Chapter 6

RECOMMENDATIONS FOR FUTURE WORK

This chapter will identify both immediate and speculative promising research directions in three major areas in this field-- (a) Alternative heterostructure material systems, (b) Device structures and transport models, and (c) RF circuit design.

6.1 Alternative Heterostructure Material Systems

We have seen that a GaAs/AlAs double barrier structure can be used to obtain room temperature negative differential resistance (NDR) with a peak-to-valley current ratio of 3:1. The peak-to-valley ratio in this material system is limited primarily by transport through the X band in the AlAs tunnel barrier. By raising the lowest energy band in the barrier through an appropriate choice of quantum well and barrier materials much better room temperature NDR characteristics can be obtained. It has been shown recently that peak-to-valley ratios of 7:1 can be obtained at room temperature from a $In_{0.53}Ga_{0.47}As$/ $In_{0.52}Al_{0.48}As$ double barrier structure [82, 83]. Both $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ are direct bandgap semiconductors with a $\Gamma-\Gamma$ conduction band discontinuity of 0.74eV. $In_{0.52}Al_{0.48}As$ also has a low electron effective mass of $0.075m_0$ which increases the tunneling probability and device current density. However, for the electric fields we anticipate in the depletion region in a QWITT diode, $In_{0.53}Ga_{0.47}As$ may possess a lower carrier velocity than GaAs [84] and that may degrade the rf performance of the device. By choosing a pseudomorphic $AlAs/In_{0.53}Ga_{0.47}As$ double barrier structure, room temperature peak-to-valley ratios of 30:1 have been obtained [16]. For indium based alloys, NDR characteristics have been obtained from $In_{0.53}Ga_{0.47}As/InP$ double barrier structures grown by MOCVD [85]. The pseudomorphic AlSb/InAs material system also appears to be attractive for electron tunneling since the lowest conduction band discontinuity [X(AlSb)-Γ(InAs)] is 1.2eV [86]. Another promising material system is lattice-matched InAs/ZnTe, for which the conduction band discontinuity is 1.6 eV [87]. In addition, InAs has a very high mobility of 33,000 cm^2/V-s at 300K, and ZnTe has a low dielectric constant of 10.4. Hence, the intrinsic RC time constant of the double barrier structure should be lower. A large valence band discontinuity of 0.96-1.1 eV can be obtained in the GaAs/ZnSe material system [87] and it should therefore be possible to see NDR through hole tunneling at room temperature in these devices.

There have been recent reports of hole tunneling in elemental semiconductor heterostructures, in the $Si/Si_{1-x}Ge_x$ material system [88]. Interest in developing microwave integrated circuits in silicon-based heterostructures at 94 GHz (called Silicon Microwave Millimeter Wave Integrated Circuits, SIMMWIC) is growing, and recently a p-$Si/Si_{1-x}Ge_x$ QWITT diode has been reported [89]. By using the concept of strain symmetrization [90] it should be possible to achieve electron tunneling in this material system.

6.2 Device Structures and Transport Models

There is considerable room for optimization of the QWITT device structure. The choice of the quantum well layer thicknesses for highest current density is still being debated [73, 91], and recently current densities around 100 kA/cm^2 have been reported [91]. Higher current density should result in higher rf output power density.

Optimization of the electric field profile in the lightly doped depletion region is incomplete. The doping spike concept described in Chapter 5 was a first attempt to tailor this electric field profile to improve the device efficiency and rf output power. Modification of the doping profile through graded layers to take advantage of velocity overshoot effects in the depletion region could significantly improve device performance. This directly leads us to the need to develop a self-consistent device model that takes into account both quantum effects and semi-classical transient transport issues. Transport through the double barrier structure has been described by quantum transport models using the Wigner function to obtain the quantum mechanical distribution function [92, 93]. Classical transport describes current in the depletion region in the QWITT diode fairly accurately. A self-consistent device model for the terminal characteristics of a QWITT device which considers both the quantum and classical regions in this structure will help explain the physical transport mechanisms involved and provide device design information to maximize device performance.

