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Effect of InGaAs capping layer on the properties of InAs/InGaAs quantum dots and lasers

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We report the effects of $In_{0.33}Ga_{0.67}As$ capping layers on the structural and optical properties of InAs self-organized quantum dots grown by gas-source molecular-beam epitaxy. With different deposition methods for the InGaAs capping layer, the quantum-dot density can be adjusted from 2.3×10^{10} to 1.7×10^{11} cm^{-2}. As-cleaved 3.98-mm-long diode laser using triple stacks of InAs quantum dots with the capping layer grown by GaAs/InAs sequential binary growth demonstrates an emission wavelength of 1305 nm and a threshold current density of 360 A/cm^2. A ground-state saturation gain of 16.6 cm^{-1} is achieved due to the high dot density. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1585125]

For almost a decade, self-assembled In(Ga)As quantum dots (QDs) formed by Stranski–Krastanow growth mode have attracted much attention because of their great potential for optoelectronic applications. The QD laser, one of its important applications, is expected to have excellent performances due to the delta-function-like density of states in the dots. In the past few years, a lot of significant improvements on the performance of QD lasers have been reported, including low threshold current density,[1] room temperature continuous-wave (cw) operation,[2] and high characteristic temperature (T_0).[3] Room temperature ground-state lasing at 1.3 μm has been achieved in lasers with In(Ga)As QD medium grown by molecular-beam epitaxy (MBE) on GaAs substrates using submonolayer (ML) deposition[4] and InGaAs capping layers.[5] Although the InGaAs QDs grown by sub-ML deposition method can extend the emission wavelength to 1.3 μm, the relatively low dot density (about $1-2\times10^{10}/\text{cm}^2$) limits the maximal gain of the ground state. Another approach for long wavelength QD lasers, which has been reported intensively, is associated with either covering or embedding InAs QDs with InGaAs layers.[5,6] It has been shown that the InGaAs layers can provide several advantages, such as extending the emission wavelength to 1.3 μm, narrowing the photoluminescence (PL) linewidths,[7] and increasing the dot density.[8–10] In general, the reported InGaAs buffer or capping layers are with an In mole fraction ranging from 0.09 to 0.15.[5–10] In this work, $In_{0.33}Ga_{0.67}As$ with a much higher In content is adopted for the capping layer overgrown on InAs QDs. Furthermore, three types of InAs/InGaAs QDs, InAs covered by Ga/InAs supply (type-A QDs), InAs covered by GaAs/InAs sequential binary growth (type-B QDs), and InAs and InGaAs with usual MBE growth (type-C QDs), are studied to optimize the optical properties of the QDs. The dot density ranging from 2.3×10^{10} to 1.7×10^{11} cm^{-2} can be achieved without a great PL intensity degradation through these deposition methods. With InAs QDs covered by GaAs/InAs sequential binary growth, we have successfully achieved 1.3 μm lasing at room temperature with good device quality.

In this work, the QDs and lasers were grown on Si-doped (100) GaAs substrates by gas-source MBE. The laser structure consists of a 500-nm-thick *n*-type GaAs buffer layer, a 1.7-μm-thick *n*-type $In_{0.49}Ga_{0.51}P$ lower cladding layer, a 200-nm-thick GaAs waveguide layer in which the QD active medium is embedded, a 1.6-μm-thick *p*-type $In_{0.49}Ga_{0.51}P$ upper cladding layer, and a 200-nm-thick heavily Be-doped GaAs contact layer. In the center of the waveguide are QD layers. In this study, three kinds of QDs, type-A QDs, type-B QDs, and type-C QDs, were grown. For growing each QD layer, 2.0 ML InAs was first deposited and followed by a 9.0 ML $In_{0.33}Ga_{0.67}As$ capping layer. In type-A QDs, the InGaAs layer was grown in the sequence of the following steps: 0.5 ML Ga deposition, 5 s As_2 illumination, and 0.25 ML InAs deposition. Between the steps, there is a 2.5 s interruption without As_2 protection. The cycle was repeated 12 times. In type-B QDs, the cycle includes 0.5 ML GaAs followed by 10 s interruption and 0.25 ML InAs followed by 2.5 s interruption. During the interruption, the sample was protected by As_2 beam, and the cycle was also repeated 12 times. In type-C QDs, all of In, Ga, and As_2 beams were used at the same time during the deposition of the InGaAs layer. Between the QD layers are 25-nm-thick GaAs spacers. The growth temperatures of InAs QDs and InGaAs capping layers were both 485 °C. After the epitaxial growth, the samples were processed into 50-μm-wide broad area lasers with different cavity lengths. The fabricated lasers were tested under pulsed mode with a pulse width of 4 μs and a repetition rate of 500 Hz. PL measurement was also used to study the as-grown QD samples.

Figures 1(a)–1(d) show the SEM images of 2.0 ML InAs, type-A, type-B, and type-C QDs, respectively. The dot density of InAs, type-A, type-B, and type-C QDs are 6.9×10^{10}, 2.3×10^{10}, 7.6×10^{10}, and 1.7×10^{11} cm^{-2}, and the corresponding base diameters are 20, 34, 29, and 27 nm, respectively. Through different deposition methods for InGaAs capping layer, the dot density changes from 2.3

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