"MICROWAVE CHARACTERISTICS OF MBE GROWN RESONANT TUNNELING DEVICES"

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ABSTRACT

Resonant tunnel devices grown by molecular beam epitaxy have been measured experimentally using network analysis techniques from 130 MHz - 20 GHz. A circuit model for the devices has been extracted for two different InGaAs well structures at a fixed bias point, which fits the measured data well and is useful for circuit design. Additionally, the device impedance has been measured as a function of bias at a fixed frequency point. Complicated capacitance characteristics were observed for the devices with large indium content wells.

INTRODUCTION

Resonant tunneling devices (RTD) where first demonstrated by Chang, Esaki and Tsu in 1979 (1). A number of theoretical studies of the devices have been published, as well as reports of application of the devices as mm wave oscillators (2,3). This paper reports direct small signal measurements of the terminal characteristics of the devices. The difficulty with such a measurement lies in stabilizing a device with a "true" terminal negative resistance from DC to several hundred GHz. The measurement was accomplished by two techniques, first by shunting the device with a chip resistor and subsequently de-embedding the device from the measurement circuit and second, by reducing the device area, thus the magnitude of the negative resistance and shunting the device with an "on chip" capacitor and de-embedding the device from the circuit.

THE DEVICES

The RTDs were grown by molecular beam epitaxy in a modified Varian Gen II system. The layer structure is listed in the following table. Two different alloy compositions were used for the $In_yGa_{1-y}As$ well. The alloy composition was determined by microprobe analysis on bulk InGaAs layers grown under the same conditions as the RTD well. The measured indium fractions were 7% (y=0.07) and 15% (y=0.15). Higher indium content decreases the bandgap of the well material, lowering the well energy with respect to the conduction band minimum of the rest of the structure. This results in resonant or peak current conditions at lower applied voltage, thus decreasing the power dissipation at the bias point.

Layer	Thick-ness [Å]	Material	Doping [cm^-3]
Contact	500	InGaAs SL	1x10^19
Anode	250	GaAs	2x10^18
Anode spacer	500	GaAs	undoped
Anode barrier	20	AlAs	undoped
Well	45	InGaAs	undoped
Cathode barrier	20	AlAs	undoped
Cathode spacer	50	GaAs	undoped
Cathode (2)	100	GaAs	2x10^18 to 1x10^17
Cathode (1)	2000	GaAs	2x10^18
Growth buffer	4000	GaAs	2x10^18
Substrate	500μm	GaAs	n+

Ion implantation damage isolated individual diodes. The complete fabrication sequence consisted of the following steps. Au/Ge/Ni/Au was deposited on the backside of the substrate and annealed to form an ohmic contact. Then Ti/Au (200 Å/4000 Å) dots were patterned on top of the InGaAs contact layer by liftoff. These dots served both as a non-alloyed ohmic contact to the anode and an implant mask. After a 1x10^13 cm^-2 dose of 40 keV boron, the top 800 Å were etched off to decrease leakage in the heavily doped, lightly damaged surface, and 50 μm diameter metal bonding pads were evaporated on each device. The wafer was then scribed and cleaved into small pieces that were epoxied into S4 pill packages.

Typical DC characteristic of the 5 µm diameter device with 15% indium well is shown in Fig. 1. I-V measurements were performed using a true DC measurement set-up to suppress oscillations that occur when the measurements are performed with a standard curve tracer. That is, the voltage was stepped up and the current was monitored at each voltage step.

MICROWAVE MEASUREMENTS

Microwave measurements from 130 MHz to 15 GHz were carried out on a range of devices using an HP 8720 Network Analyzer, with bias supplied through the analyzer bias port. The devices were stabilized by shunting the RTD with a 10 Ω chip resistor, or by reducing the device area and shunting the device. Figure 2 shows the results of measurement, with and without bias in the negative differential region (NDR) for a 14 µm diameter device with a 7% indium well. This device had a peak current of 12 mA at 1.0 V and a valley current of 4 mA at 1.4 volts.

Because of the difficulty in stabilizing the larger devices, it was found that de-embedding the measurements was very difficult, as there was an abundance of degrees of freedom for the fit. However, from these measurements we extracted a device negative resistance on the order of 150 Ω for the 14 µm devices. The measurements were then repeated over a frequency range of 130 MHz to 20 GHz for the 5 µm diameter devices with 15% indium wells. These devices had a peak current of 1.4 mA at 0.5 V and a valley current of 0.5 mA at 1.0 V. The results of these measurements for a bias point of .58 V are shown in Fig. 3. It is apparent from these measurements, that the small current devices did not show negative resistance at as high a frequency as the large current device. The terminal resistance became positive at approximately 1 GHz, as opposed to 5 GHz for the larger device. This difference is attributed to the shunting capacitance inherent in the smaller devices. The circuit model extracted from this measurement is shown in Fig. 4. Due to the stability of these devices when loaded with 50 Ω, the circuit model for this measurement is fairly simple. The value of negative resistance used in the model for the device was 640 Ω. This value of resistance gave the best fit to the microwave data and is also the reciprocal of the slope of the DC IV curve at the same bias point of .58 V. Thus, we feel that this number, while quite large, is fairly accurate. The fit to the data using the circuit model is shown in Fig. 5. Note that the starting frequency point of 130 MHz is nearly identical and the frequency point where the device resistance becomes positive is essentially the same for the data and the fit.

