as active elements for oscillators in the millimeter bands, if their output power could be increased.

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Statement of Originality

To the best of the author's knowledge, the following constitutes original work

1) The use of a microwave probe with a bias network and a 50 Ω termination, in order to measure the RTD I-V curves. This prevented the occurrence of unwanted oscillations in the NDR region, which tend to obscure this section of the I-V curves during regular I-V measurements.

2) The study of temperature effects on the output of the RTD oscillators. The most interesting observation during these experiments is the fact that the temperature coefficient of the oscillator circuits is dependant on bias. It may be possible to use this effect to design temperature compensated oscillator circuits.

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List of Abbreviations and Symbols

A	Amperes
Å	Angstroms (10^{-10} meters)
Al	Aluminum
AlAs	Aluminum arsenide
AlGaAs	Aluminum gallium arsenide
Al _{0.4} Ga _{0.6} As	Aluminum gallium arsenide (with 4 to 6 ratio of Aluminum to Gallium)
AlSb	Aluminum antimonide
Au	Gold
C _d	Capacitance of the diode (small signal model)
CRC	Communications Research Center
cm	Centimeters
°C	Degrees celsius
dB	Decibels
dBm	Decibels relative to one milliwatt
dc	Direct current
DR	Dielectric resonator
DUT	Device under test
eV	Electron volts
E	Energy operator
E ₀	First resonance of a quantum well
E ₁	Second resonance of a quantum well
E ₂	Third resonance of a quantum well
f _{max}	maximum oscillation frequency
FET	Field effect transistor
fF	Femtofarads
FM noise	Frequency modulation noise
GaAs	Gallium arsenide
Ge	Germanium
GHz	Gigahertz
GPIB	General Purpose Interface Bus
He	Helium
h	Planck's constant ($h/2\pi \approx 1.05459 \times 10^{-34}$ Joule seconds)
H	Hydrogen
H (in equations)	Hamiltonian operator
I	Current
InAs	Indium arsenide
I-V	Current - Voltage

j	Square root of negative one (also called i)
J	Joules
Js	Joule seconds
K	Kelvin
K-connector	Electrical connector rated for the K - band (20 GHz - 40 GHz)
m	Meter
m (in equations)	Mass
m^*	effective mass
m_0	rest mass
mA	Milliamperes
MBE	Molecular beam epitaxy
MESFET	Metal semiconductor field effect transistor
MHz	Megahertz
mm	Millimeters
mV	Millivolts
mW	Milliwatts
N	Nitrogen
NA	Not available or not applicable
NDR	Negative differential resistance
Ni	Nickel
nW	Nanowatts
PC	Personal computer
pF	Picofarads
PLL	Phase locked loop
ppm	Parts per million
ppm/s	Parts per million per second
ppm/°C	Parts per million per degree celsius
ps	Picoseconds
PVCR	Peak to valley current ratio
R	Resistance
R_d	Parallel resistance of a diode (small signal model)
R_s	Series resistance of a diode (small signal model)
RF	Radio Frequency
RIT	Resonant interband tunnelling
RTD	Resonant tunnelling diode
s	Seconds
S-parameter	Scattering parameter
S11	Port 1 reflection
S12	Port 2 to port 1 transmission
S21	Port 1 to port 2 transmission
S22	Port 2 reflection
Si_3N_4	Silicon nitride
SPICE	Simulation program with integrated circuit emphasis
T	Temperature

THz	Terahertz
Ti-W	Titanium-Tungsten
V	Volts
V	Potential (in equations)
VCO	Voltage controlled oscillator
W	Watts
Z_0	Reference impedance (usually 50 ohms)
Z_d	Device impedance
Γ	Reflection coefficient
Γ_d	Reflection coefficient of a device
Γ_l	Reflection coefficient of the load
μ	Mobility
μm	Micrometers
μW	Microwatts
ω	Angular velocity
Ω	Ohms
$\Omega\text{-cm}$	Ohm centimeters

1. Introduction

Resonant Tunnelling Diodes (RTDs) are electron devices which take advantage of quantum mechanical effects occurring when electrons are tightly confined in a potential well (quantum well). This results in a current peak and a Negative Differential Resistance (NDR) region in the dc I-V curves of these diodes. The concept of resonant tunnelling in semiconductors was first proposed by Esaki and Tsu in 1970 [1.1], and clear evidence of resonant tunnelling and NDR in GaAlAs/GaAs/GaAlAs structures was reported by Chang, Esaki and Tsu in 1974 [1.2].

With the rapid advances in Molecular Beam Epitaxy (MBE) and other growing techniques, the performances of RTDs have been greatly improved. Room temperature peak to valley current ratios (PVCRs) as high as 144 have been reported for Resonant Interband Tunnelling (RIT) structures [1.3] along with oscillation frequencies up to 712 GHz at room temperature [1.4]. The maximum oscillation frequency has been theoretically predicted to be over 2.5 THz [1.5]. Because of their potential for high speed circuit applications and their relative simplicity, RTDs are emerging as one of the more promising electron devices, with application ranging from millimeter band oscillators [1.6], to digital signal processing [1.7] and logic functions [1.8].

Besides their potential for ultra-high speed applications, RTDs have the added advantage of being very simple and physically small devices. Resonant tunnelling is a basic quantum mechanical effect, which depends only on the structure of the potential well and the energy of the electrons, rather than electron mobilities, scattering or electron - hole recombination, and should not be strongly influenced by temperature and other environmental effects. An investigation into the temperature dependant behaviour of the RTDs should therefore yield some rather interesting results, and RTD oscillator circuits should show relatively low temperature drift compared to circuits using other active devices (especially other two terminal devices).

In order to study the behaviour of RTDs and their applicability to low power hybrid oscillators for use in global positioning and personal communications systems, a variety of RTDs have been fabricated at the Communications Research Center (CRC) and carefully characterized. Several of these devices were installed in simple hybrid oscillator circuits. The behaviour of these circuits and the RTDs inside was studied under various bias and temperature conditions.

Chapter 2 describes the basic device theory and structure of the RTDs. Chapter 3 is devoted to an evaluation of the dc characteristics of the RTDs, while Chapter 4 deals with the RF characteristics. The behaviour of the oscillator circuits is analyzed in Chapter 5, and conclusions are given in Chapter 6. Appendix A deals with the quantum mechanics of the devices, and Appendix B explains RTD bistability and its effects.

2. Device Theory and Structure

It is possible to use a device as a 'black box' when designing circuits, considering only the measured device characteristics, without any understanding of how it works. A basic understanding of the physics and structure of the devices will however give insight into the observed characteristics and facilitate the interpretation of the results. It will also allow for a better understanding of the performance of both the devices and circuits and how they could be improved.

2.1 Device Theory

At the heart of the RTD is a potential well (quantum well) formed by two or more closely spaced barriers (usually no more than 100 Å apart), made of a semiconducting material with a wider band gap. The wider band gap means that electrons need more energy in order to occupy states in the conduction band (i.e. the potential in the barriers is higher). Because of this, electrons with lower energy than the barrier potential are confined between the barriers (i.e. in the quantum well). According to quantum mechanics, tightly confined particles may only take on certain distinct energy levels or bound states, as shown in Figure 2.1a (Appendix A1). These bound states are labelled as E_0 , E_1 , E_2 , ... (first bound state, second bound state, third bound state etc).

Figure 2.1 The structure and characteristics of an RTD

While some electrons may have enough energy to overcome the barriers, especially at high bias and/or temperature, the vast bulk will not. The electrons with an energy lower than the barrier potential do however have the possibility of tunnelling through a barrier. When a slight voltage is applied across the quantum well, electrons will tunnel through the barriers, resulting in a small net current through the device¹. As the applied voltage is increased, the probability of an electron tunnelling through the barriers increases exponentially, as does the net current through the device.

As the voltage across the double barrier structure lines up with one of the bound state energies inside the well (see Figure 2.1b), electrons tunnelling into the well will have the exact amount of energy required to occupy the bound state. As a result, the probability of an electron tunnelling through the double barrier structure is greatly increased, causing a significant increase in current. This condition is known as resonance.

If the applied voltage is increased beyond the resonance point, the electron energy in the well will no longer correspond to the bound state and the tunnelling probability will drop, reducing the current through the device (see Figure 2.1c). This reduction in current causes the NDR region at a voltage just above the resonance, which allows the device to be used as an RF or microwave source.

¹ The amount of current due to electrons tunnelling through the device when it is not at resonance is small. Most of the current seen on actual I-V curves in this region may be due to leakage current from surface conduction.

If the device were perfect (i.e. would have a perfectly uniform well width, with no resistances in the contacts, no surface leakage current or any other 'imperfections') and all measurements were taken at absolute zero temperature (i.e. there is no thermal distribution of electron energies), there would be a very sharp peak in current at resonance and little current at any other bias. The measurements are however performed at room temperature, where the electrons have a wider distribution of energies due to thermal effects and phonon scattering. This results in a widening of the current peak, a reduction in the PVCRs of the device and an I-V curve as shown in Figure 2.1d.

Any practical device will have some slight variations in well width due to uneven crystal growth, which may add a voltage periodic fine structure (i.e. a regularly spaced series of minor peaks and valleys) to the NDR region [2.1]. There will also be some series resistance due to the surrounding semiconductor material. This will alter the I-V characteristics of the device and may cause a bistability or hysteresis (Section 3.3 and Appendix B). A certain amount of leakage current, due to surface conductance or other effects, will raise the non-resonance current, and thus lower the PVCR. Added to this is the effect of unwanted oscillations, which may start up during measurement and obscure the true shape of the NDR region (Section 3.1).

Because of the symmetry of the quantum well, it will allow current to pass through both ways and the devices work for both positive and negative voltages (Figure

3.1). In fact, it was found that all the devices studied exhibited better dc and RF properties when biased in reverse (see Chapter 3).

2.2 Device structure

The devices were fabricated on double barrier single well substrates, which were grown at BNR by Molecular Beam Epitaxy (MBE). Two different substrates were used, substrate #812 and #814. Their MBE specifications are shown in Figure 2.2 and 2.3.

