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THz lasing due to resonant acceptor states in strained p-Ge and SiGe quantum-well structures

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An intense THz emission was observed from strained SiGe/Si quantum-well structures under a 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-center optical transitions between resonant and localized boron levels similar to that in compressed p-Ge.

Introduction Recently, 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 source which could utilize a much simpler quantum well (QW) structure, 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 uniaxial 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 localized 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.

The resonant states can appear for different reasons, e.g., they should exist in $Si_{1-x}Ge_x/Si$ structures which are strained internally due to the lattice mismatch. 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.

Compressed p-Ge Earlier we have demonstrated the continuous-wave (cw) operation of RSL [6] with a possibility of broadband tuning by pressure in the range between 2.5 THz and 10 THz. The lasing begins at voltages of impurity breakdown. At the impurity breakdown conditions, a current filament arises. That is why the conditions for low-voltage lasing are much harder than for high voltages when the current density is uniform in the whole sample. At low voltages, only the current filament acts as an active region. Therefore, one needs to have a high-quality resonator to excite low-voltage lasing. In our case of a resonator formed by parallel sample planes due to total internal reflection, the plane parallelism should be better than 5 arcsec to get cw operation.

Figure 1 shows the spectra of THz emission from compressed p-Ge at low voltage at which cw operation of RSL is possible and, for comparison, at high voltage [7]. The upper curve shows that the low-

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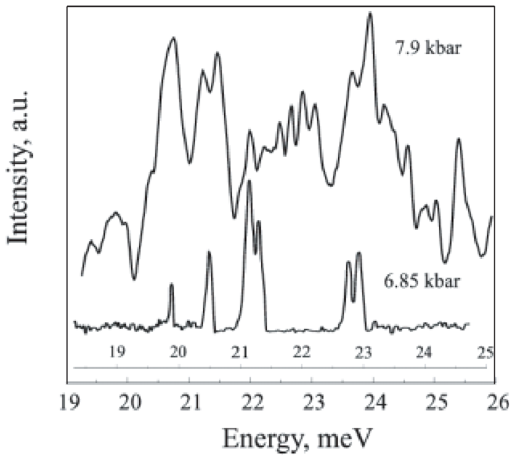

Fig. 1 THz emission spectra at 14 V/cm (upper curve) and 3 kV/cm pulsed (0.5 μs) electric field.

voltage stimulated emission spectrum contains several peaks corresponding to direct optical transitions between different resonant and localized acceptor states. The structure of the spectra shows that the nature of low-voltage stimulated emission is the same as at high fields, in spite of the heating of holes by electric field that is different in these cases: at high voltages carriers accomplish so-called streaming motion while at low voltages the heating is diffusive.

Strained SiGe structures Earlier, we have reported on the observation of stimulated THz emission from boron-doped $Si_{1-x}Ge_x$ quantum wells [8]. Here 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 the result of a population inversion between resonant and localized acceptor states similar to that in bulk p-Ge.

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. 2a). Both the buffer and cap layers were doped with one B-δ-layer. Two kinds of structures were used. In type-I QWs, the well was 20 nm thick and the 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. 2a) 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}.

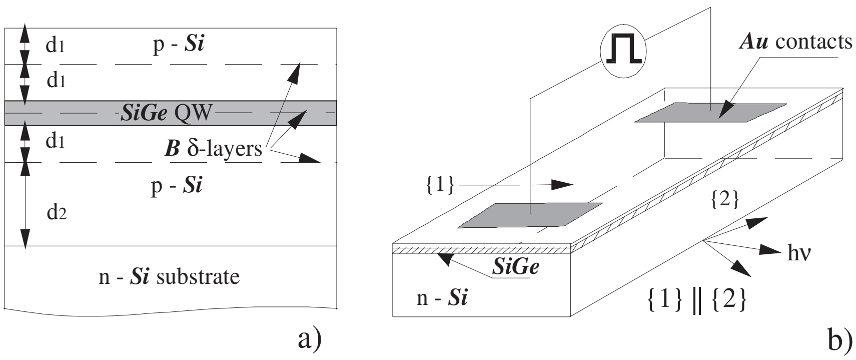

Fig. 2 Schematic view of a) structure and b) laser design.

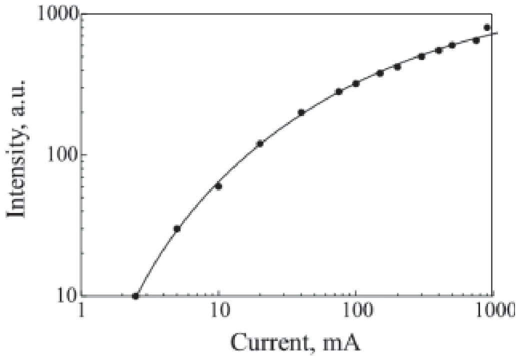

Fig. 3 THz emission intensity versus current.

