CHARACTERISTICS OF A TUNNEL DIODE OSCILLATOR AT DIFFERENT TEMPERATURES

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ABSTRACT

Current-voltage measurements were performed on a Germanium tunnel diode and the basic features of the I-V characteristics were analyzed in the temperature range 100K – 300K. A tunnel diode based oscillator is proposed and simulated using circuit analysis software (PSpice). It is shown, in particular, that the amplitude and the frequency of the obtained sinusoidal waveforms can be practically temperature independent provided that the diode is adequately biased in its negative conductance region.

KEYWORDS

Tunneling Diode, Oscillator, I-V-T characteristics, Spice simulation

INTRODUCTION

Following its discovery by Leo Esaki, the tunnel diode (TD) has been widely used in many different applications as a circuit element. This simple active semiconductor device is mainly distinguished by the peak in its forward current-voltage characteristics that is caused by the quantum-mechanical tunneling of electrons through the heavily doped p-n junction. TD application circuits include oscillators, amplifiers, and switching circuits. For example, the TD oscillator may be used as a parametric frequency converter, moving the frequency of interest from Hz to the MHz range. TDs are also commonly used in low-temperature physics experiments [1, 2] and are useful as millimeter-wave oscillators [3].

Because of the widespread use of TDs, one might anticipate that there is a wealth of data on their performance at low temperatures. Surprisingly this does not appear to be the case as that there are very few reports in this context.

The aim, in the present work, is to measure and investigate the current-voltage (I-V) characteristics of a TD at a number of temperatures between 100K and 300K, use the measured data to devise a TD model incorporable in circuit analysis software (PSpice) and to analyze the theoretical performance of a TD based oscillator. The oscillator data were analyzed by using probe (i.e. software oscilloscope) and Fourier analysis. The actual oscillator circuit has also been constructed and its performance was tested at various temperatures with comparisons with the predictions from PSpice analysis. However, due to lack of space, the latter part is not presented here but submitted for publication elsewhere.

CURRENT-VOLTAGE-TEMPERATURE CHARACTERISTICS

A Germanium 1N3712A tunnel diode was used in the present work. To be able to perform the I-V measurements even in the region where the diode shows the negative differential resistance (NDR), it was necessary to stabilize the TD with a low-inductance 51 Ω-resistor (R_p) connected in parallel so that the combined resistance is always positive. This combination TD-R_p is inserted in the cryostat close to a Si-diode calibrated and used as a temperature sensor. The temperature measurements were accurate to within 0.1K.

The current-voltage characteristics at a number of temperatures between 300K and 100K are given in Fig.1.

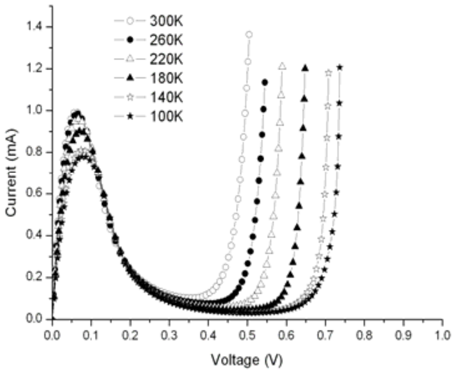


Fig.1 Measured I-V characteristics at different temperatures for the Germanium tunnel diode.

The I-V values reported here are those taken while both cooling and heating. However, readings were rechecked randomly to ensure reproducibility. In fact, the measurements were also performed at temperatures below 100K, but it was found that below 80K the dependence of the I-V curves on temperatures is effectively insignificant.

In the forward direction the current initially increases with increasing voltage and reaches a maximum of 1 mA at 300K. As the voltage increases to ~ 0.35V, the current decreases to 0.1mA at 300K. For voltages somewhat larger than 0.35V the current increases exponentially with voltage. The differential conductance curves defined as dI/dV, versus bias voltages are plotted in the Fig.2. The negative resistance regions are clearly seen at all temperatures and show a tendency to decrease with decreasing temperature.

The values of the peak current I_p and valley current I_v determine the magnitude of the NDR and as such the peak-to-valley ratio (PVR) is an important figure of merit of TDs. The experimental PVR obtained here is comprised between 9 and over 20 corresponding to a relatively large NDR. The measured peak and valley currents as a function of temperature are shown in Fig.3. Both I_p and I_v show a tendency to increase with increasing temperature. This behavior can be explained, in both cases, by the dependence of both tunneling and excess currents on the Ge bandgap which is known to decrease with increasing temperatures [4].

