Direct observation of conduction electron beam transmission through a Bi intercrystalline boundary

M. V. Tsoi
Grenoble High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung and Centre National de la Recherche Scientifique, Boîte Postale 166, F-38042 Grenoble Cedex 9, France
and Institute of Solid State Physics RAS, 142432 Chernogolovka, Moscow Region, Russia

A. Böhm and M. Primke
Grenoble High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung and Centre National de la Recherche Scientifique, Boîte Postale 166, F-38042 Grenoble Cedex 9, France

V. S. Tsoi
Institute of Solid State Physics RAS, 142432 Chernogolovka, Moscow Region, Russia

P. Wyder
Grenoble High Magnetic Field Laboratory, Max-Planck-Institut für Festkörperforschung and Centre National de la Recherche Scientifique, Boîte Postale 166, F-38042 Grenoble Cedex 9, France

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A technique for studying conduction electron/interface interactions is used to study reflection and refraction of an electron beam at a Bi intercrystalline boundary. The technique involves scanning a small laser spot over the surface of a bicrystal, exciting conduction electrons locally, and using a magnetic field to focus excited electrons onto a fixed point contact (an electron collector), after the electrons have been reflected from, or transmitted through, the intercrystalline boundary. Refraction of conduction electrons, high bicrystal interface transparency, and a correlated electron transmission through the interface have all been observed.

Reflection of conduction electrons from the surfaces of conductors has been studied for a long time using a wide variety of techniques. Studies of reflection from boundaries between two conductors are much rarer. We know of only one previous direct study of transmission—Sharvin and Sharvin used a twinning plane in Al parallel to the crystal one previous direct study of transmission—Sharvin and Sharvin used a twinning plane in Al parallel to the crystal line boundary in a Bi bicrystal. By injecting electrons into a conductor, using a magnetic field to focus these conduction electrons on the surface of the crystal, and by detecting these focused electrons using a point contact, it is possible to follow the trajectories of the electrons inside the crystal from the outside. We first describe the technique and our sample, then present our results and analysis, and then a summary and conclusions.

We describe the basic principles of the technique for a conductor with a cylindrical Fermi surface (FS), both because this is the case for Bi having the electron FS close to a cylindrical one (for details of the FS of Bi, see Ref. 6), and because it simplifies the analysis. The electrons of interest are only those on the FS. For a metal with a cylindrical FS in a magnetic field H, the electron orbits in real space are simply circles with the electron velocity always directed perpendicular to the cylinder axis, independent of the direction of H. Therefore in real space an electron in a given crystal remains in a given plane perpendicular to the cylinder axis, independent of whether it is scattered or not, so long as the scattering returns it to the same cylindrical FS. The value of H and its direction simply change the cyclotron radius Rc of the electron orbit according to the equation

\[ R_c(H, \varphi) = R_c(H, \varphi = 0) \cos \varphi = \frac{p_F c}{e H} \frac{1}{\cos \varphi}, \]

where \( p_F \) is the Fermi momentum, \( c \) the light velocity, \( e \) the electron charge, and \( \varphi \) the angle between \( H \) and the cylinder axis.

We describe the motion of an electron through a bicrystal for a pedagogically simple case as illustrated in Fig. 1. The bicrystal sample surface is in the \( xy \) plane. An intercrystalline boundary is a mirror-symmetry plane between crystal A with its FS cylinder along the \( x \) axis and crystal B with its FS cylinder along the \( y \) axis. We choose an applied \( H \) in the boundary plane so that cyclotron radii [from Eq. (1)] are equal in both crystals.

