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The effect of growth temperature of GaAs nucleation layer on InAs/GaAs quantum dots monolithically grown on Ge substrates

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The effect of the growth temperature of the GaAs nucleation layer on the properties of 1.3-μm InAs/GaAs quantum dots (QDs) monolithically grown on a Ge substrate is investigated by using transmission electron microscopy, etch pit density, and photoluminescence (PL) measurements. The photoluminescence intensity for Ge-based InAs/GaAs quantum dots is very sensitive to the initial GaAs nucleation temperature with the strongest room-temperature emission at 380 °C, due to the lower density of defects generated at the GaAs/Ge interface and prorogating into the III-V layers at this temperature. Furthermore, lasing operation up to 100 °C was achieved for Ge-based 1.3-μm InAs/GaAs quantum-dot diodes with the initial GaAs layer nucleated at 380 °C. © *2012 American Institute of Physics*. [doi:10.1063/1.3682314]

Monolithic integration of III-V compound semiconductor lasers on a Si platform is the most promising candidate for the realization of photonic integrated circuits.[1–3] Such III-V compound on Si (III-V/Si) integration overcomes the poor optical properties of Si arising from its low radiative recombination rate due to its indirect bandgap.[3] In comparison with the conventional quantum-well (QW) devices, III-V quantum dot (QD) lasers have been demonstrated with significantly lower threshold current density (J_{th}), offering temperature-insensitive operation above room temperature (RT), and lower sensitivity to defects.[4–7] These special attributes of QD technology are very promising for the development of III-V QD lasers on both Ge and Si substrates for Si photonics.[8–11] Although III-V/Si QD lasers have been demonstrated, RT lasing has only been achieved under pulsed operation, due to dislocations generated at the GaAs/Si interface and propagating into the III-V active region.[8–10] On the other hand, Ge-on-Si is a mature technology, which can effectively bridge the lattice constant gap between GaAs and Si, because of the relatively small lattice mismatch (0.08%), and closely matched thermal expansion between GaAs and Ge, and the completely miscibility between Ge and Si. However, III-V QD lasers have not become well established on Ge substrates because of the formation of antiphase boundaries (APBs) due to the non-polar/polar interface between Ge/GaAs.[12] In general, the APBs will lead to structural defects and surface roughness for III-V epitaxial layers,[13,14] which could degrade optical and structural properties of III-V layers.[14,15] Recently, we demonstrated the high-quality GaAs buffer layers grown on a Ge substrate by the use of Ga prelayer techniques to suppress the formation of APBs, and hence the first InAs/GaAs QD lasers monolithically grown on Ge substrates.[11] In this letter, we study the effect of GaAs nucleation temperature on the optical properties of 1.3-μm InAs/GaAs QDs epitaxially grown on Ge substrates. The RT photoluminescence (PL) intensity of QDs is very sensitive to the initial GaAs nucleation temperature on Ge substrates, with the strongest QD PL intensity obtained at 380 °C. In addition, we demonstrated Ge-based 1.3-μm InAs/GaAs QD lasers with low RT J_{th} and operation up to 100 °C for devices with the initial GaAs layer grown at 380 °C.

The samples were grown by solid-source III-V molecular beam epitaxy on p^+-doped (100) substrates with 6° offcut to the [111] plane. Oxide desorption was performed by holding the Ge substrate at 400 °C. The Ge substrate was then annealed at 640 °C to generate a predominantly double atomic-height step. After that, the Ge wafer was cooled down for the growth of III-V epitaxial layers. The growth of the initial GaAs nucleation layer was studied at growth temperatures of 350, 380, and 410 °C, respectively. The GaAs growth was nucleated with a 20-monolayer migration enhanced epitaxy step initiated with Ga prelayer,[11] followed by an additional 1.5-μm thick III-V buffer layer grown at high temperature. Cross-sectional transmission electron microscope (TEM) studies on the GaAs/Ge interface suggest that the defects generated at the interface are confined to within 100 nm of the GaAs/Ge interface for all three samples. Figure 1(a) shows an example TEM image for the sample with a GaAs nucleation temperature at 380 °C. This result indicates that the density of defects generated at the GaAs/Ge interface and propagating into the III-V active region is too low to be detected by cross-sectional TEM. Atomic force microscope (AFM) measurements were performed for all three samples with a Nanoscope Dimension 3100 SPM AFM system in ambient conditions using a non-contact mode. The room-mean-square surface roughness for all three samples was similar (<1 nm). A five-layer InAs/GaAs dot-in-a-well (DWELL) structure was then grown on the GaAs buffer layer at the optimized conditions normally used for GaAs substrates, with each layer consisting of 3-monolayer InAs grown on 2-nm $In_{0.15}Ga_{0.85}As$ and capped by 6-nm $In_{0.15}Ga_{0.85}As$ at ~510 °C.[16,17] 45-nm GaAs spacer

