Tenfold Magnetoconductance in a Nonmagnetic Metal Film

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We present magnetoconductance (MC) measurements of homogeneously disordered Be films whose zero field sheet conductance (G) is described by the Efros-Shklovskii hopping law $G(T) = (2e^2/h)\exp -(T_0/T)^{1/2}$. The low field MC of the films is negative with G decreasing a factor of 2 below 1 T. In contrast the MC above 1 T is strongly positive. At 8 T, G increases tenfold in perpendicular field and fivefold in parallel field. In the simpler parallel case, we observe *field enhanced* variable range hopping characterized by an attenuation of T_0 via the Zeeman interaction.

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Over the last two decades a large and diverse research effort has grown around nanostructures and low dimensional systems. Not only has this area of investigation allowed the exploration of fundamental quantum phenomena, but it also promises to impact magnetic storage technology and magnetoelectronics. In particular, the development of magnetic superlattices has produced encouraging increases in magnetic sensitivity by exploiting spin-dependent scattering of electrons at the superlattice interfaces. These systems can produce a fivefold change in magnetoconductance in fields of a few telsa, and are commonly known as giant magnetoresistance systems [1,2]. Extremely large magnetoresistance effects due to magnetic scattering have also been observed in a variety of manganite systems [3,4]. Interestingly though, there have been recent reports of large magnetoresistance effects in some *nonmagnetic* systems. The first is in the narrow band semiconductors $Ag_{2+\delta}Se$ and $Ag_{2+\delta}Te$ which can have a factor of 2 positive magnetoresistance at room temperature in fields of a few tesla [5]. The origin of this effect is not understood. A second novel system is the newly discovered anomalous metallic phase in two-dimensional (2D) metal-oxide-semiconductor (MOSFET's) devices [6]. This metallic phase is observed to be extremely sensitive to magnetic field and at low temperatures is suppressed by an arbitrarily weak field thereby producing a 2 order of magnitude increase in resistance [7]. There has been some conjecture that the anomalous metallic phase, which is quite unexpected in a 2D system [8], is stabilized by correlations [9]. If this is indeed the case, then the large magnetoresistances observed in the MOSFET 2D electron gases is, in fact, a many body effect. This is intriguing in that it is a distinctly different mechanism from the usual magnetic scattering processes that produce magnetoresistance in magnetic films, and, consequently, it offers a novel strategy for realizing magnetic sensitivity. In the present Letter, we describe an investigation of the field and temperature dependent transport of highly disordered ultrathin Be films. Beryllium was chosen because one can reproducibly grow smooth, nongranular films via thermal evaporation [10]. This allowed us to investigate field dependent electron correlation effects in a low atomic weight, high carrier system, that is free from strong spin-orbit scattering, magnetic impurities, and grain charging effects. In fact, low resistance Be films show very weak magnetotransport effects. In contrast, we have discovered that the hopping transport in high resistance films has an extremely large positive magnetoconductance that can be attributed to the convolution of e-e correlations, disorder, and the carrier spin degrees of freedom.

Beryllium forms smooth, dense, nongranular films when thermally evaporated onto glass. In fact, scanning force micrographs of the films' exposed oxide surface did not reveal any salient morphological features down to our resolution of 0.5 nm. This nongranular morphology is crucial in that it assures one that the measured resistance is representative of e-e correlation effects and *not* grain charging effects. In extremely high resistance films any significant granularity will result in field independent grain charging (Coulomb blockade) effects preempting the many body effects of interest [11,12]. This is also true of electron tunneling measurements of the density of states (DOS) and indeed, we have recently made the only direct measurement of the 2D Efros-Shklovskii Coulomb gap in Be films [13]. Another useful property of Be films is that they superconduct with a transition temperature that is a monotonically decreasing function of the sheet resistance, $T_c \approx 0$ at $R \sim 6$ kΩ [10]. By measuring the first-order spin-paramagnetic parallel critical field transition in $\sim$1 kΩ films we were able to demonstrate their extreme two dimensionality and the absence of magnetic and spin-orbit scattering [10,14,15]. In the present study we used films with thicknesses ranging from 1.5–2.0 nm and corresponding low temperature sheet resistances ranging from $R = 10$ kΩ to 7 MΩ. They were deposited by thermally evaporating 99.5% pure beryllium metal onto fire polished glass substrates held at 84 K. The evaporations were made in a 4×10^{-7} Torr vacuum at a rate $\sim$0.15 nm/s. The film area was 1.5 mm $\times$ 4.5 mm. All of the samples discussed below were of sufficiently high resistance so as to completely suppress the superconducting phase. The film conductances were measured using a standard four probe dc I-V technique.

