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# Monolithic Fabrication of InGaAs/GaAs/AlGaAs Multiple Wavelength Quantum Well Laser Diodes via Impurity-Free Vacancy Disordering Quantum Well Intermixing

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**ABSTRACT** InGaAs/GaAs/AlGaAs multiple wavelength quantum well (QW) semiconductor laser diodes (LDs) have been fabricated by impurity-free vacancy disordering (IFVD) QW intermixing (QWI) method. The IFVD-QWI process was carried out by sputtering-depositing SiO<sub>2</sub> mask layers on top of the complete InGaAs/GaAs/AlGaAs QW laser structure, emitting at 980 nm wavelength, and followed by a rapid thermal annealing at 880 °C for 60 s. The lasing wavelength of the devices fabricated from the intermixed wafer was blue-shifted with the increase of the mask layer thickness. The maximum emission wavelength blue shift of a processed as-cleaved laser reached 112 nm with the output-power more than 1000 mW. By using such an IFVD-QWI technique, multi-wavelength integrated LDs have also been successfully fabricated from a single chip.

**INDEX TERMS** Semiconductor laser, quantum well intermixing (QWI), impurity free vacancy disordering (IFVD), monolithic fabrication.

## I. INTRODUCTION

Multiple wavelength photonic integrated circuits (PICs) are greatly desired for many applications [1]–[7]. Such PICs have great potentials to reduce cost, improve operation performances, and achieve more functionalities than discrete components. Therefore, there has been a strong motivation to develop an effective quantum well intermixing (QWI) technology to tune the quantum well (QW) bandgap energy for various optoelectronic and PIC applications. As a key technology to fabricate multiple-wavelength and monolithic integration photonic devices, e.g., laser diodes (LDs), modulators, waveguides, and amplifiers, etc. QWI technology has attracted much attention. And there are many methods to perform QWI, such as: postgrowth intermixing [8]–[12], impurity-induced disordering (IID) [2]–[5], [12], impurity-free

vacancy disordering (IFVD) [14]–[19], photo absorption induced disordering (PAID) [20], and laser assisted disordering [21].

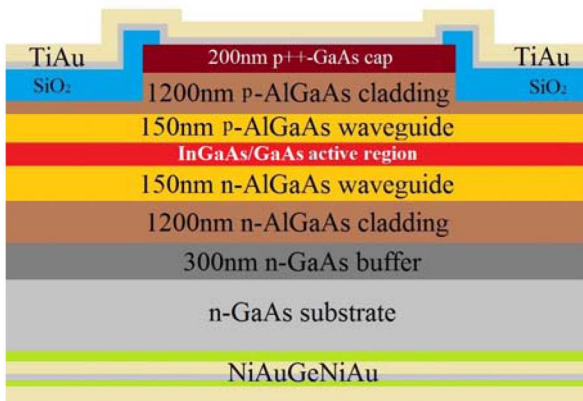
The realization of PICs with high performance is challenging since each integrated component requires different material property for a certain function. Selective area IFVD QWI method [22]–[24] has been shown to be a promising method for tailoring the QW bandgap energy for different optoelectronic devices applications. IFVD method is very simple and effective. It can be easily achieved by depositing a dielectric cap layer on top of the samples followed by a rapid thermal annealing (RTA). It does not need the sacrificial layer and can avoid sample surface damage caused by high energy ion beam bombardment [25], [26]. Though there are many reports on the bandgap tuning of GaAs/AlGaAs and AlInGaAs/(Al) GaAs single QW (SQW)

or multiple QW (MQW) structures by other QWI methods and cap material layers [17], [21], [27]–[29], and annealing temperature was more than 910 °C. The position-dependent bandgap modification is achieved by performing the IFVD with SiO<sub>x</sub> capping layers with different stoichiometries [30]. However, to the best of the authors' knowledge, no study has been reported the multiple-wavelength QWI LD based on the InGaAs/GaAs/AlGaAs QW complete structure in the 980 nm wavelength range from a single chip with single stoichiometry SiO<sub>2</sub> as capping layers yet.

In this work, development of monolithic fabrication of InGaAs/GaAs/AlGaAs multiple-wavelength LDs with the selective area IFVD QWI method, based on a complete SQW structure, has been carried out. By using such an IFVD-QWI technique, multiple-wavelength integrated LDs have been successfully fabricated from a single chip.