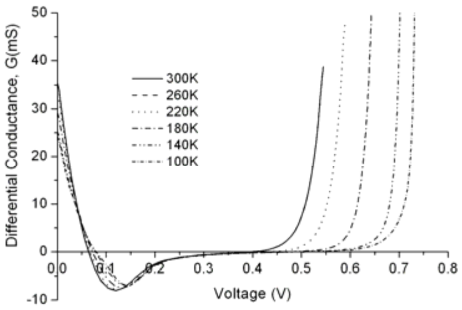


Fig. 2. Measured conductance showing a negative differential resistance (NDR) at all temperatures.

The origin of the NDR in TDs is well understood and is due to changes in the number of tunneling electrons, and hence current, when the bias voltage is varied. First, and as a consequence of high doping levels, the depletion region is very narrow allowing electrons to tunnel relatively easily through the p-n junction potential barrier. With no applied voltage no net current flows as the electron states are filled up to the same energy on both sides of the junction. As the bias voltage is increased, the electrons on one side are opposite empty states on the other side of the junction so they can tunnel across and a current flow. As the bias voltage increased further the tunnel current decreases again as there are no empty states for the electrons to occupy on the opposite side.

The I-V characteristic is, hence, the result of three current components: tunneling current I_t, excess current I_x, and thermal current I_{th}.

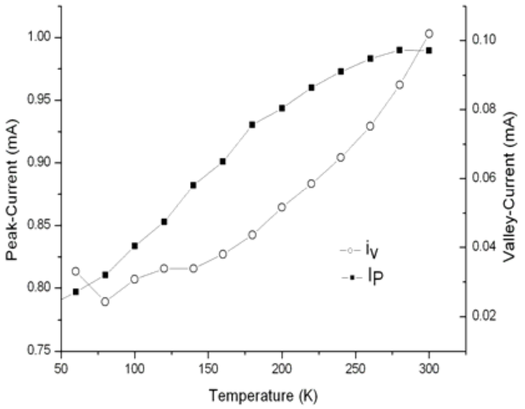


Fig.3. Variations of peak- and valley-current with temperature

The excess current occurs at forward biases in the range where the electrons in the degenerate donor levels in the n side have been raised to energies greater than those of the degenerate acceptor levels on the p side. Thus at these bias voltages, only the current produced by the forward injection of minority carriers should flow; however, the actual current is considerably in excess of the normal diode current. The tunneling current and the thermal current expressions (first term and third term in the equation below) can predict the shape of I-V curve. However, an additional empirical expression of the excess tunneling current (second term in the equation) was needed for a better description of the experimental I-V. Thus the complete static current-voltage characteristic is the sum of three current components:

$$I = I_t + I_x + I_{th} = I_p (V/V_p).e^{(1-V/V_p)} + I_x.e^{A(V-V_v)} + I_0 e^{qV/kT}$$

where Ip and Iv are the peak and valley current densities respectively, I_0 is the saturation current density and A is a pre-factor in the exponent. The tunneling current's contribution to the total current is significant for V<Vv, the excess current contribution is significant for V~Vv and the contribution of the thermal current is significant for V > Vv.

The temperature dependence of the tunneling and the excess currents are fairly small compared with the thermal diffusion current associated with the p-n junction which varies exponentially with temperature as $e^{qV/kT}$. Thus there is a weakly temperature dependent peak in I-V characteristic for a tunnel diode with falling edge of this peak being the useful part of the characteristic as it provides a negative incremental resistance.

The above equation is shown to fit reasonably well the experimental I-V-T data as shown in figure 4 for two particular temperatures (100K and 300K).

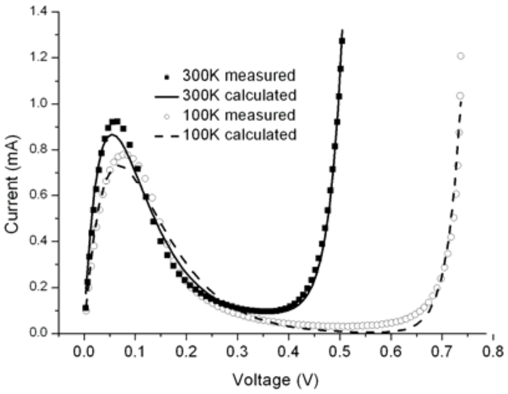


Fig. 4. I-V characteristics at 300K and 100K with fits based on the current equation above (see text).

