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# *EL*2-defect-related changes in the magnetophotoconductivity of shallow donors in bulk semi-insulating GaAs

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The far-infrared photoconductivity of semi-insulating GaAs was measured as a function of magnetic field, and transitions to excited states of shallow donors observed. The measurements were performed for two states of the material: (a) with the *EL*2 defects in the stable $EL2^0$ state and (b) with the *EL*2 defects in the metastable $EL2^*$ state. The linewidth of the donor transitions was found to be larger in the second case, in spite of the decrease in the number of charges in the sample. A model of spatial correlation between $EL2^+$ defects and ionized acceptors is proposed to explain this fact.

The shallow-donor states in GaAs have been studied for *n*-type GaAs by a variety of methods.[1] Far-infrared photoconductivity has proved to be a very useful tool in such investigations.[2] However, shallow donors in a semi-insulating (SI) material are not at all well known. Far-infrared-absorption measurements[3,4] suggest that they are in fact a quite different and very interesting entity.

The main difference between a SI and an *n*-type material is that in the former, the Fermi level is pinned near the center of the band gap by the *EL*2 level (this paper is concerned with only *EL*2-based SI GaAs). This means that there are almost no free electrons, and also that shallow-donor states at low temperatures are practically unoccupied. The lack of free electrons signifies that the Coulomb charges of ionized donors and acceptors are practically unscreened and can lead to large local fluctuations of the electric field, i.e., perforations of the conduction band.[5] Moreover, shallow-donor states, when populated, will find themselves in a totally different environment—of strong local potentials—from their counterparts in an *n*-type material. In this work we have used far-infrared magnetophotoconductivity to study the properties of shallow donors in SI GaAs.

The experimental setup consisted of a far-infrared optically pumped molecular laser, a liquid-helium cryostat, a superconducting solenoid, and a monochromatic near-infrared or visible-light source. The sample could be illuminated with both infrared and far-infrared light simultaneously. To avoid the influence of thermal radiation, a cold infrared filter was used. dc photocurrents were measured with a model 617 Keithley electrometer, while ac photocurrents were measured with an SR510 Stanford Research Systems lock-in amplifier.

In this work the dc conductivity was measured when the sample was illuminated with infrared or visible light only. The ac conductivity was measured when the sample was illuminated with both infrared (or visible) and chopped far-infrared ($\lambda = 118.8$ $\mu$m) light.

Two SI GaAs samples were used. Both were slabs of dimensions about $3 \times 1 \times 0.5$ mm.[3] The Au-Ge-Ni contacts[6] were Ohmic down to 4.2 K. The samples were cooled down to liquid-helium temperature in the dark. The resistance of the samples in this state exceeded $10^{12}$ $\Omega$.

In order to populate the shallow-donor states, the samples were illuminated continuously with infrared light ($\lambda = 0.88$ $\mu$m—corresponding to an energy slightly less than the band-gap energy). This caused electrons from the *EL*2 level and acceptor states to be excited into the conduction band (see Fig. 1). The resistivity of the sample decreased by 2 or 3 orders of magnitude, depending on the light intensity and wavelength. After a certain period of illumination, if *EL*2-bleaching wavelengths were avoided, the resistivity reached a saturation value which then remained constant in time. A steady state was thus obtained in which the processes of electron excitation and deexcitation canceled out. The effect of far-infrared light applied to the sample at this point was to decrease further the resistivity by a factor of 4 (it should be noted that for zero magnetic field the donor binding energy $E_D$ is 6 meV, while the photon energy $\hbar\omega$ for 118 $\mu$m is about 10 meV). We therefore conclude that a steady-state population of the shallow-donor states can be obtained in this fashion, making their investigation possible. Moreover, the large

 

