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INELASTIC SCATTERING OF TUNNELING ELECTRONS BY LOCALIZED VIBRATIONAL MODES IN PbTe p-n JUNCTIONS*

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Liquid-helium-temperature tunneling data for PbTe indium-doped p-n junctions exhibit a series of sharp conductance increments with ~5-mV spacing as well as the "zero-bias conductance minimum" and the LO-phonon shoulder at ~13.8 mV. Indium-gallium alloyed junctions exhibit also a second series with ~6.5-mV spacing. This periodic structure is attributed to the "inelastic scattering" of tunneling electrons by localized vibrational modes of the indium and gallium impurity atoms in the tunneling junction.

In the course of an investigation of the "zero-bias conductance anomaly" in PbTe indium-alloyed p-n tunnel junctions,[1] we have observed a sharp periodic structure, with approximately 5-mV spacing, in the curves of dI/dV vs V and d^2I/dV^2 vs V in the voltage range $|V|<30$ mV. When indium-gallium mixtures were used as the alloying material, an additional periodic structure was observed with approximately 6.5-mV spacing. The sharp periodic structure is attributed to an "inelastic scattering" of tunneling electrons by localized vibrational modes of indium and gallium substitutional "impurity" atoms in the transition region of the p-n junctions. The observed spacing is consistent with the excitation energies of the localized modes, which are calculated from the mass-defect parameter and the LO-phonon energy, for indium ($\hbar\omega_{loc} \approx 5$ meV) and for gallium ($\hbar\omega_{loc} \approx 6$ meV).

The diodes, which were formed by alloying 0.003-in.-diam indium (and indium-gallium) spheres into degenerate p-type PbTe ($n_p \approx 5 \times 10^{17}$ cm^{-3}), exhibit a "zero-bias conductance minimum"[2] and a conductance rise at $eV \approx \hbar\omega_{LO} \approx 13.8$ meV corresponding to the LO-phonon energy. The narrow conductance minima in alloyed p-n junctions in the III-V compound semiconductors[3-5] and in the IV-VI compound semiconductors[6-8] have been attributed to polaron effects[3,6] and, more recently, to impurity-induced inelastic scattering by acoustic phonons.[9] Rediker and Calawa have observed that the minima for PbTe p-n junctions disappeared at relatively low magnetic fields, whereas the minima for III-V compound p-n junctions were magnetic field independent up to fields of the order of 100 kG.[10] It was these observations which led us to undertake a detailed investigation of the zero-bias conductance anomaly in PbTe. In the present experiments, the conductance minima were studied in the temperature range $1.1°K < T < 10°K$ and in magnetic fields up to 20 kG.

Our data show that the minima have the form of an energy gap characteristic of tunneling involving a superconductor. We find that the shape of the conductance minimum[11] and its temperature and magnetic field dependence,[12] shown in Fig. 1, are qualitatively the same as those of the curve for dI/dV vs V of a superconductor-insulator-metal tunneling junction. This indicates that the minimum is associated with superconductor tunneling through a Schottky barrier at the metal-semiconductor contact. The width of the minimum indicates an energy gap of $2\Delta \sim 2$ meV. Furthermore, the observed disappearance of the minimum by $T \lesssim 7°K$ and the observed temperature dependence of the width indicates a transition temperature $T_c \lesssim 7°K$. These values are consistent with the value obtained from the BCS relation $2\Delta = 3.5kT_c$. The energy gap is believed

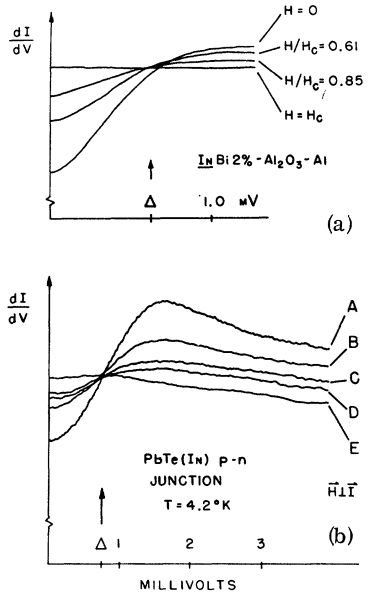

FIG. 1. (a) The tunneling conductance "minimum" associated with the energy gap 2Δ in a "dirty" superconductor (Ref. 12). (b) The "zero-bias conductance minimum" for various magnetic fields ($H_{\perp}I$). Curve A, zero field; curve B, 2 kG; curve C, 4 kG; curve D, 6 kG; curve E, 15 kG.

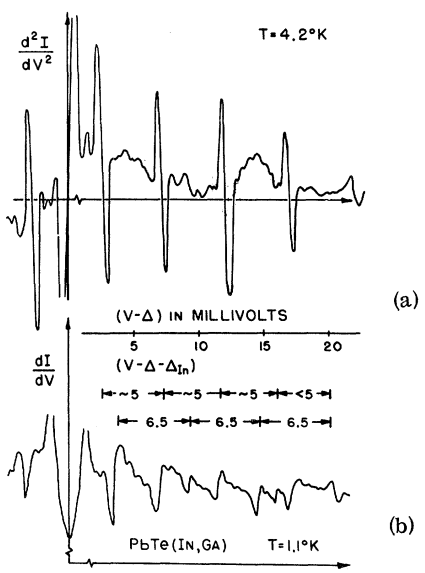

FIG. 2. (a) The curve of d^2I/dV^2 vs V for a PbTe(In) p-n junction shows the ~5-meV indium peaks. (b) The curve of dI/dV vs V shows the two sets of peaks for the indium-gallium p-n junctions. The zero-bias minimum has been included in the figure even though it occurs at a higher conductance value.

