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Metal–insulator transition of NTD ^{70}Ge : Ga in magnetic fields

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Abstract

We have determined the temperature dependence of the electrical conductivity $\sigma(N,B,T)$ of nominally uncompensated, neutron-transmutation-doped (NTD)^{70}Ge:Ga samples in magnetic fields up to $B=8$ T at low temperatures ($T=0.05$–0.5 K) to investigate both the doping-induced metal–insulator transition (MIT), $\sigma(N,B,0)\propto(N-N_c)^{\mu}$, and the magnetic-field-induced MIT, $\sigma(N,B,0)\propto(B_c-B)^{\mu'}$. Our experimental results show that $\mu=\mu'=1.1\pm0.1$ in sufficiently large magnetic fields. © 2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: Critical exponent; Metal–insulator transition; Neutron-transmutation doping; Semiconductor

The critical exponent μ of the conductivity for the metal–insulator transition (MIT) in doped semiconductors is one of the most puzzling problems of modern condensed-matter physics (see for example Ref. [1]) and $\mu\approx0.5$ has been found in a number of nominally uncompensated semiconductors including our ^{70}Ge:Ga [2,3]. According to theories [1] of the MIT, μ does not depend on the details of the system, but depends only on the universality class to which the system belongs. In this sense, the application of magnetic fields is important because the motion of carriers loses its time-reversal symmetry in magnetic fields, and the universality class changes. In this work, we aim to achieve a complete understanding of the effect of magnetic fields on the MIT in uncompensated semiconductors by studying the critical behavior of the zero-temperature conductivity as a function of both N (doping-induced MIT) and B (field-induced MIT) in magnetic induction up to 8 T for ^{70}Ge:Ga system.

All of the 12 ^{70}Ge:Ga samples used in this work were prepared by neutron-transmutation doping (NTD) of isotopically enriched ^{70}Ge single crystals. This doping process guarantees a random distribution of Ga acceptors down to the atomic level [2,3]. The electrical conductivity was measured at low temperatures between 0.05 and 0.5 K.

The zero-temperature conductivity $\sigma(N,B,0)$ of the samples in various magnetic fields obtained by extrapolation of the conductivity $\sigma(N,B,T)$ to $T=0$ is shown in Fig. 1 as a function of the normalized concentration $n=N/N_c(0)-1$, where $N_c(0)=1.860\times10^{17}\,\mathrm{cm}^{-3}$, the critical concentration at $B=0$. The critical exponent $\mu(B)$ defined by

$$\sigma(N,B,0)=\sigma_0(B)[n/n_c(B)-1]^{\mu(B)}, \tag{1}$$

increases from 0.5 with increasing B and reaches a value close to unity at $B\geqslant4$ T. The change of μ from 0.5 at $B=0$ to ≈1 at $B\geqslant4$ T can be explained by the change of the universality class.

We tuned the magnetic induction to the MIT in steps of 0.1 T for three different samples. Another critical exponent $\mu'(n)$ can be defined by

$$\sigma(N,B,0)=\sigma'_0(n)[1-B/B_c(n)]^{\mu'(n)} \tag{2}$$

for this field-induced MIT, and $\mu'=1.1\pm0.1$ is obtained for all of the three samples.

From both measurements, the phase diagram at $T=0$ is constructed on the (N,B) plane. The boundary between

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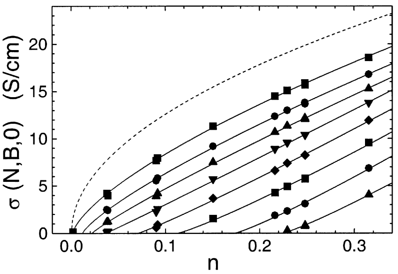

Fig. 1. Zero-temperature conductivity versus normalized concentration. From top to bottom the magnetic induction increases from 1 to 8 T in steps of 1 T. The dashed curve at the top is for $B = 0$. The solid curves represent fits of Eq. (1). For $B \geqslant 6$ T, we assume $\mu = 1.15$.

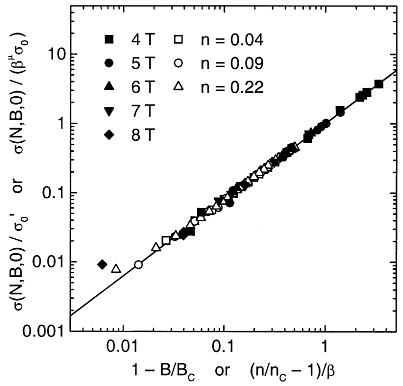

Fig. 2. Normalized zero-temperature conductivity versus dimensionless distance from the critical point. The open and solid symbols represent the results of the field-induced MIT in the range $(1 - B/B_c) < 0.5$ and the doping-induced MIT in constant magnetic fields, respectively.

metallic phase and insulating phase for ^{70}Ge:Ga is expressed by $n \propto B^{\beta}$, where $\beta = 2.45 \pm 0.09$. Based on this finding, $\sigma_0' = \beta^{\mu}\sigma_0$ and $\mu' = \mu$ are derived from a simple mathematical argument for the region $[n/n_c(B) - 1] \ll 1$ or $[1 - B/B_c(n)] \ll 1$, where an approximation $[n/n_c(B) - 1]/\beta \approx [1 - B/B_c(n)]$ holds. In order to see how well $\mu' = \mu$ holds, we plot $\sigma(N, B, 0)/[\beta^{\mu}\sigma_0(B)]$ versus $[n/n_c(B) - 1]/\beta$ with $\beta = 2.5$ and $\mu = 1.1$ for the doping-induced MIT ($B \geqslant 4$ T), and $\sigma(N, B, 0)/\sigma_0(B)'$ versus $[1 - B/B_c(n)]$ for the field-induced MIT in Fig. 2. The data points fall accurately on a single line describing a single exponent $\mu = \mu' = 1.1$.

In summary, the conductivity critical exponent for ^{70}Ge:Ga is 1.1 ± 0.1 in sufficiently large magnetic fields.

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