

# PSpice Implementation of a New Esaki Tunnel Diode Macro-Model

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## Abstract

*Tunnel diode is a very important device in industry but it is very difficult to simulate it using any circuit-simulation program. This paper proposes an Analog Behavioral Model (ABM) in Pspice of a tunnel diode. The Pspice parameters are extracted and implemented by deriving the device parameters from the device structure. Most of the device parameters are calculated from estimated values. A tunnel diode based oscillator is also proposed and simulated using circuit analysis software. The model is validated by means of comparison with experimental measurements and with the results obtained from other reference model. Excellent agreement is demonstrated between measured and simulation responses. The proposed implementation can be used in a PSpice program, designed as a subcircuit which can be called when required by the main program.*

**Keywords:** *Tunnel diode (TD); Esaki diode; Analog Behavioral Modeling (ABM); Tunnel Diode Oscillator (TDO); Device Modeling; Spice Simulation; Resonant Tunneling Diode (RTD)*

## 1. Introduction

The tunnel diode is a form of very fast semiconductor diode that can operate well into the microwave radio frequency region. It differs from other forms of semiconductor diode in that it uses a quantum mechanical effect called tunnelling. This provides the tunnel diode with a negative resistance region in its I-V characteristic curve that enables it to be used as an oscillator and as an amplifier [2].

Although they are not as widely used as some devices today, these devices do have their place within RF technology. They were used in television receiver front end oscillators and oscilloscope trigger circuits, *etc* They have been shown to have a very long life and can offer a very high level of performance when used as an RF pre-amplifier. However today, their applications are often limited because more traditional three terminal devices can offer a better level of performance in many areas [2].

The tunnel diode was discovered by a Ph.D. research student named Esaki in 1958 while he was investigating the properties of heavily doped germanium junctions for use in high speed bipolar transistors. In the course of his research Esaki produced some heavily doped junctions for high speed bipolar transistors and as a result he found that they produced an oscillation at microwave frequencies as a result of the tunnelling effect. Then in 1973, Esaki received the Nobel Prize for Physics for his work on the tunnel diode [3].

After the work by Esaki, other researchers demonstrated that other materials also showed the tunnelling effect. Holonyak and Lesk demonstrated a Gallium Arsenide device in 1960, and others demonstrated Indium tin, and then in 1962 the effect was demonstrated in materials including Indium Arsenide, Indium Phosphide and also Silicon.

Tunnel diodes are usually fabricated from germanium, gallium arsenide, or gallium antimonide [4]. Silicon is not used in the construction of tunnel diode because  $I_p/I_v$  is maximum in case of Gallium arsenide. ( $I_p$ =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  $10^{25}$  per cubic meter. Although the tunnel diode appeared promising some years ago, it was soon replaced by other semiconductor devices like IMPATT diodes for oscillator applications and FETs when used as an amplifier. Nevertheless the tunnel diode is a useful device for certain applications. Applications of the tunnel diode included uses as an oscillator, although it was also used as an amplifier and a mixer. One of the major advantages of the tunnel diode which is currently beginning to be experienced is its longevity. Once manufactured its performance remains stable over long periods of time despite its use. Other devices might degrade slightly over time.

As we know the library of the PSpice does not include a model of tunnel diode, many ways can be used to implement and incorporate a suitable tunnel diode model. An Analog Behavioral Model (ABM) method has been used in the present work to obtain static and dynamic characteristics for the tunnel diode. They are all based on the experimental I–V characteristics of the tunnel diode. This model is then used to simulate an oscillator circuit used for transient simulation.

## 2. Tunnel Diode Theory Basics

The characteristic curve for a tunnel diode shows an area of negative resistance. When forward biased the current in the diode rises at first, but later it can be seen to fall with increasing voltage, before finally rising again.

It is also interesting to note that current also flows in the reverse direction - the reverse breakdown voltage is actually zero and the diode conducts in the reverse direction. The characteristics near the origin are virtually symmetrical.

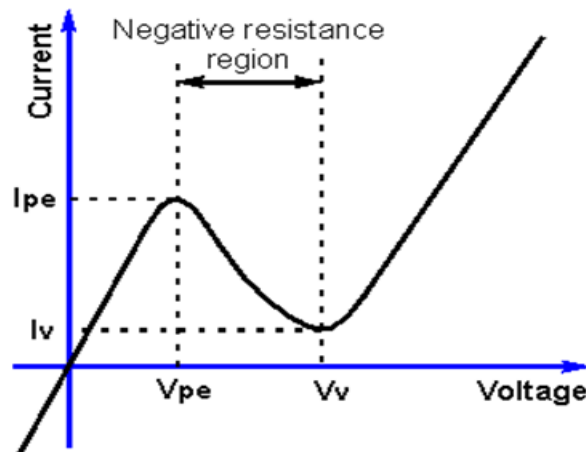


Figure 1. Tunnel Diode I-V Characteristics

The important parameters of the I-V characteristics are

- The peak current ( $I_p$ )
- Valley current ( $I_v$ ),
- Peak voltage ( $V_p$ ),
- Valley voltage ( $V_v$ ) which can be derived from the diagram. The ratio of  $I_p$  to  $I_v$  determines the signal amplitudes.

