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Spontaneous Terahertz Emission under Electrical Breakdown of a Shallow Acceptor in Ge

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The spectra of spontaneous terahertz (THz) electroluminescence at the breakdown of shallow Ga acceptor in Ge were observed for the first time and investigated. We found and characterized the emission lines corresponding to the hole transitions between the excited states and the ground state of the impurity center as well as the transitions of the hot holes from the valence band to the impurity and within the valence band. A high quantum yield of the radiative transitions will become an important factor in designing electrically pumped THz emitters for the ≈ 2 THz spectral range.

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1. Introduction

At present time a booming interest in research and development of devices able to work in terahertz (THz) band of electromagnetic spectrum (0.1–30 THz) stems from the prospects of their applications in many highly important fields of science and technology, such as medicine and biology, nanotechnology, electronic circuits processing, antiterrorism programs, and many others. Recent demonstration of a unipolar semiconductor THz laser [1], operating at intersubband optical transitions in the quantum cascade structures, has become a serious step on the way towards solid-state current-driven THz sources. Recently, the paper [2] reported the observation of an intensive spontaneous THz emission resulting from the impurity electrical breakdown in a Si(B)-based structure. In Ge the impact ionization threshold for shallow impurity states occurs at considerably lower electric fields than in Si. Therefore the emission of THz radiation can be very efficient even at the fields as low as few V/cm [3–5]. Although the integral THz emission under the electrical breakdown of shallow acceptors in Ge was studied earlier (see, e.g., [5, 6] and references therein), the spectrum of THz emission near the

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breakdown of shallow acceptors in Ge has not been investigated yet. Furthermore, the optical transitions between shallow acceptor states under the conditions of an uniaxial stress in Ge were proposed in realizing the resonant-state THz lasing mechanism [7]. Therefore, the spectroscopic studies of radiative transitions involving acceptor states in Ge are of a high importance. In this paper we report on the measurements of spontaneous THz emission spectrum under the conditions of electrical breakdown of a shallow acceptor (Ga) in Ge.

2. Experimental details

The samples were made from p-Ge(Ga) of 10 Ω cm resistivity ($N_\mathrm{A} - N_\mathrm{D} = 4\times10^{14}$ cm^{-3}) by sectioning it into plates sized 15×6 mm^2 and 1.5 mm in thickness. The ohmic contacts were made by fusing indium with gallium into lateral faces of an area of 1.5×1.5 mm^2. The samples were mounted onto the copper cold finger of a helium optical cryostat. The sample mount was enclosed inside copper helium and nitrogen shields. The windows in the helium and nitrogen shields of the cryostat were made from black polyethylene and germanium, respectively. The temperature of the cold finger was monitored by a calibrated germanium resistance-thermometer placed in the vicinity of the sample. A bias on the sample was applied in the form of pulse "bundles". The pulse duration in a bundle was 10 μs for a frequency of 50 kHz. The bundle duration and frequency were 6.2 ms and 80 Hz, respectively. The emission spectra were recorded by a home made pump-out Fourier transform spectrometer. The THz signals were measured using a liquid-helium-cooled silicon bolometer (QMS Instruments) and SR-530 lock-in amplifier. The spectra were measured with a resolution of ≈ 1.2 meV (≈ 0.3 THz). More detailed description of the experimental setup is given in [8, 9]. The low-temperature THz photoconductivity spectra were measured on the same Ge(Ga) samples to verify the correlations between the emission and photoconductivity spectra.

3. Experimental results and discussion

Figure 1 shows the typical $I{-}V$ curve of the Ge(Ga) sample and also the dependence of the intensity of the THz emission in the 0.6–49 meV (0.15–12 THz) spectral range versus the bias. A strong increase in the current through the sample correlates with the breakdown field of ≈ 3.3 V/cm. It is seen that THz emission begins from bias voltages at or above the threshold for the impurity breakdown. The THz emission spectrum measured for a bias of 4.5 V on the contacts (the corresponding field strength is ≈ 7.5 V/cm) is shown in Fig. 2. The spectrum of photoconductivity signal measured for the same Ge(Ga) sample is also shown in Fig. 2. The emission spectrum near the impurity breakdown threshold demonstrates a narrow line with a maximum at ≈ 8.2 meV (1.99 THz), whose position is close to the photoconductivity signal threshold. This narrow emission line at 8.2 meV can be attributed to the radiative transition from the first excited state

