Influence of the Disorder in Doped Germanium Changed by Compensation on the Critical Indices of the Metal-Insulator Transition

© *Rolf Rentzsch, A.N. Ionov*, Ch. Reich, V. Ginodman**, I. Shlimak**, P. Fozooni***, M.J. Lea****

Freie Universität Berlin, FB Physik, WE I, Institut für Ex-physik,
14195 Berlin, Germany
* A.F. Ioffe Physico-technical institute of Russian Academy of Sciences,
194021 St.Petersburg, Russia
** The Resnick and Pearl Inst. Bar-Ilan University,
Dept. of Physics, Ramat-Gan, Israel
*** Department of Physics, Royal Holloway University of London,
Egham, Surrey, UK
E-mail: rentzsch@physik.fu-berlin.de

We present a critical review of the present status of the critical exponent puzzle of the metal-insulator transition of doped semiconductors with the emphasis on the role of mesos- and macroscopically inhomogeneity caused by the disorder of intended or unintended acceptors and donors in the crystals. By using both the isotopic engineering and the neutron transmutation doping (NTD) of Germanium we found for low compensations (at $K = 1.4$ and 12%) that the critical exponents of the localization length and the dielectric constant are nearly $\nu = 1/2$ and $\zeta = 1$, which double for medium compensations (at $K = 38$ and 54%) to $\nu = 1$ and $\zeta = 2$, respectively.

Till now there is an intensive debate in the literature whether the Metal-Insulator Transition (MIT) is a phase transition of first or second order and what are the experimental conditions to obtain it at finite temperatures and in real (disordered) systesm [1,2]. If the MIT is as second order phase transition a further challenge is the solution of the so called puzzle of the critical index, μ for the scaling behaviour of the metallic conductivity near the MIT, i.e. just above the critical impurity concentration N_c and as small compensation, K [2–14]. In particular, in several uncompensated material (Si:P [2–4], Si:As [5,6], Ge:As [7,8]), some experimental groups obtained $\mu \approx 1/2$, other $\mu \geqslant 1$ (Si:P [13], Ge:As and Ge:Ga [14]), which also has been found in different compensated material [9–12]. On the other hand the value of $\mu \approx 1/2$ is significantly smaller than $\mu = 1 - 1.3$ predicted theoretically for an Anderson transition driven only by disorder [15–20] and also greater than Chayes et al. [21] inequality $\mu > 2/3$ for a MIT due to both disorder and electron-electron interaction.

The main uncertainty in all previous experimental work is whether the impurities, for instance, the donors at *n*-type conductivity during doping are distributed macroscopically homogeneous or not and whether during any chemical doping an unintended disorder via compensation by (background) acceptors or defects is present or not. The disorder in doped semiconductors arises mainly from the intended or unintended compensation K which is, for *n*-type material, $K = N_a/N_d$, as well as from correlated incorporation of donors and acceptors from melt grown crystals and macroscopic inhomogeneity in the impurity distribution. To avoid these uncertainties we have prepared four sets of germanium samples which were both isotopically engineered and neutron-transmutation doped. The crystals have in this case a well controlled disorder via the compensation by the isotopic enrichment of ^{74}Ge ($K = 0.014$, 0.12, 0.38 and 0.54 of *n*-type conductivity) and of a mesoscopically as well as macroscopically homogeneous distribution of the impurities with N near N_c. In the case of low compensations we got smples on both sides of the MIT.

1. Sample Preparation

Isotopically engineered bulk Ge-crystals were grown from pure ^{74}Ge, enriched up to 94%, or by a mixture of ^{74}Ge with Ge of natural isotopic content. The isotopes ^{74}Ge and ^{70}Ge transmute after irradiation with thermal neutrons to ^{75}As-donors and ^{71}Ge-acceptors. The four series of *n*-type Ge with different isotopic abundance (in %) and different K after NTD are shown in the table. The values of K are proportional to the product of the isotopic abundance and the thermal neutron cross-sections of all isotopes producing impurities, $K \cong N_{\mathrm{Ga}}/N_{\mathrm{As}}$ whereas the impurity concentration is proportional to the irradiation dose.