## Tunnel Diode Structure Basics

The tunnel diode is similar to a standard p-n junction in many respects except that the doping levels are very high. Densities of the order of  $5 \times 10^{19} \text{ cm}^{-3}$  are common.

A further difference is that the depletion region, the area between the p-type and n-type areas, where there are no carriers is very narrow. Typically it is in the region of between five to ten nano-metres, which equates to a width of only a few atoms. As the depletion region is so narrow this means that if it is to be used for high frequency operation the diode itself must be made very small to reduce the high level of capacitance resulting from the very narrow depletion region.

In terms of the material used for these diodes, the favoured semiconductor is germanium. Although other materials can be used and have been used, germanium has the advantage that it has a small energy gap that allows for more efficient tunnelling.

The reason for this is that there are a number of different components to forming the overall curve.

- Normal diode current: This is the 'normal' current that would flow through a PN junction diode.
- Tunnelling current: This is the current that arises as a result of the tunnelling effect.
- Excess current: This is a third element of current that contributes to the overall current within the diode. It results from what may be termed excess current that results from tunnelling though bulk states in the energy gap, and means that the valley current does not fall to zero.

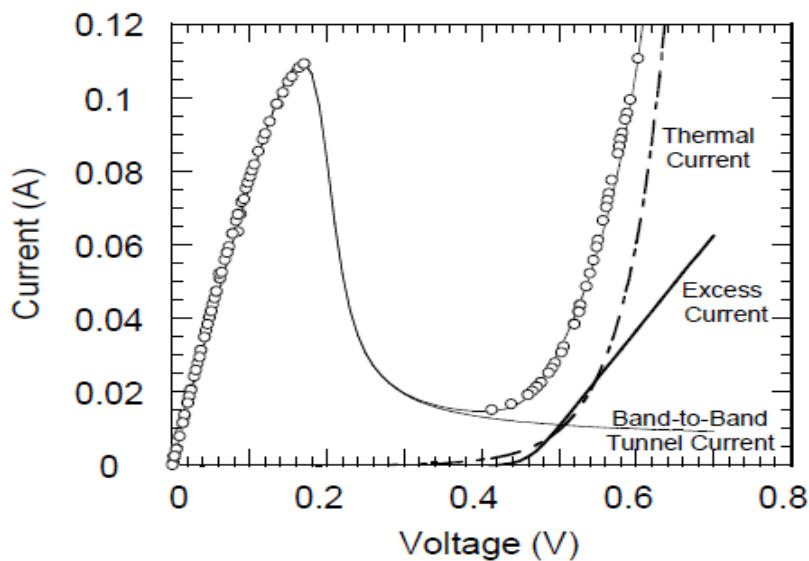


Figure 2. Tunnel Diode Current Components

## 3. Tunnelling Diode Effect

Tunnelling is an effect that is caused by quantum mechanical effects when electrons pass through a potential barrier. It can be visualised in very basic terms by them "tunnelling" through the energy barrier. The tunnelling only occurs under certain conditions. It occurs within tunnel diodes because of the very high doping levels employed. At reverse bias, the electrons tunnel from the valence band in the p-type material to the conduction band in the n-type material, and the level of the current increase monotonically. For the forward bias situation there are a number of different areas. For voltages up to  $V_{pe}$ , electrons from the conduction band find increasing

availability of empty states in the valence band and the level of current increases up to a point where the current equals  $I_{pe}$ .

Once this point is reached, it is found that number of empty states available for electrons with the level of energy they are given by the increased voltage level starts to fall. This means that the current level falls in line with this. The overall current level falls away relatively swiftly, dropping to near zero. As the current from the tunneling effect falls, so the diffusion current, which is the same action as occurs in a normal PN junction diode starts to increase and steadily becomes the dominant mechanism.

#### 4. Tunnel Diode Characteristics

The diagram towards the top of the page shows the tunnel diode  $I_V$  characteristic. This has a form of 'N' shaped curve. With an area of negative resistance between the peak voltage,  $V_{pe}$  and the valley voltage  $V_v$ .

The values for these voltages depend upon the diode material and also upon its individual characteristics.

