The tunnel diode – a forgotten switching-speed champion

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The tunnel diode was invented in 1957 by Japanese physicist Leo Esaki, who in 1973 was awarded the Nobel Prize for the theory of the quantum tunnelling effect, which he co-wrote with Ivar Giaever and Brian Josephson.

The tunnel diode is made of two semiconductor layers, P- and N-type, with high concentration of dopants, and a PN junction just several nanometers thick. The result is a quantum phenomenon manifesting itself as relatively-high current flowing through the diode at unusually low voltage. This phenomenon peaks at about 60mV (for germanium diodes) and fades with further increase in voltage, as shown by the voltage-current (VI) charact-eristic curve of Figure 1. When the diode voltage is higher than a trough-voltage V_v, this curve resembles that of the common rectifying diode; thus, the region between V_v and the peak voltage V_p represents a negative resistance.

Tunnel diodes were extensively used in 70s' amplifiers, high-speed pulse circuits and oscillators. In later years, the tunnel diode could no longer compete with other devices, such as bipolar junction transistors that offered better speed and low power.

In former Czechoslovakia, since about 1975, the semiconductor manufacturer TESLA has been producing germanium tunnel diodes GE13x, x = 0, 1, 2, 3, 4, which are scaled to the value of the peak current, ranging from 1mA to 10mA. These diodes' typical parameters are:

$$V_p \cong 60mV, V_v \cong 350mV, \frac{I_p}{I_v} \cong 8$$

In former USSR (now the Russian Federation), both germanium and gallium-arsenide (GaAs) tunnel diodes were produced. In general, the GaAs tunnel diodes have higher values of peak- and trough-voltages compared to their Ge counterparts.

Relaxation Oscillator with a Tunnel Diode

The tunnel diode's VI characteristic differs from that of other switching semiconductor devices like diacs or thyristors in that it exhibits continuous voltage jumps as current varies. Relaxation oscillators with a tunnel diode therefore use an inductor instead of a capacitor; see Figure 2.

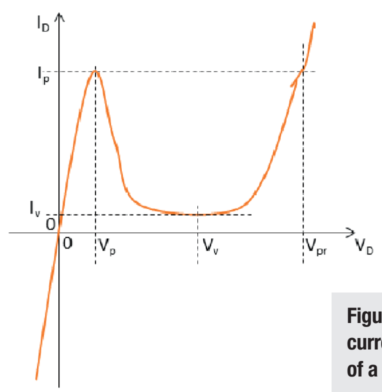

Figure 1: Illustrative volt-current (VI) characteristics of a tunnel diode

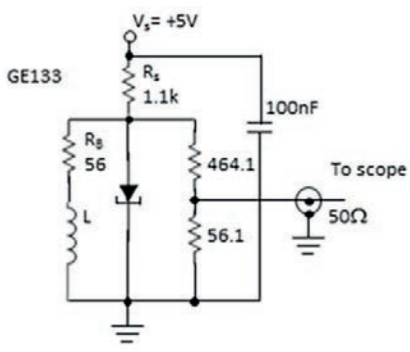

Figure 2: Relaxation oscillator with a tunnel diode

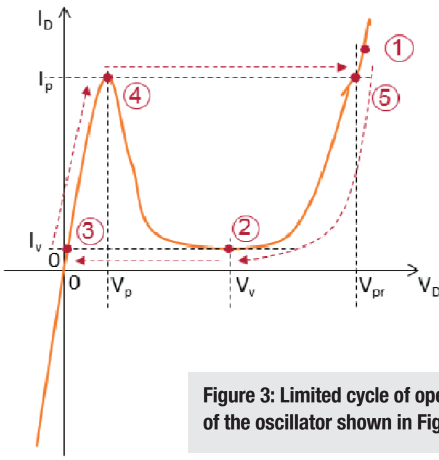

Figure 3: Limited cycle of operation of the oscillator shown in Figure 2

If the supply voltage is much higher than the maximum diode voltage, e.g. $V_s = 5V$, then the source V_s and resistor R_s can be thought of as a source of constant current I_0, where $I_0 > I_p$, or $I_0 = \frac{3}{2} I_p$.

