Peculiarities of the electric and magnetic properties of 6*H*-SiC⟨N⟩ on the insulator side of the metal-insulator transition

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The character of the low-temperature conductivity on the insulator side of the metal-insulator transition (MIT) in 6*H*-SiC⟨N⟩ is determined and the magnetic properties of the system are investigated by the ESR method. Anomalously far from the transition, the spin absorption is observed to decrease and there is a characteristic change in the spin relaxation mechanism.

1. The available experimental data in the region of the MIT in doped semiconducting materials have been accumulated primarily for the monoatomic semiconductors Si and Ge with fine impurities. In addition, the critical value of the parameter varied (concentration of the main impurity N, degree of compensation, pressure, magnetic field) was determined from the characteristic peculiarities of the low-temperature electrical properties on the insulator[1,2] or metallic[3] side of the transition. Recent measurements have shown that at superlow temperatures[3–6] these properties vary continuously near the MIT by analogy with the second-order phase transitions and can be described by the scaling theory of MIT. Information on magnetic properties in the region of MIT is even more sparse and has been almost entirely obtained for the system Si⟨P⟩.[7–9] On the insulator side of the transition the impurities here give a paramagnetic contribution to the susceptibility in accordance with the Curie law: $\chi \sim N/T$. As the transition is approached, the concentration and temperature dependence of χ weaken. As a result, the susceptibility as a function of concentration reaches a maximum near the critical value of the concentration N_c from the insulator side. The width of the ESR line of donors in Si,[10] Ge and InSb[11] has a characteristic minimum at the transition. This is related to the change in the mechanism of spin relaxation accompanying MIT, presumably due to the inclusion of the interaction with free carriers (of the so-called *s-d* interaction type) into the relaxation channel for $N \gtrsim N_c$.[7]

We report new data on the characteristics of some electric and magnetic properties with MIT in a system with significantly deeper impurities—a polytypical modification of silicon carbide 6*H*-SiC⟨N⟩, doped with a nitrogen donor impurity with ionization energy ~ 0.1 eV.

2. A series of specimens for measuring the conductivity, Hall's effect, and ESR was prepared from plates of 6*H*-SiC with a basal plane (0001), doped with nitrogen during the growth process using the procedure described in Ref. 12, and not specially compensated. The nitrogen concentration varied in the range $N = (0.17\text{–}5.4) \times 10^{19}$ cm^{-3}. The magnetic properties of the specimens were investigated with the help of

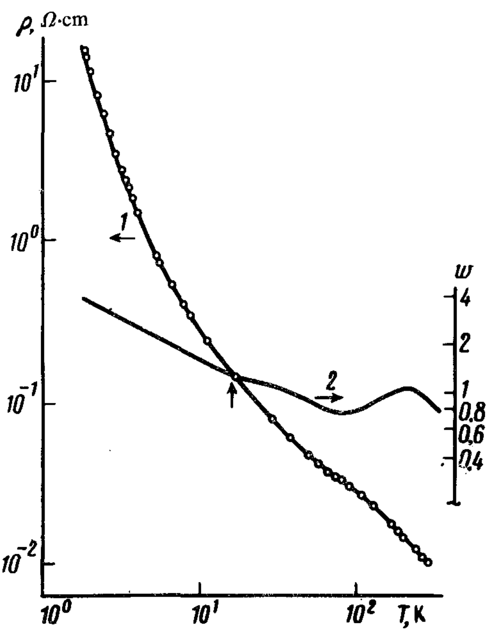

FIG. 1. Resistivity (1) and reduced activation energy (2) of a specimen with $N = 3.4\times10^{19}$ cm^{-3}.

ESR in the X region using the E-112 Varian spectrometer. The areas under the absorption curves, necessary for calculating the spin density N_s and susceptibility χ, were determined while recording the spectra of the specimen under study and of a control specimen with a standard spin density by double integration of the signal $d\chi''/dH$ with the help of a computer, combined with the spectrometer. There was no skin effect.

3. Figure 1 shows the typical temperature dependence of the specific resistance $\rho(T)$ of one of the specimens with a donor concentration equal to one-half N/C. An analysis based on the investigation of the reduced activation energy $w = -d\lg\rho/d\lg T$ (the method is described in detail in Refs. 2 and 6) showed that at sufficiently low temperatures $T \leqslant T_v$ (marked by the arrow in Fig. 1) $w \sim T^{-x}$ and

$$\rho(T) = \rho_0 \exp(T_0/T)^x, \tag{1}$$

where ρ_0 and T_0 are constants, and $x \simeq 0.5$.

