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Rapid Research Note

Room temperature electroluminescence from Ge/Si quantum dots superlattice close to 1.6 μm

V. G. Talalaev[*, 1, 2], **G. E. Cirlin**[1, 3, 4], **A. A. Tonkikh**[1, 3, 4], **N. D. Zakharov**[1], and **P. Werner**[1]

[1] Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, 06120 Halle/Saale, Germany
[2] Institute of Physics, St. Petersburg State University, Ulyanovskaya 1, 198504 Petrodvorets, Russia
[3] A. F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, Polytekhnicheskaya 26, 194021 St. Petersburg, Russia
[4] Institute for Analytical Instrumentation, Russian Academy of Sciences, Rizhsky 26, 198103 St. Petersburg, Russia

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We have fabricated a light-emitting diode on a Si(100) p^+ substrate operating at room temperature close to 1.6 μm. The growth of the structure was performed by molecular beam epitaxy. The active zone of the p–i–n diode consists of 20 layers of Ge/Si self-assembled quantum dots. The growth parameters of the active zone (Ge layers quantity, Ge thickness, Ge growth rate) were optimized for effective electroluminescence at room temperature.

Low-cost components in the fiber optic communication wavelengths based on silicon are of great interest due to the possible integration with the well-developed Si-based technology. Optical components including emitters, modulators and photodetectors are expected to operate in the range of 1.3 to 1.55 μm. However, the indirect band nature of silicon leads to a very low luminescence efficiency of Si-based structures. One possible way to realize efficient Si-based emitters is directed towards the incorporating of Ge/Si self-assembled nanostructures in an active layer of a diode. A few papers published recently report on the electroluminescence (EL) from Ge/Si structures grown by chemical-vapor deposition [1–3] and molecular-beam epitaxy (MBE) [4]. In some cases, EL was observed in the range 1.3 to 1.5 μm up to room temperature (RT). In the present paper, we report on a strong EL at room temperature extended to 1.6 μm generated by a Ge/Si self-assembled quantum dots superlattice (QDSL) containing 20 stacked Si/Ge layers.

The structures were grown on Si (100) substrates by MBE. The following deposition sequence was chosen for the active zone of the samples: (i) deposition of a Ge layer (thickness 0.7–0.9 nm) followed by (ii) a 5 nm thick Si spacer. This cycle was repeated 10–20 times; the substrate temperature was kept at 600 °C during the growth process. The active zone was doped with Sb in order to create concentration gradient. The Sb concentration measured by the SIMS was 5×10^{16} cm^{-3} in the middle of the QDSL and 10^{18} cm^{-3} at the top. The structures grown under these conditions are mostly defect-free (dislocation density $<10^5$ cm^{-2}) and show a photoluminescence (PL) signal up to RT in the range of 1.55 μm [5].

In a first stage of the experiments, we have optimized the active zone grown on semi-insulating Si(100) substrates by characterizing the samples with PL taken at RT. These PL measurements were carried out in a standard lock-in configuration. Excitation is provided by a defocused Ar-ion laser (2.54 eV) with an excitation

[*] Corresponding author: e-mail: talalaev@mpi-halle.mpg.de

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power density of 3 to 17 W/cm^2. The PL signal was 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). Figure 1 presents several PL spectra taken at RT for Ge/Si QDSL containing 20 layers (curves 1, 2) and 10 layers (curve 3). Furthermore the influence of the nominal Ge thickness is demonstrated for 0.7 nm (curves 1, 3) and for 0.9 nm (curve 2).

First, a remarkable changes in the PL behavior was found associated with an increase in the number of layers in the QDSL. Figure 1 demonstrates, as an example, the significant increase of the PL intensity for a structure of 10 layers (curve 3) to a structure containing 20 layers of 0.7 nm Ge (curve 1). The peak shift from 0.85 eV (10 layers) to about 0.80 eV (20 layers) is attributed to a transition from the individual Ge islands and Si surrounding emission [4] to the formation of an electron miniband [6] and localized holes – miniband emission. Second, a red shift of the PL peak was found with an increase of the Ge layer thickness supporting a QD-related recombination mechanism in our structures, as well as a slight intensity decrease with increasing Ge layer thickness (Fig. 1, curves 1, 2). A decrease of the Ge growth rate at the same Ge thickness led to a blue shift and to a weakening of the QDSL-related PL peak. Based on such an optimization process, the following structure was chosen as an active zone of the diode: 20 Ge QD layers, a nominal Ge thickness of 0.7 nm and a Ge growth rate of 0.02 nm/s. The nominal spacer thickness amounted to 5 nm. Finally a 50 nm thick Si cap was grown at 500 °C.

It has to be mentioned that temperature-dependent PL measurements down to 7 K yielded the luminescence is associated with the Ge islands. The determination of the activation energy of the electrons (~70–100 meV) showed that the 0.8 eV luminescence band is not related to crystal defects. Additionally, we have observed a narrow and significantly less pronounced defect-related line in a region of 0.75 eV [5] which was attributed to a contamination at the Ge/Si interface during MBE growth [7].

In the second stage of our investigations, a light-emitting p–i–n diode on a Si(100) p$^+$-doped substrate was fabricated. Sb doping was used to fabricate the n$^+$-layer ($n \approx 10^{19}$ cm^{-3}). A cross-section transmission electron microscopy image of the device structure (unprocessed) is presented in Fig. 2. We found a rather low concentration of structural defects in the samples (less than 10^5 cm^{-2}) which are mostly located in the cap region. Electrical contacts were prepared by the deposition of Cr/Au (5 nm/70 nm, front side) and of Al (70 nm, back side).

