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Plasma-Induced Quantum Well Intermixing for Monolithic Photonic Integration

Hery Susanto Djie, Member, IEEE, and Ting Mei, Member, IEEE

Abstract—Plasma-induced quantum well intermixing (QWI) has been developed for tuning the bandgap of III–V compound semiconductor materials using an inductively coupled plasma system at the postgrowth level. In this paper, we present the capability of the technique for a high-density photonic integration process, which offers three aspects of investigation: 1) universality to a wide range of III–V compound material systems covering the wavelength range from 700 to 1600 nm; 2) spatial resolution of the process; and 3) single-step multiple bandgap creation. To verify the monolithic integration capability, a simple photonic integrated chip has been fabricated using Ar plasma-induced QWI in the form of a two-section extended cavity laser diode, where an active laser is integrated with an intermixed low-loss waveguide.

Index Terms—Inductively coupled plasma (ICP), photonic integrated circuits (PICs), quantum well, quantum well intermixing (QWI).

I. INTRODUCTION

The ability to modify the bandgap energy across the single substrate is a key requirement for monolithic integration of multiple photonic devices. The quantum well intermixing (QWI) technique has generated considerable interest due to its simplicity and effectiveness to tune the quantum well (QW) properties at the postgrowth level for optoelectronic and photonic integrated circuit (PIC) applications [1]. A strong motivation to develop an effective QWI exists, since QWI is a simple and reliable process at the postgrowth level to tune QW properties. The emerged technology of QWI in the past decades, such as impurity-induced disordering (IID) [2], [3], impurity-free vacancy disordering (IFVD) [4], sputtered silica-induced intermixing [5], and pulsed-photoabsorption-induced disordering (PPAID) [6] have been utilized in wide application for PICs, such as the widely tunable sampled-grating distributed Bragg reflector laser device [7].

The development of high-density plasma, such as the inductively coupled plasma (ICP) machine, enables the use of low ion bombardment energy with high ion bombardment fluxes. ICP reactors produce high-density plasmas ($10^{10} - 10^{12}$ cm$^{-3}$) at low gas pressure ($<$ tens of millitorrs). ICPs have been used for high-etch-rate, low-etch-damage applications in a wide variety of semiconductor materials including dielectrics and III–V semiconductors and for depositing various dielectric materials. The use of plasma-enhanced QWI is attractive, since the low-energy (with hundreds of electronvolts of ion impact energy) ions generated in the plasma chamber produces no direct damage to the QW active region, thereby promising high-quality photonic devices for PIC application. Recently, a QWI technique using an inductively coupled argon (Ar) plasma process has been successfully developed, and it has proven to be very effective to tune the bandgap energy of InP-based QW materials [8]–[10].

II. EXPERIMENTS

Samples of an InGaAs/InGaAsP QWs laser structure on InP substrate with the emission wavelength around 1.55 μm are used in this study. Other material systems of InGaAs/InAlGaAs QWs laser structure on InP substrate and GaAs/AlGaAs structure QWs laser structure on GaAs substrate are adopted to further
investigate the QWI mechanism using high-density plasma and its effect and the universality of plasma-induced QWI process. The lattice-matched InGaAs/InGaAsP QWs laser structure was grown by metal–organic vapor phase epitaxy (MOVPE) on (100) oriented n-type S-doped InP substrate. The QW active region consists of five periods of 5.5-nm-wide In0.53Ga0.47As QWs with 12-nm-thick In0.27Ga0.73As0.46/P0.51 barriers. The active region is sandwiched by step-graded index waveguide core consisting of InGaAsP confining layers. The thicknesses of these confining layers (from the QWs outward) are 50 and 80 nm, respectively. The structure was completed by an upper cladding InP layer of 1.37-μm-thick doped with Zn to 7.3 × 10^{17} cm^{-3}. The contact layer consists of 50-μm-thick InGaAsP (Zn doped to 2 × 10^{18} cm^{-3}) and 100-μm-thick InGaAs (Zn doped to 1.8 × 10^{19} cm^{-3}). The samples resulted in a PL peak at 1.43 ± 0.02 μm at 77 K.

