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[7] When the order parameters corresponding to $q_a = \frac{1}{2}$ ($q = 0$) are subject to the twofold screw axis, $\varphi_{10} \to \pm\varphi_{10} \times \exp(-i\pi q_b/b^*)$ and $\varphi_{20} \to \mp\varphi_{20}\exp(-i\pi q_b/b^*)$. Therefore, the order parameters transform like two different representations of the space group, and the most general real second-order term which can be formed is $F_2 = a_1(T)|\psi_{10}|^2 + a_2(T)|\psi_{20}|^2$ and there are no mixed terms.

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# Conduction-Band Tunneling and Electron-Spin Polarization in Field Emission from Magnetically Ordered Europium Sulfide on Tungsten*

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We measured the temperature dependence of the current and spin polarization, and determined the work functions from Fowler-Nordheim plots. The current increases exponentially with decreasing temperature. Work-function data can be related directly to the height of the internal W-EuS barrier. This barrier is lowered by magnetic splitting of the EuS conduction band for one electron-spin state which should lead to a spin polarization of unity. The measured spin polarization, however, is equal to the polarization of the $4f^7$ electrons of europium.

At low temperatures europium sulfide is a ferromagnetic insulator.[1] Esaki, Stiles, and von Molnar[2] studied the internal field emission (Fowler-Nordheim tunneling) on metal-EuS-metal junctions at temperatures above and below the EuS Curie point, which is at 16.5 K for pure, annealed thin films. They discovered a decrease in the Schottky potential-barrier height due to magnetic ordering. In external field emission from metal-EuS-vacuum emitters additional information can be obtained by measuring the electron-spin polarization. The first field-emission studies and polarization measurements on EuS-coated tungsten tips were performed by Müller *et al.*[3] They found three different types of emission, two of which (*types I* and *II*) yielded high polarization; for *type I* ($P_{\max} \sim 0.5$) conduction-band tunneling was assumed but no temperature dependence of the current was reported. In this Letter we report polarization and work function measurements on W-EuS emitters which exhibit the pronounced temperature dependence of the current as observed by Esaki, Stiles, and von Molnar for internal field emission.

The layout of our apparatus is shown in Fig. 1. Oriented tungsten tips[4] with ⟨111⟩ or ⟨110⟩ directions parallel to the axis and radii of typically 50 to 100 nm were coated at room temperature with EuS by *in situ* vacuum deposition. The EuS was evaporated from a tungsten oven which could be moved in front of the tip; the rate of deposition was 70 nm/min and evaporation times ranged from 0.5 to 2 min. The tip is cooled by a helium-flow system such as that described by Reed and Graham,[5] which in our case allows temperature variation in the range from 9 to 300 K. The tip can be heated by drawing a current through the filament to which the tip is spot welded. Above 600°C the thermal glow was observed through a telescope; at temperatures below 600°C the annealing process was controlled by monitoring the temperature-dependent heating current.

During field-emission studies a pressure of about $10^{-10}$ Torr was maintained at the tip. The tip was at a potential of $-2$ kV with respect to the grounded fluorescent screen, and the variable potential of the cylindrical anode determined the emission current. A longitudinal magnetic field variable from 0 to 0.5 T was used for imaging the emitting tip surfaces onto the screen. The emission pattern can be moved by electrostatic deflection and for electron-polarization analysis one point of the pattern was selected by

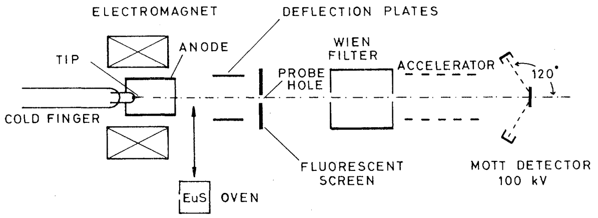

FIG. 1. Schematic diagram of the apparatus (not to scale).

steering it onto the probe hole. The beam then passed through a Wien filter (crossed electric and magnetic fields) capable of turning the polarization vector $\vec{P}$ transverse to the beam direction, as only transverse polarization can be determined by Mott scattering. The Mott-scattering setup is similar to that used at Yale University.[6] Two pairs of detectors are positioned at a scattering angle of $\theta = 120°$ and azimuthal orientations of 0° and 180° and 90° and 270°, respectively. Simultaneous measurement of two of the three components of the polarization vector is therefore possible. The third component can be measured separately with a different Wien-filter setting. Since only one spot of the emission pattern is analyzed, all the Mott-scattered electrons can be assumed to originate from a single Weiss domain.

