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Tunneling Spectroscopy in Ferromagnetic Semiconductors

Abstract: The observation of zero-bias anomalies in tunneling has received much attention but their interpretation has suffered from a lack of definition of the character of the tunneling barrier. Junctions formed from a metal with Eu-chalcogenide ferromagnetic semiconductors offer a potential means of overcoming this difficulty. We have made rectifying junctions of EuS:Eu on In. The results indicate: 1) a large resistivity peak at zero-bias voltage which, in the ferromagnetic region, has a strong magnetic-field dependence, and 2) a resistance maximum near 30 mV which has been tentatively assigned to excitation of collective modes in the bulk of the semiconductor. We interpret the present results by considering excitation of ferromagnetic magnons in the barrier region.

The observation of zero-bias anomalies in tunneling spectroscopy has received much attention, both theoretically and experimentally,[1] but interpretation has suffered from lack of definition of the character of the tunneling barrier. A well-defined Schottky tunneling barrier can be made, however, on degenerately doped EuS, whose optical, magnetic and transport properties have been extensively studied.[2]

In this study we use tunneling electrons of energy eV, where V is the bias voltage, to excite the internal degrees of freedom of the ferromagnetically ordered barrier (namely the magnon modes). Duke[1] asserts that this process gives an extra conductance of the form $\Delta G(eV) \propto \int_0^{eV} N(E)|\Gamma(E)|^2 d(E)$, where $\Gamma(E)$ is the electron-magnon coupling strength and $N(E)$ is the barrier-excitation spectrum. The predictions of this theory are that 1) the width of the anomaly should be comparable to the maximum magnon energy, and 2) the imposition of a magnetic field should always widen the anomaly by about $g\beta H$ (where $g = 2$, β is the Bohr magneton and H is the applied field) due to changes in the magnon dispersion relation. There is also a small (0.2% for Gd metal) self-energy correction to the ferromagnetic tunneling conductance,[3] which is unimportant in our low Curie temperature materials.

Samples were fabricated by vacuum-cleaving doped EuS crystals in the presence of an evaporating stream of indium atoms to avoid barrier contamination.[4] Junction quality was checked in two ways: 1) Capacitance vs voltage plots of lightly doped materials not suitable for tunneling data gave reproducible barrier heights (Fig. 1). 2) The tunnel junction showed the characteristic superconducting properties of the indium electrode (inset, Fig. 1). The superconducting transition temperature T_c of In is 3.4°K and the critical field H_c is about 290 Oe. The diode characteristics were measured by standard derivative tech-

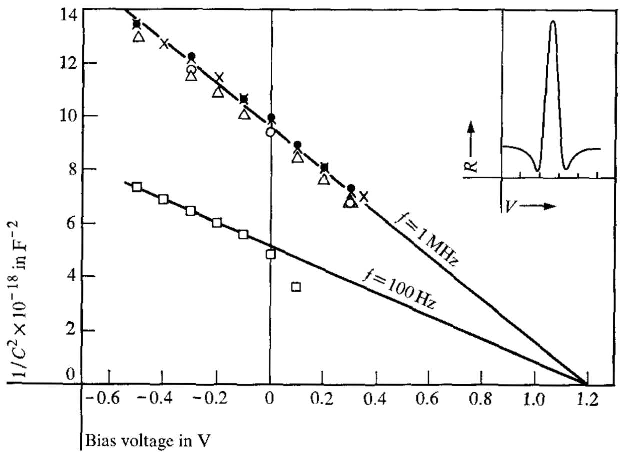

Figure 1 $1/C^2$ vs V for a doped EuSe on In junction showing extrapolation to the room-temperature barrier height (C is the capacitance). The insert shows the indium superconducting characteristics of doped EuS tunneling junction 68 at 1.4°K (1mV/division).

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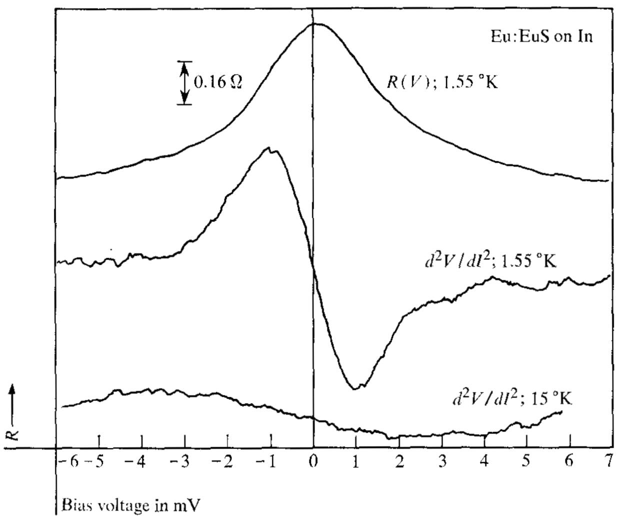


Figure 2 Temperature dependence of R and $dR/dI \equiv d^2V/dI^2$ vs V for a doped EuS junction with $H = 547$ Oe to quench superconductivity.

