Cyclotron spectroscopy of electron-phonon relaxation at point contacts

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(Submitted 7 August 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 2, 103–106 (25 January 1988)

Experiments reveal that the electron-phonon energy relaxation at point contacts is discrete in nature at high injection currents. It is possible to carry out a spectroscopy of the nonequilibrium electron distribution function through the use of a transverse focusing of electrons of certain energies.

The injection of charge carriers into a metal through a small contact is recognized as a unique technique for creating a pronounced deviation from equilibrium in an electron-phonon system. If the dimension of this point contact is small in comparison with, or comparable to, the energy-relaxation length of the current carriers, the injected electrons may acquire a significant excess energy without undergoing (or undergoing only partially) a phonon-induced energy relaxation at the contact itself. Under

 0021-3640/88/020124-05$01.00

these conditions the electron-phonon scattering causes a partial return of the injected carriers to the point contact, thus creating a return current. These processes, which are responsible for the nonlinear increment in the resistance of a point contact, underlie the method of point-contact spectroscopy of the electron-phonon interaction.[1] In addition, a significant number of the energized electrons which have been scattered by phonons do not strike the point contact and instead form nonequilibrium fluxes of electrons. The distribution of these electrons also reflects the electron-phonon relaxation in the metal.

A nonequilibrium distribution of injected electrons of this sort can be studied by the method of transverse electron focusing,[2] which makes use of the cyclotron motion of the charge carriers in a magnetic field. The inset in Fig. 1 shows the geometry of "cyclotron spectroscopy." If a nonequilibrium electron distribution function $f(\epsilon)$ is formed at emitter E, a transverse magnetic field must be applied in order to focus the nonequilibrium electrons of a given energy at collector C. The magnitude of this magnetic field is determined by the condition $2r_H(\epsilon) = L$ where $r_H(\epsilon)$ is the cyclotron radius of the electrons with energy ϵ, and L is the distance between the emitter and the collector. Consequently, the dependence of the collector potential on the magnetic field will directly reflect the energy distribution of the nonequilibrium electrons. Two conditions have to be satisfied here: 1) The relaxation of the carriers along their trajectory must be relatively slight. 2) The relaxation at the emitter itself, which forms the "phonon" structure of the nonequilibrium electron distribution function, must be clearly manifested. This situation can be arranged. Bulk bismuth is pure, while the

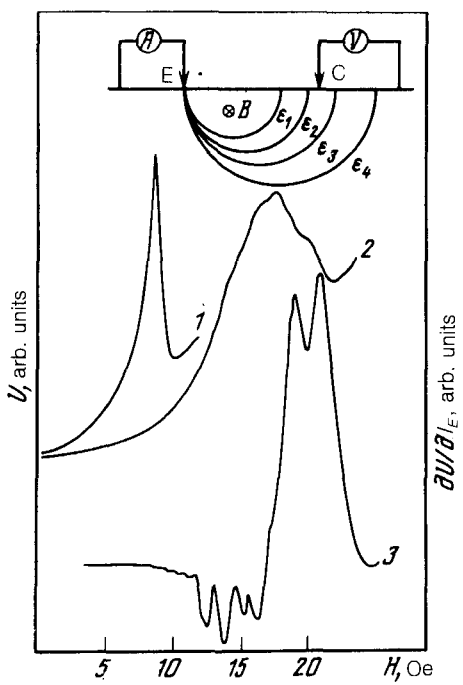

FIG. 1. 1,2—Electron-focusing signal for two values of the injection current; 3—derivative of the signal with respect to the emitter current. The independent variable is the magnetic field.

emitter is a defective region of diameter $d \sim 10^{-3}$–10^{-4} cm with a small elastic scattering length[3] $l_i \sim 10^{-5}$ cm, in which the energy relaxation length $\Lambda(\epsilon) = \sqrt{l_i \cdot l_{eph}}$ is 1.5 or two orders of magnitude shorter than the electron-phonon relaxation length l_{eph} in pure bismuth. Satisfying the first condition for electrons with an energy well above the Fermi energy may be problematical, since the relaxation rate τ^{-1} increases rapidly with increasing electron energy.[4] As follows from Ref. 4, however, this growth slows substantially at excitation energies $\Delta\epsilon \sim 1$ meV, and the electron-phonon scattering should decrease sharply as the energy increases. The minimum relaxation time found in Ref. 4 leads to mean free paths $l \sim 5 \times 10^{-3}$ cm, which are acceptable for observing electron focusing. The results reported in Ref. 5 show that the focusing signal at $L \sim 10^{-2}$ cm is formed by energized electrons in the region of higher injection currents.

