ELECTRONIC AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Effect of Parameters of Ge(Si)/Si(001) Self-Assembled Islands on their Electroluminescence at Room Temperature

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Abstract—The electroluminescence (EL) of multilayered *p-i-n* structures with the self-assembled Ge(Si)/Si(001) islands are investigated. It is found that the structures with islands grown at 600°C have the highest intensity of the electroluminescence signal at room temperature in the wavelength range of 1.3–1.55 μm. The annealing of structures with the Ge(Si) islands leads to an increase in the EL-signal intensity at low temperatures and hampers the temperature stability of this signal, which is related to the additional Si diffusion into islands during annealing. The found considerable increase in the electroluminescence-signal intensity with the thickness of the separating Si layer is associated with a decrease in the elastic stresses in the structure with an increase in this layer's thickness. The highest EL quantum efficiency in the wavelength range of 1.3–1.55 μm obtained in investigated structures amounted to 0.01% at room temperature.

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1. INTRODUCTION

A major problem in manufacturing the light-emitting structures on the basis of silicon is its low quantum efficiency of the radiative recombination of charge carriers. Nowadays it is possible to single out two methods for increasing the radiative-recombination efficiency in the structures on the basis of silicon. The first method is based on improvement of the quality of structures by decreasing the concentration of nonradiative-recombination centers for the charge carriers in them [1], and the second is the spatial localization of charge carriers in a small structure region [2, 3]. In structures with Ge(Si) self-assembled islands, it is possible to use both these ways due to the localization of charge carriers in defect-free islands [4, 5]. An important feature of devices based on the structures with Ge(Si) islands is also the possibility of their operation in the wavelength range of 1.3–1.55 μm inherent for the current optical-fiber communication lines. Bulk silicon in this wavelength range is transparent, which makes it possible to use waveguides on its basis and opens new avenues for the integration of optical and electronic components on one silicon substrate. In the last few years, various teams [6–9] reported on successes in observing the electroluminescence (EL) at room temperature from structures with Ge(Si) islands. The best results in the region of formation of light-emitting diode structures with Ge(Si) islands in the wavelength range of 1.3–1.9 μm were obtained in [10], where the EL external

quantum efficiency amounted to ~0.04% at room temperature.

The previous investigations of the photoluminescence (PL) of structures with Ge(Si) islands showed the strong dependence of spectral intensity characteristics and the temperature quenching of PL islands on the sizes, shape, composition, and surface density [11–14]. All these parameters should also strongly affect the EL signal from Ge(Si) islands. However, the effect of Ge(Si)-island parameters on their EL signal is now studied insufficiently.

This study is devoted to investigating the effect of parameters of Ge(Si)/Si(001) self-assembled islands in multilayered structures on spectral characteristics, efficiency, and temperature quenching of the EL signal from islands. The Ge(Si)-island parameters were varied due to the use of different growth temperatures, thickness of Si separating layers between neighboring layers of Ge(Si) islands, and also the post growth thermal annealing of structures.

2. EXPERIMENTAL

The structures under investigation were grown by the method of molecular-beam epitaxy from solid sources on *p*-Si (001) substrates doped with boron to $7 \times 10^{17} \text{ cm}^{-3}$. The growth of structures began with depositing the *p*⁺-Si layer 200 nm thick doped with boron to the concentration of $\sim 10^{19} \text{ cm}^{-3}$. Then we deposited the undoped Si layer 50 nm thick on which

Fig. 1. EL Spectra of the p - i - n diode structures with Ge(Si) islands grown at (1) 550, (2) 600, and (3) 650°C. The spectra were measured at temperatures of (a) 77 and (b) 300 K. The pumping-current's density for all structures is 5 A/cm².

the lattice consisting of 20 layers of Ge(Si) self-assembled islands separated by undoped Si layers was formed. The growth temperature (T_{gr}) of the lattice with islands was varied in the range of $T_{gr} = 550$ – 650°C , and the thickness of separating Si layers was varied in the range of $d_{Si} = 10$ – 32 nm. The formation of the lattice with islands is described in more detail in [15]. The structure's growth was accomplished with depositing the undoped Si layer 50 nm thick and the contact n^+ -Si layer 200 nm thick doped with antimony to the concentration of $2 \times 10^{18} \text{ cm}^{-3}$.

