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# Magnetoconductivity and potential fluctuations in semi-insulating GaAs

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**Abstract**
Low temperature measurements of the Hall effect were carried out on photoexcited electrons in EL2-rich semi-insulating GaAs before and after photoquenching of the EL2 defects. A model of conductivity in the magnetic field is proposed that takes into account essential physical aspects of the electron transport in a fluctuating electrostatic potential and describes experimental data. Both experimental results and model calculations show a decrease of the amplitude of fluctuations upon photoquenching of the EL2. However, infrared shallow donor spectroscopy measurements showed an increase of the amplitude of fluctuations upon photoquenching of the EL2. This contradiction is explained by showing that observed properties of a fluctuating pattern depend on a spatial extent of a wavefunction that probes fluctuations.

## 1. Introduction

This paper is devoted to an analysis of fluctuations of the electrostatic potential in semi-insulating (SI) GaAs. Such fluctuations result from a spatially random distribution of charged defects. The dominant defect in SI GaAs is the arsenic antisite, the EL2, and the idea of the present investigation is to study the influence of the charge state of the EL2 on potential fluctuations in this material. To make this paper more interesting for those who are not specialists in the area of the EL2, we begin with a short description of the basic facts concerning this defect and its peculiar properties. This is followed by a short introduction to the potential fluctuations in SI GaAs which indicate their importance in understanding magnetoconductivity and far infrared experiments performed on this material. These two parts of the introduction find their correspondence in the experimental procedure adopted in the present study and the theoretical model developed to analyse results on the low temperature magnetoconductivity of photoexcited electrons in SI GaAs. The main result of this paper is then described and discussed: it is shown that the observable amplitude of potential fluctuations depends on the spatial extent of the electron wavefunction that is used for probing the fluctuations.

  

EL2 is the main native point defect in undoped semi-insulating GaAs. Its properties have been drawing the attention of physicists for more than 20 years now. The EL2 pins the Fermi level to the middle of the energy gap which enables production of intentionally undoped semi-insulating substrates for electronic devices. This makes EL2-rich GaAs, and the EL2 itself, the subject of great technological interest and profound physical investigation. A review of properties of the EL2 defect can be found in [1, 2]. It is well established now that the EL2 is a double donor originating from the arsenic antisite, i.e., an As atom replacing a Ga atom. The most interesting feature of the EL2 is the possibility of transformation of this defect into the so-called metastable state, $EL2^*$. This process is known as photoquenching of the EL2 and occurs by an intracentre absorption of a photon with energy in the range of 1–1.3 eV. This transformation is irreversible at low temperatures, i.e., below 140 K in the case of SI GaAs. Microscopically, the transformation $EL2 \rightarrow EL2^*$ corresponds to a shift of the arsenic antisite along the [111] direction. Photoquenching can lead to neutralization of ionized $EL2^+$ centres in a two-step process: first an electron photoexcited into the conduction band is captured by the $EL2^+$ which then becomes neutral and is transformed by another photon to the metastable state [2].

The problem of the energy levels and spatial arrangement of atoms constituting the EL2 in its normal and metastable states is still a matter of discussion. For instance, until recently, it was generally accepted that the $EL2^*$ can only exist as a neutral centre with a unique atomic structure. This belief was recently questioned by Chadi [3] who performed first-principles calculations of the total energy of the EL2 and showed that the $EL2^*$ can exist also in three charged states with +1, −1 and −2 elementary charge. These states differ in the degree of relaxation of the arsenic antisite and surrounding atoms. Results of these calculations give a basis for interpretation of experimental data [4–7] on thermal recovery of the EL2 that cannot be explained under the assumption of a unique atomic structure of the $EL2^*$.

Another problem that still attracts much attention is that of the influence of shallow impurities on the EL2 and interaction of this defect with dopants. Chadi [3] proposed that the disappearance of the EL2 in n-doped samples is caused by the fact that the ground state of the arsenic antisite in the presence of free electrons is a doubly negatively charged metastable state of the EL2. An interaction of shallow acceptors and the EL2 was recently investigated by Fukuyama *et al* [7] and Alt *et al* [8]. A problem related to a spatial correlation of the $EL2^+$ centres and negatively charged acceptors, $A^-$, was a trigger for the present study.

A word of explanation is required concerning the terminology adopted in the present work. As can be inferred from the preceding section, transformation of the EL2 defects to the metastable state requires a change of a charge state of some of the $EL2^+$ defects. This causes also changes of the charge state of other centres such as shallow acceptors; this is a result of the principle of conservation of the electric charge. Thus it is assumed that the term 'photoquenching of the EL2' describes a process of transformation of the EL2 centres to the metastable state and all the complexity of the accompanying recharging processes.