It may be possible to engineer a double drift QWITT structure that uses electron and hole tunneling through confined conduction band and valence band states by using a material system where electron and hole effective masses are very similar. The physical device structure is then designed to support depletion regions on both sides of the quantum well [94].

The device areas used in this study were kept small to avoid excessive heating and consequent heat sinking problems. By using larger device areas with proper heat sinking, it is very likely that the QWITT diode can deliver tens of milliwatts of power at frequencies between 10-40 GHz. AlAs layers used to chemically release the GaAs substrate from the heterostructure epitaxial layers [95] is a promising approach to heat sink these devices effectively.

The highest frequency of oscillation from a QWITT diode is limited primarily by parasitic series resistance from the ohmic contacts. By using in-situ non-alloyed InGaAs contacts [75, 96] it is possible to achieve specific contact resistances below 10^{-7} Ω-cm^2.

6.3 RF Circuit Design

The immediate issue of characterizing QWITT devices at higher millimeter wave frequencies in a waveguide circuit should be undertaken. Such a study will shed more light on the output power roll off at high frequencies. In order to obtain output powers greater than what a single diode can provide would require power combining these devices in series or in parallel. A conventional TEM parallel-plate waveguide loaded periodically with resonant tunneling diodes or QWITT diodes is a very effective way of power combining these devices in parallel [97]. This periodic structure is easy to stabilize and can be fabricated monolithically.

We have performed small-signal analysis of such a periodically loaded monolithic quantum well oscillator. The analysis uses a transmission line model loaded periodically with the diode impedances. A similar analysis of a periodic oscillator using IMPATT diodes has shown excellent agreement between experiment [98] and theory [99]. A parallel-plate waveguide loaded periodically with QWITT diodes is shown in Fig. 6.1. The waveguide is modeled by an equivalent transmission line loaded with an impedance, Z_p. The impedance, Z_p, is the sum of the diode impedance and the metal post reactance. A small-signal equivalent circuit for the QWITT diode previously developed by in Chapter 2 [64] is used to obtain the diode impedance ($R_d + jX_d$) as a function of frequency. The metal post inductance, X_0, to first order is calculated using a conventional mode-matching technique [100]. The impedance $Z_p = R_d + j(X_d+X_0)$ is then normalized to the characteristic impedance of the parallel-plate waveguide. Once the impedance, Z_p, is known, simple admittance transformations are used to analyze the periodic structure. The oscillation frequency for the circuit is where the imaginary part of the input admittance, Y_{in}, goes to zero.

As an illustration, a parallel-plate waveguide loaded with four QWITT diodes has been chosen (Fig. 6.1). The dimensions of the waveguide and the QWITT diode parameters designed to operate at 94 GHz are as follows: width of the waveguide, W = 254 µm, thickness, L = 25.4 µm, distance between the diodes, d = 866 µm, and diameter of the metal post and diode = 25.4 µm. The waveguide is assumed to be filled with polyimide (ε_r = 3.4) and the waveguide terminations are assumed to be open circuited. The physical parameters of the waveguide should permit monolithic circuit fabrication using conventional integrated circuit fabrication technology.

