Electron-hole transitions in the scattering of current carriers by the surface of a bismuth sample

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(Submitted 26 January 1989)
Piz'ma Zh. Eksp. Teor. Fiz. **49**, No. 5, 290–292 (10 March 1989)

The method of transverse electron focusing {V. S. Tsoĭ, Piz'ma Zh. Eksp. Teor. Fiz. **19**, 114 (1974) [JETP Lett. **19**, 70 (1974)]} has been developed through the use of three point contacts. The following have been observed in bismuth: 1) a focusing of holes; 2) electron-hole transitions upon the scattering of current carriers by the surface; 3) a specular reflection of holes from the bisector plane during normal incidence (with a diffuse reflection of electrons {V. S. Tsoĭ and N. P. Tsoĭ, Zh. Eksp. Teor. Fiz. **73**, 289 [Sov. Phys. JETP **46**, 150 (1977)]). This specular reflection is evidence that there is positive charge at the surface.

Electron focusing has been used previously to study intervalley electron-electron transitions during scattering from the surface of a bismuth sample.[3–5] An important mechanism for surface scattering is that of electron-hole transitions, which strongly influence the kinetic properties of a sample.[6–8] In the present letter we report the use of electron focusing for a direct observation of electron-hole transitions in the scattering of current carriers by the surface of a bismuth crystal.

The samples were single-crystal disks 10 mm in diameter and 2 mm thick. The normal to the flat surface of the disk ran parallel to the C_2 direction. Figure 1a shows the orientation of the electron and hole valleys of the Fermi surface with respect to the crystallographic axis. The measurements were carried out by the following method.[2] A sinusoidal current was passed through the emitter. The alternating voltage at the collector, U_C, was measured as a function of the magnetic field H, which was directed parallel to the surface of the sample. In the experiments we used three point contacts. The experimental layout is shown in Fig. 1b. Contacts 1 and 2 were placed along the normal to the major axis of the electron ellipsoid, parallel to the plane of the sample; contacts 2 and 3 were placed perpendicular to the C_3 direction.

With the appropriate direction of **H**, this layout offers the following methodological opportunities: 1. A focusing of electrons can be observed by using contacts 1 and 2. 2. A focusing of holes can be observed by using contacts 2 and 3. 3. A focusing of electrons and holes after electron-hole and hole-electron transitions can be observed by using contacts 1 and 3. 4. A focusing of electrons and holes simultaneously can be observed at one contact (contact 2 is the collector, contact 3 is the hole emitter, and contact 1 is the electron emitter).

A hole–focusing line of sufficient amplitude could be observed only at collector-emitter distrances $L_h \lesssim 50$ μm and at $T \lesssim 1.7$ K. It can thus be concluded that the short mean free path of the holes is the basic factor hindering observation of size effects involving holes in bismuth. It follows from observations of hole focusing in multiple fields that holes are reflected in a specular fashion; the specular reflection

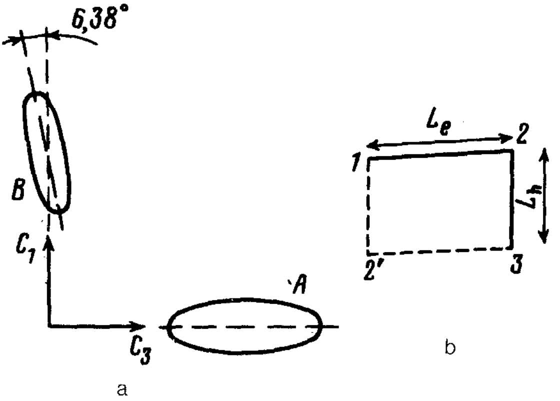

FIG. 1. a: Projection of the hole ellipsoid (A) and that of one of the electron ellipsoids (B) of the bismuth Fermi surface onto the plane perpendicular to the C_2 direction. This figure is not drawn to a common scale. b: Projection of the orbits of the electrons of ellipsoid B (1–2; 2′–3) and of the holes of ellipsoid A (2–3 and 1–2′) onto the surface of the sample. There are contacts at points 1, 2, and 3. Lines 1–2 and 2′–3 run perpendicular to the major axis of the electron ellipsoid; lines 2–3 and 1–2′ run perpendicular to the major axis of the hole ellipsoid. The magnetic field **H** lies in the plane of the sample.

probability is $q \approx 0.8$ and is obviously evidence of a significant positive charge ($\sim 10^{12}$ electron/cm^2) at the surface under study. This specular reflection of the holes stands in contrast with the reflection of electrons, which is a diffuse reflection when electrons are incident normally.[2] The surface band curvature determines the nature of the current-carrier reflection. The situation here is opposite that in antimony,[9] in which electrons are reflected in a specular fashion, and holes in a diffuse fashion, from a surface perpendicular to C_3.

