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Dimensional crossover of weak-localization and interaction effects in $Nb_{0.53}Ti_{0.47}$-Ge multilayers

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The transport properties of $Nb_{0.53}Ti_{0.47}$-Ge multilayer samples with similar $Nb_{0.53}Ti_{0.47}$ layer thicknesses but varying Ge layer thicknesses were studied. Evidence for a three- to two-dimensional crossover was observed in the temperature and magnetic field dependences of resistance when the Ge layer thickness passes through a critical thickness of ~ 30 Å, which suggests a strong effect of the barrier width on quantum diffusion processes in disordered multilayer systems.

I. INTRODUCTION

Since the scaling theory of Abrahams, Anderson, Licciardello, and Ramakrishnan[1] predicted that the electron states of a disordered material are always localized in two dimensions (2D), while a mobility edge exists in three dimensions (3D), many theoretical and experimental efforts have been directed at understanding the nature of 2D and 3D disordered systems.[2-5]

Recently, there has been interest in studying the 2D-to-3D crossover region.[6-9] A dimensional crossover usually occurs when some characteristic length scale becomes comparable to the film thickness d, and can be observed by changing the film thickness, the temperature, or the magnetic field. The length characteristic of dimensional crossover could be either of the following: (1) the deBroglie wavelength $\lambda = h/p$ (quantum size effect); (2) the Thouless length, $\sqrt{D\tau_{\rm in}}$ (the weak-localization effect, where D is the 2D diffusion constant and $\tau_{\rm in}$ is the inelastic scattering time); (3) the cyclotron radius of the lowest Landau level, $\sqrt{c\hbar/eH}$; or (4) $\sqrt{D\hbar/k_BT}$ (the so-called interaction effect). When the above characteristic lengths are larger than the effective film thickness d, the film properties are expected to become 2D-like. If a characteristic length becomes comparable to or shorter than the film thickness, 2D-to-3D crossover phenomena are anticipated.

We present here some experimental evidence of another kind of dimensional crossover which can be observed only in a multilayered structure:[10] namely, the crossover due to the interlayer coupling. To study this "tunneling" crossover in the localization and interaction effects, we require a system composed of layers of disordered conducting material, each in which is 2D-like by itself, but intercalated with insulating barriers. (The total conducting-layer thickness, on the other hand, should be larger than the characteristic lengths discussed above.) In this experiment, we chose the $Nb_{0.53}Ti_{0.47}$-Ge multilayer system. By systematically varying the Ge barrier thickness we effectively change the amount of interlayer coupling and, eventually, a dimensionality change occurs when the barrier thickness $D_{\rm Ge}$ is of the order of twice some electron-wave-function decay length k^{-1} ($\psi \sim e^{-D_{\rm Ge}k}$) in the barrier.

II. SAMPLE PREPARATION AND CHARACTERIZATION

The multilayer films were prepared by the dc magnetron sputtering technique. The details of the sputtering system and the deposition parameters are described elsewhere.[11,12] The layer periodicity and the layer thicknesses were determined from low-angle x-ray diffraction measurements and a knowledge of the deposition rate as determined from the two quartz sensors (which were calibrated with a Tenco stylus step profiler); the details of this procedure are discussed elsewhere.[12] The error in the layer-thickness determination was estimated to be $\sim 10\%$. Figure 1 shows the low-angle x-ray diffraction peaks for three of the samples studied in this paper. The transport-property measurements were performed on photolithographically defined samples with the dc four-probe technique in the variable-temperature cryostat of an SHE variable-temperature susceptometer.

