Esaki diodes live and learn

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(Contributed by Leo ESAKI, M.J.A.)

Abstract: We report, as the result of shelf-life tests for Esaki diodes, the observation of minute but tangible reductions in the tunnel current after the lapse of half a century. The reduction could be attributed to 0.25% widening in the tunnel path.

Keywords: electron tunneling, semiconductors, shelf life tests

The Esaki tunnel diode conceived in 1957[1)] is considered to be the first quantum electron device. Because of its characteristic negative resistance, it is an active semiconductor device which oscillates easily at high frequencies. Esaki has kept dozens of examples of the germanium device fabricated in 1960 in storage for half a century for shelf life tests with regard to possible changes in the tunnel current.

The shelf life of most semiconductor transport devices is supposed to be almost infinite because the diffusion length of substitutional impurities such as acceptors or donors is infinitesimal providing they are stored at room temperature. (The diffusion length of arsenic in germanium for fifty years is in the order of 10^{-8} nanometers.)[2)] However, in the case of the Esaki diode there exists such an enormous built-in field, more than 5×10^5 V/cm in the junction region, that it should be emphasized that the tunnel current is extremely sensitive to the tunneling path determined by the built-in field.

We have, therefore, paid special attention to the current peak, I_p, exhibited at V_p in the forward direction of the diode, as shown in Fig. 1, since it could be the most sensitive parameter for indications of any small structural change. The energy diagrams of the diode at two applied voltages, V_p and V_v, are schematically shown in Fig. 2, where the diagram (a) at V_p indicates electron tunneling from the n type region to the p type region, and the diagram (b) at V_v indicates no tunnel current.

From the recent measurements of current-voltage characteristics, though no virtual change in V_p, we have discovered very small but tangible reductions in the peak current from the values measured on February 4th, 1960: an average 3.3% reduction in the peak current has been observed, as shown in Fig. 3, where the vertical and horizontal axes correspond to the values measured in 2010 and in 1960, respectively. This reduction could be attributed to minute widening of the junction.

The peak tunnel current I_p is approximately expressed by[3),4)]

$$I_p = cF \exp\left(-\frac{\pi^2\sqrt{2m*}Eg^{3/2}}{2heF}\right)$$

$$= cF \exp\left(-\frac{10^7}{F}\right)$$

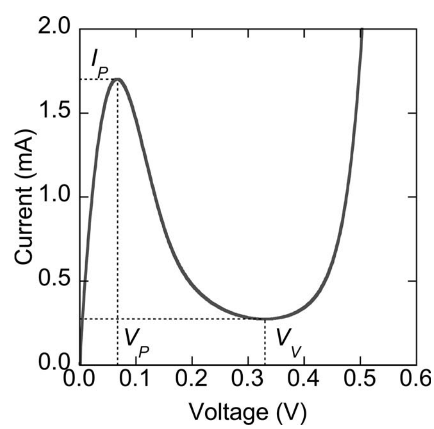

Fig. 1. Current-voltage characteristic of an Esaki diode, where I_p and V_p are the current and the voltage at the peak and V_v is the voltage at the valley.

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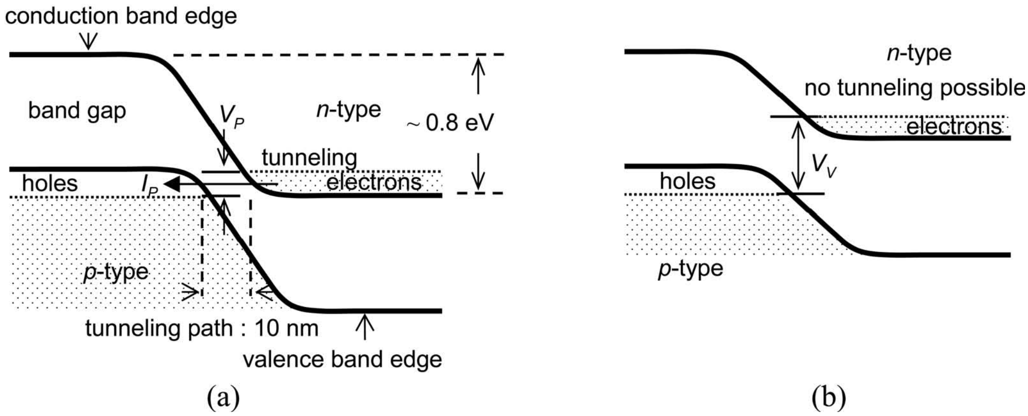

Fig. 2. (a) The energy diagram of the Esaki diode at V_p indicating tunneling from the n type region to the p type region. (b) The energy diagram at V_v indicating no tunnel current.

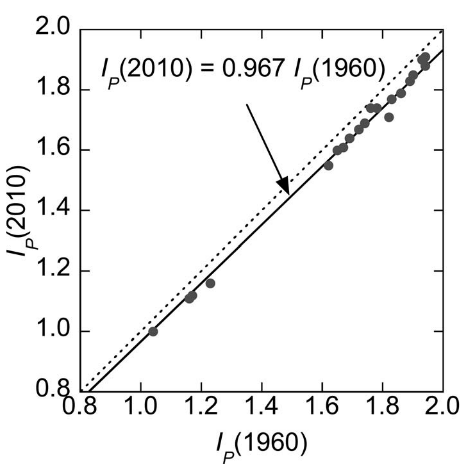

Fig. 3. Observed reductions in the peak current I_p. The vertical and horizontal axes correspond to the values measured in 2010 and in 1960, respectively.

where F, the built-in field, becomes 8×10^5 V/cm if the junction width and the built-in potential are assumed to be 10 nm and 0.8 eV, respectively, and c is just a constant. Eg and m^* are the energy gap (0.65 eV) and the effective mass (0.22 m) of germanium, respectively. Then, the new built-in field corresponding to a 3.3% reduction in the tunnel current gives a new junction width of 10.025 nm, indicating a widening of the junction of 0.25% after half a century.

The observed widening of only a four-hundredth of the tunneling path equivalent to about one tenth of the lattice constant apparently does not affect the function of the diode at all and it is just too small to be analyzed quantitatively. None the less, the following is our best guess:

1) A fair number of crystal defects may exist in the junction region since our p-n tunnel junctions were fabricated with heavily doped crystals by means of alloying techniques. The observed effect could then be ascribed to the migration of tiny amounts of impurities around crystal defects.
2) The interstitial impurities such as copper[5] may play a role because they can diffuse very fast.
3) Our device is expected to be somewhat strained because of the fabrication technique. Therefore, the easing of the strain alone might have caused the minute widening of the junction.

Incidentally, Esaki would also like to report here that his SONY FM Radio (EFM-117),[6] made in the early 1960s, still works beautifully: It was equipped with one Esaki diode similar to the ones studied here, serving as a local oscillator, and eleven germanium transistors. This is a gratifying confirmation of the longevity of the Esaki diode.

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