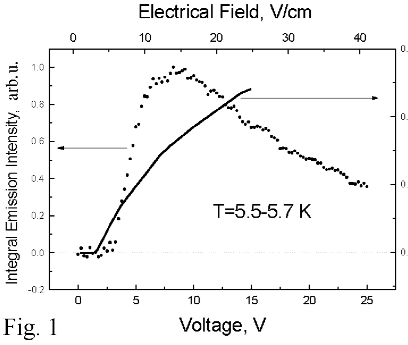

Fig. 1

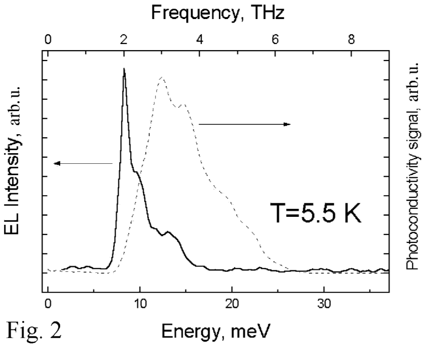

Fig. 2

Fig. 1. The $I-V$ characteristic (solid curve) and the THz emission intensity as function of the bias in p-Ge(Ga) sample ($N_\mathrm{A} - N_\mathrm{D} = 4 \times 10^{14}$ cm^{-3}) (circles). The dotted line corresponds to the zero-signal level. The temperature of the cryostat cold finger was 5.5–5.7 K in these experiments.

Fig. 2. The THz emission spectrum (solid line) at $V = 4.5$ V and $T = 5.5$ K. The dashed line corresponds to the photoconductivity spectrum. Signals have not been corrected for the spectral response of the measurement system.

to the ground state of Ga impurity in Ge ($2P{-}1S$ transition), in good agreement with a value of 10.8 meV known from literature for the impurity binding energy [10]. The high-energy asymmetry of the main line is caused by the contribution from a narrow line with a maximum at ≈ 9.7 meV (2.36 THz) and a broad line with a maximum at ≈ 13 meV (3.15 THz). The line at 9.7 meV corresponds to the optical transitions from one of the impurity excited states (e.g., $n = 3$) to the ground state. The emission at 13 meV is most probably due to the transitions of hot holes to the impurity ground state, while the characteristic energy of the holes involved in this transition should be ≈ 2.2 meV (effective temperature ≈ 26 K). The Monte Carlo calculations [11] of the nonequilibrium distribution function for the holes generated into the valence band through the impact ionization of shallow acceptors in electric field of ≈ 7 V/cm yield a value close to the indicated hole effective temperature in Ge.

It is seen from Fig. 1 that the THz emission increases at $V > 2$ V, reaches maximum at $V \approx 8.3$ V ($E \approx 13.8$ V/cm), and then decreases with increasing voltage. A maximum and a further slight decrease in the THz emission intensity as a function of voltage was observed in Ge(Ga) at the electric fields of the same order [7] and assigned to the intraband radiative transitions of nonequilibrium holes and to the streaming of the hole distribution function, respectively. A drop in the THz emission intensity observed in our experiment at $V > 8.3$ V is more pronounced than in [7] and can be caused, in addition to the aforementioned effects, by the influence of the lattice heating at voltages of order of 10–25 V.

Figure 3 demonstrates a set of THz emission spectra measured at 5, 7, and 15 V. The temperature of cold finger of the cryostat did not exceed ≈ 5.7 K in

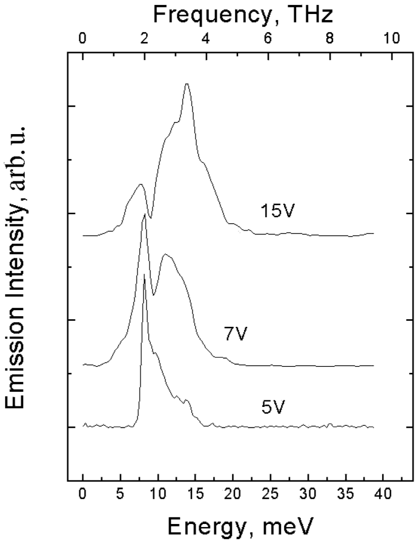

Fig. 3. The THz emission spectra at 5, 7, and 15 V. The THz signals are normalized to a maximum. The spectra are vertically shifted for clarity. The spectra have not been corrected for the spectral response of the measurement system.

