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METASTABILITY OF LOCALIZED NEUTRAL DONOR STATE IN GaAs*

C. SKIERBISZEWSKI†, W. JANTSCH, K. LÜBKE

Johannes-Kepler-Universität, 4040 Linz, Austria

Z. WILAMOWSKI

Institute of Physics, Polish Academy of Sciences
Al. Lotników 32/46, 02-668 Warszawa, Poland

AND T. SUSKI

Unipress, Polish Academy of Sciences, Sokołowska 29, 01-142 Warszawa, Poland

Investigations of the photoconductivity of GaAs:Ge under hydrostatic pressure show, in addition to the well known persistent photoconductivity due to the DX state, another giant photoconductivity caused by a neutral localised "A_1" state of the donor. We find that the top of the barrier for the electron recapture to the A_1 state is pinned to the conduction band edge and the capture cross-section $\sigma(T \to \infty)$ is surprisingly small.

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It was established both experimentally [1, 2] and theoretically [3] that in addition to the DX donor state, a deep, localised one-electron state with the A_1 symmetry can exist in GaAs. The neutral charge of this state was also clearly evidenced [1]. There are however still some open questions concerning the microscopic model of the A_1 state, namely e.g., whether the localised state originates from central cell corrections only or it is accompanied by a strong lattice relaxation; whether and to what extent the A_1 state is hybridised with the effective mass states.

In this paper we report photoconductivity experiments performed in the temperature range of 10 K to 300 K and under hydrostatic pressure up to 20 kbar. During the Hall-effect and conductivity measurements the sample was illuminated

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†Permanent address: Unipress, Polish Academy of Sciences, Sokołowska 29, 01-142 Warszawa, Poland.

(with controlled intensity) by an infrared light emitting diode (IR LED) incorporated in the pressure cell filled with a liquid. We use metalorganic chemical vapour deposition (MOCVD) grown GaAs:Ge layers (thickness: 1.5 μm) grown on semi-insulating Cr-doped GaAs substrate. The Ge-doping level varies from 10^{17} to 2×10^{18} cm^{-3}. These samples are semimetallic at low pressure. With increasing pressure the energy gap increases and the localised donor states (DX and A_1) move into the energy gap and become occupied [1].

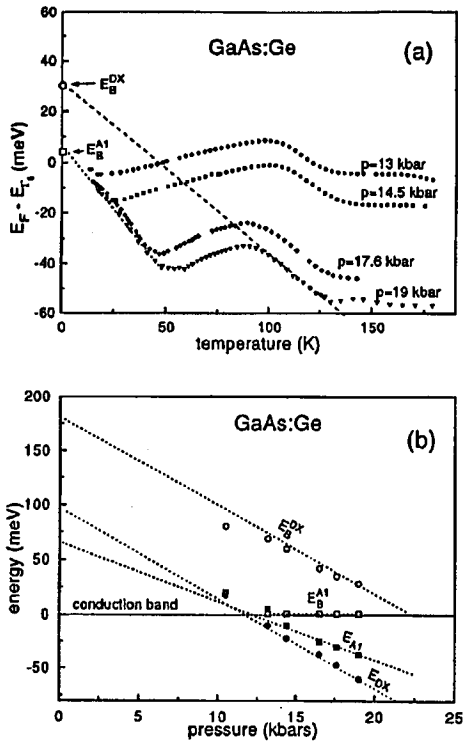

Fig. 1. (a) Temperature dependence of the Fermi level in GaAs:Ge, relative to the conduction band edge, for pressures: 13 kbar (•), 14.5 kbar (■), 17.6 kbar (full diamond), 19 kbar (full triangle). The dashed and dotted lines indicate the extrapolation used in order to evaluate the top of the barrier for the DX level, E_B^{DX} (o) and for the A_1 level, $E_B^{A_1}$ (□) respectively. (b) Pressure dependencies of the DX (•), and the A_1 (■) level and of the barriers for electron capture for the DX level E_B^{DX} (o) and for the A_1 level, $E_B^{A_1}$ (□) respectively. Dotted lines are plotted as a guide for the eye.