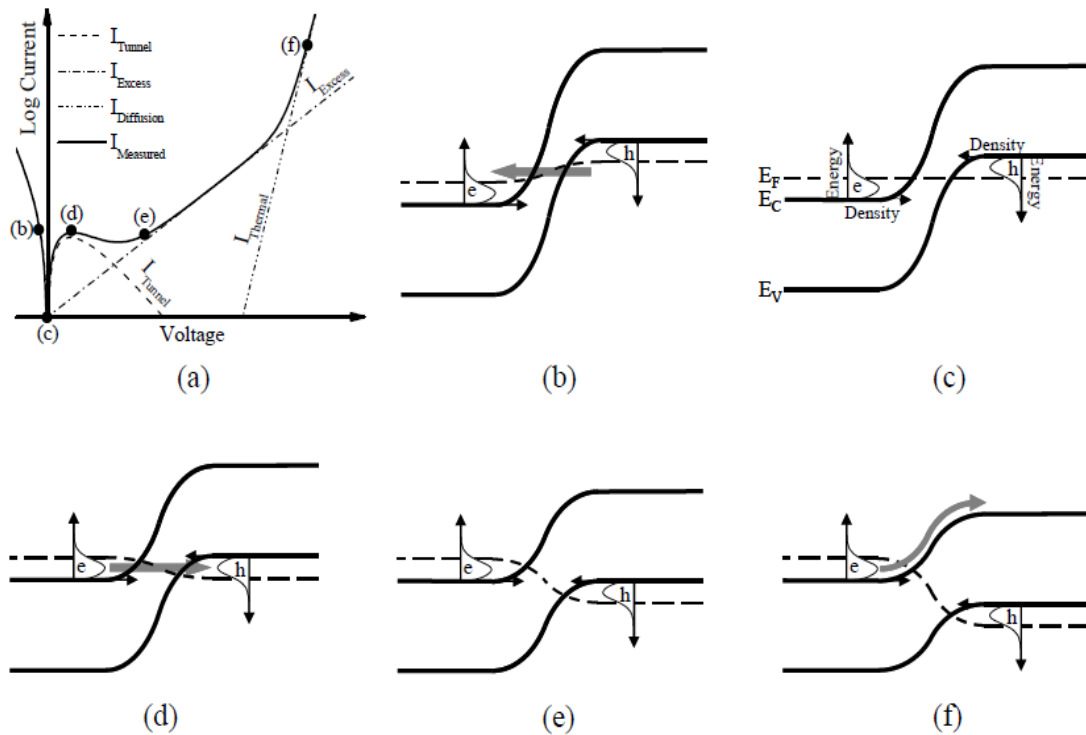
**Table I: Tunnel Diode Properties**

Tunnel diode properties for different materials			
Parameter	Germanium	Gallium arsenide	Silicon
$V_{PE}$ (mV)	40-70	90-120	80-100
$V_V$ (mV)	250-350	450-600	400-500
$I_{pe}/I_V$	10-15	10-20	3-5

One of the useful figures of merit for a tunnel diode characteristic is the peak to valley current ratio,  $I_{pe} / I_V$ . From the values in the table it can be seen that silicon has a very low value and as a result, this means that it is not normally one of the best options for a tunnel diode.

#### 5. Tunnel Diode Current-Voltage Characteristic

In the 1950's, intensive investigation into the internal field emission of pn junctions in semiconductor materials was being performed. Of great interest was the relationship of the I-V characteristics and doping concentration of the p and n type regions. Chenoweth, and other research groups, systematically increased the doping concentration in pn junctions, looking at breakdown voltages. With large enough concentrations, the breakdown was shifted to below 1V. These diodes would start to conduct a greater current density in reverse bias than in forward bias, earning them the name of Reverse Diodes. Once the doping levels became degenerate for both terminals, Esaki began to notice a breakdown of 0 V in reverse bias. The forward bias characteristic would initially rise to a  $I_P$ , then exhibit NDR and fall to an  $I_V$ , and then rise again in the traditional thermal current. This is typical "N" shape characteristic was the first direct observation of quantum mechanical tunneling, earning Esaki the Nobel Prize in Physics in 1973.

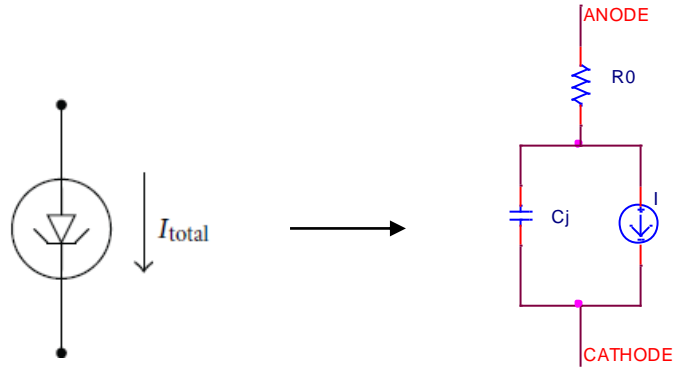


**Figure 3. (a) I-V Characteristic, and Schematic Band Diagram for (b) Reverse Bias, (c) Equilibrium, (d) Peak Tunneling Current, (e) Minimum Direct Tunneling Current, and (f) Thermal Current for a Generic ETD.**

