Density of States of Amorphous Gd_xSi_{1-x} at the Metal-Insulator Transition

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We have determined the electronic density of states of amorphous Gd_xSi_{1-x}, $N_{GdSi}(E)$, in the vicinity of the metal-insulator transition by measuring the tunneling conductance dI/dV across a Gd_xSi_{1-x}/oxide/Pb tunnel junction at low T ($T \approx 100$ mK). By applying a magnetic field we can tune through the metal-insulator transition and simultaneously measure the transport and $N(E)$ on a single sample. We find a smooth transition from a metal with strong Coulomb interactions to a developing Coulomb gap in the insulating regime. In the metallic region $N_{GdSi}(0)$ scales approximately with σ^2.

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The metal-insulator transition (MIT) in disordered systems [1] has been of significant interest as an example of a quantum phase transition [2]. Initially, transport was studied by varying the carrier density through investigating samples with different concentrations of dopants [3]. This introduces two problems: (1) an uncertainty due to geometric and inhomogeneity effects on different samples and (2) the inherent limitation of a discrete set of samples. These problems have been overcome by studies on materials where the transition can be probed by continuously changing an external parameter such as stress [4], magnetic field [5], or illumination [6].

More fundamentally, transport data alone leave ambiguity in any study of the MIT. The transport conductivity σ depends on the density of states (DOS) $N(E)$ *and* the mobility and a measurement of σ by itself is not capable of determining which is driving the change in σ. In general, the tunneling conductance dI/dV is approximately proportional to $N(E)$. Therefore a simultaneous measurement of σ and dI/dV on the same sample allows the separation of DOS from mobility effects. Tunneling studies have been performed on discrete sets of samples [7–9], but it has been previously necessary to normalize each sample as the tunnel junction resistance varied from sample to sample. A quantitative comparison of $N(E)$ through the MIT was not possible.

We report here the first *simultaneous* investigation of the transport conductivity and the tunneling conductance in a single three-dimensional sample that can be *continuously* driven through the MIT. Recently a study of a two-dimensional quantum well density of states tuned through the MIT was accomplished by a capacitive measurement [10], but that technique is inappropriate for three dimensions. We investigate a-Gd_xSi_{1-x}, an amorphous, magnetically doped semiconductor (hereafter referred to as GdSi) which has an $H = 0$ MIT at $x \approx 0.14$. If a magnetic field is applied GdSi has been shown to have a negative magnetoresistance of many orders of magnitude at low T (<4 K) [11]. If suitably doped on the insulating side, GdSi can be driven through the transition by applying a magnetic field [12].

The GdSi samples have been electron beam coevaporated from a Gd and a Si source onto a Si/SiO substrate. We have fabricated 35 samples of different concentration near $x = 0.14$ and report here on four samples (to be called #1–#4). Following an oxidation time in desiccated air we thermally evaporate three Pb cross stripes. On each sample we create three tunnel junctions between GdSi and Pb, each with $\approx 10^{-7}$ m^2 junction area. The thermally grown oxide of GdSi forms the tunnel barrier. The tunnel junctions are also used as voltage contacts for transport measurements. For all the data shown we have determined that the junction resistance is at least an order of magnitude greater than the sample resistance over the area of the junction. This ensures that the voltage drop is across the junction. Our measurements on the insulating side of the MIT are limited by this restriction. All measurements shown here are four terminal measurements. The samples are attached to the mixing chamber of a dilution refrigerator system. A magnetic field H is applied perpendicular to the GdSi film. In prior work we have found no sensitivity of magnetoresistance to field direction [11].