Fluctuations of the electrostatic potential are of importance in interpretation of optical and conductivity properties of semiconductors and are worth studying in their own right. In disordered materials, the existence of localized states at the bottom of the conduction band (CB) and the appearance of the mobility edge are among the most important manifestations of fluctuations [9]. The problem of determination of an amplitude or spatial extent of fluctuations is being attacked by more and more refined experimental and theoretical methods. For example, Mensz *et al* [10] determined a mean fluctuation for the average position of the electron wavefunction in a silicon inversion layer and in a GaAs/GaAlAs heterostructure by measurements of weak localization corrections [11] to the Drude conductivity. Recently, Mathur and Baranger [12] provided a precise relationship between such magnetoresistance measurements and the interface roughness. On the other hand, Bożek *et al* [13] determined the amplitude of electrostatic potential fluctuations on the surface of the GaN epitaxial layer using a Kelvin scanning microscope.

Fluctuations result from a random distribution of charged defects that break the translational invariance of the perfect crystal. To change a fluctuation pattern one usually has to replace a sample with another one or to vary external parameters such as temperature, electric field and pressure. Any such action introduces an ambiguity in interpretation of experimental data: while an observed result may originate from a change of the fluctuations themselves, it may also be caused by other factors such as a shift of the energy levels with external perturbing fields. EL2-rich semi-insulating GaAs offers the possibility of changing a fluctuation pattern in a way that it is free from such drawbacks. The method is based on the fact that during the process of photoquenching of the EL2, one changes the charge state of some defects and thus influences a fluctuation pattern.

A role of potential fluctuation in SI GaAs was pointed out in a number of far infrared spectroscopy and magnetoconductivity experiments [14–16]. Sadowski *et al* [14] showed in a shallow donor magnetophotoconductivity measurement that a spatial correlation exists in the positions of charged $EL2^+$ centres and shallow ionized acceptors. This conclusion was drawn from an observation of an increase of the width of $1s$–$2p^+$ transitions between shallow donors upon photoquenching of the EL2 and it was based on the following reasoning. First, it was assumed that the photoquenching leads to neutralization of the $EL2^+$, according to a generally then accepted point of view claiming neutrality of the metastable state of the EL2. Neutralization of the $EL2^+$ means a transfer of electrons from acceptor centres onto the $EL2^+$. Thus, if a certain number of $EL2^+$ are transformed into the neutral metastable state, twice as many charges are in total neutralized. Second, because of the presence of donors other than the EL2, the number of ionized acceptors is always larger than that of ionized $EL2^+$. Thus, neutralization of even all the $EL2^+$ centres leaves some acceptors ionized. Next, the intradonor transition linewidth is determined primarily by the electric fields and field gradients. Before neutralization of the $EL2^+$, shallow ionized acceptors form dipoles with charged $EL2^+$ defects. Neutralization of the $EL2^+$ centres leaves $A^-$ potentials weakly screened which leads to an increase of the amplitude of fluctuations and a broadening of the linewidth. In that experiment [14], the idea of probing the sample's properties before and after photoquenching of the EL2 was applied.

In another series of experiments done on samples cut from the same wafer as in [14], impact ionization of shallow bound states was studied and it was shown that the magnetic field ($B$) causes localization of electrons in a tail of localized states at the bottom of the CB [15, 16]. An interaction of localized electrons with optical phonons was observed in the ultraquantum limit above 15 T [16]. Results of these magnetoconductivity experiments were qualitatively explained by the influence of $B$ on the position of the electron quasi-Fermi level: an increase of $B$ causes an increase of the density of localized states at the bottom of the CB [17] and moves the quasi-Fermi energy down deeper into localized states. These experiments show that to understand magnetoconductivity in EL2-rich SI GaAs, one has to take into account both the presence of fluctuations of the electrostatic potential and localization effects induced by the magnetic field.

There are a few factors that have resulted in this work. First, we wanted to verify to what an extent the spatial correlation of positions of $EL2^+$ and $A^-$ influence dc magnetoconductivity. Second, in view of the large quantity of experimental data related to magnetoconductivity of photoexcited electrons in SI GaAs, we wanted to describe this phenomenon quantitatively. To this end we develop a theoretical model that takes into account essential factors influencing electron transport in the material investigated. In particular, we show both experimentally and theoretically that the amplitude of long range potential fluctuations decreases when the total number of charged centres decreases. Comparing this result with the increase of the amplitude of fluctuations observed by Sadowski *et al* [14] we conclude that photoquenching of the EL2 results in an *increase* of fluctuations if one performs observations on the spatial scale of a wavefunction of a shallow donor, but results in a *decrease* of fluctuations if observations are performed on the scale of a wavefunction of a free electron. In other words, a fluctuating pattern in SI GaAs has an internal structure and its observed properties depend on the spatial extent of the wavefunction that is used as the tool for probing fluctuations. To the best of our knowledge, such a relation has never been observed before for any material.

