New Method to Study the Electron-Phonon Interaction in Metals

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A new kind of point-contact spectroscopy is described: The magnitude of the transverse electron-focusing signal in a Ag single crystal is measured as a function of the energy of the injected electrons. For low energies, this is a direct measurement of the energy dependence of the electron-phonon interaction strength of electrons in a specific orbit on the Fermi surface. Also for higher energies effects of the anisotropy of the electron-phonon interaction are observed.

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The electron-phonon interaction in metals and its anisotropy are studied in many different ways. Most of the methods use the fact that, in a magnetic field, electrons move in cyclotron orbits [e.g., the radio-frequency size effect (RFSE)]. The energy-dependent part of the mean free path of electrons in a certain orbit is studied by measurement of the decrease of the signal for increasing temperature. For a review on the use of RFSE and other methods for this purpose, see Gantmakher.[1] Point-contact spectroscopy[2,3] is a method that allows direct measurement of the energy dependence. Electrons are injected with a certain amount of energy at a Sharvin point contact[4] between two metals; if the electrons scatter back through the contact, the resistance will increase. With that method it is not possible to select a specific cyclotron orbit, although via a weight factor over the Fermi surface information about the anisotropy can be obtained.[5,6]

We used a new method to study the electron-phonon interaction in Ag. The method is based on transverse electron focusing (TEF)[7-9] and combines the advantages of the methods described above. In a TEF experiment, two point contacts are placed on the surface of a metal single crystal at a distance apart smaller than the mean free path (see the inset of Fig. 1). Electrons are injected at the emitter point contact (E) and are bent back to the surface by a magnetic field. For a certain value of the field, the electrons are focused on the collector point contact (C) and a voltage peak is found. We measured the decrease of this voltage peak with increasing energy of the electrons. This is a direct measurement of the energy dependence of the scattering rate of electrons in a specific cyclotron orbit. Sharvin and Bogatina[10] used a slightly different setup (longitudinal electron focusing) to study the electron-phonon interaction in Sn. The temperature dependence of the peak height could be related to scattering processes with phonons, but the energy dependence they found was dominated by the defocusing action of the magnetic field of the injection current.

If in a TEF experiment on a metal with a spherical Fermi surface the magnetic field B is directed perpendicular to the line EC, only electrons with no velocity component along B will arrive at the collector. The electrons that give rise to the focusing peak travel half a cyclotron orbit through the crystal. If the magnetic field is rotated over an angle θ in the plane of the crystal surface, focusing still occurs. It may be shown that the electrons responsible for the focusing peak now travel along a nonextremal cyclotron orbit over an angle $\pi+2\alpha$ (α being a function of θ). Electrons that are scattered will no longer contribute to the focusing peak. If the scattering rate τ^{-1} is a function of the energy ϵ of the electron (relative to the Fermi energy), the TEF peak height P will be a function of the voltage V across the emitter point contact:

$$P(eV)=P(0)\exp[-t/\tau(eV)]. \quad (1)$$

Here $t=(\pi+2\alpha)m/eB_0$ is the time during which the electron travels through the crystal, B_0 is the value of the magnetic field for which focusing occurs, and for m we

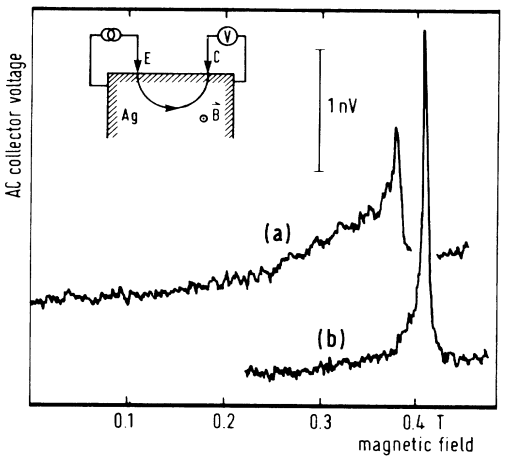

FIG. 1. (a) Collector voltage vs magnetic field for Ag(100). The magnetic field is directed along [001] and the line connecting the point contacts is perpendicular to it. (b) Same as (a), but with the magnetic field rotated over $\approx 35°$. Inset: The TEF geometry with emitter (E) and collector (C) point contacts.

take the free-electron mass.

The scattering rate of electrons with phonons depends on the energy of the electrons and on the temperature. It may be characterized by the function α^2F, the product of the average electron-phonon interaction matrix element squared and the phonon density of states:

$$\frac{1}{\tau(\epsilon,T)}=2\pi\int d\omega\,\alpha^2F(\omega)[f(\epsilon+\hbar\omega)-f(\epsilon-\hbar\omega)+2N(\omega)+1]. \quad (2)$$

Here, f and N are the Fermi-Dirac and Bose-Einstein distribution functions, respectively, and $\hbar\omega$ is the phonon energy. For $T=0$, the equation reduces to

$$\frac{1}{\tau(\epsilon,0)}=2\pi\int_0^{\epsilon/\hbar}d\omega\,\alpha^2F(\omega)=\frac{2\pi b}{3\hbar}\epsilon^3. \quad (3)$$

The last step is valid for low energies where $\alpha^2F(\omega)=b(\hbar\omega)^2$. From the decrease of the TEF peak height with increasing electron energy, the coefficient b may be determined. As the electron-phonon interaction is anisotropic, this value is an average value for the orbit that is selected by the focusing condition. Effects of finite temperature can be neglected as long as $k_BT\ll\epsilon$.

