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Self-organized InAs quantum dots in a silicon matrix

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Abstract

Self-organized three-dimensional InAs islands matching the QD size requirements were fabricated by solid source MBE in a silicon matrix on Si(1 0 0) surface. The PL line originating from this islands was observed at about 1.3 μm up to the room temperature. © 1999 Elsevier Science B.V. All rights reserved.

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Silicon is a key material in modern semiconductor technology, but the indirect bandgap nature of Si makes its applications in optoelectronics hardly possible. However, the luminescence efficiency of an indirect gap matrix can be dramatically improved by the insertion of a narrow direct gap material. Since the lattice constants for narrow gap III–V compounds and Si differ significantly, the formation of sufficiently thick narrow gap III–V layers without creation of dislocations is impossible. The alternative way is to use three-dimensional narrow gap III–V material islands in a silicon matrix to develop light-emitting devices [1].

Additionally, since a QD is a nanoscale object, it should represent a single-domain state, as opposite to the case of the III–V layer growth on Si.

One should note, however, that the InAs-Si heteroepitaxial system is characterized by the very large lattice mismatch (approximately 10.6%) and the growth can proceed via the formation of mesoscopic dislocated clusters rather than nanoscale quantum dots.

In this work we show that under optimized growth conditions InAs QDs matching the QD size requirements (3D islands with a lateral size of about 12 nm) can be fabricated in a Si(1 0 0) matrix.

The growth experiments were carried out using EP1203 MBE machine (Russia) on exactly (1 0 0)-oriented Si substrates. The silicon native oxide layer was thermally desorbed at substrate temperature of 870°C for 15 min. After this procedure a well resolved (2×1) surface reconstruction typical of cleaved Si(1 0 0) surface has been observed. Then the substrate temperature was gradually decreased to the desired experimental value and the InAs

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deposition was initiated in conventional MBE mode. The InAs deposition rate was 0.1 monolayer (ML) per second. Once the deposition of the desired average thickness of InAs has been completed, the samples were covered with Si cap layer. The thickness of Si cap layer was about 100 nm.

Calibration of the growth rate, III–V flux ratio, and monitoring the surface morphology during the growth have been performed using a reflection high energy electron diffraction (RHEED). For luminescence experiments a 514.5 nm line of the Ar^+ laser was used as an excitation source and a Ge photodiode as a detector. The excitation density was about 200 W/cm^2.

First we studied the growth conditions well proven to be optimal for the InAs QD formation on a GaAs(1 0 0) surface, i.e. the V/III ratio about 2–5 and the substrate temperature of 450–530°C [2]. At the very beginning of the InAs deposition the transition from (2×1) to (1×1) surface reconstruction has been observed. However, as growth proceeds, the RHEED pattern remains streaky up to deposition of 60 MLs of InAs and more. The intensity of RHEED pattern slowly decreases upon increasing the thickness of the deposited layer. The surface remains flat, RHEED measurements demonstrate a 2D-like diffraction pattern. Covered with a Si cap layer, the samples with the InAs insertion with the thickness in the range of 3–10 ML exhibit no PL. Only the Si substrate PL peak at 1.1 eV was observed, Fig. 1.

The experimental results for this temperature range can be interpreted as the rapid coalescence of the InAs 2D islands and the formation of the poor quality InAs layer on a Si(1 0 0) surface.

A different growth scenario occurs when the substrate temperature is reduced below 420°C. In this case, the RHEED pattern converts from streaky to spotty after 5.5 MLs of InAs are deposited. One can conclude that InAs forms a remarkably dense array of nanoscale islands (quantum dots). For the substrate temperature of 250°C this transition was observed at the InAs average layer thickness of about 2 ML at the same As flux. The dependence of the critical thickness for the 2D–3D growth transition for the InAs layer on Si(1 0 0) surface versus the growth temperature is shown in Fig. 2. One can see that the critical InAs layer thickness

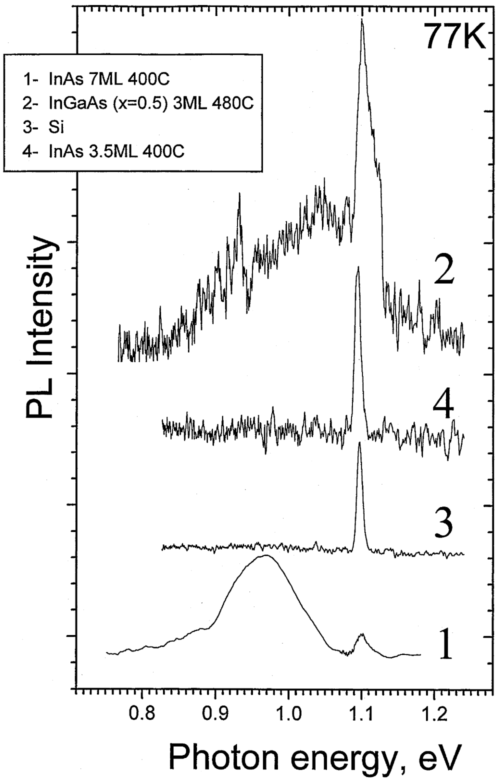

Fig. 1. Photoluminescence spectra of InAs quantum dots formed by the 7 ML InAs deposition (1) and $In_xGa_{1-x}As$ ($x=0.5$) quantum dots formed by 3 ML deposition (2) covered by 100 nm thick Si cap. The luminescence in the range of 1.3 μm is observed in only sample with InAs QDs. It is not observed for our Si(1 0 0) substrates (3) and for 3 ML thick two-dimensional InAs insertions in a silicon matrix (4).