The lattice matched InGaAs/InAlGaAs QWs laser structure was grown by molecular beam epitaxy (MBE) on a Si-doped InP substrate. The thicknesses of InP buffer layer (Si doped to 1 × 10^{18} cm^{-3}) and lower cladding layer (Si doped to 3 × 10^{18} cm^{-3}) were 500 and 300 nm, respectively. The QW active region consists of six 7-nm-wide In0.53Ga0.47As wells separated by 8-nm-thick In0.53Al0.27Ga0.2As barriers. The active region was sandwiched by 100-nm-thick In0.53Al0.27Ga0.2As waveguide cores (Zn doped to 2 × 10^{17} cm^{-3}). It was completed by a 100-μm-thick InP upper cladding layer (Zn doped to 7 × 10^{17} cm^{-3}) followed by a 50-μm-thick InGaAsP etch stop layer (Zn doped to 1 × 10^{18} cm^{-3}) and a 1200-μm-thick InP upper cladding layer (Zn doped to 1 × 10^{18} cm^{-3}). The contact layer consists of 50-μm-thick InGaAsP (Zn doped to 2 × 10^{18} cm^{-3}) and 200-μm-thick InGaAs (Zn doped to 1.4 × 10^{19} cm^{-3}). The QW area was undoped thus forming a P-I-N structure with the intrinsic region restricted to the QW layers. The samples resulted in a PL peak at 1.55 ± 0.002 μm at RT and 1.43 ± 0.002 μm at 77 K, respectively.

A GaAs/AlGaAs QWs laser structure, grown by MOVPE, is used to study the plasma-induced QWI in the short wavelength region of 0.86 μm. The active region was undoped and consisted of 25 periods of 10 nm-wide GaAs QWs with 10-nm-thick Al0.2Ga0.8As barriers. The top and bottom Al0.2Ga0.8As layers were 100 nm thick to complete the waveguide core. Both upper and lower cladding Al0.4Ga0.6As layers were 1500 nm thick and doped to a concentration of 8 × 10^{17} cm^{-3} and 9 × 10^{17} cm^{-3} using carbon and silicon, respectively. The top contact layer is a layer of 100-μm-thick GaAs doped with Zn to 1.3 × 10^{13} cm^{-3}. This as-grown material exhibited a 77 K PL peak at about 810 ± 2 nm.

The GaAs/AlGaAs multiwidth QWs damage probe structure is adopted to study the plasma-induced damage mechanism and intermixing process by tracing the damage distribution range [13], [14]. The QW structure was grown on a semi-insulating GaAs substrate by MBE, consisting of five undoped QWs labeled as QW1, QW2, QW3, QW4, and QW5 by sequence from the top to the substrate, with well widths of 9.5, 7, 4, 3 and 2.5 nm, respectively. The Al0.3Ga0.7As barriers are 300 nm thick, except the one between QW4 and QW5, which is 1000 nm thick. With this configuration, the QWs are located accordingly in order to assess the damage distribution range due to QWI process, with QW5 as a reference PL signal. The structure was completed by a layer of 100-nm GaAs cap layer on the top.

The ICP system used in this experiment uses inductive coil to generate high-density “remote” plasma with no direct contact between the plasma and the substrate. The 13.56-MHz RF and ICP power supply can provide the independent control on ion bombardment energy and ion current density with power up to 500 and 3000 W, respectively. The ICP parameter settings for the experiments were 100 scm Ar flow rate, 80 mtorr chamber pressure, 480 W RF power, 730 V RF-induced dc bias and 500 W ICP power. After Ar plasma exposure, the samples were annealed using a single-step annealing in a flowing nitrogen ambient. Two fresh pieces of GaAs proximity caps were used to provide an As overpressure environment during the annealing process and further to prevent the sample surface from outdiffusion. The annealing conditions were determined from a thermal stability test performed on as-grown samples. A control sample refers to the annealed sample without plasma exposure to determine a bandgap shift due to the annealing effect.

The experiment results are analyzed using the low-temperature and RT PL spectroscopy. The single-point PL measurements are carried out at 4 K and 77 K using a 50-μm-diameter optical fiber as a signal probe, an Nd: YAG laser (1.064 μm) for excitation, a monochromator, and a TE-cooled InGaAs photodetector associated with a lock-in amplifier. The PL map at RT enables the observation of the spatial bandgap profile after selective QWI process and its uniformity. The PL system scan has a resolution of 100 μm due to the limitation of stage controller. The illumination wavelength is at 1.064 μm using a Q switch laser with a ~10–15 μm spot diameter of the focused laser beam and 6.6 mW output power. MRS is carried out at RT to study the spatial resolution of selectively intermixed material using Renishaw model inVia Reflex. The MRS line mapping across the intermixing boundary was taken in the backscattering configuration using the laser physics Ar laser of 514.5 nm as the excitation source with a 100× objective (Leica 100× Nplan), giving a spot size diameter of ~0.4 μm.

