Magnetic field induced insulator to metal transition in amorphous-Gd$_x$Si$_{1-x}$

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Abstract

We have measured the electrical resistance and magnetoresistance near the metal–insulator transition in films of the amorphous alloys Gd$_x$Si$_{1-x}$ and Y$_x$Si$_{1-x}$ ($x \sim 0.14 – 0.15$) for $0.1 \text{ K} < T < 20 \text{ K}$ in an applied magnetic field $0 \text{ kOe} < H < 105 \text{ kOe}$. In a low magnetic field, a-Gd$_x$Si$_{1-x}$ is an insulator and the conductivity approximately follows the expected behavior for variable range hopping. With increasing field $H$ the conductivity of a-Gd$_x$Si$_{1-x}$ increases by $\sim 3$ orders of magnitude at low $T$, crosses through an insulator to metal transition and approaches the conductivity of a-Y$_x$Si$_{1-x}$, indicating that the effect of the magnetic Gd impurities on transport is diminished by the application of a magnetic field. The low-temperature conductivity on the metallic side of the transition scales approximately linearly with the applied magnetic field, indicating that the critical exponent $\mu \approx 1$.

Keywords: D. Electron–electron interactions; D. Electronic states (localized); Electronic transport; D. Phase transitions; D. Quantum localization

Electrical transport in magnetically doped semiconductors has been a recent area of interest [1–3]. Most of the work has focused on crystalline classes of materials, like mixed-valence manganites [4,5], rare earth chalcogenides [6–8] and dilute magnetic semiconductors [9–12]. In the latter two classes extensive evidence exists for bound magnetic polarons resulting from the exchange interaction [13–15]. It has been the subject of several recent studies [16,17] to extend this work to amorphous materials, which have greatly enhanced electron densities in the vicinity of the metal to insulator transition [18–24] and where thus the concept of bound magnetic polarons might not be applicable. These studies have established that doped amorphous silicon shows a striking difference in transport and magnetoresistance for $T < 70 \text{ K}$, depending whether the dopant atom has a finite magnetic moment (e.g. Gd) or not (e.g. Y, Nb). These differences are presumably due to an interaction of the transport electrons with the magnetic moments. Amorphous Gd$_x$Si$_{1-x}$ has been investigated for $T > 2 \text{ K}$ [16], where samples spanning the insulating and metallic side of the metal–insulator transition have been measured. A large negative magnetoresistance was found which was not seen in a-Y$_x$Si$_{1-x}$. Instead the a-Y$_x$Si$_{1-x}$ showed a much smaller (orders of magnitude) positive magnetoresistance. Y and Gd are nearly always trivalent and have comparable ionic radii, leading to the expectation of similar bonding structures and electronic density of states. It was thus presumed that the difference in behavior arises from the magnetic moment of Gd (due to the 4f electrons) which is absent in Y. In further work a-Gd$_x$Si$_{1-x}$ has been shown [17] to have a negative magnetoresistance of $\sim 5$ orders of magnitude by 100 kOe at $T = 1 \text{ K}$.

Here, we present results on a-Gd$_x$Si$_{1-x}$ ($x = 0.14$) which show that as a function of magnetic field we can tune the system through the metal–insulator transition. Similarly to results for rare earth chalcogenides [6–8] and dilute magnetic semiconductors [9,10] we find for $H = 0$ that the conductivity is dominated by variable range hopping in the presence of a soft Coulomb gap for the observed temperature range ($T > 100 \text{ mK}$). We find, that for high magnetic fields the transport in a-Gd$_x$Si$_{1-x}$ is metallic and is dominated by Coulomb interactions. Metallic behavior is customarily defined as the $T = 0 \text{ K}$ conductivity $\sigma_0$ being finite, i.e. $\sigma_0 = \sigma (T = 0 \text{ K}) > 0$. Insulating behavior is defined as $\sigma_0 = \sigma (T = 0 \text{ K}) = 0$. For $H \geq 40 \text{ kOe}$ a finite $\sigma_0$ can be determined. $\sigma_0$ increases linearly with applied
magnetic field. It appears that the a-GdxSi1-x conductivity will approach the conductivity of a-YxSi1-x at high magnetic fields. As H is increased the effect of the Gd magnetic moments on the transport electrons is diminished, presumably due to their becoming aligned by the field, which leads to an increase in conductivity.

