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Magnetic transition in thin wire of rare earth metals

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Abstract

Thin wires of several heavy rare earth metals (Gd, Tb, Dy and Ho) have been fabricated using a step lithographic technique with cross-section areas from 0.87×10^{-10} cm^2 to 0.58×10^{-9} cm^2. The thin films of each material were deposited in a ultra-high vacuum system by thermal evaporation and they have room temperature resistivity of 85, 145, 164 and 209 $\mu\Omega$-cm for Gd, Tb, Dy and Ho, respectively. The electrical resistance of thin wires was measured by the four-probe method in the temperature range from 1.5 to 300 K. With decreasing temperature, the resistivity of each material showed: (1) a decease in ρ with a minimum, (2) a rise in ρ with a maximum and (3) a sharp drop in ρ below the maximum. The minimum in the resistivity for each wire is associated with the localization effect. It is believed that the sharp drop in ρ after the maximum is due to a ferromagnetic transition in thin wires, which is severely suppressed compared to the corresponding bulk values.

In 1958, Anderson [1] stated that the electronic states in a disordered system would be spatially localized and in 1977 Thouless [2] predicted that the effects of localization would be experimentally observable in thin wires at low temperatures. In 1979, Giordano *et al.* [3] made the first experimental observation of the effects of localization in thin wires. Since then, there have been numerous experimental studies of thin wires [4–7]. These experiments tested the prediction of localization theory by studying the behavior of the resistance which increases with decreasing temperature at low temperatures. However, all the experimental work in the literature on thin wires have been on non-magnetic metals.

Recently we carried out the first experimental work on thin wires of magnetic metal (Gd) [8]. In this communication, we report on the electrical properties of thin wires of terbium, dysprosium and holmium. In the solid state, rare earth ions (R^{3+}) are in the trivalent state, and their magnetic moments are due to unfilled 4f-shells and are spatially localized. In rare earth metals, the localized magnetic moments interact with each other indirectly *via* a conduction electron. This is the well-known RKKY interaction [9]. The RKKY interaction strength depends on the state of the conduction electrons.

In bulk, Gd, Tb, Dy and Ho order ferromagnetically below 293 K, 219 K, 90 K and 19 K, respectively [10]. In addition, Tb, Dy and Ho order antiferromagnetically in the temperature ranges 219–229 K, 90–174 K and 19–127 K, respectively [10]. According to the localization theory, in thin wires of metals the electronic state tends to be localized at low temperature. The motivation for this work was to determine the effects on the magnetic transition in thin magnetic wires.

Thin wires of Gd, Tb, Dy and Ho were fabricated by using a step-lithographic technique developed by Prober *et al.* [11]. In this process, we chose a microscope coverglass as substrate due to their high milling rate. After a step was made on the substrate, we coated the rare earth metal onto it in an ultra-high vacuum system at a pressure of 1×10^{-9} Torr. The Gd and Tb were evaporated, Dy was sublimed from a tantalum boat and Ho was sublimed from a tungsten boat. After the coating, we used silver paint to form firm contacts leading from the step edge and to control the length of the step edge before milling for wires. The substrate was then milled at 45× to the normal and with the highest side of the glass step nearest the ion gun. The wire was the thin ribbon of metal lying along the edge of the step.

After the wires were successfully fabricated, the resistance and length of the wires were measured, and the cross-sectional area determined from these measurements and from the resistivity which was determined from films without steps. The resistance measurements were made by a standard four-probe DC method with a current of 1 μA, which was small enough to minimize the effect of Joule heating. The temperature was determined from a carbon-glass thermometer calibrated over the temperature range 1.5–300 K.

In this paper, we present the electrical properties of thin wires of rare earth metals, namely Gd, Tb, Dy and Ho. The general features of the electrical resistance

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data for these four rare earth metal thin wires with decreasing T are: (i) at first, the resistance decreases; (ii) a minimum is observed at ~55 K for Gd (Fig. 1(b)), at ~30 K for Tb (Fig. 2(b)), at ~15 K for Dy (Fig. 3(b)) and at 20 K for Ho (Fig. 4(b)) (all minimums are indicated by tilted arrows), below which the resistance rises; (iii) below 25 K, 20 K, 5 K and 4 K for Gd, Tb, Dy and Ho, respectively, there are sharp drops in the resistance down to the lowest temperatures. All of these four rare earth metal thin wires show similar features in their resistance versus temperature data. All of them have a sharp drop at low temperatures which is considered as a reduction in the ferromagnetic transition temperature from high T_c in bulk to low T_c in thin wires.