III. Universal High-Density Plasma Enhanced QWI

In order to study the effect of high-density plasma application of the ICP system, the InGaAs/InGaAsP and the GaAs/AlGaAs QWs laser structures were exposed in an ICP chamber without ICP power (pure RF power and thus low plasma density) and with ICP power (thus high-density plasma). All other affecting parameters of ICP reactor were kept constant except the ICP power, enabling a comparative study on the effect of ICP application to the intermixing results. Without ICP power application, a larger bandgap shift can be achieved only by increasing the energy of bombarding ions, while with ICP power application, the ion density acts as a factor for bandgap shift control [8]. The ICP application at the constant RF power decreases the RF bias while increasing the ion dose and plasma radiation, which are estimated to be several orders larger than the traditional ion-implantation method [15].

Fig. 1(a) shows the PL spectra comparison from the InGaAs/InGaAsP laser QWs structure at 4 K after intermixing at ICP power of 0 and 250 W. The RF-induced dc bias operation was ~840 V at pure RF power and was reduced to ~780 V.
when the ICP power was 250 W. The two intermixed PL spectra produce a comparable bandgap shift of 60 and 62 nm as compared to the as-grown spectrum for exposed material without and with ICP power application, respectively. The similar behavior can be observed from Fig. 1(b) for the case of GaAs/AlGaAs QWs laser structure that increasing the ICP power from 0 to 500 W produces the bandgap shift blue-shift of 18 and 20 nm for samples being exposed to plasma without and with ICP power application, respectively. The samples only exhibit a small increase in bandgap energy after annealing without plasma exposure as compared to the as-grown material. The annealing induced bandgap shifts on the samples are attributed to the in-diffusion of point defects from the substrate, grown-in defects on the epilayers, and the impurity. The comparable bandgap blue-shifts for both InGaAs/InGaAsP and GaAs/AlGaAs have been achieved using the ICP power application instead of pure RF power. The RF-induced dc bias reduction leads to less effect of bombarding ion energy to the induced damage, and thus this suggests that the high plasma density due to ICP application contributes to promote QWI on both QW structures. The application of ICP power induces more damage due to the plasma radiation together with high ion current density on the samples such as the relevant observation reported elsewhere using high-density plasma process in an electron cyclotron resonance (ECR) system [16]. The linewidth profile of PL spectra of the intermixed samples with ICP power application are slightly less than those without the ICP power application on both InGaAs/InGaAsP and GaAs/AlGaAs structures, suggesting a good optical quality preservation using the Ar plasma exposure at a high-density plasma.

The universality of plasma-induced QWI has also been investigated using other III–V material systems. Previous studies observed that the magnitude of the created defects increases with the plasma exposure time in the III–V material system [13, 14]. Earlier experimental data in InGaAs/InP QWs shows that the bandgap shift due to Ar plasma exposure from PL spectra saturates as the exposure time increases [15], indicating the saturation of created defect has been reached at this level [17]. The bandgap shift saturation occurs after 1 min in InGaAs/In-AlGaAs and GaAs/AlGaAs structures and 5 min in InGaAs/In-GaAsP structures for plasma condition of 500 W ICP power and 480 W RF power. This points out the universal creation of beneficial defects to the III–V materials occurred in the different time scale.

Fig. 2 depicts the PL spectra of the as-grown, the control (annealed only), and the intermixed (exposed and annealed) samples for laser structures of InGaAs/InGaAsP QWs, InGaAs/InAlGaAs QWs, and GaAs/AlGaAs QWs. Correspondingly, the plasma exposure durations are 5, 2, and 1.5 min and the annealing conditions are 600 °C for 2 min, 650 °C for 2 min, and 860 °C for 0.5 min. The annealing condition for each structure was chosen below a critical temperature from the thermal stability test, beyond which the as-grown sample started to experience appreciable bandgap shift due to other effects. After the exposure and subsequent annealing, the samples exhibit bandgap blue-shifts with inappreciable linewidth broadening, indicating the enhancement of intermixing rate due to the plasma-induced damage on the QW systems, in the form of mobile point defects, rather than the thermal induced interdiffusion. The obtained optimum bandgap shifts are 100 nm (65 meV), 66 nm (42 meV), and 23 nm (43 meV) for the three materials. The difference in the bandgap shift could be attributed to the different band offset of the three material structures. In addition to that, the defect diffusion in InGaAs/InGaAsP material is more efficient to promote intermixing in agreement with the study of defect diffusion using InP- and AlGaAs-based ion implantation induced QWI process [18]. The bandgap shift in the GaAs/AlGaAs system is comparable to the result achieved in the GaAs/AlGaAs system using multicycle H2 plasma exposure and annealing [11]. These results demonstrate the effectiveness and the universality of inductively coupled Ar plasma-induced QWI to alter the bandgap energy of III–V materials.

