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Observation of thermally activated quasiparticle interaction by ballistic electron transport and electron focusing

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Abstract

Electron focusing patterns originating from ballistic electron transport in single crystalline materials are observed in transmission. Spatially resolved excitation by scanning electron microscopy and detection by a point contact is employed for imaging. The effects of electron–phonon and electron–electron interactions are demonstrated for bismuth by observation of the thermal dependence of the spatially resolved transport properties of quasiparticles in the range of 5–100 K.

Keywords: Scanning electron microscope; Electron focusing; Ballistic propagation

1. Introduction

The dominating scattering mechanism for electrons in metals at room-temperature is the electron–phonon interaction. Therefore the mean free path of the carriers is in the range of some nanometers only. Below typically 4 K, the temperature independent impurity scattering is the dominating scattering mechanism for metals and semimetals.

By carefully preparing very pure single crystals it is possible to reduce scattering due to impurities. The mean free path can reach several hundred μm and ballistic carrier propagation can be observed [1–3]. The detected transport properties reflect the anisotropy of the Fermi surface (FS) [4]. The direction of the group velocity of the quasiparticles is oriented normal to the FS. For ballistic transport singularities in the energy transport of quasiparticles with energies in the vicinity of the Fermi energy are observed in directions where the Gaussian curvature of the Fermi surface is zero in at least one dimension. A strong directional concentration of the quasiparticle transport, the so called electron focusing (EF) is already observed for directions where the curvature is small. EF has recently been observed in real space [5,6] using light or a point contact for carrier excitation. We have developed a related technique, employing low temperature scanning electron microscopy [10] for excitation. Local heating within a small volume determined by the penetration depth of the electrons is the dominant source for carrier generation. The carriers are detected at the opposing surface of the sample by a point contact.

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2. Experiment

Fig. 1 shows the experimental setup employed for imaging of electron focusing patterns with a scanning electron microscope (SEM). The sample is mounted in thermal contact with a ^{4}He flow-cryostat operating at temperatures between 5 and 150 K. The set-up is positioned in the sample chamber of a ComScan CS44 Type SEM. The upper sample surface can be scanned with the electron beam through a hole in the thermal shield.

The electrical signal between a point contact (PC) and a reference contact connected to the edge of the sample is measured as a function of the beam position. The signal is picked up by a PAR 1900 signal transformer. The electron beam intensity is modulated with a frequency $f \approx 100$ Hz and the signal is finally detected by a lock-in amplifier. The images are computer-generated with a brightness proportional to the detected electrical signal.

The FS of bismuth (Fig. 2) consists of three approximately ellipsoid shaped surface pockets at the T point of the Brillouin zone [7,9]. The almost cylindrical centre parts of the ellipsoids lead to a pronounced enhancement of the electron flux in radial direction. Therefore observable ballistic transport is almost completely restricted to propagation directions in three planes vertical to the axes of the cylinders.

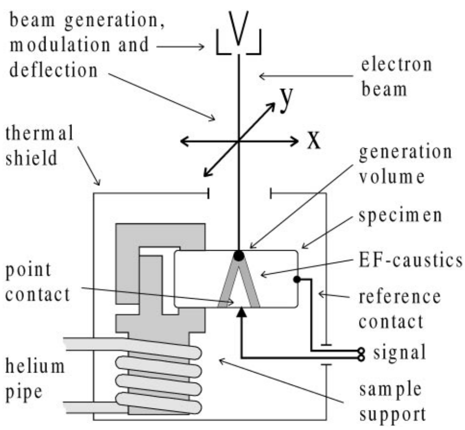

Fig. 1. Set-up for imaging of ballistic carriers. The carriers are excited in the sample by the electron beam of a scanning electron microscope. They are detected by a stationary point contact.

Fig. 3a shows an experimentally obtained electron focusing pattern of a bismuth single crystal disc [8] with its large surfaces oriented perpendicularly to the trigonal axis k_z. The experimental parameters are $U_{\rm El} = 5$ kV and $I_{\rm El} = 22$ nA where $U_{\rm El}$ is the electron beam acceleration voltage and $I_{\rm El}$ is the electron beam current at the sample. The measurement was performed at a temperature of 6 K.