The actual widths of the quantum well are only 45 Å and 50 Å respectively. The wells are surrounded by two narrow barriers (17 Å and 40 Å respectively) and a wider set of buffer and contact layers (the diagrams are not to scale). The purpose of the buffer layers is to distance the highly doped contact layers from the undoped quantum well. This prevents any of the impurities from migrating into the well during device fabrication. It has also been reported that the inclusion of these buffer or spacer layers can significantly improve the performance of the devices, by reducing ionized impurity scattering [2.2]. The contact layers are used to provide an ohmic contact to the semiconductor material [2.3].

The wafers were processed by a standard MESFET fabrication process. A wet chemical etch was used to isolate the mesa containing the quantum well and to expose the emitter contacts [2.4]. All contacts were defined using a standard Au/Ge/Ni n-type

Figure 2.2 The MBE specifications for substrate #812

Figure 2.3 The MBE specifications for substrate #814

Figure 2.4 The structure of the RTD

contact process, and an airbridge [2.5] was used to access the collector. The device was covered with an Si_3N_4 passivation layer to keep the Al in the barriers from oxidizing and degrading the device performance. A schematic of the device is shown in Figure 2.4 and an electron microscope photograph of the quantum well mesa and the connecting airbridge is shown in Figure 2.5.

A variety of RTD devices with various diode collector areas, geometries and air bridge arrangements have been fabricated at the CRC Microelectronics Facility. Because of the higher capacitances and correspondingly lower cut off frequencies of the larger devices, only the RTDs with the smallest collector areas of $7\text{ }\mu\text{m} \times 7\text{ }\mu\text{m}$ were used for these experiments. A picture of the $7\text{ }\mu\text{m} \times 7\text{ }\mu\text{m}$ device is shown in Figure 2.6. The

Figure 2.5 An electron microscope view of the quantum well mesa and the connecting airbridge

Figure 2.6 The $7\mu\text{m} \times 7\mu\text{m}$ RTD

contact pads shown in Figure 2.6 are designed for on-wafer probing using ground-signal-ground microwave probes with a 150 μm point separation.

The thesis focuses on three RTDs and their performance. The first two devices under study, RTD1 and RTD2, are from the same fabrication run using substrate #814. RTD3 came from a different fabrication run using substrate #812.

3. DC Measurements

Dc measurements on an RTD, give the first indication that the device actually works and displays an NDR region. They also show the location of the current peak and NDR region, as well as other important characteristics of the devices, such as PVCRs and whether or not the device has any bistability (see below).

The I-V characteristics of the RTDs were measured using an HP 4142B dc power source/monitor and a four-point dc probe. A typical scan of the I-V curve for an RTD is shown in Figure 3.1 (RTD2, Substrate #814).

Figure 3.1 The I-V curve of an RTD

The I-V curve in Figure 3.1 shows that the device exhibits a greater PVCR for negative voltages than for positive voltages. This may be caused by the non-symmetric widths of the buffer layers surrounding the well (100 Å and 300 Å for the upper and lower buffer layer respectively) [3.1]. A series diode effect at the buffer and contact layer interfaces and the inherent difference in the areas of the collector and emitter sides of the device mesa may also play a role. As mentioned before, all of the devices examined during these experiments showed better dc and RF properties when biased in reverse (i.e. the contact on top of the quantum well mesa is the cathode and the much larger contact surrounding the mesa is the anode). In order to take advantage of this better performance, only reverse biases were used for these experiments. To keep matters simple and to avoid dealing with inverted I-V curves, it was convenient to adopt the convention of treating the negative values as positive. For the remainder of this thesis, all biases, applied voltages and currents will be expressed as positive numbers.

3.1 RTD1

The dc characterization for RTD1 was performed with the four-point-probe setup described above, using a voltage step size of 1 mV. Both increasing and decreasing voltage sweeps were used in order to investigate any bistability (or hysteresis) in the I-V curve (Appendix B).

Figure 3.2 The I-V curve for RTD1

Figure 3.2 shows the I-V curve for RTD1 to have the current peak at 0.44 volts. The location of the E_0 resonance for this structure was calculated to be at 0.19 volts (Appendix A.3). The results of dc modelling on the I-V curves of the device suggest a series resistance of 2.2Ω (Appendix B), which would shift the peak by only 4 mV. The difference in voltage between the calculated E_0 resonance and the measured current peak may be due to a voltage drop across the contact layer and buffer layer junctions, which act like diode junctions.

The NDR region for RTD1 extends from the current peak at .44 volts to about .64 volts. The plateau at its center is not a true feature of the NDR region, but is associated

with unwanted oscillations [3.2]. The plateau is just a measure of the average current flowing through an oscillating RTD. The true shape of the NDR region is in fact a smooth curve, as indicated by the dotted line in Figure 3.2, which was calculated from the RF measurements for RTD1 and will be discussed in Chapter 4.4. Any hysteresis displayed on the I-V curve is associated with the oscillations rather than the dc characteristics of the device.

3.2 RTD2

In order to avoid the oscillation problems seen above, and to get a more realistic picture of the I-V curve, the dc characterization for RTD2 was performed using a microwave probe. The microwave probe was biased through an HP 11059A bias network, terminated with a $50\ \Omega$ load, which served to prevent any oscillations. Unfortunately this method of measuring the I-V curves could not be used on RTD1, because the device failed (burned out) before this second method was implemented.

RTD2, originating from the same fabrication run and substrate, displays similar I-V characteristics to RTD1. It does however show slightly less current and a lower peak-to-valley current ratio. The NDR region is between 0.4 volts and 0.59 volts and no bistability was detected.

Figure 3.3 The I-V curve for RTD2, measured using a microwave probe

3.3 RTD3

The dc characterization for RTD3 was performed using the method described for RTD2, and the results are displayed in Figure 3.4. The substrate used for this device had narrower well and barrier widths than the previous substrates and the barriers were made of AlAs instead of $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ (Figure 2.2). This resulted in very different I-V characteristics than the ones seen for the other two devices. The radical change in the current peak voltage however, cannot be accounted for by the slightly narrower well

Figure 3.4 The I-V curve for RTD3

width, and the higher potential of the barriers alone². It is a result of the different structure of the well in combination with the differences in the surrounding semiconductor material.

Because of the narrower barriers (17 Å instead of 40 Å), there is more current through the device (i.e. the probability of tunnelling through the double barrier structure is higher). At the same time, there is a higher series resistance associated with the semiconductor material surrounding the device (i.e. contact and buffer layers). Dc

² The resonance level for a symmetric AlAs/GaAs/AlAs well with a width of 45 Å, has been calculated to be at 0.24 V, compared to the 0.18 V resonance calculated for RTD1 and RTD2 (Appendix A.3).

modelling using SPICE suggested a series resistance of about $55\ \Omega$ (Appendix B). A calculation based on the resistivity of GaAs showed this to be a reasonable value for the resistance of the buffer layers³. The $55\ \Omega$ series resistance causes the current peak, which is about 24 mA, to be shifted by about 1.3 volts (according to Ohm's law, $V = IR$).

As mentioned before, the asymmetry of the undoped buffer layers surrounding the well, causes an asymmetry in the I-V curves of the device. The widths of the buffer layers for RTD3 were $100\ \text{\AA}$ on the collector side and $700\ \text{\AA}$ on the emitter side, compared to $100\ \text{\AA}$ and $300\ \text{\AA}$ respectively for the other two devices. This makes the I-V curves for RTD3, shown in Figure 3.5, far more asymmetric than those of the other devices (Figure 3.1 shows the asymmetry for RTD2). The forward current peak for RTD3 is at 1.2 volts and a reverse peak (i.e. the one shown in fig 3.4) is at 2.7 volts.

The combined effects of the higher current through the device, the higher series resistance, the asymmetry in the I-V curves (caused by the asymmetric buffer layers) and the voltage drops across the buffer layer and contact layer junctions (acting like diode junctions) may explain the rather large voltage offset observed for the current peak of RTD3.

³ Based on an impurity concentration between 10^{14} and 10^{15} for undoped GaAs, where the resistivity ranges from $10\ \Omega\text{-cm}$ to $1\ \Omega\text{-cm}$ [3.3], the resistance of the buffer layers lies somewhere between $11\ \Omega$ and $110\ \Omega$. The doping concentration of the other semiconductor material surrounding the well is much higher, and the other layers would therefore not contribute significantly to the series resistance.

Figure 3.5 The full, highly antisymmetric I-V curve for RTD3.

Figure 3.6 The NDR region of RTD3

The high series resistance of the device also results in a bistability [3.4, 3.5] or hysteresis (Appendix B) which gives the device two possible current states at certain bias points, one high current state on the increasing bias trace, and one low current state on the decreasing bias trace. Figure 3.6 shows the NDR region and bistability of the device in greater detail. Only the low current state exhibits any negative differential resistance. In order to bias this device in the NDR region, the bias must first be raised above 2.7 volts and then decreased. If the voltage is decreased below a certain limit, the device will be set into its stable, high current state outside the NDR region. This condition will persist until the voltage is again increased above 2.7 volts. Any oscillations with a sufficiently large amplitude could momentarily force the voltage below this limit, and thus set the device to its high current state.

As the voltage (Figure 3.6) dropped below 2.55 volts, the device shifted to its high current state. This may have been due to unwanted oscillations starting up even in the 50 Ω environment. Microwave measurements (Chapter 4.4) have shown that the NDR region extends down to at least 2.42 volts before this shift occurs. Note that the shift between the high and low current states is extremely fast, and has been measured to occur within 2 picoseconds for AlAs/GaAs/AlAs RTDs [3.6].

