Integration of an InGaAs Quantum-Dot Laser With a Low-Loss Passive Waveguide Using Selective-Area Epitaxy

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***Abstract*—An InGaAs quantum-dot (QD) laser integrated with a low-loss waveguide is demonstrated. Selective-area epitaxy is used to simultaneously form the QDs that form the active region of the laser and quantum wells (QWs) that form the waveguide section of the integrated devices. The losses in the active and passive sections of the integrated devices are 6 and 3 cm $^{-1}$, respectively. Very low losses in the waveguide section are due to a large difference of 200 meV in the bandgap energies of the selectively grown QDs and QWs.**

***Index Terms*—Integrated optoelectronics, quantum dots (QDs), selective-area epitaxy (SAE), semiconductor lasers.**

I. Introduction

FOLLOWING the theoretical predictions of lower threshold current densities [1] and better temperature-dependent performance [2] due to three-dimensional confinement of charge carriers in the active region of lasers, several groups have demonstrated quantum-dot (QD) lasers [3]–[8]. These QD structures are commonly grown in the Stranski–Krastanow (S-K) growth mode, using either molecular beam epitaxy or metal–organic chemical vapor deposition (MOCVD) for fabricating lasers. QDs grown in the S-K growth mode have random nucleation sites, with broad size distributions. It is essential to control the area of nucleation and bandgap of QDs for fabrication of photonic integrated circuits. It has been demonstrated that selective-area epitaxy (SAE), a bandgap tuning technique that has been used for fabrication and integration of quantum-well (QW) lasers with other functional devices [9]–[13], can be used to selectively control the two-dimensional to three-dimensional transition and also tune the bandgap energies of selectively grown QDs, thereby making it a promising technique for integration of QD-based devices [14], [15].

In this letter, we report on an InGaAs QD laser integrated with a passive waveguide section. The epitaxial layers that form the active region of the laser and the waveguide section are grown in a single growth step using SAE. Local growth rate enhancement due to inhibition of epitaxial growth on the masking material (SiO_2 in this work) is used to form QDs for the active region of the laser. Lower growth rate elsewhere (unmasked regions) forms QWs on other parts of the substrates for forming the waveguide.

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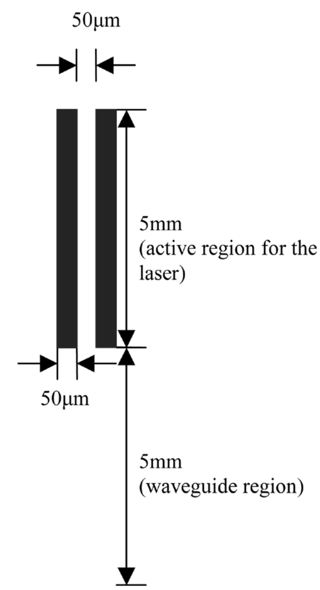

Fig. 1. Schematic of the mask pattern used in this work.

II. Experimental Details

The devices studied in this work were grown by low-pressure (100 mbar) horizontal flow MOCVD. The sources used were trimethylindium, trimethylgallium, and AsH_3 with H_2 as the carrier gas. Silane and CCl_4 were used as n- and p-type dopant sources, respectively.

A three-step growth process developed to avoid the problems associated with selective-area growth of aluminium containing compounds [16] was used to grow the full device structure. The first growth consisted of an n+ GaAs buffer, AlGaAs cladding layers, and 10-nm GaAs, to avoid the exposure of Al containing layers to atmosphere. The sample was then removed from the reactor and patterned with 100-nm-thick SiO_2 layer for the growth of the active region. Fig. 1 shows the schematic of the mask pattern used in this work. The growth parameters for the active region were optimized so that QDs were formed only between the SiO_2 stripes and QWs were formed elsewhere on the sample [15]. After growing the active region that consists of five layers of InGaAs QDs, the sample was taken out of the reactor and the SiO_2 mask was etched away using a buffered HF solution. The sample was again loaded into the reactor for the third growth step that consisted of AlGaAs cladding layers and p+ GaAs.

