$R_{xy}{}^z$ and the other to $z_{41}/R_{xy}{}^z$. However, the values subsequently deduced for $R_{xy}{}^z$ and z_{41} do depend on other parameters. We took $\omega_t = 273$ cm^{-1}, $\omega_l = 296$ cm^{-1}, $\epsilon_\infty = 11.1$, $\epsilon_0 = (\omega_l/\omega_t)^2\epsilon_\infty = 13.1$, $m^* = 0.07m_0$, and $E_G = 1.50$ eV plus the electron Fermi energy and corresponding hole energy. The correct E_G to be used is somewhat ambigous because of the fairly high doping level involved, but fortunately the results are not too sensitive at liquid-helium temperature since there the resonance enhancement factor $[E_G{}^2/(E_G{}^2 - \hbar^2\omega_i{}^2)^2]$ is only about 4.

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MAGNETOINTERNAL FIELD EMISSION IN JUNCTIONS OF MAGNETIC INSULATORS*

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The observation of internal field emission (Fowler-Nordheim tunneling) in magnetically ordered insulators is reported. A large magnetic field effect was observed and interpreted as a decrease in the barrier height due to spin ordering.

We have observed an entirely new type of magnetointernal field emission effect in magnetically ordered insulators. This is the first time that a large magnetic field effect in internal field emission (or Fowler-Nordheim tunneling) has been reported. We employed here Eu chalcogenides such as EuSe and EuS, of which the magnetic transition temperatures have been reported to be 4.7 [1] and 16.5°K,[2] respectively. The transition temperature for EuS simply means the Curie temperature, whereas EuSe below the transition temperature has a complex field-dependent magnetic structure, being antiferromagnetic in zero field and ferromagnetic for moderate applied fields.

Experimental junctions were constructed simply by successive evaporations, metal, the Eu chalcogenide, and metal, on a heated sapphire substrate without breaking vacuum. Thus the thin film sandwiched between metal electrodes provides a barrier for electrons. We prepared more than 100 units, in which the thickness of the Eu chalcogenides ranges from 200 to 600 Å. Al and Au were used as the electrode metal. X-ray measurements showed the films to be polycrystalline with the same lattice constant as the bulk. The junction area is approximately 4×10^{-4} cm^2.

The current-voltage characteristics on a semilog plot for a 300-Å EuSe junction at 4.2°K are shown in the lower right-hand side of Fig. 1. It is seen that the curve markedly shifts to lower voltages with a magnetic field of 20 kOe. The curves are always symmetric with respect to the applied voltage. We have found that for all units made, current-voltage curves at high voltages approach an asymptote expressed by

$$I = (aV^2/d^2)\exp(-bd/V), \qquad (1)$$

as shown in the upper left-hand side of Fig. 1, where a and b are constants of the material and d is the thickness. We have further verified that the application of magnetic fields affects only the constant b, making it small with increase in field.

We have made measurements of the temperature dependence of the current-voltage curves. The voltage at a given current level (normalized to its value at 4.2°K) was plotted as a function of temperature. The results are shown

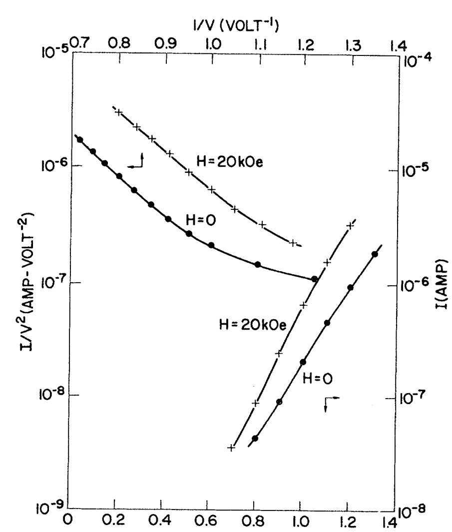

FIG. 1. Log$I$ vs V for EuSe at $H=0$ and 20 kOe in the lower right-hand side, $\log(I/V^2)$ vs I/V for EuSe at $H=0$ and 20 kOe in the upper left-hand side, at $T=4.2$°K.

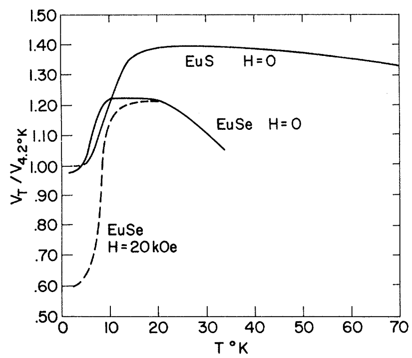

FIG. 2. $V_T/V_{4.2°K}$, the voltage at a given current level (normalized to its value at 4.2°K), versus temperature, for EuSe at $H=0$ and $H=20$ kOe and for EuS at $H=0$.

