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Section 01

Tunnel Diode Relaxation Oscillator

Tunnel diodes are a type of semiconductor device that exhibits a negative resistance region due to an effect called tunnelling. They consist of the same components as a p-n junction: an anode, a cathode and a depletion layer. The depletion layer is made up of positive and negative ions, thus an electric field exists in this region. Unlike normal p-n junctions, however, the depletion layer of a tunnel diode is extremely thin. This is the result of a process known as doping where the p-n junction is introduced to charged atoms, which can alter its electrical properties, namely its conductivity, by decreasing the thickness of its depletion region. Subsequently, the electrons from the p-side of the junction can pass through the depletion region to the positive side—the tunnel effect—which is why tunnel diodes produce a negative resistance region. The tunnel effect is based on the laws of quantum mechanics. In classical physics, a particle would be repelled by an electric field if it does not have the required energy to pass through it. On the other hand, in quantum mechanics, an electron's motion can be represented as a wave. This wave pattern means that a particle can "tunnel" through the potential barrier, even if it doesn't have enough energy.

This phenomenon is what causes the unique I-V characteristic seen in Figure 1. As voltage increases from 0V, current increases as expected. However, negative resistance comes into play between two particular voltages—the peak and valley voltages—which depend on the material of the tunnel diode. After the valley voltage, current increases very rapidly, as expected.

This negative resistance region disobeys Ohm's law, $I = \frac{V}{R}$, which predicts an increase in current as voltage increases.

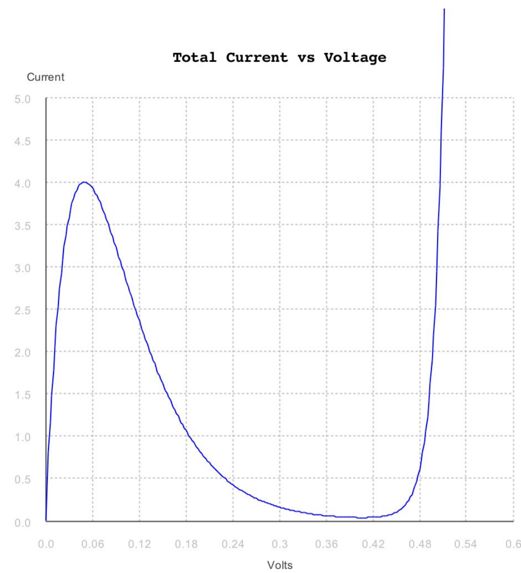

Figure 1. Tunnel Diode I-V Curve

The equation of this curve is given by the following sum of three exponential functions, which are individual equations for current as a function of voltage.

$$I_{tot} = \frac{V(t)}{V_P}(I_P e^{(1-\frac{V(t)}{V_P})}) + I_V e^{A_2(V(t)-V_v)} + I_S e^{(\frac{q \cdot V(t)}{K \cdot T})-1} \quad [1]$$

Every value is a constant that depends on the material of the tunnel diode, except for V(t), which is simply voltage that increases linearly as a function of time.

If a tunnel diode is attached to a circuit containing resistors, an inductor and a power source, it creates a relaxation oscillator (see Figure 2 for the circuit diagram). The voltage across a resistor is given by Ohm's law, while the voltage across an inductor is given by $V = L\frac{dI}{dt}$, where L is the inductance of the inductor. As voltage increases through the circuit, there is a positive change in current across the inductor. However, when the current through the tunnel diode reaches its peak voltage and enters the negative resistance region, the current would normally begin to decrease. This would be allowed, except, in order to obey the equation for the voltage across an inductor, dI/dt must remain positive when voltage is increasing. Therefore, voltage skips the negative resistance region of the tunnel diode and starts to decrease on the right side of the region. Now, there is a negative voltage across the inductor and a negative change in current in that branch. A similar switch occurs when the negative resistance region is encountered again. Thus, the current across the tunnel diode oscillates, as seen in Figure 3. The goal of this project is to write a code that plots a voltage versus time graph across the tunnel diode.