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Electron correlations in strongly disordered electronic systems tend to produce a singular depletion of the DOS near the Fermi surfaces. Efros and Shklovskii [16,17] used a dimensionality argument to show that the Coulombic interactions produce a linear correlation gap in the 2D DOS and a quadratic gap in 3D [18,19]. The 2D gap has been observed in these films [13] and produces a modified variable range hopping of the form,

$$G(T) = G_0 \exp -(T_0/T)^{1/2}, \quad (1)$$

where G is the film sheet conductance, G_0 is a constant, and T_0 is the correlation energy. Deep in the hopping regime, G_0 is expected to be of the order of the quantum conductance $G_Q = e^2/h$ [20] and $T_0 \propto 1/\kappa$ where κ is the relative dielectric constant. In the present Letter, we present a systematic magnetoconductance study of thin Be films in the hopping regime described by Eq. (1).

Shown in the inset of Fig. 1 are the normalized magnetoconductances (MC) of a moderately disordered 16 kΩ (at 50 mK) film in both parallel and perpendicular fields. Note that even in this relatively low resistance film the MC is order 30% of the total conductance. This is to be compared with the more typical 1% MC magnitudes reported in metal films [21–24]. Also note that the low field MC is negative but above 1 T the MC becomes positive for both field orientations. (We studied more than ten samples with $R > 15$ kΩ and this behavior was common to all of them.) The zero field $G(T)$ of the 16 kΩ was stronger than the usual weak localization ln(T) dependence [8] but was weaker than ES behavior of Eq. (1). Higher resistance samples had a much stronger MC. For example, in the main body of Fig. 1 we show the MC of a 3 MΩ film at 50 mK. In contrast to the 16 kΩ film, this sample was well described by the ES hopping law of Eq. (1) with $T_0 = 1.6$ K and $G_0 = 2e^2/h$ (see Fig. 3). Measurements of a somewhat higher resistance 7 MΩ film revealed ES hopping with $T_0 = 2.2$ K and $G_0 = 2e^2/h$.

There are several interesting features of the MC behavior that were observed in the $R > 1$ MΩ samples. The first was a factor of 2 decrease in the conductivity as the field was increased from zero to 0.5 T. The second was an astonishingly large, positive, linear MC above 1 T. And finally, roughly a factor of 2 difference between the high field parallel and perpendicular MC slopes. The solid lines in Fig. 1 are linear fits to the MC of the 3 MΩ sample and have slopes $1/(1.1$ T) and $1/(2.2$ T) for the perpendicular and parallel field data, respectively. Similar measurements on the 7 MΩ film gave a parallel field slope of $1/(1.2$ T). In parallel field the electron trajectories do not accumulate the Aharonov-Bohm phase and orbital effects are avoided. It is interesing that the orbital and spin contributions to the MC are comparable in the high resistance limit. Though some theoretical models predict a positive and linear orbital MC it is orders of magnitude smaller than what we observe [25,26]. For this reason we will primarily focus on the parallel field MC behavior simply because it is the easiest to interpret. In essence parallel field affects the transport only through the Zeeman energy of the electron spins. With this simplification we outline a phenomenological description of the MC behavior that considers only the energy levels of localized states. In this model localized states are characterized as being either unoccupied (UO), singly occupied (SO), or doubly occupied (DO) [27]. Because of the exclusion principle carriers can hop only to UO states or SO states of opposite final spin; see Fig. 2.

We believe that the low field negative MC in Fig. 1 is a manifestation of the polarization of correlated SO states by the applied field. As the field polarizes the electron spins, the density of opposite spin SO final states is reduced. This

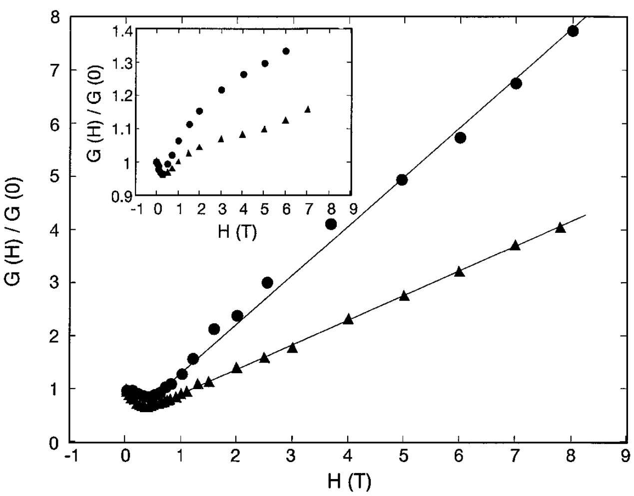

FIG. 1. Relative magnetoconductance of a 3 MΩ Be film at 50 mK. Circles: field perpendicular to film surface. Triangles: field parallel to film surface. The solid lines are linear fits to the data above 1 T with slopes of $1/(1.1$ T) and $1/(2.2$ T) for the perpendicular and parallel data, respectively. Inset: relative magnetoconductance of a 16 kΩ Be film.

