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Transport anisotropy and dimensional crossover in Ag/Ge multilayers

David V. Baxter *, Gamini U. Sumanasekera, John P. Carini

Physics Department, Indiana University, Swain Hall West, Bloomington, IN, 47405, USA

Abstract

We use magnetoresistance measurements of weak localization to investigate the anisotropy of electron transport in a series of Ag/Ge multilayers. The Ge layer thicknesses in these samples spans the cross-over from three to two dimensions.

Metal-insulator layered structures offer many opportunities for studying fundamental processes in the electronic properties of disordered materials. Recent studies have included investigations of the appropriate length scale for the enhanced inter-electron interactions in disordered media [1], the metal-insulator transition [2], and investigations of electron tunneling [3]. We have recently developed a technique whereby magnetoresistance measurements of weak localization may be used to measure the anisotropy of the electron diffusivity in layered materials [4]. Such measurements can in principle provide information about perpendicular transport in multilayers without the need to pattern the samples lithographically nor concern regarding the current uniformity and contact resistance that accompany more traditional measurements. Unfortunately, however, the theory used to date in analyzing such data runs into problems in the strong anisotropy limit, such as that expected in a metal-insulator multilayer. In this study we apply this technique to a series of Ag/Ge multilayers. The main purpose of this study is to explore the intermediate behaviour of the magnetoresistance due to weak localization as the material crosses over from an anisotropic 3D sample to many 2D layers conducting in parallel.

The multilayers were deposited using magnetron sputtering (chamber base pressure of 2×10^{-8} Torr) on to silicon substrates at either 300 or 200 K. We have studied a series of samples in which the Ag layer thickness is held constant (25 Å), with the Ge thickness covering the range from 5 to 72 Å.

As discussed in detail in an earlier publication [4], the transport anisotropy shows up as a dependence of the low temperature magnetoresistance on the orientation of the applied field with respect to the sample. This is demonstrated in Fig. 1 for a sample with 100 bilayers consisting of 72 Å of Ge and 25 Å of Ag. In this figure the open points show the data for the field perpendicular to the sample while the solid points show the measurement with the field oriented in the sample plane. Roughly speaking, the field at which the magnetoresistance deviates from zero (B_ϕ) corresponds to the area over which an electron can diffuse in a plane perpendicular to the field while maintaining phase coherence ($D\tau_\phi = \hbar/4eB_\phi$, where τ_ϕ is essentially the time between inelastic scattering events). The position of the maximum of the magnetoresistance is related to the area covered within a spin coherence time (limited by spin-orbit scattering and temperature independent). These diffusion lengths may be measured by fitting such data to the appropriate weak localization theory ([4] for 3D and [6] for 2D). Such an analysis of the data in Fig. 1 indicates that, at 4.2 K, electrons in this sample travel 60 ± 15 Å perpendicular to the Ag planes but roughly 1300 Å parallel to the planes during an inelastic scattering time, indicating that this sample is in the 2D limit. This conclusion is confirmed by the success of the 2D weak localization theory (the solid line in the figure), and the failure of the 3D theory (dashed line), to fit the data for the perpendicular orientation. For samples with much thinner Ge layer thicknesses the anisotropy is less dramatic but still easily seen directly in the data itself. For example, in samples with layer thicknesses of 25 and 15 Å for Ag and Ge respectively, the electron diffusivity along the planes is a factor of 4 greater than the diffusivity in the growth direction.

A simple theory of weak localization in an anisotropic 3D medium may be used to analyze the transport anisotropy in multilayered materials, through experiments such as those described above, provided the films are sufficiently thick and the anisotropy is sufficiently weak. [4] In the strong anisotropy limit the magnetoresistance should take on the character of 2D weak localization (for the case

* Corresponding author. Fax: +1-812-855-5533; email: dvb@gibbs.physics.indiana.edu.

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where the field is perpendicular to the sample) and this has a different functional form that is seen in the 3D case (Fig. 1). In our earlier studies of Cu/Al and Cu/Si multilayers we were able to determine values for the anisotropy from studying the spin coherence lengths but not from the phase coherence lengths because the theoretical curves did not accurately describe the data at low fields. We see similar problems with fitting the anisotropic 3D theory at low fields for the Ag/Ge data considered here when the anisotropy is larger than 400% (see Fig. 2). In our earlier studies it was impossible to determine whether these problems were associated with a failure of the theory to account for the incipient crossover to 2D or due to the presence of superconducting fluctuations in the materials investigated [4,7]. We have studied the low temperature transport of Ag/Ge sandwiches made under conditions similar to those used for the multilayers and see no trace of superconductivity to well below 0.3 K. The problems seen at low field in these samples, therefore, do reflect the inability of the anisotropic theory to account for dimensionality cross over effects rather than a complication from superconducting fluctuations.

