A Spice Behavioral Model of Tunnel Diode: Simulation and Application

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Abstract

In this study, an analogue behavioural model (ABM) for a tunnel diode is presented. The Spice (ABM) controlled sources from which the Pspice parameters were retrieved are implemented as independent parameterized blocks. Moreover, a circuit analysis programme is used to simulate and suggest a tunnel diode-based oscillator. To demonstrate the Pspice model's accuracy, the behaviour of the tunnel diode is simulated and compared to the measured data. The simulated and experimental results showed good agreement.

Keywords*: Tunnel diode, tunnel diode oscillator (TDO), Spice simulation, resonant tunneling diode (RTD), Analog Behavioral Modeling (ABM)*

1. Introduction

A tunnel diode was created by Leo Esaki and is also referred to as the "Esaki diode" in honour of its creator. It is a two terminal P-N junction diode with strong conductivity that has been highly doped—about 1000 times more so than a typical junction diode. Depletion layer width has been drastically decreased due to extensive doping to a value of 1/10000 m. A region of negative differential resistance can be seen on a TD I-V curve when a DC voltage is supplied during forward bias operation. At low voltages (< 0.5 V in Figure 1) electrons from the conduction band of the n-side will tunnel to the hole states of the valence band of the p- side through the narrow p - n junction, creating a forward bias tunnel current. In this region the energy of the potential barrier is high, while the energy of the electron and conduction bands overlap. As the voltage increases, the region where the energy of electrons in the conduction band overlap with the hole band starts to decrease and leads toa decrease in the tunneling current. This is the negative differential resistance region marked by the red line in Figure 1. At higher voltages the potential barrier decreases and the TD produces a forward diffusion current as seen in a regular p - n diode. The negative differential characteristic feature allows a TD to function as a low current ac powersource capable of very fast operation (GHz).

Following Esaki's discovery, tunnel diodes have received interest because of their remarkable multivalued I-V characteristic and inherent high switching speeds. They have been used in circuits such as amplifiers [1], oscillators, pulse generators, and analog-to-digital converters (ADCs) [2]. More recently it has been shown that incorporating tunnel diodes (Esaki diodes or resonant tunneling diodes (RTDs)) with transistors can improve circuit performance, by increasing the speed of signal processing circuitry or decreasing power consumption at the same speed. A variety of these hybrids III – V transistor/RTD circuits have been demonstrated, *e.g.*, ADCs and oscillators. A new tunnel diode differential comparator has been proposed which lowers power dissipation by a factor of two relative to a transistor-only comparator while also increasing speed [3].

Tunnel diodes are usually fabricated from germanium, gallium arsenide, or gallium antimonide [4]. Silicon is not used in the construction of tunnel diode because Ip/Iv is maximum in case of Gallium arsenide. (Ip=Peak value of forward current and I_V= Valley current). This ratio is very small for silicon and is of the order of 3. Ordinarily they are manufactured by alloying from gallium arsenide. Source materials are highly doped semiconductor crystals with an impurity concentration of the order 1025 per cubic meter.

Although PSpice does not include a built-in model for a resonant tunneling diode, various ways can be used to implement and incorporate a suitable RTD model [2]. Three different ways have been used in the present work to obtain a Spice behavioral model for the RTD. They are all based on the experimental I –V characteristics of the RTD and its large signal equivalent circuit. This model is then used to simulate a variety of circuits consisting mainly of a sinusoidal signal generator, a three state OR gate, a three state inverter and a frequency multiplier. The analyzed circuits are characterized mainly by their reduced complexity and ease of analysis.

2. Tunnel Diode Current-Voltage Characteristic

For circuit simulations a SPICE (Simulation Program for Integrated Circuits Emphasis) model is needed. The measured I-V characteristics of the interband Esaki tunnel diode are well described by the Broekaert resonant tunneling diode (RTD) Spice model [5]. The three current components have been discussed, Figure 1, can be unraveled by fitting the measured I-V characteristic, as shown for a commercial Ge tunnel diode. The first two terms in the Broekaert model are tunneling terms. The first term models the primary tunneling current giving rise to the peak in the I-V characteristic. The second term in the RTD models the second resonance state, which in the Esaki tunnel diode, models the excess, defect-assisted tunneling current. The third term in the Broekaert models describes the thermionic current. This fit to the Broekaert model was first shown in reference [6].