The construction in Fig. 1(b) describes in \( p \) space the laws of reflection from the sample surface (\( p_x, p_y \) plane) and transmission through the intercrystalline boundary (\( p_z, H \) plane) for an electron in state A. In the construction, we coincided the origins \( 0 \) (zero) of the Brillouin zones of both adjacent crystals. We treat the electron/interface scattering as elastic and for simplicity assume conservation of an electron momentum component along an interface \( p_z \). For the electron
FIG. 1. Dynamics of conduction electrons in a bicrystal in real space and in \( p \) space (b). (a) Electron focusing by a magnetic field and electron refraction at an intercrystalline boundary \((z, \mathbf{H})\) plane. The electron injection through the emitter \( E \) is uniform in direction in the \( zy \) plane. Skipping electron trajectories are drawn up to the third specular reflection from the sample surface \((xy)\) plane. Visible caustics (regions of high density of electron trajectories) cross the \( y \) and \( x \) axes at points \( A, B, C \)—points of electron focusing. Trajectories of the “focused” electrons, injected perpendicular to the surface, are shown in thick lines. Line \( E-O-C \) shows the refracting skipping path. (b) The laws of reflection from a sample surface \((p, \mathbf{p}_1, \mathbf{p}_2)\) and transmission through an intercrystalline boundary \((p, \mathbf{H})\) plane are illustrated for an electron in state \( A \). Two FS cylinders are for two parts of the bicrystal, respectively. Electron trajectories in \( p \) space—cross sections of the FS with a plane perpendicular to \( \mathbf{H} \)—are shown in thick lines. When reflecting from the surface the electron goes from state \( A \) to state \( B \). When transmitting through the boundary it goes from state \( A \) to state \( C \). For details, see the text. (c)–(e) Schematic drawing of the skipping paths \((1-3 \text{ and } 1'-3' \text{ in adjacent crystals, respectively})\) propagating along the sample surface (arrows indicate the direction of propagation for a given orientation of the magnetic field \( \mathbf{H} \)). The three paths for each crystal are due to the three “cylinders” of the Bi Fermi surface (see text). (c) No interface (all paths, \( 1-3 \text{ and } 1'-3' \), are shown coming from one emitter). (d) and (e) illustrate the possibilities of electron transmission through a boundary \([\text{paths } 1 \rightarrow 1' \text{ in (d) and } 2 \rightarrow 2' \text{, } 2' \rightarrow 1' \text{ in (e)}]\) and electron reflection from the boundary \([\text{path } 1 \rightarrow 3 \text{ in (d)}]\) for two different boundary orientations \( AA' \text{ and } BB' \).

reflection, elastic scattering impels the electron to stay on FS, and conservation of \( p_x \) impels it to stay on line \( AB \)—line of the constant \( p_y \), perpendicular to the surface. Therefore, the electron goes from state \( A \) to state \( B \). The analysis of an electron momentum change under transmission through an interface is not trivial. The basic principles of conduction electron transmission were formulated by Pippard.7 After the electron transmission from crystal \( A \) into crystal \( B \) the electron state can be determined similarly to the reflection case. In our case, the electron goes from \( A \) to \( C \) at the intersection of the constant \( p_y \), line \( AC \) (perpendicular to the \( p, p_y \) plane) with the FS of crystal \( B \).

In Fig. 1(a) trajectories of electrons injected through the emitter \( E \) are depicted in real space. In crystal \( A \), injected electrons move in the \( zy \) plane. We assume that the injection is uniform in direction in the \( zy \) plane. An injected electron will execute a part of the circle and reproduce it after the specular reflection from the sample surface. It is crucial that in a Fermi system even for electrons injected isotropically in an angle, the density of electron flux incident onto a surface is singular for points at distances \( 2R_c \), \( 4R_c \), etc., from \( E \), i.e., where electrons emitted perpendicular to the surface return to it. At these points caustics—regions of high density of electron trajectories [visible in Fig. 1(a)]—intersect the sample surface. In Fig. 1(a), trajectories of the electrons injected perpendicular to the surface are shown in thick lines. If we scan an electron collector \( C \) over the sample surface, it will collect injected electrons incident onto the surface at the collector location, and register a focusing peak (spike) only at distances \( 2R_c \) [point \( A \) in Fig. 1(a)], \( 4R_c \), etc., from \( E \) on the \( y \) axis. For perfectly specular reflection from the surface, the heights of the peaks after 0, 1, 2, etc., reflections within the same crystal will be all the same. If the probability of specular reflection is \( q < 1 \), then the ratio of the heights of adjacent peaks will be \( q \). These problems are treated in detail in regular TEF.4,5,8

Consider now what happens when crystal \( A \) has an intercrystalline boundary with crystal \( B \). As illustrated in Fig. 1(a), transmitted electrons are “refracted” at the boundary, initially moving in the \( yz \) plane, but then in the \( xz \) plane. In crystal \( B \) under the specified conditions, focusing will be at points \( B, C \), etc., where caustics intersect the sample surface. The heights and locations of the peaks give information about the transmission probability and correlation.