When the supply turns on, initially no current flows through inductor L and the full value of I_0 flows through the diode, as shown by point 1 in Figure 3. Inductor current rises steadily from zero, thus the tunnel diode voltage continuously decreases. At point 2 in Figure 3, diode current drops below I_v and the voltage across the diode jumps abruptly to a very small value. The inductor current has a value of $I_0 - I_v$ at point 2, which can be considered the same as point 3, since the transition between points 2 and 3 is very fast.

To maintain continuity of the inductor current, a negative voltage appears on it, and the inductor becomes a source of current.

Although the tunnel diode is an extremely nonlinear device, part of its VI characteristic between points 3 and 4 can be crudely modelled as a linear resistor, r_d. Current flowing through the tunnel diode can thus be determined as a superposition of two components. At the transition point 3→4 there are two sources – source of constant current I_{0L} and current i_L of the charged inductor L.

DC I_{0L} is divided between paralleled resistors R_B and r_d, and the load resistor R_L, or $R_B \| R_L = R'_B$. The DC component of the current through the tunnel diode is then:

$$I_D = I_{0L}.(R'_B \| r_d)\frac{1}{r_d} = I_{0L}.\frac{R'_B}{R'_B + r_d} \qquad (1)$$

Inductor L discharges and its current i_L decreases per Equation 2:

