K-2-4

Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp996-997

A semiconductor optical amplifier consisting of highly stacked InAs quantum dots fabricated by using the strain-compensation technique

Kouichi Akahane*, Naokatsu Yamamoto, Toshimasa Umezawa, Atsushi Kanno, and Tetsuya Kawanishi

National Institute of Information and Communications Technology
4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan
Phone: +81-42-327-6804 E-mail: akahane@nict.go.jp

Abstract

A semiconductor optical amplifier was fabricated by incorporating highly stacked InAs quantum dots (QDs) as gain media. Twenty InAs QD layers were successfully stacked through the strain-compensation technique, without any deterioration of crystal quality. A wide-range 1.55 μm band gain was observed. The maximum gain reached 15 dB at 1510 nm when the input power was below -20 dBm.

1. Introduction

Semiconductor quantum dots (QDs) grown using self-assembly techniques in the Stranski-Krastanov (S-K) mode are known to be useful in high-performance optical devices such as QD lasers and QD semiconductor optical amplifiers (SOAs) [1,2]. A significant amount of research has been carried out on the development of high-performance QD lasers and QD SOAs because of the advantages they offer, including low threshold current, temperature stability, high modulation bandwidth, and low chirp. To realize these high-performance devices, the surface QD density should be increased by fabricating a stacked structure [3]. We have developed a growth method based on the strain-compensation technique that enables the fabrication of a large number of stacked InAs QD layers on an InP(311)B substrate [4,5]. In the this study, we employed the proposed method to fabricate a QD SOA consisting of 20 InAs QD layers and investigated the characteristics of the highly stacked QD SOA module.

2. Experiments

The QD samples were fabricated using the conventional solid-source molecular beam epitaxy (MBE) technique. Stacked QD structures were fabricated on an InP(311)B substrate. The lattice constant of InP was between those of GaAs and InAs, implying that the lattice constant of InGaAlAs could be continuously varied around that of InP by simply controlling its composition. Therefore, the strain-compensation requirement could be satisfied by capping the InAs QDs with an InGaAlAs layer, the lattice constant of which was adjusted to a value slightly smaller than that of the InP substrate. A schematic of the device structure is shown in Figure 1. After growing a 150-nm-thick lattice-matched Si-doped n-type $In_{0.52}Al_{0.48}As$ buffer layer, a stack of 20 InAs QD layers and 20-nm-thick InGaAlAs spacer layers were grown. The thickness of the active region was fixed at about 420 nm. Subsequently, a 2000-nm-thick lattice-matched Be-doped p-type InAlAs cladding layer and a p-type InGaAs contact layer were grown. The ridge waveguide structure was fabricated using UV lithography, followed by dry etching that was stopped just above the waveguide. After dry etching, the ridge width was around 2.7 μm and the ridge waveguide was embedded in benzocyclobutene (BCB) polymer. Then, p- and n-contact electrodes were fabricated. The ridge waveguide was fixed at an angle of 6^{o} from the surface normal of the cleaved facet to reduce reflection of light. Finally, after cleaving the devices to a length of 2 mm, both sides of the cleaved facets were coated by the anti-reflective dielectric structure. This SOA tip was mounted on a metal stem and coupled by lenses to the single-mode fibers. The amplified spontaneous emission (ASE) spectra and optical power were measured using an optical spectrum analyzer (AQ6370; manufactured by Yokogawa Electric Corporation) and an optical power meter, respectively. The wavelength dependence of optical gain was measured using a wavelength-tunable laser.

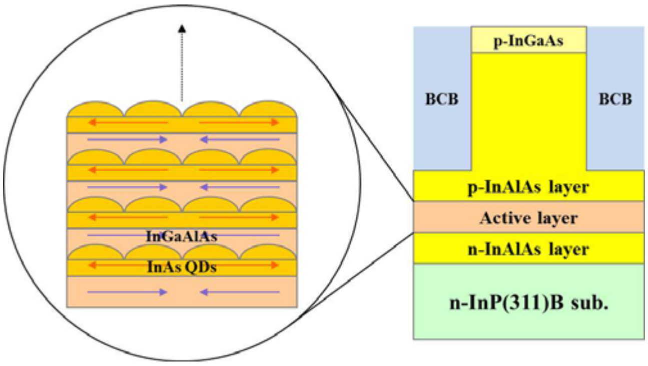

Fig. 1 Schematic of the structure of a highly stacked InAs QD SOA.

3. Results and Discussion

Figure 2 shows the dependence of the intensity of the amplified spontaneous emission (ASE) on the injection current applied to the QD SOA. ASE spectra were observed at around 1525 nm. The full width at half maximum (FWHM) for an injection current of 50 mA was 55 nm. This corresponded to the size distribution of the QDs and concurred with our previously reported observations on photoluminescence (PL) and electroluminescence (EL) [6,7]. The FWHM for an injection current of 200 mA was 33 nm, which was narrower than that obtained for 50 mA and the PL reported earlier. The narrowing of the spectrum implied a change in the carrier distribution of individual QDs. The peak of the spectrum also shifted toward the shorter-wavelength side. As a result, the recombination rate of carriers in the QDs emitted at such a wavelength was higher than that at other wavelengths. In addition, the lasing spectrum was observed at an injection current of 300 mA. This is caused by the reflection at the edge of the single-mode fiber. However, this lasing was suppressed by the optical input.

