Ann. Phys. (Leipzig) 8 (1999) Spec. Issue, SI-273 – SI-276

Critical exponent for localization length in neutron-transmutation-doped ^{70}Ge:Ga

M. Watanabe[1], K. M. Itoh[1,2], Y. Ootuka[3], and E. E. Haller[4,5]

[1]Dept. Applied Physics, Keio University and [2]PREST-JST, Yokohama 223-8522, Japan
[3]Institute of Physics, University of Tsukuba, Ibaraki 305-8571, Japan
[4]Lawrence Berkeley National Laboratory and [5]UC Berkeley, Berkeley, CA 94720, USA
michio@appi.keio.ac.jp

Received 28 July 1999, accepted 2 August 1999 by M. Schreiber

Abstract. We have determined the localization length and the dielectric susceptibility in uncompensated ^{70}Ge:Ga near the critical point for the metal-insulator transition by investigating the electrical resistivity at low temperatures (e.g., between 0.02 K and 0.2 K) and the magnetic-field dependence of the resistivity at $B < 0.4$ T in the context of the variable-range-hopping conduction. The critical exponents for these quantities are discussed.

Keywords: metal-insulator transition, semiconductor, variable-range-hopping conduction
PACS: 71.30.+h, 72.80.Cw

1 Introduction

The critical exponents for the metal-insulator transition (MIT) in doped semiconductors provide important information about the roles of disorder and electron-electron (e-e) interaction in disordered electronic systems [1]. Theoretically, the correlation length in the metallic phase and the localization length in the insulating phase diverge at the critical point with the same exponent ν. Instead of ν, experimentalists have determined the exponent μ defined by $\sigma(0) \propto (N/N_c - 1)^{\mu}$, where $\sigma(0)$ is the zero-temperature conductivity, N is the concentration, and N_c is the critical concentration. In many uncompensated semiconductors including our ^{70}Ge:Ga [2, 3], $\mu \approx 0.5$ has been found. This value violates Chayes *et al.*'s inequality [4] $\nu \geq 2/3$, which applies generally to disordered systems irrespective of the presence of e-e interaction, if one assumes the Wegner relation [5] $\mu = \nu$ derived for systems *without* e-e interaction.

In order to resolve this discrepancy, we determine ν (not μ) for uncompensated ^{70}Ge:Ga in the insulating side of the MIT.

2 Experiment

All of the ^{70}Ge:Ga samples were prepared by neutron-transmutation doping (NTD) of isotopically enriched ^{70}Ge single crystals. The NTD process assures a homogeneous dopant distribution which is a crucial condition for experimental studies of the MIT [2,