## II. EXPERIMENTAL DETAILS

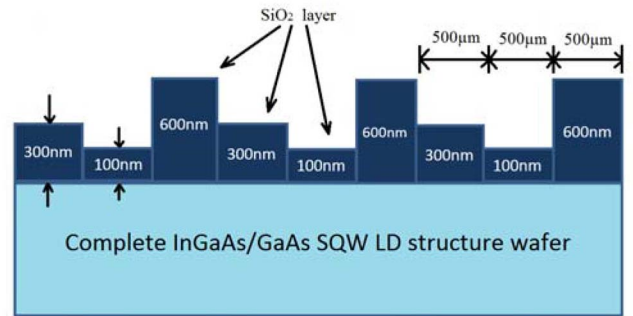
The 980-nm InGaAs/GaAs/AlGaAs SQW LD epitaxial structure used in this study was grown by an AXTRON/200 metal organic vapor phase epitaxy (MOVPE) system. Fig. 1. shows the schematic of the complete laser structure of the 980 nm InGaAs/GaAs/AlGaAs SQW LD device.



**FIGURE 1.** The schematic of the complete 980nm QW laser structure (not to scale).

The n-type GaAs (100) wafers (Si-doped:  $\sim 1 \times 10^{18} \text{ cm}^{-3}$ ) were used as the substrates. Firstly, a 300-nm-thick GaAs (Si-doped:  $\sim 2 \times 10^{18} \text{ cm}^{-3}$ ) buffer layer was grown at 680 °C to suppress the surface defect of the substrate. Subsequently, a 1200-nm-thick n-Al<sub>x</sub>Ga<sub>1-x</sub>As (Si-doped:  $\sim 1 \times 10^{18} \text{ cm}^{-3}$ ) lower cladding layer and a 150-nm-thick n-Al<sub>x</sub>Ga<sub>1-x</sub>As (Si-doped:  $\sim 1 \times 10^{17} \text{ cm}^{-3}$ ) lower waveguide layer were grown at 650 °C. The QW active region consists of a 7-nm-thick In<sub>0.15</sub>Ga<sub>0.85</sub>As SQW layer, which was sandwiched by a pair of 10-nm-thick GaAs barrier layers. The growth temperature for the QW active region was 710 °C. Then, a 150-nm-thick p-Al<sub>x</sub>Ga<sub>1-x</sub>As (C-doped:  $\sim 1 \times 10^{17} \text{ cm}^{-3}$ ) upper waveguide layer and a 1200-nm-thick p-Al<sub>x</sub>Ga<sub>1-x</sub>As (C-doped:  $\sim 2 \times 10^{18} \text{ cm}^{-3}$ ) upper cladding layer were grown separately at 650 °C. Finally, a 200-nm-thick p-GaAs cap layer (C-doped:  $\sim 2 \times 10^{19} \text{ cm}^{-3}$ ) was

grown at 650 °C. It should be noted that carbon, instead of zinc, was chosen as the P-type dopant in our InGaAs QW laser structure, since carbon is less mobile at high temperature. And thus the intermixed lasers will be more reliable [31].



**FIGURE 2.** The schematic of InGaAs/GaAs laser structure, covered with SiO<sub>2</sub>, with different thickness at different regions, for multi-wavelength QWI process (not to scale).

It has been demonstrated that GaAs/AlGaAs laser structure capped with SiO<sub>2</sub> layer of different thicknesses will emit different wavelength after IFVD-QWI process [17]. In our work, in order to fabricate the single-wavelength, double-wavelength, and three-wavelength lasers, the grown complete laser structure sample was covered by SiO<sub>2</sub> with three different thicknesses at different positions as schematically shown in Fig. 2. The SiO<sub>2</sub> layers were deposited on top of the epitaxial wafer using ion plasma sputtering method with an Ar gas flow rate of 28 sccm, a standard RF power of 150W, and the substrate temperature was set at 150 °C. Lift-off process on the photo-lithographically patterned laser wafer surface has been performed to realize different thicknesses of the SiO<sub>2</sub> layer in different thickness on the wafer as shown in Fig. 2. With three photolithography steps and subsequent lift-off processes, 100-nm-thick SiO<sub>2</sub>, 300-nm-thick SiO<sub>2</sub>, and 600-nm-thick SiO<sub>2</sub> layers at different positions of the wafer were obtained, with sputtering deposition for 15 minutes, 45 minutes, and 90 minutes, respectively. The samples covered with different thickness SiO<sub>2</sub> layer were then thermally annealed with the RTA process at the optimized 880 °C for 60 seconds for QWI. The optimization was based on the photoluminescence (PL) measurement on similar structures to the laser structures used in this work, with the consideration of both PL intensity and wavelength blue shift extent. Our work shows that the lasing wavelength of the devices fabricated from the intermixed wafer was blue-shifted with the increase of the SiO<sub>2</sub> layer thickness. Then, the SiO<sub>2</sub> layers were removed by HF acid. Subsequent to the QWI process, the integrated LDs were fabricated from the samples by using conventional LD fabrication process as described in the previous works [32]–[34].