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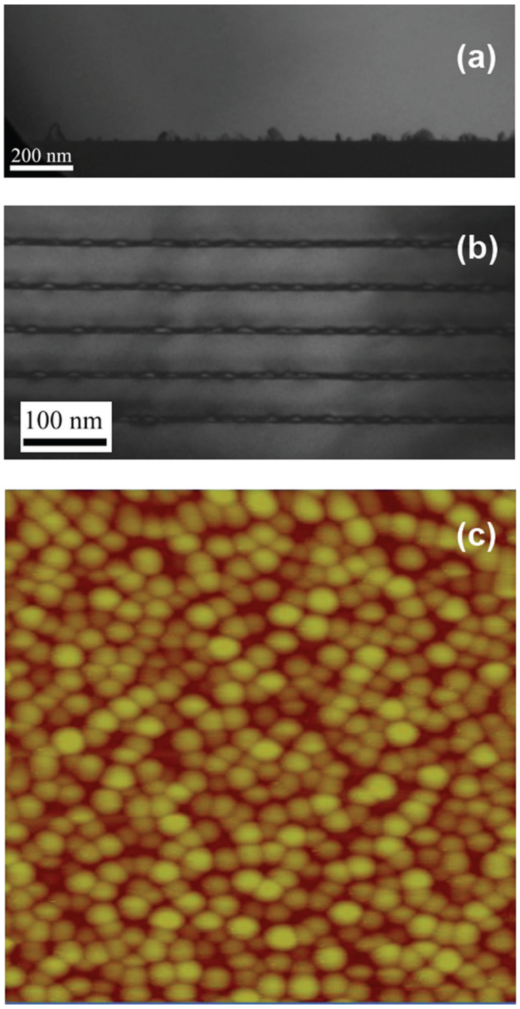

FIG. 1. (Color online) Dark field (200) TEM cross-sectional images of (a) the interface between the GaAs buffer layer and the Ge substrate for the sample with initial GaAs layer nucleated at 380 °C, and (b) five-layer InAs/InGaAs DWELL sample on Ge substrate with initial GaAs layer nucleated at 410 °C, and (c) 1.0 μm × 1.0 μm AFM image of an uncapped InAs QD sample with initial GaAs layer nucleated at 380 °C.

layers separated the InAs/InGaAs DWELLs. The InAs/InGaAs DWELL structure was then embedded between 100 nm GaAs layer grown at 580 °C, which was further confined by two 50-nm AlGaAs layers grown at 610 °C to prevent the photogenerated charge carriers from migrating to the substrate or surface at high temperatures. The growth temperatures were measured by infrared pyrometer, calibrated to thermocouple readings. Photoluminescence measurements were performed in a close-cycle He cryostat under 532 nm excitation from a diode-pumped solid-state laser. The PL spectra were dispersed by a 0.25 m monochromator and detected by a TE-cooled Ge detector. Temperature dependent PL measurements were taken from 10 K to 300 K at a laser power of 5 mW.

The structural properties of Ge-based InAs/GaAs QDs for all three samples with different GaAs nucleation temperatures are similar to those of GaAs-based QDs grown under similar growth conditions, such as the cross-sectional TEM image of 5-layer DWELL structure for the sample with the GaAs nucleated at 410 °C shown in Fig. 1(b) (Ref. 16) and the $1 \times 1\ \mu m^2$ AFM image of the uncapped InAs QDs grown on GaAs/Ge with the GaAs nucleation temperature of 380 °C shown in Fig. 1(c),[17] from which a QD density of about $4.3 \times 10^{10}\ cm^{-2}$ is obtained. The AFM result indicates that InAs QDs randomly distribute on the surface, as on GaAs substrates.[17] These results suggest that the structural properties of Ge-based InAs/GaAs QDs were not affected by the GaAs nucleation temperature. This morphology of InAs QDs in Fig. 1(c) is significantly different from that of InAs/GaAs QDs grown on a Ge-on-insulator-on-Si substrate by metal organic chemical vapor deposition, in which APBs were observed and the InAs QDs were lined with a preferential orientation along the $[1\bar{1}0]$ direction with bimodal size distribution.[18]