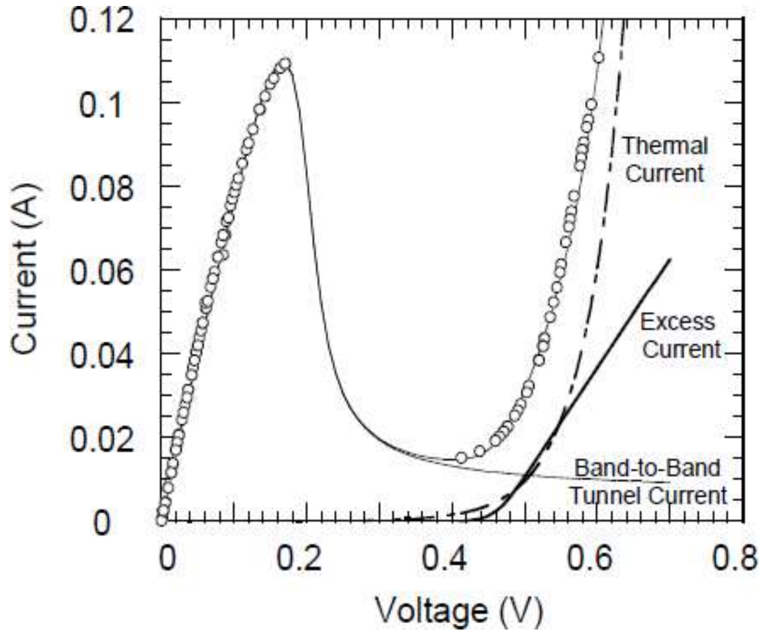
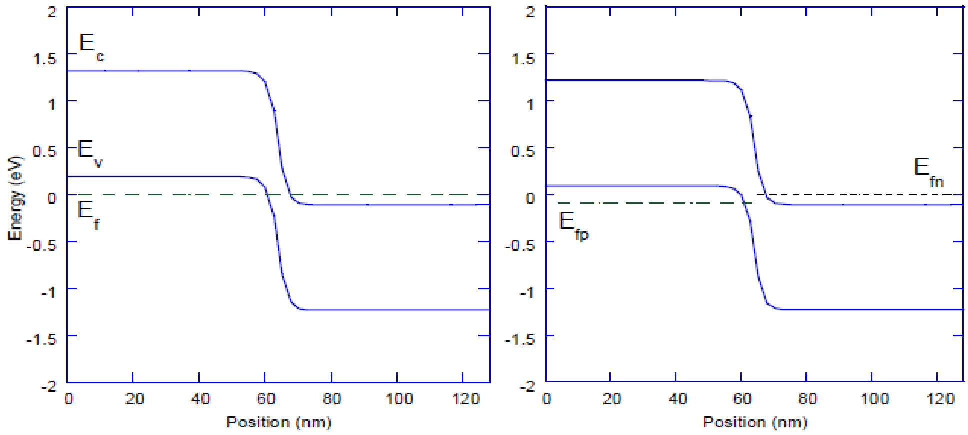


Figure 1. Measured Current-Voltage Characteristics (Open Circles) of a Geesaki Diode (TD266, Germanium Power Devices, Andover, MA). Three Current Components, Band-to-Band Tunnel Current, Excess/Valley Current, and Thermal/Diffusion Current, are shown

The behavior of the tunneling current in a degenerate p+ n+ junction can be understood by considering the computed energy band diagram of Figure 1 shown at zero bias in

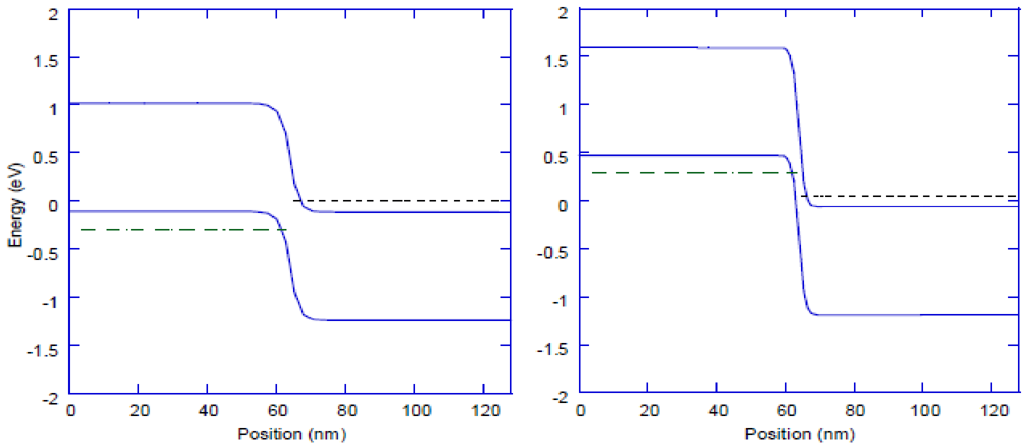
Figure 2 (a). When a forward bias is applied, Figure 2 (b), electrons in the n-type semiconductor can tunnel through the narrow depletion width to the available states in the p-type semiconductor and the current increases; the peak current density is achieved when the overlap between occupied states in the conduction band of the n-side and empty electron states in the valence band of the p-side is maximized.