## 2. Experiment

The sample, in the form of a $5 \times 1 \times 0.4$ mm$^3$ bar, was cut from an (001)-oriented undoped Czochralski grown wafer. The sample was supplied with Au/Ge/Ni contacts that were proved to be Ohmic down to liquid helium temperatures. Two of them were bar-shaped current supplying contacts and the other four were 0.2 mm diameter dot-shaped voltage probes. The electrical circuit consisted of the sample connected in series with a Keithley 220 current source. The conductivity and the Hall voltages were measured simultaneously by two Keithley 617 electrometers. The sample was placed in a helium cryostat supplied with a superconducting coil and a variable temperature insert. It was kept in a helium exchange gas at a low pressure and shielded by a black polyethylene against room temperature thermal radiation. It was verified that the shielding was necessary to avoid thermal ionization of weakly localized states.

The concentration of neutral EL2$^0$ centres, determined by measurements of optical absorption, was equal to $4.7 \times 10^{16}$ cm$^{-3}$ and the presence of other deep traps was confirmed by thermally stimulated current measurements. The sample investigated was not intentionally doped; it is known, however, that the typical residual concentration of shallow acceptors in such samples is about $5 \times 10^{15}$ cm$^{-3}$ while that of shallow donors is about $10^{15}$ cm$^{-3}$. The EL2 is the main defect in EL2-rich SI GaAs. Being a deep donor, it overcompensates acceptor centres and creates a free electron concentration of the order of $10^6$ cm$^{-3}$ at room temperature. However, at liquid helium temperatures, SI GaAs is an electrical isolator. To perform low temperature conductivity measurements on this material, a sample must be permanently illuminated to produce a stationary concentration of free electrons. To this end, during measurements, the sample was permanently illuminated with a defocused spot of 850 nm light of intensity $P$. This light wavelength was chosen because it causes neither photoquenching of the normal state of the EL2 nor photorecovery from the metastable state. Light of 850 nm wavelength was used to create a concentration of free electrons both before and after photoquenching of the EL2. It was verified during many experimental runs that unless the intensity of the 850 nm light was changed, the resistance of the samples investigated attained a stationary value that did not change in time. Practically, this was verified by checking that the current–voltage characteristics (CVC) registered before and after a series of measurements were the same. This was experimental proof that the permanent illumination did not change the state of the EL2. The photoquenching was achieved by illuminating the sample with the white light of a halogen lamp. No persistent photocurrent effects were observed either before or after photoquenching of the EL2. In each case, the monochromatic or white light was guided by the same large aperture optic fibre that ended in the proximity of the sample. It was verified that changes of the geometry of illumination did not influence the sample's conductivity qualitatively but only quantitatively. Measurements done with Au/Ge/Ni contacts covered with black polyethylene showed that the conductivity of the sample was not influenced by spurious photovoltages generated on the contacts.

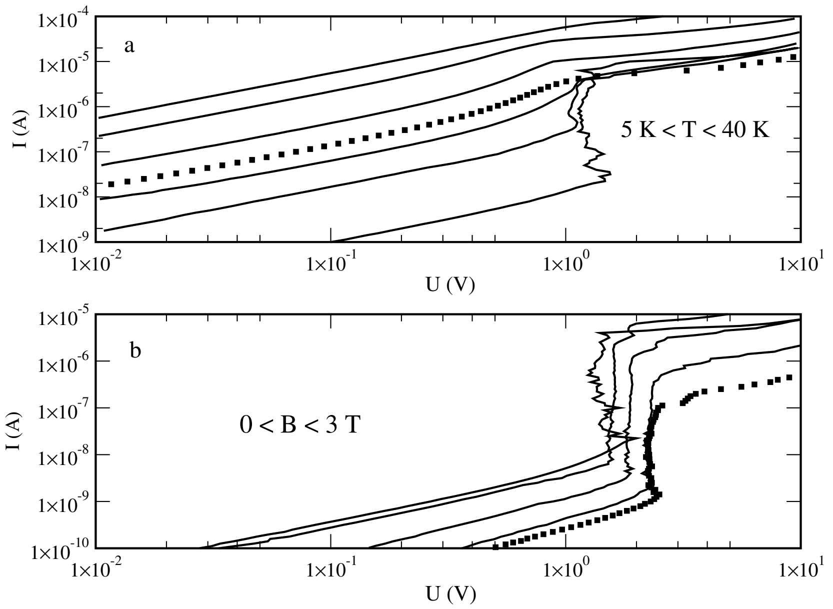


**Figure 1.** (a) CVC before photoquenching of the EL2 at 0 T (solid curves) at 5.2, 8, 11, 15.6, 24.8 and 39.7 K (from bottom to top). The dotted curve was registered at 14.6 K after photoquenching of the EL2. (b) CVC at 5 K before photoquenching of the EL2 (solid curves) at 0, 1, 2 and 3 T (from left to right). The dotted curve was registered at 5 K and 3 T after photoquenching of the EL2.