Using a generalization of Bergmann's tunneling model [3] for describing weak localization in two coupled 2D films, it is possible to develop a theoretical framework for the magnetoresistance that interpolates between the 2D and 3D limits. In this formulation, the ratio of the time taken to tunnel between the layers to the inelastic scattering time determines the dimensionality of the sample. Space limitations prevent us from discussing this formulation at length

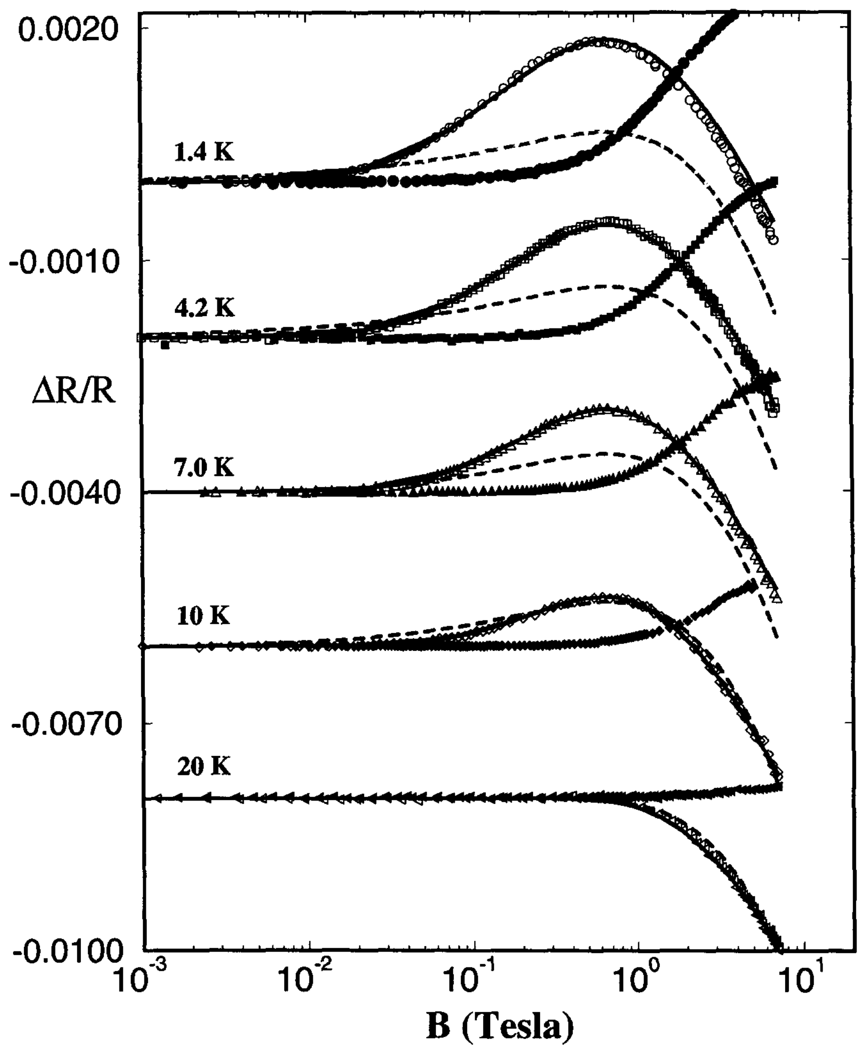

Fig. 1. Low temperature magnetoresistance for a sample with 72 Å Ge layers and 25 Å Ag layers. Open points give the data with the field perpendicular to the sample and solid points for a parallel field. The dashed curves show the anisotropic 3D fits to the data for a perpendicular field and the solid curves show the fits of the 2D theory to the same data.