The a-Gd,0.14Si1-x and a-Y,0.15Si1-x samples have been co-evaporated onto amorphous silicon-nitrate-covered Si substrates. During the evaporation and subsequent processing the sample temperature was held below 340 K.1 All resistances have been measured with a lock-in amplifier in ac four-terminal mode. For all data, and for the voltages and currents used in the measurements the resistances were independent of both the frequency of the measurement and the power dissipated in the sample. We have verified the resistances against selected I–V measurements on the same sample. The temperature was measured with a Ge-thermometer that was encased in the copper sample stage to which the sample was attached. In determining the temperature we compensated for the magnetoresistance of the thermometer. The magnetic field was determined from the magnet current, following the manufacturer calibration.

Fig. 1 shows the conductivity (log-axis) of the a-GdxSi1-x vs T1/2 for various applied magnetic fields H. The data for H = 0 and, to a lesser extent, the data for H = 10 kOe show an approximate straight line for T < 1.7 K, indicating that the transport is dominated by variable range hopping. As the magnetic field is increased the curvature of the data becomes more pronounced. For comparison similar data for Y0.15Si0.85 in H = 0 is shown as a continuous line. As H is increased, the GdxSi0.86 data approach the Y0.15Si0.85 data. (GdxSi0.86 and Y0.15Si0.85 show identical conductivity for H = 0 and T > 50 K. The difference in nominal composition, 14 vs 15%, is within experimental accuracy).

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1 GdxSi0.86 and Y0.15Si0.85 have the same conductivity for temperatures above 50 K, while for T < 50 K the Y0.15Si0.85 conductivity is higher than the GdxSi0.83 conductivity. We compare the two samples directly because of the similarity in the high-T behavior, though their composition as measured by Rutherford back-scattering are slightly different.

2 Fitting the data to log σ ∝ −(T/T0)1/2 yields a better result than a fit with an exponent 1/3 or 1/4 instead.
conductivity of the a-Gd\textsubscript{x}Si\textsubscript{1-x} goes towards the conductivity of the a-Y\textsubscript{x}Si\textsubscript{1-x}.

In Fig. 2a, we plot the same data as conductivity versus $T^{1/2}$ while Fig. 2b is a blowup of the low-temperature data. It is expected that the conductivity of a metal with Coulomb interactions follows $\sigma(T) = \sigma_0 + \sigma_1 \times T^{1/2}$, where $\sigma_0$ is the $T = 0$ K conductivity and $\sigma_1 \times T^{1/2}$ is the first-order correction due to Coulomb interactions [26,27]. An additional correction term due to quantum back-scattering effects which are eliminated by inelastic scattering events has the form $\sigma_2 \times T^{p/2}$ [1–3] ($p$ is an exponent depending on the nature of the scattering mechanism and in the further analysis will be assumed to be equal to 2, as e.g. in electron–phonon scattering. The precise value of $p$ does not affect the basic analysis that follows as this higher order term is small). Assuming $\sigma_2 \ll \sigma_1$, such $\sigma(T)$ behavior would appear as an approximately straight line in Fig. 2. We first focus on the low-temperature data in Fig. 2b. For all data
with $H \geq 30$ kOe we find for $T \to 0$ an approximately $T^{1/2}$ regime. (Including a $T^{p/2}$ term significantly improves the fit to the data, suggesting the presence of quantum back-scattering effects. The observation of an approximately straight line does however indicate that the coulomb interactions are the dominant correction.) We have included fits for $H > 40$ kOe as dashed lines in the figure. The indicated y-axis intercept is $\sigma_0$. Since $\sigma_0 > 0$ for $H \geq 40$ kOe, the samples are metallic in this region, while for $H \leq 40$ kOe we find insulating behavior according to $\sigma_0 = 0$.

Thus we have observed insulating behavior with thermally activated variable range hoping for small magnetic fields and metallic behavior for large magnetic fields on the same sample. A similar observation has been made for crystalline Gd$_{1-x}$V$_x$S$_4$ [6–8] for which it was found that the low-temperature conductivity was approximately proportional to $H - H_0$ where $H_0$ is a concentration dependent magnetic field at which the metal–insulator transition occurs. We note that the quality of the straight line fit at $H = 0$ in Fig. 1 is less than for the $x \sim 0.13$ sample [17] presumably due to the closer proximity to the insulator–metal transition of the present $x \sim 0.14$ sample. In the crossover region from insulating to metallic behavior (20 kOe $> H > 40$ kOe) we find poor fits to either model.