The sample was cooled in the dark and, after setting the intensity $P$, CVC were measured as a function of temperature $T$ (from 4 to 40 K) and the magnetic field $B$ (up to 3 T). Next, the Hall effect measurements at 5 K were carried out for a constant sample current ($I = 10^{-9}$ A) sweeping the magnetic field for four $\pm I \pm B$ configurations. After that, the sample was illuminated with a strong white halogen light for 3 min (which caused photoquenching of the EL2) and the measurements were repeated with the same $P$ as in the first case. To carry out measurements of the Hall effect at 15 K, the sample was heated to room temperature and then cooled in the dark to 5 K, and $P$ was adjusted to produce the same resistance of the sample, $R$, as in the first series of measurements. Next, $T$ was increased to 15 K and the Hall effect measurements were carried out before and after photoquenching of the EL2 for $I = 10^{-7}$ A.

## 3. Results

The temperature and magnetic field dependences of the CVC are shown in figures 1(a) and (b), respectively, before photoquenching of the EL2. A similar set of curves was obtained after photoquenching of the EL2 (two of them are shown in figure 1 as dotted curves). For lowest voltages, CVC shows a linear dependence that changes with increasing voltage to a superlinear one and ends with an abrupt increase of the current at a threshold voltage $V_{\text{th}}$. This increase is a result of impact ionization of shallow bound states, i.e., shallow donors and states created by potential fluctuations at the bottom of the CB. At lowest temperatures, impact ionization is accompanied with self-generated oscillations of an electron plasma [18] leading to an erratic voltage behaviour in an S-shaped part of the CVC. This is visible in some characteristics

**Table 1.** The Hall concentration $n_H$ and mobility $\mu_H$ at zero magnetic field, before and after photoquenching of the EL2 at 5 and 15 K.

| | Before photoquenching | | After photoquenching | |
|---|---|---|---|---|
| | 5 K | 15 K | 5 K | 15 K |
| $n_H$ (cm$^{-3}$) | $1.7 \times 10^9$ | $2.0 \times 10^{11}$ | $9.5 \times 10^7$ | $5.9 \times 10^{10}$ |
| $\mu_H$ (cm$^2$ V$^{-1}$ s$^{-1}$) | 650 | 6300 | 5000 | 7500 |

presented in figure 1. Due to thermal ionization of bound states, the current jump at $V_{th}$ decreases as the temperature grows and vanishes at about 20 K. Photoquenching of the EL2 does not change the shape of the CVC. It results only in an increase of the sample resistance, shifts $V_{th}$ to higher values and decreases the current at $V_{th}$. These changes are irrelevant from the point of view of the Hall effect measurements. At 15 K, the magnetic field moves the CVC slightly to higher voltages (by about 0.1 V). At this temperature, the Hall effect measurements were carried out with a current of $10^{-7}$ A and the sample was away from the impact ionization regime both before and after photoquenching of the EL2. At both temperatures, the sign of the Hall effect was the same before and after photoquenching of the EL2.

For $T > 10$ K, $R$ in the linear part of the CVC is activated with an energy of $E_a = 5.2 \pm 0.1$ meV both before and after photoquenching of the EL2. This value is approximately equal to the binding energy of a shallow donor in GaAs. For lower temperatures, $R$, is changing more slowly but no hopping dependence (either nearest neighbour or variable range) was observed. At 5 K, the magnetic field dependence of $\rho_{xx}$ in the linear part of the CVC shows a $B^2$ dependence for $B > 1$ T. At 15 K, $\rho_{xx}$ shows a monotonic $B^2$ dependence over the whole range of $B$. The results of the Hall measurements are summarized in table 1, which shows the Hall concentration, $n_H$, and the mobility, $\mu_H$, at $B = 0$ T. Generally, photoquenching of the EL2 causes a decrease of $n_H$ and an increase of $\mu_H$. These changes are stronger at 5 K than at 15 K. At 5 K, $n_H$ at $B = 0$ T drops by a factor of about 18 while at 15 K it drops only by a factor of 3. On the other hand, at 5 K, $\mu_H$ grows to about eightfold while a small increase by 20% was observed at 15 K.

## 4. Discussion

The crucial point in the present experiment is the generation of a stationary concentration of free carriers by the permanent illumination with 850 nm wavelength light. This is a sub-band gap excitation that does not allow creation of free electron–hole pairs. Although the sign of the Hall effect was not determined in the present experiment, the experimental facts show unambiguously that in the conditions of the present experiment the conductivity is due to electrons in the conduction band. The strongest argument comes from the far infrared spectroscopy measurements [14] in which transitions between shallow donors are observed: if the illumination with 850 nm light created free holes, shallow donors at the bottom of the conduction band could not be populated. The assumption of a stationary non-equilibrium occupation of shallow donors is consistent with the $E_a$ value of the activation energy of the resistance of the sample which is very close to the ionization energy of a shallow donor in GaAs. The process of creation of the stationary concentration of electrons at the bottom of the CB is described in more detail in [15].