If the electron-phonon interaction is studied in an RFSE experiment, the temperature dependence of the scattering rate is measured. In principle, one measures some average rate for electrons with energies within a range of the order of k_BT around the Fermi energy.[11] Wagner and Albers,[12] however, showed that, in samples that are thick with respect to the electron mean free path, only the electrons at the Fermi level contribute. The scattering rate of these electrons follows from Eq. (2) and, with the assumption of a quadratic energy dependence of α^2F, is given by

$$1/\tau(0,T)=8.4(2\pi b/\hbar)(k_BT)^3. \quad (4)$$

Equations (3) and (4) may be used to compare measurements of the energy dependence and of the temperature dependence by expressing the coefficients in the single parameter b.

The preparation of the Ag single-crystal samples that were used in the TEF experiments has been described elsewhere.[8,9] All measurements were done in a pumped He bath (1.2 K). Point contacts were made by means of two 50-μm-diam Ag wires with sharp points etched to them; the contact resistances ranged from 0.1 to 1 Ω. Both the sample and the magnetic field could be rotated in the horizontal plane with respect to the point contacts. For the point-contact separation used ($\approx 50\,\mu$m), the relative directions of EC, magnetic field, and crystal axes could be determined only up to $\pm 5°$.

A home-built current source provided a direct current and a small ac modulation (120 Hz) to the emitter point contact. The ac voltage across the emitter was chosen not larger than 0.5 mV_{rms} to prevent smearing out of the energy dependence. The ac voltage across the collector point contact was measured by use of phase-sensitive detection. The collector voltage was first measured as a function of the magnetic field for zero dc emitter voltage (the usual TEF experiment). The energy dependence was then measured by sweeping of the dc voltage for several values of the magnetic field.

Measurements were done for four different electron orbits in two Ag samples, with the normals along [100] and [110], respectively. Figure 1(a) shows the TEF signal for a Ag(100) sample with the magnetic field along [001] and perpendicular to the line connecting the point contacts (orbit 1 in Fig. 2). When the magnetic field is rotated over $\approx 35°$, a maximum is observed in the TEF peak height while the width of the peak has become smaller [see Fig. 1(b)]. In this configuration the electrons that give rise to the focusing peak follow a nonextremal belly orbit that does not come very close to the necks of the Fermi surface (orbit 2 in Fig. 2). The differences in heights and widths of the TEF signal in different configurations can be explained qualitatively by the deviations of the Fermi surface of Ag from a sphere.[9] Figures 3(a) and 3(b) show the corresponding measurements of collector voltage versus dc emitter voltage.

On the Ag(110) sample, TEF measurements were done with $\angle(EC,[1\bar{1}0])=25°$ and $B\perp EC$. The electrons then follow an orbit which is already close to the necks (orbit 3 in Fig. 2). By rotation of the magnetic field over 12°, the orbit is brought as close to the necks as possible (orbit 4 in Fig. 2). In the latter configuration, also the roles of emitter and collector were interchanged (with the magnetic field reversed), and measurements were done for $B=2B_0$ as well, when electrons are focused after being specularly reflected at the surface. In all these measurements the same voltage dependence was found.

The voltage dependence of the TEF peak height in different configurations shows the same features. For low voltages, the signal decreases because the scattering rate of electrons with phonons increases with increasing

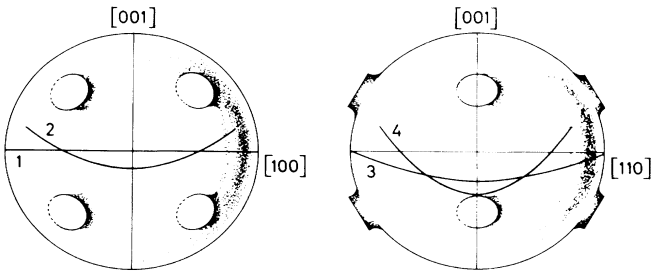

FIG. 2. The Fermi surface of Ag with orbits 1–4. Orbits 1 and 3 are extremal orbits.