The AC impedance at 130 MHz for these devices was also measured as a function of bias voltage using the HP8720 network analyzer. The results of these measurements are presented in Fig. 6. The resistance versus voltage plot shows that the resistance was essentially constant at around 270 Ω until the device was biased in the negative resistance range. The DC curve in Fig. 1 has a reciprocal slope of around 350 Ω, and also exhibits a fairly constant slope over the same bias range. The device exhibited a negative terminal resistance over a bias range of around .55 V to 1 V. The capacitance shows large variations as a function of voltage. The capacitance exhibited a peak at a slightly negative bias and then declined to a value of around 9 pF from around .1 V to .4 V. It then declined rapidly before the onset of negative resistance reaching a minimum of 2 pF at the peak in negative resistance. Note that the capacitance also exhibited a peak in the middle of the negative resistance region and there is also a peak in the resistance at the same bias point. The capacity of the device outside the negative resistance region fell to around 2.5 pF and then increased with the bias voltage. The peaks in the capacitance in the negative resistance region can probably be attributed to storage of charge within the well and accumulation layer that forms in the cathode spacer. These capacitances will dominate the depletion capacitance in this frequency range.

CONCLUSION

Resonant tunneling devices have been studied using a microwave network analyzer. The resulting circuit model is simple and shows the same trends as the data over the .13-20 GHz frequency range and can thus provide the circuit designer with an approximate model for design purposes.

ACKNOWLEDGEMENTS

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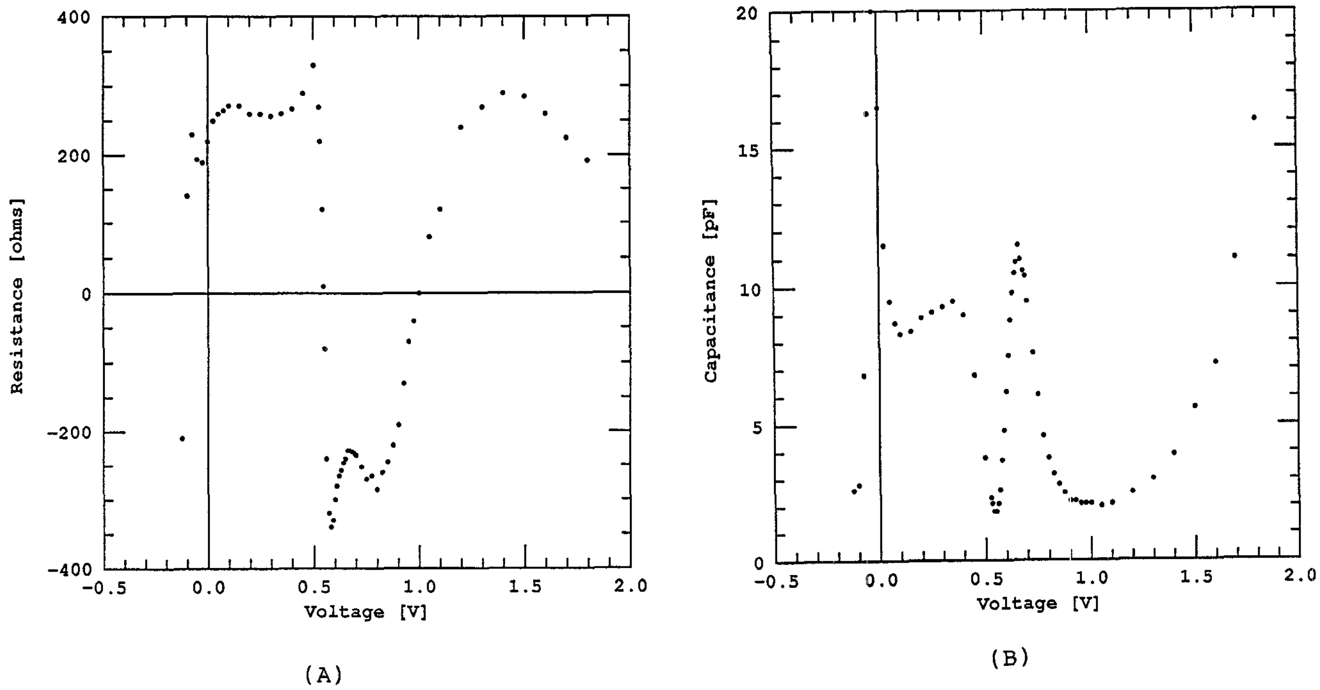

FIGURE 6. Results of the 130 MHz (A) resistance and (B) capacitance versus bias measurement for 5 µm diameter device with 15% indium well.