3.4 Temperature Effects

So far, the I-V curves for the various devices have only been examined at room temperature, without taking variations of the ambient temperature into account. For RTDs installed in oscillator circuits however, the ambient temperature will vary, and it is important to examine the effects of temperature variations on the devices. The following measurements were taken after the devices were installed in the oscillator circuits. The circuits were placed inside a thermal chamber and the I-V curves were measured at the bias input for the device. Since no attempts were made to suppress or control the circuit oscillations, the NDR regions of the devices were obscured, but all other regions of the I-V curves, including the current peaks and valleys were shown clearly (Figure 3.7).

Figure 3.7 The effects of temperature variations on the I-V curves for RTD2

Figure 3.7 shows the I-V curves for RTD2 at various temperatures ranging from 25°C to 100°C. The graph shows an increase in current at higher temperatures. This may be caused by the greater electron-phonon interaction and the increased effect of ionized impurities at higher temperatures [3.7].

The voltage at which the current peak occurs remains constant, since it is determined by the width and depth of the well, neither of which change enough to significantly effect the current peak⁴. It is possible for the current peak to be shifted by an change in series resistance with temperature, which would also affect the hysteresis [3.5]. This however was not observed during these measurements (Figure 3.7 and 3.8).

The location of the current valley on the other hand, moves closer to the current peak with increasing temperature, effectively narrowing the NDR region and reducing the PVCR. This is a result of an increase in non-resonant-tunnelling current at higher temperatures (due to leakage, phonon-electron interaction, etc), which is responsible for most of the current outside the current peak.

⁴ The thermal expansion coefficient of GaAs is 6.86×10^{-6} [3.8], which would change the well width by less than 1/1000 over 100 °C. This is insignificant compared to the natural variations in well width due to uneven MBE growth.

The variations in barrier height (ie. 0.6 times the difference in bandgap see appendix A3) are less than 3% between the values reported for room temperature and those reported for low (ie liquid He) temperatures [3.9]. The change in the resonance voltages resulting from this shift (over almost 300 K) is not significant enough to show up during the I-V curve measurements.

Figure 3.8 The effects of temperature variations on the I-V curves RTD3

Because these measurements were taken with the devices installed in their respective oscillator circuits (Chapter 5), the plateaus in the NDR region do not indicate unwanted oscillations but actual circuit oscillation. The narrowing of the plateaus at higher temperatures thus indicates narrowing of the bias range over which the circuit will oscillate.

Figure 3.8 shows a similar experiment done for RTD3. It shows a decrease in the PVCR at higher temperatures, while the location of the current peak does not change. Aside from that, no new information can be obtained from these measurements, as both

the current valley and the entire NDR region are masked by oscillations and bistability. The fact that the drop in PVCR is far less significant than that observed for RTD2 may indicate that the oscillator circuit built around RTD3 should be less affected by temperature than those built around the other RTDs.

4. RF Measurements

In order to determine how a device will perform in an oscillator circuit, its RF characteristics must be measured. These measurements indicate how the device behaves with respect to high frequency and microwave signals. This information can be used to determine characteristics like the capacitance and inductance of the devices, as well as its maximum oscillating frequency. Because of this, RF measurements are not only important in the selection of devices for the oscillator circuits, but also to gain a better understanding of the device behaviour.

In order to measure the high frequency response of the RTDs, Scattering Parameter (S-parameter) measurements were performed using a microwave network analyzer. A network analyzer works by sending a stimulus signal at a given frequency into the device under test (DUT), and measuring the relative magnitude and phase of the reflected (or transmitted) signal. For a typical 2 port network analyzer, there are two input signals (sent into the DUT) and two output signals (received from the DUT). The configuration of input signals (a_1 and a_2) and output signals (b_1 and b_2) as well as the S-parameters which result from these signals is shown in Figure 4.1 [4.1]. For a single port device, such as an RTD, only the S_{11} parameter, which is a measurement of the b_1 reflected signal relative to the a_1 input signal, is applicable, since there are no transmitted signals.

Figure 4.1 The configuration of input signals, output signals and S-parameters

4.1 Setting up the measurements

The S_{11} parameter measurements for the RTDs were performed using an HP 8510 Network Analyzer in conjunction with a Cascade probe station. After careful calibration, which allows the network analyzer to automatically account for the effects of the probes, cables and other attachments, the ground-signal-ground probe was applied directly to the contact pads on the device. The bias was applied to the device by an HP 6114A precision power supply connected to the probe via the internal biasing network of the network analyzer test set.

The measurements were performed by letting the network analyzer sweep the stimulus signal (set to a power of about -45 dBm at the probehead) from 1 GHz to 20 GHz (1 GHz to 40 GHz for RTD3) and measuring the S-parameters. The results were acquired and stored on a Personal Computer (PC) connected to the network analyzer via

a GPIB interface. Measurements were taken at a range of bias settings throughout the NDR region of the device.

These measurements were performed on the RTDs after they had been mounted in their respective oscillator circuits, but without any electrical connections. This gave a better picture of how the devices work in the circuit environment (i.e. mounted on alumina rather than as part of a wafer).

4.2 RTD1

The S11 parameters for RTD1 were measured for bias settings from 440 mV to 620 mV⁵ in steps of 10 mV. The relative magnitude and phase of the S11 measurements for RTD1 are shown in Figure 4.2 and 4.3 respectively. The gain, as indicated by the S11 magnitudes above 0 dB, is caused by the NDR of the device at these bias levels. There is a sharp rise in the S11 magnitude up to a bias of 480 mV and the gradual decline thereafter. This corresponds to the changes in the slope of the NDR region, which is at its steepest at 480 mV. The phase angle greatly decreases (it is negative) with frequency, but it is also affected by the bias. It decreases sharply up to 480 mV, where the device shows its maximum S11 magnitude (gain).

⁵ This was the bias range over which gain (ie. S11 magnitudes greater than 0 dB) could be observed. It encompasses most of the NDR region.

Figure 4.2 The relative S11 magnitude for RTD1

Figure 4.3 The relative S11 phase angle for RTD1

4.3 RTD2

S11 measurements for RTD2 were performed for bias settings throughout the NDR region, ranging 400 mV to 600 mV, with a voltage step of 5 mV. The relative magnitude and phase of the measurements are shown in Figure 4.4 and 4.5 respectively. The results are similar to those obtained for RTD1, but the device shows slightly lower gain and higher relative phase angles. Its peak S11 magnitude and lowest phase angle occur at 440 mV.

4.4 RTD3

Because of the bistability and oscillation problems associated with RTD3 (Chapter 3.3), a Wiltron K250 bias tee, attached directly to the probe, was used to supply the bias to the device. This served to minimize the oscillations and allowed S11 measurements to be taken at lower biases (i.e. closer to the critical limit below which the device shifts to its high current state). After lowering the bias from above 3 volts to 2.7 volts (because of the bistability discussed in Chapter 3.3), the bias was lowered in steps of 10 mV and the S-parameters were measured at each step. The results are shown in Figure 4.6 and 4.7.

As the applied voltage dropped below 2.54 volts, oscillations started up at certain points throughout the frequency sweep. Apparently, the system (i.e. the device with the probe and associated circuitry) was unstable at these frequencies, and the stimulus signal from the network analyzer was sufficient to start oscillations. These oscillations caused

Figure 4.4 The relative S11 magnitude for RTD2

Figure 4.5 The relative S11 phase angle for RTD2

Figure 4.6 The relative S11 magnitude for RTD3

Figure 4.7 The relative S11 phase angle for RTD3

the device to jump to its high current state outside the NDR region. It had to be manually reset by momentarily increasing the applied voltage above 3 volts, while the sweep continued. This left gaps in the measured data, which were later filled in by interpolation (indicated by the dotted lines in Figure 4.6 and 4.7).

The S11 measurements show that the NDR region of the device extends down to at least 2.42 volts, rather than 2.55 volts as seen on the I-V curve in Chapter 3.3. This indicates, that oscillations may have started up during the I-V measurements at 2.54 volts. These oscillations would have forced the device into its high current state. The network analyzer and attachments (i.e. the probes, cables, bias networks, etc), were specifically designed to reduce unwanted oscillations, which would greatly interfere with the measurements.

4.5 Small Signal Parameter Extraction

Small signal models use linear circuit elements, such as resistors, capacitors and inductors to approximate the behaviour of a device over a narrow range of input and bias conditions (i.e. the ranges over which the linear approximation is valid). If these conditions change significantly, the model parameters (i.e. the values for the various linear elements) may no longer be valid, and a new set of parameters must be found. These parameters and their change with bias and environmental conditions can reveal a lot about the device under study.

A model frequently used for RTD small signal analysis is the tunnel diode model [4.2, 4.3, 4.4] consisting of a resistance, which becomes negative in the NDR region, a parallel capacitor, and a series inductor and resistor.

A commercial simulation and optimization package, OSA90/hope, was used to find the parameters for the small signal tunnel diode model, which would most closely approximate the observed S11 behaviour of the RTDs⁶. It was found that the series inductance of the tunnel diode model was not necessary and that the device behaviour could be described by just 3 parameters (Figure 4.8).

Figure 4.8 The small signal model used for RTD parameter extraction

⁶ OSA90/hope allows the user to enter a circuit model with variable parameters (such as resistances, capacitances and even parameters for non linear elements such as transistors or user-defined current sources). It can be set up to automatically vary and optimize these parameters so that the model behaviour meets user defined specifications, such as a close approximation to the measured data. In this case the model entered into OSA90/hope was the small signal tunnel diode model, and the specification was set to match the model results to the measured S11 data (at various biases) as closely as possible.

R_d - parallel resistance of diode (negative in the NDR region)

C_d - parallel capacitance of diode

R_s - series resistance of the diode

The Values for these are shown in Table 4.1, 4.2 and 4.3.