Isotopic abundance of the four series of NTD–Ge after mass-spectroscopic analysis, compensation degree, conduction type and critical impurity concentration (see text)

Isotope	^{70}Ge	^{72}Ge	^{73}Ge	^{74}Ge	^{75}Ge	K (%)	Type	N_c (cm^{-3})
Series 1	0.2	0.7	3.2	93.8	2.1	1.4	n	$3.5\cdot10^{17}$
Series 2	1.7	2.4	1.0	93.9	1.0	12	n	$4.0\cdot10^{17}$
Series 3	5.0	6.5	2.4	82.8	3.3	38	n	$7.1\cdot10^{17}$
Series 4	8.1	11.2	ca.4	72.3	ca.4	54	n	$1.5\cdot10^{18}$

2. Results and Discussion

All samples with $N < N_c$ at $T < 1\,\mathrm{K}$ exhibited a temperature dependence of resistance according to

$$\rho(T) = \rho_0 \exp(T_0/T)^{1/2}. \quad (1)$$

Eq. (1) corresponds to variable-range-hopping conductivity with a Coulomb gap at the Fermi level [22] and with

$$T_0 = 2.8e^2/ak, \quad (2)$$

where a is the localization length and k is the dielectric constant. Fig. 1 and 2 show typical dependencies of the resistivity on temperature for low ($K = 1.4$ and 12%) and medium ($K = 38\%$) disorder. One can see that Eq. 1 is fulfilled at low temperatures for all impurity concentrations where variable rangle hopping is obtained. According to the scaling theory of the MIT both a and k diverge at the MIT with power laws [2,15]

$$a = C_1 a_B \left|(N/N_c) - 1\right|^{-\nu}, \quad (3a)$$

$$k = C_2 k_0 \left|(N/N_c) - 1\right|^{-\zeta}, \quad (3b)$$

with $\zeta/\nu = 2$, In Eq. (3a, b) $a_B \cong 4\,\mathrm{nm}$ is the Bohr radius of the Arsenic donor, $k_0 \cong 15.2$ is the static dielectric constant and C_1 and C_2 are constants. As the result, the slope of the curves in figs. 1 and 2, i. e. T_0 must decrease with a power $p = \zeta + \nu$ approaching, $T_0 = 0$ at $N \cong N_c$. Fig. 3 shows T_0 as function of $N_d = n/(1 - K)$ for different K, where n is the free carrier concentration. The linear extrapolation

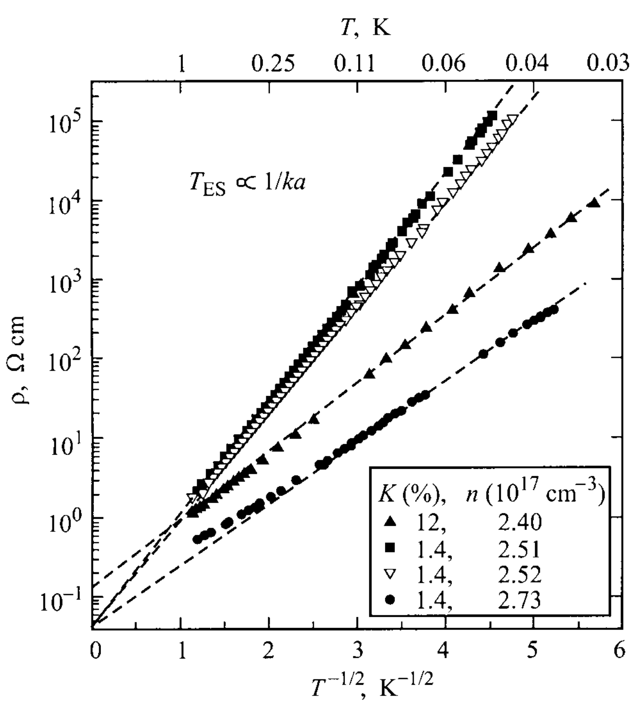

Figure 1. Temperature dependence of resistivity at low compensation, $K = 0.014$, 0.12.