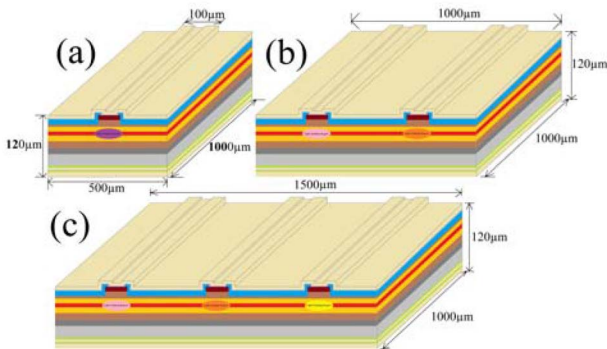
With the same procedure and different QWI conditions, six LD chips were fabricated based on the same 980nm QW laser structure. This set of devices include one as-grown wafer, three single-wavelength LDs (i.e., coating with

**TABLE 1.** The QWI LD samples with different SiO<sub>2</sub> thickness.

No.	QWI-sample with SiO <sub>2</sub> thickness(nm)
1	As-grown (without SiO <sub>2</sub> layer and QWI)
2	Single region with 100nm SiO <sub>2</sub> layer
3	Single region with 300 nm SiO <sub>2</sub> layer
4	Single region with 600 nm SiO <sub>2</sub> layer
5	Two regions with 600nm/300nm SiO <sub>2</sub> layers
6	Three regions with 600nm/300nm/100nm SiO <sub>2</sub> layers

100-nm-thick SiO<sub>2</sub>, 300-nm-thick SiO<sub>2</sub>, 600-nm-thick SiO<sub>2</sub>, respectively), one double-wavelength LD chip (i.e., coating with 300-nm-thick SiO<sub>2</sub> and 600-nm-thick SiO<sub>2</sub> at adjacent regions), and one three-wavelength LD chip (i.e., coating with 100-nm-thick SiO<sub>2</sub>, 300-nm-thick SiO<sub>2</sub> and 600-nm-thick SiO<sub>2</sub> in adjacent regions), as summarized in Table 1.

Fig. 3 (a)-(c) show the schematic diagram of the three types of QWI LDs in our work. The first type is a single-wavelength broad area LD, whose dimension is 1000(Length)×500 (Width)×120(Height) μm<sup>3</sup>; the second type QWI-LD is a double-wavelength QWI LD with the dimension of 1000(L)× 1000(W)×120(H)μm<sup>3</sup>; the last type QWI LD is a three-wavelength LD, and its dimension is 1000(L)×1500(W)× 120(H) μm<sup>3</sup>. Each of the injected current strip is 1000 (L) ×100(W) μm<sup>2</sup>. The facets of all the devices studied in this work were uncoated. The lasers were mounted p-side down onto the heatsink, and tested with a 2% duty cycle pulse current (the pulse width is 200μs, the repeat frequency is 100Hz) at room temperature.



**FIGURE 3.** The schematic diagram of multi-wavelength QWI-LD: (a) single-wavelength QWI LD; (b) double-wavelength QWI LD; (c) three-wavelength QWI LD.

### III. RESULTS AND DISCUSSION

Good performance LDs fabricated from the as-grown and QWI wafers have been received. The measured light output power-current-voltage (LIV) curves and lasing spectra from the LDs fabricated from the as-grown and single-region QWI samples are shown in Fig. 4. Fig. 4(a) shows the measurement results of the as-grown QW laser (sample No.1 in Table 1). The emission wavelength was measured to be at ~979 nm with a threshold current of ~0.13A. The power from the laser is up to 1150mW. Fig. 4(b)-(d) present the LIV

curves and lasing spectra of the single-wavelength QWI LDs corresponding to samples No. 2-4 in Table 1, respectively. These wafers have gone through QWI process at 880 °C for 60 seconds with the SiO<sub>2</sub> cover layer thicknesses of 100nm, 300nm, and 600nm, respectively, corresponding to the lasing wavelength peaks at 968 nm, 933 nm, and 867nm, respectively. From the measured lasing spectra, we note that with the increase of SiO<sub>2</sub> thickness, the wavelength blue shifted. For all the QWI lasers, the maximum output powers are around 1000 mW at a bias current of 2 A, which is similar to that of the as-grown laser (1150mW). These results indicate that the wafer quality was not significantly degraded after the QWI.