If we consider Gd thin wires as a typical case, the T_c is suppressed from the bulk value of 293 K to ~20 K (indicated by vertical arrows in Fig. 1(b)). Similarly Tb, Dy and Ho thin wires show the same kind of suppression of T_c. The Tb thin wires exhibit the T_c suppression from the bulk value of 219 K to ~14 K (indicated by vertical arrows in Fig. 2b). The minimum is observed by only one wire at ~30 K. The Tb thin wires show a significant length effect. The insets in Figs. 2(a) and (b) express the normalized resistance data as a function of temperature for Tb wires shorter than 30 μm. We can see that there are two transitions, one is observed at high temperature ~230 K (indicated by arrows in the inset of Fig. 2(a)) close to its bulk value of antiferromagnetic transition temperature $T_N \approx 229$ K, and the other is at ~15 K as for longer Tb wires. For Dy thin wires, we observed a sharp drop below ~5 K (Fig. 3(b)), which appears to be due to the suppression of T_c in the thin wires. Similar to short Tb thin wires, all Dy thin wires have transitions at 170 K (indicated by arrows in Fig. 3(a)) corresponding to the dysprosium bulk Néel temperature $T_N \approx 174$ K. In Ho thin wires, we observed the sharp drop below 4 K (indicated by vertical arrows in Fig. 4(b)) and a slope

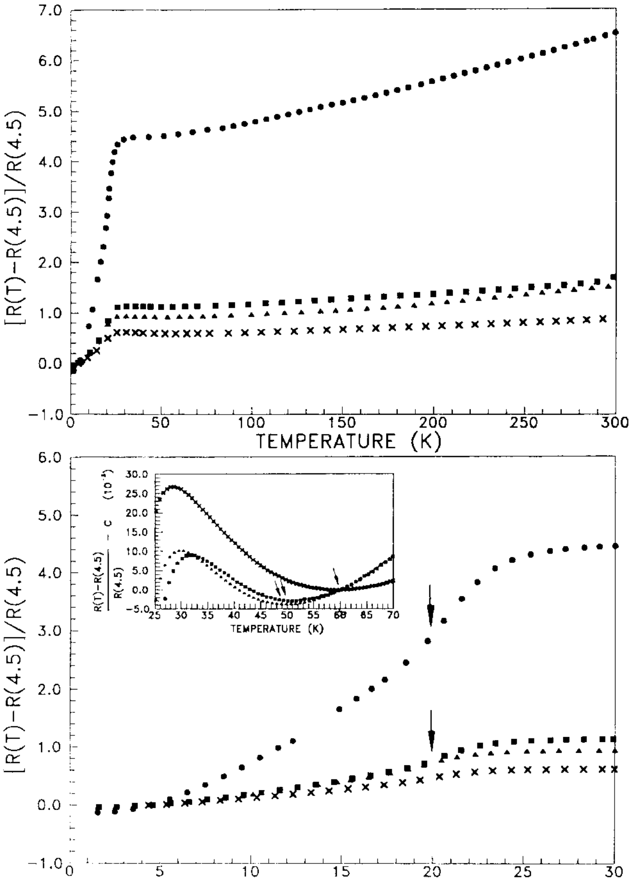

Fig. 1. (a) The normalized electrical resistance as a function of temperature for four Gd wires. The sample diameters were 1502 Å (●), 697 Å (■), 628 Å (▲) and 266 Å (×). (b) Magnified view of the same Gd wires in the low-temperature region; the inset shows the magnified view above the transition, with C equal to the normalized resistance at 60 K.