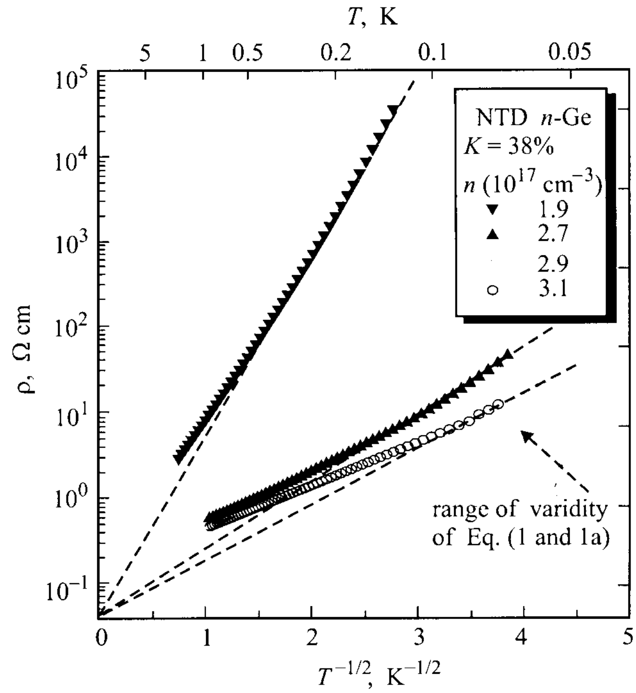

Figure 2. Temperature dependence of resistivity at medium compensation, $K = 0.38$.

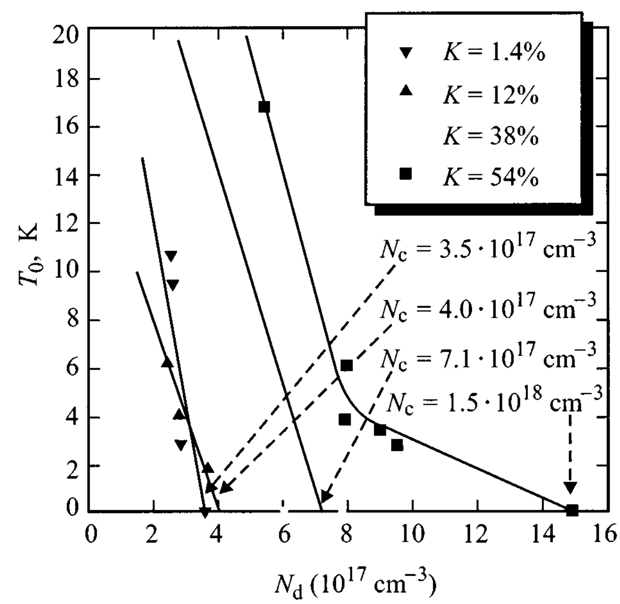

Figure 3. Determination of N_c at $T_0 \to 0$.

of the curves in Fig. 3. gives us the value of N_c which rapidly increases with K. The scaling relation of T_0 versus $\left|(N/N_c) - 1\right|$ at different K are shown in Fig. 4. At low disorder ($K = 1.4$ and 12%) the power p is close to the value of 3/2 and doubles at medium disorder ($K = 38$ and 54%) to a value of about 3. Taking into account $\zeta/\nu = 2$, one obtains $\nu \cong 1/2$ and 1, and $\zeta \cong 1$ and 2, at low and medium K respectively. The values of $a(K)$

