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Quantum Well Intermixed Tunable Wavelength Single Stripe Laser Diode

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ABSTRACT

A single waveguide laser with two separately addressed sections is fabricated using selective area intermixing of InGaAsP multiple quantum well grown on InP substrate. The selective intermixing of quantum wells is achieved by capping the two sections with PECVD grown silicon nitride and silicon dioxide respectively followed by rapid thermal annealing the device at 750°C for 30s prior to the fabrication of the quantum well laser. The fabricated device is capable of producing laser emission that can be tuned continuously from 1523 nm to 1556 nm by applying separate electrical currents into each 400 μm long section.

Keywords: Tunable laser, laser diode, multiple quantum well intermixing, fabrication

1. INTRODUCTION

Dynamic networks with wavelength reconfigurability and many spectroscopic applications demand simple tunable lasers with broad wavelength ranges. In this work, we have proposed a tunable laser consisting of two gain sections with different bandgap energy levels using selective intermixing of InGaAsP multiple quantum wells (MQW). Wavelength tuning is achieved by injecting current separately in the two gain sections with effective bandgap wavelengths corresponding to 1513 nm and 1553 nm respectively. The selectivity in the intermixing process is achieved by using different capping films during a high temperature rapid annealing process. The region that was capped by a SiO_2 film (Section A) had its bandgap energy blue shifted to 1513 nm while the region that was capped by a SiN_x film (Section B) had its bandgap energy unchanged at 1553 nm. When the currents injected in the two sections are varied, the combination of the gain spectra leads to a peak in the overall effective gain whose wavelength position depends on the relative magnitudes of the two gain spectra.

2. DEVICE STRUCTURE

In this work, the gain medium consists of five InGaAsP quantum wells that were grown by metal organic chemical vapor deposition (MOCVD) on a Si doped InP substrate at a commercial semiconductor foundry. The undoped active multiple quantum well (MQW) layer has a bandgap wavelength of the 1560 nm and has a total thickness of 275 nm. The top cladding layer is a 900 nm thick layer of Zn-doped InP capped by a 100 nm thick Zn-doped InGaAs layer. The details of the wafer design is shown in table 1.

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Layer #	Material	Thickness (nm)	Dopant
12	InGaAs	100	Zn (p ~ 1.3E19 cm-3)
11	InP	700	Zn (p ~ 1.0E18 cm-3)
10	InP	200	Zn (p ~ 5.0E17 cm-3)
9	InGaAsP	50	undoped
8	InP	50	undoped
7	InGaAsP	76	undoped
6	InGaAsP	8	undoped
5	InGaAsP	15	undoped
4	InGaAsP	8	undoped
3	InGaAsP	76	undoped
2	InP	200	Si (n ~ 5.0E17 cm-3)
1	InP	1000	Si (n ~ 1.2E18 cm-3)
0	2" (100) InP:S		S (n ~ 5.2E18 cm-3)

Table 1. InGaAsP multiple quantum well laser structure design grown by MOCVD.

3. FABRICATION

In order to characterize the controllability of the selective area QW intermixing process, several samples were coated with either varying compositions of 30 nm thick silicon nitride (SiN_x) films or 100 nm of silicon dioxide (SiO_2) films at 250°C using a PlasmaTherm 790 Series PECVD system [1]. Different mass flow rates of NH_3 and N_2O are selected during the PECVD growth process to adjust the ratio of nitrogen to oxygen in the final composition of the coated films. It was found that as the ratio between NH_3 and SiH_4 was increased, the reflective index as measured by an ellipsometer, tended to increase, table 2. The coated samples were then heated in a flowing nitrogen atmosphere at 750°C for 30s using a rapid thermal annealer (RTA)[2]. For the two-section device reported in this work, we have selected a SiN_x film that protected the MQW from intermixing with the photoluminescence (PL) peak remaining at 1553 nm while the SiO_2 coated sample had its PL peak blue shifted to 1513 nm [3] as shown in Figure 1.

Power (W)	Temp ºC	NH_3 sccm	SiH_4 sccm	He sccm	N_2O sccm	Refractive Index	Wavelengh (nm)	Shift Direction
100	250	9	180	200	30	1.59	1392	Blue
100	250	12	180	200	30	1.69	1448	Blue
25	250	0	200	0	412	1.81	1490	Blue
100	250	4	180	200	30	1.89	1515	Blue
100	250	10	200	400	0	1.95	1553	Same as As-grown
150	250	7	200	400	0	2.01	1585	Red
150	250	5.5	200	400	0	2.09	1613	Red
150	250	4	200	400	0	2.19	1660	Red
150	250	4	210	400	0	2.23	1687	Red

Table 2. Recipes for SiN/ SiO_yN_x film composition sorted with respect to their refractive index.