As temperature is increased (see Fig. 2a), the a-Gd$_{Si_{1-x}}$ data show first an increasing slope, an inflection point and then a decreasing slope as the a-Gd$_{Si_{1-x}}$ data approach the a-Y$_x$Si$_{1-x}$ data. The temperature of the inflection point decreases with increasing magnetic field. Fig. 2a argues that at $T = 0$ and $H = 0$ the electrons in this a-Gd$_{Si_{1-x}}$ sample are localized. The increase of $T$ or $H$ to a finite value increases the mobility of the electrons such that in
the limit of large $T$ or $H$ the conductivity of the non-magnetic analog $a$-Y$_{x}$Si$_{1-x}$ is approached. The $a$-Y$_{x}$Si$_{1-x}$ data for $T > 1$ K show similar behavior as previously measured $a$-Nb$_{x}$Si$_{1-x}$ [38,39] data, however for $T < 1$ K the temperature dependence decreases. This is presently not understood.

We now analyze the data in Fig. 2 in more detail. First, applying the concepts above, we determine the magnetic field at which the insulator to metal transition occurs. In Fig. 2b the $a$-Gd$_{x}$Si$_{1-x}$ data for $T < 1.7$ K for each magnetic field has been fit with a quadratic polynomial $\sigma(T) = \sigma_0 + \sigma_1 \times T^{1/2} + \sigma_2 \times T$. Fig. 3a shows $\sigma_0$ and $\sigma$ (100 mK), and $\sigma(200$ mK) vs $H$. For $H \approx 50$ kOe the behavior of $\sigma_0$ follows approximately $\sigma_0(\Omega \text{ cm}) = 0.46 \times (H - 40)$, with $H$ in kOe. The $T = 0$ K conductivity $\sigma_0$ thus vanishes at $H \approx 40$ kOe, and has a finite value for $H \approx 40$ kOe, indicating that the material undergoes an insulator to metal transition at $H = 40$ kOe as the magnetic field is increased. As the magnetic field $H$ drives the insulator to metal transition the dependence of $\sigma_0$ on $H$ in the vicinity of the transition yields the critical parameter $\mu$ (defined from $\sigma_0 \propto (H - H_0)^{\mu}$). We find $\mu \approx 1$ in agreement with various studies of other materials [6–8,28–32]. For Si:B it has been found that $\mu$ increases from $\mu < 1$ in $H = 0$ to $\mu = 1$ for large $H$ [37]. The cause of this change is presently not understood. At finite temperature we find thermally induced rounding in the transition region. In Fig. 3a, however the critical exponent $\mu = 1$ (linear dependence of $\sigma$ on $H$) is still apparent.

Fig. 3b shows the fit parameters $\sigma_1$ and $\sigma_2$ from the data in Fig. 2. We find that $\sigma_1$ remains almost constant with field at $10$ (\text{\Omega cm K}^{1/2})^{-1}$ and that $\sigma_2$ increases approximately linearly with $H$ from about 0.8 (\text{\Omega cm K})^{-1} at $H = 50$ kOe to about 1.6 (\text{\Omega cm K})^{-1} at $H = 100$ kOe. In particular we note that $\sigma_1$ stays positive for all $H$. This seems to be a characteristic of the materials with $\mu = 1$ [28–32], while the materials with $\mu = 0.5$ [33–36] show a transition from positive to negative $\sigma_1$ as $H$ is increased. This difference in behavior is however presently not understood. For $a$-Nb$_{x}$Si$_{1-x}$, $\sigma_1 = 7$ (\text{\Omega cm K}^{1/2})^{-1} has been found (approximately independent of composition) [38,39]. As Fig. 3b indicates $\sigma_1$ for $a$-Gd$_{x}$Si$_{1-x}$ might be slightly decreasing with field and tending towards the observed value for $a$-Nb$_{x}$Si$_{1-x}$ in the large field limit. We find that a linear extrapolation of $\sigma_0$ above 50 kOe reaches the observed value for $a$-Y$_{x}$Si$_{1-x}$ at $\approx 180$ kOe, which is approximately the magnetic field where an identical extrapolation of $\sigma_1$ for $a$-Gd$_{x}$Si$_{1-x}$ reaches the observed value for $a$-Nb$_{x}$Si$_{1-x}$. This value of magnetic field is also close to the estimated field at which the magnetization saturates in a linear extrapolation of the $M(H)$ data ($T = 4.2$ K data in Fig. 4 of Ref. [16]). The magnetic energy associated with a Gd moment in such a field is $\mu_H = 7 \mu_B \times 180$ kOe = $1.2 \times 10^{-21}$ J. In $H = 0$ the conductivity for $a$-Gd$_{x}$Si$_{1-x}$ and $a$-Y$_{x}$Si$_{1-x}$ are identical above $T = 70$ K which is associated with a thermal energy $k_B T = k_B \times 70$ K = 9.7 $\times 10^{-22}$ J. Since these energies agree within 20% one may conclude that the energy scale set by the interaction of the conduction electrons with the magnetic moments is on the order of $1 \times 10^{-21}$ J. We suggest the following physical picture as a possible description. The structural disorder of $a$-Y$_{x}$Si$_{1-x}$ and $a$-Gd$_{x}$Si$_{1-x}$ is equivalent but the additional spin disorder in the $a$-Gd$_{x}$Si$_{1-x}$ moves the mobility edge above the Fermi level resulting in reduced screening, stronger coulomb effects and an insulator. With increasing magnetic field, the spins align, the spin disorder is diminished, the mobility edge drops below the Fermi level and the system becomes metallic and in sufficiently high field approximately equivalent to the conducting $a$-Y$_{x}$Si$_{1-x}$.