Metallic and insulating behaviors are defined through the temperature dependence of the transport conductivity σ. If $\sigma_0 \equiv \sigma(T \to 0) > 0$ we designate this as metallic. We define insulating as $\sigma_0 \equiv \sigma(T \to 0) = 0$. Figure 1(a) shows $\sigma(T)$ for the four samples which were extensively investigated. Figure 1(b) is an enlargement of the low conductivity range around the MIT. On the left side of the graph we label the sample number, with #1 being the most metallic sample and #4 the most insulating one. On the right side we show the magnetic field at which the adjacent data trace was acquired. At $H = 0$, sample #1 is metallic, while sample #2 is barely so. Samples #3 and #4 are both insulating but become metallic for $H > 50$, 60 kOe, respectively. It is clear from these data that the behavior on the metallic side is similar to that studied previously in other systems, i.e., $\sigma(T) = \sigma_0 + \sigma_1 \times T^y$. The best linear fits can be obtained for $y \approx 0.6$–0.7 which is close to previous results for a metal with strong Coulomb interactions near the metal-insulator transition ($y = 0.5$). An additional term linear in T due to quantum backscattering

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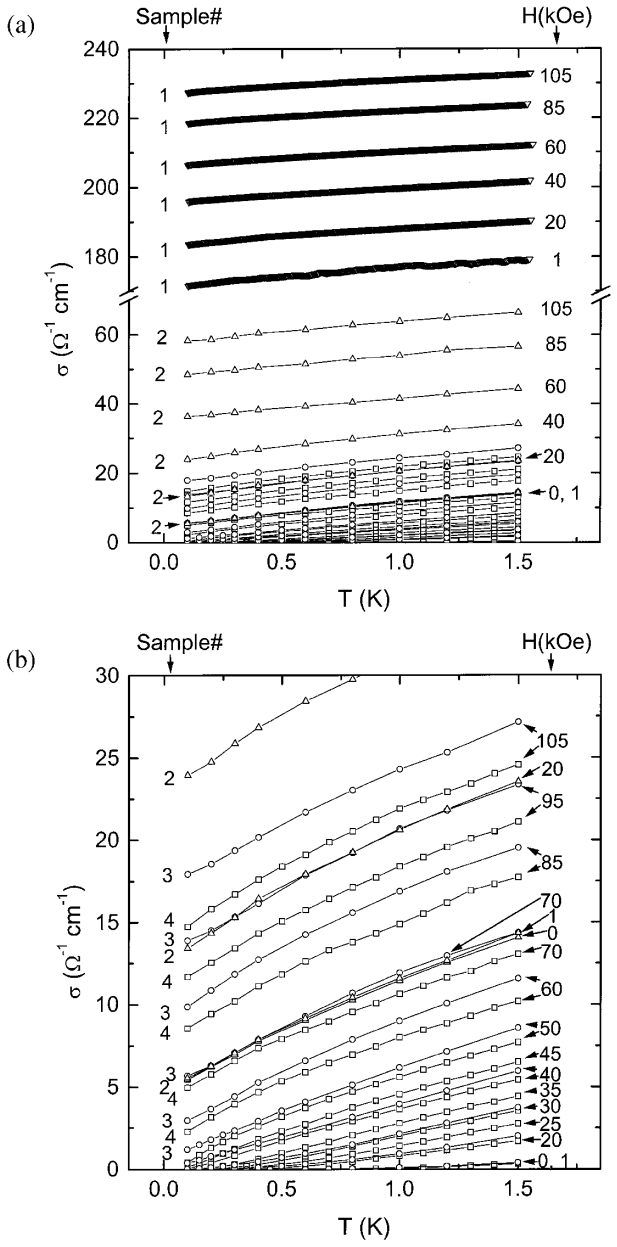

FIG. 1. (a) Transport conductivity σ versus T of Gd_xSi_{1-x} for various H. (b) Enlarged view of the low conductivity region near the MIT. Data for four samples of different x near $x = 0.14$ is shown for 0 kOe $\leq H \leq$ 105 kOe. Samples #1–#4 are shown with symbols ∇, $\triangle$, $\bigcirc$, and $\square$, respectively.

