Tunnel Diode Non-Linear Model for Microwave Circuits and Active Antennas

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Abstract — **Tunnel Diodes have a unique property: Negative Differential Resistance (NDR). The integration of tunnel diodes with other electronic devices create novel, quantum functional devices and circuits. The enhanced functionality of these devices enables design of both digital and analog circuits with reduced complexity, size and better performance. In this paper we investigate the applications of a non-linear, large signal model of the tunnel diode. This model is used to analyze tunnel diode characteristics under external conditions such as input RF signal and termination resistance. We also discuss the application of the model to simulate quantum-MMIC circuits. VCO's, and active antennas designed using tunnel diodes show power outputs in the range of –4 to –10 dBm in the 1-2GHz band. The DC to RF conversion efficiency is about 8% in VCO's and 16% in the antennas.**

I. Introduction

The attraction of portable communication devices has created a tremendous demand for smaller, faster and better integrated circuits and wireless systems. The requirements of flexibility and fast accesses to data are the driving forces for the introduction of advanced applications at higher and higher frequencies. These applications make severe demands on the technology required to implement them, with current solutions involving a mixture of technologies. One such new technology is the use of tunnel diodes [1-5]. These are semiconductor devices with a unique property: Negative Differential Resistance-NDR (Figures 1 and 3). Many novel devices that benefit from this unique property have been proposed and implemented by integrating tunnel diodes with other semiconductor devices such as HFET's. The added functionality allows the design of new and better circuits with reduced complexity and size. Many microwave circuits using tunnel diodes have been demonstrated: voltage controlled oscillators (VCO), power amplifiers, mixers, and smart antennas [6-8].

To exploit the potential of tunnel diodes, accurate models are required. The circuit model discussed in this paper is a comprehensive DC/RF, non-linear model [9]. It is extracted from on-wafer diode DC and RF characterization using Agilent ICCAP. The model is implemented in Agilent Advanced Design System (ADS) for VCO design and in a Finite Difference Time Domain (FDTD) scheme for active antenna design [10]. This

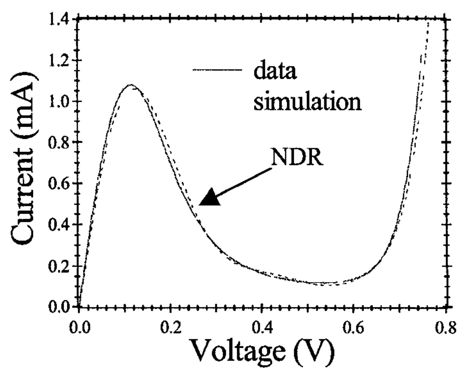

Figure 1: DC Current-Voltage characteristics of a tunnel diode showing the negative differential resistance (NDR) region. The solid line is experimental data and the dotted line is simulation result of the non-linear model.

model enables us to get useful physical insight into tunnel diode and MMIC circuit characteristics.

In section II we introduce the non-linear model of a

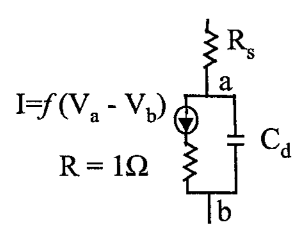

Figure 2: Non-linear model of a tunnel diode.

tunnel diode and analyze the model under different conditions such as external RF signal and biasing network. Section III discusses the application of the model to simulate some circuits containing tunnel diodes. VCO's and active antennas are considered as examples.

II. Tunnel Diode Non-Linear Model

There are many types of tunnel diodes [5] such as interband homojunction Esaki type diodes [1,2], interband heterojunction tunnel diodes [7] or intraband resonant tunneling diodes [3,4]. They have been realized in many different material systems. The basic device characteristics of all of them however are similar. The DC current–voltage (I(V)) characteristics are shown in Figure 1 for a Heterostructure Interband Tunnel Diode (HITD) with one quantum well [7]. The tunnel diode is fabricated in the InGaAs/InAlAs lattice matched to InP material system and has a dimension of 2.5x2.5 μm^2. The strong non-linearity of the I(V) characteristics makes it a simulation challenge. The RF characteristics, namely the frequency dependence of the impedance of a tunnel diode at different voltage biases is shown in Figure 3. The real part of the impedance is negative at low frequencies when the diode is biased in the NDR regime (from 0.11 V to 0.54 V). This impedance is obtained from two port S parameter measurements of the diode.

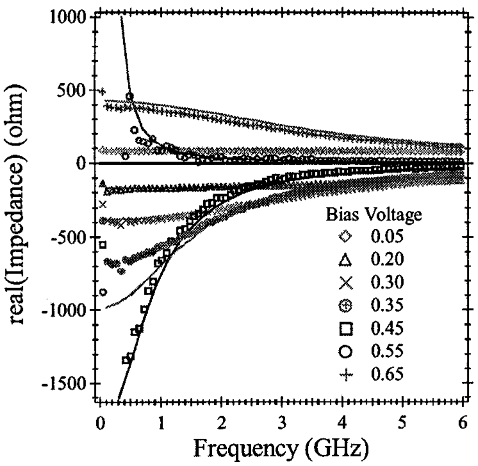

Figure 3. RF characteristics of the tunnel diode of figure 1, showing the real part of the impedance as a function of frequency at different voltage biases. The symbols are experimental data and the lines are simulation results.

