PHONON-ASSISTED TUNNELLING IN GERMANIUM*

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(Communicated by R. S. Krishnan, F.N.I.)

(*Received 2 November 1968; after revision 24 May 1969*)

Differential conductance versus voltage characteristics of germanium tunnel diodes have been measured at liquid helium temperatures. The values of phonon energies have been computed from these characteristics. Apart from the four primary phonon energies given by Brockhouse and Iyengar (1958) (scattering of cold neutrons) for the (111) direction, energies corresponding to longitudinal phonon in the (100) direction and $q = 0$ phonon have also been observed.

Measurements

The tunnel diodes used in the measurements were fabricated by alloying spheres of *In* containing a small percentage of Ga on n^+-type germanium doped with Bi and Sb. The latter material was obtained by liquid epitaxial growth (Murthy 1965) on an n-type substrate of germanium using a bismuth-antimony mixture as a vehicle. The n-type impurity concentration was in the range 2 to 5×10^{19} atoms/cc. The diodes which were obtained were mounted on nickel bottom electrodes and a thin wire was attached to the alloy dot. The I–V characteristics of the diodes were typical as shown in Fig. 1.

For the measurements, the units were mounted on the end of a hollow bakelite tube and immersed in liquid helium in a standard container. Current and voltage leads were soldered to both terminals of the diode so that measurements could be made. To correct for the voltage drop due to the (invariably) long leads, voltage-current measurements were done with a short in place of the tunnel diode before the current-voltage and differential conductance versus voltage characteristics were measured.

Results

The conductance versus bias (Tiemann 1961) as well as current versus bias plots obtained on the X–Y plotter are given in Figs. 2(*a*) and 2(*b*) for one tunnel diode both in the forward as well as in the reverse directions. In

* Paper presented at the Symposium on 'Lattice Dynamics' held at Bangalore in August 1968.

general, it is observed that many structural details are brought up in the conductance plots thus yielding more accurate data on the prominent phonon effects and also revealing at the same time weak effects. Both of these pass unnoticed in the I–V plots.

(a) Forward Bias

For vanishingly small interrogation signals and in the absence of thermal smearing of the Fermi energies, the inflections in the (dI/dV) versus V curves would appear as sharp corners giving rise to an abrupt discontinuity in the conductance. Because of the smearing effects, the increase in conductance takes place over a finite voltage range. To a first approximation, therefore, the phonon energy corresponds to the bias at the midpoint in the upward swing in the conductance.

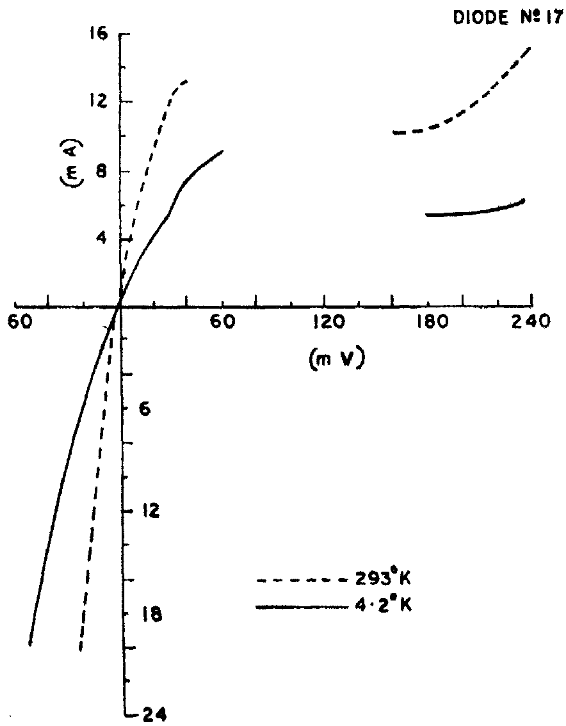

Fig. 1. I–V characteristics.

(b) Reverse Bias

The degree of inflections on dI/dV characteristics decreases in the range of the reverse bias voltage and hence the measurement of energy is more difficult than in the forward bias range. It can be shown that a linear approximation, which can be explained from Esak's formula, may hold on the (dI/dV)-V characteristics in each interval between the inflections. Using this

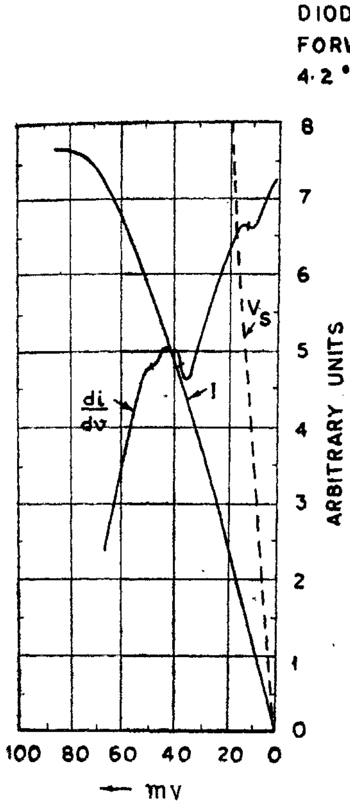

FIG. 2(a). Conductance and current versus forward bias.

