Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp994-995

Broadband near-infrared superluminescent diode based on stacked multi-color InAs/GaAs quantum dots

Nobuhiko Ozaki[1], Takuma Yasuda[1], Shunsuke Ohkouchi[2], Eiichiro Watanabe[3], Naoki Ikeda[3], Yoshimasa Sugimoto[3] and Richard A. Hogg[4]

[1] Wakayama Univ.
930, Sakaedani, Wakayama, Wakayama 640-8510, Japan
Phone: +81-73-457-8234 E-mail: ozaki@sys.wakayama-u.ac.jp
[2] NEC Corp.
34, Miyukigaoka, Tsukuba, Ibaraki 305-8501, Japan
[3] NIMS
1-2-1, Sengen, Tsukuba, Ibaraki 305-0047, Japan
[4] Univ. Sheffield
Broad Lane, Sheffield, S3 7HQ, UK

Abstract

Superluminescent diode (SLD) light source based on stacked multi-color InAs/GaAs quantum dots (QDs) was developed. The emission wavelength of QDs was controlled with a thickness of a strain-reducing layer deposited on grown QDs. The controlled ground state emission peaks enable to form dip-less broadband spectrum with contributions of first excited state emissions. The emission peak wavelength and the bandwidth of the SLD emissions were approximately 1280 nm and 140 nm, respectively, with a current density of 36.8 A/cm^2.

1. Introduction

The optical coherence tomography (OCT), which is a non-invasive optical profile imaging technique for bio/medical samples, has been rapidly developed and applied to various clinical uses for last several decades [1]. The OCT is basically operated by using the Michelson-interferometer with a low coherence (broadband) light source, which is a critical component to obtain OCT images. Self-assembled InAs quantum dots (QDs) have been recognized as one of the promising material for the OCT light source [2-4]. The InAs-QDs grown on a GaAs substrate, which are well-known as strain-driven (S-K mode) self-assembled QDs, possess naturally certain size-distribution and result in a broadband emission. The wider bandwidth contributes to higher resolution of OCT images. Further, the emission center wavelength of the QDs exhibits at near infrared (NIR) region, approximately 1.2 – 1.3 μm, which is useful for obtaining a long penetration depth in bio-samples.

In order to realize the broadband QD-based light source, we have developed various techniques for controlling emission wavelengths of the InAs-QDs by using strain reducing layers (SRLs) [5], In-flush technique [6] and bi-layer QD growth [7]. These techniques are effective for not only broadening the bandwidth of emission spectrum from QDs but also controlling the center wavelength of the emission spectrum. This controllability is suitable for obtaining large penetration depths by avoiding light absorptions in various bio-tissues. In this paper, we report on the NIR emissions induced by electric current injections from the λ-controlled QDs with SRLs for a practical electro-optical device: superluminescent diode (SLD).

2. Experimental Procedures

InAs/GaAs QDs growth

InAs-QDs were grown on a n-GaAs (001) substrate by molecular beam epitaxy (MBE). After an n-GaAs buffer layer of 300 nm in thickness was grown, a 240-nm-thick active layer sandwiched between upper and lower cladding layers of 1.5-μm-thick n-/p-$Al_{0.35}Ga_{0.65}As$ was grown. The active layer consists of GaAs layers and 4 stacked InAs-QD layers with SRLs of different thicknesses. The depositions of SRLs with different thicknesses on grown QDs enable controlling their emission center wavelengths [5].

RWG fabrication

A straight ridge waveguide (RWG) was fabricated on the QD-grown substrate as shown in Fig. 1.

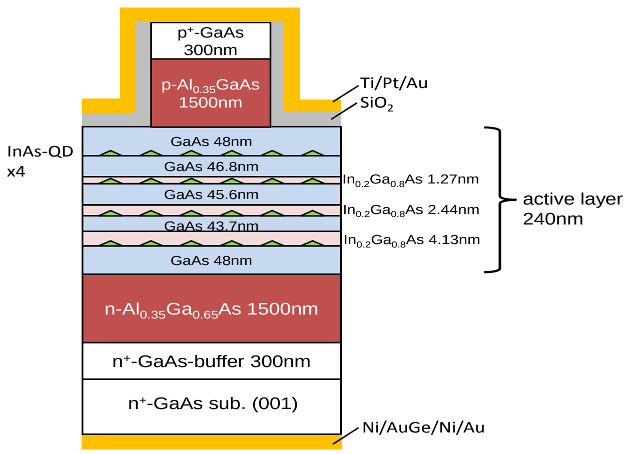

Fig. 1 Schematic profile of a RWG fabricated on a grown sample.

The height and width of the RWG were approximately 2.0 and 25 μm, respectively. The length of the RWG was approximately 1 mm. The electrodes were formed by depositions of Ti/Pt/Au for p-contact and Ni/AuGe/Ni/Au for n-contact. The emission spectra from the RWG was measured with an InGaAs array detector attached on a monochromator through an objective lens (20×, NA=0.40).

