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Lasing from quantum dots formed by activated alloy spinodal decomposition on InAs stressors

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Abstract. We demonstrate injection lasing in structures with a novel type of quantum dots (QDs) formed by activated spinodal decomposition on InAs stressors. At low temperatures the lasing is observed via the first exited QD exciton state with the lasing wavelength of 1.1 μm. With temperature increase lasing switches to higher energy states but remains up to room temperature. Simultaneous lasing via two energy states is also observed.

In recent years significant progress is achieved in fabrication, experimental and theoretical studies of lasers based on self-organized quantum dots [1–3]. Quantum dots (QDs) provide an ultimate limit of size quantization in solids, and, thus, an extreme modification of electronic properties as compared to bulk crystals. The δ-function like density of states and strong confinement of electron and hole wavefunctions in a QD result in a dramatically increased exciton oscillator strength, ultrahigh material and differential gain and can lead to reduced threshold current density and its improved temperature stability for proper device geometry. Threshold current densities as low as 60 A/cm^2 at room temperature are realized four side cleaved samples [2]. High internal ($> 96\%$) and differential (70%) efficiencies are obtained for shallow mesa InGaAs-AlGaAs lasers based on vertically coupled QDs. It is experimentally proven that QD lasers provide ultrahigh material gain of 10^5 cm^{-1} and differential gain of 10^{-13} cm^{-2} in agreement with theoretical predictions [1].

Besides their fundamental advantages QDs allows to achieve emission at longer wavelength as compared to quantum well (QW) devices. Recently it has been well understood that in case of formation of a free-standing three-dimensional island on a lattice-mismatched substrate most of the strain can relax elastically, as opposite to the case of pseudomorphic layer growth, where strain relaxation can occur only via dislocation formation. In case of three-dimensional growth coherent narrow gap islands with sufficiently large volume can be formed, and, after overgrowth, longer wavelengths emission for the given narrow gap insertion and the wide gap matrix can be realized. This can be used to extend the operation wavelength of GaAs-based light emitters and photodetectors up to 1.3 μm [4] and even up to 1.75 μm [5]. Optoelectronic devices that emit or detect in the 1.3 μm wavelength range are technologically important for use in high-bit-rate, long-haul transmission lines and application that require transparent optical propagation through Si. Until recently only InP/InGaAsP material system has been utilized to fabricate 1.3 and 1.55 μm devices. On the other hand GaAs-based device technology is, in general, both cheaper and more advanced than that of InP and permits cost-efficient production of vertical cavity devices. Recently room-temperature lasing at the wavelength of 1.31 μm has been achieved via

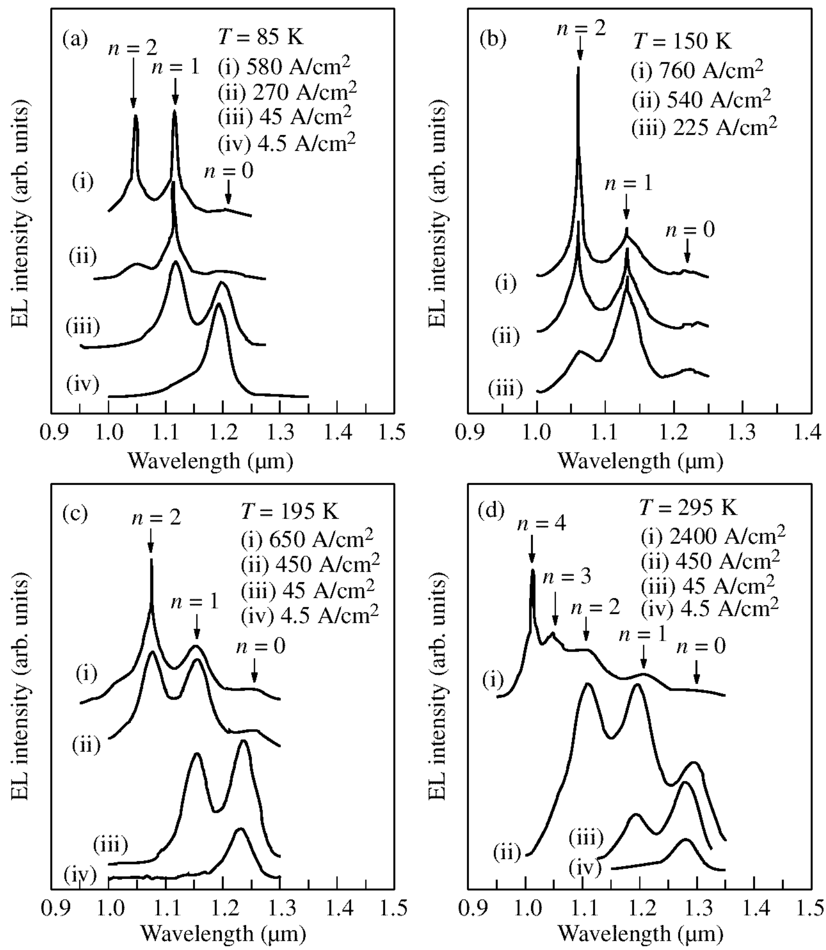

Fig. 1. Electroluminescence spectra for QD structure at different temperatures.

the $In_{0.5}Ga_{0.5}As$/GaAs quantum dots with ultra-low (10 A/cm^2) threshold current nearly temperature insensitive up to 200 K [4].

