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SEMICONDUCTOR STRUCTURES, LOW-DIMENSIONAL SYSTEMS, AND QUANTUM PHENOMENA

Injection-Induced Terahertz Electroluminescence from Silicon *p*–*n* Structures

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Abstract—Injection-induced terahertz electroluminescence from silicon p^+–n structures is observed at helium temperatures. Structures fabricated by the diffusion of boron into a phosphorus-doped *n*-Si substrate are studied. Relatively narrow luminescence lines are observed in the luminescence spectra against a broad smooth background. The spectral position of a number of emission lines corresponds to optical transitions between excited donor states and the ground state of phosphorus donors. The intracenter optical transitions of electrons at phosphorus donors are excited as a result of recombination processes occurring in the *n*-type region of the structure under the injection of nonequilibrium holes. A number of other lines in the terahertz emission spectra are associated with intracenter transitions at acceptor centers, which are also excited as a result of injection. The structureless background in the electroluminescence spectra may be due to terahertz emission upon the intraband energy relaxation of "hot" carriers having an effective temperature exceeding the lattice temperature. These "hot" carriers appear in the structure under injection conditions.

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1. INTRODUCTION

Interest in terahertz electromagnetic radiation (frequencies of 0.1 to 10 THz) has been steadily increasing over the last two decades. This interest is due to prospects for the application of diagnostic and measuring terahertz (THz) systems in various fields of science and technology, including analytical chemistry, biology and medicine, remote control technology, safety systems, and systems for ecological monitoring of the environment [1–3]. Practical applications require THz radiation sources of various kinds, and intensive research in this direction is being conducted. Considerable progress has been achieved to date: semiconductor THz quantum-cascade lasers (QCLs) with electrical excitation have been developed [4, 5]. Nevertheless, THz quantum-cascade lasers remain rather technologically complicated, and only a few laboratories in the world have mastered the fabrication technology of these lasers [1, 4, 5]. At the same time, numerous practical applications need comparatively simple THz radiation sources of the type of a THz light-emitting diode. One of the possible schemes of a comparatively simple THz emitter can be implemented on the basis of optical transitions between shallow impurity levels in semiconductors. Intracenter THz radiative transitions occur upon the energy relaxation of nonequilibrium charge carriers excited from impurity centers into an allowed band, e.g., as a result of the impact ionization of impurities in an electric field [6–10], or upon the photoionization of impurity centers by light from a CO_2 laser [11, 12]. It is important to note that THz lasing has been obtained at intracenter transitions in Ge and Si [7, 11, 12]. It has been shown recently that intracenter radiative transitions can also be excited upon the interband optical pumping of semiconductors doped with shallow impurities, and THz photoluminescence (PL) of this kind has been observed in quite a number of materials [13–15]. THz PL is due to the specific features of nonequilibrium charge-carrier recombination involving impurity centers. This recombination results in the formation of a system of charged impurity centers (e.g., donors) and free charge carriers in the allowed band (e.g., electrons in the conduction band). The capture of free charge carriers by charged impurities is accompanied by THz emission, similarly to the situation that occurs in the electrical breakdown of impurity centers [6–10]. It should be emphasized that similar processes may also give rise to impurity-related THz emission upon the electrical injection of nonequilibrium charge carriers into a doped material, e.g., in *p*–*n* structures. This kind of THz electroluminescence (EL) has been observed recently in structures with a *p*–*n* junction based on 4*H*-SiC [16]. THz emission sources based on impurity-related transitions in silicon are of particular

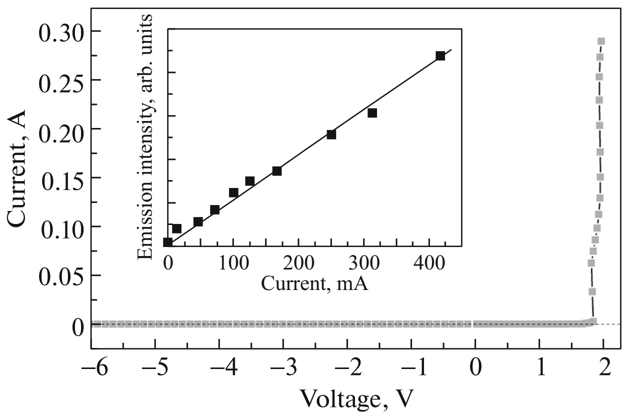

Fig. 1. I–V characteristic of a p^+–n structure at $T \approx 7$ K. The inset shows the dependence of the integrated intensity of the THz emission on the amplitude of the injection current pulse.

interest because they allow direct integration with silicon electronics.