Looking at the progression of the band structure for an ETD, the I-V characteristics become clear, Figure 3a. Without any applied bias, Figure 3c, the Fermi energy is flat and is above  $E_C$  on the n-type side and below  $E_V$  on the p-type side. Qualitative carrier density versus energy curves are provided for electrons and wholes. The pn junction has a very sharp bend. In reverse bias, Figure 3b, Zener tunneling occurs immediately, allowing for large amounts of current to flow. With a small amount of forward bias, electrons occupying states below  $E_F$  in the n-side can begin tunneling to unoccupied (holes) states above  $E_F$  on the p-side, Figure 3d. Eventually,  $E_C$  on the n-side is shifted above  $E_V$  on the p-side, which stops direct tunneling, Figure 3e. However, the current does not drop down to 0 A; instead, carriers tunnel via indirect paths resulting in an excess current (discussed in more detail in the paragraph Analog Behavioral Model of tunnel diode). Finally, after a large enough bias is applied, the pn junction starts to behave like a standard diode, and a thermal current begins to flow, Figure 3f. The doping profiles need to be very sharp so that the tunnel barrier, primarily the bending of the bands, is very sharp and on the order of 10 nm thick or less. This helps to promote a high probability of tunneling, and therefore a large  $I_p$ . Often, the tunnel barrier is approximated as triangular in shape. However, the procedure for calculating the tunneling probability is the same, except that the Wentzel-Kramers-Brillouin (WKB) approximation is used for the sloped portion of the potential. Additional affects to the tunneling probability depends on whether the semiconductor is a direct or indirect bandgap. Indirect bandgap materials require the addition of a momentum shift, usually from phonon interactions, in order to tunnel from the conduction band to valence band. Phonon-assisted tunneling is statistically less probable, and therefore  $J_p$  and consequently the PVCR is smaller than it would be for a direct bandgap material [5].

## 6. Model Spice of Tunnel Diode

Spice does not contain a model for the Tunnel Diode. To correct this omission, we used the macromodel shown in Figure 4. The intrinsic Esaki tunnel diode model consists of an ideal tunnel diode a nonlinear capacitor and a nonlinear resistor, see Figure 4.



**Figure 4. 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,

$$J_T = \frac{\sqrt{2} \cdot q^3 m^{* \frac{1}{2}} \varepsilon V_a}{4 \cdot \pi^2 \eta^2 E_g^{\frac{1}{2}}} \exp\left(\frac{-4\sqrt{2m^*} \cdot (E_g - \eta w)^{\frac{3}{2}}}{3 \cdot \xi \cdot q \cdot \eta}\right) \quad (1)$$

Where  $q$  is the electron charge,  $m^*$  is the carrier effective mass,  $\zeta$  is the maximum junction electric field,  $V_a$  is the applied reverse voltage,  $\eta = h/2\pi$  is Planck's constant,  $E_g$  is the bandgap of the semiconductor (for Si  $E_g = 1.12$  eV at 300 K), and  $\eta \cdot w$  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:

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

Where  $C_n$  is the junction capacitance of tunnel diode,  $V_{bi}$  is the built-in potential voltage,  $V_J$  is the voltage across the p-n junction,  $V_T$  is the thermal voltage,  $A$  is junction area,  $q$  is the elementary charge and  $\varepsilon$  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

$$w = \sqrt{\frac{2 \cdot \varepsilon \cdot V_{bi} - V_a}{q \cdot N_{eff}}} \quad (4)$$

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

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

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

$$\xi = \sqrt{\frac{2qN_{eff}}{\epsilon}}(V_{bi} - V_a) \tag{6}$$

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

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

Where

$$I_T = I_P \exp\left(1 - \frac{V(t)}{V_p}\right)$$

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

$$I_{TH} = I_S \left(\exp\left(\frac{qV_t}{KT}\right) - 1\right)$$

The first term is a closed-form expression of the tunneling current density which describes the behavior 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),  $I_V$  is the peak current density and  $V_V$  is the corresponding peak voltage. The parameter  $A_2$  represents an excess current prefactor. Finally, in (10),  $I_S$  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

$$R = \left(\frac{dI}{dV}\right)^{-1} = -\left[\left(\frac{v(t)}{V_p} - 1\right) \frac{I_P}{V_p} \exp\left(1 - \frac{v(t)}{V_p}\right)\right]^{-1} \tag{11}$$

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:

$$|R_{min}| = \frac{2V_p}{I_P} \tag{12}$$

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 ( $I_P/I_V$ ) the peak voltage ( $V_P$ ), and the valley voltage ( $V_V$ ) of Ge, Si and GaAs tunnel diodes are listed in Table I

**Table I: 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

## 7. Implementing Models in PSpice

PSPICE is often used for optimization of circuits and it is useful to have the ability to change the values of many passive components all together according to specific rules. Therefore we are going to create models of passive components whose values can be controlled by a voltage. This approach will also permit the simulation of components whose values depend on any voltage or current in the circuit or depend on time or any combination of them.