The EL signal was obtained for an in-plane geometry in the continuos regime using the same measurement setup as applied for PL. Typical EL spectra taken at RT are presented in Fig. 3 for different current densities. The inset shows the *I–V* characteristic of the diode structure. An intensive EL band (1.6 μm) appears at nearly the same spectral position as was observed before for the PL reference structure grown at the same growth conditions. In both cases we attribute the existence of an emission to the recombination of quasi-free electrons

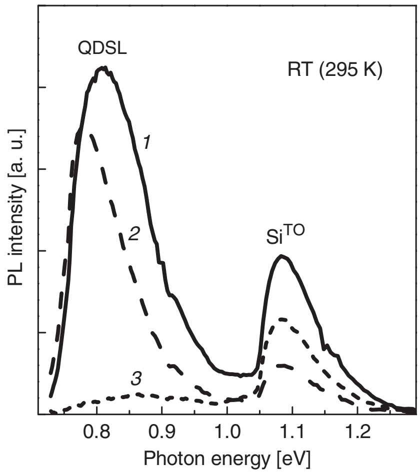

Fig. 1 PL spectra from a Ge/Si QDSL. (1) 20 Ge layers, Ge thickness 0.7 nm; (2) 20 Ge layers, Ge thickness 0.9 nm; (3) 10 Ge layers, Ge thickness 0.7 nm. Excitation power density amounted to 5 W/cm^2.

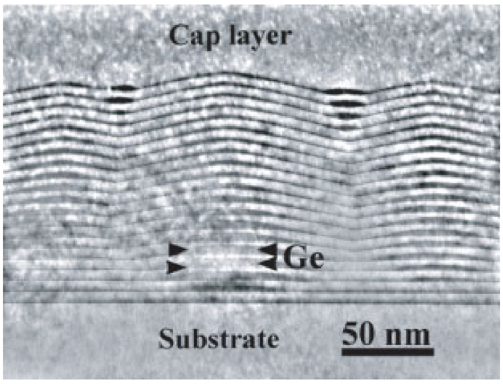

Fig. 2 TEM cross-section image of the unprocessed diode structure.

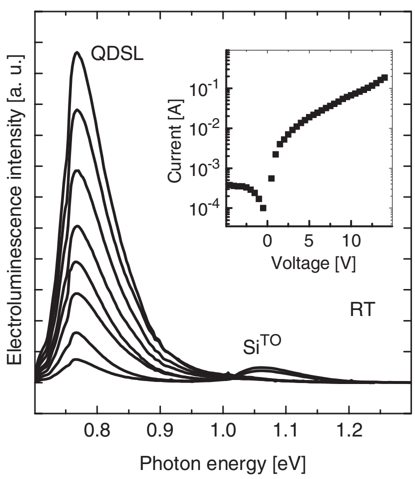

Fig. 3 EL spectra of an optimized Ge/Si QDSL diode structure measured at RT. The curves from the lower to the upper part around 0.77 eV correlate to measurements taken at different current densities varying from 1.4 A/cm^2 to 2.8 A/cm^2, respectively (in 0.2 A/cm^2 steps). Insert: Current–voltage characteristic of the diode in a semi-logarithmic scale.

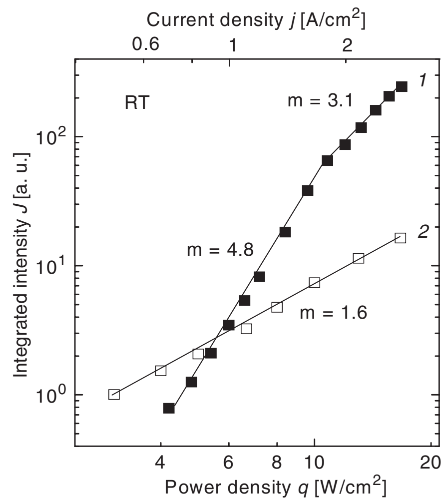

Fig. 4 EL (curve 1) and PL (curve 2) integrated intensities J in dependence on applied power density q for QDSL band. Fits of the dependence $J = q^m$ are shown by the solid lines. The current densities correspond to the same electrical input power densities as supplied by optical excitation.

in a QDSL-related miniband and the confined holes in the Ge layers [6]. An increase of the current density caused a strong increase of the EL intensity. In the two current density ranges of j = 0.7–1.8 A/cm^2 and of 1.8–2.8 A/cm^2, the increase of the EL intensity J is described by a superlinear dependence $J = j^m$ with m = 4.8 and m = 3.1, respectively (Fig. 4, curve 1). We also observed a drastic decrease of the Si^{TO} related peak at current densities of larger than 1.8 A/cm^2. The variation of m and the reduction of the Si^{TO} EL is interpreted as a band bending change, the redistribution of the electrons within the near-contact region (in our case, a Schottky-like contact on a front side was formed) and progressive filling of the electron miniband with an increase of the forward bias. A comparison of the PL and EL intensities of the QDSL-related peak demonstrates a higher efficiency for an electrical excitation (Fig. 4, curves 1, 2).

In conclusion, we have demonstrated an intense EL close to 1.6 µm (0.77 eV) at room temperature generated by a Ge/Si QD-superlattice. An optimization of the post-growth procedure and investigation of mesa-processed p–i–n diodes with similar Ge/Si QDSL structures are in progress. An additional increase of the emission intensity is expected by applying Bragg mirrors using e.g., of Si/SiO_2. The approach presented offers the promise of Si-based light emitting diodes operating efficiently at room temperature Si-based emitters.

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