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Characteristics of highly stacked InAs quantum-dot laser grown on vicinal (001)InP substrate

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Abstract

We fabricated broad-area laser diodes consisting of 30-layer stacks of InAs quantum dots by using a strain-compensation technique on a vicinal (001)InP substrate. These laser diodes exhibit ground-state lasing at 1576 nm in the pulsed mode with a high characteristic temperature of 111 K around room temperature (20–80 ºC).

1. Introduction

Quantum dots (QDs) and quantum dashes (QDHs) have attracted significant attention because of their applications to high-performance optical devices such as semiconductor lasers and semiconductor optical amplifiers [1]. High-density QDs and QDHs are necessary for fabricating high-performance devices. To increase the density of QDs, we developed a strain-compensation technique that is resistant to defects and dislocations. Our method increases the number of layers of InAs QDs that can be stacked on InP(311)B substrates [2,3]. Because (001) surfaces are commonly used in industry, they are inexpensive, and there is demand for QD structures fabricated on InP(001) substrates. Therefore, we also developed a fabrication technique for InAs QDs on a InP(001) substrate using vicinal (001) substrates and As_2 flux [4]. In the present study, we fabricated a broad-area laser with highly stacked InAs QDs using the strain-compensation technique on vicinal (001)InP substrates and evaluated the laser's properties.

2. Experimental

All the samples were fabricated using molecular beam epitaxy (MBE) on vicinal (001) InP substrates under As_2 flux. This substrate had an off angle of 6° along the [1-10] direction, which prevented the formation of a quantum-dash structure. The substrates were heated to 520 °C in order to thermally clean them. A 150-nm-thick lattice-matched n-type $In_{0.52}Al_{0.48}As$ buffer layer was grown on the cleaned substrates, and then 5-ML InAs QDs and 15-nm-thick $In_{1-x-y}Ga_xAl_yAs$ spacer layers were grown at 470 °C on top of the buffer layer, producing a 30-layer stacked structure. The InAs and spacer layers satisfied the strain-compensation conditions for preventing the degradation of the QD quality. We defined the strain-compensation conditions. Strain compensation is based on the simple approximation that the total strain energy of an InAs layer/spacer layer pair is zero. Then, a p-type $In_{0.52}Al_{0.48}As$ cladding layer and p-type $In_{0.53}Ga_{0.47}As$ contact layer were grown. The Ti/Pt/Au p-contact electrode line, which had a width of 50 μm, was fabricated using the conventional photolithography lift-off process. A SiO_2 film, which separated the InGaAs contact layer and the probe electrode, was deposited by tetraethyl orthosilicate chemical vapor deposition (TEOS-CVD). After the deposition of the Ti/Pt/Au n-contact electrode, the sample was cleaved with various cavity lengths ranging from 600 to 1400 μm, and the cleaved facets were used for the fabrication of mirrors. The light–current (L–I) characteristics and laser emission spectra were measured using a laser-diode tester (AT-143; manufactured by Yuasa Electronics) and an optical spectrum analyzer (AQ6370; manufactured by Yokogawa Electric Corporation). The post-growth surface morphology was observed using an atomic force microscope (AFM) under normal atmospheric conditions for samples without capping layers and a contact layer.

3. Results and Discussion

Figures 1 show AFM images of the InAs QD structures grown on (001) InP 6° off the substrate with As_2 flux. Although a quantum-dash structure was formed on the InP(001) substrate, high-density InAs QDs were observed in this sample. The (001) vicinal surface increased the atomic step density along the [1-10] direction, which decreased the surface diffusion of In adatoms during the growth of the InAs QDs. In addition, the As_2 flux played an important role in forming the QD structure. The lateral size and height of the QDs were 30–40 and 2–4 nm, respectively.

Figure 2 shows the spectra before (black line) and after (red line) lasing for the device with a cavity length of 600 μm. The threshold current for lasing was 1037 mA in this laser. The EL spectrum was measured at 1000 mA. This spectrum exhibits a peak at 1573 nm, which is similar to the photoluminescence (PL) spectrum measured for a sample without the cladding layer (not shown here). Therefore, the changes in the size and shape of the QDs that occurred after the growth could be ignored in our laser process. The lasing spectrum was measured at 1080 mA. The lasing wavelength was 1576 nm, which was slightly larger than that of the EL peaks. Therefore, this 1576-nm emission corresponded to the ground-state lasing of the QDs. This laser used a strain-compensation stack, resulting in a high density of QDs. Because of this high density, the laser had sufficient gain for ground-state lasing. Hence, excited-state lasing was suppressed for this laser, despite the laser's small cavity length.