In order to run a new simulation, a simulation profile has to be created. In the simulation setting of the simulation profile, users need to use browser to add the Pspice lib file "Tunnel Diode.LIB" into the design library of the simulation configuration files, as shown in Figure 5. The Pspice model of the Tunnel Diode\_ABM is able to support both time domain transient simulation and AC frequency domain simulation. Users can set both configurations in the simulation profile.

## 8. 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 ( $V_p$ ,  $I_p$ ), valley voltage and current ( $V_v$ ,  $I_v$ ) and projected peak voltage ( $V_{pp}$ ). Specific device parameters for this model:  $V_p=50\text{mV}$ ;  $I_p=5\text{mA}$ ;  $V_v=370\text{mV}$ ;  $I_v=370\mu\text{A}$ ;  $V_{pp}=525\text{mV}$

Current flow in a tunnel diode is due to three distinct effects: thermal current (analogous to a conventional diode), tunnel current (due to direct tunneling) and excess current (due to indirect tunneling).

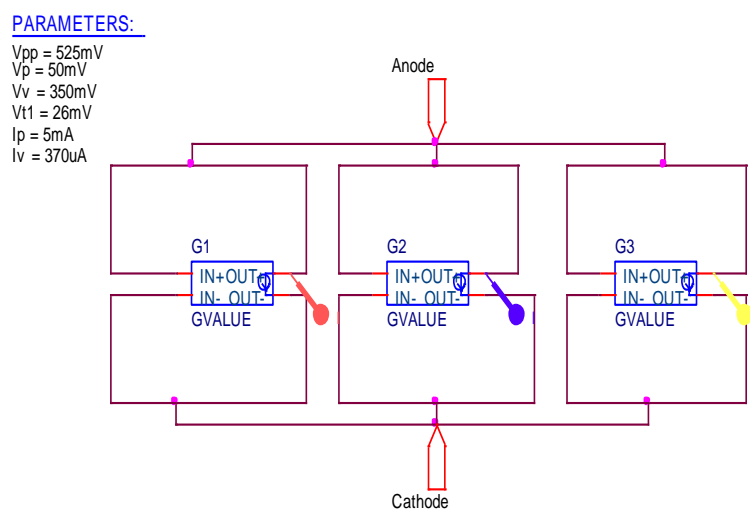


Figure 5. PSpice ABM Tunnel Diode Model





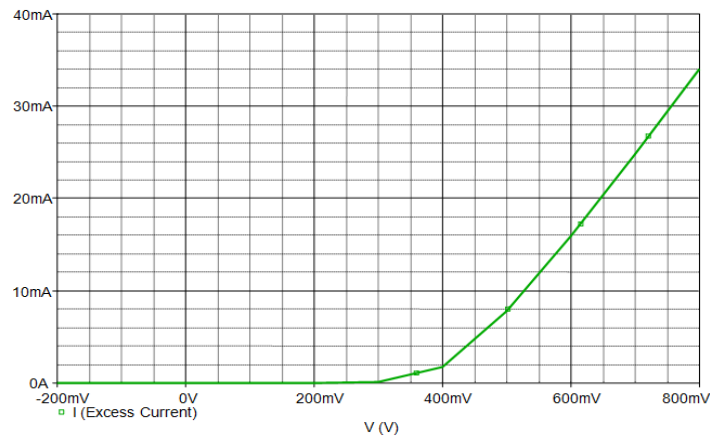
**Figure 6. SPICE ABM Tunnel Diode Model Inserted in Spice Library**

### 9. Simulation Results

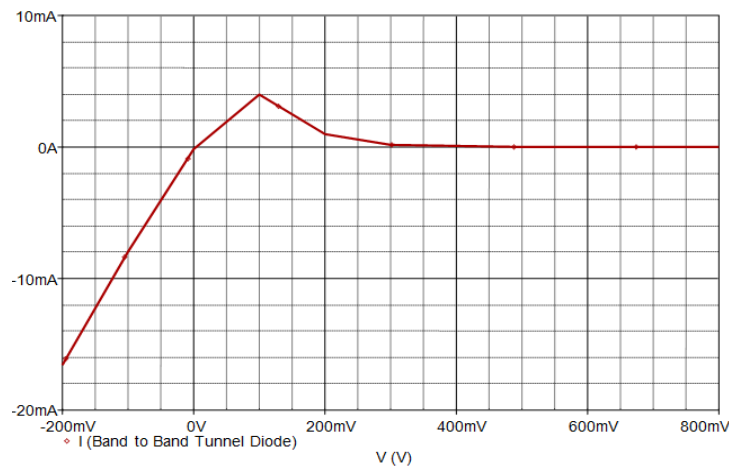
The parameterized tunnel diode model described above was implemented in Spice library. Simulated I-V characteristics of the tunnel diode using the parameter values in Table II

