

Point contact spectroscopy of magnons in metals

A. I. Akimenko and I. K. Yanson

Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR

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The nonlinear I - V characteristics of Gd, Ho, and Tb point contacts are investigated. The singularities of the dependence of the second derivative d^2V/dI^2 on eV, which correspond to the singularities of the magnon spectra of these metals, were observed and interpreted as a manifestation of the energy dependence of the electron-magnon interaction.

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The method of point contact spectroscopy has been used successfully in recent years to investigate the electron-phonon interaction in metals.¹ In principle, this method can also be used to investigate the interaction of electrons with other excitations. In this paper we present the results of investigation of small, nonlinear I - V characteristics of point contacts in rare-earth ferromagnetic metals, which can be interpreted as evidence for the dependence of electron-magnon interaction (EMI) on energy.

The largest number of experiments was performed by using the "needle-anvil"-type clamped gadolinium contacts (ratio $\rho_{300}/\rho_{4.2} = 50$). The Ho and Tb contacts ($\rho_{300}/\rho_{4.2} = 25$ and 20, respectively) were also investigated. The contact surfaces were processed only mechanically, because a very strong oxide layer, which prevented formation of a metallic contact, was formed due to high chemical activity of these metals produced by etching and electropolishing. Although after mechanical polishing the electrodes were exposed a minimal length of time to air (~ 5 min), the oxide film nonetheless considerably hindered the formation of a contact. In the experiments per-

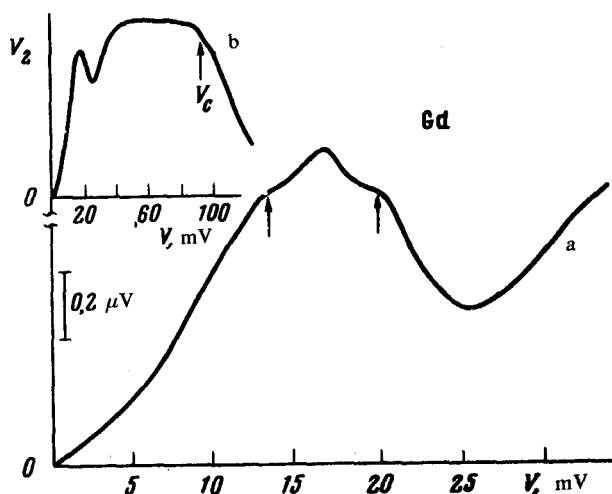


FIG. 1(a). Point contact spectrum of Gd after initial contacts between the needle and the anvil. $R = 37 \Omega$, $T = 4.2$ K, and $V_1^{(1)} = 0.8$ mV. The arrows denote the locations of singularities $\partial\omega/\partial q = 0$ on the dispersion curves for magnons, according to the data of Ref. 2; (b) the same spectrum scaled down with respect to V . The arrow denotes the value of $V_c = 3.62 kT_c/e$ corresponding to heating of the contact to the Curie temperature, according to Ref. 5. $V_1 = 0.5$ mV.

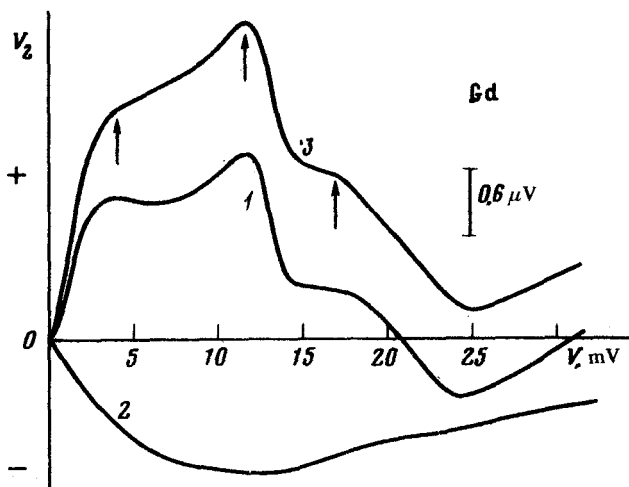


FIG. 2. Point contact spectrum of deformed Gd contacts. Curve 1 - $R = 25 \Omega$, $V_1 = 0.5$ mV, $T = 1.7$ K. Curve 2 represents the energy dependence of the background and curve 3 represents the result of subtracting the background from curve 1. The arrows denote the locations of singularities in the point contact Gd spectrum, which are repeated for different contacts.

formed at temperatures of 1.5 to 4.2 K, we recorded the dependences of the second harmonic of the modulating voltage V_2 , which is proportional to the second derivative d^2V/dI^2 , on the contact voltage V (point contact spectra). The spectra shown below were obtained from contacts with resistances of 25 and 400Ω . The contact resistance is bounded below because the following inequality must be satisfied $d < l_i$ or $d < \lambda = (l_i l_e)^{1/2}$ (d is the contact diameter and l_i and l_e are the momentum- and energy-dependent lengths of the free path of electrons).