Figure 1 shows the collector potential as a function of the magnetic field at small values of the constant emitter current $I_E \approx 1$ mA (curve 1) and also for very large values of this current, $I_E \approx 200$ mA (2). A characteristic and reproducible structure appears on curve 2. This structure can be seen most clearly when the derivative of the

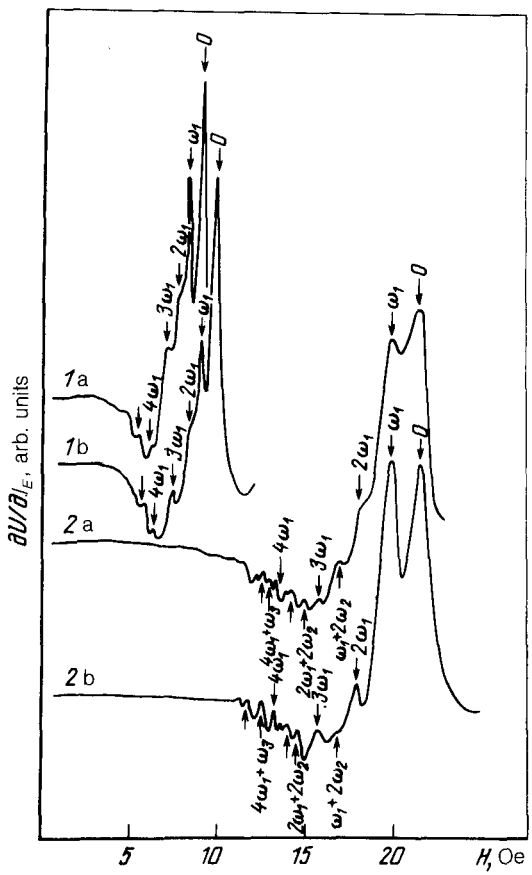

FIG. 2. Cyclotron spectra for two pairs of experiments with similar geometry. 1a, 1b—$L \approx 200$ μm; 2a, 2b—$L \approx 75$ μm.

collector voltage with respect to the emitter current, $\partial U/\partial I_E$, is recorded as a function of the magnetic field (curve 3). Figure 2 shows experimental curves of this sort for several contacts which were studied at a current[1] $I_E \approx 200$ mA.

With the field values H_n corresponding to the series of structural features on the $\partial U/\partial I_g(H)$, curves we can associate energies ϵ_n in accordance with the relation

$$\epsilon_n = \frac{(eH)^2}{2c^2 m}\left(\frac{L}{2}\right)^2 ,$$

which follows from the focusing condition $2r_H^{(n)} = L$. Let us compare the characteristic energy intervals between structural features with the energies of the relaxation phonons at multiple and combinational frequencies. Bismuth contains relaxation phonons which correspond to scattering by optical vibrations, $\hbar\omega_1 = 12.4$ meV and $\hbar\omega_2 = 9.2$ meV (Ref. 6), and by intervalley acoustic vibrations, $\hbar\omega_3 = 4.1$ meV (Ref. 7). For convenience in making this comparison, we eliminate the geometric parameters of the experiment, transforming to normalized quantities: $(H_n/H_0^*)^2 = (\epsilon_n/\epsilon_F)$. The field H_0^* corresponds to the condition for the focusing of electrons at the Fermi energy. At higher injection currents, the value of H_0 may deviate from H_0 at low currents because of the significant contribution of the intrinsic magnetic field of the injection current. The quantity H_0^*, like the maximum excess energy $\epsilon_n^{\max} - \epsilon_F$, is therefore determined in such a way that the position of the highest-energy structural feature (labeled 0 in Fig. 2) coincides with the experimental feature, and the difference between $\epsilon_n^{\max}$ and ϵ_{n-1} is $\hbar\omega_1 = 12$ meV. [For all the contacts studied we found $\epsilon_n^{\max} - \epsilon_F \approx 53$–$60$ meV $\approx (2.5$–$3)\epsilon_F$ at $I_E \approx 200$ mA.] We can then calculate the magnetic fields which correspond to energies that differ from the maximum energy by an amount equal to the multiple and combinational frequencies of phonons. These values are marked by the arrows in Fig. 2. Only some of the combinational frequencies are indicated. The correspondence between the values found for H_n and the observed structural features is seen to be quite good. This agreement supports the assertion that we are observing a phonon structure on a "cyclotron-focusing spectrum." An idea of the reproducibility of the observed effect can be gained from Fig. 2, which shows the cyclotron spectra recorded in two pairs of experiments with a similar geometry.

The observed effect could not be caused by an energy relaxation along a trajectory, since at excess electron energies a few times the Debye energy in bismuth the value of $l(\epsilon)$ is a smooth function of the energy and could not have structural features at the characteristic phonon frequencies. The contribution of relaxation on the trajectory could thus lead to a general decrease in the amplitude of the focusing signal. Consequently, the structure in the cyclotron spectrum results from the discrete nature of the energy relaxation of the electrons at the emitter, which makes the number of injected electrons a strong function of the energy.

The effect observed here demonstrates that it is possible to study the energy structure of the distribution of injected electrons after relaxation with phonons. This spectroscopic approach is based on the idea of a spatial separation of the nonequilibrium electrons of different energies which occurs in the course of transverse focusing.

We wish to thank R. I. Shekhter for a discussion of these results.

[1)]The splitting of the electron-focusing line corresponding to the two peaks furthest to the right on curve 3 in Fig. 2 was pointed out in a doctoral dissertation by V.S. Tsoĭ (Institute of Solid State Physics, Chernogolovka, 1978), where the role of phonon relaxation of electrons was cited as a possible explanation.

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Translated by Dave Parsons