**Table II: Esaki Tunnel Diode Parameters Used in Transient Simulation.**

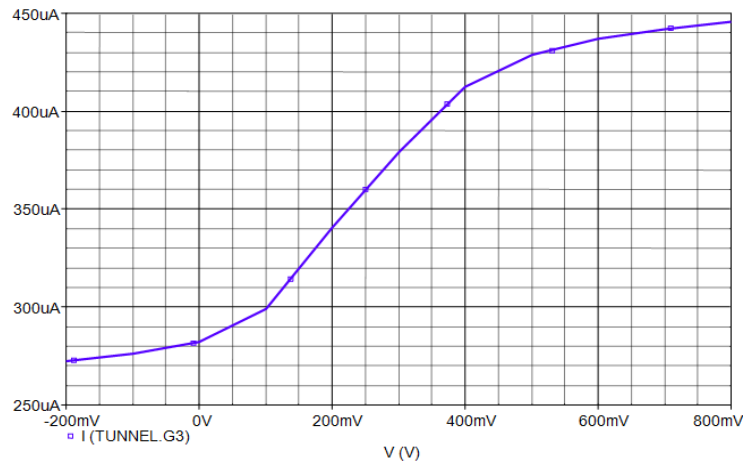
Parameter	Value
$V_{PP}$	525mV
$I_P$	4mA
$I_V$	370uA
$V_V$	370mV
$V_P$	50mV



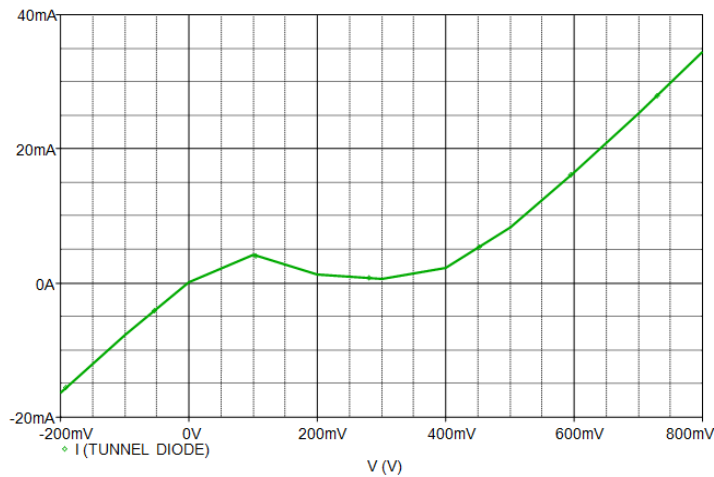
**Figure 7. Simulated Excess Current of Tunnel Diode Model ( $I_{Excess}$ )**



**Figure 8. Simulates Band to Band of Tunnel Diode Model ( $I_x$ )**



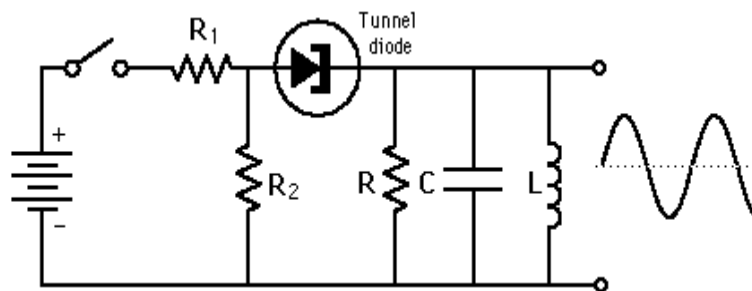
**Figure 9. Simulated Thermal Current of Tunnel Diode Model ( $I_{TH}$ )**



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

### 10. 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 [12]. There are many ways to create oscillator circuits. A simple TD oscillator is shown in figure 11 including the load  $R_L$ , which also accounts for circuit losses, and the parallel tank circuit which determines the frequency of oscillations,



**Figure 11. Schematic of Oscillator Circuit.**

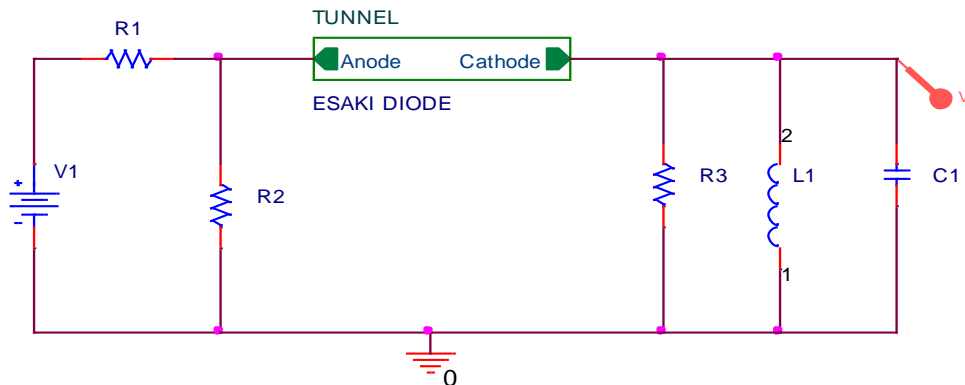
The principle of the tunnel diode oscillator (TDO) can be briefly described as follows. An LC-tank circuit is maintained at a constant amplitude resonance by supplying the circuit with external power to compensate for dissipation. This power is provided by a tunnel diode that is precisely forward biased 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,