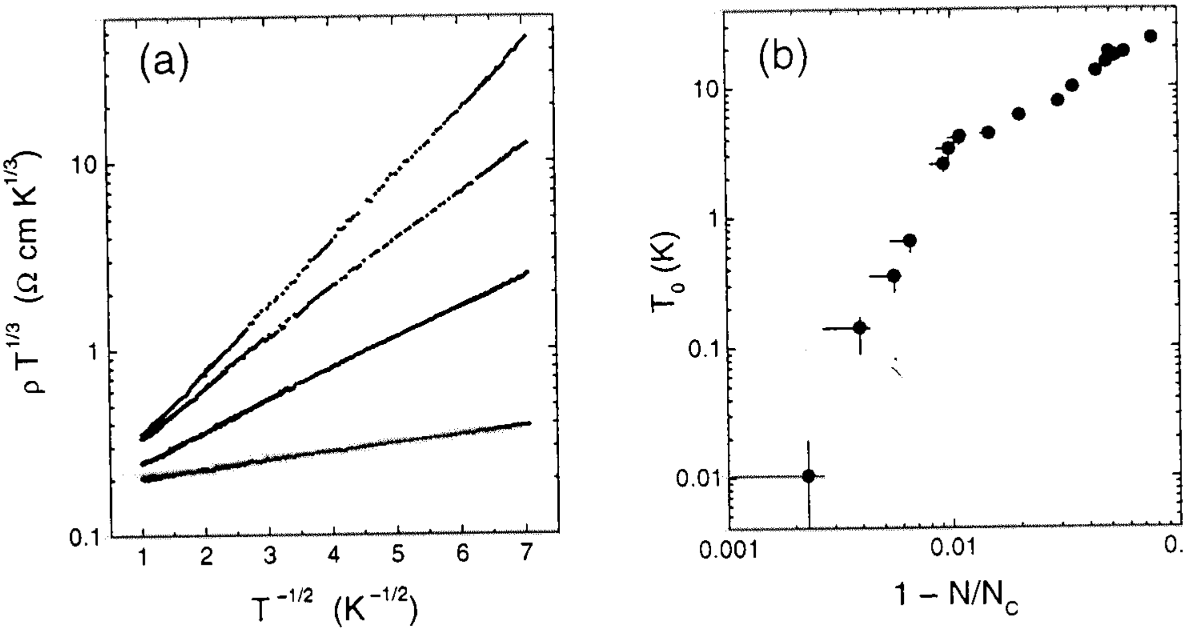

Fig. 1 (a) Resistivity ρ multiplied by $T^{1/3}$ vs $T^{-1/2}$. From top to bottom in units of 10^{17} cm^{-3}, the concentrations are 1.848, 1.850, 1.853, 1.856, respectively. (b) Parameter T_0 evaluated by the fit of $\rho(T) \propto T^{-1/3} \exp[(T_0/T)^{1/2}]$ vs $1 - N/N_c$.

3]. Details of the sample preparation and characterization including the resistivity down to 0.02 K are described elsewhere [3].

In this study, we determined the electrical resistivity of nine samples in weak magnetic fields (< 0.4 T) applied in the direction perpendicular to the current flow, and at low temperatures between 0.05 K and 0.5 K using a ^{3}He-^{4}He dilution refrigerator.

3 Results and discussion

The electrical conduction of the insulating samples is described by the variable-range hopping (VRH) at low temperatures. The resistivity $\rho(T)$ is written as $\rho(T) = \rho_0 \exp[(T_0/T)^p]$, where $p = 1/2$ for the excitation within the Coulomb pseudo gap, and $p = 1/4$ for a constant density of sates around the Fermi level [6]. In our earlier work [3], we reported that $1/p = 2$ for $N < 0.991N_c$ ($N_c = 1.860 \times 10^{17}$ cm^{-3}) and that $1/p$ increases rapidly as N approaches N_c from $0.991N_c$ and becomes much larger than 4 if one neglects the temperature variation of ρ_0, which gives a significant temperature dependence of ρ at $T \geq T_0$, i.e., near N_c. Theoretically, $\rho_0 \propto T^{-r}$ is believed, but the value of r has not been derived yet. In order to analyze the data in $0.991N_c < N < N_c$ in the context of the VRH conduction, we assume $r = 1/3$ for ^{70}Ge:Ga based on an experimental result that the conductivity $\sigma(T)$ of ^{70}Ge:Ga in the vicinity of N_c ($|N/N_c - 1| < 0.003$) is expressed as $\sigma(T) = a + bT^q$ with $q = 1/3$ [3]. Figure. 1(a) shows that $\rho(T)$ is described well with $p = 1/2$ also in $0.991N_c < N < N_c$. Employing $p = 1/2$ and $r = 1/3$, we evaluate T_0, which is shown in Fig. 1(b). According to the theory [6], T_0 is given by