Since the electron lifetime on shallow donors is long enough to make possible intradonor spectroscopy measurements, one can assume that the thermal equilibrium is attained between shallow donors and states in the CB. This allows us to use in the following the Boltzmann statistics for the energy distribution function for electrons in the CB. Thus, one can assume that under the conditions of the present experiment (and also that described in [14]) the sample of SI GaAs is similar to a compensated n-type material if one looks at it from the point of view of the electron distribution in the vicinity of the bottom of the conduction band. The Boltzmann distribution is then characterized by the quasi-Fermi energy and the lattice temperature.

The photoexcited electrons are transferred from deep levels in the band gap high into the conduction band. They relax by emission of optical and acoustic phonons. In analysing the conductivity of photoexcited electrons we assume that only thermalized electrons in the CB are responsible for the observed conductivity. In this way we exclude a possible contribution to the conductivity coming from two groups of electrons: photoexcited electrons in the CB that are undergoing the thermalization process and electrons localized at the bottom of the conduction band that could contribute to the conductivity by hopping. The first group of electrons is excluded because of an activated character of the resistance: if the contribution of these non-thermalized electrons were essential, then the resistance of the sample would not be thermally activated. Neglecting the contribution of hopping is consistent with the observed square $\rho_{xx}(B)$ dependence that is characteristic for conductivity of a non-degenerate free electron gas in the CB. Further support comes from a comparison of an average donor–donor separation (about 620 Å for a donor concentration of $10^{15}$ cm$^{-3}$) with the Bohr radius of a shallow donor in GaAs (about 100 Å).

Due to the presence of charged centres and a very low concentration of free electrons, we expect fluctuations of the electrostatic potential to significantly influence conductivity in the sample investigated. In such a case, according to the general concepts of the theory of localization [9, 19], there exists a certain energy level, the mobility edge $E_m$, such that the states in the CB with energies lower than $E_m$ are localized and they do not contribute to the conductivity. A precise form of the energy dependence of the electron's mobility, $\mu(E)$, for energies above $E_m$ for a non-degenerate electron gas is not known. One may only speculate that in the vicinity of $E_m$, $\mu(E) \sim (E - E_m)$ and for high energies it should coincide with a formula known from a theory of the classical transport in semiconductors. Thus we introduce as one of the parameters describing the semiconductor investigated an energy $E_0 > E_m$ above which the electron's mobility is described by $\mu(E) = e\tau(E)/m$, where $\tau(E)$ is an energy dependent scattering time, $m$ is the electron effective mass and $e$ is the electron charge. In calculations, $\tau(E)$ is described by the Conwell–Weisskopf formula [20] with the concentration of ionized impurities $N_i$ being a parameter of the model:

$$\tau(E) = \frac{16\sqrt{2}\pi(\epsilon_0\epsilon)^2 m^{1/2} E^{3/2}}{N_i Z^2 e^4 \ln\left[1 + \left(\frac{4\pi\epsilon_0\epsilon E}{N_i^{1/3} Z e^2}\right)^2\right]}. \tag{1}$$

$Z$ is the charge of an ionized impurity and we assumed $Z = 1$. The conductivity of electrons with energy between $E_m$ and $E_0$ is strongly influenced by proximity to the mobility edge, i.e., by localization [9, 19]. The mean mobility of these electrons is expected to be much smaller than that of carriers with energy above $E_0$. Their contribution, $\sigma_0$, to the longitudinal conductivity may be envisaged as a tunnelling through barriers of the fluctuating potential. That is why, in the model, it adds only to the $\sigma_{xx}$ component of the conductivity tensor, in correspondence with the usually neglected contribution of hopping conductivity to $\sigma_{xy}$.

An important element of the model is an experimentally justified [15, 16] assumption that the concentration of conducting electrons decreases with increase of the magnetic field. This effect is described by introducing a factor $\exp(-\alpha B/k_B T)$ multiplying components of the conductivity tensor ($k_B$ is the Boltzmann constant). The main origin of this factor is that the ionization energy of a donor increases with the magnetic field due to a shrinkage of the wavefunction of the bound electron. In GaAs, this increase is equal to about 0.5 meV T$^{-1}$ [21].