Integrated laser-waveguide structures with 4-μm-wide mesas were fabricated using the standard laser processing steps [17]. The laser optical cavity was defined by the overall length of

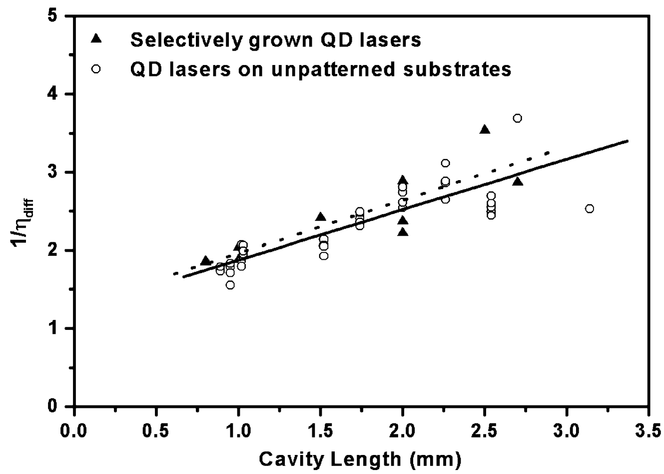

Fig. 2. Comparison between lasers fabricated from selectively grown QDs and QDs grown on unpatterned substrates.

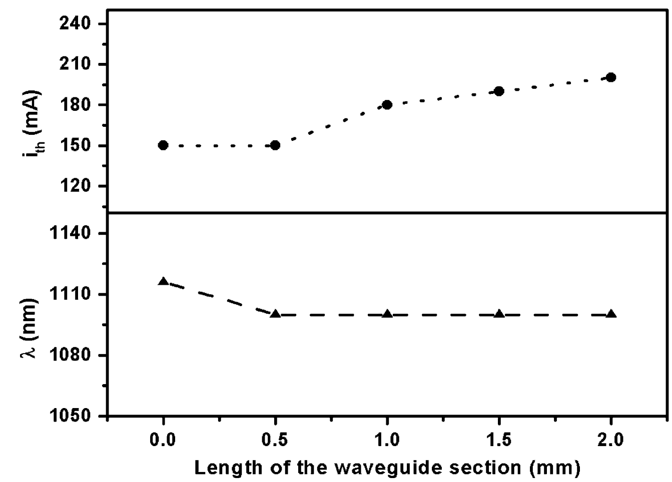

Fig. 3. Threshold current ($i_{\rm th}$) and lasing wavelength (λ) of the integrated devices with a 2-mm-long active region as a function of the length of the passive waveguide section.

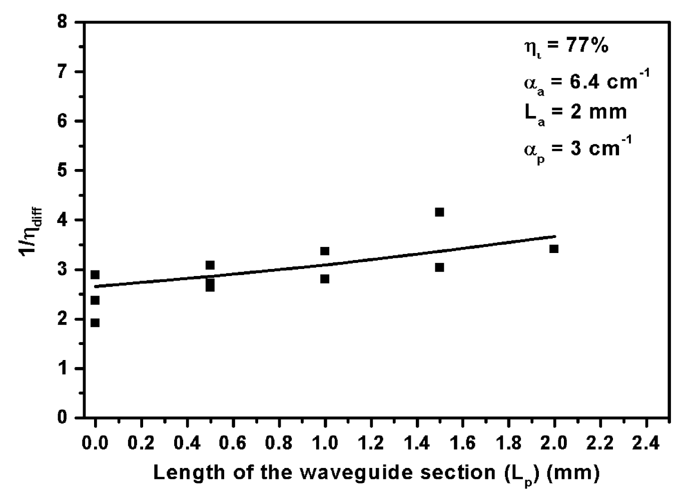

Fig. 4. Inverse differential efficiency as a function of the length of the passive waveguide section. The length of the active section is 2 mm.

the laser and waveguide. The waveguide section was electrically isolated from the laser section by etching a 50-μm-wide 0.4-μm-deep trench between the active and passive sections; and only the laser section of the integrated device was electrically pumped. The devices were tested at room temperature in pulsed mode with a duty cycle of 5% (25 kHz, 2-μs pulse).

III. Results and Discussion

First, we present results on lasers fabricated using the selectively grown QDs and compare them with lasers fabricated from QDs grown on unpatterned substrates. At room temperature, a 3-mm-long laser fabricated from selectively grown InGaAs QDs has a threshold current of 145 mA and lases at 1145 nm. A 3-mm-long laser fabricated from five layers of InGaAs QDs grown on unpatterned substrates has a threshold current of 150 mA and lases at 1150 nm. Fig. 2 indicates that the regrowth process does not introduce any significant additional losses into the lasers fabricated by SAE. The losses in both the lasers, ones fabricated from SAE and from QDs grown on unpatterned substrates, are $\sim$6 cm^{-1} (Fig. 2).

Devices with a 2-mm-long active (laser) section were cleaved with different lengths of the passive section for determining the losses in the passive section. Fig. 3 shows the threshold currents and lasing wavelengths for a 2-mm-long laser integrated with a passive waveguide of varying lengths. As the length of the passive section increases from 0 to 2 mm, due to increase in the total losses in the device, the threshold current increases from 150 to 200 mA and the lasing wavelength blueshifts from 1116 to 1100 nm. The threshold current increases by only 20% from a 2-mm-long laser without an integrated waveguide to a 2-mm-long laser integrated with a 1-mm-long waveguide.