Figure 1 shows point contact spectra of gadolinium. The spectrum produced as a result of initial contacts between the needle and the anvil is shown in Fig. 1(a) (curve 1) and its scaled-down version (with respect to V) is shown in Fig. 1(b). It can be seen that the monotonically increasing background in the energy region $eV < 25$ meV has peculiarities comparable to the singular points $\partial\omega/\partial q = 0$ on the dispersion curves for magnons that were determined from the neutron-diffraction data.² Since the Gd phonon spectrum ends at 13 meV, a part of the curve $V_2(eV)$ at $eV > 13$ meV is attributable only to the interaction of electrons with magnons. It follows from the

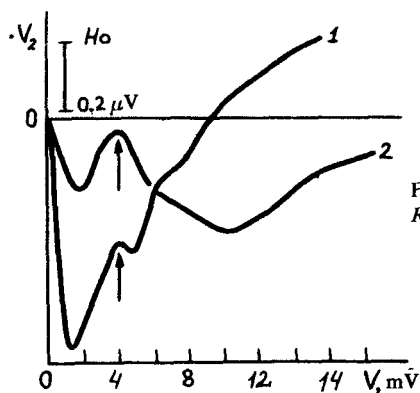


FIG. 3. Point contact spectra of two different Ho contacts: 1, $R = 50 \Omega$, $V_1 = 0.8$ mV; 2, $R = 40 \Omega$, $V_1 = 0.6$ mV, $T = 1.7$ K.

measurements of the temperature dependence of the electrical resistance³ that the electrons are scattered principally by magnons (rather than by phonons) over a wide temperature range. We can assume, therefore, that the characteristic curve $V_2(\text{eV})$ [Fig. 1(a)], which is due to electron-magnon interaction, is proportional to the density of the magnon states,⁴ and that the phonon contribution at $\text{eV} < 13 \text{ meV}$ is relatively small. A proportionality between $V_2(\text{eV})$ and the density of the magnon states means that the temperature in the contact region is always much lower than eV .^{1,3}

As the contact voltage increases, the length of the mean free path of electrons decreases and when it becomes smaller than the contact diameter, there is a transition to the thermal regime, in which the temperature at the center of the contact is related to its resistance by the simple relation $\text{eV} = 3.63 kT$. We can see in Fig. 1(b) that when $V \rightarrow V_c$ the $V_2(\text{eV})$ curve has a peculiarity due to transition of the metal in the contact region from the ferromagnetic to the paramagnetic state as $T \rightarrow T_c$.⁵

If the contact resistance is changed by increasing the contact pressure between the electrodes or by "fusing" the contact by the current, then the $V_2(\text{eV})$ curves will be deformed considerably and will acquire a shape such as that in Fig. 2 in the most typical case (curve 1). As can be seen, a part of the $V_2(\text{eV})$ curve is negative, which is a consequence of superposition of the true EMI spectrum and of the smooth background, which is detrimental for the deformed contacts. As in point-contact phonon spectroscopy, the $V_2(\text{eV})$ characteristics of extremely dirty contacts are comprised only of the background.⁶ One such characteristic is shown in Fig. 2 (curve 2). Subtracting it from curve 1, we obtain the net EMI spectrum (curve 3). The typical EMI spectra of gadolinium usually have three singularities: at $\text{eV} = 4 \text{ meV}$, at $\text{eV} = 11 \text{ meV}$ and at $\text{eV} = 17 \text{ meV}$, and the spectrum ends at 20–25 meV, in complete agreement with the dispersion curves for magnons. The intensities of the singularities of different contacts observed in the spectra may vary noticeably, which is possibly attributable to the anisotropy of EMI due to random orientation of the crystallites in the contact region. The location of the singularities on the V axis varies little ($\pm 1 \text{ meV}$).

Figure 3 shows the $V_2(\text{eV})$ curves for the Ho-Ho point contacts. As is known, Ho undergoes a transition from the antiferromagnetic to the ferromagnetic state at 20 K. According to the neutron data,⁷ the magnon spectrum of Ho has low-frequency branches corresponding to the intensive maximum in the density of magnon states at $\text{eV} = 4\text{--}5 \text{ meV}$. The maxima (or kinks) at this voltage, which are observed in all the spectra of Ho contacts, are due to the EMI, since the density of the phonon states of Ho is small in this energy region and does not have any maxima.⁸ The first maximum of the density of the phonon states of Ho occurs at 6–7 meV and its weak traces can also be observed in certain point contact spectra (curve 1 in Fig. 3). As in the case of Gd, the background of the spectra of Ho contacts contains a gap with negative values of V_2 . The width of the region of negative values of V_2 varies from one contact to another; the location of the magnon maximum on the V axis in this case does not vary. It is important to note that a 2-kOe magnetic field shifts the maximum for Ho at 4 meV toward smaller energies by approximately 10%.

The point contact Tb spectra are similar to the spectra for Gd examined above, except for the fact that they end at 14.5 meV, consistent with the neutron data for magnons.⁹

All the EMI spectra are symmetrical with respect to the origin, and the width of the bands is proportional to kT , consistent with the theory.⁴ The observed nonlinearities correspond to a total variation of the differential contact resistance by approximately 10%. These observations, along with the obvious correlations between the locations of the peculiarities of the V_c (eV) characteristics on the energy axis and the singular points on the dispersion curves for magnons, convince us that we were able to record the spectral functions of the EMI in Gd, Ho, and Tb in our experiments. Earlier, such attempts were made by Leppin and Wohlleben,¹⁰ who apparently achieved only the thermal regime.

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¹⁾ V_1 is the effective voltage of the first harmonic of the modulating signal at the contact.

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