In spite of the numerous advantages of QDs devices there still exists, however, a problem to bring unique results realized for QD lasers in the low temperature range to room temperature, where the characteristics of QD lasers are only approaching to those of the best quantum well (QW) devices. Thus, it seems to be very important to develop novel approaches for QD fabrication.

In this study we propose to fabricate QDs by activated InGaAs spinodal decomposition using sheet of predeposited InAs stressors [6, 7]. The details of MBE growth are presented elsewhere [7]. In this study we will focus on electroluminescence properties of these structures.

Figure 1(a) shows the spontaneous emission spectra for the laser samples with four cleaved sides at 85 K. At the current density of 4.5 A/cm^2 the emission is mainly from the ground states at $\sim$ 1.2 μm with a full width at half-maximum of about 30 meV. A band filling with increasing current occurs, which shows the first excited state at 1.12 μm and the second excited state at 1.05 μm. The peaks due to the emission from different QDs

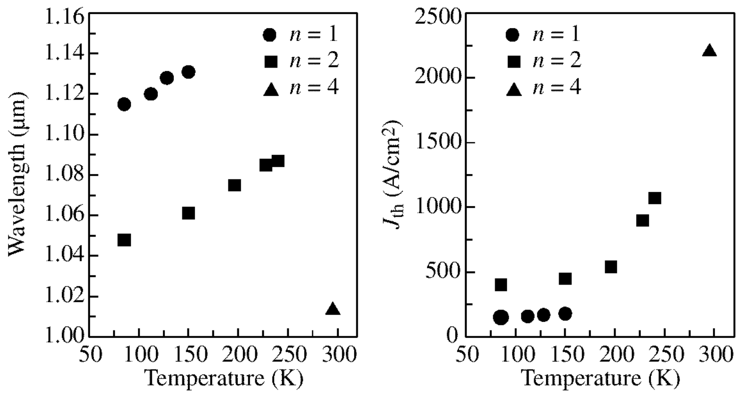

Fig. 2. Temperature dependences of the lasing wavelength and threshold current.

energy levels are well resolved and energy separation between ground and first and first and second energy levels can be estimated as 77 meV and 70 meV correspondingly.

At about 150 A/cm^2 lasing starts via the first excited level. At current densities higher than 400 A/cm^2 an additional lasing line due to the lasing via the second excited level appears in the spectra. Since the self-organized QD has the atomic-like density of states maximal gain increases with n as degeneracy of electron levels. At higher temperatures devices exhibit lasing via the $n = 2$ transition (Fig. 1(b)), and then via the $n = 3$ and $n = 4$ transitions at room temperature (Fig. 1(d)).

The temperature dependencies of the threshold current and wavelength are shown on Fig. 2. The threshold currents for $n = 1$ and $n = 2$ transitions are temperature independent up to 200 K due to the very deep confinement potential for these dots. At higher temperatures there is a significant increase in the threshold current density. Since at high temperatures lasing occurs via excited (i.e. shallower) energy levels we attribute this behavior to carrier escape from QDs to the GaAs waveguide region.

Even at low temperatures the $n = 0$ transition has insufficient gain to lase in the present structure. We believe that the main reason is low QD density of approximately 1×10^{10} cm^{-2} in this structure. Recent theoretical studies revealed that characteristics of the QD lasers (material gain, characteristic temperature (T_0), threshold current density (J_{th}), etc.) depend significantly on parameters characterizing arrays of QDs, such as surface density of QDs, size dispersion, QD localization energy, and structure geometry [8, 9]. One of the most important parameters is the dots surface density and optimization of this quantity can affect the device performance very significantly. It was shown that there exists a minimal surface density required to attain lasing at given inhomogeneous line broadening and total losses. The optimal surface density minimizing the J_{th} was estimated to be on the order of 10^{11} cm^{-2} for realistic QD size dispersion and typical losses [8]. As the typical density of InGaAs QDs is usually smaller than this value, the gain for the ground state transition may be not sufficient to overcome losses. Thus one can assume that after the QD density is increased high quality devices with low thresholds and high temperature stability can be realized.

To conclude we have studied the laser with active region based on quantum dots formed by activated alloy spinodal decomposition on InAs stressors. The lasing wavelength is 1.1 μm at 80 K which is to our knowledge significantly longer than that for quantum wells in the same material system. The threshold current has low temperature sensitivity up to 200 K.

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