If **H** deviates from the direction of the major axis of the ellipsoid (if the line of the collector-emitter contacts, **L**, is perpendicular to this major axis), the electron-focusing line in bismuth shifts up the magnetic-field scale. Accordingly, and despite the difference between the sizes of the electron and hole ellipsoids, it is possible to direct the magnetic field **H** in such a way that the electrons which have been emitted from emitter 1 are focused at collector 2 at the same value of the field, H_0, at which the holes emitted from contact 2 are focused at contact 3 (curves 1 and 2, respectively, in Fig. 2a). Without varying the direction of **H** we then used contact 1 as an emitter, and contact 3 as a collector. Under the condition[3] $\mathbf{S}_e + \mathbf{S}_h = \mathbf{L}$, where $\mathbf{S}_e$ and $\mathbf{S}_h$ are the extreme displacement vectors of the electrons and holes along the surface, a voltage peak should appear at the collector in the same field H_0, because of a focusing of current carriers upon the electron-hole transition (curve 3 in Fig. 2a). For a given **L** there are, in general, two other possible mechanisms for the appearance of an electron-focusing line: 1. A focusing of carriers by noncentral cross sections of the Fermi surface. 2. A trajectory transport of the field of a point charge.[10] However, the shape of the ellipsoids of the bismuth Fermi surface and the mean free path of the current carriers in the given experimental geometry clearly point to the conclusion that the observed electron-focusing line is due to specifically electron-hole transitions.

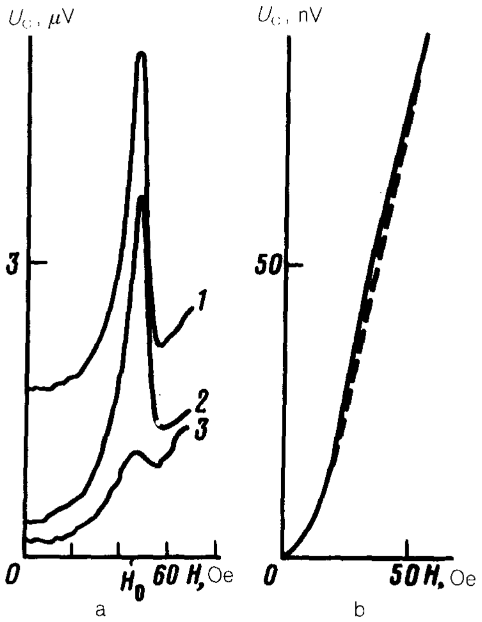

FIG. 2. Collector voltage versus the magnetic field. a: There are three contacts at the surface of the sample, 1, 2, and 2. 1—Focusing of electrons (1 is the emitter, and 2 the collector); 2—focusing of holes (2 is the emitter, and 3 the collector); 3—focusing of electrons (holes) which have undergone an electron-hole (hole-electron) transition (1 is the emitter, and 3 the collector). The sensitivity was increased by factors of 6.32 and 31.6 for the recording of curves 2 and 3, respectively. b: There are two contacts at the surface of the sample; their orientations with respect to the crystallographic axis of the sample are the same as the orientation of contacts 1 and 3 in case *a*.

In the experimental geometry used here, the carriers which have been emitted from emitter 1 and which have undergone an electron-hole transition at point 2 and a hole-electron transition at point 2′, will be focused at collector 3 (Fig. 1b). When we reverse the direction of the magnetic field and use contact 1 as the collector and contact 3 as the emitter, the electron-hole transitions will occur at point 2′, and the hole-electron transitions at point 2. The experiments show that the amplitude of the line is not changed in the process.

Since structural defects form in the sample when a contact (a needle tip) is placed near it, the reflection conditions are different at points 2′ and 2. When the contacts are installed on a non-defective section of the surface in the same experimental geometry, but without the installation of contact 2, the electron-focusing line due to electron-hole transitions shrinks considerably in amplitude and becomes broader (Fig. 2b; compare with curve 3 in Fig. 2a). The meaning is that the defects which appear near contact 2 cause a substantial increase in the probability for an electron-hole transition.

The distance between the electron and hole ellipsoids in the Brillouin zone is comparable to the magnitude of the reciprocal-lattice vector of the surface, and electron-hole and hole-electron transitions should be accompanied by a large change in the tangential component of the quasimomentum, which differs from the reciprocal-lattice vector of the surface. If such processes are to be possible, there must be a roughness at the atomic scale on the surface. This circumstance appears to be related to the increase in the probability for an electron-hole transition after contact 2 is installed.

From the shape of the electron-focusing line (curves 1 and 2 in Fig. 2a) we can determine the size of the region in which the electron focusing is effective. Noting that the amplitude of the line due to electron-hole transitions (Fig. 2a, curve 3, and Fig. 2b) is proportional to the number of carriers which are focused at the collector, and assuming an isotropic scattering, we can find the probabilities for electron-hole (q_{eh}) and hole-electron (q_{he}) transitions for defective and nondefective regions of the surface:

$q_{eh} \approx q_{he} \approx 0.04$ for a defective region,

$q_{eh} + q_{he} \approx 0.02$ for a nondefective region.

By choosing the appropriate direction for the magnetic field we can also arrange events such that the electrons and holes emitted from emitters 1 and 3 are simultaneously focused at collector 2 (Fig. 1b). In the experiments we measured three dependences of the collector voltage: 1) U_C^e, during the focusing of electrons; 2) U_C^h, during the focusing of holes; and 3) U_C^{e+h}, during the simultaneous focusing of electrons and holes. Within the experimental error ($\sim 1\%$) the results are additive: $U_C^{e+h} = U_C^e + U_C^h$. We were not able to find any nonlinear effects even when we heated the collector region by passing a direct current of 10 mA through contact 2 (the collector) (the resistance of the collector was 2 Ω).

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Translated by Dave Parsons