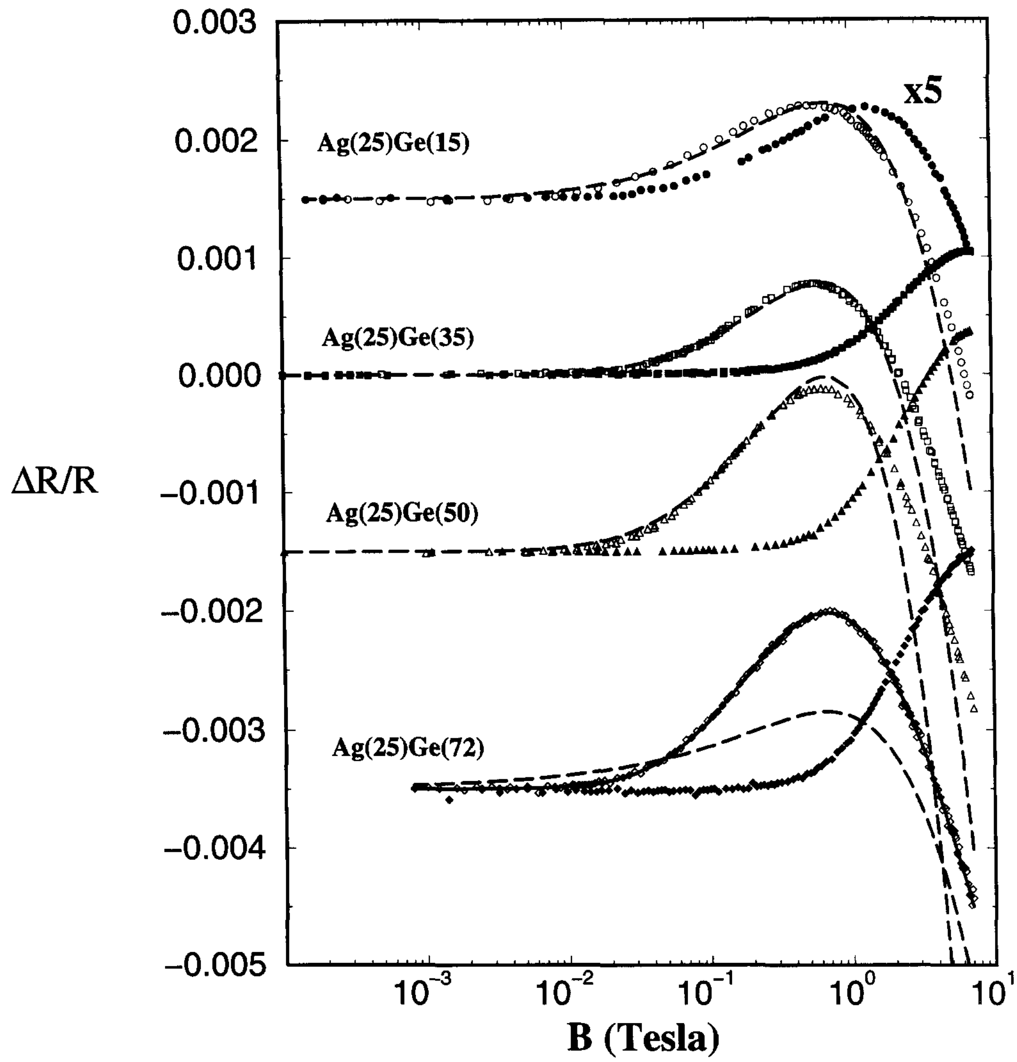

Fig. 2. Magnetoresistance at 4.2 K for Ag/Ge multilayers with various Ge layer thicknesses (as marked in Å). Open points give the data with the field perpendicular to the sample and solid points for a parallel field. The dashed curves show the anisotropic 3D fit to the open points while the solid curve gives the 2D fit for t_{Ge} = 72 Å. The curves for t_{Ge} = 15 Å have been multiplied by a factor of 5 in order to fit them into the same figure as the others.

here, but it will be the subject of a future publication [5]. We would like to point out here, however, that this may provide a theoretical framework in which metal–insulator multilayers may be used to study electron tunneling.

We have used the anisotropy of the magnetoresistance due to weak localization to investigate the anisotropy of electron transport in a series of Ag/Ge multilayers. For Ge layers thicker than 15 Å a simple anisotropic 3D theory fails to describe the magnetoresistance data. At a Ge layer thickness of 72 Å the magnetoresistance with the field oriented perpendicular to the film is well described by 2D weak localization theory.

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