III. EXPERIMENTAL RESULTS

A. The temperature dependence of the resistance

Figure 2 depicts the temperature dependence of the normalized sheet resistance (per layer) of four samples with a similar $Nb_{0.53}Ti_{0.47}$ layer thickness ($D_{\rm NbTi} \sim 3.5$ Å, which is about a monolayer), but with systematically varying Ge layer thicknesses. It is seen that the temperature dependence deviates from the predicted 3D ($R_\square \sim \sqrt{T}$) behavior at a Ge layer thickness of ~ 30 Å, and approached 2D

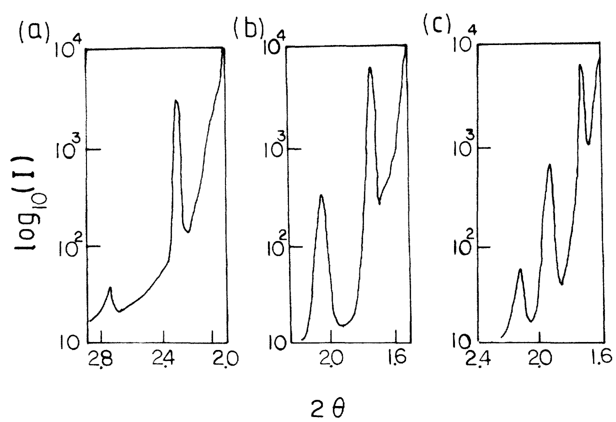

FIG. 1. The low-angle θ-2θ x-ray diffractometer scan. The $Nb_{0.53}Ti_{0.47}$-Ge thicknesses are (a) 3.5 Å/19 Å, (b) 3.5 Å/26 Å, (c) 3.5 Å/40 Å.

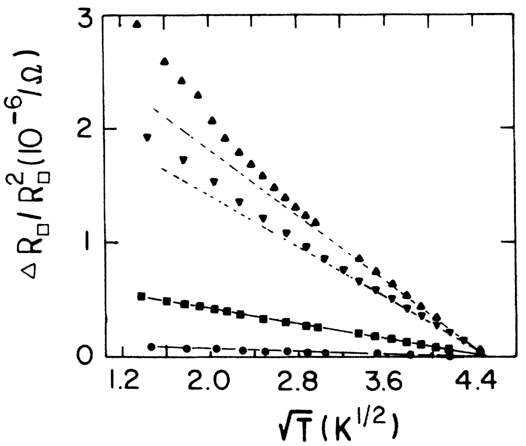

FIG. 2. The temperature dependence of the normalized differential resistance, $[R_\square(T)-R_\square(20\text{ K})]/R_\square^2(20\text{ K})$, for four samples with $Nb_{0.53}Ti_{0.47}$-Ge layer thicknesses designated as ▲, 3.5 Å/40 Å; ▼, 3.5 Å/26 Å; □, 3.5 Å/19 Å, ●, 3 Å/4 Å. The lines are guides to the eye.

behavior for thick D_{Ge} samples [see also Fig. 3(a)].

Figure 3 shows the resistance versus temperature curves for different parallel magnetic fields for a "3D sample" [$D_{NbTi}/D_{Ge}\simeq 3.5$ Å/19 Å, $R_\square(T)\sim\sqrt{T}$] and a "2D sample" ($D_{NbTi}/D_{Ge}\simeq 3.5$ Å/40 Å, $R_\square\sim \ln T$). We see that the temperature dependence of the resistance has the same functional form irrespective of the magnetic field, but with an increasing slope for higher magnetic fields. The increasing slope in a magnetic field is usually ascribed to the suppression of the weak antilocalization effect by the magnetic field.[5]