Figure 2(a) compares the RT PL spectra of InAs/GaAs QDs grown on Ge substrates at the different GaAs nucleation temperatures and with a reference QD sample grown on GaAs substrate. The InAs/GaAs QDs yield RT emission at ~1.3 μm with a full width at half maximum (FWHM) of ~30 meV for all the samples shown in Fig. 2(a). The PL linewidth of Ge-based InAs/GaAs QDs is comparable to the values reported for 1.3-μm InAs/GaAs QDs grown on GaAs

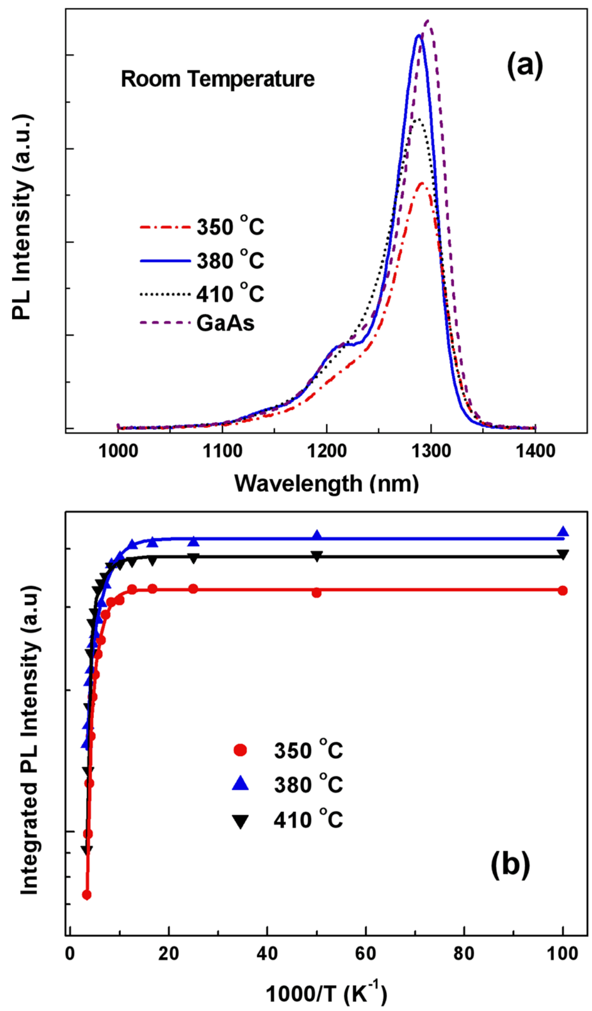

FIG. 2. (Color online) (a) Room-temperature PL spectra for Ge-based InAs/GaAs quantum-dot samples with different growth temperatures for initial GaAs nucleation layers. The RT PL spectrum of InAs/GaAs QDs grown on a GaAs substrate is also shown as a reference. (b) The Arrhenius plots of the temperature dependence of integrated PL intensity for Ge-based InAs/GaAs quantum-dot samples with initial GaAs nucleated at 350, 380, and 410 °C, respectively.

substrates.[19] Of considerable significance is that the PL intensity of the ground-state transaction of InAs/GaAs QDs grown on the Ge substrate is strongly dependent on the growth temperature of the initial GaAs nucleation layer. The strongest PL intensity for InAs/GaAs QDs on a Ge substrate is obtained from the sample grown with a GaAs nucleation temperature of 380 °C, and is almost identical to that of reference QDs grown on GaAs substrate. It should be mentioned that the reference InAs/GaAs QDs were grown under optimized conditions and represent very high optical quality as the QD laser diode based on identical growth parameters gives an extremely low J_{th} and high output power at RT.[16,17]