W-EuS emitters which exhibited the pronounced temperature dependence of current, as observed by Esaki, Stiles, and von Molnar with Al-EuS-Al junctions, were obtained by using moderate annealing temperatures at which the thermal glow of the tip was not visible; e.g., annealing either for 1 h at a temperature between 300–350°C or for several seconds at some higher temperature not exceeding 600°C.[7] Emission occurred from the (112) planes of tungsten.[8] Usually the spots had different emission intensities, apparently because of different layer thicknesses. For deposition layers of 35 nm, which were the thinnest junctions prepared, short annealing times sufficed; thicker deposition layers had to be annealed repeatedly and presumably EuS migration over the tip occurred in these cases. Such migration was observed by Swanson[9] even at temperatures below 400°C.

Figure 2 shows our results for the temperature dependence of the emission current and electron polarization. The exponential decrease of the current for $T \to T_c$ makes polarization measurements in the vicinity of $T_c$ very difficult. The polarization shown is $P = |\vec{P}|$. At $T = 10.5$ K the polarization is greater than 0.9; extrapolation gives a polarization of unity at 0 K. The direction of $\vec{P}$ of the electrons leaving the tip is nearly transverse to the beam direction.[10] From measurements with a strong external field of $B = 0.5$ T it follows that $\vec{P}$ is antiparallel to $\vec{B}$, which means that the magnetic moments of the emitted electrons have the direction of the magnetization.

The electric field at the tip penetrates into the EuS, with the internal field strength $F_i$ related to the external field strength $F_e$ by $F_i = F_e/\epsilon$,

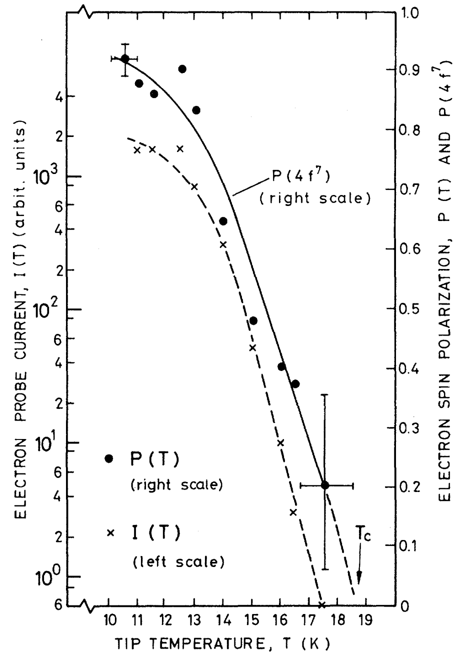

FIG. 2. Current, $I(T)$, and electron-spin polarization, $P(T)$, obtained with a W-EuS field-electron emitter which consisted of a ⟨111⟩-oriented tungsten tip and a EuS layer, with a deposition thickness of about 140 nm before annealing at 300–600°C for 10 sec. The data were taken with a constant extraction voltage of 393 V and a longitudinal external magnetic field of 20 mT. The total emission current at $T = 10$ K was 20 nA. As a measure of the probe current entering the Mott detector the average counting rate (counts/second) of the four electron detectors was plotted here (left scale, arbitrary units). The polarization of the $4f^7$ electrons, $P(4f^7)$, was computed from Eq. (2) by using work-function data shown in Fig. 3. The shown dependences are reversible with temperature.