might account for the increased y, i.e., $\sigma(T) = \sigma_0 + \sigma_1 \times T^{0.5} + \sigma_2 \times T$ as shown previously [12]. The parallelism of all these curves on the metallic side implies that the major variation with H and concentration comes from the variation of σ_0 while σ_1 is approximately constant [12]. In the overlap region of samples #2–#4 we find similar effects of magnetic field H and Gd concentration x on the data; i.e., an increase in either parameter shifts the conductivity to larger values. An increase in H increases the alignment of the Gd moments, thereby reducing the disorder and lowering the mobility edge E_C. An increase in x raises the Fermi energy E_F. The similar dependence of $\sigma(T)$ on H and x suggests that the parameter driving the MIT is the difference $E_C - E_F$, as suggested for crystalline vacancy doped Gd_3S_4 [5].

Figure 2 shows the tunneling conductance dI/dV versus the bias voltage V_{bias} at $T = 100$ mK. In the inset in Fig. 2(a) a schematic view of the four contact measurements is shown. Positive bias corresponds to the GdSi at positive potential. For samples #2–#4 the junction resistance changes by orders of magnitude due to the proximity of the MIT. Therefore these data have been acquired as IV measurements and numerically differentiated. This is the cause of the increased noise in the data. We first focus on the $H = 0$ data in Fig. 2(a) which are offset by $1 \times 10^{-4}\ \Omega^{-1}$ for clarity. We find a sharp superconducting gap at $V_{\text{bias}} = \pm 1.40$ mV and pronounced phonon structure at $V_{\text{bias}} = \pm 6.1$ mV and $V_{\text{bias}} = \pm 10.0$ mV. These features are associated with the Pb superconductivity and signal that the dominant conduction mechanism across the junction is single step quantum tunneling. The background slope in the data is due to N_{GdSi}, as we will show now. With a small magnetic field $H = 1$ kOe the Pb is driven normal and the superconducting gap and the signature of phonons disappear. For low voltages it is reasonable to assume a constant DOS of Pb and thus $dI/dV(V_{\text{bias}}) \propto N_{\text{GdSi}}(E)$ for $H \geq 1$ kOe. For the data in Fig. 2(a) for 1 kOe $\leq H \leq$ 105 kOe the vertical shift for various magnetic fields is a result of the variation of N_{GdSi} with H. At low bias ($V_{\text{bias}} < 15$ mV) we find an approximate constant shift in $dI/dV(V_{\text{bias}})$ with H, much as we observe a constant shift in $\sigma(T)$ with H (Fig. 1). We interpret this shift as an increase in $N_{\text{GdSi}}(E)$ with H. Without the ability to tune the material using the same tunnel junction, we could not make this striking observation. We thus find that applying a magnetic field H simultaneously increases the conductivity $\sigma(T)$ and the DOS $N_{\text{GdSi}}(E)$. Fitting the data for 1 kOe $\leq H \leq$ 105 kOe in Fig. 2(a) to $dI/dV(V_{\text{bias}}) = dI/dV(0) + dI/dV_1 \times V_{\text{bias}}^x$ we find good agreement with $x \approx 0.5$. The parallelism of the data for various H indicates that increasing H results in an increase in $dI/dV(0)$, which is proportional to $N_{\text{GdSi}}(0)$. Summarizing the observations in Fig. 2(a), we conclude that the MIT in GdSi is driven by a concomitant change in the DOS. To our knowledge this is the first *direct* evidence for this in a continuously driven MIT in three dimensions.