$$\omega = \frac{1}{\sqrt{L \cdot C}}$$

## 11. Validation of the Tunnel Model

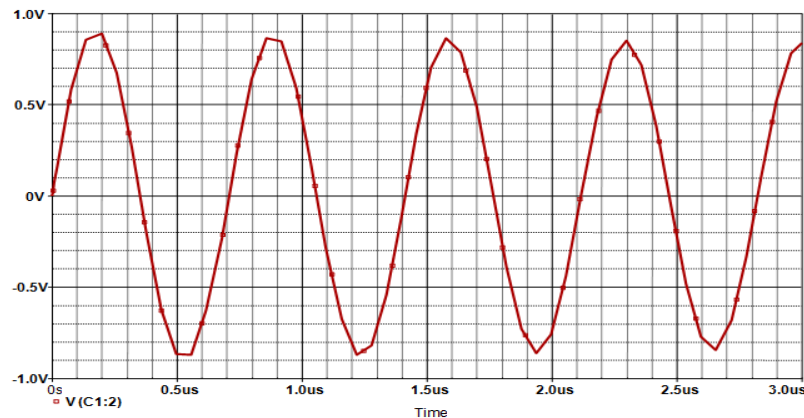
The Esaki tunnel diode model was implemented in a Spice circuit simulator. A transient simulation was also performed on a canonical oscillator circuit containing the tunnel diode to demonstrate the switching characteristics of the device. The circuit used along with the values of the components is shown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

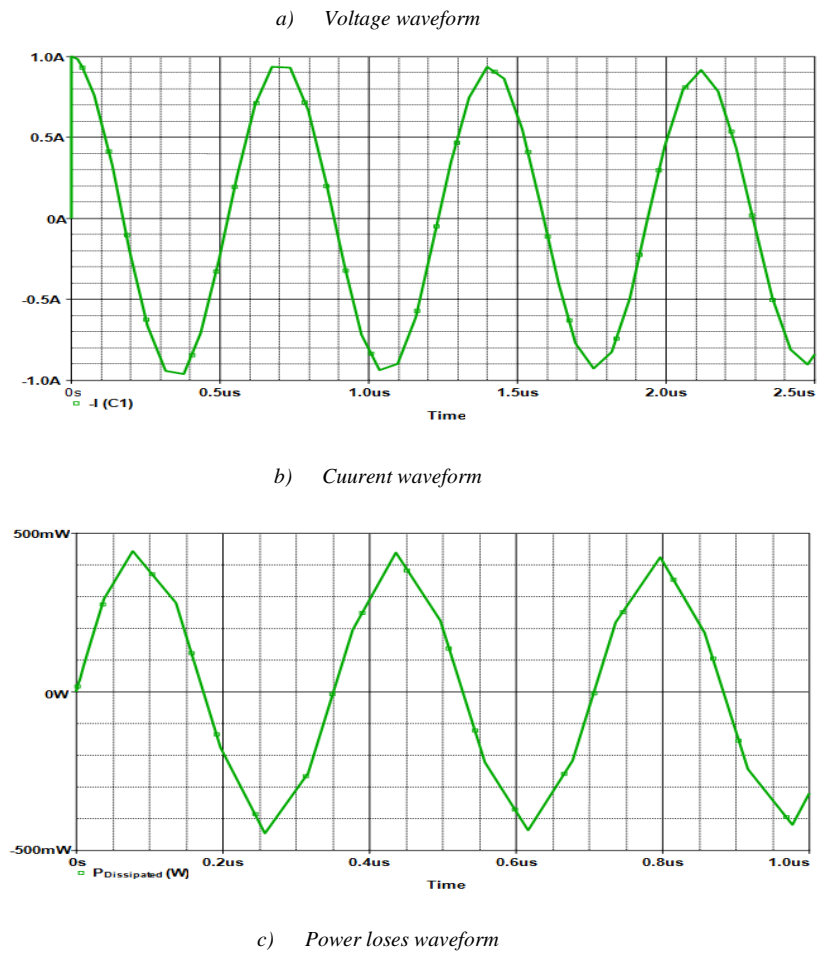
The circuit of Figure 12 was simulated using the Pspice 10.5 simulator with the following circuit elements and bias conditions: R1 =280Ω, R2=20Ω, R3=1KΩ, L = 100 nH, C1=100nF and V1 = 1V.