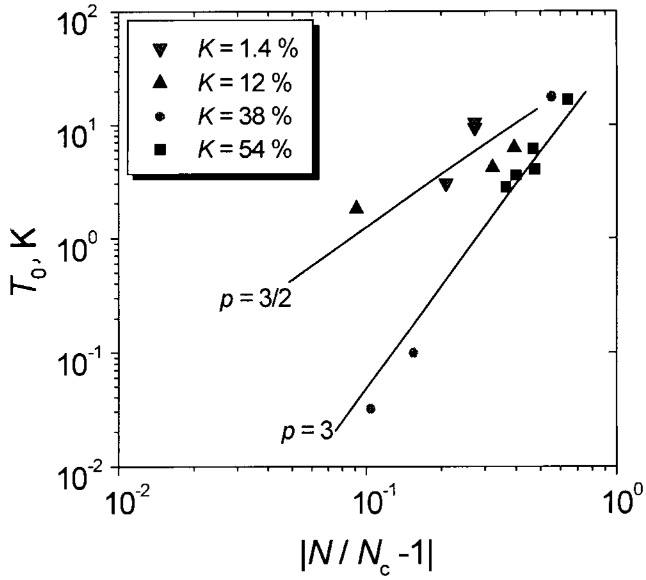

Figure 4. T_0 vs. $|(N/N_c) - 1|$ at different K.

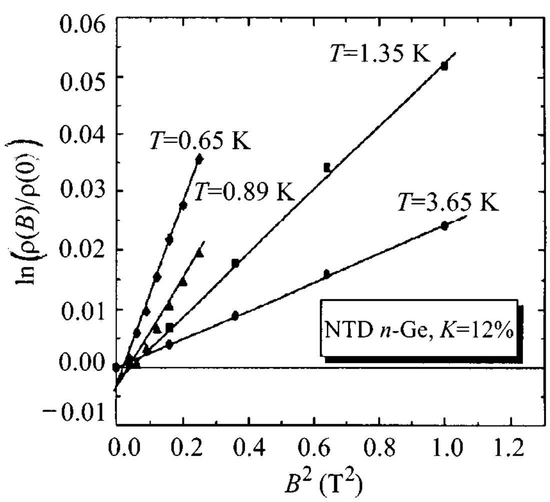

Figure 5. Typical dependence of the hopping megnetoresistance of B^2.

can be independently determined from measurements of the positive magnetoresistance. In all samples at $T < 0.5$ and at $B = 0.5 - 2\,\mathrm{T}$ the positive magnetoresistance was found [23] to fulfil the theory in [22]:

$$\ln\bigl(\rho(B)/\rho(0)\bigr) = +(e^2/\alpha h^2)\, a^4 (B^2/T^{3/2})$$

$$= +B^2/B_0(a,T)^2, \qquad (4)$$

where $\alpha \cong 660$ is a numerical coefficient. Fig. 5 shows the typical dependence of the hopping magnetoresistance, which confirms the quadratic dependence on a low magnetic field appearing in all samples. The analysis of the temperature dependence according to Eq. (4) is shown in Fig. 6 indicating the range of valid at about $T = 0.2 - 1.5\,\mathrm{K}$ for this sample. From Eq. (4) we calculated $a(K)$ of all samples. By a combination of $T_0 \propto (ak)^{-1}$ of the temperature dependence of resistivity without magnetic field by using Eqs. (1 and 2) we also estimated $k(K)$. Both dependencies as functions of $|(N/N_c) - 1|$ are shown in Fig. 7 and 8, confirming the above estimates for the slopes $\nu \cong 1/2$ and 1, and $\zeta \cong 1$ and 2 for the scaling behavior of a and k, at low and medium K respectively.

From the experimental point of view the puzzle of the critical indices has been solved by well controlled disorder via the compensation degree and homogeneously doping by the combination of artificially changed isotopic content (isotopic engineering) and NTD which give rise to mesoscopic and macroscopic homogeneity. The determination of N_c from

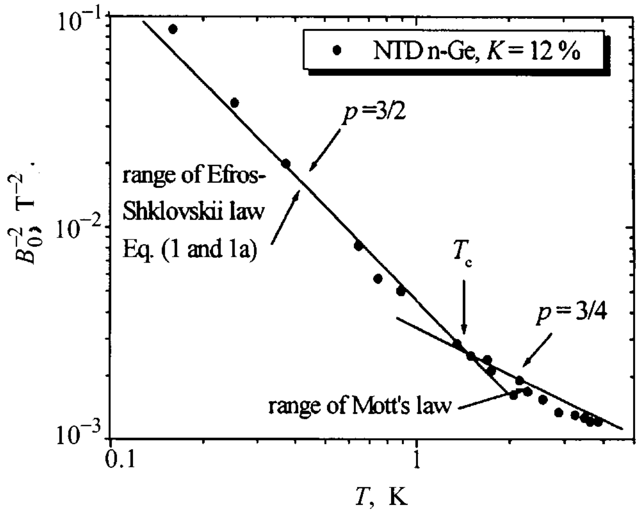

Figure 6. Temperature dependence of the positive hopping magnetoresistance. The upper straight line shows the range of validity of Eq. (4).