The law (1) is characteristic for hopping conductivity with variable hopping length in the region of a Coulomb quasigap of the form $g(E) = g_0(E - E_F)^2$ in the density of localized states $g(E)$ in the vicinity of the Fermi level E_F.[13] In the region of weak localization the exponential law (1) at temperatures $T \gtrsim T_v$ transforms into a power law,

$$\rho(T) \sim T^{-m}, \tag{2}$$

where $0 < m < 1$.

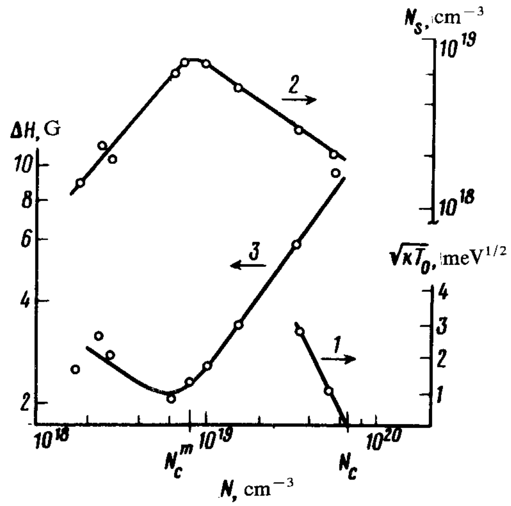

FIG. 2. The parameter $\sqrt{kT_0}$ (1), spin density (2), and ESR line width (3) on the insulator side of the MIT.

Such a transition from (1) to (2) was studied in the system Ge⟨As⟩ in Refs. 5 and 6, where it was attributed to the thermal "smearing" of the Coulomb gap. As in these works, in our case the parameters m, ρ_0, T_0, and T_v decrease as the MIT is approached, which is due to the "collapse" of the gap at the transition. For MIT the critical donor concentration N_c was found from the condition that the low-temperature activation energy vanish[2,5,6]: $\lim T_0(N) = 0$. The procedure for determining N_c is illustrated in Fig. 2. As is evident from this figure, $N_c = 6.6 \cdot 10^{19}$ cm^{-3}, which agrees well with Mott's criterion for MIT[1]: $N_c^{1/3} a \cong 0.25$, where the Bohr radius $a = 5$–7 Å.[14,15]

4. Figure 2 also shows the dependence of the spin density N_s on the level of doping, measured with the help of ESR absorption. It is evident that $N_s \simeq N$ up to values $N \simeq N_c$ 10^{19} cm^{-3}. At $N \gtrsim N_c^m$ the concentration of spins responsible for ESR absorption is observed to decrease. Thus in the region of MIT only ~3% of impurity electrons have a magnetic moment. We note that in contrast to Si⟨P⟩, in 6*H*-SiC⟨N⟩ the temperature dependence of the susceptibility $\chi \sim \int_0^\infty \chi'' dH$ is satisfactorily described by Curie's law and the behavior of $\chi(N)$ is analogous to $N_s(N)$ everywhere on the insulator side of the MIT. According to the existing point of view, the vanishing of spins on the insulator side of the MIT is a result of the formation of exchange-coupled pairs and complexes whose ground state is the spin singlet state. The concentration N_c is characteristic for exchange coupling in 6*H*-SiC⟨N⟩. We note that according to our electrical measurements it corresponds to the region of the transition from strong to weak localization.

The concentration dependence of the line width $\Delta H(N)$ correlated with $N_s(N)$: the line narrows slightly with an increase in the level of doping in the region of strong localization ($N \lesssim N_c^m$) and begins to broaden in the region of weak localization ($N \gtrsim N_c^m$) (Fig. 2), which reflects the acceleration of relaxation of the spin system. The well-known explanation of such acceleration near MIT due to exchange with free carriers is hardly possible in our case because in 6*H*-SiC⟨N⟩ the concentration N_c is displaced almost by an order of magnitude to the insulator side and at helium temperatures the fraction of free carriers is so small that they cannot be responsible for spin relaxation of localized electrons. For this reason, we conclude that a) in 6*H*-SiC⟨N⟩ for $N > N_c$ the rate of spin relaxation and exchange rapidly increase due to weakening of the localization of electronic states of the impurity band; b) the anomalous displacement of N_c toward the insulator occurs because the weakly localized states, in contrast to semiconductors with fine impurities, appear much farther away from the transition, i.e., they appear at much smaller ratios N/N_c.

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