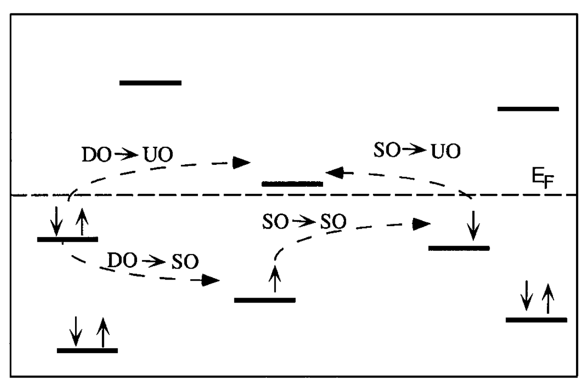

FIG. 2. Schematic diagram showing the allowed hopping transitions between doubly occupied (DO), singly occupied (SO), and unoccupied (UO) states near the Fermi energy. We have neglected the Coulomb interaction energy of DO sites. An applied magnetic field will tend to polarize the spins, thereby cutting off the SO → SO channel. At the same time DO states can lower their energy by ionizing (i.e., a DO → UO transition with a spin flip).

in turn suppresses the SO to SO hopping transitions [27]. If we assume that the SO states have quasifree spins then the suppression should be proportional to

$$P(H_\parallel, T) = \left[1 - \tanh\left(\frac{\mu_B H_\parallel}{k_B(T - \Theta)}\right)\right], \qquad (2)$$

where μ_B is the Bohr magneton and Θ is the Weiss temperature. If we take $\Theta = 0$ then $P(H_\parallel, T)$ is simply proportional to the free spin density oriented counter to the field. In Fig. 3 we have isolated the negative MC of Fig. 1 by subtracting off the linear dependence of the parallel high field data. The solid line is a best single parameter fit to Eq. (2) giving $\Theta = -93$ mK. The negative Weiss temperature indicates a small antiferromagnetic interaction among the localized states [28]. A similar fit to the data in the inset of Fig. 1 gave $\Theta = -50$ mK. The quality of the fit in Fig. 3 is compelling evidence that the negative low field MC is indeed due to SO polarization.

We now turn our attention to the linear high field MC in Fig. 1. We believe that this unusually large positive MC may be associated with field ionization of DO sites. If we assume that the DO sites have a wide distribution of binding energies, then there will be a significant number of DO sites for which the first excited state is unbound. Furthermore, such weakly bound DO sites are constrained to be in a spin-singlet state by the exclusion principle, therefore the spin-triplet state is also unbound. Consequently, when the Zeeman splitting is of order the binding energy a DO site will ionize via the relaxation of the counteraligned spin. It is natural to assume that the field ionization of DO sites will elevate carriers to UO sites at higher energies thereby *increasing* the number of SO sites involved in hopping conduction. The net result should be a decrease in the overall correlation energy T_0. This is, in fact, the case as can be seen by the data in Fig. 4 where we have made a semilog plot of G as a function of $T^{-1/2}$ at several parallel fields. The ES hopping behavior of Eq. (1) is preserved in field as evidenced by the linearity of the 3 T and 7 T curves. We quantitatively verified this by varying the exponent in Eq. (1) and fitting the data with a standard least squares and a percent deviation procedure [29]. Both procedures gave exponents between 0.47 and 0.53 for all the data sets; see inset of Fig. 4. The slopes of the curves in Fig. 4 are proportional to T_0 and clearly decrease with increasing field, and thus represent field enhanced variable range hopping.

Though the intercepts in Fig. 4 change slightly in field, we believe that the parallel high field MC in Fig. 1 is almost completely dominated by field dependence of $T_0(H_\parallel)$. In fact, we can test the consistency of this conjecture by assuming that the high field MC is linear in $H_\parallel$, $G(H_\parallel, T) = G(0,T)[1 + H_\parallel/H_0]$, where H_0 is the inverse of the slope in Fig. 1. We can now use this expression for $G(H_\parallel, T)$ to invert Eq. (1) in order to obtain $T_0(H_\parallel)$,

$$T_0(H_\parallel) = \left[\sqrt{T_0(0)} + \sqrt{T}\,\ln\left(\frac{H_0}{H_0 + H_\parallel}\right)\right]^2. \qquad (3)$$

In Fig. 5 we have plotted the values of T_0 extracted from curves such as those in Fig. 4 as a function of parallel field. The solid line is the field dependence of Eq. (3) with no adjustable parameters. The values of $H_0 = 2.2$ T and $T_0(0) = 1.6$ K were obtained from the data in Figs. 1 and 4, respectively.