Bias (V)	R_s (Ω)	R_d (Ω)	C_d (fF)
0.44	4.6	-483	94
0.46	3.2	-181	100
0.48	2.6	-149	102
0.50	2.6	-155	100
0.52	2.8	-179	98
0.54	3.1	-217	97
0.56	3.5	-281	95
0.58	3.9	-400	93
0.60	4.4	-689	92
0.62	4.8	-2524	91

Table 4.1 The extracted small circuit parameters for RTD1

Bias (V)	R_s (Ω)	R_d (Ω)	C_d (fF)
0.40	11.0	12238	118
0.42	9.0	-234	123
0.44	8.6	-166	124
0.46	9.1	-179	122
0.48	9.5	-219	120
0.50	9.9	-280	119
0.52	10.2	-369	118
0.54	10.4	-515	117
0.56	10.7	-855	117
0.58	11.0	-3070	117

Table 4.2 The extracted small circuit parameters for RTD2

Bias (V)	R_s (Ω)	R_d (Ω)	C_d (fF)
2.42	19.6	-102	77
2.45	20.6	-126	71
2.48	17.5	-158	70
2.51	16.7	-199	68
2.54	15.3	-252	67
2.57	13.8	-334	66
2.60	12.6	-463	64
2.63	11.6	-692	63
2.66	10.6	-1234	63
2.69	9.9	-3910	61

Table 4.3 The extracted small circuit parameters for RTD3

The tables indicate a rise in parallel capacitance (C_d) and a fall in series resistance (R_s) for decreasing negative resistances (R_d). The parallel capacitances and series resistances are comparable for RTD1 and RTD2, but are quite different for RTD3, which was expected because of the different structure and fabrication run for RTD3.

The value for R_s is a parameter extracted for a small signal model and does not coincide with the value for the series resistance found from the dc analysis of the device (2.2 Ω , 3.1 Ω , and 55 Ω for RTD1, RTD2 and RTD3 respectively).

The complex impedance of the device (as a function of frequency) may be calculated from the small signal model parameters.

$$\begin{aligned}
 Z_d &= R_s - \frac{R_d}{1 - j\omega C_d R_d} \\
 &= R_s - \frac{R_d}{1 + \omega^2 C_d^2 R_d^2} - \frac{j\omega C_d R_d}{1 + \omega^2 C_d^2 R_d^2}
 \end{aligned} \tag{4.1}$$

where ω = angular frequency in radians per second

The complex impedance is related to the S11 parameter (reflection coefficient) by

$$\Gamma = \frac{Z_d - Z_0}{Z_d + Z_0} \tag{4.2}$$

where Γ = reflection coefficient (S11 parameter)
 $Z_0 = 50\Omega$

and can be used to fill in any gaps left in the S11 measurements by unwanted oscillations or bistability.

The complex impedance may also be used to estimate the maximum oscillating frequency of the devices. Equation 4.1 shows that the real part of the impedance goes to zero when

$$R_s = -\frac{R_d}{1 + \omega^2 C_d^2 R_d^2} \tag{4.3}$$

from which the maximum oscillation frequency may be calculated to be

$$f_{\max} = \frac{\sqrt{\frac{-R_d}{R_s} - 1}}{2\pi C_d R_d} \tag{4.4}$$

This results in the following maximum oscillation frequencies:

RTD1: 78 GHz at 0.48 volts

RTD2: 33 GHz at 0.44 volts

RTD3: 40 GHz at 2.45 volts

These values do however extrapolate the model results to frequency ranges for which no actual S11 parameters were measured, and may therefore be considered as estimates only.

A detailed and theoretical analysis of RTDs, using a more complicated equivalent circuit model has been performed by Buot and Rajagopal [4.5]. The capacitance of RTDs has been the subject of much debate, and has been calculated from both theoretical models [4.6, 4.7] and experimental observations [4.3].

The variations in both parallel capacitance (C_d) and series resistance (R_s) are one of the major hurdles in creating an accurate large signal model for the device, which will be necessary if RTDs are to be used as devices in large circuits (i.e. logic applications and memory cells). It is relatively easy to accurately describe the dc characteristics using a combination of a diode, a gaussian (or near gaussian) current source, and a series resistance [4.8]. Modelling the capacitance of the devices is more difficult.

The total resistance of the diode is $R_d + R_s$. The inverse of this value is the conductivity of the device, which is the slope of the I-V curve. By (numerically) integrating the conductivity over a given voltage range, it is possible to fill in any

'blanks' left in the I-V curves due to oscillations or other effects. This method was used to approximate the true shape of the I-V curve for RTD1 (dotted line in Figure 3.2).

5. RTD Oscillators

In order to study the properties of RTD oscillators as microwave sources for low power communications applications, three simple hybrid oscillator circuits were built using the devices characterized in Chapters 3 and 4. Table 5.1 lists the devices along with the oscillation frequency of the circuits they were installed in. The circuits were analyzed in terms of output power spectrum, frequency stability as well as frequency dependence on ambient temperature and dc bias.

Device used	Oscillation frequency	Section
RTD1	1.77 GHz	5.4
RTD2	16 GHz	5.5
RTD3	37 GHz	5.6

Table 5.1 The three oscillator circuits

5.1 Principles of oscillator operation

For an NDR device, such as an RTD, oscillations occur when part of the RF output is fed back to the device. The NDR causes the feedback signal to be amplified and

sent out again. The amount of amplification is given by the reflection coefficient of the device Γ_d , which is equivalent to the S11 parameter. The conditions for oscillation are:

$$\begin{aligned} |\Gamma_f| |\Gamma_d| &= 1 \\ \angle \Gamma_f + \angle \Gamma_d &= 2\pi n \quad n = 0, 1, 2, \dots \end{aligned} \tag{5.1}$$

where $|\Gamma_d|$ = magnitude of device reflection coefficient ($S11_{RTD}$)
 $\angle \Gamma_d$ = angle of device reflection coefficient
 $|\Gamma_f|$ = magnitude of feedback reflection coefficient
 $\angle \Gamma_f$ = angle of feedback reflection coefficient

In other words, the amount of amplification must be sufficient to overcome any power lost in the feed-back loop (including the power used as output), and the phase delay around the loop must be a multiple of 360°.

5.2 Circuit Design and Construction

Because the oscillator circuits did not need to meet any specific design specifications (other than having a microwave output which could be fed into a spectrum analyzer), the design could be kept as simple as possible, without the need for extensive modelling, simulation and re-iterative circuit design and construction.

The circuit (Figure 5.1) was built on a 0.010" alumina substrate. The back side of the substrate was metallized with about 500 Å of titanium - tungsten (Ti-W) and 1 µm of gold (Au). The same metallization was used to create a 50 Ω transmission line (0.010"

Figure 5.1 The simple hybrid oscillator circuit

wide) on the top surface of the alumina. One end of the transmission line was left open ended in order to reflect the signal back to the device, which was connected to the transmission line via a 100 pF capacitor and a set of bond wires. The capacitor acted as a block for the dc bias of the device, in order to keep it away from the output port, which consisted of a K-connector on the other end of the transmission line. The dc bias for the RTD was provided via a filtercon (i.e. an RF choke), which separated the power supply from the RF. The device was grounded through a hole, drilled through the alumina using a sonic drill, to the brass carrier, on which the entire circuit was mounted. The open ended transmission line could be shortened to any desired length by using a diamond tipped grinder, which allowed the circuit to be tuned. Figure 5.2 shows a photograph of the 1.77 GHz oscillator circuit (Chapter 5.4).

Figure 5.2 The 1.77 GHz oscillator circuit.

5.3 Oscillator measurement procedure

The bias for the circuits was provided by an HP 6114A precision power supply, and their RF output was fed into an HP 8569A Spectrum analyzer. A Personal Computer (PC) was hooked up to the spectrum analyzer via a GPIB interface, allowing for

automatic acquisition and storage of the measured data⁷. An HP 3478A digital multimeter was also attached to the PC, which allowed for automatic acquisition bias applied to the circuit and the ambient temperature (using a thermocouple).

The first measurement performed on the oscillator circuits was a scan of the frequency spectrum between 10 MHz and 22 GHz⁸. This showed at which frequencies and under which bias conditions the circuit oscillated. Next, the device was placed into a thermal chamber and its output was measured under varying thermal and bias conditions. In each case, the trace data was stored along with the applied bias, and ambient temperature.

In order to estimate the short term stability of the circuits, the instruments were set up to automatically take measurements at regular time intervals ranging from 1 to 5 seconds. The data was stored along with the time of measurement. One problem was that, although the spectrum analyzer could be read and triggered by the computer, its settings, such as center frequency, range and bandwidth, could not be adjusted by GPIB. Thus it was not possible to automatically track the oscillation frequency as it drifted (due to

⁷ The trace data from the spectrum analyzer was read and stored as a string of 480 binary values (2 bytes each), reflecting the position of the trace on the spectrum analyzer screen. This data, along with the header, which included information about center frequency, scales, and reference power. This information could later be used to calculate the actual frequency - power spectra.

⁸ The 37 GHz oscillator was connected to the spectrum analyzer via an HP 11517A external mixer. With this external mixer, the range of the Spectrum analyzer becomes 22.9 to 40 GHz.

changes in temperature for example). The analyzer could either be set to monitor a wide frequency window, resulting in a poor resolution, or it could be set to monitor a narrow frequency window, in which case a slight frequency drift would place the oscillation frequency outside the window. It was necessary to find a compromise, set up the spectrum analyzer accordingly, and measure only over short time spans in order to avoid problems with drift (i.e. 500 measurements 5 seconds apart was too long).

A long term stability measurement was done for the 37 GHz oscillator. In this case, the experiment was set up to automatically take measurements at half hour intervals for 40 days⁹. The ambient temperature of the oscillator was recorded with each measurement, and could later be used to compensate the observed frequency drift for any change in temperature, based on the already observed temperature dependence of the output signal. Unfortunately, it was not possible to repeat this procedure for the other circuits due to limited availability of the spectrum analyzer.

5.4 The 1.77 GHz Oscillator

RTD1 was used as the active device in the first oscillator circuit (shown in Figure 5.2). The output power spectrum of this circuit (Figure 5.3), shows a fundamental oscillation at 1.77 GHz and 3 harmonics at 3.45 GHz, 5.16 GHz and 6.89 GHz.