The coefficients of the correction terms due to Coulomb interactions (see e.g. Ref. [40] for a formula including the subsequent corrections) and quantum back-scattering (for weak localization) are calculated [1–3,40] to be given by:

$$\sigma_1 = \frac{e^2}{4\pi^2} \frac{1.3 \sqrt{k_B}}{2\hbar D} \left( \frac{4}{3} - \frac{3}{2} F_\sigma \right), \quad \sigma_2 = \frac{e^2}{\pi^2 \hbar a}$$

where $e$ is the electron charge, $\hbar$ the Planck constant, $D$ the diffusion constant, $k_B$ the Boltzmann constant, $F_\sigma$ a constant related to the Fermi liquid parameter $F$ and $a$ represents a microscopic length scale of the system. Using the electron density $n = 2.0 \times 10^{22}$ (cm$^3$)$^{-1}$ and assuming a free electron model we calculate the diffusion constant

$$D = \frac{1}{3} \frac{v_F^2 \tau}{\hbar} = \frac{1}{3} \left( \frac{\hbar}{m (3\pi^2 n)^{1/3}} \right)^2 \frac{m}{ne^2} \sigma_0$$

from the $T = 0$ conductivity $\sigma_0$. With $D \approx 1 \times 10^{-2}$ (cm$^2$/s) and $\sigma_1 = 10$ (\text{\Omega cm K}^{1/2})^{-1}$ we find

$$\left( \frac{4}{3} - \frac{3}{2} F_\sigma \right) \approx 0.49 \quad \text{or} \quad F_\sigma \approx 0.56$$

This is smaller than the observed values for SiB [37] and Cd$_{1-x}$MnTe [11,12] which both also show a decrease of $F_\sigma$ as the material becomes more insulating. Using $a = \frac{k_F^{-1}}{1.2 \times 10^{-8}}$ cm we expect from localization theory $\sigma_2 = (e^2/\pi^2 \hbar a) = 2000$ (\text{\Omega cm K})$^{-1}$ while close to the metal–insulator transition we measure $\sigma_2 = 1.2$ (\text{\Omega cm K})$^{-1}$. This disagreement is presently not understood but we note that the theory was derived in the limit of weak localization and might be only qualitatively valid in a strongly disordered system like a-Gd$_{x}$Si$_{1-x}$ close to the critical region.

In summary, we have measured the electrical resistance and magnetoresistance of amorphous Gd$_{x}$Si$_{1-x}$ and a-Y$_{x}$Si$_{1-x}$. We have found that a-Gd$_{x}$Si$_{1-x}$ of composition $x = 0.14$ shows a large negative magnetoresistance, such that the a-Gd$_{x}$Si$_{1-x}$ data approaches the a-Y$_{x}$Si$_{1-x}$ data as the magnetic field is increased. The conductivity in $H = 0$ is

$^3$ The electron density was determined by measuring the Gd concentration through Rutherford back-scattering (6.8 $\times 10^{21}$ Gd/cm$^3$ for 15 at% Gd) and assuming 3 conduction electrons per Gd.
indicative of a variable range hopping insulator, while the application of a magnetic field $H \approx 40$ kOe leads to metallic behavior in the presence of Coulomb interactions. The field dependence of the low-temperature conductivity on the metallic side yields a critical exponent $\mu = 1$.

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References