To investigate the effects of GaAs nucleation temperature on the optical properties of Ge-based InAs/GaAs QDs further, we studied the integrated PL intensity (IPLI) over the temperature range 10–300 K for all three Ge-based InAs/GaAs QD samples. Figure 2(b) shows the Arrhenius plot of the IPLI signals. The slopes of the line at high temperatures yield thermal activation energies of about 258, 265, and 270 meV for the samples with the initial GaAs layer nucleated at 350, 380, and 410 °C, respectively. The thermal activation energies are similar and are close to the energy difference (such as ~290 meV in Ref. 20) between the QDs ground state and InGaAs quantum well, confirming that there are no significant band structure variations caused by varying the GaAs nucleation temperature on Ge substrates. It is well established that the reduction in IPLI is attributed to the thermal escape of carriers from QD ground states into the InGaAs QWs followed by non-radiative recombination in the barriers.[20] Therefore, the IPLI differences among three samples shown in Fig. 2(b) could be understood in term of the different density of defects generated at GaAs/Ge interface and propagating into the III-V active region. This is further confirmed by etch-pit density (EPD) measurements. The etchant used for the EPD delineation is a mixture of H_3PO_4, H_2O_2, and H_2O (in a 1:1:3 ratio).[21] The defect densities of 1.7×10^7, 8.0×10^5, and $3.7 \times 10^6\,cm^{-2}$ were obtained for the samples with the initial GaAs layer nucleated at 350, 380, and 410 °C, respectively.

Ge-based InAs/GaAs QD laser devices were studied with the initial GaAs layer nucleated at 380 °C. The laser was grown on a p^+-doped Ge substrate and consisted of the following layer consequence. First, a 1.5-μm p^+-doped GaAs buffer layer and a 1.5-μm $Al_{0.4}Ga_{0.6}As$ p-doped cladding layer were deposited, followed by a 55-nm $Al_{0.2}Ga_{0.8}As$ guiding layer and a 70-nm GaAs barrier layer. Next 5-layer InAs/InGaAs DWELLs were grown with the same conditions as the samples shown in Fig. 2. Following that, a 70-nm GaAs barrier layer, a 55-nm $Al_{0.2}Ga_{0.8}As$ guiding layer, a 1.5-μm $Al_{0.4}Ga_{0.6}As$ n-doped cladding, and a 300-nm n^+-doped GaAs contact layer were grown. Broad-area laser device with a width of 50 μm were fabricated using standard etching and lithography. Devices with a length of 2.5 mm were bar-tested and directly probed without any mounting and bonding. Laser characteristics were measured in pulsed mode using a pulse width of 0.1 μs and duty cycle of 0.01%. The inset in Fig. 3 shows the laser optical spectrum above threshold at RT, in which lasing at 1.306 μm is observed. The main part of Fig. 3 shows the output power against current at various temperatures. A RT J_{th} of ~106 A/cm^2 is

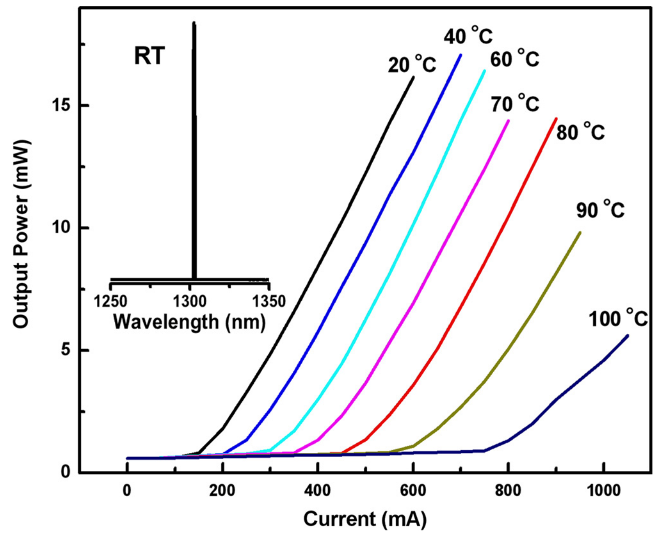

FIG. 3. (Color online) Light output against current characteristic for InAs/GaAs quantum-dot laser grown on Ge substrate for operating temperatures between 20 and 100 °C. The inset shows the laser optical spectrum above threshold at RT.

obtained, with lasing up to 100 °C and characteristic temperature, T_0 of 47 K between 20 and 100 °C, which is comparable to the performance of 1.3-μm InAs/GaAs QD lasers grown on GaAs substrates.[22]

In conclusion, we have demonstrated that the RT PL intensity of InAs/GaAs QDs grown on Ge substrates is strongly dependent on the GaAs nucleation temperature, with the highest RT PL intensity observed at 380 °C. A 1.3-μm InAs/GaAs QD laser monolithically grown on a Ge substrate with 2.5-mm cavity has been demonstrated with a RT threshold current density of 106 A/cm^2 and with operation up to 100 °C. This study is an essential step towards the monolithic integration of 1.3-μm InAs/GaAs QD lasers on Si substrates via the use of Ge-on-Si substrates.

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