In this work, we report the discovery and analysis of THz EL from forward-biased p–n structures at helium temperatures ($T \approx 7$ K).

2. EXPERIMENTAL

The study was carried out on asymmetric p^+–n structures fabricated by the diffusion of boron into an n-Si substrate with a resistivity of 250 Ω cm (phosphorus is the main impurity; the uncompensated donor concentration is $N_D - N_A \approx 2 \times 10^{13}$ cm^{-3}). The concentration of uncompensated acceptors in the p^+ region of the structure was $N_A - N_D \sim 10^{20}$ cm^{-3}. These doping parameters of the structures provided the nearly single-sided injection of nonequilibrium charge carriers under forward bias, specifically, the injection of holes into the n-type region. The substrate thickness was 400 μm, and the thickness of the p^+-type region was ~1 μm. The samples to be studied were fabricated in the form of 3 × 3 × 0.4 mm rectangular parallelepipeds. A solid electrical contact to the substrate was deposited onto the lower face of the sample. A second contact (to the p^+-type region) was deposited onto the upper face of the sample in the form of a disk with a window diameter of 1.5 mm.

The samples under study were mounted on the cooling finger of a helium optical cryostat optimized for the THz spectral range. Electrical bias was applied to the samples in the form of a pulse train with a repetition frequency of 75 Hz. Each train contained 8 pulses with a width of 220 μs and a time interval between pulses of 660 μs. This bias was chosen to minimize the influence exerted by the Joule heating of the samples on the measurement results. Spectral measurements were made with a Fourier spectrometer for the spectral range 5–350 cm^{-1} with step-by-step scanning of the interference pattern, as described in detail in [10, 17]. In most cases, the spectral resolution was 8 cm^{-1}. The THz radiation signal was measured with a Si bolometer cooled by liquid helium by the lock-in detection method at a repetition frequency of pulse trains of the electrical bias of 75 Hz. In the course of measurements, the temperature of the cooling finger of the cryostat did not exceed 7 K, which was monitored with a germanium resistive thermometer attached in close proximity to the sample under study.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows a dc current–voltage (I–V) characteristic typical of the silicon p^+–n structures under study, measured at $T \approx 7$ K. It can be seen that the structures have more or less ordinary rectifying properties even at helium temperatures. At an impurity concentration of ~10^{20} cm^{-3} in the p^+-type region of the silicon structure, the impurity centers are delocalized and the hole gas is degenerate. Therefore, there is normal current flow through the structure due to the injection of holes into the n-type region of the structure in a wide temperature range, including helium temperatures.

Measurements of the spectrally integrated THz radiation in the working frequency range of the Fourier spectrometer demonstrated that emission is only observed for forward-biased structures. In this case, THz EL is seen upon observation both from the side of the upper face and from the sample edge. It was found that, in the latter case (upon observation from the edge of the structure), the intensity of the THz radiation was several times higher than that observed through the upper face. This is in all probability due to the greater influence exerted by free-charge-carrier absorption in the p^+-type layer of the structure in the case when emission emerges perpendicularly to the upper face. Therefore, the main THz EL measurements were made in the configuration in which emission was observed from the edge of the structures. The inset in Fig. 1 shows how the signal of the integrated THz EL depends on the pulse amplitude of the current through the structure. It can be seen that the THz EL intensity nearly linearly depends on the injection current.

Figure 2 shows the characteristic spectrum of injection-induced THz EL from silicon p^+–n structures. It can be seen that the THz emission spectrum contains a smooth broad background onto which comparatively narrow emission lines are superimposed. A similar type of THz EL spectra has also been observed previously in p^+–n structures based on 4H-SiC [16].