$$i_L = (I_{0H} - I_v).e^{\frac{R_B + r_d}{L}.t} \qquad (2)$$

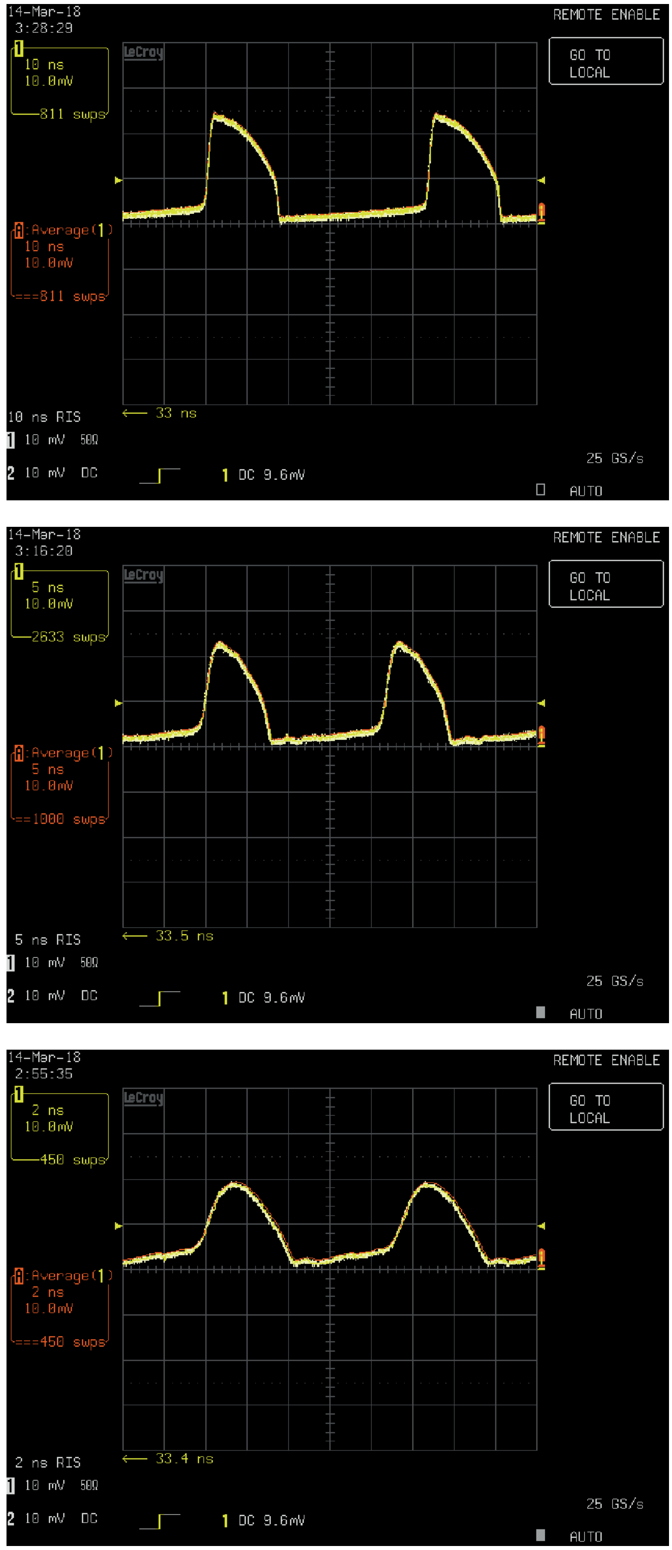

Figure 4: Voltage waveform of the tunnel diode in the tested oscillator: (a) for L = 1.473 with a ferrite core; (b) for L = 0.47 with a ferrite core; (c) coreless, fully-shielded inductor with L = 0.12

Note that the vertical voltage scale has to be multiplied by a factor of 18.55 to get true voltage values

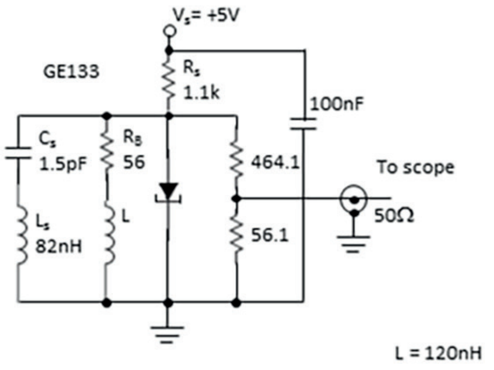

Figure 5: By paralleling a series resonance circuit to the tunnel diode, the relaxation oscillator can be converted into a harmonic oscillator

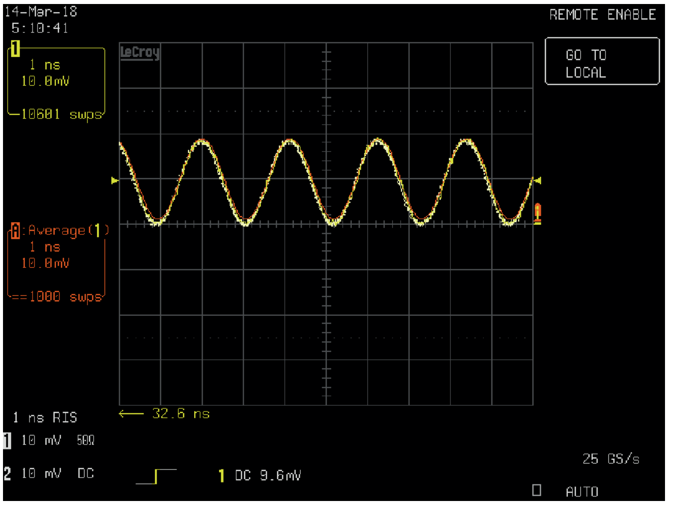

Figure 6: Voltage waveform of the tunnel diode in the oscillator of Figure 5. The frequency of oscillation is 454MHz and the voltage swing 352mV