these measurements. One can see that the emission spectrum changes substantially with a rise in the field strength. The contribution of optical transitions of hot holes from the valence band to the impurity ground state increases. Also one can see the appearance of low-energy wing of the $2P{-}1S$ line at higher electric fields. The latter spectral feature can be explained by the contribution from the intraband radiative transitions of nonequilibrium holes (most probably transitions between the states of heavy and light holes), resulting in the emission at energies of $\approx 3{-}7$ meV (0.75–1.69 THz).

The estimate of the power of THz emission gives the value of ≈ 17 nW for a p-Ge sample of $1.5 \times 1.5 \times 6$ mm^3 size and an input electric power of 1 W at $T = 5.6$ K. Such a high intensity of THz spontaneous emission observed from Ge(Ga) encourages further steps of design of relatively simple and inexpensive electrically pumped THz emitters.

4. Conclusion

The spectrum of spontaneous terahertz (THz) emission near the threshold of electrical breakdown of a shallow acceptor (Ga) in Ge has been measured for the first time. At temperatures of order of ≈ 5 K and the electric field of ≈ 7.5 V/cm the emission spectrum exhibits narrow lines with the maxima at 8.2 meV (1.99 THz) and 9.7 meV (2.36 THz). These energies correspond to the radiative transitions of holes from excited acceptor states to the ground acceptor state. A broad emission band at ≈ 13 meV (3.15 THz) results from the radiative transitions of hot holes between the free states in the valence band and acceptor ground state. The contribution of radiative hole transitions from the states in the valence band increases with an increase in the electric field strength. In addition, the optical transitions of holes between the states of heavy and light holes within the valence band appear in the emission spectrum at high electrical fields. The yield of terahertz emission typically achieves ≈ 17 nW with 1 W of the input electric power.

Acknowledgments

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References

[1] R. Köhler, A. Tredicucci, F. Beltram, H.E. Beere, E.H. Linfield, A.G. Davies, D.A. Ritchie, R.C. Iotti, F. Rossi, *Nature* **417**, 156 (2002).

[2] T.N. Adam, R.T. Troeger, S.K. Ray, P.-C. Lv, J. Kolodzey, *Appl. Phys. Lett.* **83**, 1713 (2003).

[3] S.H. Koenig, R.D. Brown, *Phys. Rev. Lett.* **4**, 170 (1960).

[4] S.R. Thomas, H.Y. Fan, *Phys. Rev. B* **9**, 4295 (1974).

[5] L.V. Berman, L.I. Gavrilenko, Z.F. Krasilnik, V.V. Nikonorov, S.A. Pavlov, A.P. Chebotarev, *Semiconductors* **19**, 369 (1985).

[6] Yu.L. Ivanov, in: *Voprosy fiziki poluprovodnikov (Materials of XI Winter School of Physics of Semicond.)*, Ioffe Institute, Leningrad 1984, p. 160.

[7] Y.P. Gousev, I.V. Altukhov, K.A. Korolev, V.P. Sinis, M.S. Kagan, E.E. Haller, M.A. Odnobludov, I.N. Yassievich, K.A. Chao, *Appl. Phys. Lett.* **75**, 757 (1999).

[8] N.N. Zinovev, A.V. Andrianov, V.N. Nekrasov, V.A. Petrovskii, L.V. Belykov, O.M. Sresely, G. Hill, J.M. Chamberlain, *JETP Lett.* **74**, 100 (2001).

[9] N.N. Zinovev, A.V. Andrianov, V.N. Nekrasov, L.V. Belykov, O.M. Sresely, G. Hill, J.M. Chamberlain, *Semiconductors* **36**, 226 (2002).

[10] R. Newman, W.W. Tyler, in: *Solid State Physics*, Vol. 1, Ed. F. Seitz, D. Turnbull, Academic Press, New York 1959, p. 50.

[11] W. Quade, G. Hüpper, E. Schöll, *Phys. Rev. B* **49**, 13408 (1994).