DIRECT OBSERVATION OF PHONONS DURING TUNNELING IN NARROW JUNCTION DIODES

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Esaki has shown that narrow p-n junctions between degenerate n- and p-type regions of a semiconductor can give rise to a pronounced current maximum in the direction of forward bias.[1] This component of the forward current is attributed to the tunneling of electrons from states lying near the bottom of the conduction band to states near the top of the valence band. Keldysh and Kane[2,3] have shown that in a semiconductor such as Ge or Si, where the conduction and valence band edges lie at different points in k space, the tunneling process may require the participation of one of the phonons having a wave number corresponding to the separation of the two minima. These phonons are the ones involved in optical transitions in these semiconductors. This paper reports measurements on tunnel diodes made from germanium and silicon which show distinct structure at voltages corresponding to the onset of these phonon-assisted processes, and which permit a precise measurement of the energies of the phonons involved. In addition, the experiments provide further insight into the relative probabilities of direct and indirect tunneling processes.

The phenomenon which we report was first observed by Holonyak and Lesk in heavily doped silicon junctions, cooled to 4.2°K. Distinct discontinuities in slope (cusps) of the current-voltage characteristic were noted for small forward and reverse voltages. The lack of sharpness of these cusps is attributed largely to thermal broadening. The current-voltage characteristic of one of these diodes is shown in Fig. 1. This junction was constructed with such a small donor concentration that the negative-resistance region is nearly absent. The cusps were found to occur in all of the silicon junctions which exhibited a measurable tunnel current. They appeared at the same voltages, for junctions made using P, As, or Sb as the donor impurity, and did not vary as the donor concentration was changed in the range between 2×10^{19} and 10^{20} cm^{-3}. They did not depend upon crystal orientation, and were clearly observed using polycrystalline material in which the junction covered several different grains.

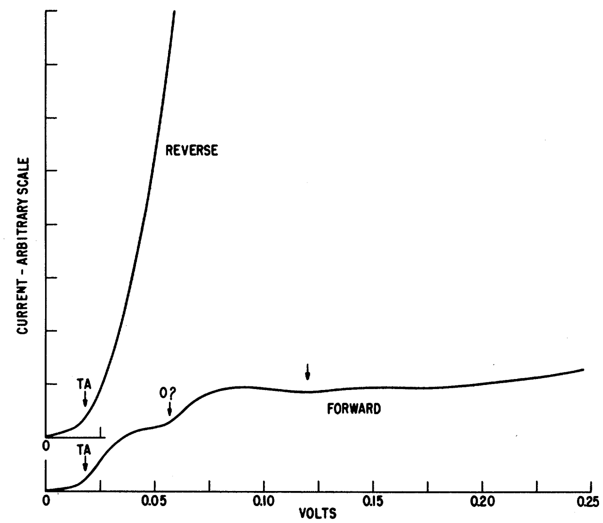

FIG. 1. Recorder tracing of current-voltage characteristic of a Si junction at 4.2°K. The cusps at the lowest energies are identified with transverse acoustical (TA) and probably optical (O) phonons. The third cusp, which corresponds to a phonon or phonons observed in optical data, remains unidentified.

Similar cusps were observed at 4.2°K in tunnel diodes made from germanium when Sb was used as the donor impurity, as shown in Fig. 2. However, they appear much less prominently in diodes made with P or As as the donor impurity, using a range of donor concentrations (0.8×10^{19} to 6×10^{19} cm^{-3}) which included that used for the Sb-doped diodes.

We interpret the cusps as evidence that lattice phonons are required in order to conserve momentum during the tunneling process. The cusps occur in pairs, at equal forward and reverse voltages, and their locations agree within experimental error with the phonon energies which are deduced from optical measurements of Si and Ge.[4,5] In Ge, we find these energies to be (7.9 ± 0.1 and 27.5 ± 0.5) $\times10^{-3}$ ev, respectively, and it is clear that they correspond to the transverse and longitudinal acoustic phonon energies. At present, we are unable to resolve clearly any structure which can

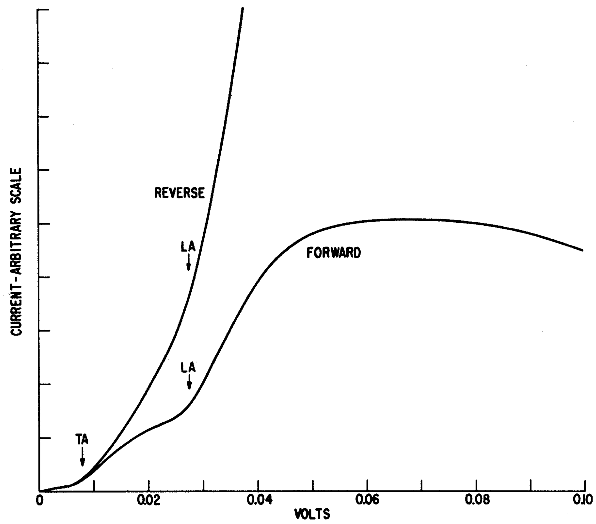

FIG. 2. Recorder tracing of current-voltage characteristic of a Ge junction at 4.2°K. Arrows indicate the locations of the cusps which are identified with the transverse and longitudinal acoustic (TA and LA) phonons.

be attributed to optical phonons. In Si, three cusps are observed at $(18.0 \pm 0.5,\ 57 \pm 1,$ and $120 \pm 5) \times 10^{-3}$ ev. The first corresponds to the transverse acoustic phonon energy, and the second appears to be due to one of the optical phonons. The third is unidentified, although it is also observed in the optical data.[4,5]

We examined tunnel diodes made from GaSb and found no evidence of any cusps. This behavior is understandable inasmuch as both band edges are located at $k=0$ in this material,[6] so that tunneling can proceed without assistance from phonons.

In germanium junctions made using P or As as the donor impurity, the cusps are difficult to resolve, indicating that the tunnel current in these junctions results largely from transitions which do not involve lattice phonons. This dependence upon the specific donor impurity is difficult to understand, and will be the subject of further study. It is conceivable that with large concentrations of these impurities, the density of states in the conduction band is modified in such a way that an appreciable number of conduction band states are found at $k=0$ below the Fermi level, and that the degree of this modification depends specifically upon the impurity involved. In pure germanium, the $k=0$ minimum is only 0.15 ev above the (111) minimum,[7] and therefore this heavily doped material might have its band edge at (000) modified sufficiently to permit an appreciable rate of direct tunneling transitions. This tailing of the band edge is similar to that calculated by Parmenter[8] who considered the effect of moderately large concentrations of hydrogenic impurities on the band structure in the vicinity of a simple edge. Additional evidence for tailing of the band edge is provided by studies of the shape of the negative-resistance region in tunnel diodes. It is found that this region always extends to higher voltages than is expected from the known impurity concentration and the density of states of the pure semiconductor.

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