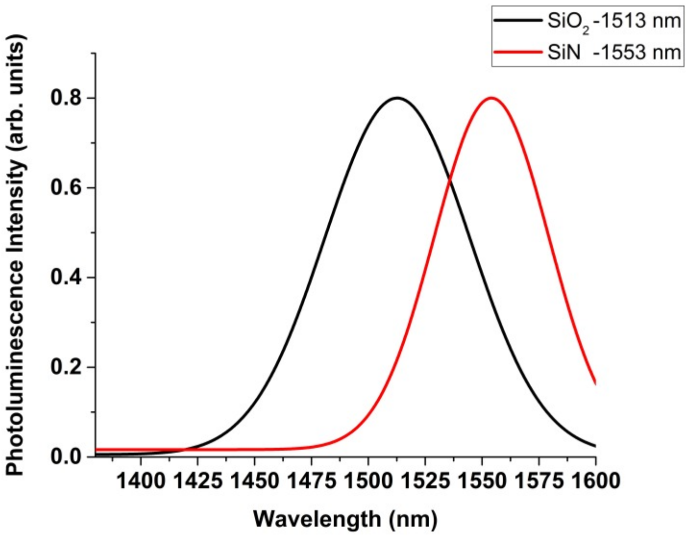

Figure 1. PL emission spectra of the MQW device after rapid thermal annealing while covered by different SiN films and SiO_2 corresponding to their refractive indices.

The device fabrication was started by coating the MQW sample with a 30 nm thick SiN_x film that has a reflective index of 1.96 by PECVD. A film thickness of 30 nm was necessary to avoid film cracking because of the high stress that occurred during high temperature annealing of the sample. Using photolithography and reactive ion etching (RIE), the SiN_x film was removed over half of the sample [3, 4]. The whole sample was then coated by PECVD with a 100 nm thick film of SiO_2 and then heated at 750°C for 30s in a nitrogen flowing rapid thermal annealer (RTA). The high temperature annealing process resulted in two distinct sections of the sample with one side containing basically un-intermixed MQWs (section A coated with SiN_x) and the other side containing intermixed MQWs (section B coated with SiO_2) whose bandgap energy is blue shifted according to the degree of quantum well intermixing[5]. The films of SiN_x and SiO_2 were removed by RIE and the sample was re-coated with a 200 nm thick film of SiO_2 to serve as a mask during the wet chemical etching of the ridge waveguides. Positive photoresist was spun on top of the SiO_2 and 4.5 μm wide stripes of SiO_2 that run perpendicularly across the two different intermixed sections are delineated using contact mask photolithography and RIE. The waveguide ridges were then formed by wet etching the top layers of InGaAs, InP, and the etch stop layer of InGaAsP using selective etch mixtures of $H_2O_2(1){:}H_2O(25){:}H_3PO_4(3)$, $H_3PO_4(1){:}HCl(1)$, and $H_2O_2(1){:}H_2O(10){:}H_2SO_4(1)$ respectively[6]. After the SiO_2 film was removed, a 2.8 μm thick layer of bisbenzocyclobutene (BCB), an insulating protective resin, was spin-coated on top of the sample. The BCB film was cured[7] in a nitrogen flowing oven that was programmed at a temperature of 250°C for 1 hour followed by 200°C for 30 minutes and 150°C for 30 minutes. The BCB film was thinned down using RIE until 250 nm of the top of waveguide ridged were uncovered. Negative photoresist was then spun on the top surface of the sample followed by photolithography and lift off process to define 20 μm wide p-type metal contact that covered the top of the waveguide strips while leaving a 4 μm wide gap at the interface between the two

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intermixed sections. The metal contact deposited by vacuum thermal evaporation, consisted of a 7 nm thick layer of titanium followed by a 4 nm thick layer of zinc, capped by a 300 nm thick layer of gold. The sample was annealed at 430°C for 30s and the substrate was lapped down and polished to a thickness of 100 μm. After the sample was thoroughly cleaned, the n-type metal contact that consisted of a 4 nm thick layer of nickel followed by a 20 nm thick layer of germanium, capped by a 200 nm thick layer of gold, was then deposited by vacuum thermal evaporation[8] and the sample was again annealed 430°C for 30s. Finally, the sample was cleaved off into three separate arrays of laser devices. One device contained an array of 500 μm long laser diodes in the non-intermixed MQWs ($\lambda_{PL} = 1553$ nm). The second device contained an array of 500 μm long laser diodes in the intermixed MQWs ($\lambda_{PL} = 1513$ nm). The third device contained an array of 800 μm long laser diodes with a 400 μm long section spanning the intermixed MQWs and the other section spanning the un-intermixed MQWs. Each of the devices with the p-side up was mounted using electrically conductive epoxy on a copper header that served as the ground terminal as well as a heatsink.