A circuit as shown in Figure 2 models these characteristics. C_d is the capacitance of the diode and R_s is a parasitic series resistance. This is a comprehensive DC/RF model for tunnel diode and uses a voltage controlled current source (VCCS) to model the diode properties. This model is more than just a data based large signal RF model of a tunnel diode and it is compatible with DC simulation [4,9]. The model provides useful physical insight into the device operation. A polynomial fit to the DC current-voltage characteristics is used as the function $f(V_a-V_b)$. R_s and C_d are determined from a small signal measurement at one bias in the NDR region. For the diode characteristics shown in figure 1, they are 8 ohm and 0.1pF respectively.

This model represents both the DC and RF properties of the diode with a high degree of accuracy. Figure 3 shows the comparison between the experimental data and the simulation results of the RF impedance-frequency characteristics of the tunnel diode of Figure 1. The simulation and the experimental data agree quite well over the entire bias range of the tunnel diode, in NDR region as well as out of it, and involving a wide change in the impedance values.

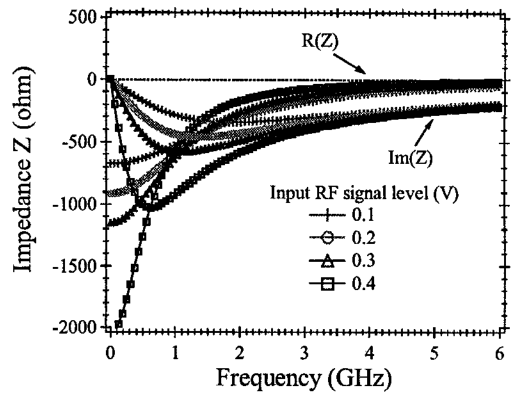

Figure 4: Simulation results of the effect of input RF signal level on real and imaginary parts of diode impedance. The applied DC bias voltage is 0.3 V.

The large signal model enables us to investigate the characteristics of the diode under an applied RF signal. The diode impedance is found to be dependent upon input RF voltage level for a given applied DC bias (Figure 4). When the input signal level is very high, the output current sweeps a larger span, resulting in larger negative resistance at low frequency and smaller cut off frequencies. This analysis is performed in time domain. A voltage pulse of a given magnitude is applied on top of the dc bias. The current through the diode is simulated using the large signal model. The impedance as a function of frequency is calculated from the Fourier transform of the current.

The non-linear model also enables us to investigate the stability of tunnel diodes. We observe that, particularly for tunnel diodes with high currents, the shape of the DC I(V) characteristics in the NDR regime is strongly dependent upon any external passive components and also on the biasing network. We also observe that it is not possible to obtain reliable RF S-parameter measurements on these diodes in that regime. These observations are indications of diode instability [11]. The strong non-linearity of a tunnel diode results in unwanted oscillations. Figure 5 shows the simulation results of a time domain analysis performed in ADS on the tunnel diode model. The simulation is performed for different values of termination resistance in the biasing circuit. We observe that for low values of termination resistance no oscillations are predicted by the simulation and the predicted DC I(V) is smooth. For higher values of the termination resistance the simulation predicts oscillations and the DC I(V) curve shape changes. This analysis suggests methods that can be utilized to stabilize circuits containing tunnel diodes.

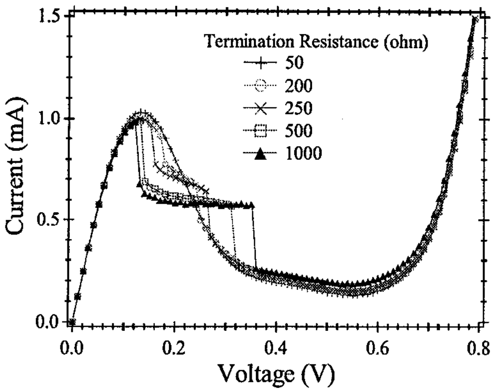

Figure 5: Simulation results of time domain analysis performed in ADS on the non-linear model of the tunnel diode. The effect of termination resistance in the biasing network on the shape of the DC characteristics is investigated.

III. TUNNEL DIODE APPLICATIONS

In this section we will discuss some applications of tunnel diodes designed using the large signal model. We have designed VCO's [12], amplifiers, mixers and antenna arrays [13] using this model. VCO's and antennas are natural applications for tunnel diodes. The non-linearity and NDR of the tunnel diode is tuned by an external circuit to obtain well-defined oscillations in these applications.

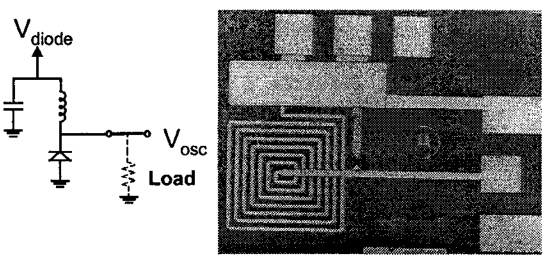

Figure 6: Schematic and layout of a VCO circuit.