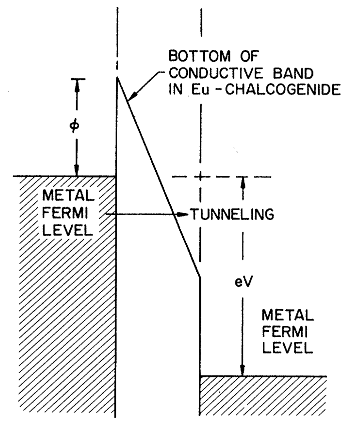

FIG. 3. The potential barrier of the junction at an applied voltage V. φ, barrier height.

in Fig. 2 for EuSe and EuS junctions, where the dashed line indicates the EuSe junction with a magnetic field of 20 kOe. The curves reveal several interesting facts: (1) a rapid change near the magnetic transition temperature of these materials, (2) with magnetic fields, a significant enhancement of this change for EuSe junctions and only a slight one for EuS junctions, and (3) no temperature dependence above and below the transition temperature except for a gradual decrease above 20°K for EuSe junctions and 40°K for EuS junctions.

We think it is reasonable to assume the existence of a potential barrier at a metal-insulator or -semiconductor contact. If the insulator or the semiconductor, sandwiched between the same metal, is relatively pure and as thin as a few hundred angstroms, we will obtain a roughly square potential barrier at no applied voltage. The top of the barrier corresponds to the bottom of the conduction band of the material.

Now, in the Eu chalcogenides, it has been suggested that the $5d$ states provide a conduction band[3] and its width was recently calculated to be a few electron volts by Cho.[4] Thus it is believed that the barrier height φ in our junctions is determined by the energy difference between the Fermi level in the metal and the $5d$ band.

Our experimental results, particularly Eq. (1) and its temperature independence at low temperatures (except for the magnetic transition region), seem to suggest that the current is primarily carried by tunneling at the barrier between the metal and the Eu chalcogenide. Specifically, as shown in Fig. 3, internal field emission or Fowler-Nordheim tunneling[5] becomes observable when the field reaches about 3×10^5 V/cm. Once electrons tunnel into the conduction band from the metal, they can travel in the band to the other metal electrode without much resistance.[6] This tunneling barrier height, φ, can be calculated to be ~0.5 eV for EuSe and Al electrodes from the constant b in Eq. (1) where[5]

$$b=4\sqrt{2}\,m^{*1/2}\varphi^{3/2}/3e\hbar, \tag{2}$$

assuming that the effective mass m^* is equal to the free electron mass. The Au electrodes have been found to result in higher barriers but not as high as the work-function difference between Au and Al.

With this model, one can see that the magnetic ordering has an effect only on the barrier height φ, which is directly related to the constant b in Eq. (2). The magnetic field effect

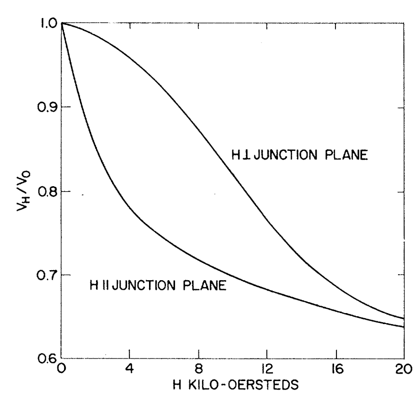

FIG. 4. V_H/V_0, the voltage at a given current level (normalized to its value at $H=0$), versus magnetic field H, for EuSe at 4.2°K.

on the barrier height of EuSe junctions is rather dramatic. This is shown in Fig. 4, where the voltage at a given current level (normalized to its value at $H=0$) V_H/V_0 is plotted versus H for an EuSe junction, where

$$V_H/V_0=b_H/b_0=(\varphi_H/\varphi_0)^{3/2}.$$

This ratio has been verified to be virtually constant over the range of our measurements, 5×10^{-9}-5×10^{-6} A. The decrease of about 35% in voltage means that the barrier height is lowered by as much as 25% with 20 kOe. This effect appears to confirm the shift, due to spin ordering of the $4f$ electrons, of the $5d$ band with respect to the metal Fermi level, thus with respect to the vacuum level. The small magnetic field effect in the EuS junctions probably comes from the fact that not only is EuS a normal ferromagnet but also the applied field is much lower than its Weiss field. The decrease in the barrier height is indeed reminiscent of a shift of all 4.2°K optical absorption curves toward longer wavelengths with applied magnetic fields.[7] The difference between the fields applied parallel and perpendicular to the junction plane, as is shown in Fig. 4, can be interpreted as being due to the demagnetizing effect in the film. ($4\pi M$ in the bulk is as large as 13.8 kOe.)

We have presented here a new phenomenon resulting from spin ordering in magnetic insulators and have proposed a tunneling model which explains the experimental results.

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[6]We might rule out other current transport mechanisms at the applied voltages involved here, such as the space-charge limited current (it follows $I\propto V^n$, $n=\frac{3}{2}$ or 2 and $n\geq2$ if trap dominated), avalanche breakdown (it requires applied voltages higher than the energy gap), impact ionization (it will have an onset voltage for sharp current increase), etc. We believe the effect comes from the junction rather than the bulk. We have made units from Gd-doped EuSe source which give the same results as pure EuSe. Since each Gd atom should provide an impurity or, at least, a trap, the characteristics should be vastly changed with doping if this is a bulk effect. This reason, as well as the fact that no time delay is observed in the dc and ac measurements, leads credence to the assumption that traps play an insignificant role in our measurements.

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