(a) (b)

Figure 2. Computed Energy Band Diagram of an Abrupt P+N+ Junction with P And N Dopant Densities As 1 X 1020 Cm^{-3} for (A) Zero Bias, (B) Forward Bias of 100 Mv

A further increase in the forward bias causes a decrease in the tunneling current density until Ec on the n-side and Ev on the p-side align, Figure 2 (c), and there are no more states available to tunnel to as the electrons now see the forbidden gap. Defects in the semiconductor however, can lead to states in the forbidden gap and defect assisted tunneling, a phenomenon known as the excess current. Increasing the bias, increases the thermionic current as the built-in barrier reduces. Figure 2 (d) shows the reverse bias condition where Zener tunneling dominates and the current increases super-exponentially with reverse bias.



(c) (d)

Figure 3. Computed Energy Band Diagram of an Abrupt P+N+ Junction With P and N Dopant Densities As 1 X 1020 Cm^{-3} For (C) Forward Bias Of 295 Mv, And (D) Reverse Bias of -350 Mv

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3. Modeling the Esaki Tunnel Diode

The intrinsic Esaki tunnel diode model consists of an ideal tunnel diode a nonlinear capacitor and a nonlinear resistor, see Figure 4.

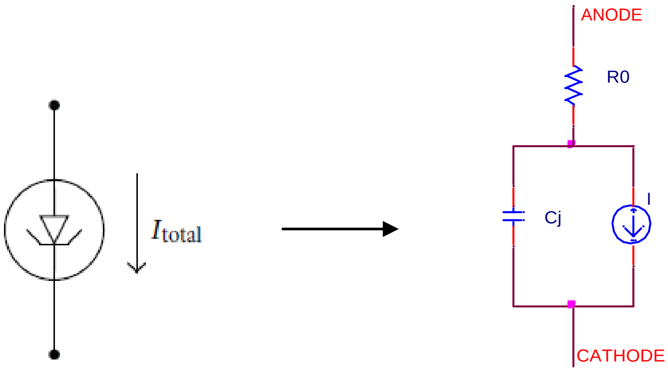


Figure 4. Esaki Tunnel Diode Circuit Model

An analytic expression for tunneling current density in a p+n+ junction is given by Sze [13] for the indirect tunneling case,

$$T = \frac{\sqrt{2}\,q^3 m^{*\frac{1}{2}} \xi V_a}{4.\pi^2 y^2 E_g^{\frac{1}{2}}} exp\left(\frac{-4\sqrt{2m^*}.(E_g - yw)^{\frac{3}{2}}}{3.\xi.q.y}\right) \quad (1)$$

Where q is the electron charge, m* is the carrier effective mass, ζ is the maximum junction electric field, Va is the applied reverse voltage, η = h/2π is Planck's constant, Eg is the bandgap of the semiconductor (for Si Eg = 1.12 eV at 300 K), and η.*w* is the phonon energy. The phonon term is small compared to the bandgap energy (0.063 eV for the optical phonon in Si) and can be ignored.

The depletion layer introduces a junction depletion capacitance, which is bias dependent and it is given by:

$$\frac{1}{C_n^2} = \frac{2(V_{bi} - V_J - 2V_T)}{A^2.q.\mathcal{E}.m^*} \quad (2)$$

Where Cn is the junction capacitance of tunnel diode, Vbi is the built-in potential voltage, Vj is the voltage across the p-n junction, V_T is the thermal voltage, A is junction area, q is the elementary charge and ε is the relative permittivity of the material used to form the tunnel diode.