THE EQUIVALENT CIRCUIT OF THE TUNNEL DIODE AND PSPICE MODEL

The approximate equivalent [5] circuit is shown in Figure 5, R_n is determined by the slope of the I-V characteristic at the bias point which is lying between the peak (I_p, V_p) and valley (I_v, V_v) points.

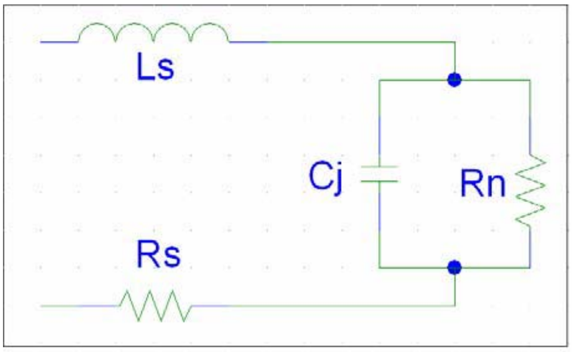


Fig. 5. Tunnel diode equivalent circuit

Since I-V characteristic of the TD in the region of negative resistance is non-linear, R_n is in fact a sensitive function of the bias voltage. The remaining elements, R_s, C_j and L_s represent the spreading resistance, the junction capacitance and the parasitic inductance mainly associated with leads and the bulk resistance of the semiconductor material. The series resistance R_s includes the lead resistance, the ohmic contacts, and the spreading resistance which is given by: ρ/2d, where ρ is the resistivity of the semiconductor and d is the diameter of the diode area. Some increase in the value of R_s must be expected at high frequency due to skin effect (for the TD used in this work R_s~1.5 Ω). A method by which the series inductance L_s can be estimated is based on the well-known formula of the inductance of a coaxial cable $L_s = \frac{2.303\mu_0 l}{2\pi}\ln(\frac{r_2}{r_1})$, where μ_0 is the permeability of the medium, *l* is the length, and $r_1$and r_2 are the inner and outer radii of the coaxial line, respectively.

Each of these passive components (R_s, L_s and C_j) has an equivalent circuit model in PSpice which mimic the "real" component behavior to a greater or lesser precision. Additional attributes such as temperature coefficient of resistance can also be included. PSpice, however, does not have a ready-built in model for the the TD, but does include voltage-controlled sources that can be used to simulate the TD behavior based on its measured I-V characteristics and the equivalent circuit. These are 4-terminal devices which can be wired as 2-terminal by connecting together the voltage and current leads. GVALUE, part of the analog behavioral modeling capability of PSpice [6], was used in this work to reproduce (Fig.6) the characteristics of the TD using the mathematical equation above.

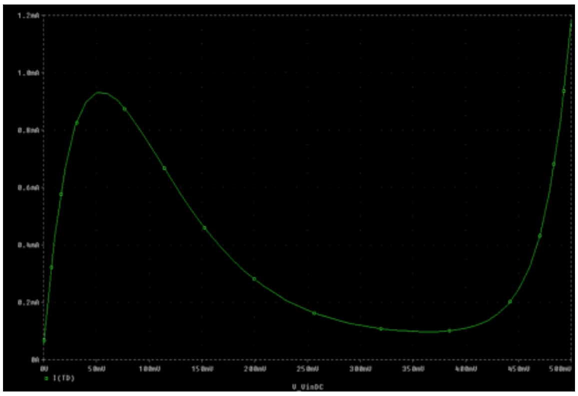


Fig.6. I-V characteristics of the TD obtained using Spice simulations

TUNNEL DIODE OSCILLATOR AND ANALYSIS

A simple TD oscillator is shown in figure 7 including the load R_L, which also accounts for circuit losses, and the parallel tank circuit which determines the frequency of oscillations, $\omega = \frac{1}{\sqrt{L(C_3 + C_j)}}$.

Beside the TD represented by its equivalent circuit consisting of a voltage-controlled source (GVALUE) and the passive elements R_s, L_s and C_j, there is a DC voltage source, a pulse generator and two transmission lines. The DC source was used to initially bias the diode in its NDR region.