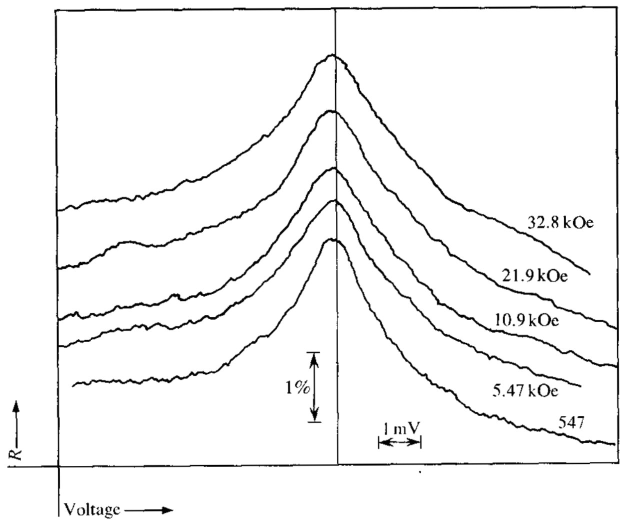
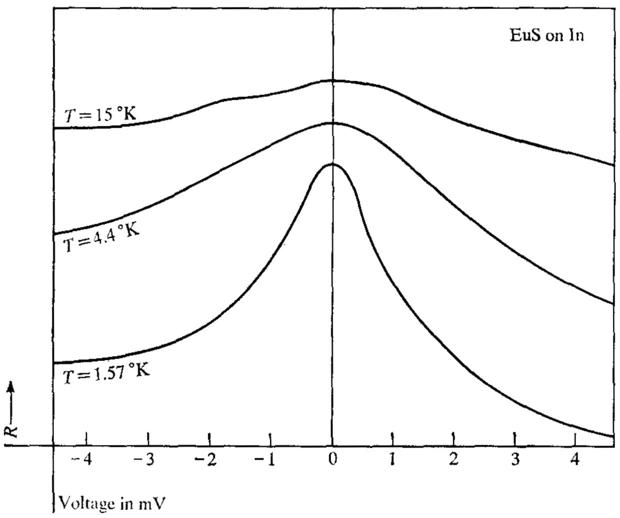


Figure 4 Magnetic field dependence of R vs V at 1.57°K. The low-field value was sufficient to quench superconductivity.

Figure 3 Temperature dependence of R vs V with $H = 547$ Oe. Peak height at low temperature is three percent of total resistance.



niques. The junctions were mounted on a temperature stage in a vacuum can with the magnetic field perpendicular to the current flow. A superconducting coil provided fields up to 35 kOe. Measurements were performed on four EuS tunneling diodes having a dopant concentration of Gd or Eu greater than $2 \times 10^{19}/\text{cm}^3$ and ordering temperatures varying between 30 and 40°K. The general features of the tunneling curves are a temperature- and field-dependent resistance peak at zero bias (which we will examine in detail), a general asymmetry of the background tunneling in the higher voltage region (expected for this doping level) and a five percent resistive peak at 30 mV. A peak at 30 mV with a 5-mV width is not magnetic-field sensitive and has been identified as the longitudinal optical phonon mode having an energy of 31 meV in EuS.[5]

The zero-voltage peak, representing an increase in conductance as the bias is applied, is interpreted as tunneling via magnon emission. The width of this peak, on the assumption that the electron-magnon coupling strength is independent of energy, should be approximately twice the energy width of the magnon dispersion curve. In the EuS fcc lattice, for nearest neighbor interactions only, a width of $32JS$ is calculated,[6] where $S = 7/2$ and J is determined from the ordering temperature. The resulting value, 4.6 meV, is in reasonable agreement with the experimental width, about 5 meV, for the lowest temperature measurement shown in Figs. 2 through 4. With increasing temperature (Figs. 2 and 3) the magnon peak is thermally smeared and disappears into the background inelastic phonon conductance well below the magnetic ordering temperature. This effect is expected since, at one-half the magnetic ordering temperature, thermal smearing predominates. The phonon scattering, however, is expected to persist to considerably higher temperatures since it is related to the Debye temperature ($\theta_D = 208$°K for EuS).

The application of a magnetic field introduces a gap of width $g\beta H$ at the bottom of the magnon dispersion curve and, on the basis of Duke's model, is expected to broaden the magnon peak by this amount without changing the peak height. The magnetic-field dependence of the peak in Fig. 4 clearly shows this effect. The observed shift at the highest field is in good agreement with the expected value, $g\beta H \approx 0.4$ meV.

Duke's theory of inelastic tunneling appears to consistently explain the experimental results for this well-defined ferromagnetic system. More quantitative comparison with the theory requires measurements at lower temperatures and higher fields for different doping levels in order to separate magnon and phonon contributions.

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