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THz lasing of SiGe/Si quantum-well structures due to shallow acceptors

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An intense THz emission was observed from strained SiGe/Si quantum-well structures under strong pulsed electric field. The p-type structures were MBE-grown on n-type Si substrates and δ-doped with boron. Lines with wavelengths near 100 microns were observed in the emission spectrum. The modal structure in the spectrum gave evidence for the stimulated nature of the emission. The origin of the THz emission was attributed to intra-centre optical transitions between resonant and localized boron levels.

Introduction Recently, the activity towards the quantum cascade THz laser on the basis of SiGe/Si heterostructures has started [1]. Here we discuss the possibility to create an alternative type of THz laser sources which could utilize a much simpler quantum-well (QW) structures, i.e. a resonant-state laser (RSL) [2, 3]. Population inversion in the RSL is realized for the states of a shallow acceptor split under external stress. If the strain is high enough (above ~3 kbar for Ge), the split-off acceptor state enters the light-hole branch of the valence band and creates a resonant state [4]. An applied electric field depopulates the local impurity states due to impact ionization. A population inversion of resonant states with respect to the impurity states in the gap is then formed [5] and THz lasing occurs.

Since thin layers of binary alloys like, for example, $Si_{1-x}Ge_x$, are strained internally due to the lattice mismatch, acceptor levels are split initially, and stimulated emission can, in principle, be obtained just by applying electric field. Acceptor-doped $Si_{1-x}Ge_x$ is very attractive for fabricating the RSL because of its good thermal properties, low absorption in the THz range, well established, relatively cheap technology, as well as possible integration with Si-based electronics.

Earlier, we have reported on the observation of stimulated THz emission from boron-doped $Si_{1-x}Ge_x$ quantum wells [6]. In this report, we present studies of the emission from $Si_{1-x}Ge_x$/Si structures of various potential and doping profile. We also present evidence that the lasing is a result of population inversion between resonant and localized acceptor states similar to that in bulk p-Ge. A transverse electric field is found to affect the appearance of the resonant states.

Experimental We studied p-type $Si_{1-x}Ge_x$ structures MBE-grown pseudomorphically on n-type Si substrates. The SiGe QW was sandwiched between Si buffer and cap layers and was δ-doped with boron in the QW middle with the concentration of 6×10^{11} cm^{-2} (Fig. 1 a). Both, the buffer and cap layers, were

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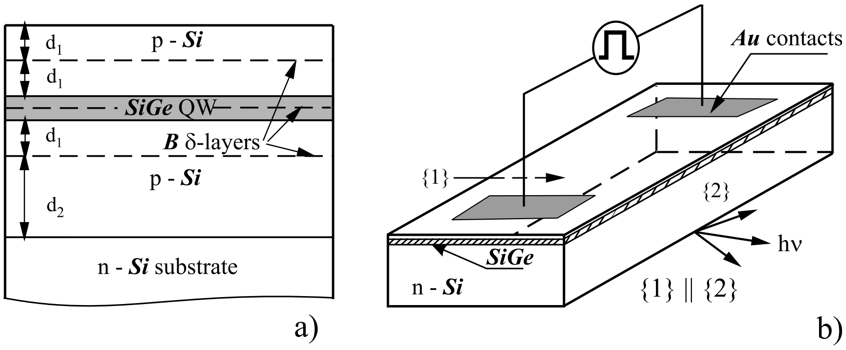

Fig. 1 Schematic view of structure (a) and laser design (b).

doped with one B-δ-layer. Two kinds of structures were used. In type-I QWs, the well was 20 nm thick and Ge content x in SiGe alloy was 0.15. The thickness of cap and buffer layers was 60 and 130 nm, respectively. The boron δ-layers in the barriers, with concentration from 4×10^{11} to 10^{12} cm^{-2}, were positioned each at the distance $d_1 = 30$ nm from respective QW interfaces. The QW thickness in type-II structures was about 13.5 nm. Other parameters (see Fig. 1a) were: $x = 0.15$, 0.1, and 0.07, and $d_1 = 19$ nm and $d_2 = 62$ nm. The concentration of B in the δ-layers was 6×10^{11} cm^{-2}.

We used pulsed bias of 0.2 to 4 µs duration in order to avoid overheating. Bias was applied to the SiGe layer via thermal-diffusion made Au contacts as shown in Fig. 1b. The distance between contacts was 6 mm. Emission spectrum was measured by a grating monochromator and registered with a cooled Ga-doped Ge photodetector. Measurements were made at temperatures between 8 and 30 K.

An optical resonator was formed due to the total internal reflection between the top and bottom surfaces of the sample, which were perpendicular to the growth direction, and two lateral facets ({1} and {2} in Fig. 1b) which were parallel polished.

