Electron Critical Scattering in EuS-In Ferromagnetic Tunnel Junctions*

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We have observed a Curie-Weiss temperature dependence for electron critical scattering in In-EuS junctions which applies to within a few degrees of the ordering temperature T_c. The law holds both above and below T_c from 4.2 to 300°K. Above T_c the magnetoconductance is $G(H,T)=G_0(T-T_c)+G_1TH^2(T-T_c)^{-2}$, where G_0 and G_1 are constants. These results are explained by a model based on critical scattering in the mean-field limit.

We have observed a new tunneling effect in the paramagnetic region of a ferromagnetic semiconductor. The effect is the scattering of tunneling electrons in the barrier region by magnetic fluctuations of the concentrated spin system.[1] The scattering follows a Curie-Weiss temperature dependence which can be explained by a simple model of critical-point scattering. Previous tunneling experiments had been concerned with isolated spin scattering in the barrier.[2] The experiment also contrasts with bulk critical scattering[3] in that tunneling critical scattering is the dominant process involved without the complications of other scattering processes which are always observed in the bulk, such as phonon and grain boundary scattering.

A magnetic spin fluctuation above the ordering temperature T_c is a group of neighboring spins which spontaneously align for some time t and then diffusively die away to the unaligned state. Electrons in the barrier are scattered by these fluctuations and the scattering increases as the critical temperature is approached due to the rapid increase of spin fluctuations. The extent of the spin correlation becomes greater than the barrier width near T_c. Thus at T_c we expect a peak in the electron scattering intensity (i.e., the resistance peaks and the conductance goes through a minimum). Figure 1 shows the experimental tunneling conductance at zero bias as a function of temperature for a tunnel junction of In versus single-crystal EuS:Gd, containing 8×10^{19} carriers/cm^3 as measured by the Hall effect. In the absence of scattering the conductance would be independent of temperature over this temperature range[2] but Fig. 1 shows a definite conductance minimum which we attribute to magnetic scattering. T_c was determined by magnetic-moment measurements using a force balance and was 25°K for this tunneling sample. Above T_c, Fig. 1 shows a Curie-Weiss temperature dependence (50 to 300°K) extrapolating to the magnetic ordering temperature. Below T_c a Curie-Weiss temperature dependence is also seen, extrapolating to the same ordering temperature; in addition, the slope of the curve below T_c is greater than the slope above T_c. We also find that application of a magnetic field tends to reduce the size of the conductance depression. We will discuss the exact experimental field and temperature dependence later in the paper.

The n-type EuS crystals, whose magnetic ordering temperature is a sensitive function of the electron concentration,[4] were doped to the 10^{19}-cm^3 range. The tunneling samples were prepared by vacuum cleaving single crystals in the pres-

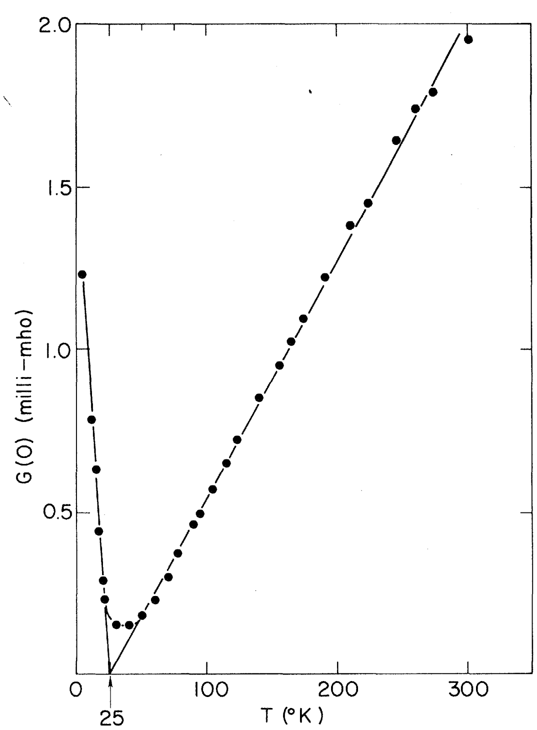

FIG. 1. Tunneling conductance at zero bias and zero magnetic field as a function of temperature for a junction of In-EuS with the EuS doped to 8×10^{19} cm^{-3} with Gd.

ence of an indium vapor stream. Quality checks on the resulting EuS-In junctions were twofold: First, by measuring the capacitance versus voltage on the low-doped samples, we observed the Schottky-barrier voltage dependence and a barrier-height value of 1.2 V; second, at low temperatures we measured the tunneling characteristics of the superconducting indium counterelectrode for all the junctions and obtained the expected energy gap, critical field, and transition temperature for indium.

At present there is no complete tunneling calculation for these magnetic fluctuation effects.[5] However, we can get a reasonable idea of the temperature and magnetic field dependence of the scattering by noting the following: First, we know that in the absence of scattering the zero-voltage tunneling conductance is relatively temperature independent below room temperature; and second, we know that the tunneling probability is highly peaked in the forward direction.[2] Any scattering out of this direction leads to a lower overall tunneling probability. Our model proposes that an electron in the barrier region can be scattered by magnetic fluctuations into a direction having a much lower tunneling probability and hence does not contribute to the tunneling current. The resistance is proportional to the amount of this scattering. We will ignore all matrix-element effects and attempt to obtain the temperature and magnetic field dependence of the resistance by examining the differential scattering cross section of an individual electron scattering off an individual spin fluctuation. The scattering cross section is an integral over energy and time of the dynamic spin correlation function averaged over initial states, and is given by[6]

$$d\sigma/d\Omega = \int dw \int dt\, e^{-i\omega t} \sum_R \langle S_0(0) S_R(t)\rangle e^{i\vec{q}\cdot\vec{R}}, \quad (1)$$

where $S_0(0)$ is the spin at the origin and zero time, $S_R(t)$ is the spin at site R and at time t, q is the momentum transfer, and ω is the energy transfer. Two approximations are used to evaluate the spin function. The standard spin diffusion approximation of Van Hove[7] replaces the dynamic correlation function by the static one and we assume the limit $k_F d \to 0$, where k_F is the electron wave number and d is the distance between scatterers (Eu-Eu nearest-neighbor distance). This limit should apply to these ferromagnetic semiconductors since the Fermi energy is on the order of 0.05 V above the conduction-band edge. With these approximations the correlation function is independent of the integration parameters and