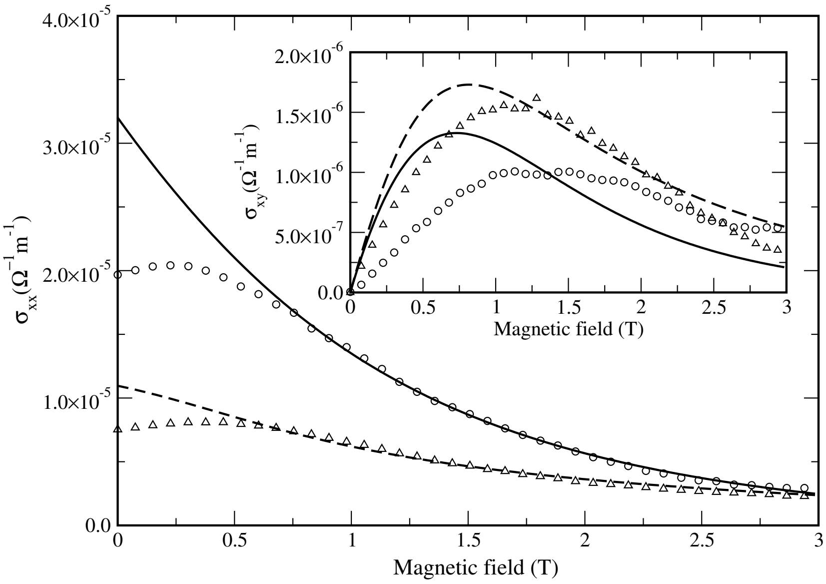


**Figure 2.** $\sigma_{xx}$ and $\sigma_{xy}$ (inset) measured at $T = 5$ K before (circles) and after (triangles) photoquenching of the EL2. Solid and dashed curves are the results of calculations using the parameters shown in table 2.

Thus, as the magnetic field increases, fewer electrons are thermally excited from shallow donors to the conduction band. Another factor leading to a decrease of the concentration of conducting electrons is an increase of the density of states at the bottom of the CB in the magnetic field [17]. This causes a shift of the quasi-Fermi level, down in energy. This effect, however, is not included in the proposed model.

Taking the above considerations into account we describe the magnetoconductivity investigated by the following equations:

$$\sigma_{xx}(B) = \exp(-\alpha B/k_\mathrm{B}T)\left(\sigma_0 + \frac{e}{3\pi^2 k_\mathrm{B}T}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{E_0}^{\infty}\mathrm{d}\epsilon\,\epsilon^{3/2}\frac{\mu(\epsilon)}{1+\mu^2B^2}\mathrm{e}^{-(\epsilon-\epsilon_\mathrm{F})/k_\mathrm{B}T}\right) \quad (2)$$

$$\sigma_{xy}(B) = \exp(-\alpha B/k_\mathrm{B}T)\frac{e}{3\pi^2 k_\mathrm{B}T}\left(\frac{2m}{\hbar^2}\right)^{3/2}\int_{E_0}^{\infty}\mathrm{d}\epsilon\,\epsilon^{3/2}\frac{\mu^2(\epsilon)B}{1+\mu^2B^2}\mathrm{e}^{-(\epsilon-\epsilon_\mathrm{F})/k_\mathrm{B}T} \quad (3)$$

where $\epsilon_\mathrm{F}$ is the Fermi energy. The conduction band is assumed to be parabolic and spherical and its bottom is the energy reference level.

The fitting procedure involves five parameters: $E_0, \sigma_0, \alpha, N_\mathrm{i}$ and $\epsilon_\mathrm{F}$. The first three describe the influence of potential fluctuations on the conductivity. The fitting was done simultaneously for $\sigma_{xx}$ and $\sigma_{xy}$ curves. It was subject to a constraint that before photoquenching of the EL2, the parameters $E_0$, $\alpha$ and $N_\mathrm{i}$ should be the same for both 5 and 15 K; the same was required for fitting of data measured after photoquenching of the EL2. This condition reflects the assumption that the structures of the fluctuations are the same at both temperatures. Thus we neglect possible changes of screening resulting from an increase of concentration of free electrons with temperature.

Results of the fitting are compared with measured $\sigma_{xx}$ and $\sigma_{xy}$ dependences in figures 2 and 3. The proposed model describes the conductivity investigated very well at 15 K. There are a few factors that make an analysis of the conductivity at 5 K more difficult. First, keeping the

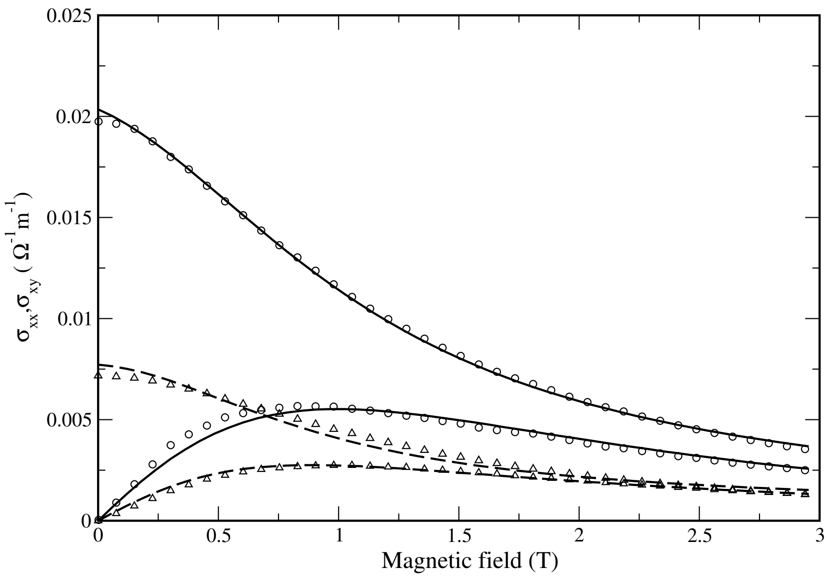


**Figure 3.** $\sigma_{xx}$ and $\sigma_{xy}$ measured at $T = 15$ K before (circles) and after (triangles) photoquenching of the EL2. Solid and dashed curves are the results of calculations using the parameters shown in table 2.