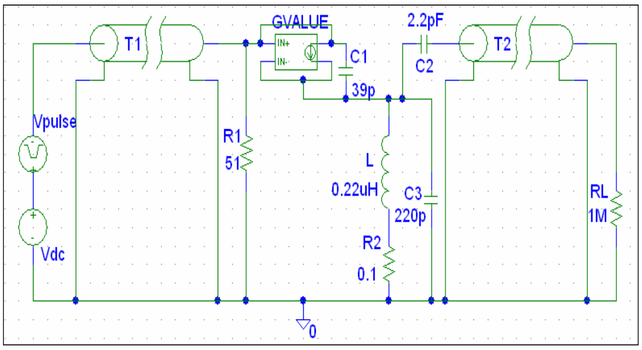


Fig. 7 Tunnel diode based oscillator used in Spice simulations

We have used the DC parametric scan to show how the behavior of the circuit changes as a result of varying the bias voltage over a range of values. In fact, the variations of the negative conductance with temperature (Fig.2) provides rough guidance for a suitable operating range of the bias voltage, 0.2 V ≤ V_{bias} ≤ 0.3 V, where the negative conductance tends to be constant and temperature independent. Also, it has been effectively noted that as the bias voltage is moved too high or too low from this range, the oscillations abruptly decay so that the desired types of oscillations cannot be achieved by biasing the oscillator away from this region. The oscillator circuit was simulated using parametric analysis over a range from 0.2V to 0.28V in 0.02 V steps. The pulse generator VPULSE was used to provide the initial transient to start off oscillations (this is not needed in practice because some transient or noise is usually the stimulus for oscillations). This is a pulse train specified by: initial voltage, pulse voltage, delay, rise and fall times, pulse width and pulse period. The pulse period was so large that only the first pulse was important. The remaining parameters were specified with care so that one could see the growth of oscillations with time. The VPULSE device was thus useful to provide an initial stimulus without affecting subsequent operation of the circuit.

The transmission lines T1 and T2 were added to the circuit to represent the coaxial cables (~ 1m long) that might be used in practice for measurement purposes. Each transmission line was given a characteristic impedance of 50 Ω and transmission delay of 5.5ns. The transmission delay (td) was taken as the ratio of the transmission line length (1m) and the phase velocity in the line, $v = c/\sqrt{\varepsilon} = c.CZ_0/120\pi\varepsilon_0$, with c being the velocity of light in free space, C is the capacitance per unit length of the line (C ~ 100pF/m), Z_0 the characteristic impedance, and ε_0 the permittivity of free space.

The necessary condition for self starting oscillation, is that the impedance of the tank circuit on resonance should be larger than $-R_n$ (i.e. $R>R_n$). With this in mind, one needs a tunnel diode with -Rn only slightly smaller than R to sustain marginal oscillations. Given the correct condition for initiation of oscillations, there will be an exponential increase of the amplitude until the excursion of the negative resistance characteristic becomes sufficient for non-linear effect to occur, beyond this point the small-signal linear circuit theory cannot predict the behavior and the use of non-linear circuit theory is required.

Transient analysis in PSpice does, in fact, take account of the non-linearities in the circuit. This analysis determines the output variables (current and voltage) as a function of a specified time interval. To specify the stop-time and the incremental time-step size, we have assumed that the circuit used for simulation oscillates at 20MHz and the output is a sinusoidal wave, which has an output period of 1/20MHz = 0.05µs. To compensate for phase delay and parametric circuit parameters, it is usually recommended that the stop-time be ≥ period x 2 = 0.1 µs. As a rule of thumb, the step should be at least the period x 2/100 = 1ns. These of course are the minimum values with which the simulation can be run. In light of this, to ensure accuracy and to reduce the possibility of skipping important features of the circuit response, a 1 ns time step was judged small enough and best to be use. To assure that many points are calculated for wave analysis the stop-time was given 100 µs which is 1000 times of the minimum recommended value. The nature of oscillations was, hence, examined from zero to 100 µs. Initially the oscillations were not observed for 1µs which was the time delay specified for VPULSE to start off oscillations. The oscillations started then to grow with time as shown in Fig.8. Above a certain initial build-up time the output waveforms were found to be stable and sinusoidal.

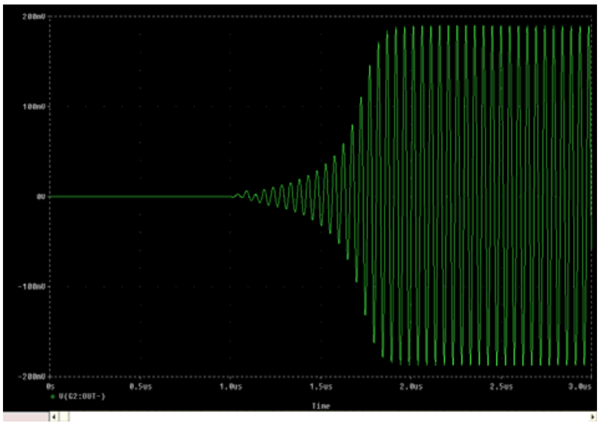


Fig. 8 Oscillations waveform obtained from the TD circuit above

The simulations were repeated for all the temperatures (100K – 300K) for the same bias range. The oscillation amplitudes are shown to vary very little with temperature or bias voltage. The output results from transient analysis at 300K at selected voltages are shown in Figure 9. As it can be seen from this figure, the waveforms are sinusoidal with peak-to-peak amplitudes of about 400 mV in all cases. Fourier analysis were carried out to yield both the bias and temperature dependence of the frequency of the circuit.