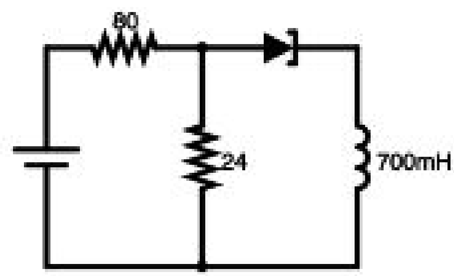

Figure 2. Tunnel Diode Relaxation Oscillator circuit

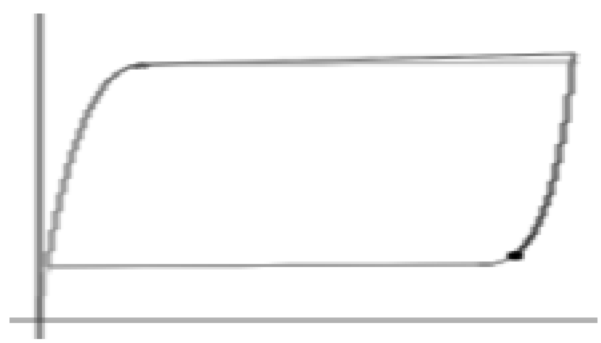

Figure 3. Oscillation of the current across the tunnel diode

This is the description of the oscillator in words, but solving numerically becomes rather tricky since it is an oscillating circuit. In order to do so, I followed the SPICE Algorithm for non-linear circuits. First, I derived equations using Kirchoff's voltage laws. Equation 2 is the current through the 24 Ω resistor, whereas Equation 3 is the current across the tunnel diode and the inductor. Equation 4 is the current across the power source based on the junction law, which states that all current exiting a junction is equal the current entering the junction. It is important to note that these equations were derived under the assumption that both the wires and battery are ideal, meaning their internal resistance is negligible.

$$I_n = I_{n-1} + \frac{R_1 V_{TD} dt}{R_1 R_2 + R_1 L + R_2 L} \qquad [2]$$

$$I_n = I_{n-1} + \frac{R_2 (I_n - I_{n-1})}{L} - \frac{V_{TD} dt}{L} \qquad [3]$$

$$I_{source} = I_1 + I_2 \qquad [4]$$

Second, I came up with the proper model given the SPICE Algorithm for solving this particular circuit. The procedure is as follows:

1. Guess a voltage across the tunnel diode
2. Solve for the currents in all three branches using equations 2, 3 and 4
3. Find the corresponding voltage across the tunnel diode using Equation 1, given the current across the tunnel diode
4. Using this new voltage, find the current in the three branches using equations 2, 3 and 4
5. Test for convergence (if the current across the power source is within a very small tolerance for consecutive iterations)
    a. If not convergent, repeat steps with the voltage found in Step 3 as the new guessed voltage for Step 1

b. If convergent, end the loop and assign the found voltage as the voltage across the tunnel diode for this iteration

This process is repeated for many time steps until an arbitrary final time.

Figure 4 is the results obtained from applying this model in the Java Code while Figure 5 are results obtained from experimentally as a way of validating my results.

