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Room temperature electroluminescence from multilayer GeSi heterostructures

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Details of silicon diodes with Ge/Si multilayer quantum dot heterostructures embedded in the Si p–n junction grown by molecular beam epitaxy emitting in the range of 1.4–1.7 μm at room temperature and continuous injection pumping are discussed. Output power of the light emitting diode reaches 1 $\mu W/cm^2$ at applied current density of 2 A/cm^2. Photoluminescence and transmission electron microscopy show that the origin of intense luminescence is defect free stacked Ge quantum dot array formed inside the structure. It is shown that doping by antimony improves structure quality and increases photoluminescence efficiency at room temperature.

1 Introduction

The development of an efficient silicon based light emitting device is the challenge task in modern semiconductor physics. One of the promising approach is to utilize a concept of Ge nanostructures (quantum dots (QDs), wells, super lattices) embedded in a Si matrix. A lot of efforts have been done in this direction [1–4]. In particular, it was established [5] that the radiative life time of the carriers in the Ge quantum dot is ~3 μs which is much smaller (3 orders of magnitude) than typical life time of the carriers in pure bulk Si. This means that Ge QDs embedded in a Si matrix could serve as efficient channels of the carriers recombination. The problem of Ge inclusions in a Si matrix is low binding energy of the electron–hole pair due to the II-type nature of the Ge/Si heterojunction. The hole is localized in the Ge QD, but Ge is a potential barrier for the electrons, so latter could be localized to the QD interface due to the Coulomb hole–electron attraction and due to the strain induced conduction band lowering. Electron–hole binding energy in the Ge QD is ~25 meV [6] and thermal energy ($k_B T$) at room temperature totally destroys such a complex. Therefore, photo- and electroluminescence at 300 K from Ge QDs are vanished.

In this paper we present an approach which leads to the increase of electron–hole binding energy and to the decrease life time of the carriers in the Ge/Si heterostructure. We have designed multilayer Ge/Si heterostructures with closely stacked Ge QDs. A low height of the QDs leads to the formation of an electron miniband in the coordinate space. From the other side, the accumulated strain in the multilayer structure leads to the higher electron activation energies which increase the electron–hole binding energy.

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2 Experiment

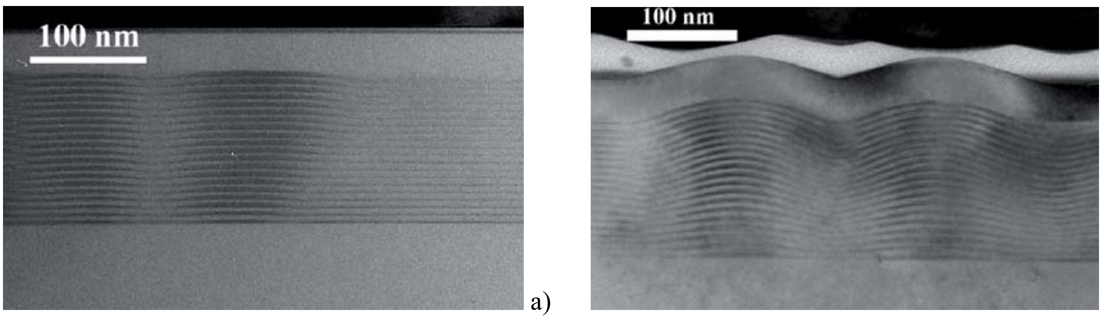
The structures are grown on Si(100) p-type substrates by Riber SIVA 45 molecular beam epitaxy (MBE) setup. Samples consist of a Si buffer layer, a Ge/Si multilayer and a Si cap layer. The temperature of the growth was 600 °C. In the case of light emitting diode (LED) structures the Si cap layer is doped by Sb having bulk concentration of 1×10^{18} cm^{-3}. The effective Ge thickness in each layer is amounted to 0.7–0.9 nm. Reflection high energy electron diffraction system (RHEED) is used to monitor *in situ* the surface of the samples. The formation of Ge QDs in the first Ge layer of each sample is documented by RHEED system. Si spacer thicknesses are varied in the range of 5–15 nm. In some cases, Si spacer is doped by Sb. The Sb concentration measured by the secondary ion mass spectroscopy in the Ge/Si multilayer structure is 5×10^{16} cm^{-3}. The number of QD periods is 2–20. Si diode structures are grown on a p$^+$-type ($\rho \sim 0.015\ \Omega$ cm) Si(100) substrates. Metal contacts to the n-side of the diode structures are formed using Al/Au deposited by magnetron sputtering technique. Indium is used to form p-side metal contact. Photoluminescence (PL) measurements are carried out in a standard lock-in configuration. Excitation is provided by a defocused Ar-ion laser (2.54 eV). The PL signal is collected by a 0.5 m grating monochromator coupled to a cooled Ge photodetector (Edinburgh Instruments, Inc.) having a photoelectric threshold of 1.7 μm (0.73 eV). A Philips CM20 electron microscope is used to perform structural characterization of the samples.