A part of the grown structures was thermally annealed in nitrogen atmosphere for 1 min at the temperatures of 650 and 700°C . The X-ray-diffraction investigations were performed using a DRON-4 diffractometer. The structures were investigated by electron microscopy using Philips CM20 and JEM 4010 microscopes with accelerating voltages of 200 and 400 kV, respectively. For measuring EL, we formed the Au/Ti ohmic contact of 0.5 mm in diameter on the surface of samples from the structure's side. The second

ohmic contact was formed by depositing the Al continuous film on the substrate's back side. The structures with contacts were split into separate pieces (chips) of 2×2 mm in size. The EL spectra were measured on chips in the pulsed mode to avoid overheating the samples. The pulse duration amounted to 4 ms, and the repetition period was 25 ms. The EL spectra were detected with the help of the Ge: Au liquid-nitrogen-cooled photodetector. The emission power was measured in the continuous mode using a PD300-IRG power meter based on InGaAs detector operating in the wavelength range of 800–1700 nm. We directly measured the power emitted in the direction of the normal structure-surface into the solid angle limited by the power meter's aperture. The total emitted power was found by recalculating into the total solid angle assuming that the emission is isotropic. The fact that the emission diagram is close to isotropic was confirmed experimentally. For estimating the external quantum efficiency (η), we used the formula from [16]

$$\eta = \frac{Pe}{Ih\nu}, \quad (1)$$

where P is the emitted power, e is the elementary charge, I is the current through the structure, h is Planck's constant, and ν is the photon frequency.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The EL-spectra investigations showed that, in all p - i - n structures with Ge(Si) islands, the EL signal at room temperature was observed from islands in the energy range of 0.75–1.0 eV ($\lambda \approx 1.25$ – $1.65 \mu\text{m}$) (Fig. 1). It was found that if the EL-signal's intensity from islands grown at various temperatures is approximately identical (Fig. 1a) at low measurement temperatures (~ 77 K), the islands grown at $T_{gr} = 600^\circ\text{C}$ show the highest intensity of the EL-signal (Fig. 1b) at room temperature. Previously [11], it was found that the dome-shaped islands grown at $T_{gr} = 600^\circ\text{C}$ have the highest PL-signal intensity at room temperature in comparison with the PL signal from islands grown at other temperatures, which is related to the best hole localization in islands grown at $T_{gr} = 600^\circ\text{C}$. It is caused by the fact that, on the one hand, an increase in the growth temperature above 600°C results in increasing the diffusion of silicon into islands [17, 18]. According to the X-ray diffraction analysis, the average Ge content in islands in the investigated structures with $d_{Si} = 25$ nm decreases from $x = (45 \pm 3)\%$ to $x = (37 \pm 3)\%$ when T_{gr} increases from 600 to 650°C . The growth of the Si fraction in islands leads to decreasing the valence-band discontinuity at the heterojunction between silicon and the Ge(Si) island, to decreasing the potential-well depth for the holes in the island, and, as a consequence, to the deterioration of their spatial localization.

On the other hand, a decrease in the growth temperature from 600 to 550°C leads to the qualitative change

Fig. 2. EL spectra of the diode structure with Ge(Si) islands grown (1) at 600°C before annealing and after annealing at (2) 650 and (3) 700°C. The spectra were measured at 300 K.

Fig. 3. EL spectra of the diode structures with Ge(Si) islands grown at 600°C with thickness of the Si separating layer of (1) 25 and (2) 32 nm. The spectra were measured at 300 K.

in the growth of self-assembled Ge(Si) islands [19, 20]. In this temperature range, the type of islands dominating on the surface changes from the dome nanoislands to the pyramidal (hut) ones, which is accompanied by a sharp decrease in the average height of islands [20]. Due to quantum-dimensional effects, the last circumstance causes the expulsion of an energy level of holes in the island towards the edge of the silicon valence-band that also results in the deterioration of localization of holes in islands. The indication of the weaker localization of holes in structures with hut-islands is the occurrence of the EL signal from Si at room temperature in these structures (Fig. 1b). One more factor, which can result in decreasing the EL-signal's intensity from islands with the growth temperature, is an increase in the point-defect concentration in the structures, which were grown at low temperatures [21]. The increase in the point-defect concentration leads to increasing the concentration of centers of the radiationless recombination of charge carriers. Thus, the best spatial localization of holes in the investigated structures is realized in Ge(Si) dome islands grown at 600°C. It results in an insignificant temperature quenching at the room temperature and the highest EL-signal intensity from islands grown at this temperature.

The increase in the EL-signal's intensity from Si(Ge) islands can be attained due to decreasing the concentration of centers of the nonradiative recombination at the thermal annealing of structures. It was previously shown [15] that the PL-signal's intensity from islands at low (77 K) measurement temperatures increases with annealing temperature as a result of annealing under the same conditions as in this study. However, the temperature quenching of the PL signal from islands [15] increased. The carried out investigations showed that the similar dependence on the annealing temperature is observed also for the EL signal from

islands: with increasing the annealing temperature, both an increase in the EL-signal's intensity at low measurement temperatures and an increase in its quenching temperature occurs. The observed increase in the temperature quenching of the PL and EL signals with increasing the annealing temperature is associated with the deterioration of localization of holes in islands as a result of an additional diffusion of Si into islands during the annealing [15]. The shift of peak positions for the PL and EL signals from the islands towards higher energies after annealing [15] is the confirmation of the Si-fraction increase in islands (Fig. 2). It is necessary to note that the EL signal from islands at room temperature somewhat increases (Fig. 2) despite an increase in the temperature quenching of the EL signal from islands in the structures annealed at moderate temperatures (650°C). Hence, there is an optimum mode of annealing the structures with Ge(Si) islands, which, on the one hand, would reduce the number of defects in the structure and, on the other hand, would not significantly affect the islands parameters (in particular, the composition) and lead to no substantial deterioration of localization of holes in islands.