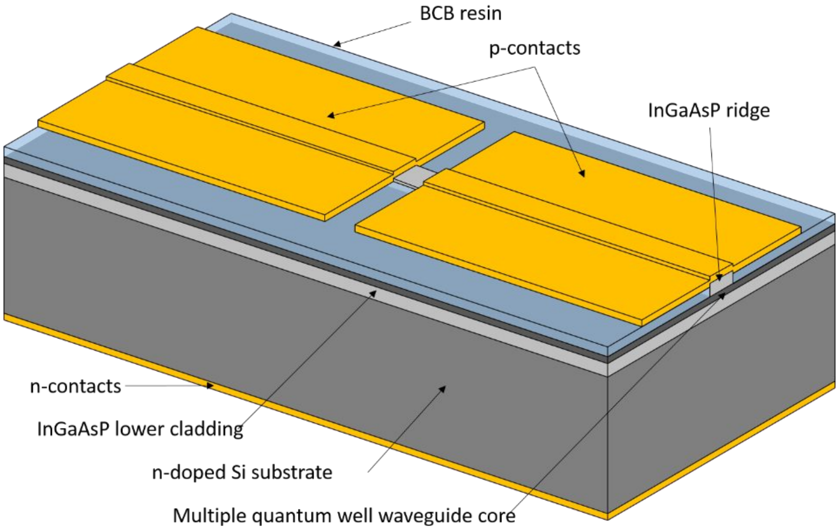

Figure 2. Schematic of the tunable laser diode device after cleaved.

4. RESULTS

The light emitted through one of the cleaved facets, was collected by a 25X microscope objective lens and focused into the end of an optical fiber that is connected to an optical spectrum analyzer (OSA) to measure the spectrum of the light. The light output from the other cleaved facet was captured by the sensor head of an optical power meter that was used to measure the output power as a function of the injection current. First, the laser diodes that contained the un-intermixed MQWs was tested. The results in figures 3a and 3b, show that the devices on average, exhibited a laser threshold current of 89 mA and the slope efficiency was measured to be 0.126 W/A. It was observed that when the current was increased from 100 mA to 200 mA, the lasing wavelength increased from 1553 nm to 1556 nm indicating that the heat-sinking was insufficient as the thermal effect was overriding the expected gain peak shift to lower energy. Figures 4a and 4b, shows the results obtained for the laser diodes that contained the intermixed MQWs. In this case, the threshold current was found to be 96 mA and the slope efficiency was measured to be 0.103 W/A.

When the current was increased from 105 mA to 200 mA, the laser wavelength was observed to increase by 4 nm from its initial value of 1513 nm again indicating insufficient heat-sinking. As a baseline reference, a separate laser device was fabricated from an as-grown sample of the MQW structure. As shown in figures 5a and 5b, that device exhibited a laser threshold current of 84 mA with a slope efficiency of 0.24 W/A, while its lasing wavelength was at 1556 nm.

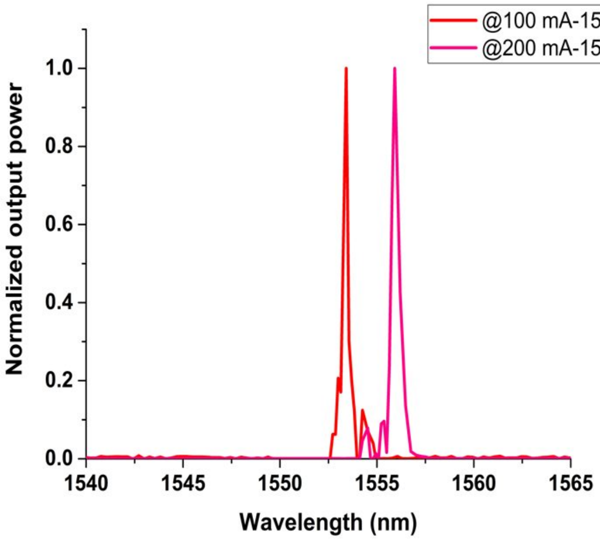

Figure 3a. The laser spectrum for the intermixed SiN (Section A) at 1553 nm with 100 mA and at 1556 with 200 mA.