The instant t = 0 is valid here for point 3. Applying a superposition of the two currents, the tunnel diode current i_D is then:

$$i_D = I_D - i_L \quad (3)$$

At point 4 of the VI characteristic, i_D reaches a value of I_p and the voltage u_D across the tunnel diode jumps to a high level, shown by point 5 in Figure 3. The duration T_L of the low-level part of the u_D waveform can be determined by plugging Equations 1 and 2 into Equation 3, and setting $i_D = I_p$:

$$I_p = I_{0L}\cdot\frac{R_B'}{R_B'+r_d} - (I_{0H} - I_v).e^{-\frac{R_B+r_d}{L}.T_L} \quad (4)$$

After rearranging Equation 4, we get:

$$T_L = \frac{L}{R_B+r_d}.\ln\frac{I_{0H}-I_v}{I_{0L}\cdot\frac{R_B'}{R_B'+r_d}-I_p} \quad (5)$$

With $R_L = 490.5\Omega$ and $R_B = 56\Omega$, $R_B' = R_B \| R_L = 50.26\Omega$ for the tunnel diode (GE133) parameters of $I_p = 3mA$, $I_v = 0.375mA$, $V_p = 60mV$, $V_{pr} = 0.45V$ and $r_d \approx 9\Omega$. $I_{0H} = \frac{5V - V_p}{R_s} = 4.504mA$, and $I_{0L} = \frac{5V - V_{pr}}{R_s} = 4.15mA$ are obtained from Equation 5 for $T_L = 1.527\tau$, where $\tau = \frac{L}{R_B + r_d}$ is the time constant of inductor L's discharging. For $L = 1.473\mu H$, $T_L = 34.58n\sec$.

The experimental value of 36ns, which can be seen in Figure 4a, agrees well with the circuit's model.

Estimating Output Voltage Rise-Time

The transition 4→5 in Figure 3 can be extremely fast; however, diode capacitance and relatively low supply current slow it down. Rise-time of the v_D waveform can be roughly estimated as:

$$t_r \approx \frac{C_d.(V_{pr} - V_p)}{I_0 - I_v}$$

For $C_d \approx 9.5pF$ and variable values as discussed earlier, $t_r \approx 0.9n\sec$. The experimental value can be read out conveniently in Figure 4c, proving its agreement with the estimated value.

At point 5 of oscillator operation, inductor L starts to charge from the tunnel diode's voltage, which initially has a value of V_{pr}. As current i_L flowing through the inductor rises, diode current i_D and voltage v_D decrease. The process is "smooth" until voltage v_D reaches the value of trough-voltage value V_v, shown by point 2 in Figure 3. The VI characteristic of the tunnel diode between points 5 and 2 is extremely nonlinear, and this lack of linearisation comes into account.

We assume a simplified equivalent circuit diagram for this part of the cycle, with the tunnel diode represented as a highly nonlinear resistor. The supply voltage V_s together with resistor R are considered a source of constant current with a value of

$$I_0 \cong \frac{V_s - V_{pr}}{R}.$$

According to the first Kirchhoff's Law, it holds true that:

$$i_L + i_D = I_0 \tag{6}$$

and following the second Kirchhoff's Law:

$$R_B . i_L + L\frac{di_L}{dt} = v_D \tag{7}$$

The VI characteristic of the tunnel diode for the voltage $v_D \ni \langle V_v, V_{pr} \rangle$ can be approximated by a parabolic dependence:

$$v_D = V_v + (V_{pr} - V_v)\sqrt{\frac{i_D - I_v}{I_p - I_v}} \tag{8}$$

By expressing i_L from Equation 6 and substituting it together with v_D from Equation 7 into Equation 8, and then rearranging the nonlinear differential equation of the first order, we obtain:

$$\frac{1}{i_D - I_0 + \frac{V_v}{R_B} + \frac{V_{pr} - V_v}{R_B} . \sqrt{\frac{i_D - I_v}{I_p - I_v}}} . \frac{di_d}{dt} = -\frac{R_B}{L} \tag{9}$$