The three bright lines result from electrons of the three Fermi ellipsoids. EF occurs in planes

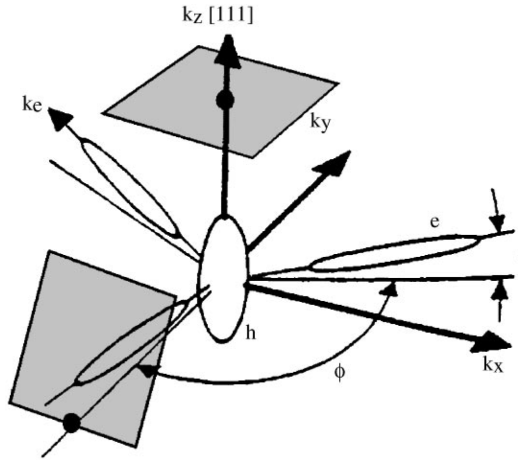

Fig. 2. Fermi surface of Bi (e: electrons, h: holes, $\theta \approx 6°$, the size of the pockets is exaggerated with respect to their distance). The two shaded squares identify the two different orientations of the surfaces of the samples used in the experiments.

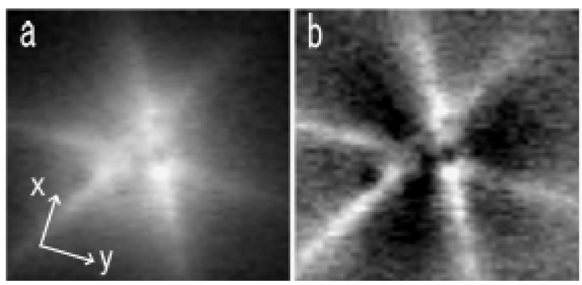

Fig. 3. Electron focusing pattern observed for ballistic transport of electrons in a bismuth single crystal. The observation plane is the k_z-plane (1 1 1), image frame $(110\ \mu m)^2$, crystal thickness $d = 45\ \mu$m, acceleration voltage $U_{\rm El} = 5$ kV, beam current at the sample $I_{\rm El} = 22$ nA, sample temperature $T = 6$ K. (a) Measured data, (b) has been created by subtracting a diffuse background from (a).

perpendicular to k_e due to the small curvature in this direction. The three EF lines do not intersect in one point because of the small tilt of the ellipsoids against the $(k_x k_y)$ plane. A fraction of the electrons apparently undergo multiple scattering processes and produce a diffuse background in the image centre. This structure has been modelled by a Gaussian potential distribution $V(\boldsymbol{r}) = V_0 e^{-(\boldsymbol{r}-\boldsymbol{r}_0)^2/d^2}$, where $\boldsymbol{r}$ and $\boldsymbol{r}_0$ lie in the observation plane and d is the sample thickness. Fig. 3b has been computed by fitting this distribution to the measurement and subtracting it from the data. In Fig. 3b the three focusing lines are dominating the image. In the center of the image three dark structures outside the inner triangle are visible. These have also been reported [5] in light induced electron focusing measurements on bismuth crystals. They are attributed to slow transverse phonons. The phonons heat the sample surface and produce a thermal gradient in the point contact. They drag carriers from the hot spot towards and through the point contact (phonon drag). These effects generate a thermoelectric signal at the Bi–Cu point contact which is detected.

Fig. 4 shows EF-images of another bismuth single crystal [8]. The sample surfaces lie in the (1 0 0) plane of the crystal. The experimental parameters are $U_{El} = 20$ kV and $I_{El} = 35$ nA. The temperature varies from 6 K in (a) to 100 K in (h). To represent all signal contributions in a comparable way in the images, the brightness is chosen proportional to the magnitude of the signal. Therefore bright areas can result from electron contributions and from phonon contributions dragging electrons to the PC or generating a thermoelectric signal in the PC. Since the signal amplitudes vary with the temperature, the amplitude scale of each image, denoted in the lower right corner, is adjusted for optimum contrast.