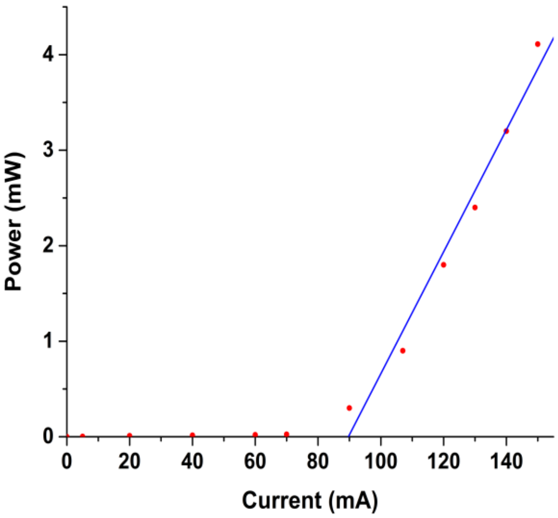

Figure 3b. The L-I curve as a function of injected current into section A.

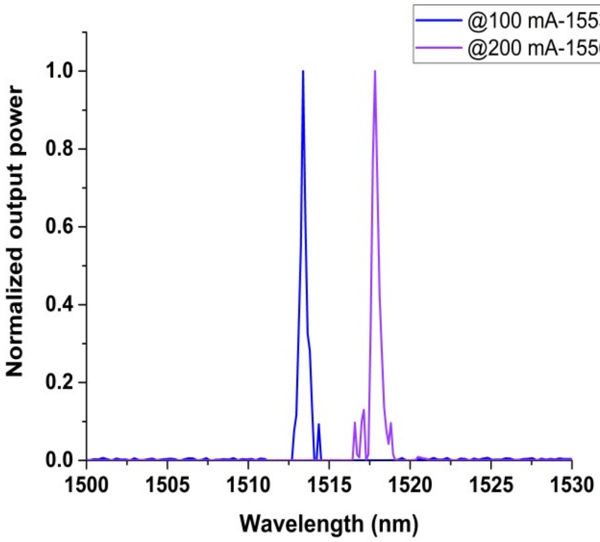

Figure 4a. The laser spectrum for the intermixed SiO_2 (Section B) at 1513 nm with 105 mA and at 1517 with 200 mA.

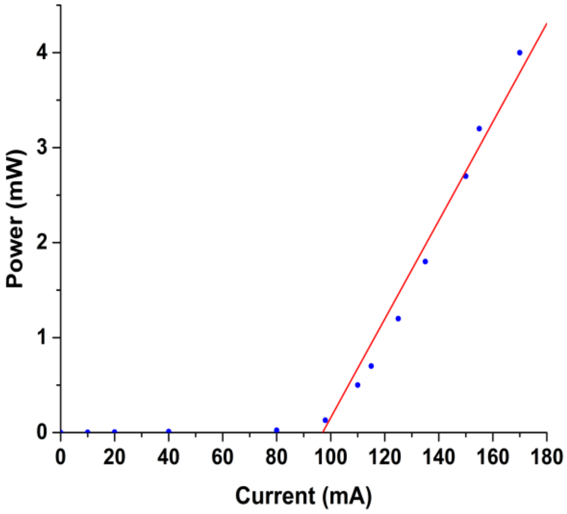

Figure 4b. The L-I curve as a function of injected current into section B.

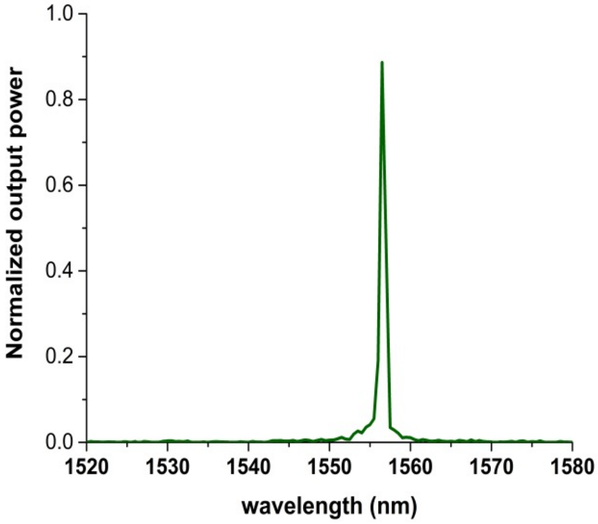

Figure 5a. The laser spectrum for as-grown sample.

