

Optical properties and device applications of (InGa)As self-assembled quantum dots grown on (311)B GaAs substrates

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We have studied the optical properties of (InGa)As self-assembled quantum dots grown on (311)B-oriented GaAs substrates. The luminescence linewidth is considerably narrower than that of similar samples grown on (100). The difference is explained in terms of the in-plane coupling of dots which is more significant in (311)B. In order to assess the device potential of (311)B (InGa)As dots, we have studied the properties of edge emitting lasers by extending the well-known technology for (100) to the (311)B devices. © 1998 American Institute of Physics. [S0003-6951(98)02136-6]

Quasi-zero-dimensional semiconductor heterostructures are of great interest because of their potential applications as optoelectronic devices, e.g., light emitting diodes (LEDs) and lasers. Much attention has been focused on the epitaxial growth of self-assembled quantum dots (QDs).^{1,2} In particular, $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ QDs have shown good optical properties.³⁻⁵

Recently, it has been shown that the photoluminescence (PL) properties of $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ QDs on GaAs can be improved by growing the dots on high index ($n11$) substrates.⁶⁻⁹ A clear morphological ordering of (311)B (InGa)As QDs has also been observed.^{10,11}

In this letter we report the PL properties of $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}/\text{GaAs}$ self-assembled QDs grown on (311)B oriented GaAs substrates. The dot PL spectra are characterized by a linewidth narrower than that found in (100) substrate samples. These findings are discussed in terms of the morphological properties of QDs as inferred from atomic force microscopy (AFM). In order to exploit the good optical properties of QDs grown on (311)B, we fabricated and studied laser diodes having QDs as the active layer. The results show the possibility of obtaining good light sources in (311)B-based devices.

The samples were grown by molecular beam epitaxy on (100) and (311)B GaAs substrates. A 0.7- μm -thick GaAs buffer layer was grown, the first 0.2 μm at 580 °C and the remaining 0.5 μm at 600 °C. Before deposition of the $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ strained layer, the substrate temperature was reduced from 600 to 450 °C. The structure was completed with a 25 nm GaAs cap, also grown at 450 °C. The (100) and (311)B samples were grown simultaneously. For each substrate orientation, the reflection high-energy electron-diffraction pattern indicated a transition from two-dimensional (2D) to 3D growth mode at a thickness $L \sim 1.1$ nm.

The PL and electroluminescence (EL) measurements were performed at temperature, T , ranging from 4.2 to 300 K. For PL, optical excitation was provided by the 514.5 nm

line of an Ar^+ laser. The luminescence was dispersed by a 3/4 m monochromator and detected by a cooled Ge diode detector. The dot morphology was investigated by contact mode AFM. For AFM imaging, QDs were grown under the same conditions as above, but they were not capped.

Figure 1 shows the low-temperature PL spectra of two 1.1-nm-thick $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ layers deposited on (100) and (311)B substrates. The PL peak position for (311)B QDs is blueshifted by 25 meV with respect to the (100) sample. The PL spectrum linewidths [full width at half maximum, (FWHM)] are 17 and 45 meV for (311)B and (100) samples, respectively. The AFM images are shown in Fig. 1 (inset). The dots grown on (100) have an average diameter of $d = 36$ nm, height $h = 2.2$ nm, surface density $\rho = 4.5 \times 10^{10} \text{ cm}^{-2}$, and appear isolated from each other. For the (311)B sample the surface coverage due to the dots is more uniform with $\rho = 1.5 \times 10^{11} \text{ cm}^{-2}$, $d = 26$ nm, and $h = 1.0$ nm. The density and the size of the dots clearly affect the electronic properties of the samples as revealed by the optical measurements. The higher energy emission for the

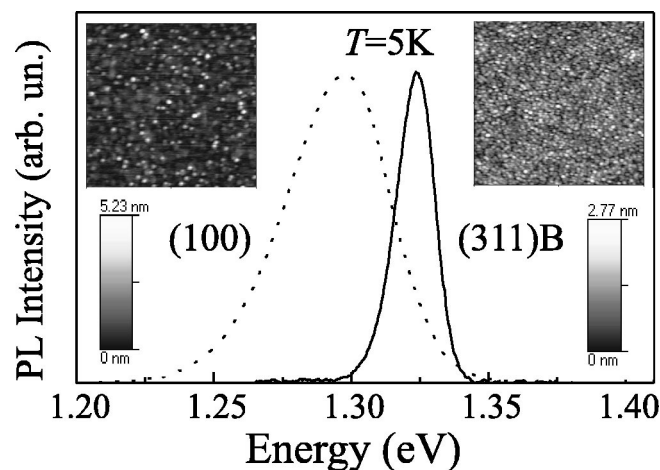


FIG. 1. Low-temperature PL spectra on $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ QDs grown on (100) (dashed line) and (311)B (continuous line) oriented substrates. The excitation wavelength and power are 514.5 nm and 0.5 W/cm², respectively. The (InGa)As thickness is 1.1 nm. An AFM image (1 $\mu\text{m} \times 1 \mu\text{m}$) with the corresponding height scale is shown for each layer.