In a VCO the tuning is done by on chip capacitors and inductors. One example is shown in Figure 6. Harmonic balance analysis using ADS on the non-linear model of the diode is used to simulate this circuit. We have experimentally realized VCO's with frequency of oscillation between 1-2 GHz and power outputs as high as –4 dBm and phase noise of –115 dBc/Hz 1 MHz away from the center. The DC-to-RF conversion efficiency is around 8%. In another design this VCO circuit is improved by introducing a gain stage consisting of an integrated HFET to buffer and enhance the oscillation output. Power outputs as high as 10 dBm are observed [12]. These VCO's act as building blocks for higher level multifunctional integrated circuits such as self-oscillating mixers and receivers.

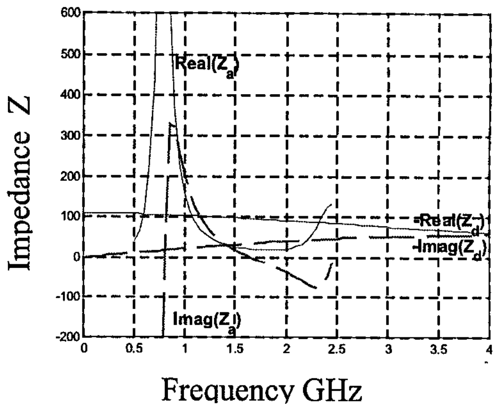

Figure 7: Simulated impedance of active antenna board (Z_a) and tunnel diode (Z_d). Negative of Z_d is plotted for easy comparison. Antenna layout is shown in the inset of Fig. 8.

In an active antenna the oscillator and radiator are coupled. Oscillations occur when the imaginary part of the antenna board impedance is cancelled by the imaginary part of the tunnel diode impedance. If the real part of the diode impedance is negative and more in magnitude than the real part of the board impedance then oscillations are sustained.

Figure 7 shows the simulation of one of the active antennas using FDTD. The FDTD scheme is run twice. In the first run passive structures including matching transmission lines, are simulated and the driving point impedance, where the diode is to be inserted, is obtained. Then, the input impedance is compared with the diode impedance to find potential oscillation points. Figure 7 shows the antenna slot input impedance (Z_a,) and the negative of the tunnel diode impedance (-Z_d). We see that the imaginary parts are cancelled at a frequency of 1.42

GHz, while the diode has enough negative real part of the impedance at that frequency to sustain the oscillations.

With the knowledge obtained from first simulation, a second run is undertaken by adjusting the FDTD parameters in order to achieve the desired oscillation frequency. When the second run is completed, the instant field at one mesh point in the vicinity of structure is recorded. The oscillation frequency is found very close to the one obtained in figure 7. The designed circuit was fabricated and tested. The measured oscillation frequency is 1.4744 GHz, as shown in figure 8. The tunnel diode used in this antenna design and fabrication is different from the diode characteristics shown in figure 1. The measured oscillation frequency is in good agreement with the simulation data.

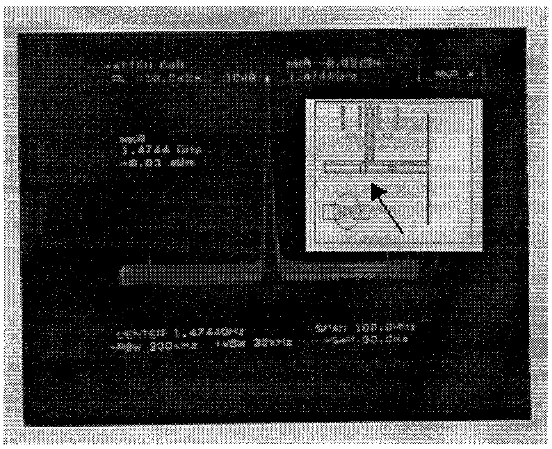

Figure 8: Frequency spectrum of an active antenna using a 5x5 um^2 diode. Bias voltage is 0.37 V and current 2.11mA. The antenna oscillates at 1.4744GHz with a power output of -8.83 dBm giving 16.7% DC to RF conversion efficiency.

Increasing the length of the slot antenna shifts Z_a towards lower frequencies, and hence the crossing point of $-Z_d$ and Z_a will also shift to the left in figure 7. This results in a lower oscillation frequency. This phenomenon was observed in the experiment by adjusting the slot length. It is interesting to note that the active antenna oscillation frequency is higher than the passive antenna resonant frequency, which is 810.0 MHz in the case as shown in figure 7.

IV. Conclusion

A non-linear, large signal model of the tunnel diode is implemented in the ADS simulation tool. This model is used to investigate tunnel diode characteristics. The model is utilized in harmonic balance analysis to simulate VCO's. A FDTD scheme is used along with the diode model to simulate active antennas.

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