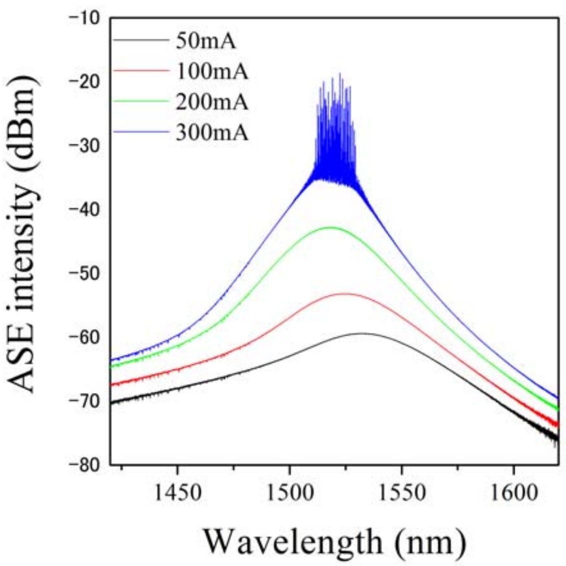

Fig. 2 Dependence of ASE intensity on the injection current applied to SOA module.

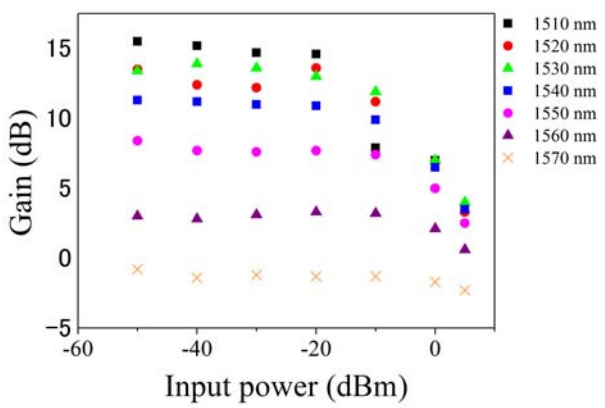

Fig. 3 Module gain dependence on input optical power at different wavelengths.

Figure 3 shows the module gain dependence on input optical power at different wavelengths. The measurements were carried out with an injection current of 300 mA. A maximum gain of 15 dB was obtained at 1510 nm with a small input power (below -20 dBm). This gain was nearly the same as that represented by the peak of the ASE spectrum. The longest wavelength that yielded a gain was 1560 nm, while the shortest wavelength to have yielded a gain could not be determined because the wavelength-tunable laser could not provide wavelengths lower than 1510 nm. Nevertheless, the shortest wavelength that yielded a gain could be estimated to be 1470 nm by the ASE spectrum. This gain region was wide and covered the S and C bands for fiber optic communication systems. Since the applied injection current level was not so high, we could expand the operating wavelength and increase the gain at higher injection current levels. Further, we successfully developed a growth technique to obtain QDs that show wide-band emission in highly stacked structures [8]. Consequently, ultra-wide-band SOAs could be potentially realized.

4. Conclusions

We have fabricated an SOA module with highly stacked QDs. This device included 20 layers of InAs QDs made by using the strain-compensation technique. No deterioration in the crystal quality of the QDs was observed. The device showed an ASE at 1525 nm. The maximum gain reached 15 dB at 1510 nm with an input power of -20 dBm and an injection current of 300 mA.

Acknowledgement

We would like to acknowledge the technical support extended by the staff at the Photonic Device Laboratory, National Institute of Information and Communications Technology (NICT) for the fabrication of the devices. This study was conducted as a part of a research project entitled “R&D of high-precision imaging technology using 90 GHz band linear cells,” supported by the Japanese Government funding for “R&D to Expand Radio Frequency Resources” by the Ministry of Internal Affairs and Communications.

References

[1] Y. Arakawa and H. Sakaki, Appl. Phys. Lett. 40 (1982) 939.

[2] M. Sugawara, N. Hatori, M. Ishida, H. Ebe, Y. Arakawa, T. Akiyama, K. Ohtsubo, T. Yamamoto, and Y. Nakata, J. Phys. D **38** (2005) 2126.

[3] M. Ishida, N. Hatori, T. Akiyama, K. Otsubo, Y. Nakata, H. Ebe, M. Sugawara, and Y. Arakawa, Appl. Phys. Lett. **85** (2004) 4145.

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

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

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

[7] K. Akahane, N. Yamamoto, and T. Kawanishi, IEEE Photonics Technol. Lett. **22** (2010) 103.

[8] K. Akahane, and N. Yamamoto, J. Cryst. Growth **323** (2011) 154.