$$k_B T_0 = \beta e^2 / 4\pi\epsilon_0\, \epsilon(N)\, \xi(N) \tag{1}$$

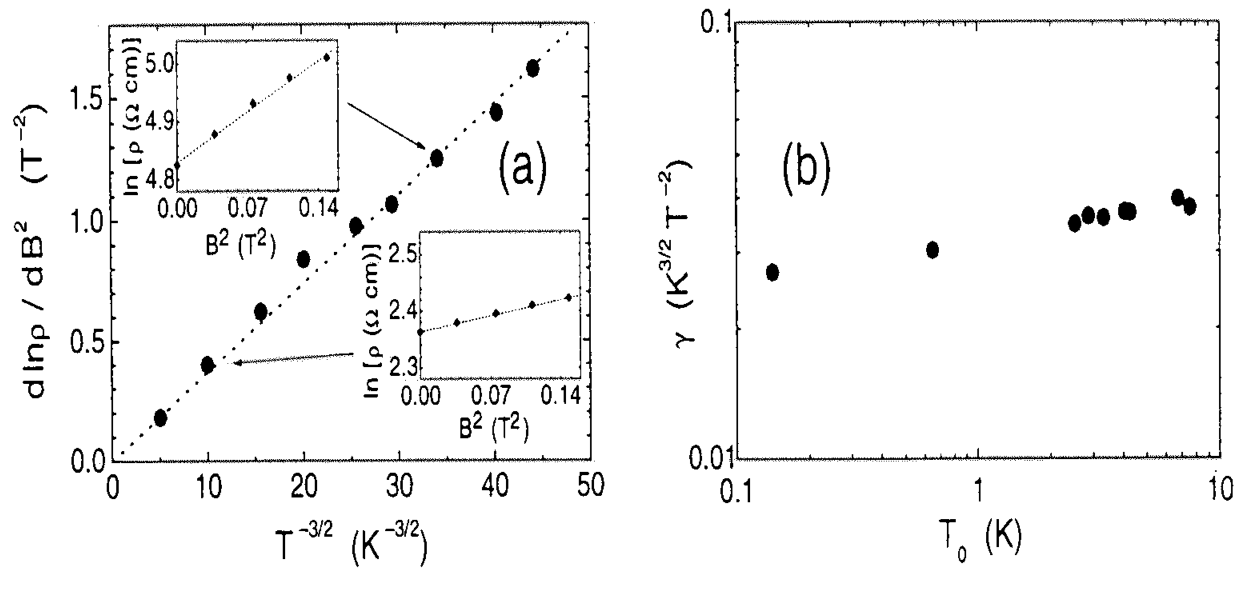

Fig. 2 (a) Slope $d\ln\rho/dB^2$ vs $T^{-3/2}$ for the sample with $N = 1.840 \times 10^{17}$ cm^{-3}. Insets are the plots of $\ln\rho$ vs B^2 at $T = 0.095$ K (upper) and 0.215 K (lower). (b) Coefficient γ defined by Eq. (3) vs T_0.

in SI units, where $\beta = 2.8$ is a numerical factor, $\epsilon(N)$ is the dielectric constant, and $\xi(N)$ is the localization length.

Our next step is to separate T_0 into ϵ and ξ. The theory predicts

$$\ln[\rho(B,T)/\rho(0,T)] = t\,(\xi/\lambda)^4\,(T_0/T)^{3/2} \qquad (2)$$

for $\xi/\lambda \ll 1$. Here, $\lambda \equiv \sqrt{\hbar/eB}$ is the magnetic length and $t = 0.0015$ is a numerical factor. The functional relationship of Eq. (2) is confirmed in the present system as shown in Fig. 2(a). From Eq. (2),

$$\gamma \equiv d^2 \ln\rho/dT^{-3/2}\,dB^2 = t\,(e/\hbar)^2\,\xi^4\,T_0^{3/2}\,, \qquad (3)$$

so that $\xi = t^{-1/4}\,(\hbar/e)^{1/2}\,\gamma^{1/4}\,T_0^{-3/8}$. We have determined γ for nine samples. [See Fig. 2(b).] We show ξ and $\chi = \epsilon - \epsilon_h$ evaluated based on Eqs. (1) and (2) in Fig. 3. Here, ϵ_h is the dielectric constant of the host Ge, and hence, χ is the dielectric susceptibility of the Ga acceptors. We should note that both ξ and χ are sufficiently larger than the Bohr radius (8 nm for Ge) and $\epsilon_h = 16$, respectively. According to the theory of the MIT, both ξ and χ diverge at N_c as $\xi(N) \propto (1 - N/N_c)^{-\nu}$ and $\chi(N) \propto (N_c/N - 1)^{-\zeta}$, respectively. We find, however, both ξ and χ do not show such simple dependence on N in the range shown in Fig. 3, and there is apparently a kink at $N \approx 0.99N_c$. In both sides of the kink, the concentration dependence of ξ and χ are expressed well by the scaling formula as shown in Fig. 3. Theoretically, the quantities should show the critical behavior when N is very close to N_c. So $\nu = 1.2 \pm 0.3$ and $\zeta = 2.3 \pm 0.6$ may be concluded from the data in $0.99 < N/N_c$. However, the other region ($0.9 < N/N_c < 0.99$), where $\nu = 0.33 \pm 0.03$ and $\zeta = 0.62 \pm 0.05$ are obtained, is also very close to N_c in a conventional experimental sense. Concerning Chayes *et al.*'s inequality [4]