At low ion energy (hundreds of electronvolts), the majority of the impinging ions of Ar plasma is stopped within the first few atomic monolayers of material and may cause lattice disruption and damage up to a depth of a few tens of nanometers [19], thus avoiding direct damage to the QW active regions which are located deeper than 1.5 μm below the sample surface. We further investigate the plasma-induced damage mechanism causing the intermixing using GaAs/AlGaAs multiwidth QWs damage probe structure. Fig. 3 shows the comparison of 77 K PL spectra
normalized to the PL peak intensity of the deep most QW (QW5) after exposure at 500 W ICP power for 1 min and subsequent annealing. The annealing condition at 765 °C for 2 min has no pronounced thermal shift of QWs. Fig. 3(iii) clearly exhibits six peaks for the as-grown QWs probe structure, one for each QW and the GaAs substrate at 822 nm. After exposure [Fig. 3(ii)], the PL intensity of the shallowest QW (QW1) is clearly reduced by 32%, suggesting that the high-density plasma generates the near surface damage at a depth of more than 0.4 μm, in the form of mobile point defects, leading to an increase in nonradiative recombination and a decrease in PL intensity. Upon annealing [Fig. 3(iii)], the PL intensity of QW1 is recovered to the level close to that of the as-grown sample with the shift of the PL peak for all the QWs. The PL intensity recovery indicates that the annealing process has restored the created surface damage during plasma exposure. Upon annealing, the PL peaks of all QWs have been blue-shifted. The result suggests that the created damage, in the form of mobile point defects, propagates deeper to the deep-most QW (QW5) more than 2.32 μm and promote the intermixing between wells and barriers.

IV. SPATIAL RESOLUTION STUDY

Recently, there has been increasing interest in scaling the PICs monolithically on a single wafer. In order to achieve high-density photonic integration, the QWI process must be capable of tuning the material bandgap with high spatial selectivity. For example, the spatial resolution requirement of quasi-phase-matching grating for the second harmonic generation would be in the micrometer range [20], [21]. However, the selective intermixing induced by the interdiffusion of the near surface defects tends to give a low spatial resolution due to the spreading of mobile point defects formed on the top surface in the lateral direction as they propagate to the QW region during annealing. Thus, interruption of QW epitaxy growth process and a sacrificial layer removal are required to improve a high spatial resolution QWI [3]. Therefore, the investigation on the spatial resolution of plasma-induced QWI and its improvement is necessary to be carried out.

Two samples of InGaAs/InGaAsP QWs laser structures with dimensions of 8 x 8 mm² were coated by a 300-nm-thick Si₃N₄ layer using a plasma-enhanced chemical vapor deposition (PECVD) as an intermixing mask. The Si₃N₄ material was chosen due to its minimal solubility of group III atoms, thus minimizing the III–V species outdiffusion from the area patterned with the dielectric mask [22]. After the lithography process, an RIE process using CF₄/O₂ mixture followed by the diluted HF solution was done to produce 2 x 2 mm² arrays of Si₃N₄ patterns with different stripe widths of 50, 20, 10, and 5 μm, as depicted in Fig. 4(a). By varying the width of the patterned stripes, the sum of intermixed and unintermixed PL spectra can be collected as a direct evidence of spatial resolution. The samples were exposed for 5 min under Ar plasma using 500 W ICP power.

Prior to annealing, the Si₃N₄ pattern was removed in one sample using diluted HF solution, while it was preserved in another sample. During high-temperature annealing, the stress field on the film/QW material interface is modified due to the mismatch of the linear thermal expansion coefficient between Si₃N₄ layer (∼2.8·10⁻⁶°C⁻¹) and InP-based material (∼4.6·10⁻⁶°C⁻¹). A study by Pepin et al. reveals that the Si₃N₄ layer deposited on GaAs material during the high annealing temperature is at a very high tensile stress (∼3.5 GPa) as estimated from the measured Si₃N₄ intrinsic stress, σ_in at RT after deposition [23]. We believe that the Si₃N₄ layer deposited onto the QW material is similar to the case of GaAs material that Si₃N₄ is under compressive strain during annealing, while the QW material under the trench is under tensile strain. This generates the modulation of the stress field distribution under Si₃N₄ masked region oriented in a direction perpendicular to the sample surface. The amplitude of stress is modulated strongly between the masked and unmasked region and enhanced compressive stress exists at the Si₃N₄ pattern edges, as shown in the previous calculation of strain distribution using the finite-element method [24].