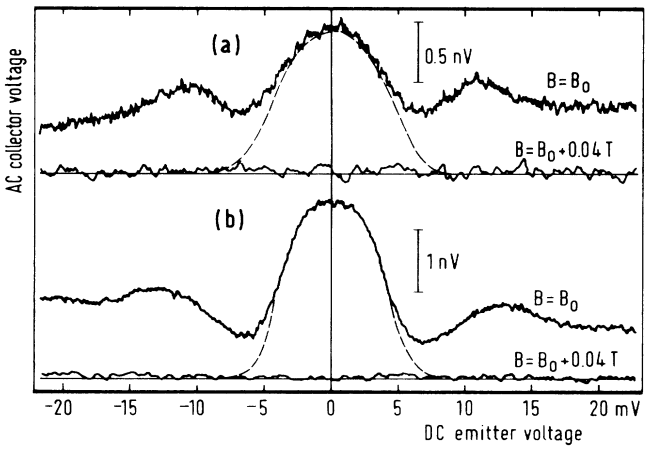

FIG. 3. (a) Collector voltage vs dc emitter voltage for Ag(100). The magnetic field is directed along [001] and the line connecting the point contacts is perpendicular to it. Traces are for the focusing peak of Fig. 1(a) ($B=B_0$) and for $B=B_0+0.04T$. The dashed line is a fit with $b=60$ eV^{-2}. (b) Same as (a), but with the magnetic field rotated over $\approx 35°$. Traces are for the focusing peak of Fig. 1(b) ($B=B_0$) and for $B=B_0+0.04T$. The dashed line is a fit with $b=75$ eV^{-2}.

electron energy. For higher voltages, a background signal is observed, which is due to electrons that have lost their energy close to the emitter. These electrons again have a large mean free path. The smaller the source of these electrons is, the narrower and higher their focusing peak will be. The background signal has maximum that depends on the configuration [compare Figs. 3(a) and 3(b)]. It also shows a slight asymmetry for positive and negative emitter voltages, which is due to the magnetic field generated by the emitter current.[13]

The parameter b was determined by fitting of the expected voltage dependence of the TEF signal [Eq. (1)] to the measurements [see the dashed lines in Figs. 3(a) and 3(b)]. We assumed that the background signal is zero for $V_{dc}=0$ and that it increases monotonically for increasing absolute value of the emitter voltage. In Table I, we compare our TEF results for the parameter b with measurements of the temperature dependence of RFSE lines by Gasparov[14] and by Johnson and Goodrich.[15] These values of b are calculated from the coefficients of the temperature dependence with the use of Eq. (4). The data for orbit 1 may be compared directly. For the other orbits, we tabulated how the b value is related to the value for the nearest orbit that was measured in Refs. 14 and 15. Gasparov, Lebech, and Saermark[16] measured the temperature dependence of time-of-flight effect signals in Ag and found up to 30% higher values for the coefficient than the RFSE results of Ref. 14. The temperature dependence of the magneto-acoustic effect in Ag[17] yields the same values as the RFSE results of Ref. 15.

Our values for b are lower, but they are not unreasonable in view of the discrepancy in the published values. On the other hand, Gasparov[14] and Johnson and Goodrich[15] do qualitatively agree on the anisotropy of b, while the TEF measurements show rather the opposite trend, except for the orbit very close to the necks. An explanation for this discrepancy may be found in the fact that the TEF experiment measures the electron-phonon interaction in the energy range 1–5 meV, while the measurements on temperature dependence probe the range 0.1–1 meV. Although the results of both experiments are consistent with $\alpha^2F=b(\hbar\omega)^2$, the measurements only extend over a limited energy range and the ω dependence of α^2F and its anisotropy may well be more complicated.

TABLE I: Values of the parameter b in eV^{-2} for electrons in four different orbits on the Fermi surface of Ag. The orbits are shown in Fig. 2. For the RFSE measurements of the same (1) or nearby (2,3,4) orbits, the values of b are calculated from the temperature dependence with the use of Eq. (4).

Orbit	This work (TEF)	Ref. 14 (RFSE)	Ref. 15 (RFSE)
1	60 ± 15	115	76
2	75 ± 15	<115	<76
3	45 ± 10	$\gtrsim125$	$\gtrsim90$
4	100 ± 15	$\gg125$	$\gg90$

A comparison in terms of the coefficient b between TEF and point-contact spectroscopy is difficult because the latter measures some average value over the whole Fermi surface. In addition, point-contact spectroscopy is not very sensitive for low energies when the electrons are scattered far from the emitter. For high-electron energies, however, the two methods are very similar. The main difference is that, in TEF, the electrons that are scattered close to the emitter are detected at a collector point contact instead of at the emitter. This means that scattering processes are selected in which the electrons are scattered into a specific direction, namely the starting direction of the focusing orbit. Both the TEF signal and the point-contact spectrum[3] of Ag show a maximum for $\epsilon\approx12$ meV that corresponds to the main peak of α^2F. The TEF signal also shows a dependence of the position of this maximum on the configuration (i.e., on the focusing orbit), and so also for high energies TEF yields information about the anisotropy of the electron-phonon interaction.

In conclusion, TEF is of great use to study the electron-phonon interaction in metals. For low energies, it directly measures the energy dependence of the scattering rate of electrons in a specific orbit on the Fermi surface. Other methods like RFSE study the energy dependence through the temperature dependence of the electron mean free path. The results of the present TEF measurements on Ag do not in all aspects agree with the earlier RFSE results. This may be because the methods

probe slightly different energy ranges. For high electron energies, TEF is in principle very similar to point-contact spectroscopy. The different experimental setup of TEF, however, yields very specific information about the anisotropy of the electron-phonon interaction.

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