⁹ The spectrum analyzer was set up to monitor a 50 MHz wide frequency window. This resulted in a resolution of 100 kHz or about 3 ppm.

Figure 5.3 The output spectrum of the 1.77 GHz oscillator

Focusing on the fundamental peak, the bias was adjusted in order to produce the strongest and narrowest oscillation peak possible. This occurred at a dc bias of 0.541 volts, and resulted in an oscillation at 1.7707 GHz with an output strength of -18 dBm.

Slight variations in the bias of the device resulted in a frequency drift as displayed in Figure 5.4. The highest frequency was achieved at 0.541 volts, which also resulted in the narrowest oscillation peak. This was also the bias at which the circuit was found to be most stable. At this bias setting, any slight variations in dc bias will have a minimal effect on the output frequency (i.e. the change in frequency with bias is 0).

Figure 5.4 The variations in oscillation frequency with bias

Figure 5.5 The frequency dependence on temperature

The results of an investigation into the changes in oscillation frequency with temperature are displayed in Figure 5.5. In the range of 5 °C to 45 °C (i.e. near room temperature), a nearly linear relationship with a slope of 0.314 MHz/°C (176 ppm/°C) is observed. It is interesting to see that the frequency actually increases with temperature, rather than decreases, as it does for most non-temperature-compensated hybrid oscillators [5.1].

Figure 5.6 shows the frequency fluctuations (in ppm) observed at room temperature and a bias of 0.541 volts dc over time intervals ranging from 0.3 to 4 seconds at room temperature. There seems very little difference between the fluctuations over 0.3 seconds and those over 4 seconds (other than the fact that there are more data points at 0.3 seconds). This suggests that the time frame over which these fluctuations occur, is shorter than the 0.3 seconds (the smallest interval over which the spectrum analyzer could sample the spectrum and output the results to the PC). A possible source for these fluctuations is 60 Hz noise. Notice that higher frequency noise (FM noise) and random noise would show up as a broadening of the spectral peak, rather than a fluctuation in the peak frequency [5.2]. From the data in Figure 5.6 the maximum fluctuation (short term stability) of about 4 ppm.

Figure 5.6 Short term frequency fluctuations observed over various time intervals

5.5 The 16 GHz Oscillator

RTD2 was used as the active device for this circuit. The RTD was directly connected to the open ended transmission line, without the coupling capacitor shown in Figure 5.1. Although the omission of the capacitor necessitated the use of an external dc block at the output port, in order to isolate the spectrum analyzer from the dc bias, it was thought that this would make the circuit simpler, with fewer components to be considered in the analysis. When the circuit was biased at 0.5 volts, the output power spectrum (Figure 5.7) showed just a single peak at 16 GHz.

Figure 5.7 The output spectrum of the 16 GHz oscillator circuit

Figure 5.8 The output frequency variations for the 16 GHz oscillator

In order to gain a better understanding of the effects of temperature and voltage on the output of the circuit, the effects of bias variations were observed at ambient temperatures ranging from $-30\text{ }^{\circ}\text{C}$ to $90\text{ }^{\circ}\text{C}$ (Figure 5.8). This could not be done for the 1.77 GHz circuit because the device failed before these measurements were set up. Several interesting results could be observed.

1) The bias range over which the oscillations occur, decreases with temperature. Oscillations always start at a bias of about 0.415 volts, which is just inside the NDR region of the device (the current peak is at 0.40 volts). The bias point at which the oscillations stop however decreases with increasing temperature. This is a result of the narrowing of the NDR region at higher temperatures, discussed in Chapter 3.4.

2) The frequency does not vary continuously with bias. Several jumps in the frequency are observed. These jumps occur, at the same frequencies (more or less), regardless of bias or temperature. It should be noted that these jumps are not instantaneous jumps from one frequency to another as the bias crosses some threshold. The oscillations actually stop as the bias is raised above the threshold and then resume at a higher frequency when the bias is increased further (Figure 5.8 does not show this). These jumps may be related to the cables and the bias network connected to the circuit output since their period (70 MHz corresponding to a wavelength of 4 m in air) suggests it is caused by something larger than the circuit dimensions would allow. The total length of cable attached to the circuit corresponded to about $1/2$ wavelength at 70 MHz.

Figure 5.9 The frequency variations with temperature at low biases

3) The frequency drift with temperature, is dependant on the bias: At low biases it is positive and it becomes negative with increasing bias. This is shown more clearly in Figure 5.9, which displays the frequency of oscillation as a function of temperature for various biases ranging from 0.415 volts to 0.445 volts. At a bias of 0.415 volts the oscillation frequency increases with temperature, while at 0.445 volts there is a definite decrease. This trend continues as the bias is increased further (Figure 5.8). At a bias of 0.428 volts, where there are no jumps over the temperature range from -30 °C to 90 °C, the frequency decreases by 0.19 MHz/°C (-12 ppm/°C) while at 0.424 volts the decrease is only 37 kHz/°C (-2.3 ppm/°C) over temperature range from 10 °C to 60 °C. A temperature dependence of near zero ppm/°C (from 30 °C to 60 °C) is achieved at a bias

of 0.420 volts. The reason for this change in temperature dependence may be that the NDR region is less affected by increasing temperatures near the current peak, than it is at higher biases (Section 3.4).

An examination of the short term stability of the circuit showed results similar to those observed for the 1.77 GHz oscillator. A plot of the frequency fluctuations over a variety of time intervals (Figure 5.10) showed a maximum observed fluctuation of 5 ppm/s.

Figure 5.10 The short term stability for the 16 GHz oscillator circuit

Figure 5.11 The output spectrum of the 37 GHz oscillator

5.6 The 37 GHz Oscillator

The 37 GHz oscillator uses RTD3 as its active device. Because its output frequency was above 22 GHz, the output signal was fed into the spectrum analyzer through an HP 11517A external mixer, which extends the range of the instrument from 40 GHz. After some experimentation and tuning of the transmission line's length, the circuit produced the power output spectrum shown in Figure 5.11 (at room temperature and a dc bias of 2.50 volts).

When an external mixer is used, a number of 'ghost peaks' will appear on the output trace. These peaks are not produced by the oscillator circuit, but are the result of harmonics generated by the mixer. When the internal mixers are used, these peaks are automatically eliminated by the spectrum analyzer's preselector circuit. This circuit is bypassed when external mixers are used, and the oscillation peaks must be identified manually. The spectrum analyzer provides an identification function, which may be used to do this. The 37 GHz peak was identified as an actual oscillation peak.

The circuit was placed inside a thermal chamber and, focusing on the oscillation peak observed at 37 GHz, the bias was adjusted to maximize the output power (about -25 dBm at 2.52 volts and room temperature). The output was now measured as a function of temperature and bias. The results (Figure 5.12) show a steady increase in the oscillation frequency with both bias and temperature. An analysis of the frequency dependence on temperature at 2.50 volts showed an increase of $0.784 \text{ MHz}/^{\circ}\text{C}$, or about $21 \text{ ppm}/^{\circ}\text{C}$ (Figure 5.13), and a drop in the output power of $.076 \text{ dB}/^{\circ}\text{C}$ (Figure 5.14).

The short term (1 to 3 sec) fluctuations in output frequency are shown in Figure 5.15. The results indicate a maximum fluctuation of 5 ppm/s . The results of a long term observation of the oscillation frequency over 40 days are shown in Figure 5.16. The long term stability, observed as a gradual frequency drift over several days, was estimated to be 10 MHz or 270 ppm , while a medium term stability, observed as several spikes lasting a few hours, was found to be 7 MHz or about 200 ppm .

Figure 5.12 Output frequency variations of the 37 GHz oscillator

Figure 5.13 Output frequency variations with temperature at 2.5 V

Figure 5.14 Output power variations with temperature at 2.5 V

Figure 5.15 The frequency fluctuations for the 37 GHz oscillator

Figure 5.16 The long term frequency stability over 40 days

5.7 Discussion

The performances of the three oscillator circuits are summarized in Table 5.2.

Active Device	Oscillation Frequency	Output Power	Frequency Stability	
			Temperature	Short Term
RTD1	1.77 GHz	-18 dBm (16 μ W)	176 ppm/ $^{\circ}$ C	4 ppn/s
RTD2	16 GHz	-42 dBm (60 nW)	12 ppm/ $^{\circ}$ C (varies)	5 ppm/s
RTD3	37 GHz	-25 dBm (3.2 μ W)	21 ppm/ $^{\circ}$ C	5 ppm/s

Table 5.2 The performance of the three oscillator circuits

The use of RTDs as active devices in low power oscillator circuits seems to be limited mainly by the available output power. Careful oscillator design, including proper load matching and better resonant cavities (with high Q factors) can improve these values, but ultimately it all depends on the active device. Output powers of 60 μW at 56 GHz have been reported for AlAs/GaAs/AlAs RTDs [5.3]. RTDs made of other materials, such as InAs/AlSb have been reported with powers up to 50 times those of AlAs/GaAs RTDs [5.4], and may improve the performance further.

The available RF power greatly decreases with increasing frequency due to the capacitance associated with the devices (Chapter 4.4) [5.5]. In order to produce RTD oscillator circuits with higher output powers and frequencies, devices with low capacitances, high PVCRs and low series resistances are needed (see equation 4.4). RTD3 for example had a high PVCR, and a relatively low capacitance (resulting in a high frequency) but the high series resistance reduced the output power, as a large part of the output RF power was dissipated by the series resistance.

The output frequency variations with temperature, was 176 ppm/ $^{\circ}\text{C}$ for the 1.77 GHz oscillator, 21 ppm/ $^{\circ}\text{C}$ for the 37 GHz oscillator and varied with bias for the 16 GHz oscillator. While this variation in temperature coefficient with bias was only observed for the 16 GHz oscillator, there is no reason that a similar effect should not be present in the 1.77 GHz oscillator (it was not observed because the device failed before the necessary measurements were performed). It did not occur for the 37 GHz oscillator because of the

bistability of the device, which caused the section of the NDR region near the current peak (i.e. where this effect would be most pronounced) to be inaccessible.