where $\epsilon = 10.2$ is the static dielectric constant of EuS.[11] From our experimental conditions it must be concluded that this field penetration causes the external barrier to be lowered below the Fermi level of tungsten. The probability for traversing the external barrier then becomes unity and the emission current $I(T)$ is governed by the W-EuS internal barrier. It can be shown from the Fowler-Nordheim equation for internal tunneling[12,13] that in this case the internal barrier height, $\varphi_i(T)$, given by the difference between the tungsten Fermi level and the bottom of the EuS conduction band, can be determined by

$$\varphi_i(T) = \epsilon^{-2/3}\delta\psi(T), \tag{1}$$

where $\delta = (R/r)^{2/3} \sim 1.2$ is a geometric correction factor with $R$ the radius of the EuS-vacuum bound-

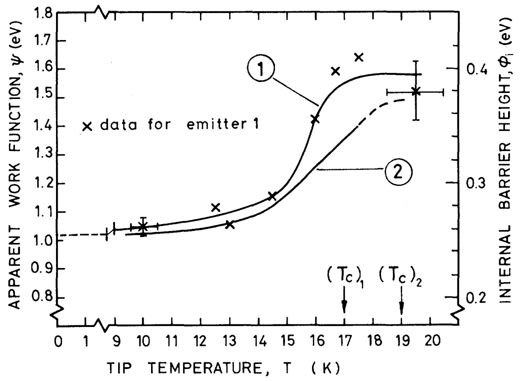

FIG. 3. Work-function data obtained with two W-EuS emitters. Curve 1: ⟨111⟩-oriented tungsten tip, EuS deposition thickness 580 nm before annealing. Data points were obtained from Fowler-Nordheim plots. Curve 2: Emitter with which the data of Fig. 2 were taken. The work function at $T = 10$ K was obtained from a Fowler-Nordheim plot; the other values were calculated by fitting the Fowler-Nordheim equation for internal tunneling to the $I(T)$ curve of Fig. 2. The relation between $\psi$ (left scale) and $\varphi_i$ (right scale) is given by Eq. (1).

ary and $r$ the radius of the tungsten tip, and $\psi(T)$ is the "apparent work function" obtained from a Fowler-Nordheim plot by standard procedures.[12] Work-function data for two emitters are given in Fig. 3 with scales for $\psi$ and $\varphi_i$.[14] The lowering of the work function can be understood as a result of the EuS conduction-band splitting due to magnetic ordering. The difference $\Delta\varphi_i(T) = \varphi_i(T_c) - \varphi_i(T)$ is half the conduction-band splitting at temperature $T$ and by extrapolating to zero temperature we obtain $\Delta\varphi_i(0) = 0.14 \pm 0.03$ eV for emitter 1, in good agreement with values reported by Thompson *et al.*[15] Emitter 2 shows a higher Curie temperature and a smaller band splitting, which can be understood by assuming a higher concentration of impurities.[16] The apparent work-function values of Fig. 3 are lower than all previously reported values for W-EuS emitters. Müller *et al.*[3] measured a work function of about 1.8 eV for their *type-I* emission. It is unlikely that the low values observed here are due to surface roughness; before annealing, when the surface was presumably rougher, no emission current was obtained with extraction voltages as used for annealed layers.

The spin polarization of the ferromagnetic electrons, $P(4f^7)$, is equal to the relative spontaneous magnetic moment, $\sigma(T)/\sigma(0)$. The latter can be obtained from the barrier height as was shown by Thompson *et al.*[15]:

$$P(4f^7) = \Delta\varphi_i(T)/\Delta\varphi_i(0). \qquad (2)$$

The $\varphi_i$ data for emitter 2 were used for computing $P(4f^7)$ and the result is shown in Fig. 2 for comparison with the $P(T)$ data obtained with the same emitter. From the tunneling mechanism one would conclude that the emitted electrons have a spin polarization of unity below $T_c$, since the change in barrier height with decreasing temperature causes the current to increase exponentially for one electron-spin state and to decrease exponentially for the other.

The internal barrier thus transmits only electrons with their spin direction antiparallel to the Weiss magnetic field into the EuS conduction band. The good agreement between the $P(4f^7)$ and the $P(T)$ data indicates that spin-exchange collisions with the $4f^7$ electrons are frequent enough such that the conduction electrons are depolarized from $P = 1$ to $P = P(4f^7)$ before they escape into the vacuum.

