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# Comparison of the Effects of the Doping-Compensation and Magnetic-Field on the Metal-Insulator Transition of Ge:Ga

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## 1. Introduction

The critical exponent $\mu$ for the electrical conductivity at zero-temperature $\sigma(0)$ is given by

$$\sigma(0) \propto |N/N_c - 1|^{\mu}, \tag{1}$$

where $N_c$ is the critical value of the doping concentration $N$ that separates the insulating and metallic phases of a doped semiconductor. We have recently provided a strong evidence for $\mu \approx 0.5$ in the absence of an external magnetic field for uncompensated semiconductors[1)] supporting the original claim of Rosenbaum *et.al.*[2)] On the other hand, it is well known that perturbations such as doping compensation[3–7)] or external magnetic fields[8–12)] result in $\mu \approx 1$. Although both perturbations lead to the same value of $\mu$ within the typical experimental uncertainty, it is not clear whether the effects of the compensation and magnetic field are the same in terms of the universality class for the transition. The present work compares the effect of the two and shows a convincing experimental evidence that they are different. In order to show the difference between the two, we employ a so-called finite temperature ($T$) scaling analysis of the conductivity $\sigma(t,T)$;

$$\sigma(t,T) \propto T^{x} f(|t/t_c - 1|/T^{y}), \tag{2}$$

where $t$ in the present study is either the doping concentration ($N$) or the maginetic field ($B$) with the corresponding critical values $t_c \equiv N_c$ or $B_c$. The conductivity critical exponent from this analysis is given by $\mu = x/y$.

Two series of homogeneously doped p-type Ge samples: i) nominally uncompensated neutron-transmutation-doped (NTD) $^{70}$Ge:Ga samples with the compensation ratio $K < 0.001$, and ii) intentionally compensated NTD $^{nat}$Ge:Ga,As samples with $K = 0.32$ are investigated in this study. Low temperature electron transport properties with and without magnetic field are probed in the critical regime for the metal-insulator transition.

## 2. Experimental Results

Figure 1 shows the finite temperature scaling analysis of 13 deliberately compensated ($K = 0.32$) NTD $^{nat}$Ge:Ga,As samples. Some of the data (open circles), which have been published in Ref.13, were provided directly to us by A. G. Zabrodskii. The range of temperatures used for the measurements are $T = 0.25 - 1$K and $0.65 - 2$K for filled and open circles, respectively. In order to determine the values of $x$ and $y$ for Fig. 1, we have performed a least-square fitting with the following equation with open circles only because they cover a wide range of concentration spanning the both insulating and metallic phases while filled circles cover only the limited regions of the insulating phase.

$$\ln\frac{\sigma(t,T)}{T^{x}} = \left[a_0 + a_1\left(\frac{N/N_c - 1}{T^{y}}\right) + a_2\left(\frac{N/N_c - 1}{T^{y}}\right)^2 + a_3\left(\frac{N/N_c - 1}{T^{y}}\right)^3\right]. \tag{3}$$

The solid curve in Fig. 1 is the best fit obtained numerically with $x = 0.33$, $y = 0.32$, $a_0 = 1.05$, $a_1 = 4.55$, $a_2 = -5.69$, and $a_3 = 2.90$ using Eq. (3). It is shown convincingly that the conductivity of the $K = 0.32$ series (especially open circles for they are the data used for fitting) collapse to form one universal curve for a very wide range of concentration $0.25N_c < N < 2.4N_c$. As expected, the value of the conductivity critical exponent $\mu = x/y = 1.01 \pm 0.04$ found from this analysis is in excellent agreement with previous studies.[3–7)] The slight deviation between the series of open and filled circles in Fig. 1 is most likely due to the small difference in the calibration of the concentration $N$ because the two series have been neutron irradiated in different reactors. However, one sees in Fig. 1 that each series (∘ and •) collapses onto separate single curves and the difference between the two is very small. The result of the analysis with Eq. (3) is practically unchanged even if we combine the open and filled circles.

Figure 2 shows the finite temperature scaling of $\sigma(B,T)$ for the case of a magnetic field induced transition of the nominally uncompensated series of NTD $^{70}$Ge:Ga. $\sigma(B,T)$ measured at $B = 2$–$6$T and $T = 50$–$500$ mK for the metallic samples, and $B = 2 - 6$T and $T = 100 - 250$ mK for the insulating samples have been used for the analysis based on the criterion that $\sigma(B,T)$ of each sample is $\propto T^{1/2}$ with approximately the same $d\sigma/dT$. The solid curve in Fig. 2 is the best fit using Eq. (3) with