These are depicted in Figure 10. Initially the frequency increases with increasing the bias voltage from 0.2V to 0.26V, but sudden decreasing in the frequency is observed beyond 0.26V, this was not expected nor understood. The frequency does not seem to vary as the temperature is decreased and this is expected since Rn is almost temperature-independent in the voltage region over which the simulations were performed.

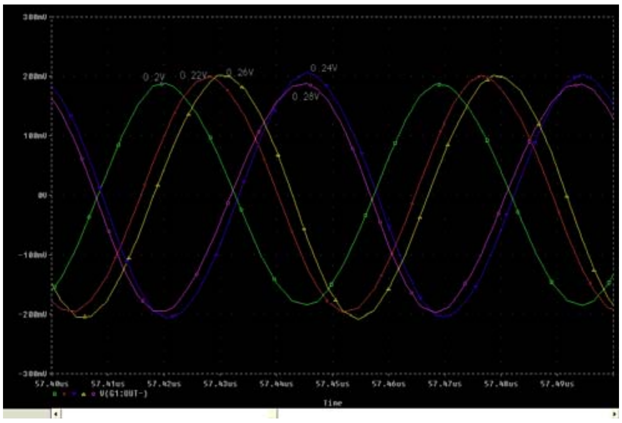
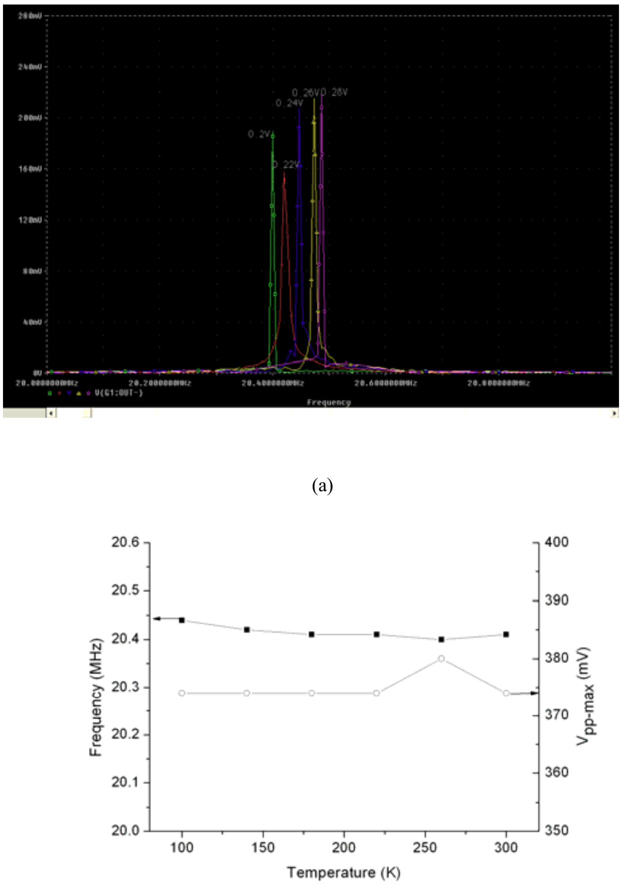


Fig. 9. Sinusoidal oscillations as the bias-voltage is varied (the amplitude is practically constant).



(a)

(b)

Fig. 10(a, b). Fourier spectrum of oscillations at different bias voltages (a) and variations of the amplitude and frequency of oscillations with temperature (b)

CONCLUSION

In conclusion, the current-voltage characteristics of a tunnel diode were measured and analyzed in the temperature range 100K – 300K. Based on these measurements and the equivalent circuit of the diode, a Spice compatible model was created using the analog behavioral modeling option. The model was used with other components to build an oscillator and investigate its performance as the operating temperature is varied. It was found in particular, that both the amplitude and the frequency of oscillations are not significantly affected by the operating temperature if the TD is properly biased in its NDR region.

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