The outstanding agreement between Eq. (3) and the measured values of $T_0(H_\parallel)$ is strong evidence that the linear MC is indeed arising from the field dependence of T_0. Note that by Eq. (1) the magnitude of the MC could be much larger if it were measured at lower temperatures. Again, Eq. (3) was derived in order to demonstrate that the field dependence of T_0 accounts for the high field MC

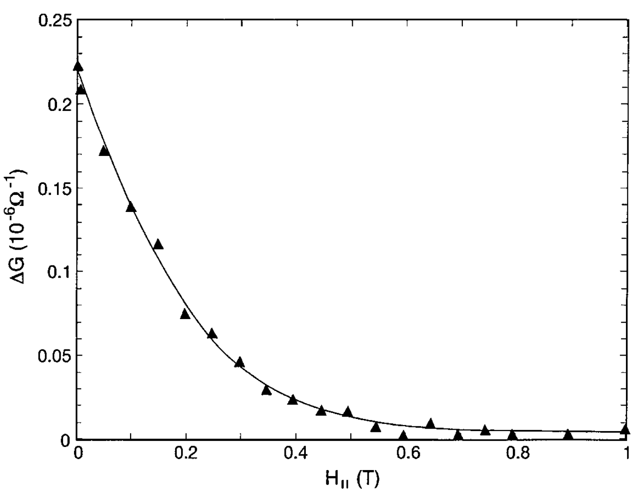

FIG. 3. The parallel low field magetoconductance of the 3 MΩ film in Fig. 1 after subtracting off the high field linear dependence. The solid line is a fit to Eq. (2) where only Θ was varied.

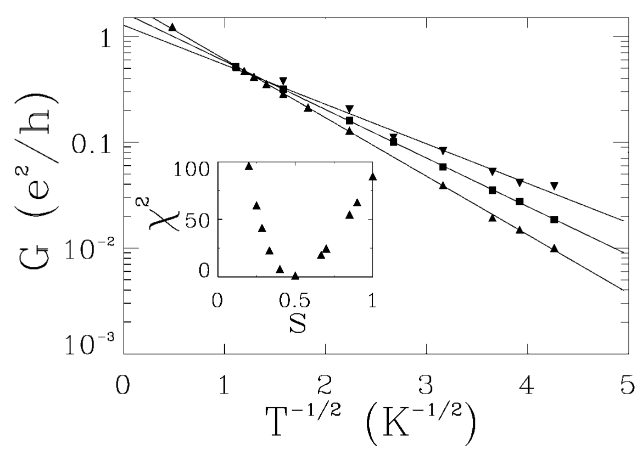

FIG. 4. Semilog plot of the film conductance as a function of $T^{-1/2}$ at three different parallel magnetic fields. Up triangles: $H_\parallel = 0$. Squares: $H_\parallel = 3.0$ T. Down triangles: $H_\parallel = 7.0$ T. The solid lines are linear fits to the data from which $T_0(H_\parallel)$ were obtained via Eq. (1). Inset: Chi-squared as a function of the exponent in Eq. (1) from a fit to zero-field data.

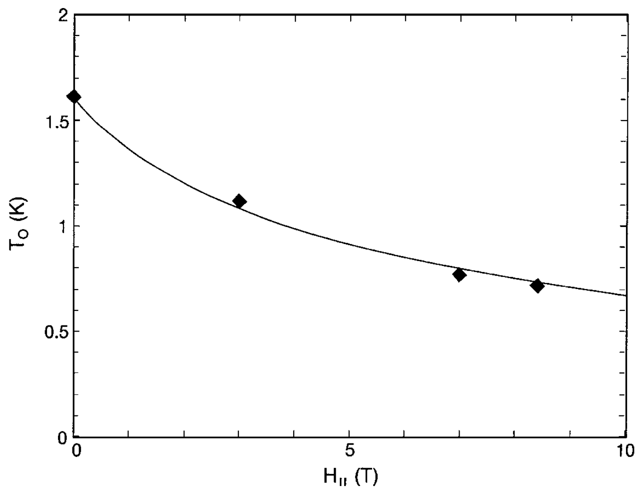

FIG. 5. Measured values of T_0 as a function of $H_{\|}$. The solid line is the prediction of Eq. (3) with no adjustable parameters.

in Fig. 1. We do not know, however, whether or not the MC will remain linear in $H_{\|}$ at significantly higher sheet resistances.

In conclusion, we find one of the largest MC's ever observed in a nonmagnetic metal film. The parallel field MC is a manifestation of the Zeeman splitting of correlated hopping channels. We believe that the extreme uniformity of Be films unmasks this essential many body effect which can be phenomenologically characterized by a field-dependent T_0. The extraordinary field sensitivity of the hopping conductance highlights the dramatic role correlations and exchange energies play in determining the localization and screening lengths in a highly disordered 2D system. Concurrent tunneling measurements of the DOS along with magnetotransport measurements of T_0 should prove interesting and in principle would enable one to extract the field dependence of the microscopic parameters.

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