As illustrated in Fig. 4(b), a 300-nm-thick Si₃N₄ mask patterned on the sample surface is expected to block the point defect creation during the plasma exposure in the masked region and minimizes the defect diffusion in the lateral direction due to the stress effect during the annealing process. The Si₃N₄ mask here can be utilized as a stress-inducing dielectric mask during annealing. The created surface defects propagate downward to the QW active region to promote intermixing during annealing, and in the meantime the lateral diffusion of defects smear the boundary of intermixing area so that the two PL peaks tend to merge as the pattern pitch are getting smaller. Therefore, by
varying the stripe width and observing the disappearance of the intermixed PL peaks, the spatial resolution of the process can be determined [25].

PL spectra at 77 K were then measured from each array using a 50-μm-diameter multimode optical fiber as a probe. Due to the fiber spot size dimension, the PL spectra from the patterned samples contain PL signals from both masked (unintermixed) and unmasked (exposed, thus intermixed) regions. Fig. 5 shows the comparison of PL spectra from arrays annealed with and without the presence of a stress-inducing dielectric mask with different stripe widths. The unintermixed and intermixed PL spectra refer to the PL signal probed from relatively large areas of masked and unmasked portions of the same substrate, respectively, are included for comparison. The PL spectra of the patterned area exhibit two peaks corresponding to both intermixed and unintermixed regions. The differential bandgap shifts between intermixed and unintermixed regions are 74 and 66 nm for annealed samples with and without stress-inducing dielectric mask, respectively. The sample with stress-inducing dielectric mask exhibited a larger bandgap shift due to the in-diffusion enhancement caused by the group V out diffusion from the presence of a small gap between sample and GaAs proximity cap during annealing. The appearance of well-separated dual peaks shifted due to the interdiffusion enhancement caused by the group V out diffusion from the presence of a small gap between sample and GaAs proximity cap during annealing. The appearance of well-separated dual peaks suggested that high selectivity is obtainable in QW samples using a stress-inducing dielectric mask.

The interesting finding here is that in the sample annealed with a stress-inducing dielectric mask, the dual peaks of PL spectra are better defined for the stripe widths of 50, 20, and 10 μm, while for the stripe width of 5 μm, the PL spectrum only has a single peak, similar to the PL spectrum from the intermixed sample. Thus, it is concluded that the spatial resolution is better than 5 μm. The interesting finding here is that in the sample annealed with a stress-inducing dielectric mask, the dual peaks of PL spectra are better defined for the stripe widths of 50, 20, and 10 μm, while for the stripe width of 5 μm, the PL spectrum only has a single peak, similar to the PL spectrum from the intermixed sample. Thus, it is concluded that the spatial resolution is better than 5 μm.
the masked region. The dual peak PL spectrum shows a nearly perfect line shape fit with two Gaussian curves. The absence of any appreciable linewidth difference between two regions from the Gaussian fits suggests that the plasma-enhanced QWI does not introduce any significant degradation of optical quality with respect to the protected region during plasma exposure. In addition, the RT PL mapping was measured to provide the uniformity of bandgap distribution profile from sample annealed with a stress-inducing dielectric mask. The resolution of the PL mapping system is 100 μm, which is the smallest step size of mapping scan. Fig. 6(b) shows the two-dimensional map profile and one-dimensional line profile of PL peak distribution across the selectively intermixed sample revealing the distinct dual bandgap across the sample with a good uniformity across the selectively intermixed sample with dimension of 1.2 × 1.2 mm. It is worth noting that the uniform PL linewidth distribution (not shown here) provides a further evidence of the optical quality preservation of the intermixed QWs.

