Post-Growth Control of the Quantum-Well Band Edge for Optimized Widely-Tunable Laser-X Devices

Erik J. Skogen, James W. Raring, Jonathon S. Barton, Steven P. DenBaars, and Larry A. Coldren

Abstract—We describe a quantum well intermixing process for the monolithic integration of various devices each with a unique band edge. The process involves a single ion implant followed by multiple etch and anneal cycles. We have applied this method to design and fabricate widely-tunable sampled-grating DBR lasers with integrated electroabsorption modulators. The devices employ three unique band edges, and demonstrate exceptional tuning, gain, and absorption characteristics.

Index Terms—Ion implantation, laser tuning, semiconductor lasers, wavelength-division multiplexing.

I. INTRODUCTION

MONOLITHIC integration of widely-tunable lasers with supplementary optoelectronic components offer cost reduction, improved performance, and added functionality over existing fixed wavelength components used in optical networks. The sampled-grating (SG) DBR laser is ideal for this purpose, as the lithographically defined mirrors allow for the manipulation of light on chip. The difficulty arises when optimization requires each of the integrated components to possess a unique band edge. Limited by the one-dimensional growth platform used to produce the epitaxial material, the push for monolithic-integration has lead to either compromises in device design or complex processing to achieve the goals.

The solution is the development of a manufacturable wafer-scale process, which allows for the precise control of the band edge across the wafer. We have developed a quantum well intermixing (QWI) process specifically for this purpose. For example, each section of the SGDBR laser should be designed with band edges specific to the function of the particular section. Quantum well intermixing allows for the as-grown active region band edge to be shifted precise amounts in the mirror and phase sections to achieve low propagation loss while attaining high tuning efficiency [1].

In this paper, we describe a process, and present device results using QWI [2] to tune the band edge of the quantum well active region across the wafer. The process consists of a single ion-implant, producing vacancies in an implant buffer layer, followed by short rapid thermal anneal, and finally, the selective etching of the implant buffer layer in regions where the desired extent of intermixing has been reached. This concept can be extended to more complex photonic integrated circuits requiring several band-edge specific components, such as the SGDBR laser integrated with a modulator, shown in Fig. 1.

We report on the results achieved using this QWI process to fabricate widely-tunable SGDBR lasers with integrated electro-absorption modulator (EAM).

II. EXPERIMENT

A. QWI for Monolithic Integration

Increased functionality, improved reliability, and cost reduction, fuel the desire for the monolithic integration of discrete optoelectronic components. In the past, monolithic integration has been accomplished through several methods.
One method is based on the use of offset quantum wells, where the multi-quantum well (MQW) active region is grown above the waveguide. This allows for the selective etching of the MQW in regions where gain is not required, leaving the non-absorbing waveguide. Once the active and passive regions have been defined, the upper cladding is regrown [3]. Although this is a relatively simple process and does not add significant processing steps in the case of the SGDBR laser, it will allow for only two band edges, one from the MQW and one from the waveguide. Not only is the modal gain in the offset quantum well design less than optimal, but also when integrating an EAM with the SGDBR the trade-off between loss, tuning, and absorption may lead to reduced performance of one or more components.

Another method involves the selective removal of the as-grown waveguide/MQW region followed by the regrowth of waveguide/MQW material with the desired band edge. This method is commonly referred to as butt-joint regrowth [4]. Although the butt-joint regrowth process does allow each integrated component to possess a unique band edge, the difficulty associated with matching thickness and achieving the desired composition to avoid reflection and loss at the interface is great. Furthermore, the complexity is compounded as the number of desired band edges increases.

Selective area growth has been shown to be useful in providing multiple band edges in across the wafer in a single growth step [5]. In this method a mask is patterned on the wafer, which is then subjected to epitaxial growth. Growth is limited to regions between the mask, where thickness and composition of the growing layers are modified based on the mask pattern. The abruptness of the transition region is limited by the surface diffusion of the growth constituents, which may be on the order of tens of microns. Additionally, the optical mode overlap with the MQW may not be ideal in all sections due to the thickness variation.