The maximum electric field in an abrupt p-n junction, is related to the thickness of the depletion layer, W, by

$$\xi = \frac{2(V_{bi} - V_a)}{w} \quad (3)$$

Where V_{bi} is the junction built-in voltage. The depletion layer thickness is given by

$$w = \sqrt{\frac{2.\mathcal{E}}{q} \frac{V_{bi} - V_a}{N_{eFF}}} \quad (4)$$

Where N_{eff} is the effective doping density which can be calculated using

$$N_{eff} = \frac{N_A.N_D}{N_A + N_D} \quad (5)$$

Where the terms N_A and N_D are the acceptor and donor densities, respectively. Using Eqs. (4) and (5), the expression for electric field becomes

$$\xi = \sqrt{\frac{2.q.N_{eFF}}{\varepsilon}(V_{bi} - V_a)} \qquad (6)$$

From Equation (6), it is clear that to obtain a high electric field, high doping densities are required.

The tunnel diode current is typically described as the sum of three exponential functions derived from quantum mechanical considerations. This formulation appears in Sze [13], although here the physics is limited only to the forward-bias direction. Referring to Figure 1, this is expressed as

$$I_{tot} = \frac{(t)}{V_p} I_T + I_X + I_{TH} \qquad (7)$$

Where

$$I_T = I_p ex(1 - \frac{V(t)}{V_P}) \qquad (8)$$

$$I_X = I_V \exp(A_2(V(t) - V_V)) \qquad (9)$$

$$I_{TH} = I(\exp(\frac{q.Vt}{KT}) - 1) \qquad (10)$$

The first term is a closed-form expression of the tunneling current density which describes the behaviour particular to the tunnel diode. This includes the negative resistance region which captures the core functionality of the tunnel diode. The second term describes the excess tunneling current density while the third term is the normal diode characteristic. In (8), I_P is the peak current density and V_P is the corresponding peak voltage. In (9), IV is the peak current density and V_V is the corresponding peak voltage. The parameter A2 represents an excess current prefactor. Finally, in (10), IS is the saturation current density, q is the charge of an electron, K is Boltzmann's constant, and T is the temperature in degrees Kelvin.

The tunneling resistance can be obtained from the first part of equation (7) and is given by

$$R = (\frac{dI}{dV})^{-1} = -[(\frac{v(t)}{V_P} - 1)\frac{IP}{V_P}\exp(1 - \frac{v(t)}{V_P})]^{-1} \qquad (11)$$

When the tunnel diode is forward biased, the point at which the negative slope is maximum gives the minimum negative resistance. This value can approximate as follows:

$$|R_{min}| = \frac{2V_p}{I_P} \qquad (12)$$

This negative resistance is often exploited for switching, amplification and oscillation purposes, and therefore implemented in high speed switching circuits and microwave amplifier and oscillators. Typical values of the peak –to- peak valley current ratio (IP/IV) the peak voltage (VP), and the valley voltage (VV) of Ge, Si and GaAs tunnel diodes are listed in Table 1.

Table 1. Typical Parameters of Tunnel Diodes

Semiconductor	(I_P/I_V)	V_P(V)	V_V(V)
Ge	8	0.055	0.35
Si	3.5	0.065	0.42
GaAs	15	0.15	0.5

4. Analog Behavioral Model of Tunnel Diode

The tunnel diode has frequently been used as an example of SPICE device modeling using polynomials. The static current/voltage characteristic of the device contains a region of negative dynamic resistance. The transitions from positive to negative resistance and back again are smooth - there are no discontinuities in slope and the device does not exhibit hysteresis. The device is only operated in the vicinity of the negative resistance region; typically a span of one or two volts. These attributes make the device eminently suitable for polynomial representation (it is no coincidence that this device has been used for illustration so often in the past). Main characteristics of a tunnel diode current/voltage curve are peak voltage and current (Vp, Ip), valley voltage and current (Vv, Iv) and projected peak voltage (Vpp). Specific device parameters for this model: VP=50mV; Ip=5mA; Vv=370mV; IV=370uA; Vpp=525mV

Current flow in a tunnel diode is due to three distinct effects [8]: thermal current (analogous to a conventional diode), tunnel current (due to direct tunneling) and excess current (due to indirect tunneling). Writing these three terms in PSpice's extended syntax