Figures 2(b)–2(d) show similar data for the lower conductance and insulating samples #2–#4. For samples #3 and #4, data below $H = 40$ kOe and $H = 45$ kOe could not be acquired as the resistance of the GdSi became very large. In $H = 0$, sample #2 is at the MIT, while samples #3 and #4 are insulating but become metallic for $H \gtrsim 50, 60$ kOe, respectively. A comparison of the data in Figs. 2(a)–2(d) shows the behavior of the DOS $N_{\text{GdSi}}(E)$ in the vicinity of the MIT. $N_{\text{GdSi}}(0) \rightarrow 0$ and $\sigma_0 \rightarrow 0$ approximately coincide in H. Far on the metallic side [Fig. 2(a)] we find $N_{\text{GdSi}}(E) \propto N_{\text{GdSi}}(0) + N_1 \times E^z$ with $z \approx 0.5$. In the transition region, the exponent z

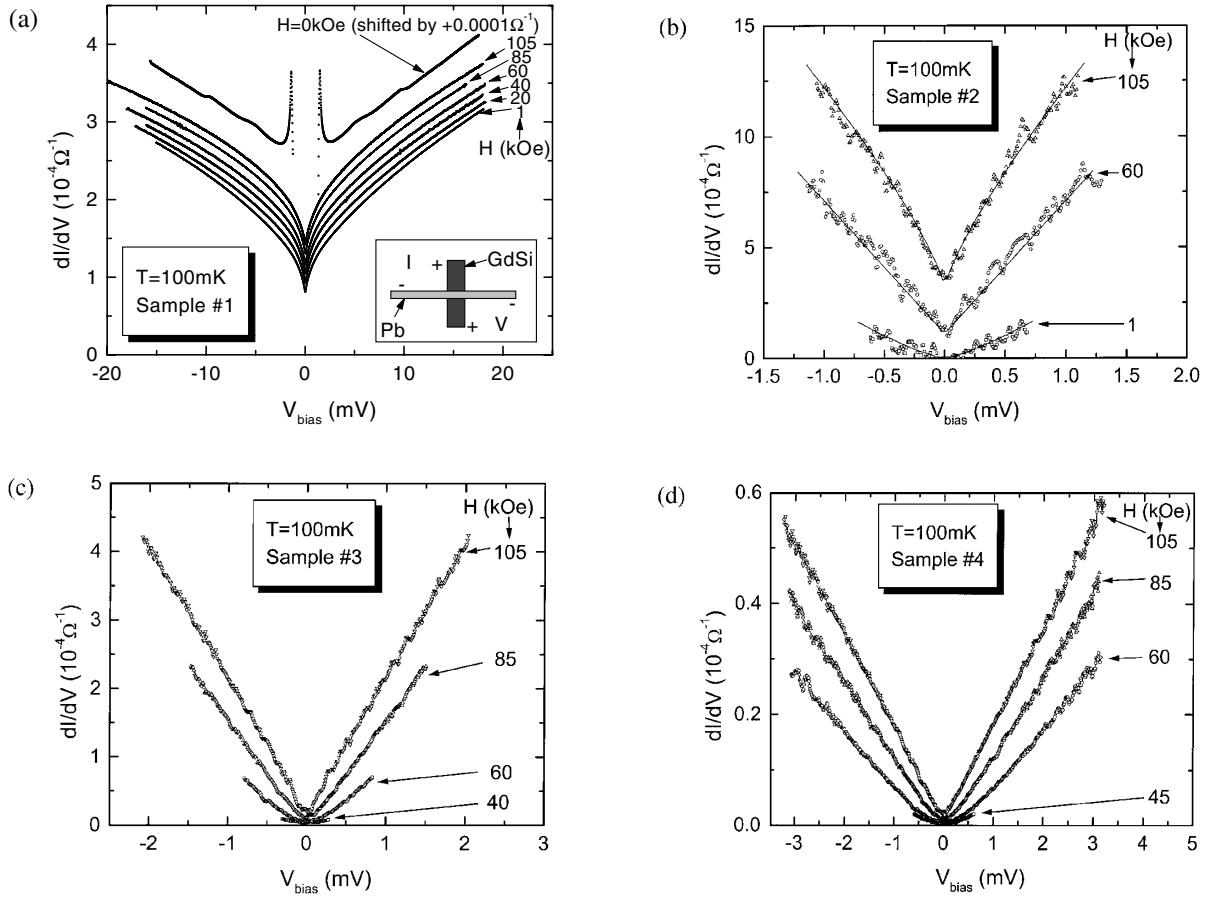

FIG. 2. (a)–(d) Tunneling conductance dI/dV versus bias voltage $V_{\rm bias}$ of four Gd_xSi_{1-x}/oxide/Pb tunnel junctions [see inset in (a) for geometry] at $T = 100$ mK for indicated magnetic fields H. (a) Sample #1 is the most metallic sample reported. The $H = 0$ data are offset by $1 \times 10^{-4}\ \Omega^{-1}$ for clarity; other H data are *not* offset. With increasing $H > 1$ kOe, dI/dV increases. (b) Sample #2 is very close to the MIT at $H = 0$. As H is increased we find a transition from $dI/dV(V_{\rm bias}) \propto V_{\rm bias}^x$ with $x > 1$ to $dI/dV(V_{\rm bias}) - dI/dV(0) \propto V_{\rm bias}^x$ with $x < 1$. (c) Sample #3 is metallic for $H \gtrsim 50$ kOe. (d) Sample #4 is metallic for $H \gtrsim 60$ kOe.

increases monotonically with decreasing conductivity σ_0 [see Figs. 2(b)–2(d)]. In the most insulating data acquired we find $z \approx 1.5$, still less than $z = 2$ as expected from a fully developed soft Coulomb gap [13]. The sample is presumably still in transition.