The temperature stability of the circuits could be improved by including temperature compensating elements, such as dielectric resonators (DRs) [5.6, 5.7] into the circuit design. DRs are commercially available with a variety of temperature coefficients, which may be used to counteract the temperature drift of the circuit¹⁰. For comparison, Table 5.3 gives some recent accomplishments for microwave oscillators using DRs as resonant cavities (with temperature compensation).

Active Device	Output Frequency	Output Power	Temperature stability	Reference
Bipolar Transistor	2.65 GHz	> 20 mW	1.8 ppm / °C	[5.8]
Gunn Diode	5.5 GHz	> 3 W	NA	[5.9]
GaAs FET	9.46 GHz	26 mW	0.8 ppm / °C	[5.10]
GaAs FET	36 GHz	> 10 mW	1 ppm / °C	[5.11]
Gunn Diode	93 GHz	30 mW	NA	[5.12]
Gunn Diode	93.8 GHz	40 mW	NA	[5.13]

Table 5.3 Recent oscillator achievements

¹⁰ Dielectric resonators are frequently used as resonant cavities for applications such as microwave oscillators or filters. They are available in a variety of temperature coefficients, which may be used to counteract any temperature drift found in the circuit.

It should be noted, that three terminal devices such as field effect transistors (FETs) will usually have a higher stability than two terminal devices, like RTDs and Gunn diodes, which are greatly affected by changes in bias. The reported values are also for circuits which were specifically designed for temperature stability, it was not possible to find temperature stability data on non-temperature-compensated oscillators. Even so, the temperature stability of the 16 GHz oscillator could be adjusted to obtain values which were comparable, but only over a temperature range of about 30 °C, rather than over the 100 °C range over which the values in Table 5.3 were measured.

If RTD oscillator circuits are to be used as oscillators for personal communications however, it is necessary to improve the temperature stability even further by using phase locking. Since all three circuits could be tuned by adjusting the bias (Figure 5.4, Figure 5.8 and Figure 5.12), it should be possible to use such circuits as voltage controlled oscillators (VCOs) in a phase locked loop (PLL). This technique would greatly improve the temperature stability as well as the short, medium and long term stabilities of the oscillators.

6. Conclusion

6.1 Summary and Conclusions

A variety of AlGaAs/GaAs/AlGaAs RTDs have been fabricated at CRC. Three of these devices were studied, both as discrete devices and integrated in simple hybrid oscillator circuits.

The dc characterization of the devices was initially hindered by the occurrence of unwanted oscillations starting up during the measurement. This problem was avoided by using a microwave probe instead of a regular dc probe. One of the devices (RTD3) was found to exhibit a considerable bistability, which meant that biasing the RTD in the NDR region required taking the device through a hysteresis loop first. An analysis of the temperature effects on the I-V curves showed a narrowing of the NDR region and a decrease in the PVCRs at higher temperatures for all 3 RTDs.

The RF measurements of the devices showed that both the magnitude and the phase of the S11 parameters were strongly affected by the bias. Small signal parameter extraction showed a considerable bias dependent variation in the capacitance and negative resistance of the devices. These variations allowed the output frequency of the oscillator circuits to be tuned by adjusting the bias, which would allow the use of phase locking techniques to stabilize the oscillations.

Under the right bias conditions, the RTDs were found to oscillate readily. These oscillations could be controlled by a very simple hybrid circuit, consisting of no more than an open ended transmission line and an output port. Three such simple hybrid oscillator circuits were built using the characterized RTDs. They were found to oscillate at 1.77 GHz (60 μ W), 16 GHz (60 nW) and 37 GHz (3.2 μ W).

All three circuits displayed a short term frequency stability of about 5 ppm/s. The temperature drift was found to be 176 ppm/ $^{\circ}$ C for the 1.77 GHz oscillator, and about 21 ppm/ $^{\circ}$ C for the 37 GHz oscillator. The temperature drift of the 16 GHz oscillator was dependant on the bias, and could be adjusted to almost zero ppm/ $^{\circ}$ C. Since this temperature drift variation seems to be intrinsic to the devices (it was not observed in the 1.77 GHz oscillator because the RTD failed and it was hidden by the bistability of the 37 GHz circuit), it should be possible to use this effect to produce highly temperature stable circuits.

It appears that most of the temperature dependence of both the RTDs and the circuits is due to an increase in the non-resonant-tunnelling current of the devices (Section 3.4). This current is highly dependant on both temperature and bias. In order to reduce the temperature effects, it will be necessary to decrease this current.

With careful circuit design, RTDs could provide simple and effective RF sources for hybrid (or fully integrated) oscillators in the millimeter and sub-millimeter bands, if the output power of these devices can be improved. With advances in crystal growing techniques, device fabrication and new materials, resulting in increased device performance, RTDs show a great deal of promise.

6.2 Considerations for future work

In order to efficiently design RTD circuits, it will be necessary to create a large signal model for these devices. While it is possible to accurately describe the I-V curves of an RTD, the RF characteristics, especially the capacitance and inductance of the devices are not fully understood, and more work is needed to model these characteristics.

The on-wafer probing techniques used in this thesis to study the devices could only be used at room temperature. Further experiments, exploring the temperature dependence of the dc and RF characteristics, will be necessary to gain a better understanding of the temperature dependent behaviour of RTD circuits. For these experiments, it will be necessary to permanently mount and package the RTDs, so that they will be non-recoverable for other applications (such as building circuits).

The RTDs examined in this thesis showed a significant amount of non-resonant-tunnelling current, which seems to be responsible for most of the temperature effects

associated with the devices, such as reduced PVCRs and changes in oscillator output. Any reduction in this current would greatly enhance the RTD performance and temperature stability. This reduction may be achieved by using different RTD structures, such as resonant interband tunnelling (RIT) structures [6.1] or quantum wells isolated by ion implantation instead of mesa etching (which would reduce the leakage current). Repeating these experiments using RTDs with lower non-resonant-tunnelling currents should yield some very interesting results.

Appendix A. The Quantum Mechanics of the RTD

A.1 The Particle in a Box

In order to see how the barriers restrict a particle to certain allowed energy levels, consider the classic 'Particle in a Box' problem. A particle, such as an electron, is confined to a 'box' of width L by infinite potential barriers on both sides, as shown in Figure A.1.

Figure A.1 The infinite potential well.

Start with the time-independent Schrödinger Equation.

$$H\Psi = -\frac{\hbar^2}{2m} \frac{d^2\Psi}{dx^2} + V\Psi = E\Psi$$

where $\Psi = \Psi(x)$, the wavefunction of the particle
 H = Hamiltonian operator
 E = energy of Ψ
 $\hbar$ = Planck's Constant ($6.582 \times 10^{-22} \text{ MeVsec}$)
 m = mass of the particle
 V = Potential function

(A1)

The potential V is infinite outside of the box, and zero inside (i.e. for x between 0 and L). Any wavefunction (representing a particle) can therefore only exist inside the box, where $V(x) = 0$. Equation A1 becomes

$$\frac{d^2\Psi}{dx^2} + \frac{2mE}{\hbar^2} \Psi = 0 \quad (\text{A2})$$

$$\text{let } k^2 = \frac{2mE}{\hbar^2} \quad (\text{A3})$$

then

$$\frac{d^2\Psi}{dx^2} + k^2\Psi = 0 \quad (\text{A4})$$

The solutions to this equation are

$$\begin{aligned} \Psi &= A \sin(kx) \\ \text{and} \\ \Psi &= A \cos(kx) \end{aligned} \quad (\text{A5})$$

Since the wavefunction does not exist ($\Psi=0$) outside the box, and the function must be continuous at the boundaries ($x=0$, $x=L$), the following boundary conditions are imposed

$$\Psi_{x=0} = \Psi_{x=L} = 0 \quad (\text{A6})$$

The cosine solution does not satisfy these conditions (for $A \neq 0$) since $\cos(0) = 1$.

The sine solution results in

$$kL = n\pi \quad n = 1, 2, 3, 4, \dots$$

$$\text{where } k^2 = \frac{2mE}{\hbar^2} \quad (A7)$$

Solving equation A7 for the energy results in

$$E = \frac{n^2 \pi^2 \hbar^2}{2mL^2} \quad n = 1, 2, 3, 4, \dots \quad (A8)$$

Clearly, the wavefunction (particle) inside the box can only take on certain discrete energy levels (bound states). The first three permissible wavefunctions are shown in Figure A.2, along with their relative energies (in units of $\pi^2 \hbar^2 / 2mL^2$) and quantum numbers.

Figure A.2 The solution to the 'particle in a box' problem

A.2 The Finite Potential Well

In order to get a more realistic picture of the energy levels inside an RTD, consider a well of finite potential depth as shown in Figure A.3. Here the potential outside the well is V and there is a zero potential inside. The axes are defined so that $x = 0$ is at the centre of the well, and the boundaries of the well are at $\pm a$.

Figure A.3 The finite potential well

As before, start with the time independent Schrödinger Equation.

$$-\frac{\hbar^2}{2m} \frac{d^2\Psi}{dx^2} + V\Psi = E\Psi \quad (\text{A9})$$

which may be rewritten as

$$\frac{d^2\Psi}{dx^2} + \frac{2m}{\hbar^2}[E - V]\Psi = 0 \quad (\text{A10})$$

$$\text{let } k^2 = \frac{2mE}{\hbar^2} \quad \text{and} \quad q^2 = \frac{2m(V-E)}{\hbar^2} \quad (\text{A11})$$

Because of the symmetry of the well, any solution must also be symmetric, either even or odd (Figure A.4 and A.5). The even solutions may be written as

$$\begin{aligned}
 \Psi &= A e^{q(x+a)} + B e^{-q(x+a)} & x < -a \\
 \Psi &= C \cos(kx) & -a < x < a \\
 \Psi &= F e^{q(x-a)} + G e^{-q(x-a)} & x > a
 \end{aligned}
 \tag{A12}$$

Certain conditions must be applied in order to solve for the constants.