A strong spin-exchange interaction with a magnetically nonsaturated surface layer was assumed by Siegmann[17] and Busch, Campagna, and Siegmann[18] in order to explain that photoelectrons from the $4f^7$ states of EuS have a polarization substantially lower than $P(4f^7)$. The interpretation of our polarization results requires spin-exchange collisions between the electrons in the conduction band and the ferromagnetic $4f^7$ electrons; our data show no evidence of a depolarizing surface layer.

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[7] Earlier we used annealing temperatures exceeding 800°C. This did not lead to junctions showing the pronounced temperature dependence of the current. Cf. G. Baum, E. Kisker, A. H. Mahan, and K. Schröder, to be published.

[8] This is concluded from the field-emission pattern which exhibits a threefold symmetry if the tip is ⟨111⟩ oriented and a twofold symmetry (a rectangular pattern) if the tip is ⟨110⟩ oriented. A comparison in size of the W-EuS emission pattern with that of W, made by scaling the external magnetic field proportional to the square root of the extraction voltage (to insure equal electron optics), also agreed with this assignment. We do not yet know to what extent epitaxial growth is essential for the layer formation.

[9] L. W. Swanson, private communication.

[10] Typically the polarization vector $\vec{P}$ has an angle of about 80° with respect to the tip axis at low magnetic field. When a stronger magnetic field is applied, the direction of $\vec{P}$ turns longitudinally; typically an angle of 10° to the tip axis is observed in a field of 0.5 T. The dependence of current and polarization on external field strength is currently under investigation. At high field strengths a higher polarization as well as an increased emission current has been observed.

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[13] W. Franz, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1956), Vol. 17, p. 205. Inside the EuS layer the effective electron mass was assumed to be equal to the free-electron mass (cf. Ref. 2).

[14] The barrier height $\varphi_i(T_c)$ should be equal to the difference between the work function (3.3 eV) and the electron affinity (2.4 eV) of EuS as pointed out by Müller *et al.* (Ref. 3). This is caused by a charged monolayer of $4f^6$ ions at the W-EuS boundary which enables a matching of the Fermi levels of the two materials. Our measured $\varphi_i(T_c) = 0.4$ eV is considerably smaller than that difference and may be caused by the influence of an additional dipole layer near the boundary.

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# Black Holes in Thermal Equilibrium

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It is argued that a black hole can remain in thermal equilibrium with a heat bath even in the presence of particle interactions. This is achieved by proving the identity of the Hartle-Hawking Feynman propagator and a certain thermal Green's function.

Hawking[1,2] has discussed the problem of particle emission from black holes using quantum field theory on classical background geometries. He has shown that if the particles do not interact among themselves, then the probability for the emission of a particle of energy $E$ relative to infinity, in a state $s$, from a Schwarzschild black hole of mass $M$, $P_e(E, s)$, is related to the probability of absorption by the black hole from that state, $P_a(E, s)$, by

$$P_e(E, s) = \exp[-8\pi ME] P_a(E, s) \tag{1}$$

(in units such that $G = c = \hbar = k = 1$). This is, by the principle of detailed balance, a sufficient condition for the black hole to remain in thermal equilibrium with a heat bath of temperature

$$T = 1/8\pi M. \tag{2}$$

Because of the basic nature of this latter result, one would expect that it would remain valid in the presence of particle interactions even though Eq. (1) would no longer do so. This is especially important since the regime in which the Hawking process is of observational significance is that of possible miniature black holes formed in the early universe,[3,4] for which $T \sim 10^{12}$ K and the emitting region is $\sim 10^{-13}$ cm where strong interactions are obviously significant. In this Letter, we shall show that to all orders of perturbation theory for any renormalizable interaction, a nonrotating, neutral black hole can indeed be in thermal equilibrium with a heat bath at a temperature given by (2).

For simplicity we shall restrict our attention to a neutral scalar field $\varphi$, mass $m$. We enclose the black hole in a box with perfectly reflecting