Nanostructures formed by sub- and close-to-critical Ge inclusions in a Si matrix

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Abstract

We report on the defect-free (i) nanostructures formation by sub-critical (less than 1 monolayer) inclusions of Ge in a Si matrix and appearance of the new photoluminescence lines from the multilayer structures correlated with the formation of these nanostructures, and (ii) multilayer structures containing close-to-critical Ge insertions in a Si matrix exhibiting strong photoluminescence at room temperature for the optimally grown samples.

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All structures are grown by molecular beam epitaxy on Si(1 0 0) oriented substrates. The structures have been consisted of Ge (0.5–5.2) Å monolayers (ML)/Si 50 Å superlattice (SL) (20 pairs) capped with a 5–20 nm Si layer. The substrate temperatures ($T_\text{S}$) are varied within 600–750°C. In some cases, doping of the samples is used.

For capped sub-critical Ge content SL we have found that for the growth temperatures within 600–700°C and 0.5–0.75 ML of Ge deposited new PL lines are appeared in photoluminescence (PL) spectra in comparison with Si substrate PL spectrum. These lines are in the range (0.98–1.01), (1.04–1.07) and (1.11–1.13) eV at 15 K depending on the Ge amount deposited [1]. We attributed PL lines to the SL$^{TO+0}$, SL$^{TO}$ and SL$^{NP}$ recombination processes, respectively. In the diffraction pattern taken from the SL formed by 0.5 ML Ge, the number of Fourier harmonic is two times less than in the case of 1 ML one. High-resolution transmission electron microscopy (TEM) cross-section images manifest the distribution of Ge atoms over (in same cases) tens of ML for 0.5 ML Ge sample and very smooth Ge-spread layer for 1 ML structure [2]. Compositional spherically shaped non-uniformities of a very high density are clearly resolved in the plan-view TEM image of the 0.5 ML sample (size of the inclusions 4–7 ML, surface density $\sim 5 \times 10^{11}$ cm$^{-2}$) as opposite to the smooth TEM image of the 1 ML structure [2]. The appearance of the new PL lines is unambiguously correlates with Ge islands formation. An additional increasing of PL

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intensity (up to 50 times) is realized by the doping of the structure.

Recently, several papers reported on the room temperature PL originating from Si/Ge QD structures [3–5] were published. In our case, for capped close-to-critical Ge content SL we have found that intentional doping leads to significant changes in optical properties. There is a significant PL red shift of the doped structure in comparison with undoped one (1.57 and 1.4 μm, respectively), both samples contain 5.2 ML of Ge. Optimally doped samples grown at appropriate $T_s$ exhibit strong room temperature emission. PL integrated intensity versus excitation density $I \sim P^m$ for the optimized samples shows unambiguously super-linear behavior for the with factor $m = 1.65$ within the range 0.1–5000 W/cm$^2$ and $m = 1.15$ for 5–20 kW/cm$^2$ at room temperature. TEM images show no defect formation for the stacked island structures up to 20 layers. Very high spatial ordering is observed both in growth and in-plane directions [6].

We have also found that Ge growth rate significantly influence on both sizes and shape of the islands and, hence, on the optical properties of the structures. In Fig. 1a,b plan-view TEM images for the samples both containing 5.2 ML of Ge in each layer grown at the growth rates 0.02 and 0.2 Å/s, respectively. The morphology of the first sample (a) is characterized by the presence of the two groups of the nanoislands having larger and smaller lateral sizes, whereas for the second sample (b) the islands are mostly larger in size and distributed more homogeneously. The thickness of the islands taken from the cross-section TEM images (not shown here) are $\sim 1–2$ nm (platelet-like islands) for the sample A and $\sim 3–5$ nm (pyramid-like islands) for the sample B.
The sample A is characterized by the strong PL at room temperature, but PL intensity of the sample A is nearly vanishes at nitrogen temperature of observation. In Fig. 2 we compare low-temperature PL spectra for both samples. As we expected from TEM investigation, two PL bands responsible for emitting from relatively small (band SI on the spectrum) and larger (LI1 band) islands are observed for the sample A. Moreover, a signal from a wetting layer (WL1) is resolved. At the same time, for the sample B only one island-related band (LI2) is found. The different spectral position of the WL-related bands in samples A and B is correlated with the point that smoothening of the surface is energetically more favorable when low growth rate is used, e.g. for InAs/GaAs system [7].

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References