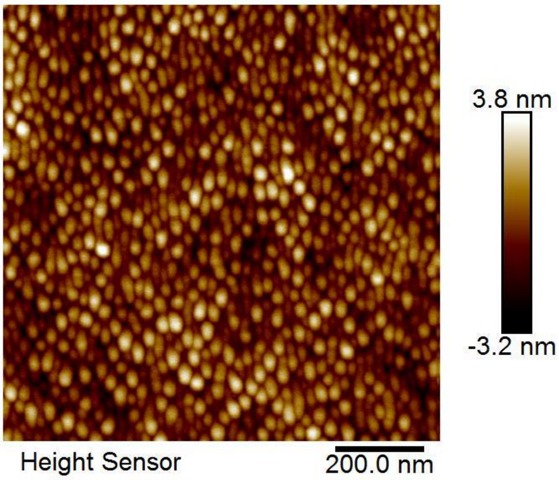

Fig. 1 AFM image of InAs QDs grown on InP(001) 6° off substrate with As_2 flux.

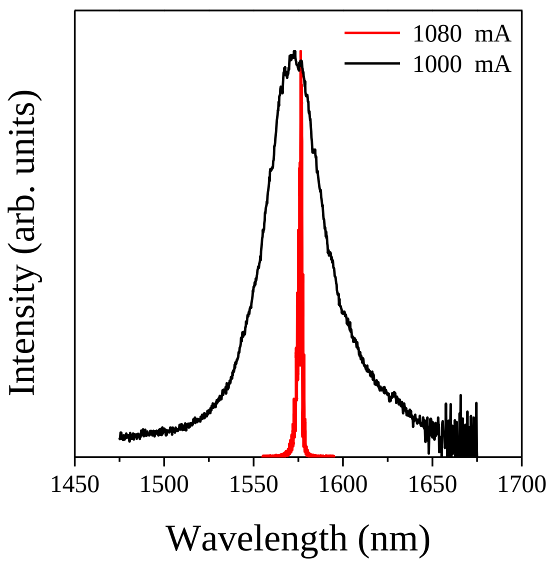

Fig. 2 EL (black line) and laser (red line) spectra of 30-layer stacked QD laser at room temperature. Ground state lasing was obtained at 1576 nm with this laser.

Figure 3 shows plots of the output power with respect to the current at various temperatures for a QD laser with a cavity length of 1 mm. This laser can operate at temperatures up to 80 °C without any large decrease in the slope efficiency. Moreover, the increase in the threshold current of the QD laser is not as large as that of a 1.55-µm conventional semiconductor laser. The inset of Fig. 3 shows the relationship between the threshold current and expressed as $I_{th} = I_0 \exp(T/T_0)$. The value of T_0 for the QD laser was 111 K, which is greater than the T_0 value of a 1.55-µm conventional semiconductor laser and almost same as that of the QD laser that we developed on a InP(311)B substrate [1]. This is because the QDs used as gain media have discrete energy levels. Moreover, we developed a temperature-stable QD laser with a wavelength around 1.55 µm by using an InP(001) substrate with a small off angle along with As_2 flux, which is advantageous for fabricating industrial products.

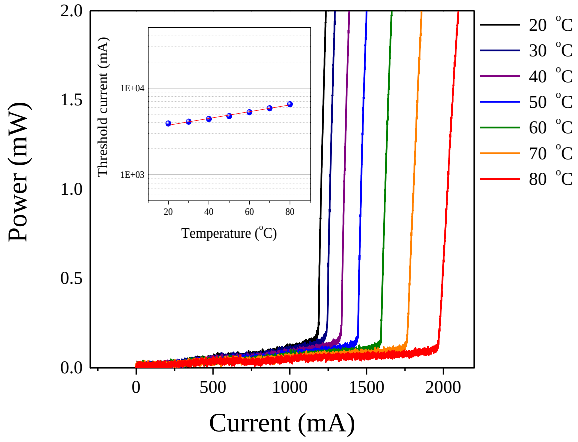

Fig. 3 Temperature dependence of I-L characteristics. Inset: temperature dependence of threshold current.

4. Conclusions

We fabricated a highly stacked InAs QD structure using a strain-compensation technique on vicinal (001)InP substrates and incorporated the structure into a QD laser. Ground-state lasing at 1573 nm was observed at a threshold current of 1037 mA. A large characteristic temperature of 111 K was observed, implying that the strain-compensation technique can be used to fabricate high-quality QDs.

Acknowledgements

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References

[1] K. Akahane, N. Yamamoto, and M. Tsuchiya, Appl. Phys. Lett., 93, (2008) 041121.

[2] K. Akahane, N. Ohtani, Y. Okada, and M. Kawabe, J. Cryst. Growth, 245 (2002) 31.

[3] K. Akahane, N. Yamamoto, and T. Kawanishi, Physica Status Solidi A 208 (2011) 425.

[4] K. Akahane, and N. Yamamoto, Physica Status Solidi C 10 (2013) 1509.