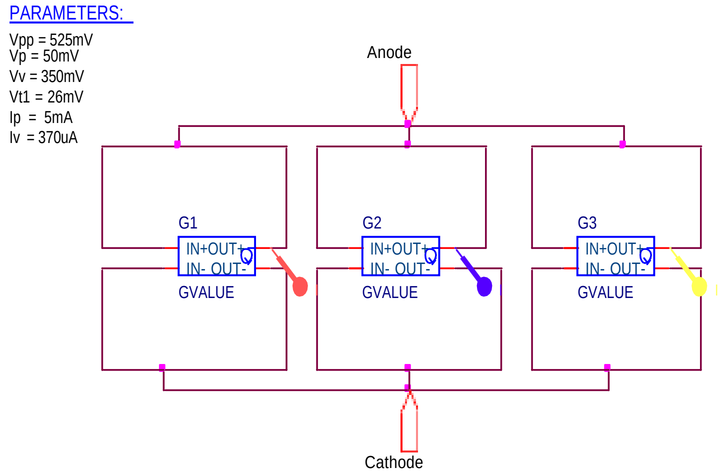


Figure 5. PSpice ABM Tunnel Diode Model

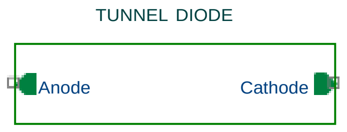


Figure 6. SPICE ABM Tunnel Diode Model Inserted in Spice Library

5. Simulation Results

The parameterized Esaki tunnel diode model described above was implemented in Spice library [9]. Simulated I-V characteristics of the tunnel diode using the parameter values in Table 2.

Table 2. Esaki Tunnel Diode Parameters Used in Transient Simulation

Parameter	Value
V_{PP}	525mV
I_P	4mA
I_V	370uA
V_V	370mV
V_P	50mV

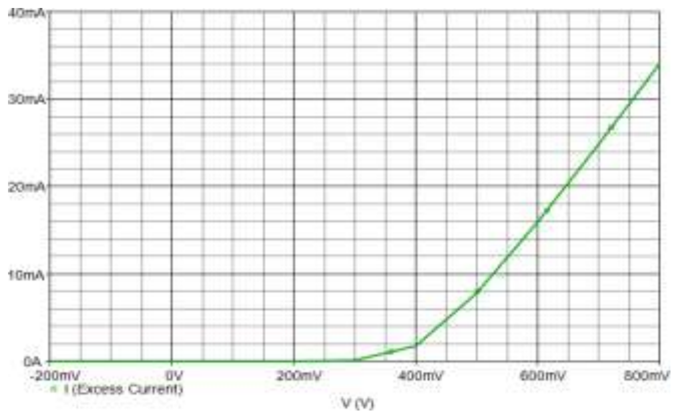


Figure 7. Simulated Excess Current of Tunnel Diode Model (I_{Excess})

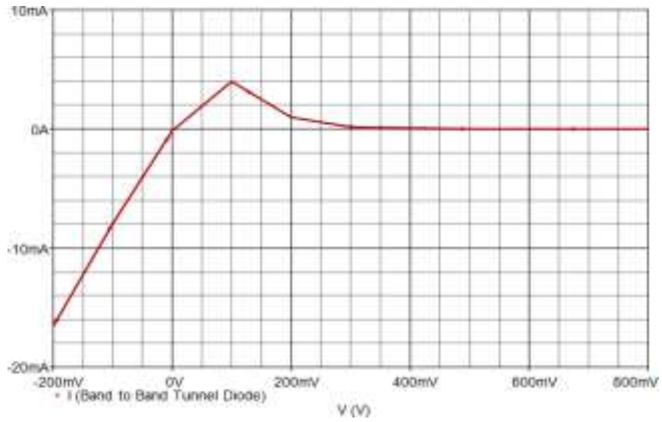


Figure 8. Simulates Band to Band of Tunnel Diode Model (IX)

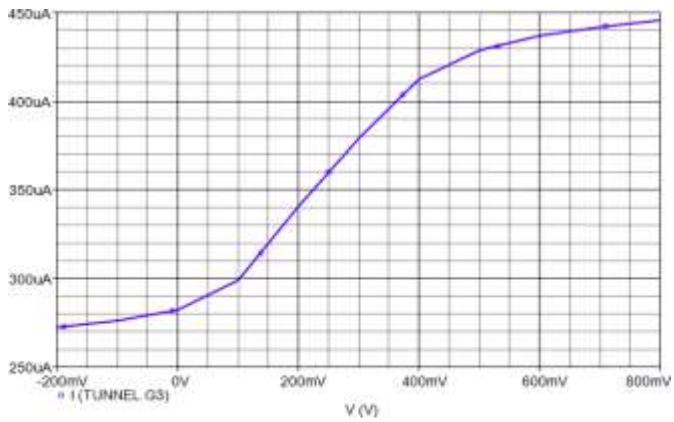


Figure9. Simulated Thermal Current of Tunnel Diode Model (I_{TH})