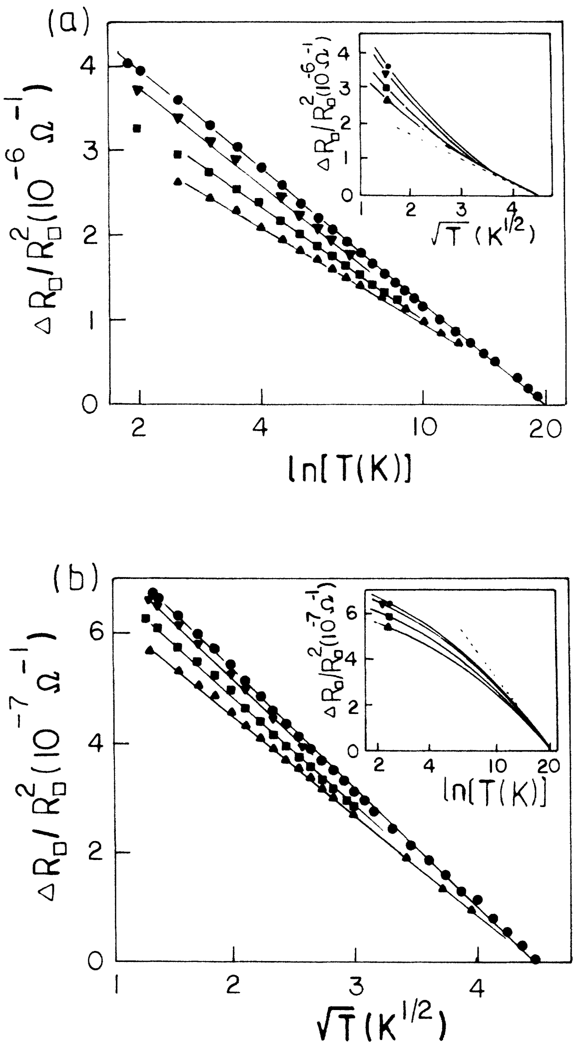

FIG. 3. The temperature dependence of the normalized differential resistance for different magnetic fields: ▲, 0; ■, 2 T; ▼, 4 T; ●, 5 T. The inset shows the same data on each sample but plotted with a different functional dependence of temperature. The $Nb_{0.53}Ti_{0.47}$-Ge layer thicknesses are (a) 3.5 Å/40 Å, (b) 3.5 Å/19 Å.

B. The magnetoresistance

The results of magnetoresistance measurements with the field parallel and perpendicular to the film plane (but perpendicular to the current) orientation are shown in Figs. 4(a) and 4(b), respectively. A strong correlation between the magnitude of the magnetoresistance and the Ge layer thickness is observed, with the magnetoresistance of the thickest Ge layer sample 12 times larger than that of the thinnest Ge sample. We note here that the difference in zero-field sheet resistance, at 20 K, is only ~30% between samples (the zero-field sheet resistances measured at 20 K are 3.8, 4.4, 4.3, and 2.8 kΩ for samples with D_{NbTi}/D_{Ge} = 3.5 Å/40 Å, 3.5 Å/26 Å, 3.5 Å/19 Å, and 3 Å/4 Å, respectively). Figure 4(c) shows the difference between the perpendicular and parallel magnetoresistance for each sample. We see that the sample with the thinnest Ge layers is isotropic, and we note that the degree of anisotropy increases as the Ge layer thickness increases. We note also that the anisotropy of the magnetoresistance decreases at high fields and appears to approach an isotropic behavior. (The magnetoresistances will become isotropic when the magnetic length becomes comparable to d at a field $H_c\sim c\hbar/ed^2$, where each $Nb_{0.53}Ti_{0.47}$ layer is by itself 3D like.)

The perpendicular magnetoresistance versus $\ln H$ slope (in units of $e^2/2\pi^2\hbar$) of the sample with $D_{Ge}=40$ Å was found to be ~0.5 at high fields consistent with the 2D weak-antilocalization theory.[13] Hence, it is likely that the magnetoresistance is mainly due to the weak-antilocalization effect.

The weak-field (< 1 T) perpendicular magnetoresistance data were fitted with the Maekawa-Fukuyama theory,[14] using the following parameters, $\tau_{SO}\simeq 5.6\times 10^{-14}$ s, $\tau_0=1.25\times 10^{-15}$ s, $D=0.44$ cm^2/s, where τ_{SO}, τ_0, D are the spin-orbit scattering time, elastic scattering time, and two-dimensional diffusion constant, respectively. The Fermi velocity, $v_F=2.64\times 10^7$ cm/s, averaged over the Fermi surfaces of Nb and a mean free path of 3.3 Å (the interatomic distance) were used to estimate τ_0 and D.[15] Due to the short mean free path of an alloy system, we assume that τ_0 and D do not change drastically by the layering in our system. The bulk spin-orbit scattering time of the $Nb_{0.44}Ti_{0.56}$ alloy[16] was used for multilayers on the grounds that Ge has an atomic number which is about the average of that of Nb