If \( H \) is made so large that \( 2R_c \) becomes less than the diameter \( d \) of the electron emitter, then the series of ballistically produced focusing peaks collapse together to give skipping paths where an apparently continuous electron flux simply propagates along the sample surface in directions perpendicular to the axes of the electron cylinders in each crystal [skipping path \( E-O-C \) in Fig. 1(a)]. We called this case drift flux to distinguish it from the ballistic flux when \( 2R_c \gg d \) as illustrated in Fig. 1(a). Figures 1(c)–1(e) show schematically the paths that would be followed by electrons transmitted or reflected from the boundary, now assigning three different electron cylinders to each crystal, to illustrate what is actually expected in Bi, where the FS contains three noncollinear electron cylinders. A mobile collector scanned over the entire surface allows direct visualization of the drift flux both before it is incident upon the boundary and after it is reflected and refracted, for chosen \( \mathbf{H} \) and boundary orientations.

In the actual experiments, a laser beam focused to a small spot on the surface of a Bi bicrystal (emitter \( E \)) creates electronic excitations (electrons) (Ref. 9) that are focused by a uniform and constant magnetic field \( \mathbf{H} \) onto a point-contact collector \( C \) (the technical setup is described in Ref. 10). Previous TEF measurements11 proved the similarity of an ohmic microcontact emitter with an electric current passing through it and a small laser spot emitter. In the actual situation, the laser spot (\( d \approx 15 \mu \text{m} \)) is scanned over the sample surface, inducing an electron-hole flux due to thermoelectric effects and producing a voltage at \( C \) (Ref. 12) that varies with the position of \( E \). For ease of exposition, we describe the alter-
The sample studied was a Bi bicrystal accidentally obtained from growth in a polished quartz demountable form. The common ballistic electron mean-free path in the two crystals was about 0.2 mm ($T = 1.2$ K). The $C_3$ axes of the two crystals were parallel to each other and inclined by $12^\circ$ from the normal to the sample surface. The interface was parallel to the axis of one of the electron cylinders in crystal A. Crystal B was rotated relative to A around the $C_3$ axis by about $30^\circ$. The intercrystalline boundary at the surface was made visible by etching the surface. Electron reflection from such an etched surface in Bi is expected to be diffuse with a high probability of electron-electron intervalley scattering, i.e., under reflection from such a surface, an electron on one cylinder can be scattered to another cylinder, thereby changing its plane of motion within the same crystal.

With this background, we now turn to our data.

**Drift Flux.** Preliminary measurements were made to check the interface location and to determine the planes of electron motion (skipping paths) in both crystals, to allow a direction of $H$ to be chosen that would yield good visualization of the electron paths. Figure 2(a) shows a typical experimental two-dimensional (2D) gray-scale pattern for $H$ large enough to produce a drift flux. Lighter color indicates higher flux intensity. The emitter was located above the scanned area at about $(150,-50)$. Visible are the incident electron flux coming from the top center of the picture; the boundary designated by a white line; and the refracted electron flux exiting from the picture at the bottom, left of center. The angle of refraction is $\sim 30^\circ$, in good agreement with the relative crystallographic orientation of the two crystals. The fluxes in both crystals damp and broaden as they propagate, behaviors that we attribute to electron relaxation and intervalley transitions, exacerbated by the surface damage produced by the etching used to make the boundary visible.

