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# Room Temperature Electroluminescence from InAs/GaAs Quantum Dots Grown on Ge/Si Substrate by Metal Organic Chemical Vapor Deposition

Mohan Rajesh[1], Katsuaki Tanabe[1], Satoshi Kako[1], Kenichi Kawaguchi[2], Masao Nishioka[3], and Yasuhiko Arakawa[1,3]

[1] NanoQuine, The University of Tokyo.
4-6-1 Komaba, Meguro-Ku, Tokyo 153-8505, Japan
[2]Fujitsu Laboratories, Ltd., 10-1 Morinosato-Wakamiya, Kanagawa 243-0197, Japan
[3] Institute of Industrial Science, The University of Tokyo
4-6-1 Komaba, Meguro-Ku, Tokyo 153-8505, Japan
Phone: +81-3-5452-6098 Ext. 57711, E-mail: rajesh@iis.u-tokyo.ac.jp

**The first room temperature (RT) observation of electroluminescence (EL) from InAs/GaAs quantum dots (QDs) grown directly on Ge/Si substrate by metal organic chemical vapor deposition is reported. RT EL at 1.24 μm was observed from the double hetero structure, containing high density 8-layer stacked InAs/Sb:GaAs QD active region. These results are promising for the realization of monolithically integrated QD laser for silicon photonics application.**

Since the proposal by Arakawa and Sakaki [1], research on quantum dots (QDs) and its application to the next-generation photonic devices have been gaining increasing interest, due to their 3-D quantum confinement properties. Recently, a variety of devices such as lasers [2], solar cells [3], photonic crystals [4] etc. employing QDs have been demonstrated. On the other hand, integration of photonic devices with Si-based electronics has become necessary due to ongoing advances in the microprocessor technology. Monolithic integration of III-V-on-Si is problematic due to material incompatibility. Recently, Ge-based Si substrate has drawn considerable attention for the direct growth of III-V-on-Si because it's both lattice matched to GaAs and compatible with Si technology [5]. Room temperature (RT) continuous wave QD laser have recently been demonstrated on Ge/Si substrate by MBE [6]. However, MOCVD process is preferred over MBE for industrial application, and fabrication of QD laser by MOCVD is of great interest. Here, we report on the growth, fabrication and RT electroluminescence (EL) of 8-layer stacked InAs/Sb:GaAs QDs on Ge/Si substrate.

The samples were grown by low pressure (76 Torr) metal organic chemical vapor deposition (MOCVD) on Ge/Si substrate. A 1 μm Ge layer was grown on [100]Si substrate with 6° off-cut towards [011] by ultra-high vacuum chemical deposition by two-step technique. A high structural quality undoped GaAs layer with a smooth surface was first grown on Ge/Si substrate by three-step growth method [5] followed by a 1.6 μm n-GaAs ($1 \times 10^{18}$ $cm^3$), a 1.4 μm n-$Al_{0.4}Ga_{0.6}As$ ($6 \times 10^{17}$ $cm^3$) lower cladding layer (LCL), the InAs/Sb:GaAs QDs active region, a 1.4 μm p-AlGaAs ($6 \times 10^{18}$ $cm^3$) upper cladding layer (UCL), and a $p^+$-GaAs contact layer ($6 \times 10^{19}$ $cm^3$). Silane and diethylzinc were used as the n- and p- doping material. The LCL and UCL were grown respectively at 700 and 600° C. InAs QDs were grown according to the antimony-surfactant mediated growth method [7]. We obtained high density (above $5 \times 10^{10}$ $cm^2$) QDs [Fig. 1 inset (a)] on GaAs/Ge/Si substrate by investigating the effect of various growth parameters and optimizing the conditions. The QDs exhibit ground state (GS) emission in the 1.3 μm band at RT with a full width at half maximum (FWHM) of ~ 46 meV [Fig. 1 (black curve)], when capped by a 7 nm $In_{0.05}As_{0.95}As$ strain reducing layer and a 40 nm GaAs layer. For laser application, it is necessary to stack QD layers to further increase the density of QDs in order to achieve sufficient GS modal gain. Here, the stacking procedure is based on indium-flushing method [8]. Fig. 1 inset (b) shows 1 x 1 $\mu m^2$ AFM image of the eighth QD layer. The QD density and uniformity in the stacked layer up to 8-stack are almost identical to those on the first layer [Fig. 1 inset (a) compared to inset (b)]. Fig. 1 shows the RT PL spectra of the stacked QD layers with different stacking number.

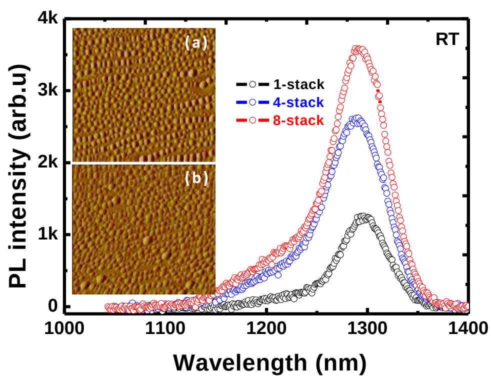


Fig. 1 RT PL spectra of the InAs/Sb:GaAs stacked QDs with different stacking number grown on Ge/Si substrate. The inset shows 1 x 1 $\mu m^2$ AFM images of the first (a) and eighth (b) layer of the uncapped InAs/Sb:GaAs QDs.