Quantum well intermixing allows for the strategic, post-growth, tuning of the quantum well band edge in a relatively simple procedure. Thus, QWI breaks the trade-off associated with the offset quantum well method. There are several methods to accomplish QWI, as discussed in the following section. Here, we employ ion-implantation-induced-intermixing, in which the transition region between sections with differing band edges is predicted to be on the order of a micron [6]. Also, because QWI does not change the average composition, but only slightly changes the compositional profile, there is a negligible index discontinuity at the interface between adjacent sections. This eliminates parasitic reflections that can degrade performance. Our method allows any number of band edges, limited only by the practical number of etch and anneal cycles.

In our case, each section of the sampled-grating DBR laser should be designed with band edges specific to the function of the particular section. Quantum well intermixing allows for the as-grown active region to be shifted precise amounts in the mirror and phase sections to achieve low propagation loss while attaining high tuning efficiency [1].

B. Quantum Well Intermixing Background

There are several techniques used to accomplish QWI, impurity-induced disordering (IID) [2], the impurity-free vacancy-enhanced disordering (IFVD) [7], [8], and photoabsorption-induced disordering (PAID) [9] are just a few.

In this work we employ the implant enhanced interdiffusion method, which relies on the diffusion of point defects, specifically vacancies, created during an ion implantation. This method has been shown to have good spatial resolution, and be controllable using anneal time, temperature, and implant dose [10]. Wide ranges of implant energies have been used in this process from the MeV range down to tens of keV. Commonly, these implants are performed on full lasers structures, where the vacancies are created in the upper cladding, and must diffuse long distances before reaching the quantum wells. Although this is not detrimental to the intermixing itself, the device performance may be hindered by the redistribution of precisely placed doping interfaces. This can be avoided by using a partially grown laser structure and a sacrificial cap layer, which can be subsequently removed, and the upper cladding regrown as described in [11]. While [11] demonstrated such a concept, the process was not optimized, as multiple implant and anneal cycles were required to achieve significant intermixing.

It has been shown previously that significant intermixing can be achieved in a one-step QWI process using a low-energy ion implant to generate the required vacancies in an InP implant buffer layer, which can be subsequently removed [1]. Here we show that multiple band-edges can be realized by selectively removing the implant buffer layer, after an initial anneal, over regions where the desired band-edge has been obtained. The intermixing then continues during subsequent anneals in regions where the implant buffer layer remains intact.

C. SGDBR Background

The SGDBR itself consists of four sections; gain, phase, front mirror, and back mirror. A backside absorber has been monolithically integrated to reduce reflection from the back facet. A schematic of the SGDBR laser is shown in Fig. 1.

The sampled-grating DBR mirror is a special form of DBR mirror, where the gratings are periodically blanked in order to create a comb-like reflectivity spectrum [12]. The sampling periods in the front and back mirrors differ, which provides the front and back mirrors with a different peak reflectivity spacing, so that only one set of reflectivity peaks is aligned within the desired tuning range. By differentially tuning the front and back mirrors a small amount, adjacent reflectivity peaks can be aligned, and the laser will operate at this new wavelength. The simultaneous tuning of front and back mirrors allow wavelength coverage between mirror reflectivity peaks. The phase section provides cavity mode tuning, which ensures that the laser cavity mode is aligned with the mirror reflectivity peaks. The tuning in the mirrors
and phase sections is based on carrier injection, producing a negative change in refractive index. In order to keep the loss to a minimal level over the desired wavelength operating range, the tuning sections make use of higher bandgap material or MQW regions whose quantized energy state is greater than that of the active region.

The lithographically defined sampled-grating mirrors and the relatively simple process used to render the phase and mirror sections passive, make this device ideal for monolithic integration. In fact, the offset quantum well SGDBR has been monolithically integrated with several other components, such as, electro-absorption modulators [13], semiconductor optical amplifiers [3], and integrated wavelength monitors [14]. These are by no means the limits of what can be accomplished with the SGDBR; the SGDBR can itself become the integrated component in larger more complex photonic integrated circuits.

D. EAM Background

In an EAM a reverse electrical bias is used to shift the band edge of the modulator section to lower energy, thereby increasing the absorption of that region. In our case, QWI only smears the interfaces between the quantum wells and barriers, such that the quantum wells still remain after the intermixing, although slightly shallower and rounded. This allows for the exploitation of the quantum confined Stark effect in the EAM. The rounded shape of the intermixed quantum well also contributes to increased absorption efficiency in the modulator [10].

Electro-absorption modulators have been monolithically integrated with the SGDBR, and are spaced 10 microns from the front SGDBR mirror. The mask was such that single section EAMs of varying lengths were included. A schematic of one of the integrated devices is shown in Fig. 1.