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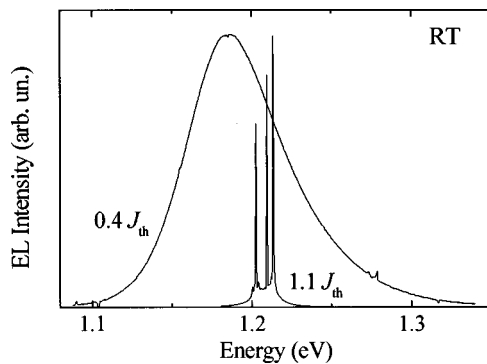


FIG. 2. Room temperature EL spectra below and above the threshold current of an injection edge emitting laser based on (311)*B* $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$; $J_{\text{th}} = 500 \text{ A/cm}^2$. The spectra are recorded in pulsed mode with a pulse width of $0.2 \mu\text{s}$ and a duty cycle equal to 5%.

(311)*B* samples is due to the smaller size of the dots, which pushes the electronic levels closer to the GaAs band edge.¹² Moreover, in the (311)*B* sample, the small distance between nearest neighbor dots ($\sim 10 \text{ nm}$) produces an electronic coupling which, in turn, allows the relaxation of the carriers in the lowest local energy minimum. As a consequence, the PL arises from only the lowest energy section of the dot size distribution, which results in a smaller luminescence linewidth compared to that of the (100) dots. The population of higher energy dots can be achieved by increasing either the power density or the temperature. We believe that the carrier transfer between different dots might take place through tunnelling and/or carrier diffusion in the wetting layer. In the (311)*B* sample, the real dot size distribution also reappears in PL by reducing the in-plane carrier transfer with a magnetic field, *B*, applied along the growth direction. In fact, at $B = 40 \text{ T}$, the PL linewidth is 80% higher than at zero field.¹³ These results provide strong evidence of a high degree of coupling between the dots.

In order to test the possible application of (311)*B* substrates in optical devices we fabricated laser structures based on $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ QDs, extending the well-established processing technology for (100) substrates to (311)*B*. To our knowledge there is only one previous report of quantum disk lasers grown on high-index planes formed by $\text{In}_{0.25}\text{Ga}_{0.75}\text{As}$ embedded in $\text{Al}_{0.15}\text{Ga}_{0.75}\text{As}$ and grown by metalorganic vapor phase epitaxy.¹⁴ Our devices are index-guided, in-plane lasers obtained by standard etching and lithography. The cavity length is 2 mm with a width equal to $15 \mu\text{m}$. The basic structure consists of a cavity formed by three $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ quantum wells (QWs) each 10 nm in width, separated by barriers of 10 nm . The dots are formed by depositing a 1.1-nm -thick $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ layer in the center of each QW in order to minimize the effect of carrier thermal escape from the ground state.¹⁵ The cavity is clad by $1.5 \mu\text{m}$ of $\text{Al}_{0.6}\text{Ga}_{0.4}\text{As}$ (the latter layer is *n* doped on the substrate side and *p* doped on the top side). The QDs and the cavity were grown at 450°C and the (AlGa)As cladding layer at 600°C .

Figure 2 shows the room temperature EL spectra below and above the threshold current, J_{th} , of a laser grown on (311)*B*. The value of J_{th} is 500 A/cm^2 . In a similar device grown on (100), a J_{th} as low as 200 A/cm^2 has been ob-

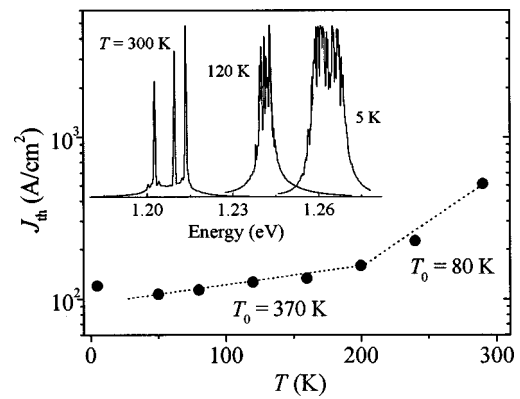


FIG. 3. Temperature dependence of J_{th} for the device shown in Fig. 3. The dashed lines are a fit to the data using the following formula: $J_{\text{th}} = J_0 \exp(T/T_0)$. The values of T_0 are given in the figure. The inset shows the laser spectra recorded at different temperatures ($J = 1.1 J_{\text{th}}$).

tained. These values compare with the best values reported in the literature.¹⁶

The T dependence of J_{th} is shown in Fig. 3. The characteristic temperature T_0 is 370 K for T between 50 and 200 K , and it decreases to $T_0 = 80 \text{ K}$ for $T > 200 \text{ K}$. The same figure also shows the EL spectra above the threshold current at different temperatures. The laser luminescence spectra are characterized by a multi-mode emission, whose energy spacing is not related to the cavity length. The relative intensity of the modes strongly depends on the temperature and an interesting narrowing of their distribution can be observed with increasing T . The intrinsically disordered morphology of the active medium can be invoked to explain the large linewidth of the laser spectrum at $T = 5 \text{ K}$. Then a higher value of the temperature might allow an enhanced carrier drift towards the dots where the lasing action preferentially takes place. Finally, at room temperature this gives rise to a laser spectrum having very few modes. Further investigation is needed to better clarify this anomalous behavior.

In conclusion, we have studied both the optical and morphological properties of $\text{In}_{0.5}\text{Ga}_{0.5}\text{As}$ self-assembled quantum dots grown on (311)*B* and standard (100) substrates. The narrower luminescence linewidth found in the (311)*B* samples is explained in terms of carrier tunneling into those dots of the ensemble which have low energy ground states. We have fabricated lasers grown on each of the substrate orientations. The (311)*B* lasers show good properties compared with similar devices grown on (100) and with the results reported in the literature.

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