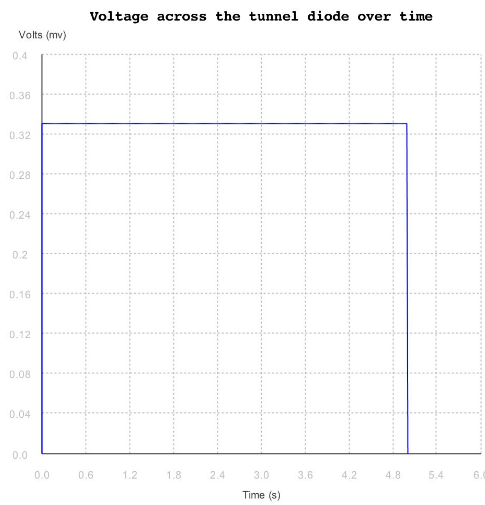

Figure 4. Results obtained from my code

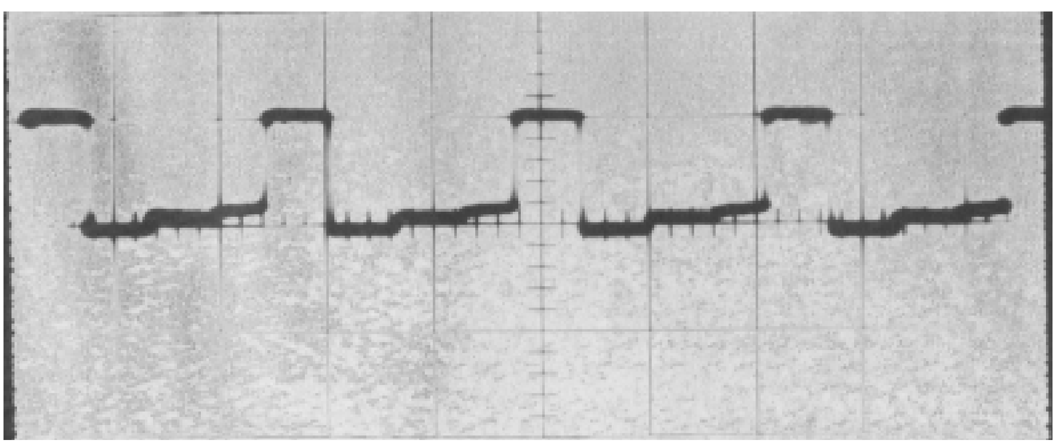

Figure 5. Results obtained experimentally

It is clear that my results do not replicate the oscillations of the circuit, but rather one period of oscillation. This is because the model I used did not account for the portion of the curve where the voltage decreases. In other words, it was only designed for an increase in voltage and hence could not adjust for the decreasing portion of the oscillations. Nevertheless, my results do match one period of oscillations from the experimental results. They both follow the rectangular oscillation pattern of a standard tunnel diode relaxation oscillator. Not only does this prove that my test for convergence is accurate, but that, if the model was intended for oscillation, then increasing the total time of the simulation would lead to an oscillation similar to that of the experimental results. Another thing that proves that the convergence test is effective: changing the time step and retesting the code. If the plot stays the same, then it proves that the same convergence is always reached. Figure 6 shows three different plots with varying time steps of $5 \cdot 10^{-5}$ μs, $5 \cdot 10^{-4}$ μs and $5 \cdot 10^{-3}$ μs, respectively.

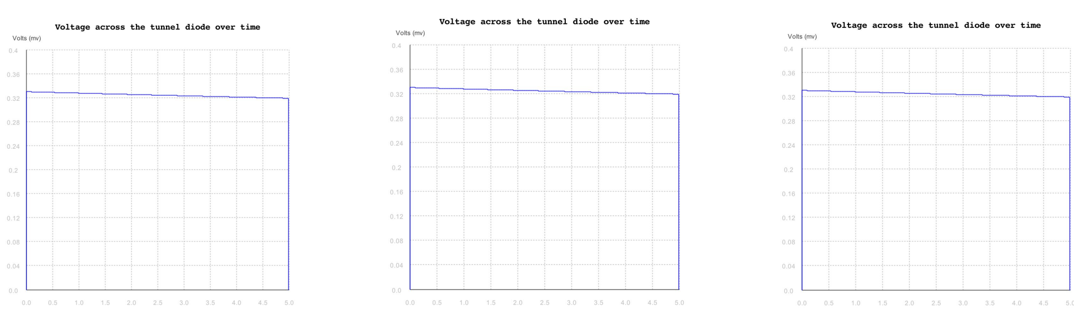

Figure 6. V vs t plot for three different time steps

In conclusion, despite the lack of oscillation, the goal was still achieved. The voltage versus time graph produced by the code did match the expected results as intended. This validates the SPICE model I used, the formulas I derived and the code I wrote for one period of oscillation.

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