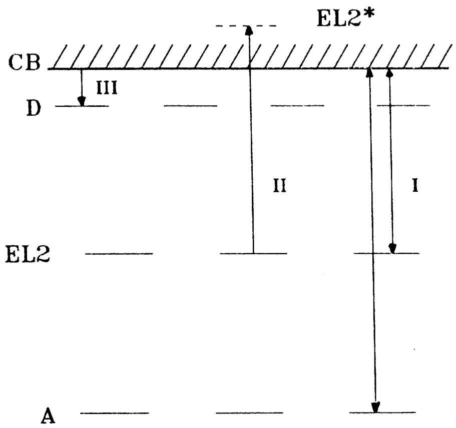


FIG. 1. Schematic of processes occurring in the semi-insulating GaAs sample illuminated with infrared or visible light. I: processes of pumping electrons from acceptors and *EL*2 into the conduction band, as well as deexcitation; II: transfer of *EL*2 into the metastable state, resulting in the annihilation of all $EL2^+$ states (for a certain range of wavelengths); III: deexcitation of electrons from the conduction band onto shallow-donor states.

effect of the far-infrared light on the resistivity in the steady state suggests that more electrons occupy the shallow-donor states than the conduction band (the far-infrared light alone does not affect the resistivity at all). The fact that it is possible to populate the donors for periods of time sufficient to observe their excited states can be due to two factors: (a) the deep level from which an electron is pumped becomes displaced, in configuration coordinates, making rapid direct recombination impossible; (b) the electron excited to the conduction band becomes localized after thermalization in a local minimum of the conduction band and settles on a donor which is far away in real space from the parent deep center.

When the sample was illuminated with 1.05 $\mu$m light, the dc conductivity first increased when the light was turned on, achieved a certain maximum value, and then decreased gradually in time, finally becoming unmeasurably small. This is consistent with the *EL*2-photoquenching spectrum,[7] as $\lambda = 1.05$ $\mu$m corresponds to the maximum of *EL*2 intracenter absorption. To obtain a measurable conductivity of the sample after the *EL*2 state was bleached, i.e., transferred to its metastable ($EL2^*$) state, a He-Ne laser ($\lambda = 0.63$ $\mu$m) had to be used to pump electrons into the conduction band. The dc conductivity of such an illuminated sample with the *EL*2 defect in the metastable state—compared to that with the *EL*2 defect in its ground state—decreased by a factor of 5. This shows that the main source of conduction electrons is the photoionization of the *EL*2 defect in the $EL2^0$ state.

When the steady-state donor population was obtained, the sample illuminated with chopped far-infrared light and the magnetic field swept, a peak in the ac photocurrent could be observed at about 3.7 T, which is a characteristic value for the intradonor $1s$-$2p^+$ transition in GaAs. The same shape of the photoconductive response was observed when above-band-gap light (0.63 $\mu$m) was used. The shape was also independent of the bias voltage, in the linear region of the *I*-*V* characteristic ($U < 1$ V for our samples). In all cases, the width of the $1s$-$2p^+$ peak is considerably larger than for a pure *n*-type sample, which is consistent with the expected local fluctuations of electric fields.

In order to observe the influence of the *EL*2 defect on the shallow donors, the *EL*2 defect was then bleached by illumination with 1.05-$\mu$m light for a sufficiently long period of time, so that the dc conductivity became unmeasurably small at this light intensity and wavelength. The sample was then illuminated with both 0.63- and 118-$\mu$m light and the magnetic field swept.

Figure 2 shows the results of this experiment: the ac far-infrared photoconductivity of a sample illuminated by 0.63-$\mu$m light with the *EL*2 defect in the $EL2^0$ state (curve *a*) and in the $EL2^*$ state (curve *b*). It can be seen that the $1s$-$2p^+$ peak is noticeably wider (by about 50%) when the *EL*2 defect is in the metastable state. The same result was obtained for two samples obtained from different sources.

To understand how the state of the *EL*2 defect influences shallow-donor states, let us discuss in more detail what happens when the transition $(EL2^0) \rightarrow (EL2^*)$ occurs.