Control experiments were performed, in which the temporal characteristics of the integrated THz EL from Si-based p^+–n structures were measured with a fast THz photodetector based on a Ge:Ga photoresis-

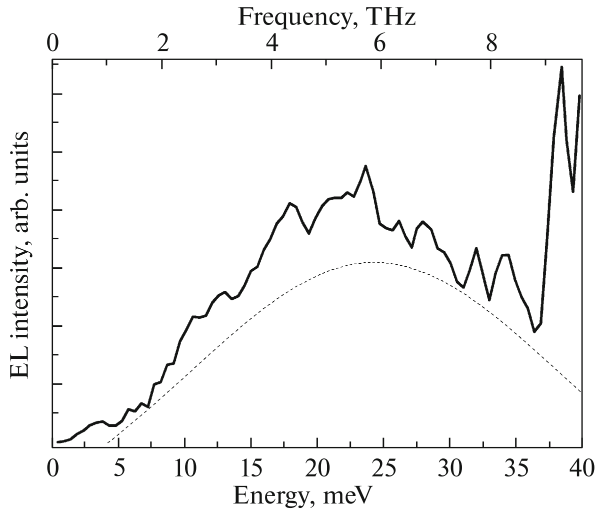

Fig. 2. THz EL spectrum of Si-based p^+–n structure at a bias pulse amplitude of 2.4 V and current pulse amplitude of 400 mA. The emission spectrum is normalized to the spectral sensitivity of the measuring system. The dashed curve represents the smooth function chosen to fit the background.

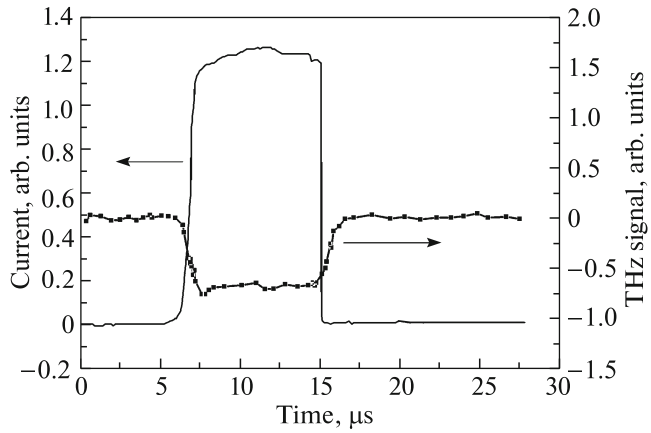

Fig. 3. Pulse shapes of the forward current pulse through the Si-based p^+–n structure under study and the THz emission signal measured by a THz detector based on a Ge:Ga photoresistor situated close to the structure.

tor situated close to the silicon structure under study. The experiments demonstrated that the THz EL signal is rather fast (see Fig. 3) and reproduces the shape of the injection-current pulse to within the response time of the photodetector (the response time of the Ge:Ga photodetector, found in a separate experiment to be ~(1.3–1.5) μs, was determined by the cable capacitance and ballast resistance in the photoconductivity circuit). This fact indicates that the observed THz EL from the p^+–n structures is of purely electronic nature, whereas the thermal contribution that could be possible due to lattice heating is unimportant under the experimental conditions. The broad background in the THz EL spectrum (see Fig. 2) is possibly due to THz emission upon the intraband energy relaxation of hot carriers with an effective temperature T_e exceeding the lattice temperature, which appear in the structure due to injection.

The structureless background can be mathematically subtracted from the observed THz emission spectrum by using a fitted smooth function (for an example of such a function, see Fig. 2) describing the background. Figure 4 shows a modified THz emission spectrum obtained after subtraction of the background.

A number of emission lines in the THz emission spectrum (Fig. 4) rather well agree in their spectral positions with the expected lines of intracenter optical transitions at phosphor donors in Si [18]. The lines with a peak at 21.5 and 34.2 meV can be attributed to the optical transitions of electrons from the excited state $2P_0$ of the phosphor donor to sublevels $1S(E)$ and $1S(A_1)$ of the ground state of the donor, respectively. The emission line at 23.2 meV is close in energy to optical transitions between the $2P_0$ and $1S(T_2)$ states of the phosphor donor. The THz emission lines peaked at 28.4 and 31.9 meV can be interpreted as optical transitions to the $1S(T_2)$ sublevel of the ground state of the phosphor donor from the excited states $3P_0$ and $4P_\pm$, respectively, which is in good agreement with the data on far-IR absorption in Si:P [18].