Using $\sqrt{i_D - I_v} = z$, Equation 9 can be simplified as:

$$\frac{2z}{z^2 - I_0 + I_v + \frac{V_v}{R_B} + \frac{V_{pr} - V_v}{R_B} . \frac{z}{\sqrt{I_p - I_v}}} . \frac{dz}{dt} = -\frac{R_B}{L} \tag{10}$$

Equation 10 can next be made clearer by compressing the constants:

$$\frac{2z}{z^2 + bz + c} . \frac{dz}{dt} = -\frac{R_B}{L} \tag{11}$$

where $b = \frac{V_{pr} - V_v}{R_B} . \frac{1}{\sqrt{I_p - I_v}}$ and $c = -I_0 + I_v + \frac{V_v}{R_B}$.

By integrating Equation 11 with the limits given by points 2 and 5 in the oscillator's operational cycle, we obtain:

$$\left[\ln(z^2 + bz + c) - \frac{b}{\sqrt{c - \frac{b^2}{4}}} .arctg \frac{z + \frac{b}{2}}{\sqrt{c - \frac{b^2}{4}}} \right]_{\sqrt{I_p - I_v}}^{0} = \left[-\frac{R_B}{L} .t \right]_0^{T_H} \tag{12}$$

Applying the given limits produces:

$$\ln \frac{I_p - I_v + b.\sqrt{I_p - I_v} + c}{c} - \frac{b}{\sqrt{c - \frac{b^2}{4}}} arctg \frac{\frac{\sqrt{I_p - I_v}}{\sqrt{c - \frac{b^2}{4}}}}{1 + \left(\sqrt{I_p - I_v} + \frac{b}{2} \right) . \frac{b}{2} . \frac{1}{c - \frac{b^2}{4}}} = \frac{R_B}{L} \tag{13}$$

By substituting constants c, b from Equations 11 into Equation 13 and rearranging, we obtain:

$$\ln \frac{I_p - I_0 + \frac{V_{pr}}{R_B}}{I_p - I_0 + \frac{V_v}{R_B}} - \frac{1}{\sqrt{\frac{c}{b^2} - \frac{1}{4}}} arctg \frac{\frac{V_{pr} - V_v}{R_B} . \sqrt{\frac{c}{b^2} - \frac{1}{4}}}{-I_0 + I_v + \frac{V_{pr} + V_v}{2R_B}} = \frac{R_B}{L} .T_H \tag{14}$$

For GE133 $V_v \cong 350mV$, $I_0 = 4.15mA$, $R_B = 56\Omega$ and $L = 1.473\mu H$. The dimensionless constant $\sqrt{\frac{c}{b^2} - \frac{1}{4}}$ is present in Equation 14 twice and was therefore evaluated separately as $\sqrt{\frac{c}{b^2} - \frac{1}{4}} = 1.2411$. Final evaluation of T_H from Equation 14 results in $T_H = 14.58n\sec$. Thus, the calculated value is in good agreement with the duration of the high-level of voltage, which can be read from Figure 4a as 17ns.

Harmonic Oscillator

Interestingly, if a high-quality series resonance circuit tuned to about 500MHz is paralleled with the tunnel diode in the relaxation oscillator with a relatively short period of oscillation, e.g. 9ns, the circuit is forced to oscillate with a period of around 2ns. The added series resonance circuit comprises a capacitor $C_s \cong \frac{C_D}{6} \cong 1.5pF$, where $C_D \cong 9.5pF$ is the capacitance of the tunnel diode, and, further, a coreless inductor with inductance $L_s \cong \frac{t_r^2}{\pi^2} . \frac{1}{C_s} \cong 82nH$ as in Figure 5, and $t_r \cong 1n\sec$ is the rise time of the voltage waveform across the tunnel diode. In this circuit, the resonance at a frequency of around $f_{osc} \cong \frac{1}{2t_r} \cong 500MHz$ dominates, and the waveform in Figure 6 can be considered a harmonic one. EW