3 Results and discussion

Cross-section transmission electron microscopy images of undoped and doped by Sb multilayer structures are compared in Fig. 1. The undoped structure (Fig. 1a) demonstrates flat heterointerfaces and surface, QD lateral size increases from the lower to the upper layers, Si spacer between the nearest QDs in stack is less than the spacer thickness between corresponding Ge wetting layers. The doped structure (Fig. 1b) has sharp heterointerfaces and corrugated surface, QD lateral sizes are nearly the same for the top and bottom layers. The "wavy-like" surface is the sign of the elastic strain, accumulated in the structure.

To understand the difference in the structural properties of the samples discussed Ge QDs formation on a Si surface with presence of the Sb has to be considered [7]. It was shown that the presence of the Sb leads to the increasing of the Ge QD surface density and the decreasing of QD sizes due to the decreasing of the Ge adatoms migration on a surface. During Ge QDs overgrowth by Si the migration length of the Si adatoms is decreased as well, and the spacer thickness between QDs in neighbouring layers increases. In addition, no misfit dislocation formation is observed in the doped sample.

Difference in the structural properties has a strong impact on the optical properties of the samples discussed. Figure 2a shows the PL spectra taken at room temperature from undoped (curve 1) and doped (curve 2) samples. The undoped sample has only one pronounced spectral band which is attributed to the fundamental Si-TO transition. The dominant band in the spectrum of the doped sample is centered at



a) b)

Fig. 1 a) Undoped Ge/Si heterostructure. b) Doped by Sb Ge/Si heterostructure.

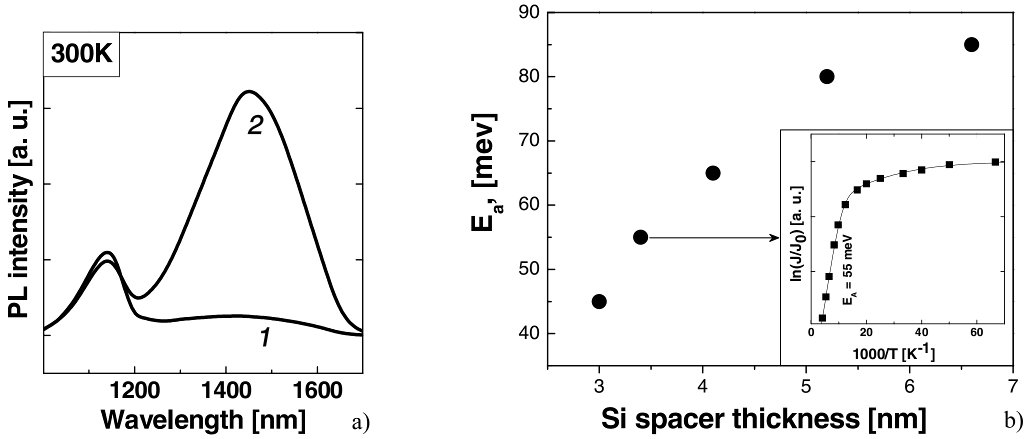


Fig. 2 a) PL spectra of undoped (curve 1) and doped (curve 2) samples. b) Activation energy of the electrons localized in the Si spacer layer between Ge QDs (doped samples) versus Si spacer thickness dependence. Insert shows the dependence of the integral PL intensity on the temperature (dots); solid curve is Arrhenius fit.

~1.55 μm. It was shown by Cirlin et al. [8] that the long wavelength band corresponds to the Ge/Si transitions between holes, localized in the Ge QDs, and the electrons in the miniband. A miniband is formed in the conduction band of Ge QD multilayer structure due to the electron tunnelling between neighbouring Si quantum wells. It should be mentioned that the formation of the QD-related spectral band is possible at room temperature due to the increasing of the electron activation energy in the Si quantum wells. Figure 2b shows the electron activation energy versus spacer thickness dependence. The latter is obtained by the Arrhenius analysis of the temperature dependences of the integral intensities of the long wavelength band in the spectra of doped samples. The increasing of the activation energy with spacer thickness means that the energetic distance between electronic level in the Si quantum well and the states of the continuum is increased. We have obtained 85 meV activation energy at the spacer thickness of 6.7 nm for the electrons in the Si quantum wells between Ge QDs. Significant increasing of the electron activation energy is due to the strain accumulation in the doped multilayer structure [9]. Referring to the Fig. 2a we can conclude that higher spacer thickness as well as strain accumulation in the doped structure leads to the room temperature PL from Ge QD multilayer.