In Fig. 1a, the temperature dependence of the quasi Fermi level (E_F^*), determined from the Hall concentration is shown relative to the conduction band (CB) edge under continuous illumination for different pressures for a sample with $n_{Ge} = 2 \times 10^{18}$ cm^{-3}. The observed behaviour of E_F^* is typical of all investigated samples with a Ge concentration of 1×10^{17}–2×10^{18} cm^{-3} at pressures higher than

12 kbar. There are 4 characteristic temperature regimes which provide information about different details of the Ge related donors:

(i) At temperatures $T > 140$ K no metastability is observed. The system, including the DX states, is in thermal equilibrium there. There E_F^* is pinned to the DX state and thus the position of E_F^* indicates the energy of the DX level, E_{DX}. The pressure dependence of E_{DX} is shown by dots in Fig. 1b.

(ii) In the temperature range 75 K $< T <$ 140 K, thermal emission from the DX state is much weaker than the optical one induced by the IR LED and E_F^* is established by the steady state equilibrium between optical emission of electrons from the DX state and the thermally activated capture of electrons to the DX state. It was shown by Jantsch et al. [4, 5] that under these conditions, a linear extrapolation of E_F^* to $T = 0$ K indicates the energy of the top of the barrier between DX and the neutral states (shallow and A_1 state), E_B^{DX}. The positions of the E_B^{DX} for different pressures, as obtained by a linear extrapolation towards zero temperature, is shown in Fig. 1b by open circles.

(iii) For 50 K $< T <$ 80 K, the thermal electron recapture to the DX states is already frozen and under illumination no DX states are occupied. Nevertheless, the temperature is still high enough to treat the subsystem of neutral donors and conduction electrons as remaining in equilibrium. Consequently, E_F^* is pinned to the A_1 level indicating its energetic position, E_{A_1}. Proof for the neutral charge of this donor state was given in [1] and the name "A_1" is inferred from the paper of Wasilewski et al. [6] and Dmochowski et al. [7]. The pressure variation of E_{A_1} is depicted by full squares in Fig. 1b.

(iv) In the low temperature range an additional giant increase in photoconductivity is observed for pressures higher than 13 kbar, seen as an increase in E_F^* below 50 K in Fig. 1a. Switching the light off leads to a decrease in the electron concentration by orders of magnitude to values which correspond to an E_F^* located at the A_1 state. For pressures higher than 14 kbar, low temperature measurements were possible only under illumination. The linear dependence of E_F^* vs. temperature results from the steady state equilibrium between optical emission from and recapture to the A_1 state. According to a similar approach as presented by Jantsch et al. for the DX case [4], extrapolation of E_F^* for $T = 0$ K indicates the top of the barrier for the A_1 state, $E_B^{A_1}$. The experimental points (see Fig. 1b) show that $E_B^{A_1}$ coincides with the CB edge and does not depend on pressure. The coincidence between $E_B^{A_1}$ and the CB edge suggests, however, that there is no substantial lattice barrier and the conduction electrons can be trapped practically without any activation energy. In such case the capture rate is described by the expression $\tau^{-1} = \sigma v_{th} n_{D+}$, where σ — capture cross-section, τ — the time constant of the transient, v_{th} — the thermal velocity of electrons and n_{D+} — the number of empty donor states (taking into account compensation). To evaluate whether electrons are captured from the CB or from electron traps, the temperature dependent kinetics was measured. The Arrhenius plot of the experimentally determined capture cross-section gives an activation energy of 5 ± 2 meV and $\sigma_{exp}(T \to \infty) \approx 10^{-20}$ cm^2. These two numbers show that the weakly temperature dependent capture — its activation energy is only of the or-

der of kT in the accessible range — is impeded mostly by the apparently very small capture coefficient $\sigma_{exp}(T \to \infty)$. Nevertheless, weak activation behaviour of σ_{exp} indicates that the observed kinetics is affected by additional traps (located below the CB edge or mobility edge). When the concentration of the electrons on these traps (n_t) is higher than the concentration of mobile electrons (n_c), then the capture cross-section for the A_1 state, σ, is given by the following equation: $\sigma \approx \sigma_{exp} \frac{n_t}{n_c}$. This means that σ is in the order of 10^{-17}–10^{-20} cm^2 depending on n_t ($n_c \approx 10^{13} - 10^{14}$ cm^{-3}, while $n_c < n_t < 10^{18}$ cm^{-3}). Whatever concentration of traps is assumed, this very rough approximation shows that the A_1 state has an extremely small capture cross-section.

In summary, we conclude that a new giant photoconductivity is caused by the A_1 state which exhibits an exceptionally small effective capture cross-section, indicative of some orthogonality of CB states and the A_1 symmetry donor states. Our results are in agreement with the finding of very weak anticrossing of the A_1 — and effective mass like states by Wasilewski [6].

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