Magnetic freeze-out and impurity band conduction in n-InSb

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Abstract

Non-ohmic conduction of n-InSb with different donor concentrations (N_d = 2 10^{14}‘1 10^{15} cm^{-3}) in perpendicular magnetic fields has been measured at low temperatures, in order to infer the impurity band mobility μ_i with the aid of the two-band analysis. The decrease of μ_i with increasing magnetic fields has been found to reflect exactly the shrinkage of donor wave functions due to magnetic field and the magnetic-field induced metal-insulator transition is an event in the impurity band. The temperature dependence of μ_i in moderate magnetic fields above the transition field B_c appears to obey the Mott variable-range hopping law as $\mu_i = \mu_0$ exp[-$(T_0/T)^x$] with x=1/4.

Key words: n-InSb, magnetic freeze-out, non-ohmic conduction, metal-insulator transition, variable-range hopping

1. Introduction

The effective Bohr radius of donors in n-InSb is very large (a_0 = 65 nm) on account of its small electronic effective mass ($m^* = 0.014m_0$). In the absence of a magnetic field, the donor wave functions even for a pure n-InSb attainable tend to overlap and the metallic impurity band is formed because the concentration of donors of $N_d \sim$ 2 10^{14} cm^{-3} at least is expected meaning the average distance between donors of ∼100 nm) [1]. Because of *softness* of the donor wave function to magnetic field in this material, the metal-insulator (M-I) transition can be induced in a moderate magnetic field ($\gamma = \hbar\omega_c/2R_y^* \sim 1$ at B = 0.13 T, where $\omega_c = eB/m*$) [2] and the ‘magnetic freeze-out’ shows up with increasing magnetic field [3] reflecting the shrinkage of the wave functions due to magnetic field [4]. The conspicuous non-ohmic behavior with the increase of electric field is observed in n-InSb at low temperatures, which was explained by Miyazawa-Ikoma as the transfer of carriers from the impurity band to the conduction band due to the impact ionization in high electric fields [5]. In this paper, we demonstrate the non-ohmic conduction of n-InSb with different carrier concentrations n_0 systematically in perpendicular magnetic fields at low temperatures, and discuss the temperature and magnetic-field dependence of the impurity band mobility extracted from the two-band analysis [5,6].

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2. Results and Discussion

Investigated samples in the present work are selected from the ones described in the ref. [1] so that the carrier concentration n_0 (= N_d - N_a) ranges from 8 10^{13} to 5 10^{14} cm^{-3} with nearly constant compensation ratio $K = N_a/N_d = 0.5 \sim 0.6$.

Typical characteristics of the non-linear electric-field effect under magnetic fields on rather high-purity sample C2-462a (n_0 = 1.3 10^{14} cm^{-3}) at liquid He temperatures are shown in Fig.1, which shows the resistivity ρ at various transverse magnetic fields as a function of electric field. A sharp decrease of ρ appears near between 0.1∼1.0 V/cm, depending on magnetic field and temperature, followed by the slow decrease characterized by independence of temperature. The effect of electric field on the Hall coefficient (which is not shown) is also striking. We have analyzed these data by

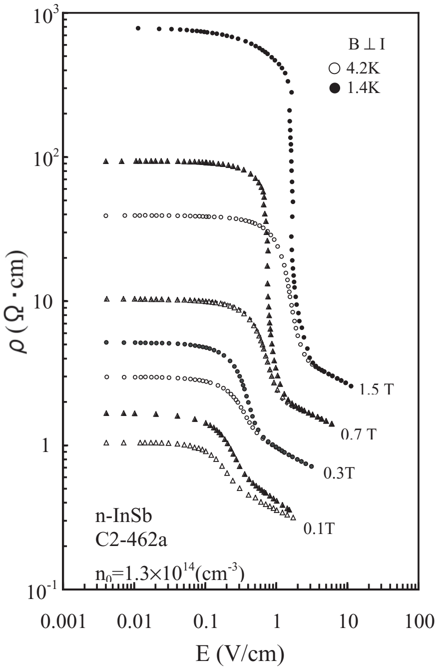

Fig. 1. Electric-field dependence of the resistivity under various transverse magnetic fields at 4.2 and 1.4 K for C2-462a.

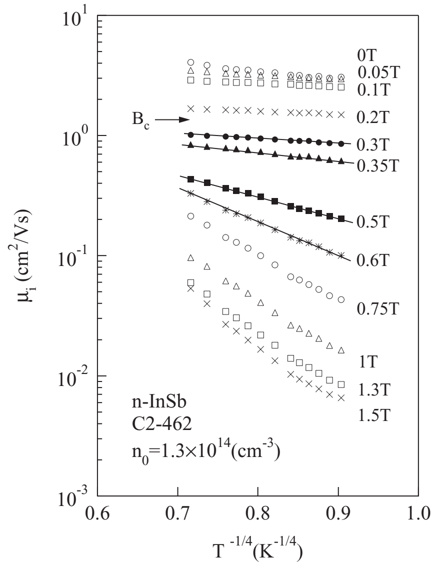

Fig. 2. Impurity band mobility μ_i in the ohmic region is plotted as a function of $T^{-1/4}$ under various magnetic fields for C2-462a.

the method proposed by Miyazawa-Ikoma [5], assuming the two-band model in the presence of a magnetic field, obtaining n_c/n_0 (n_c : the concentration in the conduction band) and the mobility of the donor band μ_i as a function of electric field under various magnetic fields.

According to the Yafet-Keyes-Adams (YKA) theory [4], the wave function in the perpendicular direction is the form: $\Psi(r) \sim \exp(-r^2/4a_\perp^2)$ where $a_\perp$ is the radius of a donor wave function in direction perpendicular to the magnetic field [4]. Assuming μ_i in the ohmic region $|\Psi(r_s)|^2$, μ_i tends to be proportional to $\exp(-r_s^2/2a_\perp^2)$ where r_s gives one-half the average distance between donors [5,6]. The variation of the impurity band mobility $\mu_i(B)$ (at 1.4 K) obtained for each sample with increasing magnetic field has been found to follow exp $(-r_s^2/2a_\perp^2)$ definitely below the critical magnetic field B_c of the magnetic-field induced M-I transition [6]. The magnetic-field induced M-I transition in n-InSb has been the subject of much interest. Shayegan et al. [7] and Choi et al.[8] explained that the M-I transition occurs in the impurity band, based on the magneto-transport data under high magnetic fields [7]. $\mu_i(B)$ obtained is almost independent of temperature below B_c and the ratio $\mu_i(4.2\text{K})/\mu_i(1.4\text{K})$ starts to increase just around B_c with increasing field [6], which is surely an event in the impurity band. Our result provides another evidence for the occurrence of the M-I transition in the impurity band.

The temperature dependence of μ_i under various magnetic fields is plotted in Fig. 2 as log μ_i versus $T^{-1/4}$ for the sample mentioned ($B_c \sim 0.24$ T). In moderate magnetic fields above B_c, μ_i appears to follow $\mu_i = \mu_0\exp[-(T_0/T)^x]$ with x=1/4 indicating the variable-range hopping (VRH) between localized states in three dimension. Here, $T_0 = 16/[kN(E_F)\xi^3]$[9] where $N(E_F)$ is the density of states at the Fermi level, ξ the localization length. T_0 steeply decreases from 1000 K for B = 0.6 T to 5.2 K for B=0.35 T with decreasing magnetic field, reflecting the rapid growth of ξ as the system approaches B_c from the insulating side.

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