3. Results and Discussion

Figure 2 shows EL spectra from the RWG with different injection currents; current density (*J*) was varied from approximately 2.16 to 36.8 A/cm^2 with almost even intervals. Broadband emissions contributed from the stacked InAs-QDs with different emission center wavelengths were obtained and the emission wavelengths are consistent with PL measurements of QDs grown with same conditions, which exhibit the center wavelengths ranging between approximately 1220 and 1300 nm of ground state (GS) emissions and ranging between 1150 and 1200 nm of first excited state (ES) emissions. The 3-dB bandwidth of the EL is approximately 140 nm at *J*=36.8 A/cm^2.

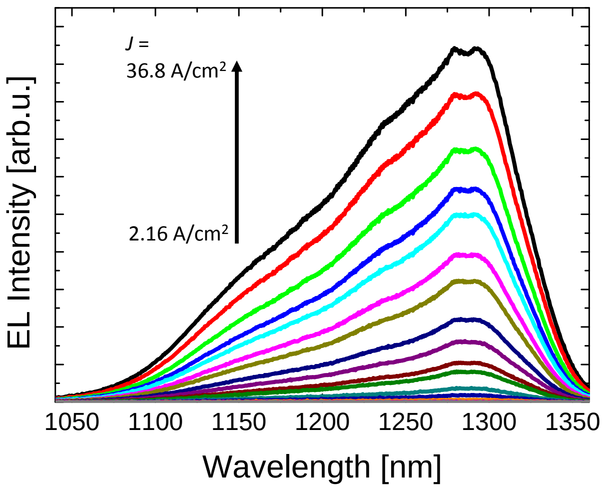

Fig. 2 EL spectra from the RWG including 4-stacked multi-color InAs-QDs with different injection current densities.

The dependence of the EL intensity on the injection current density *J* was investigated. As shown in Fig. 3, the total integrated intensity calculated from the EL spectra was increased with a superlinear relation to *J*. Also, the EL intensities at certain wavelengths exhibit superlinear behaviors against *J* with different gain variations. Although the gain of GS-related emissions at 1250 and 1300 nm is higher than that of ES related emissions at 1150 and 1200 nm with *J* lower than 30 A/cm^2, the gain of ES emissions increases with *J* above 30 A/cm^2 due to the filling of GS of QDs. From above results, the broadband NIR emissions of a SLD based on the multi-color QDs are confirmed.

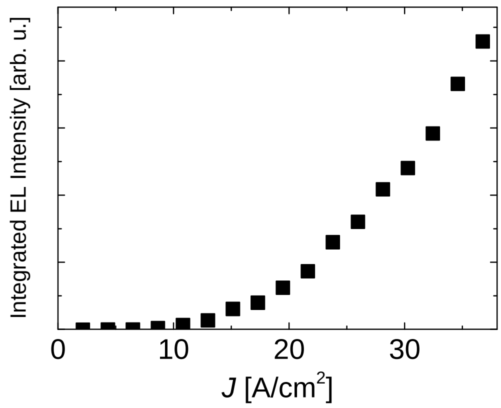

Fig. 3 Integrated EL intensities against injected current densities.

4. Conclusions

We have fabricated a broadband NIR light source based on multi-color InAs-QDs. The emission wavelengths of QDs were controlled with SRL thicknesses and 3-dB bandwidth of 140 nm was achieved. The integrated emission power exhibited superlinear behavior against the injection current density and the SLD based on multi-color QDs was demonstrated.

Acknowledgements

This study was partly supported by the Grants-in-Aid for Scientific Research (KAKENHI) Grant Number 25286052 and the Canon Foundation. Fabrications of the RWG were supported by the NIMS Nanofabrication Platform in "Nanotechnology Platform Project" sponsored by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

References

[1] Adam M. Zysk, Freddy T. Nguyen, Amy L. Oldenburg, Daniel L. Marks, Stephen A. Boppart, J. Biomedical Opt. **12,** 051403 (2007).

[2] Z. Z. Sun, D. Ding, Q. Gong, W. Zhou, B. Xu, Z. G. Wang, Optical Quant. Electron. **31,** 1235 (1999).

[3] M. Rossetti, L. H. Li, A. Fiore, L. Occhi, and C. Vélez, *Handbook of Self Assembled Semiconductor Nanostructures for Novel Devices in Photonics and Electronics* (Elsevier Ltd., Amsterdam, 2008), p.565-599.

[4] Z. Y. Zhang, R. A. Hogg, X. Q. Lv, and Z. G. Wang, Adv. Opt. Photon. **2**, 201 (2010).

[5] N. Ozaki, K. Takeuchi, S. Ohkouchi, N. Ikeda, Y. Sugimoto, K. Asakawa, R.A. Hogg, J. Cryst. Growth **323**, 191 (2011).

[6] Yuji Hino, Nobuhiko Ozaki, Shunsuke Ohkouchi, Naoki Ikeda, Yoshimasa Sugimoto, J. Cryst. Growth, *in press*.

[7] N. Ozaki, Y. Nakatani, S. Ohkouchi, N. Ikeda, Y. Sugimoto, K. Asakawa, E. Clarke, R.A. Hogg, J. Cryst. Growth, *in press*.