current constant and increasing $B$, one approaches impact ionization conditions at $B \geqslant 2.5$ T that significantly change the electron distribution function and the concentration of free carriers. Second, a maximum of $\sigma_{xx}$ is observed at about 0.3 T. Although the mechanism leading to the appearance of the maximum was not investigated in the present experiment, one can tentatively ascribe it to weak localization [10]. At present, the argument supporting this interpretation is the disappearance of the maximum with increasing temperature. This point is worth further investigation since a possibility of observation of weak localization in bulk samples in a non-degenerate electron gas is not usual. Due to the presence of the maximum, fitting of data measured at 5 K was limited to $B > 0.75$ T. Neither impact ionization nor any mechanism leading to a non-monotonic $\sigma_{xx}(B)$ dependence was included in the proposed model. Third, at 5 K, $\sigma_{xy}$ is an order of magnitude smaller than $\sigma_{xx}$ and the fitting procedure is not very sensitive to $\sigma_{xy}$ values. Taking the above into account we find the results of fitting the 5 K data satisfactory. We would like to point out that this is the simplest model found by us that enabled a reasonable description of experimental data. Neglecting any of its essential components (two types of conducting carrier—with energy below and above $E_0$; magnetic field induced electron freeze-out) makes fitting of the experimental results impossible.

The values obtained for the fitting parameters are shown in table 2. For a better comparison with experimental data, instead of $\epsilon_F$ we show $n$ which is what the total concentration of electrons in the CB would be if it were a parabolic and spherical one: $n = \int_0^\infty \mathrm{d}\epsilon\, \varrho(\epsilon) \mathrm{e}^{-(\epsilon-\epsilon_F)/k_B T}$ with $\varrho(\epsilon)$ being the density of states in the parabolic and spherical band [22]. After photoquenching of the EL2, the concentration of ionized centres, $N_i$, decreases and parameters that describe potential fluctuations show a reduction in their influence on the conductivity. The value of $E_0$ moves towards the bottom of the CB which means a decrease of the amplitude of the fluctuations. Both a decrease of $E_0$ and a decrease of the concentration of scattering centres are in agreement with the increase of the Hall mobility upon photoquenching of the EL2 (see table 1). A shift of $E_0$ to lower values means also a decrease of the concentration

**Table 2.** Fitting parameters corresponding to curves presented in figures 2 and 3. GaAs parameters used in calculations were taken from [22].

| | Before photoquenching | | After photoquenching | |
|---|---|---|---|---|
| | 5 K | 15 K | 5 K | 15 K |
| $n$ (cm$^{-3}$) | $1.3 \times 10^9$ | $2.2 \times 10^{11}$ | $1.5 \times 10^8$ | $4.8 \times 10^{10}$ |
| $\sigma_0$ ($\Omega^{-1}$ m$^{-1}$) | $2.6 \times 10^{-5}$ | $5.0 \times 10^{-3}$ | $6.2 \times 10^{-6}$ | $2.0 \times 10^{-3}$ |
| $N_i$ (cm$^{-3}$) | $2.0 \times 10^{16}$ | | $1.2 \times 10^{16}$ | |
| $E_m$ (meV) | 2.5 | | 1.5 | |
| $\alpha$ (meV T$^{-1}$) | 0.34 | | 0.15 | |

of low mobility electrons which is reflected in a decrease of $\sigma_0$ upon photoquenching of the EL2. Finally, the value of the freeze-out parameter, $\alpha$, is comparable with the increase of the binding energy of a shallow donor in GaAs in the magnetic field, i.e., 0.5 meV T$^{-1}$. We find this agreement satisfactory, since a description of the CB for energy less than $E_0$ is only approximate and in fact compacted to one parameter, $\sigma_0$. It can be argued that $\alpha$ both describes the freeze-out and is sensitive to localization of electrons in potential fluctuations. If this is so, a decrease of $\alpha$ upon photoquenching of the EL2 means that the electron localization by the magnetic field is less efficient in shallower fluctuations, as one could expect. Generally, the model description predicts a decrease of the concentration of the ionized centres and a decrease of the amplitude of the potential fluctuations upon photoquenching of the EL2, in agreement with a statistical approach in which the amplitude of the fluctuations is proportional to $\sqrt{N_i}$ [23].

The principal benefit ensuing from using the proposed model is that it allows one to estimate the amplitude of the potential fluctuations influencing the electron conductivity and to show how this amplitude depends on the charge state of the EL2 centres. Just from the model description, we can state that the mobility of electrons increases upon photoquenching of the EL2 *both* due to a reduction of the concentration of ionized centres *and* due to a decrease of fluctuations.