to be associated with a superconducting alloy of Pb:In.[13]

The sharp ($\delta V \approx kT$) periodic structure observed in the indium-alloyed samples is shown in the curve of d^2I/dV^2 vs V in Fig. 2(a). The structure, which corresponds to an increase in tunneling current, occurs at voltages given by

$$|eV-\Delta| = nE_1 - E_0, \quad n = 1, 2, 3, \cdots, \tag{1}$$

where $E_1 \approx 5$ meV and $E_0 \approx 2.6$ meV. The two sets of periodic structure observed when indium-gallium mixtures (ranging from 95%:5% to 60%:40%) were used as the alloying material are shown in the plot of dI/dV vs V in Fig. 2(b). One set is the same as in the pure-indium case and the other occurs at voltages given by

$$|eV-\Delta| = mE_2 - E_0, \quad m = 1, 2, 3, \cdots, \tag{2}$$

where $E_2 \approx 6.5$ meV and $E_0 \approx 2.6$ meV, the same as in the pure-indium case. The voltages at which the structure appears are independent of temperature and magnetic field over the ranges studied ($1.1°K \leq T \leq 4.2°K$ and $|\vec{H}_0| \leq 20$ kG).

We attribute this periodic structure to the "inelastic scattering" of tunneling electrons by localized vibrational modes of indium (and gallium) "impurity" atoms in the transition (tunneling) region of the junction.[14,15] The excitation energies of localized modes of a light-mass impurity atom are given by[16]

$$E_{\mathrm{loc}} = \hbar\omega_{\mathrm{loc}} = (\epsilon_\infty/\epsilon_0)^{1/2}(1-S^2)^{-1/2}\hbar\omega_{\mathrm{LO}}, \tag{3}$$

where ϵ_∞ and ϵ_0 are the high-frequency and static dielectric constants of the medium, $S = 1 - M_i/M$ (for $M_i < M$) is the "mass-defect parameter," M_i is the mass of the impurity atom, and M is the mass of the atom at whose lattice site the impurity is located. Using $\epsilon_\infty = 32$,[17] $\epsilon_0 = 400$, $\hbar\omega_{\mathrm{LO}} = 13.8$ meV, and $M = M_{\mathrm{Pb}}$, the spacing between energy levels $\hbar\omega_{\mathrm{loc}}$ is calculated to be ~5 and ~6 meV for indium and gallium, respectively. The origin of the shift $-E_0$ is not well understood.

No periodic structure is observed in data on Schottky tunneling junctions consisting of indium contacts on n-type PbTe ($n_e \approx 10^{17}$ cm^{-3}). This is consistent with the fact that no alloying is involved in the fabrication procedure and thus no indium "impurities" should be present within the (Schottky) tunneling barrier. On the other hand, for temperatures below the superconductive transition temperature of indium ($T_C \approx 3.4°K$), the curves of d^2I/dV^2 vs V exhibit the characteristic phonon structure and energy gap of the tunneling density of states of indium.[18] Structure observed at $|eV-\Delta_{\mathrm{In}}| \approx 13.6$ meV is associated with the LO phonon in PbTe and the form of the

structure is consistent with the predictions of the many-body calculations of Mahan and Conley.[19]

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SEMICLASSICAL TRANSPORT THEORY IN STRONG MAGNETIC FIELDS

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In this Letter we present a new formulation of the theory of galvanomagnetic phenomena in strong magnetic fields, where $\omega_c\bar{\tau} \gg 1$. (ω_c is the cyclotron frequency and $\bar{\tau}$ is some average relaxation time.) The present work differs from the usual treatments[1,2] in that it is not limited to Ohmic conductivity (linear response in the electric field), nor does it depend on the existence of a relaxation time. We consider instead the asymptotic state of the system when $\omega_c\bar{\tau} \to \infty$ and seek to determine the corresponding asymptotic distribution function (ADF), which serves as the zero-order function in a perturbation theory expansion in $1/\omega_c\bar{\tau}$. Only the semiclassical theory will be presented in this Letter.

The semiclassical description of transport phenomena is based on the Boltzmann equation, which is generally insoluble except in instances where the effect of collisions may be represented by a relaxation time. When such simplification is not possible, numerical techniques are required to solve even the Ohmic transport problem. An example is provided by polar optical-phonon interactions, where variational methods have been employed.[3]

We first sketch our theory for the case of classical statistics (no exclusion principle) and then present the modifications for Fermi statistics. The general characteristics of the ADF are established and the special case of Ohmic conductivity is treated in detail, where explicit expressions are derived for the transport coefficients. The case of polar optical-phonon interactions is treated as an example and exact formulas for the conductivity are given.

The steady-state Boltzmann equation to be solved is

$$e[\vec{E}+\vec{v}\times\vec{B}]\cdot\nabla_{\vec{p}} f = \hat{C}f = \int d\vec{p}'[f(\vec{p}')T_{\vec{p}'\vec{p}} - f(\vec{p})T_{\vec{p}\vec{p}'}], \qquad (1)$$

where $\hat{C}$ is the usual collision operator, and the electric ($\vec{E}$) and magnetic ($\vec{B}$) fields are taken in the x and z directions, respectively. In order to calculate the ADF we introduce the path-variable transformation,[4] for which we must first