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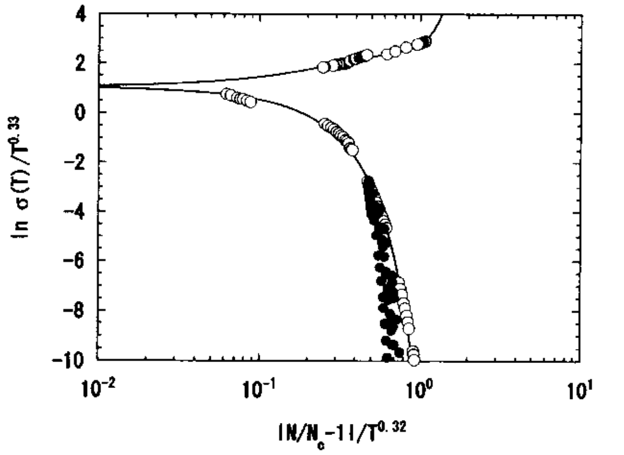


Fig. 1. Finite temperature scaling analysis of $\sigma(N,T)$ using Eq. (3) with $x = 0.33$ and $y = 0.32$ for the concentrations $N = 0.25N_c - 2.40N_c$. The solid curve is the best fit to the data represented by open circles. Filled circles represent the samples prepared and measured by the present authors while open circles are the data provided by A. G. Zabrodskii.[13]

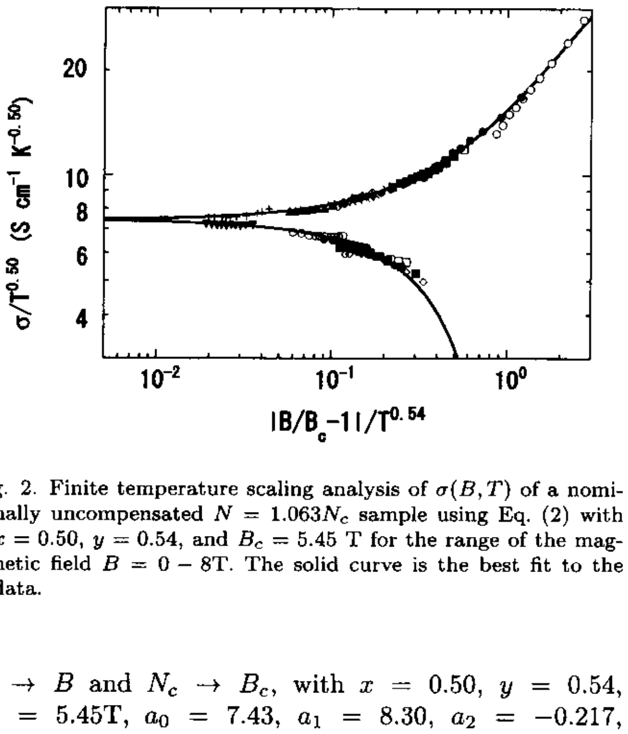


Fig. 2. Finite temperature scaling analysis of $\sigma(B,T)$ of a nominally uncompensated $N = 1.063N_c$ sample using Eq. (2) with $x = 0.50$, $y = 0.54$, and $B_c = 5.45$ T for the range of the magnetic field $B = 0 - 8$T. The solid curve is the best fit to the data.

$N \to B$ and $N_c \to B_c$, with $x = 0.50$, $y = 0.54$, $B_c = 5.45$T, $a_0 = 7.43$, $a_1 = 8.30$, $a_2 = -0.217$, and $a_3 = -0.063$. The conductivity critical exponent $\mu = x/y = 0.93 \pm 0.10$ obtained here for the magnetic-field tuning of a Ge:Ga with $N = 1.063N_c$ is in good agreement with the results of the conventional extrapolation analysis $\mu = 1.1 \pm 0.1$ determined for a transition in a constant magnetic field.[12]

## 3. Discussion and Summary

According to the general theory of a metal-insulator transition, the critical exponent $\mu$ does not depend on the details of the system, but depends only on the universality class to which system belongs.[14] $\mu = 1.2 \pm 0.2$ obtained with the compensated series without $B$ and $\mu = x/y = 0.93 \pm 0.10$ from $B$-tuning of the nominally uncompensated series agree with each other within their experimental uncertaintities, i.e., one may conclude that they belong to the same universality class. However, we note that the values of $x$ and $y$ obtained with the compensation and magnetic field are different. This difference implies the difference in the so-called dynamical critical exponent $z$. According to the theory of non-interacting particles in three dimensions, we expect $\nu = \mu$, $z = 3$, $x = 1/z$, and $y = 1/z\nu$ where $\nu$ is the critical exponent for the localization (correlation) length. From $x \approx y \approx 1/3$ for the case of compensation, we obtain $z \approx 3$ which agrees with the prediction of non-interacting theory. For the case of magnetic field, however, we have $x \approx y \approx 1/2$ leading to $z \approx 2$, which does not agree with the non-interacting theory, i.e., interaction must be more dominant. $z \approx 2$ has been obtained also for Si:B in a constant magnetic field.[10]

The fact that we have obtained different values of $z$ for a compensation and magnetic field strongly implies that they belong to different universality classes for the transition even though the values of $\mu$ are very similar. It is also possible that $\mu$ for the compensation and magnetic field are actually different within our experimental uncertainty. Further experiments with better precision are needed in order to explore such possibility.


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