Fitting the differential efficiency as a function of the length of the passive section with (1) [18] yields a loss of 3 cm^{-1} in the waveguide (Fig. 4)

$$\eta_d = \eta_i \frac{\alpha_p L_p + \ln\left(\frac{1}{R}\right)}{\left[\alpha_a L_a + \alpha_p L_p + \ln\left(\frac{1}{R}\right)\right]} \times \frac{2(1-R)e^{-\alpha_p L_p}}{(1+e^{-\alpha_p L_p})(1-\mathrm{Re}^{-\alpha_p L_p})} \quad (1)$$

where η_d is the differential efficiency of the integrated device, η_i is the internal efficiency of the lasers fabricated by SAE, α_p and α_a denote the losses in the passive and active sections, respectively, L_p and L_a are the lengths of the passive and active sections, respectively, and R is the power reflection coefficient of the cleaved facet.

The low losses in the waveguide region are due to a large difference in the bandgap energies of the epitaxial layers in the laser region and the waveguide region. A bangap energy shift of 200 meV is evident from Fig. 5, which shows the lasing spectra of lasers fabricated from the selectively grown QDs (that form the active region of the integrated devices) and QWs (that form the passive section of the integrated devices).

The butt-joint problem in the conventional method for fabricating a laser integrated with a waveguide is eliminated in this approach by growing the QDs and QWs in a single growth step. Unlike other postgrowth processing techniques like intermixing that rely on introducing defects into the epitaxial layers, SAE does not alter the quality of the epitaxially grown layers in the active region. The large difference in the bandgap energies of the

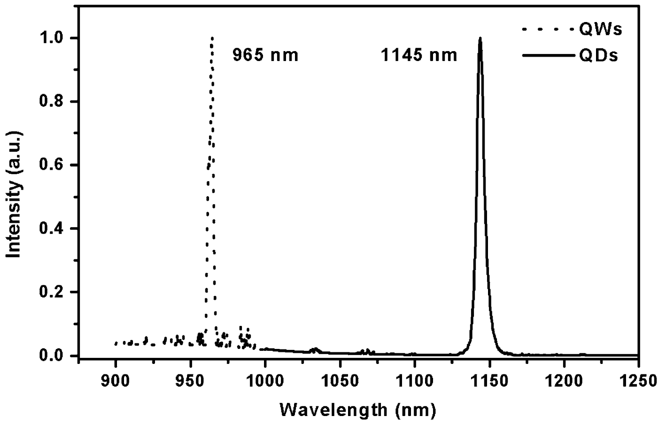

Fig. 5. Lasing spectra of lasers fabricated from selectively grown QDs and QWs.

QDs in the active region of the laser and the QWs in the passive waveguide region, that leads to very low losses in the waveguide region of the integrated devices studied in this work, is difficult to achieve using intermixing techniques without leaving any residual defects in the active region.

IV. Conclusion

To summarize, we have demonstrated a QD laser integrated with a low-loss passive waveguide. Selective-area MOCVD is used to simultaneously grow the QDs for the active region of the laser and QWs for the waveguide section, enabling a large differential bandgap of 200 meV to be achieved between the active and passive regions that is essential for low losses in the passive waveguide section of the integrated devices. To the best of our knowledge, this is the first report on a QD laser integrated with a passive waveguide, fabricated from QWs.

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References

[1] M. Asada, Y. Miyamoto, and Y. Suematsu, "Gain and threshold of three dimensional quantum-box lasers," *IEEE J. Quantum Electron.*, vol. QE-22, no. 9, pp. 1915–1921, Sep. 1986.

[2] Y. Arakawa and H. Sakaki, "Multidimensional quantum well laser and temperature dependence of its threshold current," *Appl. Phys. Lett.*, vol. 40, no. 11, pp. 939–941, 1982.

[3] N. Kirstaedter, O. G. Schmidt, N. N. Ledentsov, D. Bimberg, V. M. Ustinov, A. Egorov, A. E. Zhukov, M. V. Maximov, P. S. Kopev, and Z. Alferov, "Gain and differential gain of single layer InAs/GaAs quantum dot injection lasers," *Appl. Phys. Lett.*, vol. 69, no. 9, pp. 1226–1228, 1996.

[4] F. Heinrichsdorff, M. H. Mao, N. Kirstaedter, A. Krost, D. Bimberg, A. O. Kosogov, and P. Werner, "Room-temperature continuous-wave lasing from stacked InAs/GaAs quantum dots grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 71, no. 1, pp. 22–24, 1997.