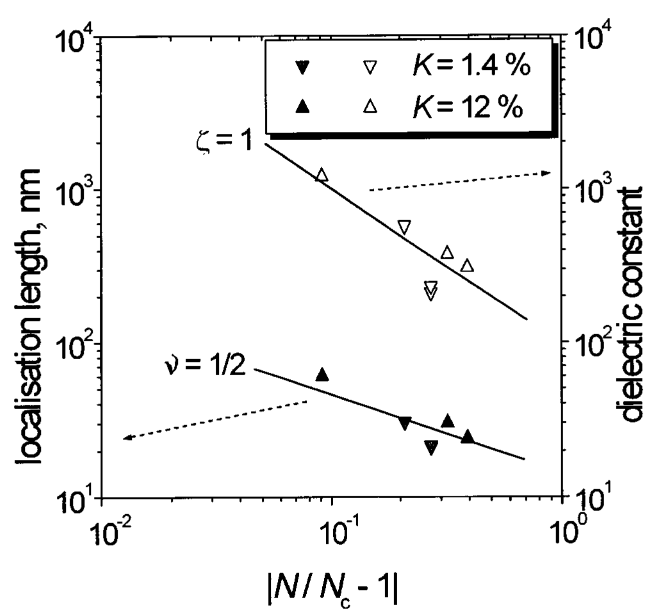

Figure 7. a and k vs. $|(N/N_c) - 1|$ at low K.

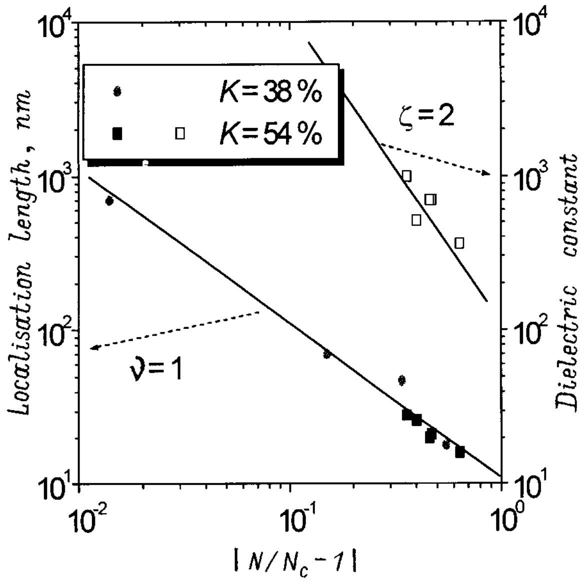

Figure 8. a and k vs. $|(N/N_c) - 1|$ at medium K.

the extrapolation of $T_0(N) \to 0$ at Efros–Shklovskii variable range hopping agrees well with N_c from the metallic side.

For low disorder (at $K = 1.4$ and 12%) that the critical exponents of the localization length and the dielectric constant are nearly $\nu = 1/2$ and $\zeta = 1$, respectively. The value of $\nu = \mu$ at low disorder agree well with early Si:P [2] and Ge:As [6] as well as with recent results on uncompensated NTD Ge:Ga [8] results. At medium desorder (at $K = 38$ and 54%) the critical indices double to $\nu = 1$ and $\zeta = 2$, respectively. These results are in accordance with results on different chemically doped material Si:P [13] and Ge:As/Ga [14] where the crystal homogeneity could be less. Additionally some disorder by unintended compensation or correlated impurity distribution is possible [11]. However, the puzzle of the critical indices between theory and experiment remains unsolved because to our knowledge till now there is no unique theory taking into accounts both disorder and strong electron-electron interaction.

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