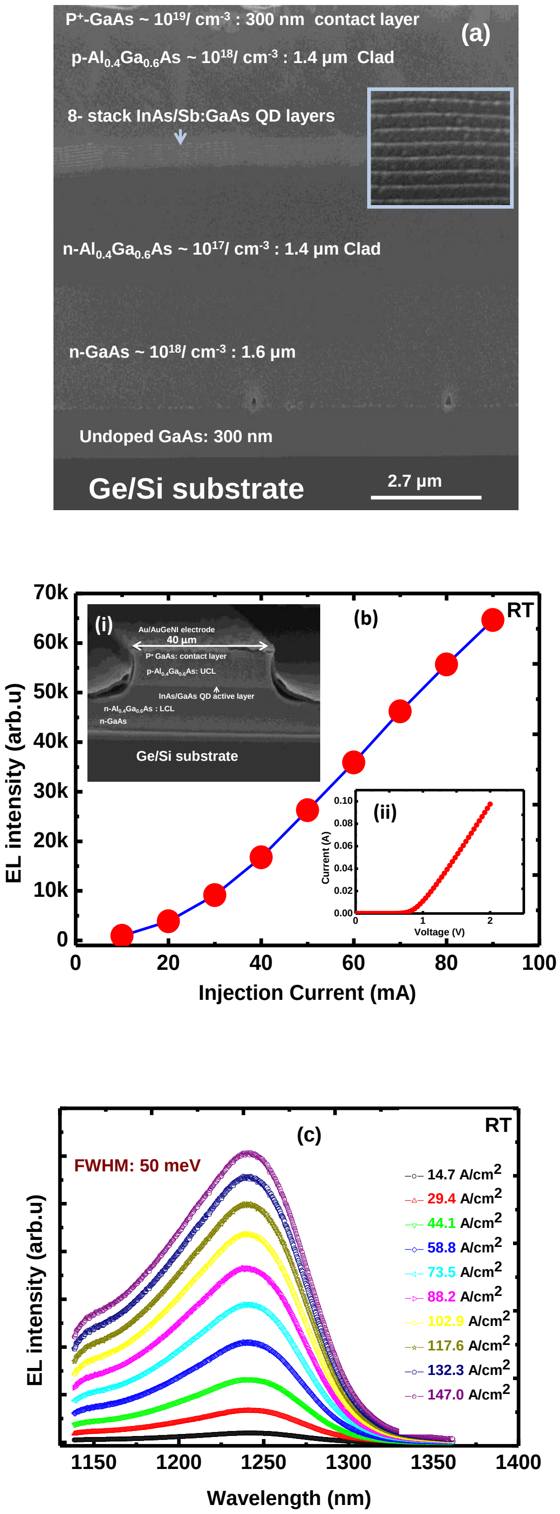


Fig. 2 (a) Cross-sectional HRSEM of the sample. The thickness and doping concentration of each layer is indicated. The inset shows a detailed image of the QD layers. (b) Light-current characteristics of the device [inset (i)] at RT. Inset (ii): plot of forward bias I-V characteristics of the diode. (c) EL spectra of the device at RT for different injection currents.

8-layer stacked QD active region was embedded in a p-n double heterostructure. Fig. 2 shows cross-sectional high resolution scanning electron microscope (HRSEM) image of the as-grown sample. For EL measurement edge-emitting devices were fabricated by standard photolithography and wet etching technique in the form of mesas with varying widths. After $SiO_2$ passivation, electrodes were deposited. Au/AuGeNi was used for n- and p- contacts. 1 - 2 mm long devices were formed by cleaving after thinning the substrate to ~ 150 μm [Fig. 2 (b) (inset (i)]. The forward bias current-voltage (I-V) characteristic of a ~1.7 mm-long device with a mesa width of ~ 40 μm is shown in Fig. 2 (b) inset (ii). The device shows typical diode I-V characteristics with a turn-on voltage of ~ 0.8 V, and a series resistance of ~ 8 ohms, these values are almost comparable to the MBE grown diodes on similar substrate [6], though the resistance remains little high. Fig. 2 (b) shows light-output versus current (L-I) plot of the preliminary device. The light output intensity increases with increase in the injection current. The evolution of EL spectra as a function of injection current density at RT is shown in the Fig. 2 (c).The GS emission is peaked at 1.24 μm, with a FWHM of ~ 50 meV. It is observed that the FWHM of the EL peak is almost constant (~ 50 meV). Furthermore, no excited state peaks were observed even at high injection currents [Fig. 2 (c)]. However, significant blue shift (BS) is observed between the EL and the PL maxima [Fig.2 (c) compared to Fig. 1]. The BS may be attributed, among other reasons to In/Ga intermixing due to annealing of QDs during the growth of UCL. Reports [9] on In(Ga)As QDs have shown that high temperature anneal can potentially introduce severe changes in the QD size due to In/Ga intermixing, resulting in the BS. However, this undesirable BS can be suppressed by further optimizing the QD and UCL growth conditions.

As a conclusion, EL of a MOCVD grown high density 8-layer stacked InAs/GaAs QDs on Ge/Si substrate has been demonstrated for the first time. The fabricated double heterostructure device is shown to exhibit turn-on voltage of ~ 0.8 V and emit at a peak wavelength of 1.24 μm at RT. This is an important step to demonstrate lasing, which is currently under progress.

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