Spectroscopy of THz radiation induced by impact ionization of shallow acceptors in Ge

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Abstract—**We report results of spectroscopic studies of terahertz (THz) spontaneous emission at conditions of electrical breakdown of impurity centers in Ge(Ga) with N_a-N_d~ 1.6x10^{14} cm^{-3}. The samples were deformation-free or subjected to compressive strain along [111] axis. The experiments were performed at T~5 K with using a step-scan Fourier spectrometer. The maximum level of the compressive strain was 3 kbar.**

I. Introduction And Background

In the recent years, there has been increasing interest in terahertz (THz) (0.1-10 THz) sources with electrical pumping. These devices potentially can be compact, reliable and cost effective and, therefore, may find the applications in a variety of disciplines (e.g. biology, chemistry and medicine). THz sources employing low energy optical transitions of non-equilibrium carriers stimulated by impact ionization of shallow impurity states in semiconductor crystals are of particular interest. The structure of energy levels for a shallow acceptor in Ge crystal allows achieving of population inversion and THz stimulated emission in the uniaxially deformed p-Ge due to resonant-state lasing mechanism [1]. In spite of observation of THz emission at electrical breakdown of impurity states in Ge has been reported long time ago [2], the understanding of spectral properties of this radiation is far from being complete. Here we present results of the spectral and polarization resolved studies of THz radiation from p-Ge crystals under electrical breakdown of shallow acceptors.

II. Experimental Detailes

The THz emission spectra were measured using a step-scan Fourier spectrometer for a range of 5-350 cm^{-1}. The radiation was detected by liquid-He cooled Si bolometer using lock-in technique, as described in [3]. The experiments were performed on Ge(Ga) samples with a resistivity of 20 Ω cm (N_A-N_D~ 1.6x10^{14} cm^{-3}). To create uniaxial compressive strain in the [111] direction the sample was embedded in an organic glass frame and the entire assemblage was cooled down to low temperature in a helium cryostat. Calibration and measurements of the stress in p-Ge samples achieved in our setup were implemented optically. It was done by the measurements of THz photoconductivity spectra for deformation-free and deformed samples, and a comparison of the results with published data [4]. The results show that the level of stress is 3±0.3 kbar at T=5 K. The sample holder design allowed for rotation of the sample around optical axis of the cryostat. This property in combination with a linear polarizer placed in front of the Fourier spectrometer allowed us to analyze the emission polarization against the stress axis (**e** ⊥ **P** and **e** || **P** geometries, respectively).

III. Results And Discussion

Typical spectrum of THz electroluminescence observed for deformation-free Ge(Ga) near the impurity breakdown threshold is shown on the Fig. 1. The THz emission is unpolarized as expected from a simple symmetry analysis. The spectrum demonstrates emission lines resulting from the optical transitions of non-equilibrium holes between exited and ground states of the acceptor (lines at 8.3 and 9.7 meV, see Fig. 1a) and also optical transitions from states in the valence band to the acceptor ground state (line at 13 meV). The transitions from the second excited acceptor state ($2\Gamma_8^-$) dominate in the emission spectrum near the acceptor breakdown threshold for deformation-free Ge(Ga) crystals ($2\Gamma_8^- \rightarrow 1\Gamma_8^+$ optical transitions, line at 8.3 meV). The contribution of optical transitions from the valence band states increases with the electric field increase. It is important to note

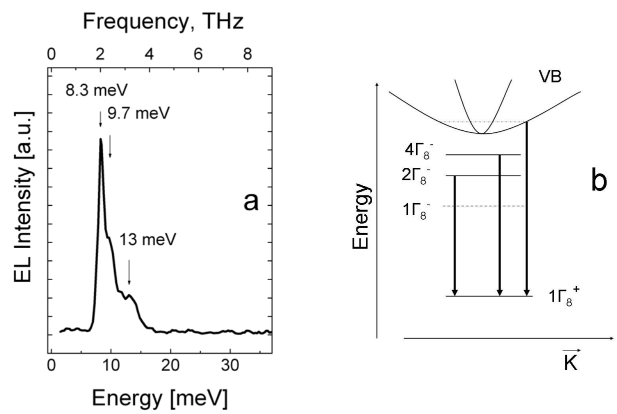

Fig. 1. a) THz electroluminescence spectrum for a deformation-fee Ge(Ga) sample at T=5 K and E=7.5 V/cm.
b) A schematic picture of the optical transitions responsible for the THz emission near the impurity breakdown threshold in Ge(Ga).

that the transitions from the first excited acceptor state ($1\Gamma_8^-$) do not contribute to the emission spectrum (Fig. 1a) because of the oscillator strength for the $1\Gamma_8^- \rightarrow 1\Gamma_8^+$ transitions is almost two orders of magnitude lower than the value for the $2\Gamma_8^- \rightarrow 1\Gamma_8^+$ transitions [5].