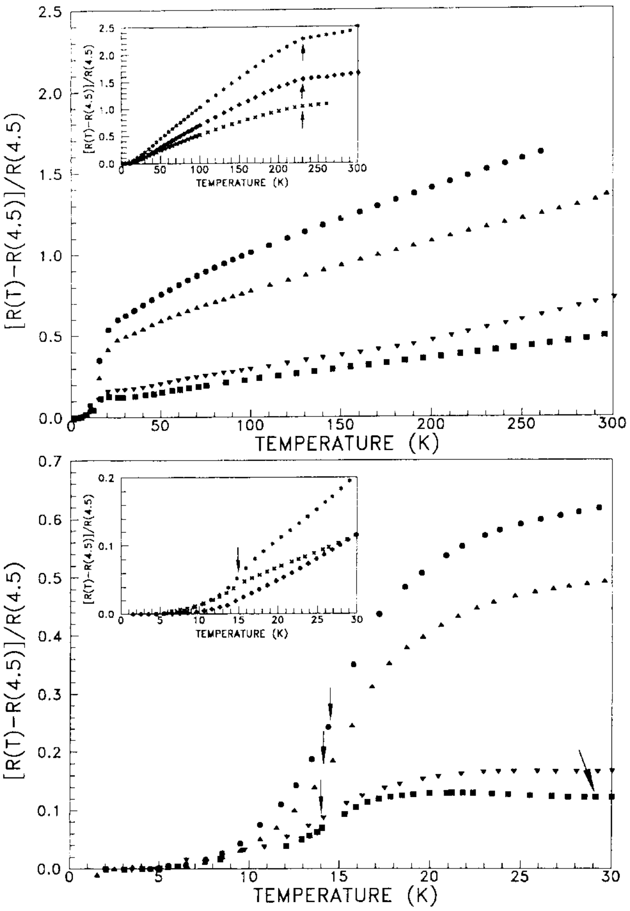

Fig. 2. (a) The normalized electrical resistance as a function of temperature for seven Tb wires. The sample diameters and lengths were 1160 Å and 60 μm (●), 1353 Å and 46.7 μm (▲), 880 Å and 33.4 μm (■), 295 Å and 60 μm (▼), 1310 Å and 26.7 μm (*), 841 Å and 23.3 μm (+) and 454 Å and 26.8 μm (×). (b) Magnified view of the same Tb wires in the low-temperature region.

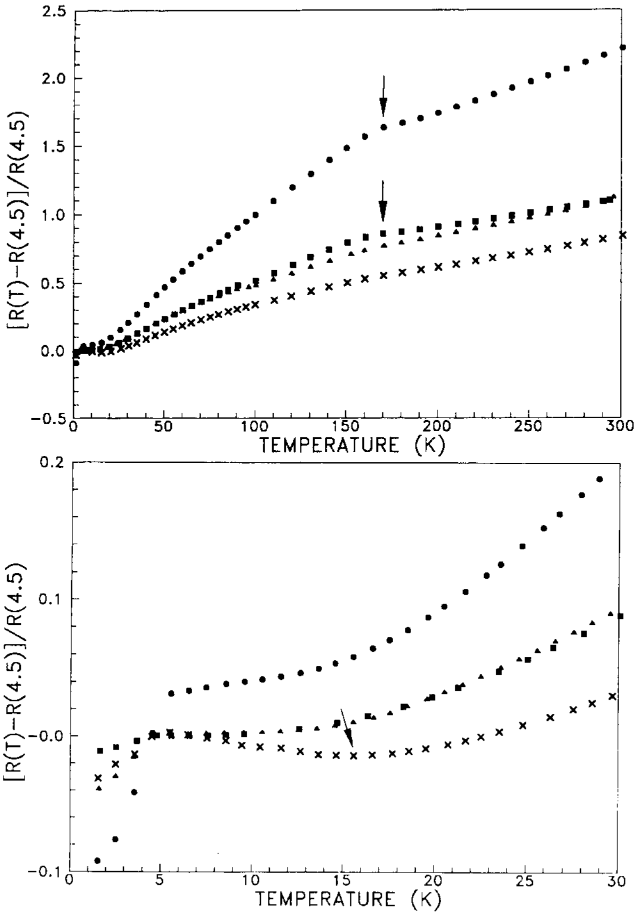

Fig. 3. (a) The normalized electrical resistance as a function of temperature for four Dy wires. The sample diameters were 1440 Å (●), 1120 Å (■), 1028 Å (△) and 670 Å (×). (b) Magnified view of the same Dy wires in the low-temperature region.