We have observed some unusual optical properties of doped samples. First, the integral intensity of QD PL band at room temperature is characterized by a N^2 function with increasing of the number of structure periods (Fig. 3). A super linear dependence of intensity versus number of periods is due to increasing of

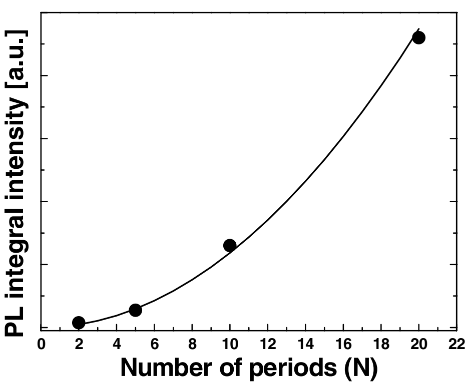


Fig. 3 Integral PL intensity dependence on the Ge QD periods number (filled circles); curved line is a quadratic approximation.

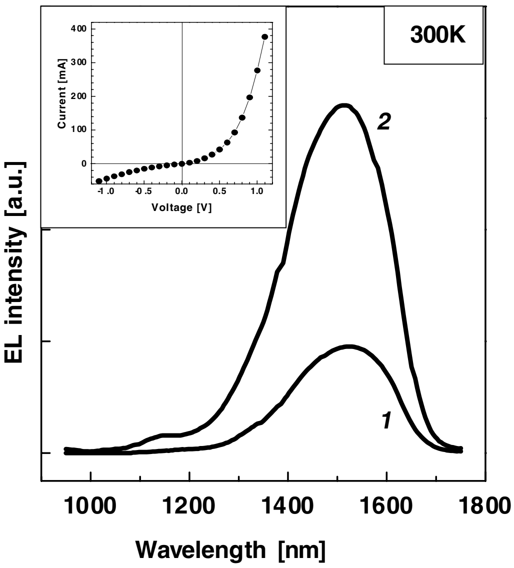


Fig. 4 EL spectra of Si LED with multilayer Ge/Si heterostructure at different injection current: $j = 0.4$ A (curve 1), $j = 1$ A (curve 2). The inset shows the current–voltage characteristic of the diode.

the electron–hole wave function overlapping integral because of the electronic miniband formation. Second, time resolved PL taken at 10 K at the wavelength of 1.55 μm shows fast (to the best of our knowledge, shortest for such a system) time of PL decay $\tau \sim 0.1$ μs. It should be mentioned that continuous Ar-ion laser pumping during PL measurements absorbs mostly in Si substrate. In spite of this the PL integral intensity of the Ge QD band is higher than Si-TO one, and fast PL decay kinetics means that Ge/Si QD multilayer is an efficient channel of the carrier recombination in the samples considered.

Growth parameters for the multilayer Ge/Si heterostructures are tuned to obtain higher PL intensity of Ge QD multilayer at room temperature. The best structures are used as an active region of the LED structures. Typical EL spectra of Si LED are shown in Fig. 4. An EL maximum for the given sample is centred on 1.55 μm. Different LEDs demonstrating the EL maxima in the range of 1.4–1.7 μm have 0.7–0.9 nm of Ge deposited in each QD layer. A higher effective thickness of Ge corresponds to the longer EL wavelength maxima. It should be mentioned that Si-TO band in the EL spectra of the LED is significantly decreased due to fact that carrier recombination takes place mainly in the space charge region of the LED structure. In comparison to the previously published data on Si LEDs [10], our LEDs are grown on a highly doped p^+-type Si substrates in order to prevent Schottky barrier formation from the p-side metal contact. Current–voltage characteristic of the diode shown in the inset of the Fig. 4 demonstrates low dark current and high p–n junction quality.

The EL band of Ge QDs is detected in the spectra if the applied voltage exceeds 0.7 V. External efficiency of the output light power measured using Ulbricht sphere method is 0.04% at current density of 2 A cm^{-2}. The corresponding output power from a unit surface area at room temperature and continuous injection pumping is 1 μW cm^{-2}.

4 Conclusion

Defect free Ge QD multilayer structures are designed to obtain intense room temperature photoluminescence in the range of ~1.55 μm. High electron activation energy and fast carrier recombination kinetics in Ge/Si multilayer structures leads to intense room temperature photoluminescence. The Si LED with Ge/Si multilayer in the space charge region of a p–n junction demonstrate electroluminescence in the range of 1.4–1.7 μm at room temperature and permanent pumping with external efficiency of 0.04% at driving current density of 2 A cm^{-2}.

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