In multilayered structures with self-assembled islands, the thickness of the Si separating layer between neighboring layers of Ge(Si) islands [13, 22] is one more parameter substantially affecting the parameters of islands and their optical properties. The variation in the thickness of the Si separating layer between the neighboring layers with Ge(Si) islands grown at 600°C showed that, when increasing this layer's thickness from 25 to 32 nm, the EL-signals intensity from islands and the external quantum efficiency of the radiative recombination grow fivefold (Fig. 3). The increase in the EL-signal's intensity and quantum efficiency of the radiative recombination observed with increasing the thickness of the Si separating layer is associated with

Fig. 4. TEM pattern of a fragment of the diode multilayered structure with Ge(Si) islands grown at 600°C and separated by Si layers of 32 nm thick.

the fact that the elastic stresses in the structure decrease with increasing this layer's thickness. The reduction of elastic stresses, first, leads to a decrease in the Si diffusion stimulated by them into islands and, as a consequence, to an increase in the Ge fraction in the islands [22]. The Ge-fraction's growth in islands with increasing d_{Si} is confirmed by the X-ray diffraction analysis according to which the average Ge content in islands increases from $(45 \pm 3)\%$ to $(51 \pm 3)\%$, when d_{Si} increases from 25 to 32 nm. The increase in the Ge fraction in islands with the thickness of the Si separating layer is confirmed also by the shift of the EL-signal's peak from islands towards lower energies (Fig. 3). Second, a decrease in elastic stresses results in decreasing the misfit-dislocation density in the structure, which also leads to a decrease in the number of nonradiative-recombination channels and an increase in the EL-signal's intensity. The low density of crystal-lattice defects in the structure with thick Si separating layers is confirmed by the investigations carried out by transmission electron microscopy (TEM). These investigations also enabled us to establish that a strong vertical correlation (Fig. 4) is observed even in the structure with $d_{\text{Si}} = 32$ nm between the next-layer islands. This indicates that the elastic stresses from the previous layers with islands affect the formation of islands in the subsequent layers. In addition, the TEM pattern shows that the sizes of islands increase with the layer number (Fig. 4). The increase in the island sizes in upper layers of a multilayered structure can be caused by an increase in the Si fraction in the islands due to the elastic-stress accumulation [22]. Thus, it is possible to expect that the further (more than 32 nm) increase in the thickness of Si separating layers leads to an increase in the Ge fraction in islands and, as a consequence, to the growth of

Fig. 5. Dependence of the integrated power of EL of Ge(Si) islands on the pumping-current's density for the structure with islands grown at 600°C and separated by Si layers of 32 nm thick.

the quantum efficiency of radiative recombination in multilayered structures with Ge(Si) islands.

The measurements of the EL integrated power from Ge(Si) islands showed that it superlinearly depends on the pumping-current's density (Fig. 5). This means that, according to Eq. (1), the quantum efficiency of radiative recombination in the investigated structures increases with the pumping-current's density. The greatest value of the external quantum efficiency of EL in the investigated structures was obtained for the structure grown at 600°C in which Ge(Si)-island layers were separated by thick ($d_{\text{Si}} = 32$ nm) Si layers. The value of the external quantum efficiency at room temperature for this structure amounted to $\sim 0.01\%$. In this case, the integrated power of EL in the wavelength range of 1.3–1.55 μm for the pumping-current's density of 5 A/cm² amounted to ~ 3 μW .

4. CONCLUSIONS

In this paper, we present the results of the investigation of the effect of growth conditions, structure parameters, and annealing temperature on the EL of multilayered *p-i-n*-diode Ge(Si)/Si(001) structures with the self-assembled islands. It is found that the islands grown at 600°C have the greatest EL-signal intensity at room temperature. This result is related to the best localization of holes in islands grown at this temperature. The annealing of structures with Ge(Si) islands leads to an increase in the EL-signal's intensity at low temperatures but impairs its temperature stability, which is caused by an additional Si diffusion into islands during annealing. An increase in the EL-signal's intensity with the thickness of the separating Si layer is associated with a decrease in the elastic stresses in the structure with increasing the layer's thickness. The

largest value of the external quantum efficiency of EL in the wavelength range of 1.3–1.55 μm obtained as a result of optimization of parameters of the investigated structures amounted to $\sim 0.01\%$ at room temperature.

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