However, the similar intensities of the fluxes just on the two sides of the boundary indicate that any intensity change at the boundary is small and that the transparency of the boundary for the drift flux is close to unity. Separate experiments to better examine the reflected flux confirmed that the reflected intensity was only a few percent.

**Ballistic Flux.** As a reference for our boundary refraction and reflection studies with ballistic flux, we first examined the ballistic flux TEF pattern for our bicrystal far from the intercrystalline boundary. Figure 2(b) shows that we could resolve three gradually broadening and weakening focusing peaks generated from an emitter located outside of the picture at about $(420,-110)$. For the TEF boundary studies, $H$ was chosen to give a cyclotron radius of about the distance of the emitter from the boundary. Once the skipping paths in the two crystals were known, $E$ was set at a distance of $\sim 100 \mu m$ from the boundary [i.e., at about $(130, -50)$ in Fig. 2(c)] in crystal A, and $C$ was scanned over the area of interest around the boundary to determine the direction of $H$ and its precise value to give the most intense focusing peaks due to the transmitted electrons. In the resulting geometry, the ballistic flux was incident nearly normal to the boundary. Figure 2(c) shows the presence of two focusing peaks after refraction at the boundary (white line)—a fairly well-defined peak at about $(25,135)$ for one electron cylinder in crystal B, and a less well-defined one at about $(170,110)$ for another electron cylinder. Two peaks originated in splitting at the boundary of a single electron beam for one cylinder in crystal A into two electron beams for two different cylinders in crystal B. The presence of these two peaks requires correlated transmission of electrons through the boundary. The fact that the intensities of the refracted peaks are much lower than those of the unrefracted peaks in Fig. 2(b), shows that the probability of correlated transmission is low ($< 0.1$). A more quantitative determination of this transmission prob-

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**FIG. 2.** Density distributions of injected through-the-emitter electrons over the Bi bicrystal surface in a magnetic field $H$. (a) 2D gray-scale density plot of the drift flux refracting at the intercrystalline boundary (indicated as a white line). Lighter color indicates higher flux intensity ($H = 50$ Oe in, approximately, the $x$ axis direction). For $(x,y)$, the flux enters from approximately $(200,0)$ and exits at approximately $(150,400)$. (b, c) 2D gray-scale density plots of the ballistic flux (TEF). (b) Without the boundary ($H = 10$ Oe in, approximately, the $x$ axis direction). Three ordinary TEF peaks are visible centered at, roughly, $(430,10)$, $(440,120)$, and $(450,240)$. The emitter position is approximately $(420,-110)$ out of the scanned area. (c) Transmission through the boundary (indicated as a white line; $H = 6$ Oe in, approximately, the $x$ axis direction). Two broad, weak TEF peaks after electron transmission through the boundary are visible, one at approximately $(25,135)$ and another at approximately $(170,110)$. The emitter position is approximately $(130,-50)$ out of the scanned area. The white region within $(90-130,0-50)$ is due to the enhanced contrast needed to make the two weak peaks visible.
ability is complex and will require a detailed theoretical analysis that does not yet exist.

To summarize, we have applied a technique, involving TEF with light-induced electron excitation, for the study of conduction electron transmission through (with refraction), and reflection from, an intercrystalline boundary in Bi for both drift and ballistic fluxes. For the drift flux, the observed uncorrelated transmission probability was nearly unity and reflection was only a few percent. For the ballistic flux, in contrast, the correlated transmission probability was small (<0.1). Therefore the high intercrystalline electron transparency originates in uncorrelated electron transmission. Note that the technique can be used for the analysis of an interface structure in situ probing the interface with conduction electrons.5

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7 A. B. Pippard, The Dynamics of Conduction Electrons (Gordon and Breach, New York, 1965).
9 The laser beam also creates hole excitations (holes) that we neglect as having a very short mean-free path in Bi compared with an electron mean-free path. I. F. Sveklo and V. S. Tsoi, Zh. Eksp. Teor. Fiz. 103, 1705 (1993) [JETP 76, 839 (1993)].
12 The voltage (current) across the collector is proportional to the electron flux incident onto it.