Fig. 5 shows the LIV results of the double-wavelength QWI-LD, i.e., sample No. 5 in Table 1. The maximum output power of this monolithic device is more than 350 mW. The single chip achieves two emitting wavelengths of 936-nm ( $\Delta\lambda$  is 2.2-nm) and 951-nm ( $\Delta\lambda$  is 2.8 nm), respectively, as shown in the inset of Fig. 5. And the wavelengths blue shift of the QWI LD can be up to 43 nm and 28 nm, respectively.

Fig. 6 shows the measured LIV curve and the emission spectrum of the three-wavelength QWI LD chip, i.e., sample No.6 in Table 1. The maximum output power of the device is more than 450 mW. As shown in the inset of Fig. 6, three lasing wavelengths of 934.5-nm, 947.9-nm, and 955-nm were achieved from the single chip. The 934.5 nm, 947.9 nm, and 955 nm laser emitting regions were corresponding to the region under 600-nm-thick, 300-nm-thick, and 100-nm-thick SiO<sub>2</sub> cap layer, respectively. Regarding the wavelength blue shifts, they are up to 44.5 nm, 31.1 nm, and 24.0 nm, respectively.

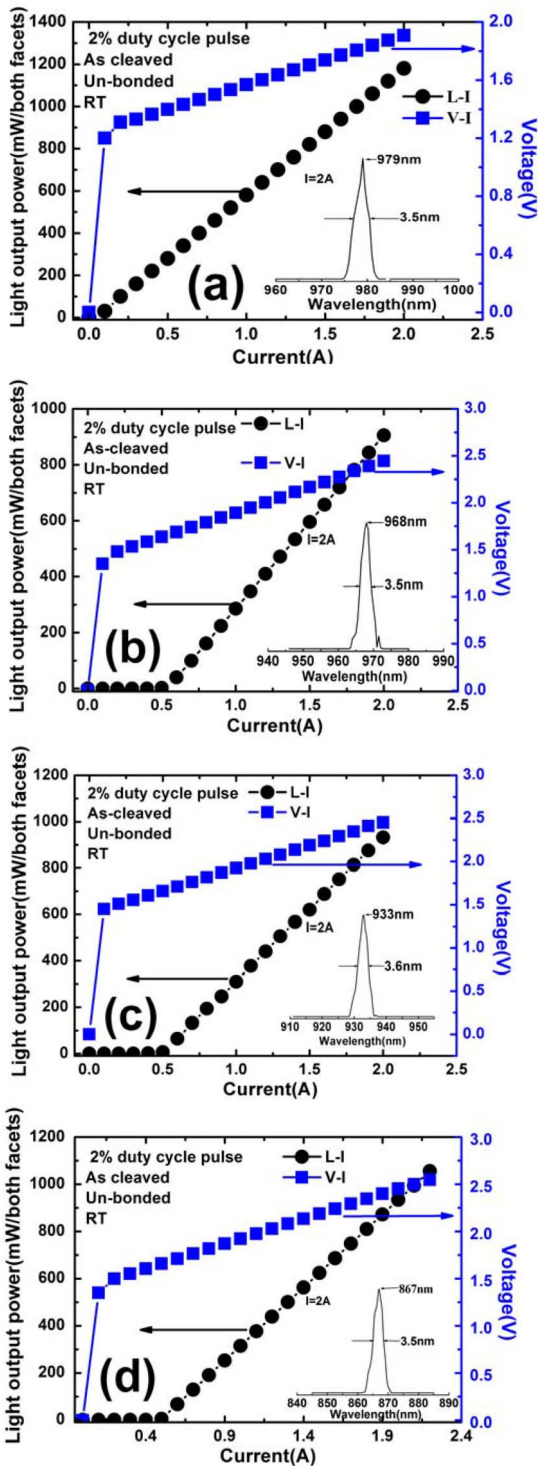
It can be noted from the above work that the LDs fabricated from the QWI wafers with thicker SiO<sub>2</sub> mask layer have larger lasing wavelength blue shift.

The reason may be explained as follows: it is well known that, in the InGaAs/GaAs/AlGaAs material system, the atoms' diffusion rates during the QWI process is Ga>In>Al [17]. When the SiO<sub>2</sub> cap layer is thicker, more Ga atoms will enter SiO<sub>2</sub> layer [17], thus, the vacancy density in the InGaAs/GaAs/AlGaAs material system is higher. As a consequence, out-diffusion of Al and indium atoms is enhanced. Furthermore, indium atoms (in InGaAs QW layer) have stronger mobility than that of Al atom, which can out-diffuse into the GaAs barriers and even into the AlGaAs waveguide layers, which causes the In composition of the InGaAs QW layer reduced, leads to the QW emission wavelength blue shift.