Helmy et al. found that the MRS was suitable as a sensitive technique for characterizing QWI processes with high spatial resolution by studying features of the Raman-mode spectra, such as relative mode amplitudes and integrated mode area [27]. Such variation in the amplitude-peak mode due to the interdiffusion of atoms in InGaAsP alloys is related to the relative density of corresponding bonds [28]–[31]. The change in Raman peak intensity and its ratio between the two consecutive Raman spectra across the intermixing boundary indicates the spatial resolution of the QWI process due to compositional alterations that modifies the vibrational properties of the crystal lattice. A uniform penetration depth of ≈90 and ≈110 nm below the sample surface is predicted from the calculation of its absorption length directly for InP and GaAs material, respectively [32]. Thus, the Raman modes with the largest signal-to-noise ratio were dominantly generated from the InGaAsP GRIN layers of the QW active region. Fig. 7(a) shows a unique variation of Raman spectra in the transition region between the intermixed and unintermixed area taken from 3.6 to 6 μm spatial distances, unambiguously indicating the interdiffusion process has started beneath the masked region due to the atomic lateral diffusion of the QWI process. The resulting line map Raman spectra were further analyzed, by monitoring the amplitude-mode of InAs (I_{InAs}) and GaP (I_{GaP})-like LO phonon peaks together with the amplitude-mode ratio (I_{InAs}/I_{GaAs} and I_{GaP}/I_{InP}) to reveal the extent of lateral diffusion across intermixing boundary [30], [31], as depicted in Fig. 7(b). The similar lateral transition trends were obtained for GaAs (I_{GaAs})- and InP (I_{InP})-like LO phonon peaks with lower amplitude-mode contrasts, which are not shown here. An obvious decrease in the GaP-like LO mode amplitude with an increase in the InAs-like LO mode amplitude at a separation of 2.4 μm was observed that is similar to the amplitude-mode ratio transition across the map line. These transitions unambiguously indicate that the spatial resolution from the laterally compositional interdiffusion is about 2.4 μm. This value from MRS study was consistent to the spatial resolution obtained using PL measurements, indicating that the stress-inducing dielectric mask improves the spatial resolution of Ar plasma-induced QWI to ~2.4 μm.

The intermixing of QWs under the masked region could be due to the combined effects of: 1) lateral spread of surface defects during Ar plasma exposure and 2) lateral diffusion of defects during annealing. The improvement of spatial resolution is ascribed to the existence of the stress-inducing dielectric mask, which provided the vertical stress across the mask interface during annealing [33]. The edges of the dielectric mask cause the modulation of the material stress during the annealing stage due to the large difference in the thermal coefficient expansion between Si_{x}N_{y} layer and the QW material. The compressive state of the QW material under the Si_{x}N_{y} masked region generates a higher compressive strain at the pattern edge and thus forming the stress field lines oriented in a direction perpendicular to the sample surface. The vertical stress field lines act as a barrier to limit the point defect diffusion in the lateral direction, since it is difficult for the mobile point defects to move across the vertical stress field lines due to the presence of the stress-inducing dielectric mask. As a result, the vertical stress will minimize the lateral diffusion of point defects underneath the mask during annealing, thus giving rise to an improvement of spatial resolution, i.e., ~2.4 μm analyzed from the PL and the MRS measurements.

V. ONE-STEP MULTIPLE BANDGAP CREATION

The lateral control of bandgap across a single chip is crucial for the implementation of PICs because different optical components on a PIC module commonly have different bandgap requirements. Since most defects are introduced on the near sample surface during plasma exposure, the lateral diffusion of defects below the spatial resolution of plasma-induced QWI can be utilized to modulate the defect concentration reaching the QW active region using a spatially masked pattern; thus, different degrees of the intermixing can be obtained in single expo-
sure-annealing step. The spatial defect modulated intermixing (SDMI) takes advantage of the lateral defect migration during annealing similar to the multiple-bandgap approach in the IFVD technique [4], by varying the window exposure area percentage, below its spatial resolution investigated in the previous section, as depicted in Fig. 8(a).

Two samples of InGaAs/InGaAsP QWs laser structure were deposited with a 300-nm-thick SiO2 layer by electron beam evaporation and spin-coated with a 1.5-μm-thick AZ 5214 photoresist. The photoresist layer was patterned into eight stripe arrays and transferred to the SiO2 layer in a CF4/O2 RIE process followed by photoresist removal, so that, as shown in Fig. 8(b), the areas opened to plasma exposure in the stripe arrays were 0%, 30%, 40%, 45%, 50%, 75%, 90%, and 100% of the 2.5-μm-wide stripe areas as a control mask, respectively. The pattern samples were exposed to Ar plasma for 5 min. After the SiO2 removal using diluted HF solution, a subsequent annealing was done at 600 °C for 2 min. The SiO2 removal prior to annealing is necessary to improve the lateral defect migration for the given stripe widths, as suggested from the previous spatial resolution study without the stress-inducing dielectric mask. PL spectra at 77 K were measured using a similar optical fiber probe to each array.