THz emission due to intracenter transitions at phosphor donors under the injection of nonequilibrium holes into the n-type region of the structure may appear as a result of h–D^0 recombination (free hole–electron bound to a donor) [13, 14] and also as a result of donor–acceptor recombination [16]. Recombination processes of this kind result in the formation of a

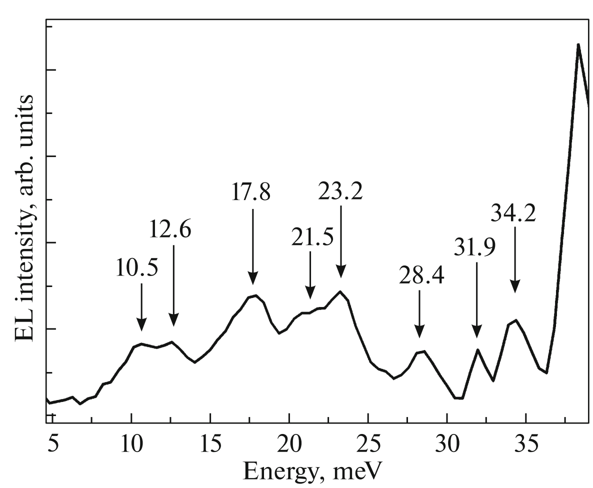

Fig. 4. THz EL spectrum obtained from the experimentally measured spectrum by subtraction of the background. The arrows mark the emission line peaks discussed in the text; the energies are given in meV.

system of ionized donors and free electrons in the n-type region, with free electrons coming to the n-type region of the structure from the contact to maintain electroneutrality in this region. In turn, the capture of free electrons by ionized donors is accompanied by intracenter transitions and, accordingly, gives rise to THz luminescence.

The THz emission spectrum also contains lines with a peak at 10.5, 12.6, and 17.8 meV, which cannot be attributed to intracenter transitions in phosphor donors. It is not improbable, however, that these lines may be due to optical transitions at acceptor centers. Indeed, estimates made with consideration for the results of [19, 20], where the energy spectrum of acceptor states in Si, including the boron impurity, were calculated, demonstrate that intracenter optical transitions with these energies are possible in acceptors. The excitation of intracenter transitions at acceptor centers may also occur as a result of the injection of nonequilibrium charge carriers in the structures under study. The feature at 38.4 meV, seen at the boundary of the experimentally available range (see Fig. 4), is possibly also related to THz optical transitions at acceptors associated with the boron impurity. It is noteworthy that the absorption line at 38.4 meV is well known for Si:B and belongs to the so-called 3/2 series in the far-IR absorption spectra [21].

Thus, the THz EL induced by the current injection of nonequilibrium charge carriers was discovered in silicon p^{+}–n structures at helium temperatures and studied. It was found that the emission is fast and has a purely electronic nature. The THz EL spectrum is a superposition of a smooth broad background and comparatively narrow emission lines. The peaks of a number of THz emission lines, found upon subtracting the smooth background, are in rather good agreement with the energies of the intracenter optical transitions from excited states to the sublevels $1S(E)$, $1S(T_2)$, and $1S(A_1)$ of the ground state of the phosphor donor, which is the main doping impurity in the n-type region of the structure. The intracenter optical transitions of electrons in phosphor donors are excited as a result of recombination processes initiated by the injection of nonequilibrium holes into the n-type region from the p^{+} emitter. Several lines in the THz EL spectrum can be attributed to the intracenter optical transitions at acceptor centers, which can also be excited as a result of injection. The smooth background observed in the THz EL spectrum is probably due to the emission generated upon the intraband energy relaxation of hot carriers. These hot carriers with an effective temperature exceeding the lattice temperature may appear in the structure under injection conditions.

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