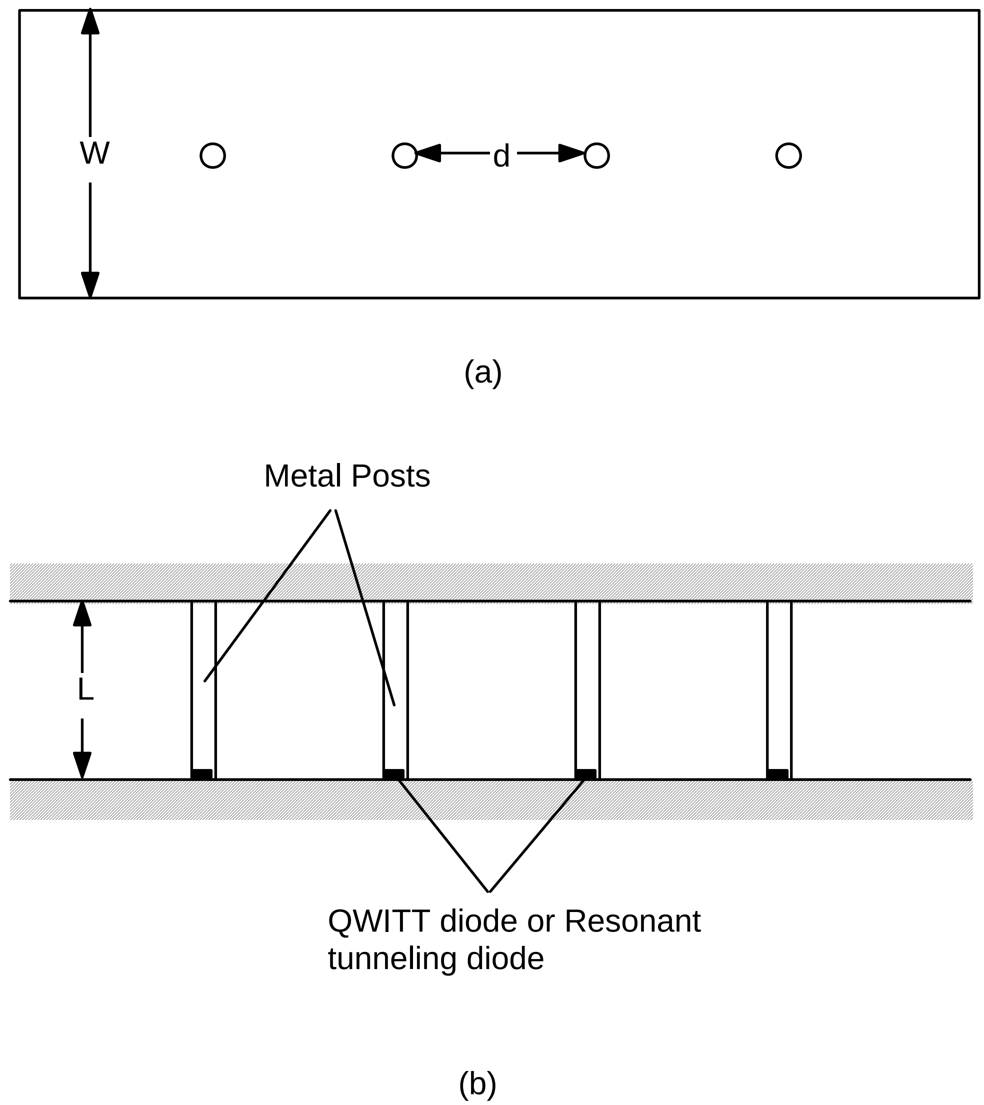

Fig. 6.1: Schematic representation showing top and side views of the parallel plate waveguide circuit periodically loaded by QWITT diodes or resonant tunneling diodes.

The calculated input admittance as a function of frequency is shown in Fig. 6.2. The circuit oscillates at 94 GHz where the imaginary part of Y_{in} becomes zero and the real part is at a negative maximum.

Retaining all diode and circuit parameters the same as those at 94 GHz, the distance, d, between the diodes is varied to obtain other resonant frequencies. At any desired operating frequency, the distance between the diodes must equal half the guide wavelength. Thus, as the oscillation frequency is increased, the distance between the diodes decreases as 1/f (Fig. 6.3). Hence, the periodicity of the structure, i.e., the distance between adjacent diodes, determines the oscillation (resonant) frequency of the circuit. The analysis also shows how variation in the width and thickness of the waveguide affects the oscillation frequency of the circuit designed to operate at 94 GHz. A deviation in width or thickness of the waveguide by even a factor of four causes less than 1% change in the oscillation frequency. Hence, the width and thickness of the waveguide, which determines its characteristic impedance, do not affect the oscillation frequency significantly. This is a distinct advantage from a circuit fabrication point of view.