Fig. 9 summarizes the measured PL spectra and the corresponding bandgap shifts and linewidths of InGaAs/InGaAsP QW laser structure. Only a small variation of the linewidth was observed as the exposure coverage increases and the PL spectra did not appear to be double peaked, suggesting that the intermixing process is uniform with 2.5-μm-wide diffusion control mask. The 0% exposed area was found to be almost fully inhibited from intermixing, while 100% exposed area was intermixed by about 100 nm (66 meV). The degree of intermixing increases linearly as the exposed percentage area increases indicating that the correlation between the amount of created mobile defects on the surface and the achieved degree of bandgap shift, similar to that in the case of QWI using IID using ion implantation [18]. The linear dependency underscores that the single-step multiple bandgap process permits the implementation of multiple wavelength control across a substrate with a simple and reliable semiconductor processing technology. This spatial defect modulation approach can be widely applied to achieve multiple bandgap with other existing QWI techniques.

VI. PHOTONIC INTEGRATED DEVICE: EXTENDED CAVITY LASER

The monolithic integration of an active laser and a low-loss passive waveguide in the form of an extended cavity laser (ECL), which is transparent to the laser emission, is an essential step toward the realization of PIC technology [34]. Such integration is thus of great importance for monolithically integrated tunable laser diodes, low-loss distributed Bragg reflector lasers, lasers integrated with optical modulators, high-power grating-coupled emission lasers, superluminescent diodes, and integrated extended cavity mode-locked lasers. Since the Ar plasma-induced QWI is an impurity free process, the demonstration of low loss waveguide is extremely demanded. Losses introduced by nonradiative recombination centers of free carriers, as in IID technique, are expected to be significantly reduced.

From Fig. 10(a), the bandgap at passive waveguide sections were selectively intermixed in order to reduce the propagation loss at the lasing wavelength from the unintermixed active laser section. A sample of InGaAs/InGaAsP QWs laser structure with a pattern of variable stripe widths (with hundreds-of-micrometers-wide SiO2 patterns as an intermixing mask) was exposed under Ar plasma for 5 min and annealed. Fig. 10(b) shows the normalized PL spectra at 77 K obtained from the partially masked sample. The masked section has 6-nm bandgap shift and 5.2-nm linewidth broadening, which is attributed to thermal shift. The unmasked section has a much larger bandgap shift of 92 nm, thus producing a bandgap difference of 86 nm with a small differential linewidth broadening of 0.3 nm. These results imply the high selectivity obtainable using 200-nm-thick SiO2 layer as intermixing mask with good preservation of optical quality from the minimal linewidth broadening. Following the intermixing step, the broad area ECLs was fabricated. The removal of the 150-nm-thick highly doped InGaAs/InGaAsP
cap layer minimizes current spreading into the passive section and the absorption of light in this section. A 200-nm-thick SiO$_2$ was deposited using PECVD and a 50-μm contact window was defined using dry etch in RIE machine followed by wet etch. A p-contact of Ti/Au layers was defined over the laser active sections using a lift-off process to ensure electrical isolation between active and passive sections. The sample was then thinned down and n-metal contact of Au/Ge/Au/Ni/Au layers was formed and alloyed using rapid thermal processor. The final ECLs devices [as shown in Fig. 11(a)] were tested at RT under pulsed current operation (1% duty cycle). Fig. 11(b) shows the plot of light output versus injected current (L-I) characteristics of 800-μm-long active section lasers with passive section length of 1200 μm. For comparison, 800-μm-long all active lasers (AAL) were cleaved from the same sample. The threshold current was increased by 18% from 481 mA for AAL to 569 mA, which can be attributed to diffraction losses within intermixed passive section. The slope efficiency undergoes a little decrease by 9%, from 0.174 W/A to 0.159 W/A per facet. As shown in the inset of Fig. 11(b), the wavelength emission of ECL exhibits an apparent blue-shift (1.535 μm) as compared to unprocessed AAL laser (1.542 μm). The 7-nm blue-shift in wavelength emission might be due to the band filling effect from the increase in threshold current in the ECL rather than the graded bandgap on the passive–active interface due to the plasma-induced QWI process, as revealed from the spatial resolution study earlier. This shift of the wavelength will cause the propagation losses to increase slightly, since the energy of the photons is now closer to the bandgap of the passive waveguide section.

From the L-I characteristics, it is possible to define the relationship between AAL threshold current ($I_{AA}$), ECL threshold current ($I_{ECL}$), and the propagation loss in the passive section ($\alpha_p$). The threshold currents are related by the formula [35]

$$\ln \left( \frac{I_{ECL}}{I_{AA}} \right) = \frac{\alpha_p L_P + \ln \left( \frac{g_0}{g_L} \right)}{\Gamma g_0 L_A} \tag{1}$$