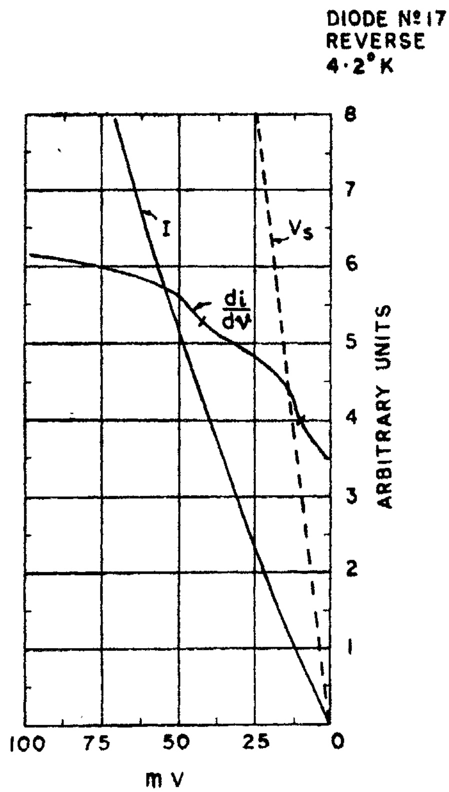

FIG. 2(b). Conductance and current versus reverse bias.

linear approximation, it becomes very easy to determine the phonon energies as indicated in Fig. 3.

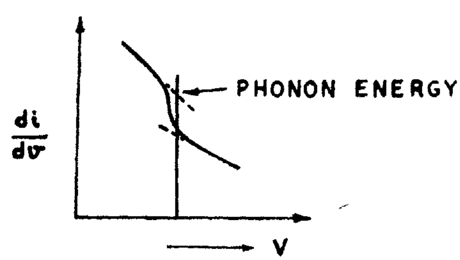

FIG. 3. Computation of phonon energy.

The results obtained thus for the diodes are given in Table I.

TABLE I

Inflection energies observed by differential conductance curve

Diode No.	Inflection energies
17	8·68, 28·0, 30·40, 37·65
20	8·3, 26·2, 28·95, 34·76
23	6·35, 22·65, 25·42, 30·23, 34·8

The inflection energies are average values when the inflections have been observed both in the forward and reverse bias directions.

DISCUSSIONS

The lattice vibrational spectrum of Ge in the (100) and (111) directions determined by the scattering of cold neutrons has been given by Brockhouse and Iyengar (1958). Multiplying the frequency values given therein by Planck's constant will yield the phonon energies. The phonon energies for (111) direction observed from neutron scattering in germanium and their assignments (Chynoweth *et al.* 1962) are given in Table II. Values obtained from our experiments are included in the next column.

TABLE II

Comparison of phonon energies observed with those reported from neutron scattering

Assignment	Phonon energy in 10^{-3} eV	
	From neutron scattering	Observed from tunnelling
Transverse Acoustic (111) ..	8·0	8·3, 8·68
Longitudinal Acoustic (111) ..	26·6	25·42, 26·2
Longitudinal Optic (111) ..	30·5	30·23, 30·40
Transverse Optic (111) ..	34·6	34·75, 34·8

It can be observed from Table II that the inflection energies are quite close to the phonon energies obtained from neutron scattering experiments.

However, inflection energies like $6{\cdot}35\times10^{-3}$ eV and $22{\cdot}65\times10^{-3}$ eV do not correspond to any of the phonon energies as obtained from neutron scattering. Other inflection energies like 28·0 and $28{\cdot}95\times10^{-3}$ eV can be considered as equivalent to a L(100) phonon and $37{\cdot}65\times10^{-3}$ eV as equivalent to the TO($q = 0$) phonon.

Acknowledgements

The author wishes to acknowledge his gratefulness to Professor Junichi Nishizawa of Tohoku University, Sendai, Japan, for having allowed him to conduct this study and to the Director, Solid State Physics Laboratory, for permitting him to present this paper at the Lattice Dynamics Symposium held at the Indian Institute of Science, Bangalore, in August 1968. He is deeply indebted also to Professor R. S. Krishnan for communicating this paper for publication.

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