For the samples with the optical resonator, we observed that an intense THz emission arose at a threshold voltage above 100 V. Spectra of the intense emission were measured in the energy range of 9.8 to 15.5 meV. Shown in Fig. 2a are parts of the spectra indicating lines for the samples of type I (Fig. 1a). The peak near the wavelength 104 µm is observed. The spectral position of the peak varied from 103 to 108 µm for different samples. At higher voltages, it was possible to observe additional maxima at larger wavelengths, shown in the inset of Fig. 2a. The line near 100 µm was observed in type-II samples with 0.15 Ge content (Fig. 2b). The intense emission was observed also from the type-II samples with $x = 0.1$

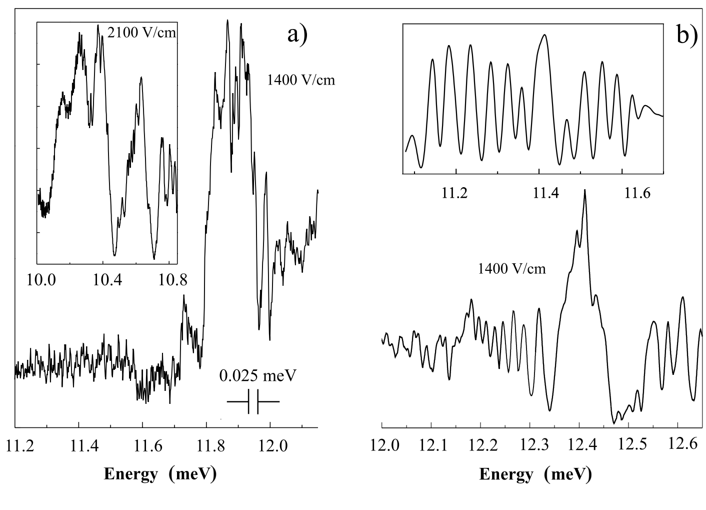

Fig. 2 Spectra of stimulated THz emission in structures of type I (a) and type II (b) at 1400 V/cm. Insets: a) additional lines arisen in the spectrum at 2100 V/cm, b) modal structure.

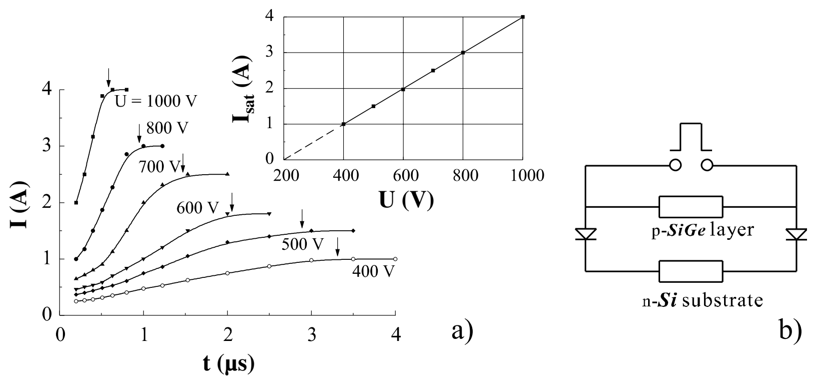

Fig. 3 a) Current vs. time during thermal breakdown of the substrate. Arrows show the onset of stimulated emission. Inset: voltage dependence of saturation current. b) Equivalent circuit of SiGe/Si structure.

and 0.07. Shown in the inset in Fig. 2b is the modal structure of the emission for one of the samples. The distance between lines is near 0.04 meV and corresponds to an optical path inside the structure due to total internal reflection. Line widths of modes observed are not larger than those determined by the spectral resolution of the monochromator (the width of output slit) and allow us to estimate the value of resonator quality; it is better than 300.

Discussion We believe that the lasing we have observed results from a population inversion in the QW layer due to the resonant states of boron. The resonant acceptor state is created when the energy splitting between the ground and split-off acceptor states exceeds the binding energy. In the case of $Si_{1-x}Ge_x$ structures, the splitting energy of the valence subbands is about 31 meV [7]. According to variational calculations, the binding energy of shallow acceptors is about 27 meV; the same value was obtained [7] for the energy difference between the split-off acceptor state and the edge of higher-energy valence subband. Thus, one can expect that the internal strain in the $Si_{1-x}Ge_x$ layer is sufficient for the split-off state to become resonant. The situation can be improved by an existence of built-in strong electric field, as the position of space-quantization levels is controlled by electric field. We have shown [8] that the built-in transverse electric field exists in our structures due to surface charge. Additional transverse electric field arises due to thermal ionization of donors in the substrate, caused by Joule heating of the SiGe layer. Time dependence of this process is shown in Fig. 3. The intense emission arises, as a rule, at the beginning of current saturation. As a result of donor ionization, the substrate resistance decreases strongly (200 Ω for Fig. 3, see the inset). A potential drop on one of two p–n junctions (it is just a cut-off voltage in the inset) between p-contacts and n-Si substrate (Fig. 3b) which acts as a barrier, creates rather large transverse electric field between SiGe layer and the substrate. This field inclines the valence subbands in the QW and gives the possibility for resonant states to appear even if the internal strain is insufficient.

Calculations [6] show that Fermi energy in our structures is near the first level of size quantization in the QW. The ionization of donors in the substrate can effect on Fermi level position due to a compensation of acceptors in SiGe layer by electrons from the substrate. The compensation should improve the conditions for intra-impurity inversion.

In conclusion, we have demonstrated THz lasing by SiGe/Si QW structures. The lasing is attributed to stimulated intra-centre transitions between the resonant and localized states of shallow acceptors. Thus, SiGe structures δ-doped with boron are promising for realisation of resonant-state laser (RSL) operating in THz region.

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