where $L_A$ and $L_P$ are lengths of the active and passive sections; $g_0$ is the gain of the active structure; $\Gamma$ is the optical transmission coefficient at the interface of the active to passive sections; and $\Gamma$ is the overlap integral within the QWs. An estimated value of $\Gamma g_0 \sim 30$ cm$^{-1}$ was used [36] and $\kappa$ is obtained from the QWI-induced refractive index change with a calculated step profile to be 0.999998. This value of $\kappa$ confirms that negligible reflection occurs at the passive/active interface. Comparing ECL with active (passive) length of 800 μm (1200 μm) and AAL with 800 μm cavity length, $\alpha_P$ is calculated to be 2.98 cm$^{-1}$ or 12.9 dBcm$^{-1}$, which corresponds to about 2.6 dBcm$^{-1}$ per well. The increase of threshold current density partly is ascribed to the divergence of the lasing mode within the extended cavity, which reduces the amount of light returning to the pumped laser region. Taking into account the interface reflectivity due to the spatially graded interdiffusion profile and lateral optical spreading loss of 7.9% at the active-passive interface, the corrected value of waveguide loss $\alpha_P$ is 2.3 cm$^{-1}$. If compared to the LID technique, the estimated residual loss here was comparable to the calculated loss (2.4 cm$^{-1}$) from the ECL with a similar active length of 800 μm and slightly higher than to the pure ridge waveguide loss of 2.1 cm$^{-1}$ measured using Fabry–Pérot measurement [36]. The quantum efficiency degradation in the presence of integrated passive section can be expressed as [37]

$$\eta_{ECL} = \frac{\eta_{AA} \alpha_A + \frac{L_P}{L_A} \ln \frac{1}{\eta_{AA}}} {\alpha_A + \frac{L_P}{L_A} \ln \frac{1}{\eta_{AA}} + \alpha_P L_P} \tag{2}$$
where \( R \) is the facet reflectivity, calculated to be 0.27 for the as-cleaved structure. The ratio calculated with the above equation is 0.87, which is in agreement with the measured value of 0.91 from the L-I characteristics. This small discrepancy can be explained by noting that the effective length of gain section is shorter than the physical active pumped section due to the graded bandgap interface region after intermixing, which can lead to increase in the threshold current without any contribution to the gain.

VII. CONCLUSION

The capability of plasma-induced QWI technique for high-density photonic integrated devices has been investigated on three aspects: 1) universality to the wide range of III-V materials; 2) spatial resolution; and 3) single-step multiple bandgap creation. High plasma density due to ICP application has been found to contribute in promoting the intermixing in QW structures besides the pure ion bombardments while preserving the optical quality after the process. The analysis from the intermixing process of GaAs/AlGaAs multiwidth QWs damage probe structure reveals that the point defects are created at near sample’s surface during plasma exposure and upon the subsequent annealing, they propagate deeper to a depth beyond \( \sim 2.3 \mu m \) to promote intermixing between well and barrier. The demonstration of tuning the GaAs/AlGaAs and InGaAs/InAlGaAs QWs in addition to the InGaAs/InGaAsP QWs underscores the universal QWI process in a wide range of the GaAs-based and InP-based material.

We have investigated the effect of the dielectric mask induced stress to the spatial resolution of plasma-enhanced QWI. The presence of dielectric mask induced stress gives an improvement in the spatial resolution to \( \sim 2.4 \mu m \), which might be applicable for the spatial resolution improvement in various shallow defect-induced QWI techniques, such as using low energy ion implantation, sputtered silica deposition, anodic-oxide-induced interdiffusion, low-temperature InP, and excimer laser-induced disordering, in a simple way. Utilizing the lateral diffusion of defects below the spatial resolution of plasma-induced QWI, a simple and reliable way to obtain a controlled multiple bandgap was achieved by using the spatial defect modulated intermixing using control dielectric mask with variable window exposure area. Eight bandgap levels were realized using single exposure-annealing step with a linear relationship to the fraction of the open area under plasma exposure. Eventually, the simple photonic integration has been demonstrated using the plasma-induced QWI process in the form of extended cavity lasers. A low-loss extended cavity laser has been fabricated with the measured waveguide loss as low as 2.1 cm\(^{-1}\) with 1200-\(\mu\)m-long passive waveguide.

These results highlight the capability of plasma-induced QWI technique in the application of high-density photonic integration, allowing the realization of multiple-section photonic device across a single chip using a one-step processing technique. This work provides an alternative approach of QWI by adopting conventional process available in the semiconductor industry and thus may bring the impact to the development of PICs technology.

Note: During the paper communication, the plasma-induced QWI technique has also been adopted to reduce the absorption loss in asymmetric twin waveguide laser tapers [38] and to realize the wavelength monitoring with low-contrast multimode interference waveguide [39].

REFERENCES