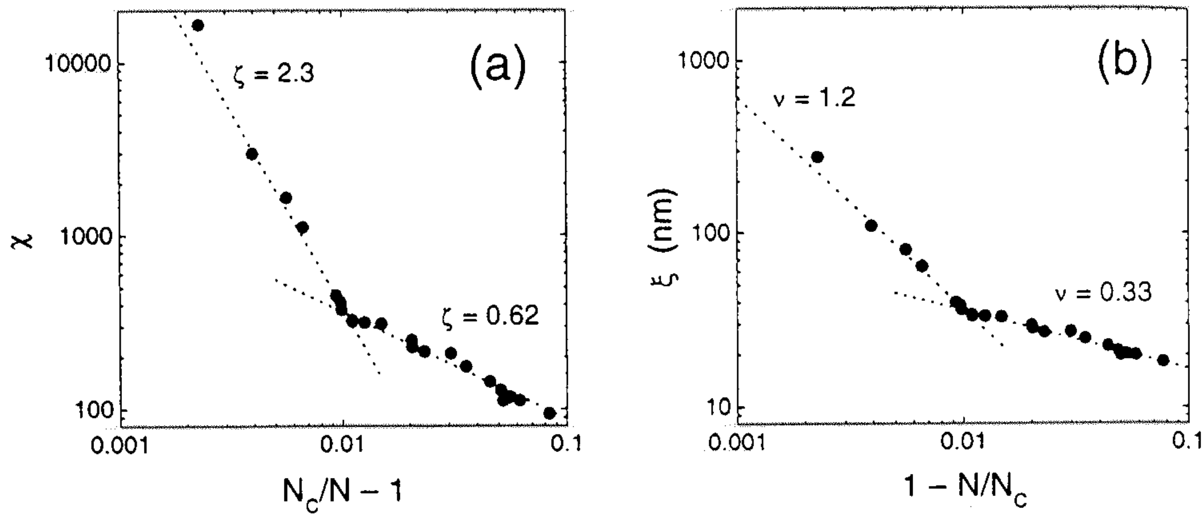

Fig. 3 Concentration dependence of (a) the dielectric susceptibility and (b) the localization length. The dotted lines represent the best fits.

$\nu \geq 2/3$, it holds only in the former region. It is interesting to point out that the relation $\zeta/\nu \approx 2$ holds in the both regions.

4 Conclusion

We have determined the behavior of both the localization length and the dielectric susceptibility in ^{70}Ge:Ga in the vicinity of N_c. The simple critical behavior is observed within only 1% of N_c. In this concentration range, Chayes *et al.*'s inequality [4] $\nu \geq 2/3$ is satisfied.

Most of the low-temperature measurements were carried out at the Cryogenic Center, the University of Tokyo, Japan. One of us (M. W.) is a (post-doctoral) Research Fellow of the Japan Society for the Promotion of Science (JSPS). The work at Keio was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture, Japan. The work at Berkeley was supported in part by the Director, Office of Energy Research, Office of Basic Energy Science, Materials Sciences Division of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098 and in part by U. S. NSF Grant No. DMR-97 32707.

References

[1] For a review, see D. Belitz and T. R. Kirkpatrick, Rev. Mod. Phys. **66** (1994) 261
[2] K. M. Itoh et al., Phys. Rev. Lett **77** (1996) 4058
[3] M. Watanabe, Y. Ootuka, K. M. Itoh, and E. E. Haller, Phys. Rev. B **58** (1998) 9851
[4] J. Chayes, L. Chayes, D. S. Fisher, and T. Spencer, Phys. Rev. Lett. **57** (1986) 2999
[5] F. J. Wegner, Z. Phys. B **25** (1976) 327; *ibid.* **35** (1979) 207
[6] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors*, Springer-Verlag, Berlin 1984