In Fig. 4a two bright lines resulting from electron focusing are visible. Since the orientation of the sample is (1 0 0) only two of the focusing planes cross the surface while the third one is orientated nearly parallel to the surface. When the temperature rises signals resulting from scattered transport dominate the image. This situation is shown in images (b) and (c), for $T = 7$ K, respectively, $T = 8$ K. In image (d) in the upper right and the

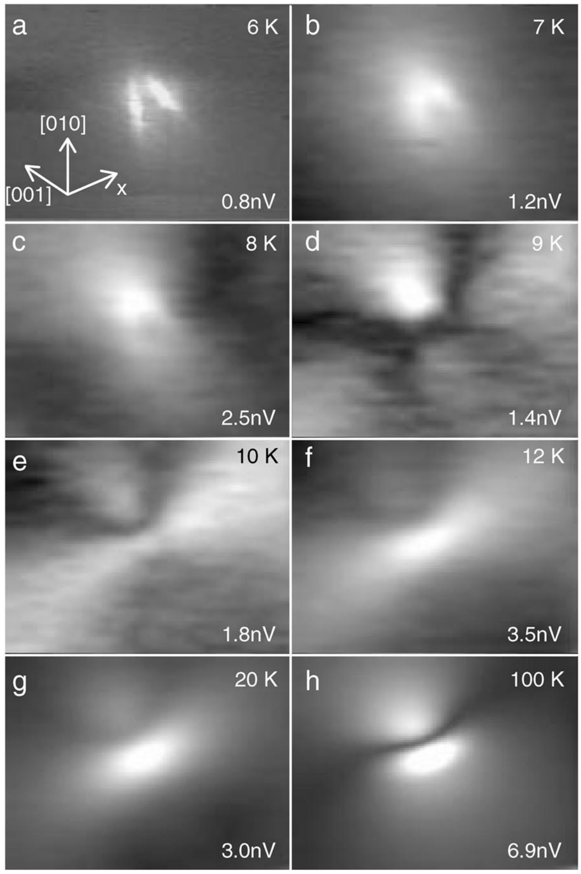

Fig. 4. Temperature dependence of the quasiparticle transport in bismuth. The observation plane is (1 0 0), image frame 3050 μm × 2300 μm, crystal thickness $d = 300$ μm, $U_{El} = 20$ kV, beam current at the sample $I_{El} = 35$ nA. The temperature, noted in the upper right corner of each image, varies between 6 K (a) and 100 K (h).

lower left corner a new signal contribution arises which is attributed to ballistic phonons. The thermoelectric signal at the point contact resulting from phonon propagation has inverse polarity with respect to the signal caused by electrons. Therefore the amplitude vanishes in regions, where both contributions are detected with equal intensity. With rising temperature, the phonon part of the signal rises while the electron part remains nearly constant. This can be seen in images (e) and (f) for $T = 10$ K respectively $T = 12$ K. The phonon part is more pronounced than the electron part. Therefore the electron signal contribution appears lower in image (f), even though at a comparable level as in image (e) is present. For a temperature of 20 K, demonstrated in image (g), the phonon signal intensity rises and gets more concentrated in the centre of the image, where the point contact is positioned, due to scattering of the phonons. A further increase of the temperature leads to a more pronounced electron contribution as demonstrated in image (h). The black line between the electron spot and the phonon spot is the area where both contributions generate opposing electrical signals at the point contact.

3. Conclusion

Spatially resolved detection of the temperature dependence of the transport properties of electrons in bismuth has been performed employing an electron beam for carrier generation. Ballistic carrier propagation governed by electron focusing is dominant for low temperatures. For rising temperatures a complex scenario resulting from thermally induced quasiparticle interaction is demonstrated. Even at 100 K the observed combined transport properties of electrons and phonons show distinct spatial dependencies which can not be represented by simple diffusive transport. The developed technique based on electron microscopy offers the possibility to investigate the transport properties of electrons and other quasiparticles in real space with microscopic resolution.

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