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NON-ACTIVATED CONDUCTIVITY OF HOT ELECTRONS IN LOCALIZATION REGIME*

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Temperature (T) dependence of conductivity (σ) was studied in semi--insulating GaAs as a function of the magnetic field (B) for 1.8 K< T < 40 K for high electric fields. An infrared illumination of a sample and application of an electric field caused a non-equilibrium distribution of electrons in the conduction band. An increase in B caused a localization transition which manifested itself by a gradual disappearance of the impact ionization of shallow bound states. The transition was connected with a change from a non-activated to an activated conductivity only if T > 4 K, otherwise σ showed only a non-activated character. It is proposed that for T < 4 K the electron distribution function is mostly determined by optical and electric field excitations, which results in a non-activated conductivity. For T > 4 K thermal excitations become dominant which leads to an activated character of σ.

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1. Introduction

Magnetic field induced localization is often observed as a change from a non-activated to an activated conductivity in semiconductors which are degenerate at low temperatures at zero magnetic field [1]. In a typical experimental procedure much care is taken to maintain a sample as close to the thermodynamic equilibrium as possible. This implies performing measurements at low currents and small electric fields. The present paper describes a localization transition in a system in which all these typical conditions are violated. The investigated system was driven far from the equilibrium by an external illumination and a high electric field. In such conditions a non-activated conductivity in the localization regime was observed. It is proposed that this unusual behaviour reflects a dominant influence of the illumination and the electric field on a non-equilibrium distribution function of electrons.

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The experiments were performed on samples of an undoped semi-insulating (SI) GaAs with the EL2 as the dominant deep level. A presence of shallow donors and shallow acceptors as well as deep centres other than the EL2 was confirmed by luminescence [2] and thermally stimulated current [3] measurements. Thus it was shown that the investigated material was a doped compensated semiconductor in which a spatially random distribution of localised charges was a source of fluctuations of the electrostatic potential. In this material, at liquid helium temperatures the Fermi level is pinned to the EL2 which results in a total lack of free carriers. Low-temperature conductivity measurements were enabled by a permanent illumination of a sample with an infrared light which transferred electrons from deep levels to the conduction band. Some of excited electrons were captured by shallow donors which was directly shown by a magneto-optical experiment [4]. A long lifetime of optically excited electrons in the conduction band and on shallow donors is caused by a configurational barrier for capturing an electron on the EL2 [5] and a spatial separation of an excited electron from its parental centre [6]. A sufficiently high electric field caused impact ionization of electrons bound on shallow donors and in wells of the fluctuating potential at the bottom of the conduction band. This resulted in an abrupt increase in the current which caused a kink-like shape of current-voltage characteristics. Details of the experimental setup are described elsewhere [6].

2. Results and discussion

Figure 1 shows current–voltage characteristics measured for $B = 0$ at different temperatures at a constant illumination intensity and Fig. 2 shows the temperature dependence of the conductivity as a function of the magnetic field. It should be underlined that Fig. 2 refers to a conductivity of free hot electrons, since the chosen electric field (equal to 53.3 V/cm) was greater than that causing the avalanche breakdown at any applied magnetic field.

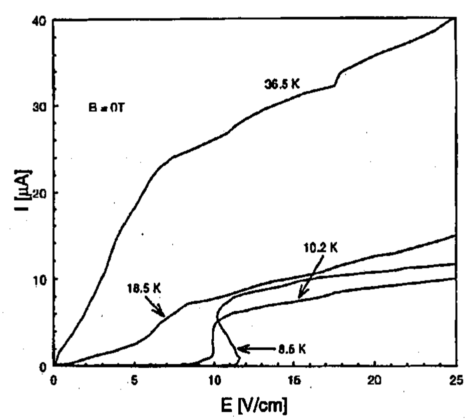

Fig. 1. Current–voltage characteristics of an SI GaAs sample measured at the indicated temperatures.

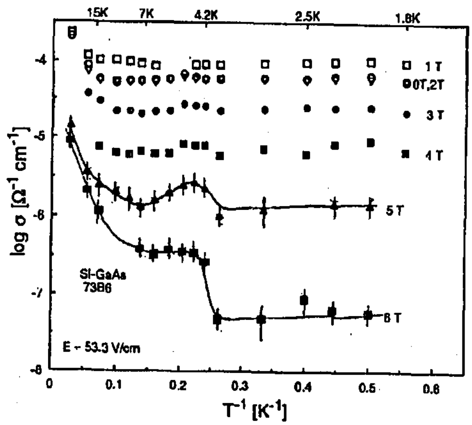

Fig. 2. Temperature (T) dependence of the conductivity (σ) of an SI GaAs sample as a function of the magnetic field.

The shape of characteristics changed when the temperature decreased. For highest T no impact ionization was observed for any applied B. The breakdown occurred only for $T < 15$ K. For $T > 15$ K the conductivity showed an activated character with an activation energy increasing with the magnetic field. For $15\text{ K} > T > 4$ K the conductivity was activated only for $B > 4$ T. For lowest temperatures ($T < 4$ K) the conductivity did not depend on the temperature, even for the highest B. A maximum in the $\sigma(T)$ dependence was observed for $T \approx 4.5$ K and it was proposed that it was related to correlations in positions of localized charges [7].

Vanishing of impact ionization for $T > 15$ K means that in this range of the temperature a concentration of localized electrons is much smaller than that of free ones. A decrease in the temperature leads to an increase in population of states which can be ionised by impact processes. A population of these states is essential only for $T < 15$ K. This can be inferred from a gradual appearance of the jump of the current on current–voltage characteristics measured for $T < 15$ K (Fig. 1).

For $4\text{ K} < T < 15$ K one observes a transition from a non-activated ($B < 4$ T) to an activated ($B > 4$ T) character of σ. This change is a fingerprint of a magnetic field induced localization transition. The transition is caused by an increase in the density of localised states at the bottom of the conduction band [8] and a decrease in an effectiveness of the impact ionization in the magnetic field [9].

For $T < 4$ K one observes a strong dependence of the conductivity on the magnetic field which is not accompanied by a change from a non-activated to an activated conductivity. Thus, from the point of view of $\sigma(B)$ dependence one may interpret this as a localization transition, while $\sigma(T)$ dependence shows the contrary. What is more, it seems reasonable to assume that the localization should occur for $T < 4$ K since it is observed for $T > 4$ K.

A proposed explanation of this contradiction is based on an assumption that in the investigated system at low temperatures optical and electric field excitations dominate over the temperature in determination of the electron distribution function. In such a case free electron concentration and mobility do not depend strongly on T which results in a non-activated conductivity. On the other hand, magnetic field increases the density of states at the bottom of the conduction band which causes localization and a strong $\sigma(B)$ dependence. Thus, in non-equilibrium systems investigation of $\sigma(T)$ dependence may not supply a direct confirmation of a localization transition.

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