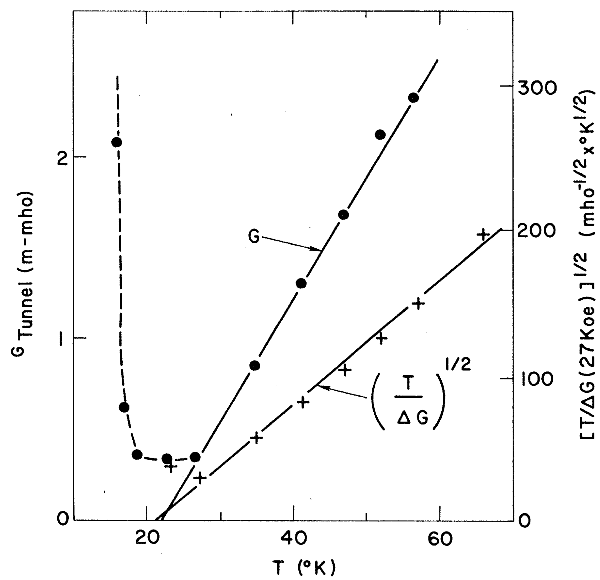

FIG. 2. Upper curve shows the zero-bias, zero-magnetic-field tunneling conductance for a junction of In-Eus, doped to 1.4×10^{19} cm^{-3} with Eu, as a function of temperature. The lower curve shows the function $(T/\Delta G)^{1/2}$ versus temperature for this sample, where ΔG is the conductance change between 0 and 27.3 kOe.

leads to the result that the scattering resistance ρ is directly proportional to the static correlation function $(q=0)$ which is the susceptibility χ,[8] i.e.,

$$\rho \sim \chi(T,H). \quad (2)$$

Therefore, the zero-field tunneling resistance will follow a Curie-Weiss temperature behavior when mean-field theory applies (i.e., when $\Delta T/T_c > 1/Z$, where $Z=12$ is the number of nearest neighbors).[8] The Curie-Weiss behavior is illustrated in the data of Fig. 1. Figure 2 shows the zero-bias, zero-field tunneling conductance for a lower-doped sample (1.4×10^{19} cm^{-3}). It also shows the Curie-Weiss dependence which is extrapolated to $T_c = 22$°K in agreement with the value obtained from magnetic-moment measurement. Below T_c the temperature and field dependence of the barrier dominates the conductance for the low-doped samples.[9]

The magnetoconductance above T_c is given by the inverse mean-field susceptibility whose field dependence is contained in the square of the magnetic-moment term obtained from an expansion of the Brillouin function.[8] In the low-field limit, where the moment is approximately the zero-field susceptibility times the field, the tunneling

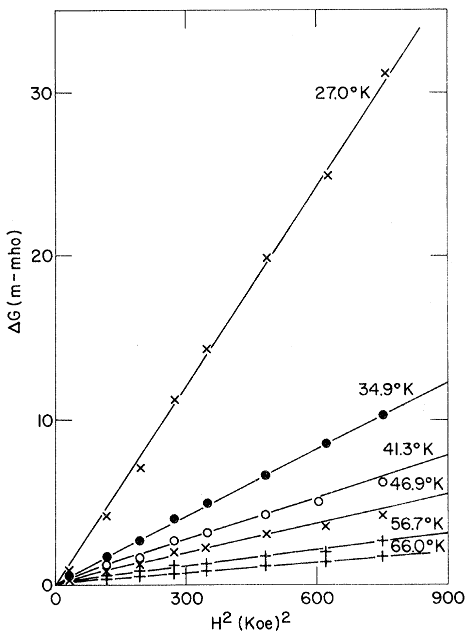

FIG. 3. The change in the zero-bias tunneling conductance as a function of the square of the magnetic field for various temperatures above T_c. The curves are for the low-doped junction shown in Fig. 2.

conductance is given by

$$G(H,T)=G_0(T-T_c)+G_1TH^2(T-T_c)^{-2},$$

where G_0 and G_1 are constants. It is seen that the model predicts an H^2-dependent term which diverges at T_c. Experimental confirmation of this prediction is shown in Fig. 3. The temperature dependence of the magnetoconductance term is $[T/\Delta G(27\text{ kOe})]^{1/2}$ which should vary as $T-T_c$. The lower curve in Fig. 2 is experimental proof of this relationship.

In conclusion, we have described a new tunneling phenomenon, namely, the observation of electron scattering by magnetic fluctuations in the barrier region. We have explained these results using a simple model of critical-point scattering. The model predicts that the scattering resistance is directly related to the susceptibility, and we have shown that this scattering is the dominant process in the junctions above T_c. The experimental results indicate a zero-field Curie-Weiss behavior and a temperature and field dependence as given by the mean-field susceptibility.

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