We now address the issue of the variation of the low temperature conductivity σ_0 and the zero bias density of states $N(0)$ with magnetic field in the critical regime near the MIT. While there is still discussion as to where the critical region is, it must be *well below* the conductivity at the Ioffe Regal condition ($k_F\lambda \approx 1$). We estimate this conductivity to be $\approx$500 $(\Omega\ {\rm cm})^{-1}$. It is seen from Figs. 1(a) and 1(b) that our studies are for conductivities 1–2 orders of magnitude below this number. Interestingly, for crystalline Si:P a similar estimate for the Ioffe Regal condition yields $\approx$30 $(\Omega\ {\rm cm})^{-1}$ and would suggest that the region equivalent to the data presented here is $\lesssim$1 $(\Omega\ {\rm cm})^{-1}$.

An analysis of σ_0 versus $N(0)$ is meaningful only for samples which are metallic (finite σ_0) or just at the MIT ($\sigma_0 \to 0$). To avoid ambiguity, we use the *measured* conductivity at the lowest available temperature $\sigma_{100\ {\rm mK}} \equiv \sigma(T = 100\ {\rm mK})$ and $N_{100\ {\rm mK}}(0) \equiv N(0)\,(T = 100\ {\rm mK})$ for the analysis. From Fig. 1 we find that $\sigma_{100\ {\rm mK}} \propto h$, where $h \equiv H - H_c$ and H_c is the critical field for each sample. This confirms the result which we reported previously on different samples [12] and is consistent with a conductivity critical exponent $\mu = 1$. From the tunneling data, we find a different exponent for the DOS: $N_{100\ {\rm mK}}(0) \propto h^2 \propto \sigma_{100\ {\rm mK}}^2$. Hence $\sigma_{100\ {\rm mK}}$ and $N_{100\ {\rm mK}}(0)$ go to zero with a different functional behavior. This behavior is clearly illustrated in Fig. 3 where we plot $\sigma_{100\ {\rm mK}}^2$ versus $N_{100\ {\rm mK}}(0)$ for samples #1 and #2. Excellent linear fits are found that go through the origin, confirming that the MIT is signaled by both values going to zero. The slopes of these two data sets are arbitrary because they are determined by the tunnel junction barrier, a parameter which can be only approximately controlled. It is the ability to tune a *single* sample through the critical region which allows us to determine the relationship $N_{100\ {\rm mK}}(0) \propto \sigma_{100\ {\rm mK}}^2 \propto h^2$. The extrapolated values $\sigma_0 \equiv \sigma(T = 0)$ and $N_0(0) \equiv N(0)\,(T = 0)$ show the same results.