1) The wavefunction must vanish as x tends toward $\pm$ infinity, because outside the well $V > E$. This means that both B and F must be zero.

2) The function and its derivative must be continuous at the boundaries ($x=-a$ and $x=a$). Thus

$$\begin{aligned}
 A &= C \cos(-ka) \\
 qA &= -kC \sin(-ka)
 \end{aligned}$$

and

$$\tag{A13}$$

$$\begin{aligned}
 G &= C \cos(ka) \\
 -qG &= -kC \sin(ka)
 \end{aligned}$$

This results in

$$\begin{aligned}
 A &= G \\
 q &= k \tan(ka) \\
 A &= C \cos(ka)
 \end{aligned}
 \tag{A14}$$

3) The integral of square of the function (Ψ^2), is the probability of the particle being inside a given space. The integral of Ψ^2 evaluated over all space (i.e. from $-\infty$ to

$+\infty$) must therefore be unity, since the particle must be located somewhere between these two bounds.

$$\int_{-\infty}^{+\infty} |\Psi|^2 dx = 1$$

$$\int_{-\infty}^{-a} A^2 e^{2q(1-a)} dx + \int_{-a}^a C^2 \cos^2(kx) dx + \int_a^{+\infty} G^2 e^{-2q(1-a)} dx = 1 \quad (\text{A15})$$

$$C^2 \left[\frac{x}{2} + \frac{\sin(2kx)}{4k} \right]_{-a}^a + A^2 \left[\frac{-e^{-2q(1-a)}}{q} \right]_{-a}^{+\infty} = 1$$

$$C^2 \frac{2ka + \sin(2ka)}{2k} + \frac{A^2}{q} = 1 \quad (\text{A16})$$

By combining the results from conditions 2 and 3, it is possible to solve for the constants A, C and G from equation A12 and A14.

$$C = \sqrt{\frac{2kq}{2kqa + q\sin(2ka) + 2k\cos^2(ka)}} \quad (\text{A17})$$

$$A = G = \sqrt{\frac{2kq\cos^2(ka)}{2kqa + q\sin(2ka) + 2k\cos^2(ka)}} \quad (\text{A18})$$

The odd solutions to equation A9 may be found by a similar procedure, resulting in

$$\begin{aligned}
 \Psi &= Ae^{q(x+a)} & x < -a \\
 \Psi &= D\sin(kx) & -a < x < a \\
 \Psi &= Ge^{-q(x-a)} & x > a
 \end{aligned}
 \tag{A19}$$

$$q = -k\cot(ka)$$

$$D = \sqrt{\frac{2kq}{2kqa - q\sin(2ka) + 2k\sin^2(ka)}} \tag{A20}$$

$$A = G = -\sqrt{\frac{2kq\sin^2(ka)}{2kqa - q\sin(2ka) + 2k\sin^2(ka)}} \tag{A21}$$

Figure A.4 The first two even solutions

Figure A.5 The first two odd solutions

To find the energy levels associated with these states, consider

$$q = k\tan(ka) \quad [\text{even states}]$$

and

$$q = -k\cot(ka) \quad [\text{odd states}]$$

$$\text{let } Y = \frac{2mVa^2}{\hbar^2} \tag{A23}$$

$$\text{then } \frac{\sqrt{Y - (ka)^2}}{ka} = \tan(ka) \quad [\text{even state}] \quad (\text{A24})$$

$$\text{and } \frac{\sqrt{Y - (ka)^2}}{ka} = -\cot(ka) \quad [\text{odd state}] \quad (\text{A25})$$

These equations must be solved (for ka) either numerically or graphically as shown in Figure A.6 (the solutions occur where the lines intersect).

Figure A.6 Solving the finite potential well problem graphically

Once the solutions for ka have been found, the energy associated with these solutions may be calculated from equation A3, which may be re-written as

$$E = \frac{k^2 \hbar^2}{2m} \quad (\text{A26})$$

As the potential of the well (V) increases, which is represented by an increase in Y (see Figure A.6), there will be more bound states (more solutions), and the energy of the various bound states will increase. Notice that the solutions for very large values of V (or Y) approach those of the infinite potential well problem.

A.3 Calculating the Energy levels

The equations developed in Appendix A.2 apply to a quantum well with infinitely wide barriers. It has however been shown that the width of the barriers has very little effect on the energy levels within the well [A.1], which are mainly determined by the well width and the barrier height. It is therefore possible to use these equations to do a rough calculation of where the energy levels and resonances for a given quantum well substrate are.

First, the barrier height must be found from the energy band gaps of the materials. For AlAs, the energy band gap is 2.168 eV [A.2], for GaAs it is 1.424, while for AlGaAs it may be calculated by the formula

$$E_g(x) = 1.424 + 1.247x \quad (\text{A27})$$

where x = Mole Fraction of AlAs

which is valid for $0 < x < 0.45$ [A.2]. Because of the way the energy bands align at the junction, the barrier height is 0.6 times the difference in energy band gap between the barrier material and GaAs [A.3]. The remaining 0.40 of the differences constitute a potential well in the valence band rather than the conduction band (i.e. a quantum well for holes). This results in the following barrier potentials (V):

Substrate #812: 0.446 eV (7.15×10^{-20} J)

Substrate #814: 0.299 eV (4.80×10^{-20} J)

The other values necessary for calculation are:

half well width (a):	2.25*10 ⁻⁹ m (#812) 2.5*10 ⁻⁹ m (#814)
Effective mass of an electron ¹¹ (m):	6.1034*10 ⁻³² kg
Planck's Constant (h):	1.05459*10 ⁻³⁴ Js

From equation A23

$$Y = \frac{2mVa^2}{\hbar^2}$$

which results in

$$Y = 3.97 \text{ (substrate \#812)}$$

$$Y = 3.29 \text{ (substrate \#814)}$$

Solving equations A24 and A25 numerically results in one even and one odd solution in both cases, with the following electron energies

Substrate #812:	0.119 eV (even)	0.402 eV (odd)
Substrate #814:	0.090 eV (even)	0.287 eV (odd)

An electron inside a symmetrical quantum well must have lost half its energy (relative to the bottom of the well) tunnelling through the first barrier. Thus the voltage across the well at resonance must be at twice that of the resonance energies inside the well, giving the following resonance voltages

¹¹ The effective mass = 0.067 m₀ for electron in GaAs [A.3].

Resonance	E_0	E_1
Substrate #812	0.24 V	0.80 V
Substrate #814	0.18 V	0.57 V

Table A.1 The calculated resonance voltages

These voltages will be increased by any series resistance and diode effects due to the surrounding semiconductor material.

Appendix B. Bistability

There are two types of bistability (or hysteresis) associated with RTDs, intrinsic and extrinsic bistability.

Intrinsic bistability is caused by effects within the quantum well itself, such as a charge buildup during resonance, which may affect the relative potentials of the quantum well structure [B.1]. This leads to different conductive properties for the case when the voltage sweep had just passed through the region of resonance (i.e. there was the charge buildup), and the case when it had not (i.e. no charge buildup). These effects are mainly discussed in theoretical papers [B.1], and there is question as to whether it has actually been experimentally observed [B.2].

Extrinsic bistability on the other hand is due to effects outside the well itself, such as series resistances or other quantum wells (in a multi-quantum well diode) [B.3, B.4], and is consistent with the observations during these experiments.

Consider a quantum well in series with a sufficiently large resistor (i.e. larger than the negative resistance of the well). The load lines for this circuit would be as shown in Figure B.1. There are 3 possible load points when a voltage B is applied, as indicated by

the intersection of the lines. Each of these load points has its own unique current associated with it, and thus the device can be in three possible current states.

Figure B.1 The load lines for a quantum well in series with a resistor

When the voltage across the circuit is slowly increased from 0 volts, as in the case of an I-V measurement, there is only one possible current state, until voltage A is reached. Past voltage A there are two current states, but the device will stay in whatever current state it currently is in (in this case the high current state). As the voltage is increased above voltage C, only the low current state exists, and the circuit will shift states. This will result in a sudden drop in current (measured to occur as quickly as 2 ps [B.5]).

When the voltage across the circuit is decreased starting from above voltage C, the circuit will stay in its low current state until the voltage drops below voltage A. At this point, the device will shift to its high current state, and a sudden increase in the current is observed.

The switching between two possible current states described above, gives rise to the bistability observed in RTD3. In order to illustrate this concept further, an I-V curve similar to the one for RTD1 was SPICE modelled with a range of series resistances (from 0Ω to 250Ω). The results are displayed in Figure B.2.

Figure B.2 The effect of adding a series resistance to an RTD

Figure B.2 shows a gradual skewing of the current peak with increasing series resistance (the peak starts out symmetric). Bistability is first seen at a series resistance of 200 Ω . RTD1 and RTD2 however showed only very slight skewing, and the series resistances were calculated to be 2.2 Ω and 3.1 Ω respectively. For a device like RTD3, which has a higher peak to valley current drop (13 mA, compared to the 0.8 mA for RTD1), less series resistance is required to achieve hysteresis. Computer simulation using SPICE, have shown that a series resistance of about 55 Ω is required in order to skew a symmetric current peak and end up with the I-V curve for RTD3 (including hysteresis).