Furthermore, the increased SiO<sub>2</sub> cap layer thickness can cause larger tensile strain to the GaAs surface due to the significant difference in the thermal expansion coefficient between SiO<sub>2</sub> and GaAs. This interface stress also enhances the atoms' diffusions and thus results in larger blue shift [26].

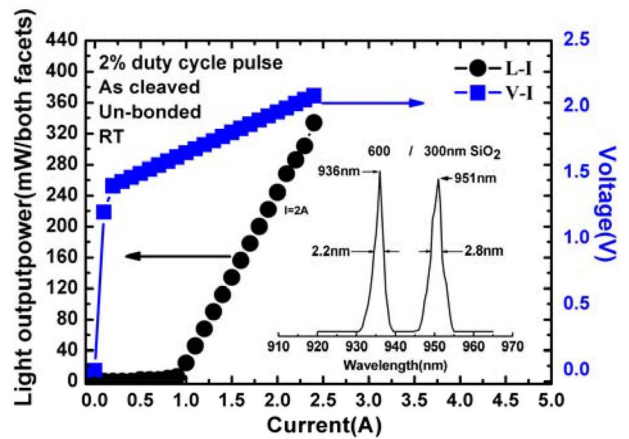
In considering the above two reasons, larger blue shift of emitting wavelength would be expected from QWI laser with thicker SiO<sub>2</sub> layer.



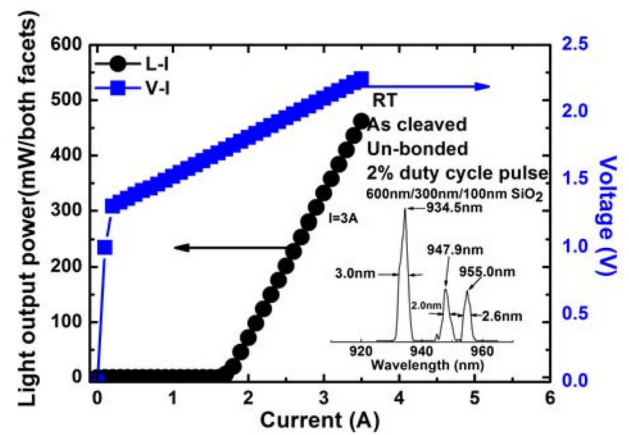


**FIGURE 4.** (a) LIV curve and lasing spectrum of conventional 980 nm LD (sample No.1, without QWI); (b) LIV and lasing spectrum curve of one single wavelength 968 nm QWI LD (sample No. 2, capped with 100 nm SiO<sub>2</sub>); (c) LIV and lasing spectrum curve of one-wavelength 933 nm QWI LD (sample No. 3, capped with 300 nm SiO<sub>2</sub>); (d) LIV and spectrum curves of one-wavelength 867 nm QWI LD (sample No. 4, capped with 600 nm SiO<sub>2</sub>).

On the other hand, it is interesting to note that even the SiO<sub>2</sub> thickness is the same, but the single-region devices have different blue shift behavior than that of the multiple-region



**FIGURE 5.** LIV curve of double-wavelength QWI-LD and emission spectrum of two-wavelength QWI LD (The sample No.5 was capped with 300-nm, 600-nm-thick patterned SiO<sub>2</sub> for QWI).



**FIGURE 6.** LIV curve of three-wavelength QWI LD and emission spectrum of three-wavelength QWI LD (The sample No. 6 was capped with 100-nm, 300-nm, and 600-nm-thick patterned SiO<sub>2</sub> for QWI).

devices. Possible explanation can be that, during the QWI process, the interface stress between the SiO<sub>2</sub> layer and the laser structure is different in the single-region and the multiple-regions. This is because the strain may be relaxed in the multiple-region devices due to the existence of the adjacent regions, which may cause the different blue shift behaviors.

**IV. CONCLUSION**

InGaAs/GaAs/AlGaAs QW multiple wavelength LD chips have been developed by IFVD-QWI method. The lasing wavelength of the devices fabricated from the intermixed wafer blue shifted with the increase of the mask layer thickness during the QWI. The maximum lasing wavelength blue shift of the LDs from the QWI wafer as compared with that of the LDs from the as-grown wafer reached 112 nm and the output power of the LD fabricated from the QWI wafer is more than 1000 mW. By using the IFVD-QWI technique, multi-wavelength integrated LD chips

(i.e., single-wavelength laser, double-wavelength laser, and three-wavelength laser) have been successfully fabricated and developed from a single chip.

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semiconductor photonic

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