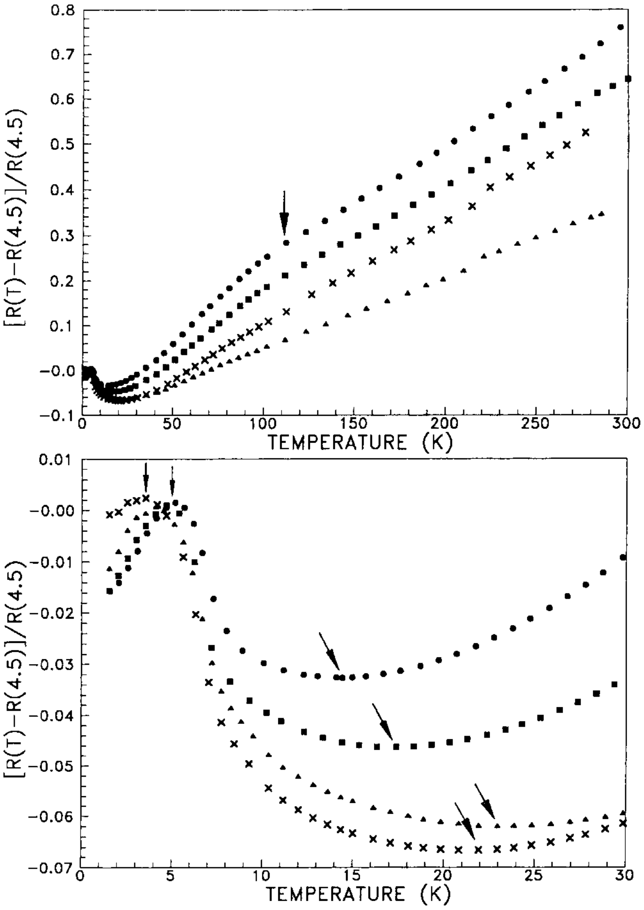

Fig. 4. (a) The normalized electrical resistance as a function of temperature for four Ho wires The sample diameters were 1160 Å (●), 1090 Å (■) 830 Å (△) and 780 Å (×). (b) Magnified view of the same Ho wires in (a) in the low-temperature region.

change in R versus T at 110 K (indicated by an arrow in Fig. 4(a)) close to its value of bulk $T_N \approx 129$ K. But all Ho thin wires exhibit a relatively deep minimum around 20 K.

In summary, the electrical resistivity study of thin wires of Gd, Tb, Dy and Ho, show a localization effect evidenced by a minimum in resistivity. We also observed the Néel temperature T_N to be 170 K, 130 K and 110 K in thin wires of Tb, Dy and Ho. These values of T_N are not too far away from the corresponding values of T_N for the bulk metals. Therefore, one can conclude that the exchange interactions in thin wires of heavy rare earths are very near the bulk values. However, we also observed a sharp reduction in the ferromagnetic transition temperatures T_c to 20 K, 14 K, 5 K and below 4 K for the thin wires of Gd, Tb, Dy and Ho, respectively, compared to their bulk values of 293 K, 219 K, 90 K and 19 K. In previous studies of rare earth yttrium multilayers[12,13], it was found that the ferromagnetic transition temperature is completely suppressed (*e.g.* Dy/Y and Er/Y multilayers). This lack of ferromagnetic transition has been associated with the clamping effect of the Y layers on the Dy and Er magnetostriction. The ferromagnetic ordering in heavy rare earths (bulk) is driven by the reduction in the magnetorestrictive energy associated with the ferromagnetic state compared to the antiferromagnetic state. In the case of the thin wires of heavy rare earths, the large surface to volume ratio and the presence of the substrate effects may provide sufficient clamping of the magnetorestrictive energy and hence sharp reduction in the ferromagnetic transition temperatures.

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