We also show data from samples #3 and #4 on a greatly enlarged scale in the inset of Fig. 3. Since both

samples are well inside the insulating phase until fields of 50–60 kOe, there is only a very small dynamic range of metallic behavior where $\sigma_{100\,\mathrm{mK}}$ and $N_{100\,\mathrm{mK}}(0)$ are meaningful. Again there is a linear relationship between $\sigma^2_{100\,\mathrm{mK}}$ and $N_{100\,\mathrm{mK}}(0)$, but the extrapolation of sample #3 does not go through zero on this enlarged scale. This can be seen directly in the data of Fig. 2(c) where there appears to be a tiny "leakage" conductance in this junction and $N_{100\,\mathrm{mK}}(0)$ does not go precisely to zero on the insulating side. We ascribe the offset to a minor imperfection in this junction. We thus conclude $N_0(0) \propto \sigma_0^2 \propto h^2$. We reemphasize that this result has not previously been observed as previous studies could not quantitatively compare different junctions. Here a single junction probed the material as it was tuned through the MIT.

The behavior $\sigma_0 \propto h^\mu$, where $\mu = 1$ is theoretically expected. At the moment, we do not have any deep insight into the critical behavior of the DOS near the MIT, $N_0(0) \propto h^2$. It is well established that the dependence of the DOS $N(E) \propto E^{1/2}$ comes as a result of strong Coulomb interactions [14]. The experiments described here suggest that the important parameter for *both* conductivity σ_0 and DOS $N_0(0)$ is $E_C - E_F$. We have shown that modifying E_F by carrier density or E_C by applied field H accomplishes similar results.

In summary, we have simultaneously measured the transport conductivity and the tunneling conductance on a three-dimensional material which can be continuously driven through the $T = 0$ metal-insulator transition. This allows us to determine *directly* the density of states in a continuous way in the vicinity of the metal-insulator transition. We found that there is a gradual and monotonic transition of a metal with strong Coulomb interactions to an insulator with a developing Coulomb gap. The vanishing of the transport conductivity and the zero bias tunneling conductance coincides in magnetic field. On the metallic side of the transition we find that the conductivity σ_0 scales as h^μ and the density of states at zero bias $N(0)$ scales as $dI/dV(0) \propto h^{2\mu}$, where $h \equiv H - H_c$ and the critical conductivity exponent $\mu = 1$.

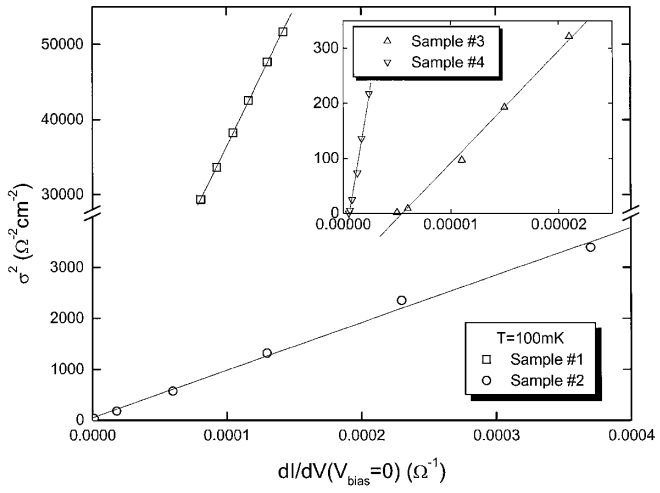

FIG. 3. Experimentally measured σ^2 versus $dI/dV(0)$ at $T = 100$ mK for samples #1 and #2; each data point represents data taken at an applied field H as shown in Figs. 1 and 2. The inset shows on a greatly enlarged scale the same data for samples #3 and #4 for fields where the samples exhibit metallic behavior. Linear fits to each data set are shown.

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