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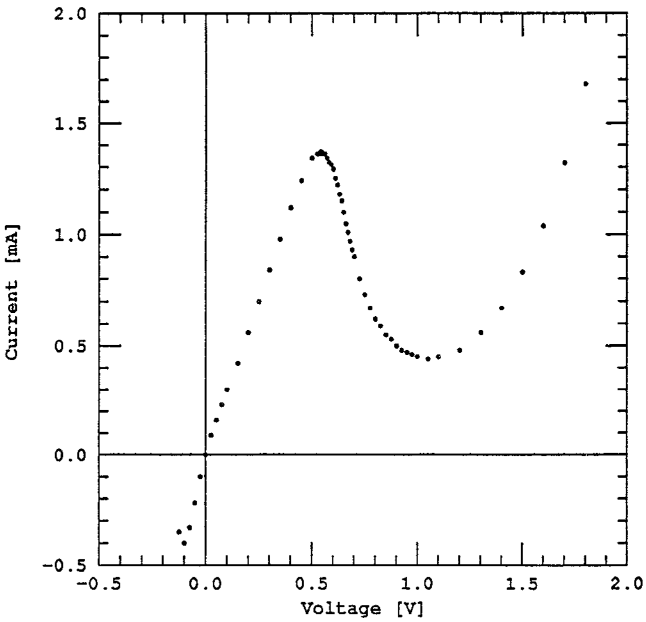

FIGURE 1. D.C. IV characteristics of 5μm diameter RTD with 15% indium well.

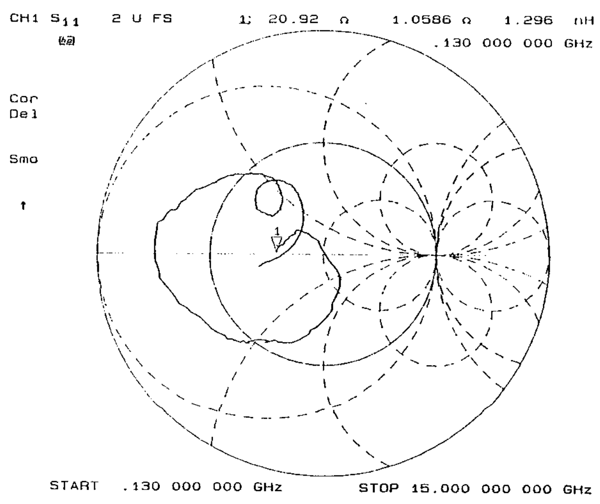

FIGURE 2. Results of microwave measurements on the 14 μm diameter device with 7% indium well at 1.00 V bias (in NDR Region)

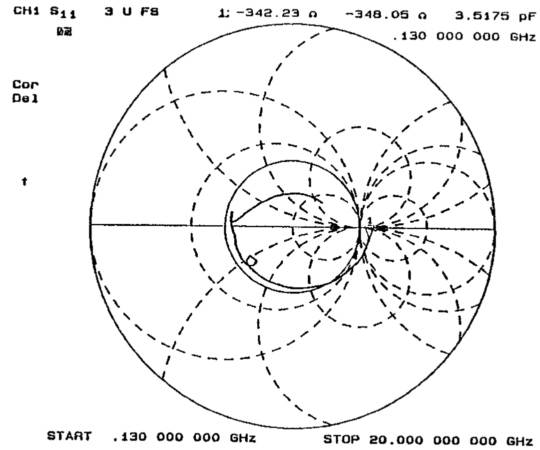

FIGURE 3. Results of microwave measurements on the 5 μm diameter device with 15% indium well at 0.58 V bias (in NDR Region)

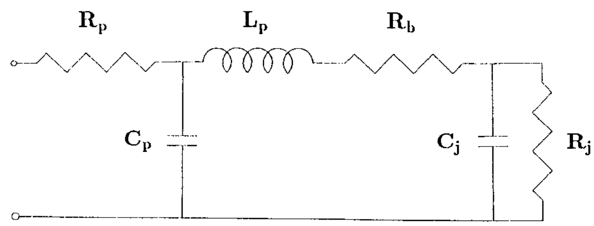

FIGURE 4. The equivalent circuit for the fixture and diode used in TOUCHSTONE to model the measurements. The element values are L_p=.25 nH, R_b=3 Ω, C_p=.25 pF, R_p=3 Ω, and C_{sh+j}=1.45 pF, R_j=-640 Ω.

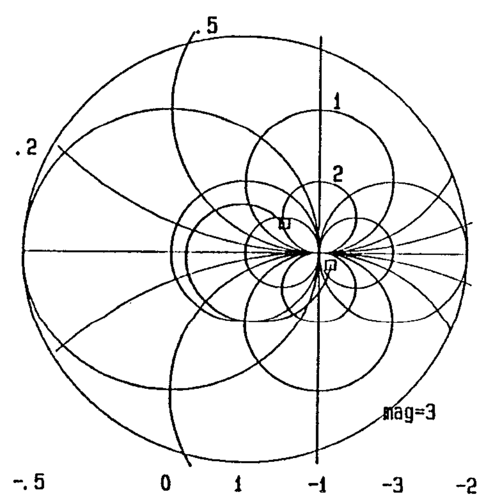

FIGURE 5. Results of the simulation of the RTD in the test fixture using the equivalent circuit shown in Fig. 4.