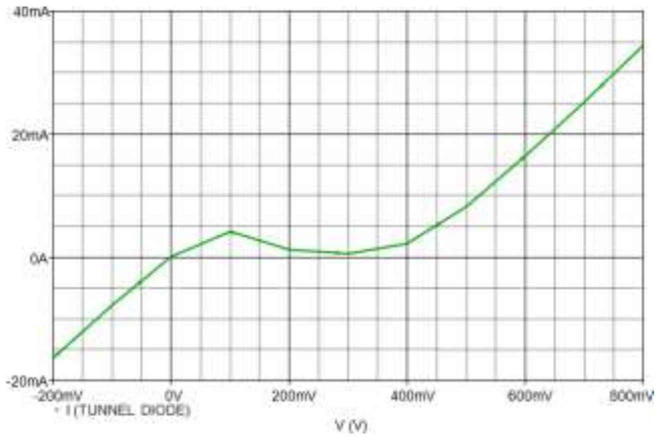


Figure 10. Simulated Forward Tunneling Characteristics of Tunnel Diode (I_{tot})

6. Tunnel Diode Oscillator Circuit

The term oscillator is used to describe a circuit which will produce a continuing, repeated waveform without input other than perhaps a trigger [10]. There are many ways to create oscillator circuits. A simple TD oscillator is shown in figure 11 including the load RL, which also accounts for circuit losses, and the parallel tank circuit which determines the frequency of oscillations,

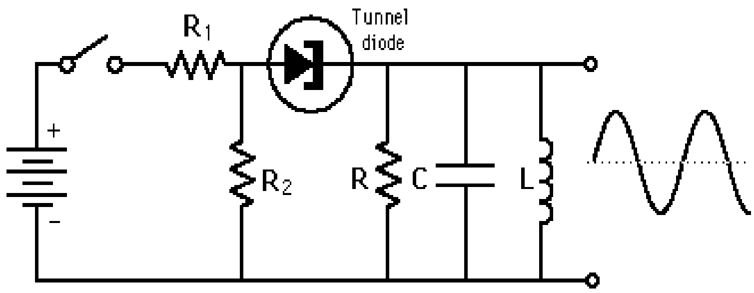


Figure 11. Oscillator Circuit Used for Transient Simulation

The principle of the tunnel diode oscillator (TDO) can be briefly described as follows. An LC-tank circuit is maintained at a constant amplitude resonance by supplying the circuit with external power to compensate for dissipation. This power is provided by a tunnel diode that is precisely forward biased with a voltage in the region of negative slope of its I-V characteristic, or the so-called negative resistance region. Such an arrangement makes it a self-resonant circuit as the power supplied by the diode maintains continuous oscillation of the LC-tank operating at a frequency given by the standard expression,

$$w = \frac{1}{\sqrt{L.C}}$$

7. Validation Model

The parameterized Esaki tunnel diode model was implemented in a Spice circuit simulator. A transient simulation was also performed on a canonical oscillator circuit containing the tunnel diode to demonstrate the switching characteristics of the device. The circuit used along with the values of the components is shown in Figure 12. A snapshot of the simulated output voltage versus time in Figure 11 shows the circuit oscillating at approximately 150 MHz.

The circuit of Figure 12 was simulated using the Pspice 10.5 simulator with the following circuit elements and bias conditions: R1 =280Ω, R2=20Ω, R3=1KΩ, L = 100 nH, C1=100nF and V1 = 1V.