[5] K. Kamath, P. Bhattacharya, T. Sosnowski, T. Norris, and J. Phillips, "Room-temperature operation of $In_{0.4}Ga_{0.6}As$/GaAs self-organised quantum dot lasers," *Electron. Lett.*, vol. 32, no. 15, pp. 1374–1375, 1996.

[6] G. Park, O. B. Shchekin, D. Huffaker, and D. G. Deppe, "Low-threshold oxide-confined 1.3 μm quantum-dot laser," *IEEE Photon. Technol. Lett.*, vol. 13, no. 3, pp. 230–232, Mar. 2000.

[7] J. Tatebayashi, N. Hatori, H. Kakuma, H. Ebe, H. Sudo, A. Kuramata, Y. Nakata, M. Sugawara, and Y. Arakawa, "Low threshold current operation of self-assembled InAs/GaAs quantum dot lasers by metal organic chemical vapour deposition," *Electron. Lett.*, vol. 39, no. 15, p. 1131, 2003.

[8] P. Lever, M. Buda, H. H. Tan, and C. Jagadish, "Characteristics of MOCVD-grown thin p-clad InGaAs quantum-dot lasers," *IEEE Photon. Technol. Lett.*, vol. 16, no. 12, pp. 2589–2591, Dec. 2004.

[9] R. M. Lammert, T. M. Cockerill, D. V. Forbes, G. M. Smith, and J. J. Coleman, "Submilliampere threshold buried-heterostructure InGaAs/GaAs single quantum well lasers grown by selective-area epitaxy," *IEEE Photon. Technol. Lett.*, vol. 6, no. 9, pp. 1073–1075, Sep. 1994.

[10] M. L. Osowski, T. M. Cockerill, R. M. Lammert, D. V. Forbes, D. E. Ackley, and J. J. Coleman, "A strained-layer InGaAs-GaAs-AlGaAs single quantum well broad spectrum LED by selective-area metalorganic chemical vapor deposition," *IEEE Photon. Technol. Lett.*, vol. 6, no. 11, pp. 1289–1292, Nov. 1994.

[11] R. M. Lammert, G. M. Smith, D. V. Forbes, M. L. Osowski, and J. J. Coleman, "Strained-layer InGaAs-GaAs-AlGaAs buried-heterostructure lasers with nonabsorbing mirrors by selective-area MOCVD," *Electron. Lett.*, vol. 31, no. 13, pp. 1070–1071, 1995.

[12] R. M. Lammert, G. M. Smith, J. S. Hughes, M. L. Osowski, A. M. Jones, and J. J. Coleman, "MQW wavelength-tunable DBR lasers with monolithically integrated external cavity electroabsorption modulators with low-driving-voltages fabricated by selective-area MOCVD," *IEEE Photon. Technol. Lett.*, vol. 8, no. 6, pp. 797–799, Jun. 1996.

[13] R. M. Lammert, S. D. Roh, J. S. Hughes, M. L. Osowski, and J. J. Coleman, "MQW DBR lasers with monolithically integrated external cavity electroabsorption modulators fabricated without modification of the active region," *IEEE Photon. Technol. Lett.*, vol. 9, no. 5, pp. 566–568, May 1997.

[14] J. Tatebayashi, M. Nishioka, T. Someya, and Y. Arakawa, "Area-controlled growth of InAs quantum dots and improvement of density and size distribution," *Appl. Phys. Lett.*, vol. 77, no. 21, pp. 3382–3384, 2000.

[15] S. Mokkapati, P. Lever, H. H. Tan, C. Jagadish, K. E. McBean, and M. R. Phillips, "Controlling the properties of InGaAs quantum dots by selective-area epitaxy," *Appl. Phys. Lett.*, vol. 86, pp. 113102–113104, 2005.

[16] T. M. Cockerill, D. V. Forbes, H. Han, B. A. Turkot, J. A. Dantzig, I. M. Robertson, and J. J. Coleman, "Wavelength tuning in strained layer InGaAs-GaAs-AlGaAs quantum well lasers by selective-area MOCVD," *J. Electron. Mater.*, vol. 23, no. 2, pp. 115–119, 1994.

[17] M. Buda, J. Hay, H. H. Tan, J. Wong-Leung, and C. Jagadish, "Low loss, thin p-clad 980-nm InGaAs semiconductor laser diodes with an asymmetric structure design," *IEEE J. Quantum Electron.*, vol. 39, no. 5, pp. 625–633, May 2003.

[18] L. A. Coldren and S. W. Corzine, *Diode Lasers and Photonic Circuits*. New York: Wiley, 1995, p. 446.