A strong linear polarization of THz electroluminescence has been found for uniaxially deformed crystals. The emission polarization degree and the orientation of the emission polarization vector with respect to the strain axis change along the emission spectrum. The polarization level of order of 90% for the main emission lines is observed at the electrical bias fields close to the acceptor breakdown threshold and the stress P ~ 3 kbar. Fig. 2a shows THz electroluminescence spectra for a strained p-Ge(Ga) sample measured near the impurity

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breakdown threshold. The strong emission line at 7.6 meV in

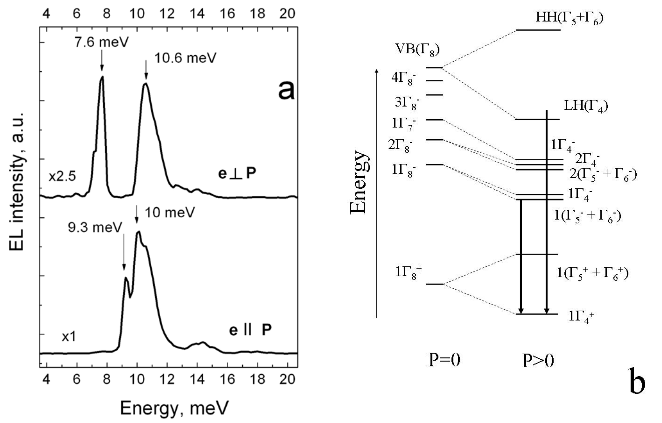

Fig. 2. a) Polarization resolved THz emission spectra of a Ge(Ga) sample uniaxially deformed along the [111] direction for T=5 K, E=5.43 V/cm and stress of 3±0.3 kbar.
b) Scheme of ground and several excited states of a shallow acceptor in Ge for the absence of strain and in the presence of uniaxial compressive strain along the [111] direction.

the spectrum for **e ⊥ P** polarization geometry is caused by optical transitions from the first exited acceptor state ($1\Gamma_{5+6}^{-}$) to the acceptor ground state ($1\Gamma_4^{+}$) (see Fig. 2b). The spectral position of this line and its high degree of linear polarization (ρ~93%) transversely to the strain axis support the attribution of this line to the $1\Gamma_{5+6}^{-} \rightarrow 1\Gamma_4^{+}$ transitions. These results indicate also that the oscillator strength for optical transitions from the first exited acceptor state grows enormously under uniaxial strain. The recent calculations [6] support our conclusion about the strain induced increase of the oscillator strength of optical transitions from the first acceptor excited states.

Apart of above mentioned spectral features we observe intense, strongly polarized emission lines with the spectral energies of 9.3, 10 and 10.6 meV (see Fig. 2a). These lines are predominantly polarized parallel to the strain axis and the polarization degrees of them attain 93, 67 and 40 % respectively near the impurity breakdown threshold. Most likely the emission line at 9.3 meV originates from optical transitions from an upper excited acceptor state of Γ_4^{-} symmetry to the acceptor ground state. The strong emission lines at 10 and 10.6 meV correspond with optical transitions from states in the light hole band (LH) (see Fig. 2b) to the acceptor ground state. However, the high level of linear polarization of the THz emission indicates that other type of optical transitions contributes to the emission in the region of ~ 10 meV. Optical transitions between resonant acceptor states, which originate from upper excited acceptor states under uniaxial pressure exceeding 2 kbar and concentrate near the bottom of the light hole band [4], and the localized ground acceptor state can contribute to the THz emission nearby 10 meV and can be responsibly for the high level of emission linear polarization. It is necessary to emphasize that the optical transitions from such resonant acceptor states can be responsible for low-threshold THz lasing earlier reported for axially strained p-Ge [7].

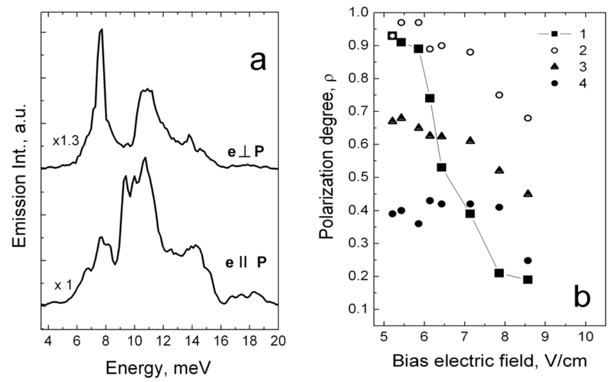

Fig. 3. a) THz emission spectra for a Ga(Ga) sample under enlarged electric field – 7.9 V/cm. T=5 K, uniaxial stress P in [111] direction is 3±0.3 kbar. b) Electric field dependence of the emission polarization degree for different emission energies: 1- 7.6 meV (**e ⊥ P**), 2- 9.3 meV (**e ∥ P**), 3- 10 meV (**e ∥ P**), 4- 10.6 meV (**e ∥ P**).

The emission polarization degree decreases with increase of bias electric field (Fig. 3). Though, the decay of the polarization degree under the electric field strength increase has different sharpness for the different emission lines (see Fig. 3b). We assign this decrease of the emission polarization level to growth of effective electron temperature of nonequilibrium carriers and, therefore, to increase of the population of high energy states. The population of high energy states increases the contribution of optical transitions with competing polarization selection rules. The decay of the polarization degree of the 7.6 meV line can be explain by increase of the population of the $1\Gamma_4^{-}$ state, which is close in energy to the $1\Gamma_{5+6}^{-}$ acceptor state, but is lying a bit higher [8]. Optical transitions from the $1\Gamma_4^{-}$ state are allowed also for the **e ∥ P** polarization [9]. It results in a reduction of total polarization of the THz emission at 7.6 meV under the increase of electric field, and the Fig. 3b demonstrates that. The reduction of the polarization degree of the emission in the region of 10 meV can be explained by contribution of optical transitions between heavy and light holes bands, which must be predominantly polarized transversely to the strain axis.

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