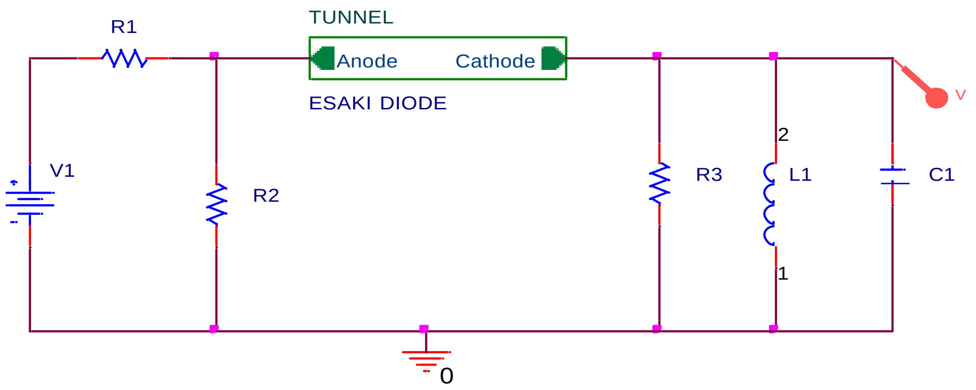
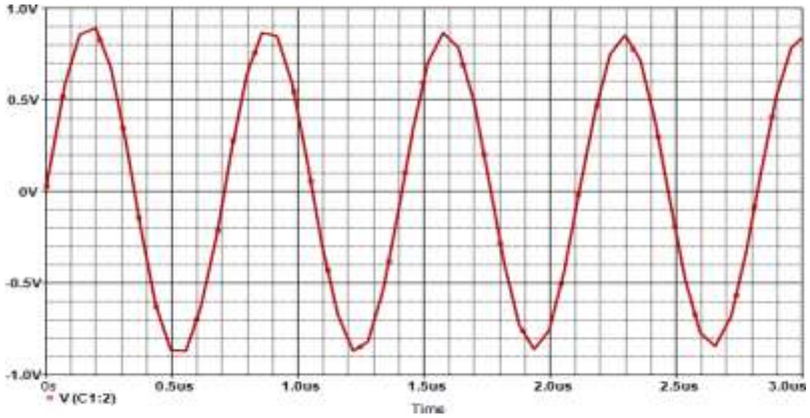
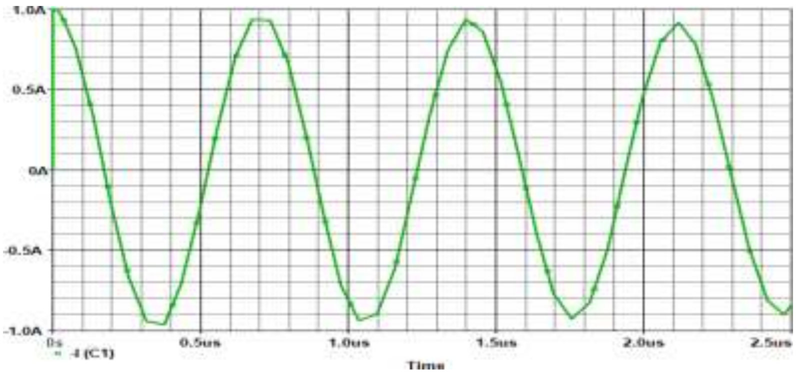


Figure 12. Tunnel Diode Based Oscillator Used in Spice Simulations

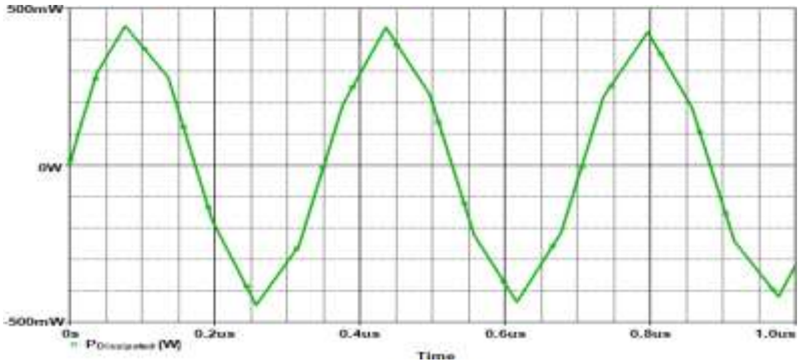
The principle of operation of the circuit is as follows: The tunnel diode has DC instability in its (NDR) region [11]. This means that if the tunnel diode is DC biased in the NDR region of its characteristic, it will oscillate; the oscillations resonant with the LC tank are selected.



