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METAL-INSULATOR TRANSITION IN NEUTRON-TRANSMUTATION DOPED n-TYPE GERMANIUM

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It is shown that the homogeneous introduction of a compensating impurity up to $K = 9\%$ does not affect the absolute value of the critical index m compared to the uncompensated case.

For three-dimensional disordered systems the scaling theory of localization predicts that the electric conductivity for $T \to 0$ should vary continuously as one transfers from an atomic or microscopic to a macroscopic scale length - in other words, the metal-insulator transition (MIT) should occur smoothly rather than in a jump as was believed earlier [1]. Also, in the region of the MIT the conductivity should vary as

$$\sigma(0) = C\frac{e^2}{\hbar a}(n/n_c - 1)^\nu \tag{1}$$

Here a is the wave function localization radius far from the transition, the constant $C < 1$, n_c is the critical impurity concentration corresponding to the MIT, and ν is the critical index which is unity if spin scattering and electron-electron interactions are not included.

Experiments have shown that the metal-insulator transition occurs continuously and in accordance with (1) in all the disordered systems studied thus far. Note that for metallic alloys $\nu = 1$, whereas in uncompensated crystalline semiconductors, such as Ge:As, Si:P, Ge:Sb, the transition occurs more steeply, so that $\nu = 0.5$.

The value $\nu = 0.5$ is predicted in the model of Hikami [2] which included spin scattering from localized magnetic moments. In crystalline semiconductors this scattering should grow with increasing compensation when the enhanced potential fluctuations in the C-and V-bands result in an increase of the probability for localized magnetic moments to appear [3]. Hence, if in an uncompensated semiconductor $\nu = 0.5$ due to the Hikami's mechanism, then in a compensated sample this value of the index should not change.

As follows from the investigation of Thomas et.al. [4], however, ν grows rapidly with compensation. The experiments were carried out on single crystal germanium doped in a Sb and B melt. The degree of compensation was estimated from the temperature dependence of mobility. It was found that for a compensation $K = 5\%$, $\nu = 0.7$, while for $K = 20\%$ the index is already close to 1.

Believing the observation of a strong dependence of the critical index on compensation K to be extremely important, we decided to check it on germanium samples with precisely known compensation and a more homogeneous impurity distribution compared to that used by Thomas et.al. [4]. We used for this purpose germanium samples prepared by neutron-transmutation-doping (NTD) [5]. Germanium was chosen also because it is more suited to NTD than Si and GaAs. It also has the advantage that one can introduce both donors, $^{74}Ge \rightarrow ^{75}As$, $^{76}Ge \rightarrow ^{77}Se$, and an acceptor impurity $^{70}Ge \rightarrow ^{71}Ga$, which enables both n-and p-type crystals to be produced by varying the isotopic composition. The slow neutron absorption cross sections of these isotopes are such that the impurities in samples of a typical size are homogeneously distributed over the bulk. Also by controlling the exposure to the neutron flux one can obtain a broad variety of samples with different concentrations of uncompensated carries, including those that correspond to metallic conduction, and (most important) with the same values of compensation (a problem that practically cannot be solved using conventional melt doping).

The heat treatment employed in NTD and needed for annealing the radiation defects is comparatively shot (usually not in excess of 24 hours) and is carried out at a moderate temperature ($T_c \sim 460°C$), thus preventing any noticeable correlation of the impurities. This is another essential difference between the NTD and melt doping techniques.

In our case the isotopic composition of germanium was such that after NTD the samples became n-type with compensation $K = 9\%$ [6] (the thermal neutron absorption cross sections for ^{74}Ge and ^{70}Ga were taken from Ionov et.al. [7]).

The inhomogeneity in the resistivity determined by the spreading method over a sample length of 10 mm at 293K did not exceed 1%, which was at the threshold of sensitivity of ASR-100 equipment.

The Hall concentration of charge carriers was measured in a field $H = 2.0$ kOe under the assumption that over the concentration range studied, $1.086 < n/n_c < 1.94$, the Hall factor does not differ from unity.

In the temperature range 4.2-0.3 K the conductivity of all samples was measured in the dc mode with a Keithley Nanovoltmeter Model 181 in a ^3He refrigerator [8]. Samples with concentration close to n_c, whose conductivity varies stronger with temperature, were studied down to 0.02 K in a $^3He - ^4He$ dilution refrigerator using a resistance bridge at 25 Hz [10].

An analysis of the low-temperature conductivity measurements of all samples showed that samples with electron concentration $n < 3.2 \times 10^{17}$ cm^{-3} were in the insulating state while those 4 with $n > 3.6 \times 10^{17}$ cm^{-3} were already metallic. One can thus assume that in our case $n_c = (3.4 \pm 0.2) \times 10^{17}$ cm^{-3}.

Fig.1 presents on a log scale the dependence of σ on $(n/n_c - 1)$ for metallic samples where $\sigma(0)$ was found by extrapolating to $T = 0$ the $\sigma(T)$ dependence. As follows from the figure, the conductivities extrapolated to $T = 0$ obey relation (1) with a critical index $\nu = 0.5$. Taking into account that the electron localization radius for an isolated As impurity in Ge is $a = 40Å$ [10], we come to the value $C = 0.09$, which turns out to be close to the theoretical prediction of $C = 0.1$ [12].

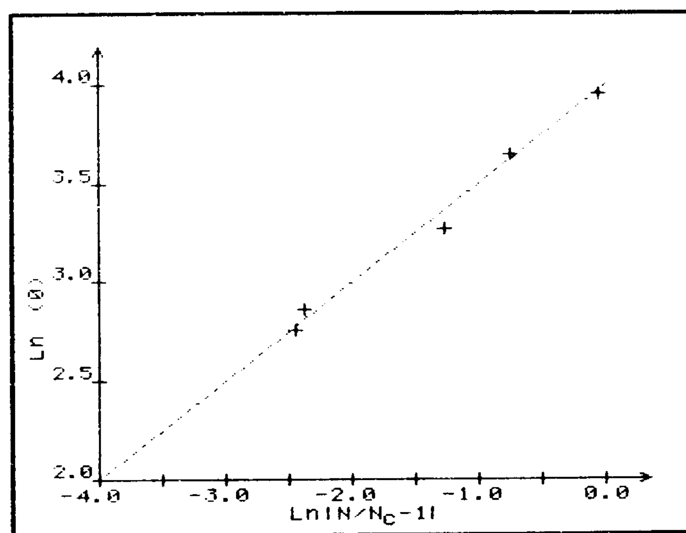

Fig.1. Plot of $\ln(\sigma(0))$ versus $\ln(n/n_c - 1)$ for NTD Ge enriched with the ^{74}Ge isotope

Thus, the homogeneous introduction of a compensating impurity up to $K =$ 9% does not affect the absolute value of the critical index compared with the uncompensated case where $\nu = 0.5$, in agreement with the model of Hikami [2].

The behaviour of the critical index with compensation revealed by us differs from the result obtained by Thomas et.al. [4]. This difference may be due to the fact that those authors [4] did not take into consideration a possible shift of the critical concentration n_c toward higher values with increasing compensation. Another cause could be that when doping in the melt, the donor and acceptor impurities are strongly correlated thus forming a kind of alloy in the germanium lattice which from the physical standpoint does not differ from metal alloys for which, as is well known, $\nu = 1$.

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