Pulsed bias of 0.2 to 4 μs duration have been used in order to avoid overheating. Bias was applied to the SiGe layer via thermal-diffusion made Au contacts (Fig. 2b) with the distance 6 mm. The emission spectrum was measured by a grating monochromator and registered with a cooled Ga-doped Ge photodetector. Measurements were made at liquid-He temperatures.

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. 2b) which were parallel polished.

For the samples with the optical resonator, we observed that an intense THz emission arose at a threshold voltage above 100–300 V/cm for different samples. Shown in Fig. 3 is the dependence of photodetector signal on pumping current. Spectra of the intense emission were measured in the energy range 9.8 to 15.5 meV. Shown in Fig. 4a are parts of the spectra indicating lines for the samples of type I. 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

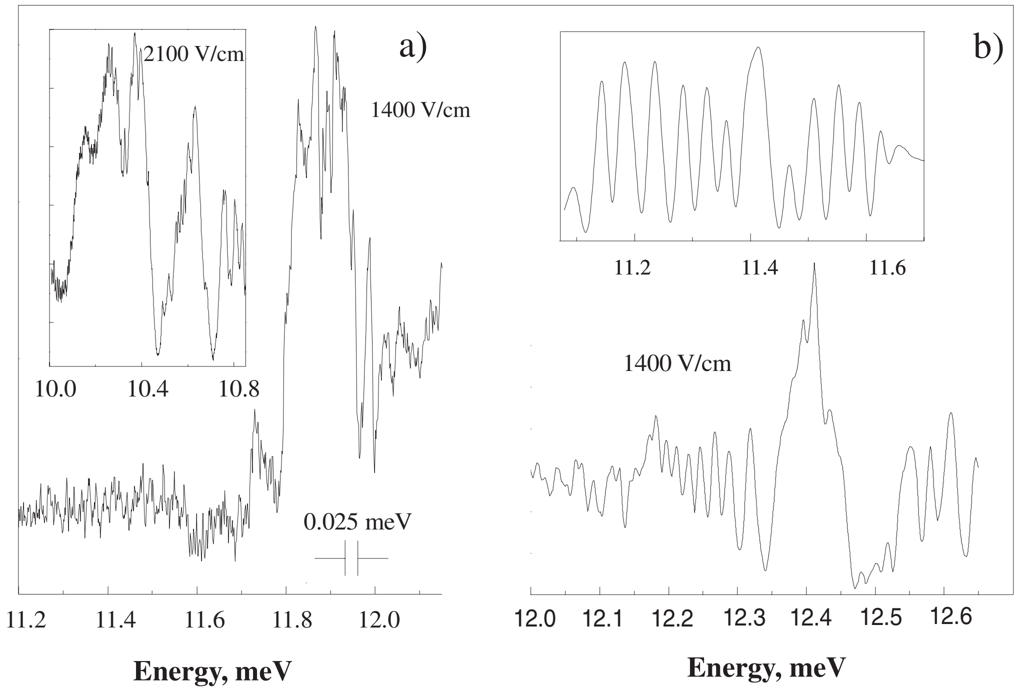

Fig. 4 Spectra of stimulated THz emission in structures of a) type I and b) type II at 1400 V/cm. Insets: a) additional lines arising in the spectrum at 2100 V/cm, b) modal structure.

larger wavelengths, shown in the inset of Fig. 4a. The line near 100 μm was observed in type-II samples with 0.15 Ge content (Fig. 4b). The intense emission was observed also from the type-II samples with $x = 0.1$ and 0.07. Shown in the inset in Fig. 4b 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.

We believe that the observed lasing results from a population inversion of resonant states of boron in the QW layer. A resonant acceptor state is created when the energy splitting between the ground and split-off acceptor states exceeds the binding energy. For $Si_{1-x}Ge_x$ structures with $x = 0.15$, the splitting energy of the valence subbands is about 31 meV [9]. According to variational calculations, the binding energy of shallow acceptors is about 27 meV. The same value was obtained [9] 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.

We attribute the main line of the THz lasing observed to stimulated optical transitions between the resonant and first excited localized acceptor states (E_p). The resonant state is 4 meV above the edge of the heavy-hole band. Using the value $E_g/4$ for a rough estimation of E_p ($E_g \approx 27$ meV is the energy of ground acceptor state mentioned above), we expect the energy of the transition to be about 11 meV. This is consistent with the observed quantum energy of 11.8 meV. It is natural to connect the additional maxima observed at lower energies with optical transitions from the same resonant state to higher excited localized states.

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

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