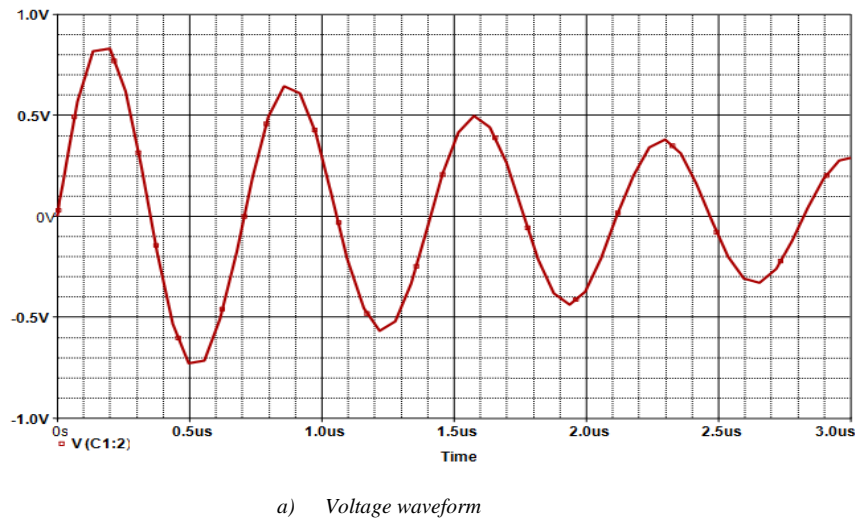
**Figure 12. Tunnel Diode Based Oscillator Used in Spice Simulations**

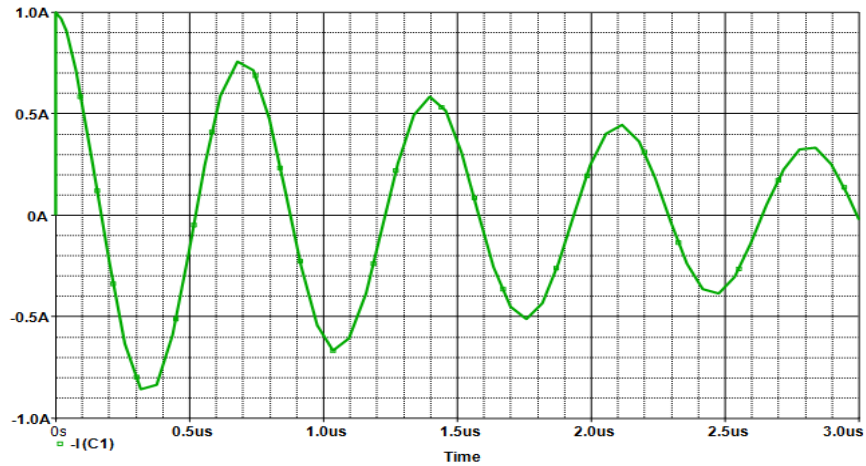
The principle of operation of the circuit is as follows: The tunnel diode has DC instability in its (NDR) region. This means that if the tunnel diode is DC biased in the NDR region of its characteristic, it will oscillate; the oscillations resonant with the LC tank are selected.



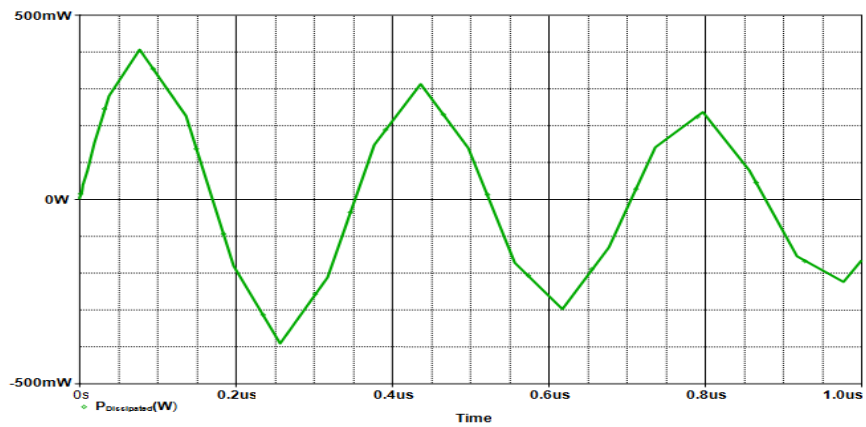


**Figure 13. Simulation Results of the Tunnel Diode Oscillator Circuit with  $R1 > R2$**





b) Current waveform



c) Power losses waveform

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

Figure 13 and 14 shows the output signal trace of voltage, current and power losses with the TDO operating at a resonance frequency around 8MHz. 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.

## 12. Conclusion

The Pspice circuit simulator is powerful tools which enable the designer to estimates the effects of different devices in a power converter circuit using time domain analysis. In this paper an equivalent circuit model for tunnel diode using the analog behavioral modeling (ABM) option that is suitable for use with Pspice simulator has been demonstrated. The current-voltage characteristics of the tunnel diode were simulated and analyzed. The model has been used with other components to build an oscillator and investigate its performance. The most important advantage of the proposed model lies in its immanent simplicity to be implemented in modern simulators.

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