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ELECTRIC FIELD ENHANCED EMISSION OF HOLES FROM THE DOUBLE DONOR LEVEL OF THE EL2 DEFECT IN GaAs

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Strong electric-field enhancement of the thermal emission rate of holes from the doubly ionized charge state of the EL2 defect was revealed with the deep-level transient spectroscopy in *p*-type GaAs and analyzed in a model of phonon-assisted tunnel effect. Similar dependence observed for the electric field directions parallel to three main crystallographic axes suggests tetrahedral symmetry of the defect which is consistent with its identification as the arsenic antisite.

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1. Introduction

Technologically important native defect in GaAs, known as EL2, introduces two deep energy levels into the band gap. Apart from the well-known midgap level corresponding to the single donor level (0/+) of the defect, it gives rise to the double donor level (+/++) in the lower half of the band gap [1]. Although the EL2 defect was a subject of very extensive research in the past decade, much less attention has been focused on its double donor level mainly because of difficulties in preparing good-quality Schottky diodes on *p*-type GaAs. A deep-level transient spectroscopy (DLTS) peak in *p*-type GaAs corresponding to a hole-emission activation energy of 0.52 eV was attributed to this level by Lagowski et al. [2], however, the energy value of 0.54 eV was obtained for the level from more recent investigations [3].

In the present paper we report an electric-field enhancement of the thermal emission rate of holes from the doubly ionized charge state of the EL2 defect observed with the DLTS technique in *p*-type GaAs Schottky diodes.

2. Experimental

Two kinds of Zn doped liquid-encapsulated Czochralski (LEC) grown crystals with different shallow-acceptor concentrations were investigated in order to obtain the emission rates over a large variation of the electric field. The hole concentration was 5×10^{16} cm^{-3} in the crystal A (supplied by ITME, Poland) and 1.4×10^{17} cm^{-3} in the crystal B (supplied by Wacker-Chemitronic, Germany).

Schottky diodes were performed by Al and Au evaporation onto either the (100) or (110) or (111) surfaces of the samples cut from both crystals. Before evaporating the samples were chemically polished and passivated in ammonium sulfide [4] in order to increase barrier height of the diodes. The diodes exhibited the barrier heights in the range from 0.75 to 0.80 V, as measured from their forward-bias I–V characteristics, and the leakage current below 10^{-4} A/cm^2 at the reverse bias of 3 V.

The measurements of electric field effect on the hole thermal emission were performed using the double-correlation DLTS technique [5] to obtain emission rates corresponding to well-defined electric field intensities, which were calculated from the C–V data. The experimental results, presented in Figs. 1 and 2, were obtained from DLTS spectra recorded with three emission rate windows for each field intensity and analyzed to obtain the activation energy and prefactor for thermally activated emission.

3. Results and discussion

A hole trap associated with the double donor level of the EL2 defect was the dominant deep-level trap revealed with DLTS in the both investigated crystals. Its activation energy was 0.54 eV when measured at a low electric field and shifted to lower values for higher field intensities. The trap concentrations in the crystals A and B were 6×10^{15} cm^{-3} and 5×10^{15} cm^{-3}, respectively. The hole-emission rates from the traps as a function of the electric field measured in the samples with different orientations cut from the crystal A are presented in Fig. 1. Similar dependence observed for the field directions parallel to the three main crystallographic axes indicates tetrahedral symmetry of the EL2 defect being in the doubly ionized state.

The dashed line in Fig. 1 represents an enhancement of emission rate with electric field as predicted by the classical Pool–Frenkel effect [6] calculated for a single acceptor trap with the attractive Coulombic potential. In the case of hole emission from a doubly ionized donor, which we deal with in the experiment, repulsive Coulombic interaction between the emitted hole and the positively charged center should result in a still weaker electric-field dependence of the emission rate. On the contrary, as seen from Fig. 1, the measured hole-emission rates show, for the electric field intensities larger than 1×10^5 V/cm, a much stronger field dependence thus suggesting a phonon-assisted tunneling of holes from the deep level to the valence band [7].

The experimental results for both crystals, covering a broader range of electric-field variation, show an enhancement of the emission rate by over three

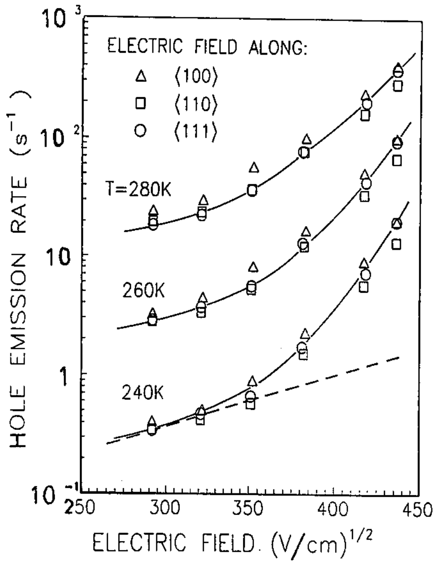

Fig. 1. Electric-field dependence of hole-emission rates from the doubly ionized EL2 defect at various temperatures measured in the samples of different orientations cut from the crystal A. The dashed line represents an electric-field enhancement of emission rate according to the classical Pool–Frenkel effect. The solid lines act as a guide to the eye. Note the square root of the electric field intensity is plotted on the abscissa.

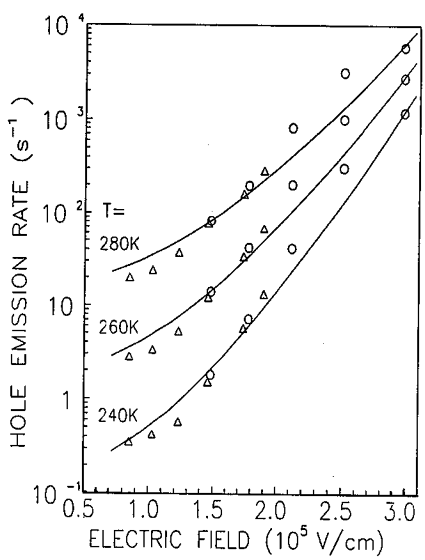

Fig. 2. Electric-field dependence of hole-emission rates from the doubly ionized EL2 defect measured in the crystal A (triangles) and B (circles) at various temperatures. The solid lines represent theoretical fit with a model of the phonon-assisted tunneling.

orders of magnitude for the threefold increase in the electric field (Fig. 2). The results were fitted with the quantum theory of the phonon-assisted tunnel effect proposed by Makram-Ebeid and Lannoo [7]. The theoretical curves, denoted with solid lines in Fig. 2, describe both the temperature and field dependence of the experimental data yielding a large value of the Franck–Condon shift, $S\hbar\omega$, of about 180 meV.

In conclusion, a very strong electric-field enhancement of the thermal emission rate of holes from the double donor level of the EL2 defect was observed in p-type GaAs. The effect can be described using a model of the phonon-assisted tunneling emission with a strong coupling of the defect to the lattice vibronic modes. The fact that the effect is the same when measured at the field directions parallel to the three main crystallographic axes provides an argument for tetrahedral symmetry of EL2 which is consistent with the defect identification as the As antisite.

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