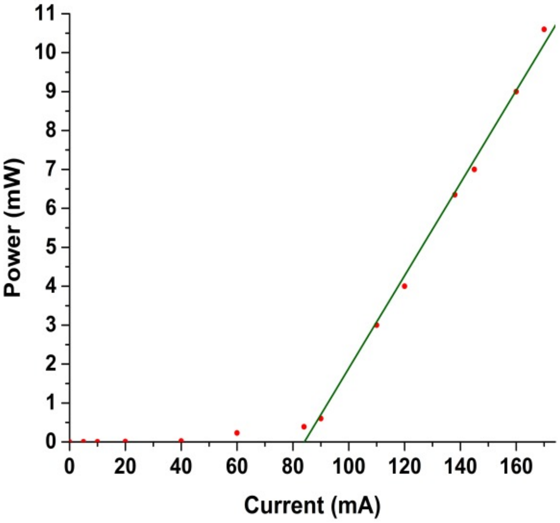

Figure 5b. The L-I curve as a function of injected current.

Finally, the two-section laser diode device that contained both un-intermixed (A, $\lambda_{PL} = 1553$ nm) and intermixed (B, $\lambda_{PL} = 1513$ nm) sections was tested. For this device to lase, electrical current needed to be injected into both sections. It was observed that for a wide range of combinations of currents, the most natural laser wavelength for this device was 1536 nm. However, for certain combinations of currents shown in Table 2, the laser wavelength was tuned from 1523 nm to 1556 nm. By keeping the current applied to section B at 90 mA, the laser wavelength was tuned from 1536 nm to 1556 nm as the current applied to section A was increased from 34 mA to 58 mA. Similarly, by keeping the current applied to section A at 80 mA, the laser wavelength was tuned from 1536 nm to 1523 nm as the current applied to section B was increased from 35 mA to 55 mA. By changing both current source systematically, we were able to tune the laser light in total of 33 nm from 1523 nm to 1556 nm as it can be seen in table 3 and figure 6.

Current in Section B I_B (mA)	Current in Section A I_A (mA)	Laser Wavelength λ_{lase} (nm)
90	34	1536
90	39	1539
90	44	1544
90	48	1547
90	53	1550
90	58	1556
35	80	1536
40	80	1533.9
45	80	1529.5
49	80	1526.8
53	80	1523

Table 3. The laser wavelength tuning range as function of the injected currents I_A and I_B in the sections A & B.

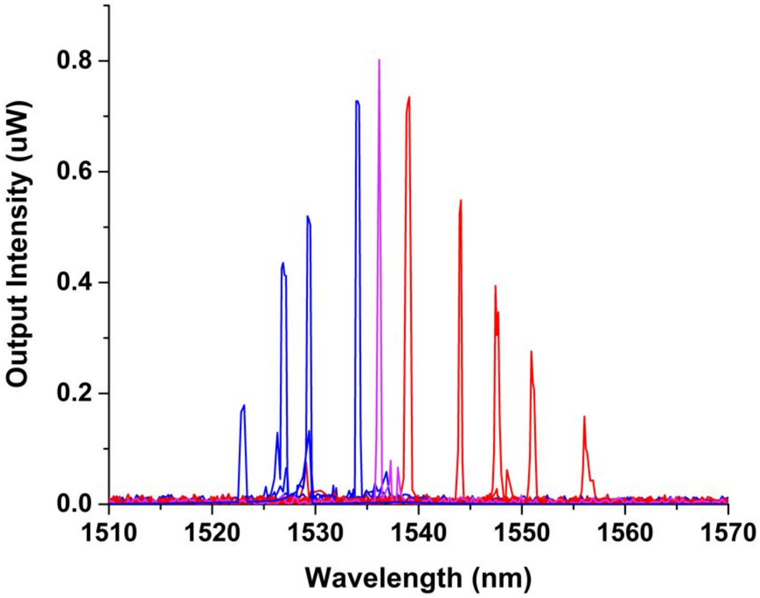

Figure 6. The laser spectra obtained from the two-section laser diode with different currents applied to the two sections.

5. CONCLUSION

Using a controlled technique for selective area intermixing of InGaAsP MQWs, a two-section laser diode whose wavelength of operation can be tuned by varying the injected current applied to the two sections has been demonstrated. The fabricated device was capable of producing laser emission that was tunable from 1523 nm to 1556 nm depending on the currents injected into the two sections. The L-I measurements for individual devices fabricated in either sections show only a small degradation from the characteristics of a reference device fabricated in the as-grown MQW sample. We are currently working on a device that can enable a larger range of wavelength tunability.

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