References

- [1.1] L. Esaki and R. Tsu, "Superlattice and negative differential conductivity in semiconductors", IBM J. Res. Dev. **14**, p 61 (1970).
- [1.2] L.L. Chang, L. Esaki and R. Tsu, "Resonant tunnelling in semiconductor double barriers", Appl. Phys. Lett **24** (12), p 593 (1974).
- [1.3] H.H. Tsai, Y.K. Su, H.H. Lin, R.L. Wang and T.L. Lee, "P-N double quantum well interband tunnelling diode with peak-to-valley current ratio of 144 at room temperature", IEEE Elec. Dev Lett **15** (9), p 357 (1994).
- [1.4] E.R. Brown, J.R. Sönderström, C.D. Parker, L.J. Mahoney, K.M. Molvar and T.C. McGill, "Oscillations up to 712 GHz in InAs/AlSb resonant-tunnelling diodes", Appl. Phys. Lett **58** (20), p 2291 (1991).
- [1.5] T.C.L.G. Sollner, W.D. Goodhue, P.E. Tannenwald, C.D. Parker and D.D. Peck, "Resonant tunnelling through quantum wells at frequencies up to 2.5 THz", Appl. Phys. Lett. **43** (6), p 588 (1983).
- [1.6] E.R. Brown, T.C.L.G. Sollner, W.D. Goodhue and C.D. Parker, "Millimeter-band oscillators based on resonant tunnelling in a double-barrier diode at room temperature", Appl. Phys. Lett. **50** (2), p 82 (1987).
- [1.7] S. Sen, F. Capasso, A.Y. Cho and D. Sivco, "Resonant tunnelling device with multiple negative differential resistance: Digital and signal processing applications with reduced circuit complexity", IEEE Transactions on Electron Devices **ED-34** (10), p 2185 (1987).
- [1.8] K. Maezawa and T. Mizutani, "A new resonant tunnelling logic gate employing monostable-bistable transition", Jpn. J. Appl. Phys. **32**, p L42 (1993).
- [2.1] O. Berolo, E. Fortin and L. Allard, "Analysis of Voltage Periodic Structures in the Negative Differential Resistance Region of Double Barrier Resonant Tunnelling Diodes", Superlattices and Microstructures **17** (2), p 163 (1995).
- [2.2] H.M. Yoo, S.M. Goodnick and J.R. Arthur, "Influence of spacer layer thickness on the current-voltage characteristics of AlGaAs/GaAs and AlGaAs/InGaAs resonant tunnelling diodes", Appl. Phys. Lett **56** (1), p 84 (1990).

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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PRECISIONSM RESOLUTION TARGETS

- [2.3] R.E. Williams, Gallium Arsenide Processing Techniques, Artech House, Dedham, MA (1984), p 225.
- [2.4] R.E. Williams, Gallium Arsenide Processing Techniques, Artech House, Dedham, MA (1984), p 214.
- [2.5] R.E. Williams, Gallium Arsenide Processing Techniques, Artech House, Dedham, MA (1984), p 334.
- [3.1] T. Wei, S. Stapleton and O. Berolo, "Capacitance and hysteresis study of AlAs/GaAs resonant tunnelling diode with asymmetric spacer layers", J. Appl. Phys. 77 (8), p 4071 (1995).
- [3.2] J.F. Young, B.M. Wood, H.C. Liu, M. Buchanan, D. Landheer, A.J. SpringThorpe and P. Mandeville, "The Effect of Circuit Oscillations on the dc Current-Voltage Characteristics of Double Barrier Resonant Tunnelling Structures", Appl. Phys. Lett 52, p 1398 (1988).
- [3.3] S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., Wiley, New York (1981), p 33.
- [3.4] B. Jogai and E.T. Koenig, "A Parametric Study of Extrinsic Bistability in the Current-Voltage Curves of Resonant-Tunnelling Diodes", J. Appl. Phys. 69 (7), p 3381 (1991).
- [3.5] J.G. Chen, J. Chen, R.A. Wilson, W. Johnson and C.H. Yang, "On the Intrinsic Bistability in Resonant Tunnelling Structures: Observations of Area and Temperature Dependence of Hysteresis", J. Appl. Phys. 70 (4), p 2473 (1991).
- [3.6] J.F. Whitaker, G.A. Mourou, T.C.L.G. Sollner and W.D. Goodhue, "Picosecond switching time measurement of a resonant tunnelling diode", Appl. Phys. Lett 53 (5), p 385 (1988).
- [3.7] S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., Wiley, New York (1981), p 28.
- [3.8] S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., Wiley, New York (1981), p 851.
- [3.9] G. Bastard, Wave Mechanics applied to Semiconductor Heterostructures, Les Editions de Physique (1988), p 34.
- [4.1] T.S. Laverghetta, Practical Microwaves, Howar W. Sams & Co., Inc., Indianapolis (1984), p. 277.

- [4.2] T.C.L.G. Sollner, E.R. Brown, W.D. Goodhue and H.Q. Le, "Observations of millimeter-wave oscillations from resonant tunnelling diodes and some theoretical considerations of ultimate frequency limits", *Appl. Phys. Lett.* **50** (6), p 332 (1987).
- [4.3] T. Wei, S. Stapleton and E. Berolo, "Equivalent circuit and capacitance of double barrier resonant tunnelling diode", *J. Appl. Phys.* **73** (2), p 829 (1993).
- [4.4] R. Bouregba, O. Vanbesien, L. Saint Pol and D. Lippens, " $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ -GaAs microwave resonant tunnelling oscillator", *Ann. Telecommun* **45** (3-4), p184 (1990).
- [4.5] F.A. Buot and A.K. Rajagopal, "High-frequency behaviour of quantum-based devices: Equivalent-circuit, nonperturbative-response, and phase-space analysis", *Phys. Rev. B* **48** (23), p 17217 (1993).
- [4.6] Y. Hu and S.P. Stapleton, "Capacitance of a resonant tunnelling diode", *Jpn. J. Appl. Phys* **31**, p 23 (1992).
- [4.7] J. Genoe, C. Van Hoof, W. Van Roy, J.H. Smet, K. Fobelets, R.P. Mertens and G. Borghs, "Capacitances in double-barrier tunnelling structures", *IEEE Trans. on Electron Devices* **38** (9), p 2006 (1991).
- [4.8] Z. Yan and M.J. Deen, "New RTD large-signal dc model suitable for PSPICE", *IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems* **14** (2), p 167 (1995).
- [5.1] I. Bahl and P. Bhartia, *Microwave Solid State Circuit Design*, John Wiley & Sons, Inc, New York (1988), p 449.
- [5.2] Hewlett Packard Application Note 207, "Understanding and measuring phase noise in the frequency domain"
- [5.3] E.R. Brown, T.C.L.G. Sollner, W.D. Goodhue and C.D. Parker, "Millimeter-band oscillations based on resonant tunnelling in a double-barrier diode at room temperature", *Appl. Phys. Lett.* **50** (2), p 83 (1987).
- [5.4] E.R. Brown, J.R. Sönderström, C.D. Parker, L.J. Mahoney, K.M. Molvar and T.C. McGill, "Oscillations up to 712 GHz in InAs/AlSb resonant-tunnelling diodes", *Appl. Phys. Lett* **58** (20), p 2291 (1991).
- [5.5] R. Bouregba, O. Vanbesien, L. Saint Pol and D. Lippens, " $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ -GaAs microwave resonant tunnelling oscillator", *Ann. Telecommun* **45** (3-4), p184 (1990).

- [5.6] J.K. Plourde and C. Ren, "Applications of Dielectric Resonators in Microwave Components", IEEE Trans. on Microwave Theory and Techniques **MTT-29** (8), p 754 (1981).
- [5.7] J. Horna, "Dielectric resonator oscillator: Designing for temperature stability", Conf. Proc. 20th European Microwave Conference 90, vol 2, p 1742 (1990).
- [5.8] Y. Hong-Biao and G. Mo-Lin, "Dielectric resonator stabilized transistor oscillator", Proc. 2nd International Symposium on Recent Advances in Microwave Technology, p 554 (1989).
- [5.9] D. Jaisson and F. Bachelot, "An oscillator with gunn diode integrated in a dielectric resonator", Microwave Journal **37** (2), p 117 (1994).
- [5.10] J. Sun and C. Wei, "A highly stabilized GaAs FET reflection-type oscillator with a dielectric resonator in X-band", Microwave Journal **35** (4), p 72 (1992).
- [5.11] A.P.S. Khanna and E. Topacio, "A highly stable 36 GHz GaAs FET DRO with phase-lock capability", Microwave Journal **32** (7), p 117 (1989).
- [5.12] H. Barth, "A 93 GHz-dielectric resonator oscillator", Conf. Proc. 21st European Microwave Conference, p 364 (1991).
- [5.13] S.S. Sarin, M.R. Kumar and D. Singn, "Bias-tuned gunn oscillator serves W-band FMCW radar", Microwaves & RF **37** (7), p 73 (1994).
- [6.1] M. Sweeney and J. Xu, "Resonant interband tunnel diodes", Appl. Phys. Lett **54** (6), p 546 (1989).
- [A.1] M. Tsuchiya, H. Sakaki and J. Yoshino, "Room temperature observations of differential negative resistance in an AlAs/GaAs/AlAs resonant tunnelling diode", Japn. J. Appl. Phys. **24** (6), p L466 (1985).
- [A.2] S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., Wiley, New York (1981), p 713.
- [A.3] G. Bastard, Wave Mechanics applied to Semiconductor Heterostructures, Les Editions de Physique (1988).
- [A.4] S.M. Sze, Physics of Semiconductor Devices, 2nd Ed., Wiley, New York (1981), p 850.
- [B.1] N.C. Kluksdahl, A.M. Krivan, D.K. Ferry and C. Ringhofer, "Self-consistent study of resonant-tunnelling diode", Phys. Rev. B. **39** (11), p 7729 (1989).

- [B.2] J.G. Chen, C.H. Yang and R.A Wilson, "On the intrinsic Bistability in resonant tunnelling structures: Observations of the area dependence of hysteresis", J. Appl. Phys. 69 (7), p 4132 (1991).
- [B.3] B. Jogai and E.T. Koenig, A parametric study of the extrinsic bistability in the current-voltage curves of resonant-tunnelling diodes", J. Appl. Phys. 69 (5), p 3381 (1991).
- [B.4] J.G. Chen, J. Chen, R.A. Wilson, W. Johnson and C.H. Yang, "On the Intrinsic Bistability in Resonant Tunnelling Structures: Observations of Area and Temperature Dependence of Hysteresis", J. Appl. Phys. 70 (4), p 2473 (1991).

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