The *EL*2 defect is transferred to its metastable state without a change of the charge state, i.e., $(EL2^0) \rightarrow EL2^*$. As the number of $EL2^0$ states decreases, electrons from the ionized acceptors can populate ionized $EL2^+$ states ($EL2^+ + e^- \rightarrow EL2^0$), decreasing the number of ionized acceptors and charged *EL*2 states. The resulting $EL2^0$ state can then be transferred to the metastable state.

Since the linewidths of intradonor transitions are thought to be due primarily to the electric fields and field

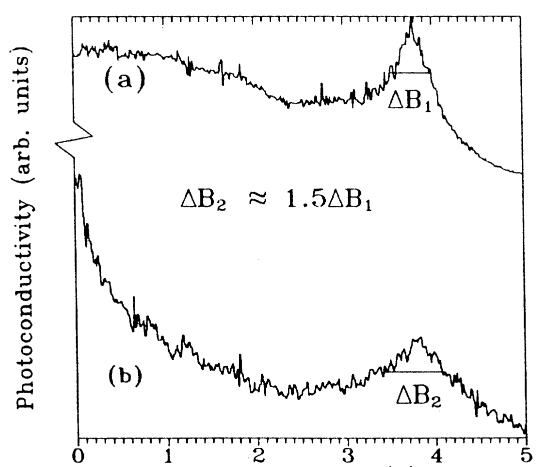


FIG. 2. Photocurrent vs magnetic field for a semi-insulating GaAs sample. Curve *a*: the *EL*2 defect in the stable $EL2^{0/+}$ state; curve *b*: the *EL*2 defect in the metastable $EL2^*$ state. The shallow-donor states in both cases were populated by 0.63-$\mu$m light, while the far-infrared wavelength was 118.8 $\mu$m. A constant dc voltage of 0.2 V was applied to the sample. The temperature was 4.2 K.

gradients in the sample,[8] line *broadening* when the number of electric charges (ionized acceptors and $EL2^+$ defects) *decreases* is the exact opposite of what one would expect. To explain it, we suggest the following qualitative model, based on an earlier tentative suggestion[9] that the $EL2$ defect might be paired with an acceptor.

If charged $EL2^+$ defects are spatially correlated with ionized acceptors ($A^-$), they form plus-minus charge pairs (dipoles). This pairing could be due to, e.g., preferential ionization of the $EL2$ defect: the possibility that all $EL2$ states are so correlated is by no means ruled out. The effect of such pairing is to screen the electric fields of the remaining point charges in the sample.[10]

When the $EL2$ defect is bleached, all the $EL2$ defects are in the metastable (zero-charge) state. There are no $EL2^+$ states and therefore no possibility of forming $EL2^+$-$A^-$ charge pairs. The donors are then subjected to the electric fields of the remaining randomly located point charges (ionized acceptors and donors), which results in an increase of the linewidth.

The above model could mean that the immediate environment of the $EL2$ defect depends on its charge state, i.e., the symmetry of the $EL2^0$ state could be different from that of the $EL2^+$ state. This would explain certain apparent discrepancies in experimental results: the symmetry of the $EL2^0$ state was found to be tetrahedral,[11] while other measurements which probed the $EL2^+$ state showed $C_{3v}$ symmetry.[12]

It could be argued that local deformations of the lattice around the $EL2$ defects, caused by the change in the defect's structure during the transition to the metastable state, could be responsible for the observed change of the linewidth. Such a possibility seems less probable since the defect is neutral both before and after the transition, but it cannot be completely ruled out at this point. Further measurements for samples with different ratios of $EL2^0$ to $EL2^+$ should settle the question definitely.

The reasons for the different shapes of curves *a* and *b* in the low-field part of the spectrum are as yet unknown. A possible explanation is that photoionization of the donors by the far-infrared light—a normally forbidden process—becomes allowed because of the potential fluctuations in SI GaAs and the increased disorder due to the $EL2^0 \rightarrow EL2^*$ transition, postulated in our model.

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