a) Voltage Waveform

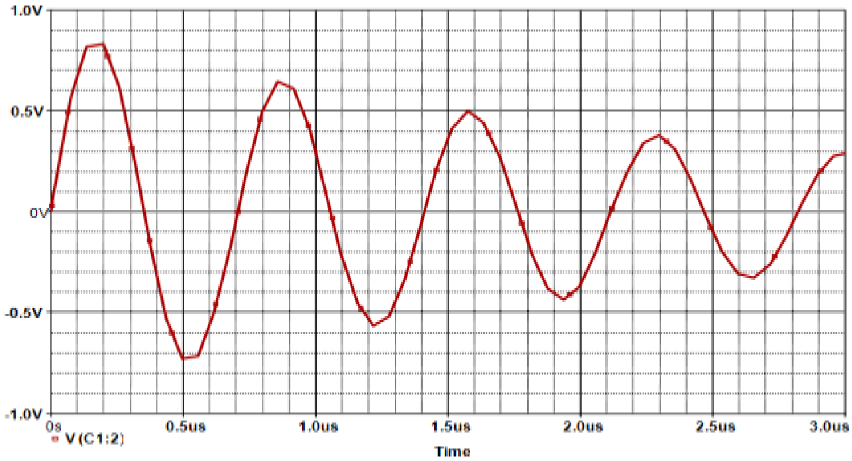


b) Current Waveform

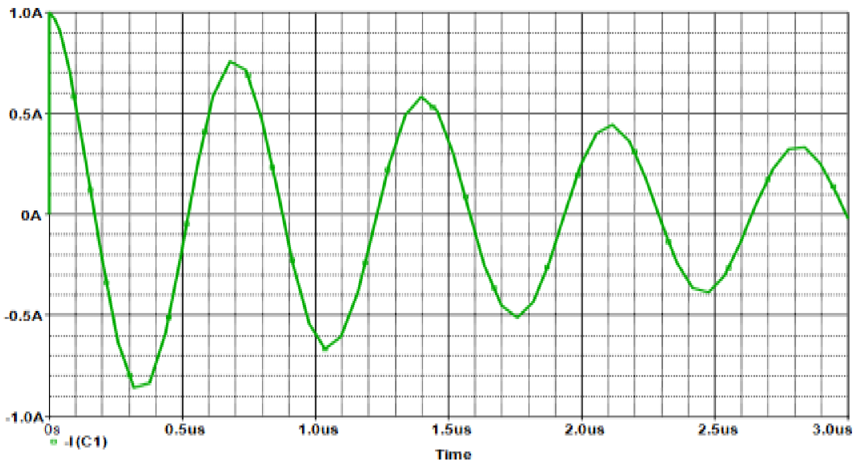


c) Power loses waveform

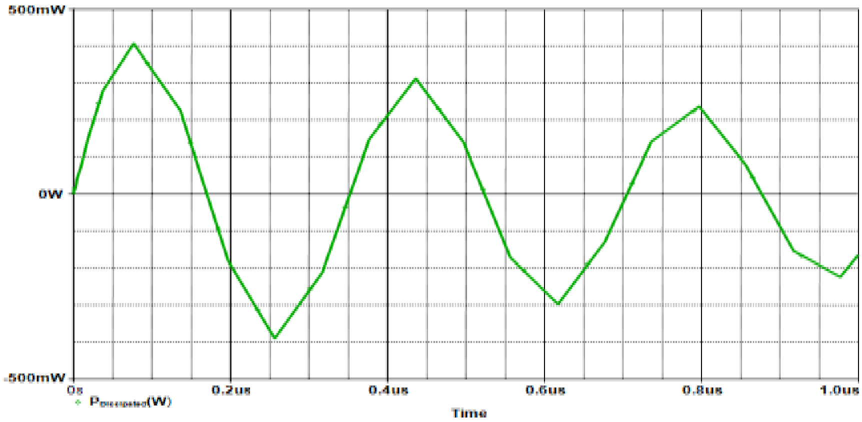
Figure 13. Simulation Results of the Tunnel Diode Oscillator Circuit with R1>R2



a) Voltage Waveform



b) Current Waveform



c) Power Loses Waveform

Figure 14. Simulation Results of the Tunnel Diode Circuit with R1<R2

Figure 12 and 13 show the output signal trace of voltage, current and power loses with the TDO operating at a resonance frequency around 6 MHz. A clean nearly sinusoidal waveform is apparent with a peak-to-peak amplitude of around 90mV. The amplitude can be adjusted by tuning the diode bias voltage in the narrow.

8. Conclusion

In conclusion, the current-voltage characteristics of a tunnel diode were simulated and analyzed. Based on these simulations and the equivalent circuit of the tunnel diode, a Spice compatible model was created using the analog behavioral modeling (ABM) option. The model was used with other components to build an oscillator and investigate its performance. The basic advantage of the proposed model lies in its immanent simplicity and flexibility as to be implemented in modern simulators, adopting Spice programming (such as Berkeley Spice, Pspice).

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