It may also be possible to power combine quantum well devices in series much like earlier work done on tunnel diodes [101] and Gunn diodes [102-105]. The circuit conditions to maintain identical voltage drop across individual devices to maintain the same dc bias point may be the subject of future work.

Although it is widely accepted that tunneling is a low noise transport mechanism, the noise characteristics of any quantum well oscillator have not been measured to date. A study of the sources of noise in these devices and possible ways

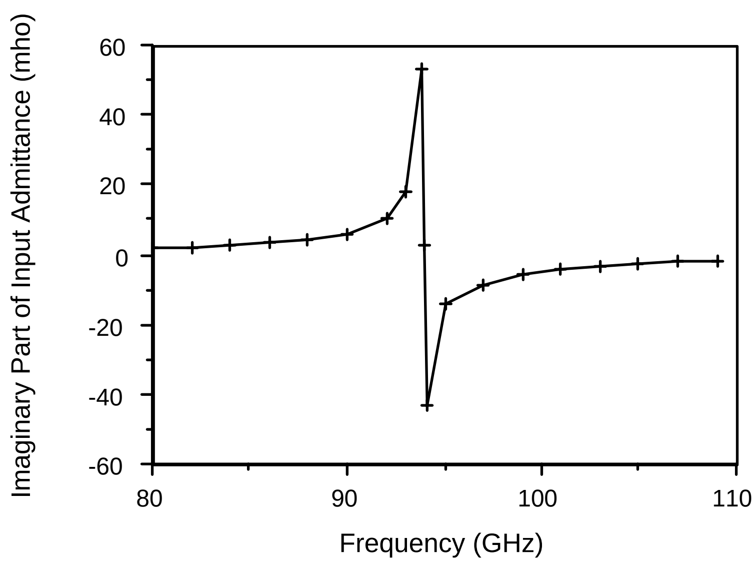

Fig. 6.2: Imaginary part of the input admittance as a function of frequency for a periodic oscillator circuit designed to operate at 94 GHz.

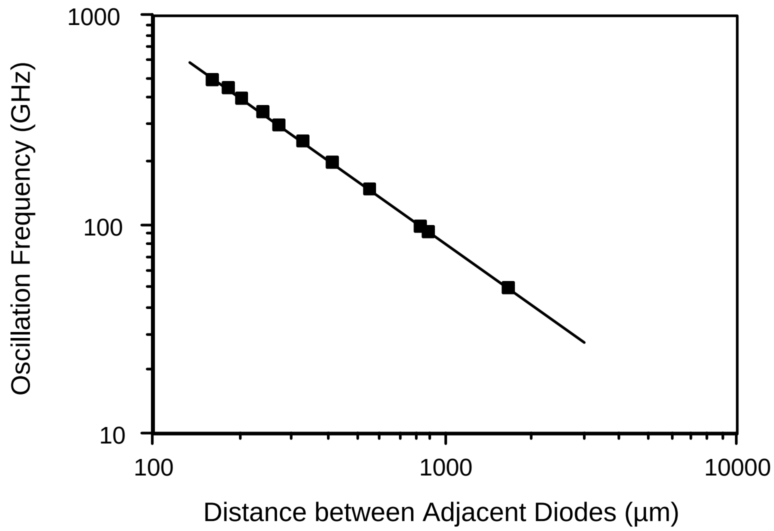

Fig. 6.3: Oscillation frequency as a function of the distance between adjacent diodes. At any desired oscillation frequency the distance between the diodes must be half the guide wavelength.

to reduce them would help these devices find increased acceptance as high frequency, low noise sources.

Self oscillating mixers find promising applications in millimeter and submillimeter wave receiver technology. We have demonstrated that self oscillating mixers using the QWITT diode as local oscillator (LO) possess conversion gain at microwave frequencies [79, 80]. Extending this study to higher frequencies and characterizing their noise figure and noise temperature remains to be completed.