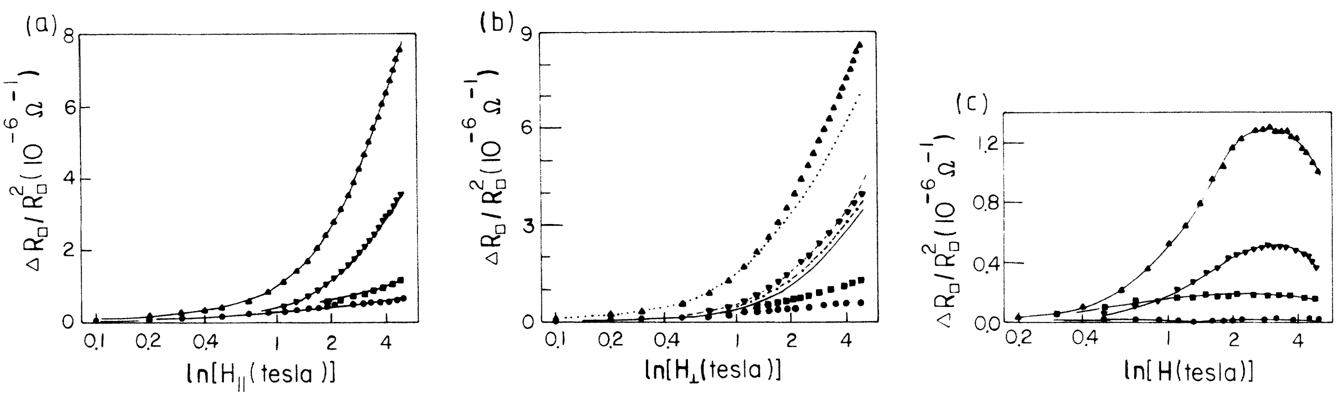

FIG. 4. The normalized magnetoresistance (negative magnetoconductance) of four samples. The symbol conventions for the samples are the same as in Fig. 2. (a) **H**∥film⊥**I**; (b) **H**⊥film⊥**I**; (c) the difference of (a) and (b). The solid lines in (a) and (c) are for eye guidance. The line in (b) is the 2D theoretical fit to the low-field (< 1 T) data, where the $Nb_{0.53}Ti_{0.47}$-Ge layer thickness and the fitting parameter τ_{in} of each line are as follows: dotted line: 3.5 Å/40 Å, $\tau_{in} = 1.2\times10^{-11}$ s; dashed line: 3.5 Å/26 Å, $\tau_{in} = 6.3\times10^{-12}$ s; dash-dotted line: 3.5 Å/19 Å, $\tau_{in} = 5.6\times10^{-12}$ s; and solid line: 3 Å/4 Å, $\tau_{in} = 5.1\times10^{-12}$ s.

and Ti, so that the spin-orbit scattering time will not vary much due to the interface scattering. Determination of these parameters can be found in a previous paper.[15] The inelastic scattering time was the remaining free parameter for the fitting. The results are shown in Fig. 4(b). We see that the 2D theory, when extended to high fields (~ 5 T), is consistent with the experimental results for samples with large Ge layer thicknesses, but deviates considerably from the experimental results for thin Ge layer samples, which further suggested a 2D-3D crossover at a Ge layer thickness of ~ 30 Å.

IV. CONCLUSIONS

We have studied the effect of insulating barriers on the transport properties of disordered $Nb_{0.53}Ti_{0.47}$-Ge multilayers. Evidence for a dimensional crossover in the temperature dependence of the resistance and the perpendicular magnetoresistances was observed at a Ge layer thickness of ~ 30 Å. Hence, we estimated that the electron wave-function decay length in *a*-Ge is about 15 Å. The magnitude of both the parallel and perpendicular magnetoresistance depended strongly on the Ge layer thickness. The slope and the degree of anisotropy of the magnetoresistance also seems to indicate the 2D nature of the thicker Ge layer samples.

To understand this continuous 3D-to-2D transition and the parallel magnetoresistances, when the barrier width is systematically increased in a multilayer system, a theory incorporating additional parameters, such as the exchange integral *w* proposed by Prigodin and Firsov,[10] a Kronig-Penney-type diffusion in the film normal direction, and an anisotropic spin-orbit scattering time, would be highly desirable.

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