The question arises of how the charge state of the EL2 changes upon photoquenching of the EL2. Until recently, the answer was well established: since the metastable state of the EL2 could only be neutral, all the neutral EL2 centres were transformed directly into neutral EL2* by absorption of a photon, and ionized $EL2^+$ centres first captured an electron photoexcited to the CB and then were transformed to the neutral EL2* [2]. As was mentioned above, this scenario leads to neutralization of twice as many charges as the initial concentration of the $EL2^+$. In the case of a material with a typical residual concentration of shallow acceptors equal to about $5 \times 10^{15}$ cm$^{-3}$ and one of shallow donors equal to about $10^{15}$ cm$^{-3}$, one gets the concentration of the $EL2^+$ before photoquenching equal to $4 \times 10^{15}$ cm$^{-3}$. In such a case, photoquenching of the EL2 decreases the concentration of ionized impurities by $8 \times 10^{15}$ cm$^{-3}$. This is exactly the difference between the $N_i$ values obtained in the fitting procedure and shown in table 2. Although we consider this agreement somewhat accidental (since the exact donor and acceptor concentrations are unknown) it is an argument confirming an essential decrease of the total concentration of charged defects resulting from photoquenching of the EL2 and also the physical assumptions leading to the theoretical model described above. Such a reduction is also in agreement with an unambiguous increase of the mobility upon photoquenching of the EL2. Thus we conclude that in the case of the present experiment, photoquenching of the EL2 leads predominantly to neutralization of the $EL2^+$. The charged metastable states of the

EL2 described in [3], if created, do not occur in a large concentration in our sample and the standard scenario [2] of transformation of the EL2 to the metastable state can be applied.

Results of Chadi [3] do not change the basis of the interpretation of the far infrared experiment given by Sadowski *et al* in their paper [14]. This interpretation explains a broadening of the 1s–2p$^+$ transition line caused by an increase of the fluctuations of the electrostatic potential. Such an increase may result from the disappearance of EL2$^+$–A$^-$ correlations as well as the creation of charged metastable states.

Let us now discuss the most important conclusion resulting from the present study. There are two experiments that give information about the influence of the charge state of the EL2 on the amplitude of the potential fluctuations: the present one and that described in [14]. In the present experiment we observe an increase of the Hall mobility upon photoquenching of the EL2 and interpret this result as arising from a decrease of the concentration of ionized centres and a decrease of the amplitude of potential fluctuations. On the other hand, a broadening of the line of the 1s–2p$^+$ transition upon photoquenching of the EL2 was interpreted in [14] as resulting from an increase of the potential fluctuations.

To resolve this discrepancy we note the following. In the case of intradonor transitions, one deals with a wavefunction whose extent is of the order of the Bohr radius, enclosing a volume $V$ of about $10^{-17}$ cm$^3$. This wavefunction is localized and influenced only by a small number of nearest charges or dipoles, as can be seen by noticing that $V$ is an average volume for one impurity centre when the impurity concentration is equal to $10^{17}$ cm$^{-3}$. On the other hand, the concentration of charged centres in the sample investigated is only of the order of $10^{16}$ and $10^{15}$ cm$^{-3}$ before and after photoquenching of the EL2, respectively. According to [14], after photoquenching of the EL2, the small scale potential fluctuations are greater because elimination of positively charged EL2$^+$ causes the disappearance of the small scale correlation in the positions of the EL2$^+$ and A$^-$.

In transport measurements, one deals with a quite different situation. Wavefunctions of conducting electrons are delocalized and a free electron is scattered by the electrostatic potential created by a large number of charged centres. The amplitude of the long wavelength potential fluctuations responsible for scattering is determined by the spatial fluctuations of the total concentration of localized charges. Elimination of the dominant concentration of charged centres by neutralization of the EL2$^+$ leads to a decrease of the amplitude of the large scale potential fluctuations, which contributes to the experimentally observed increase of the mobility.

Comparing the results of these two experiments we show that the observed properties of the fluctuation pattern in SI GaAs depend on the spatial extent of the electron wavefunction which probes the fluctuations. This result seems to be of general character and applicable to any case where correlations change the statistical distribution of the fluctuations on a certain spatial scale. Additionally, we show that the delocalized wavefunction of a free electron in SI GaAs is not sensitive to local, small scale electrostatic potential fluctuations. The behaviour of conducting electrons is mainly governed by large scale fluctuations.

In conclusion, a peculiar property of the EL2 defect, i.e., the possibility of its transformation to a neutral metastable state at low temperatures by an optical method, provides a tool for investigation of fluctuations of the electrostatic potential in SI GaAs. A comparison of results from far infrared spectroscopy and the present magnetoconductivity experiment reveals an internal structure of the fluctuating potential in the material investigated and shows that the observable properties of the fluctuations depend on the spatial extent of the electron wavefunction that interacts with the charged centres. A model of the conductivity in a magnetic field is proposed that allows us to describe quantitatively the measured components of the conductivity tensor and gives an estimation of the amplitude of the potential fluctuations relevant to the conductivity of free electrons.

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