for the 2D–3D growth transition increases with the increase in substrate temperature. But at temperatures exceeding a certain critical value than T_C no transition is observed. At temperatures near T_C the point of the 2D–3D transition depends on both the substrate temperatures and the As flux.

Covered with a Si cap layer, the sample with the InAs islands formed by the deposition of 7 ML of InAs at 400°C and arsenic pressure of 1×10^{-8} Torr exhibits a broad PL line at about 1.3 μm at 77 K with the superposition of sharper features observed at lower temperatures, Fig. 1. Decrease in the excitation density results in a shift of the maximum of the broad PL line towards lower energies. TEM and HREM image of this sample showed that

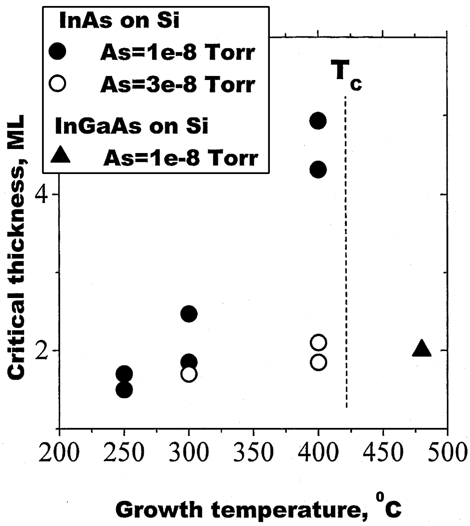

Fig. 2. The dependence of the critical thickness for the 2D–3D growth mode transition for InAs layer on Si(1 0 0) surface versus the growth temperature. At temperatures exceeding T_C no 3D growth mode for InAs is observed.

the dislocation free islands with a lateral size about 12 nm are formed in a Si matrix [3].

The absence of the same peak for the samples grown in the 2D growth mode (the substrate temperature is higher than T_C) and for the samples without InAs insertion indicates that this peak is directly associated with the InAs islands. The temperature dependence of the PL spectra for the sample with InAs quantum dots in Si matrix is presented in Fig. 3. It should be noted that for the samples with InAs QDs grown at temperatures lower than 350°C no PL was observed.

Weak PL peak was also observed for the sample with 3 ML of $In_{0.5}Ga_{0.5}$ As grown at 480°C, Fig. 1. In this case, the different value of the lattice mismatch between the substrate and the deposited layer leads to the increase in critical temperatures for the 2D–3D growth transition to 490°C. The critical thickness for the 2D–3D transition is shown in Fig. 2. The blue shift of the PL peak position indicates the reduction in the carrier localisation energy. Reduced carrier localisation energy seems to be the reason for the decrease in PL intensity.

To conclude, we demonstrated the possibility to form arrays of InAs quantum dots in a silicon matrix. The InAs QDs formed under the optimal growth conditions exhibit the luminescence line at ~ 1.3 μm up to the room temperature.

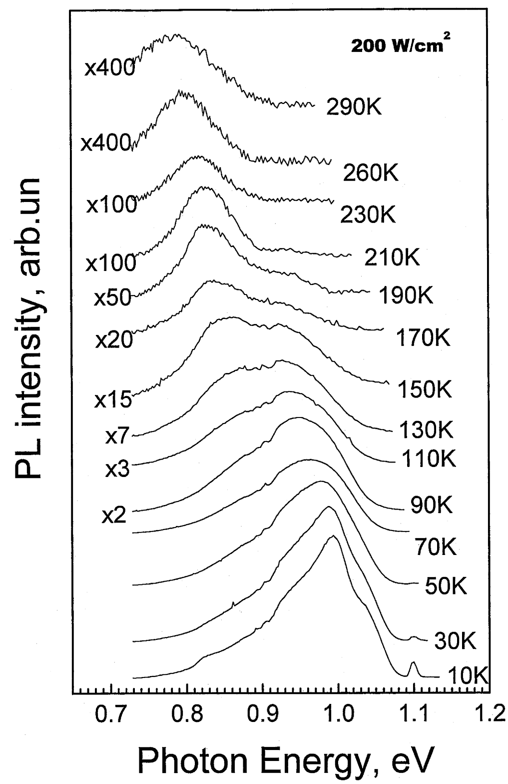

Fig. 3. Photoluminescence spectrum of InAs quantum dots formed by 7 ML InAs deposition at different observation temperatures.

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