III. PROCESS

The epitaxial base structure, shown in Fig. 2, was grown on a sulfur doped InP substrate using a Thomas Swan horizontal-flow rotating-disc MOCVD reactor. The active region consists of either seven or ten 7.0 nm compressively strained (1.3%) quantum wells, separated by 8.0 nm tensile strained (0.3%) barriers, centered within two 1.3Q layers designed to optimize the optical mode overlap with the quantum wells. Following the active region, a 15 nm InP stop etch, a 20 nm 1.3Q stop etch, and a 450 nm InP implant buffer layer was grown.

The active regions were masked with 500 nm of Si$_3$N$_x$, and an ion implant was carried out using P$^+$ at an energy of 100 keV, yielding a range of 90 nm, with a dose of 5E14 cm$^{-2}$, at a substrate temperature of 200 °C [15]. The implant buffer layer was designed to completely capture the ion implant, creating vacancies far from the active region. These vacancies were then partially diffused through the structure during a 90-second, 675 °C rapid thermal anneal (RTA), yielding the desired band-edge for the EAM. The implant buffer layer above the EAM sections was removed using a wet etching process, stopping on the 1.3Q stop etch layer. The sample was then subjected to an additional 110-second rapid thermal anneal blue-shifting the regions where the implant buffer layer remained. This second anneal was used to obtain desired band edge for the mirror and phase sections. The remaining implant buffer layer and 1.3Q stop etch layers were removed using a wet etch process, leaving a thin planar InP surface just above the waveguide. This gives access to the high field region of the optical mode, which is ideal for etching high coupling coefficient gratings, on the order of 300 cm$^{-1}$, directly into the waveguide.

The sampled grating mirrors were defined by RIE etching deep gratings, 800Å, directly into the waveguide through a Si$_3$N$_x$ sampling mask. The gratings were...
then planarized using an optimized MOCVD regrowth. Following the planarizing regrowth, a ridge was RIE etched through the waveguide structure, etch damage was removed using a bromine-based polishing etch. The ridge was buried in p-type InP with an InGaAs contact layer during a second MOCVD regrowth designed to yield a planar buried ridge stripe (BRS) geometry. The contact layer was etched to a width of 6 µm, positioned directly above the original etched ridge. A proton implant was performed along side the laser and EAM structures to reduce current leakage and parasitic capacitance in the device [16]. A blanket of Si$_x$N$_y$ was deposited 200 nm thick, and a via to the contact layer etched to facilitate the Ti/Pt/Au contact, patterned using a lift-off process. The substrate was lapped to a thickness of 90 µm, and a Ti/Pt/Au contact was deposited for the back-side n-contact. The devices were cleaved into bars and anti-reflection coated. The die were separated, soldered to aluminum nitride carriers, and wire bonded, for continuous-wave testing. The completed device is shown in Fig. 3.

**Fig. 3.** Electron micrograph of completed SGDBR/EAM device.

**Fig. 4.** Peak photoluminescence peak shift as a function of anneal time, showing the initial linear increase in the peak shift and the complete halting of the peak shift for samples for which the implant buffer layer has been etched. Symbols indicate nonimplanted (triangles), implanted (circles), and samples with partial anneal followed by the removal of the implant buffer layer (squares).

**Fig. 5.** Photoluminescence spectra for a ten-quantum well sample showing three band-edges achieved with a single ion implant. Symbols indicate active region photoluminescence (diamonds), EAM photoluminescence (squares), and mirror and phase section photoluminescence (triangles).

**Fig. 6.** Extraction of passive region modal loss by plotting differential efficiency of active/passive devices as a function of passive region length for both the mirror band edge (dotted line), and the EAM band edge (solid line). Modal loss values were computed to be 5.1 cm$^{-1}$ and 8.0 cm$^{-1}$, for the mirror band edge and EAM band edge, respectively.

IV. RESULTS

A. Quantum Well Intermixing

The intermixing process was calibrated using several samples cleaved from an implanted seven quantum well base structure, as described in the previous section. These samples were annealed at 675°C for various times ranging from 30-seconds to 300-seconds at 30-second intervals and the extent of the intermixing was measured by room-temperature photoluminescence. As the vacancy front moves through the quantum well region the blue-shift increases linearly. Once the vacancy front has moved through the quantum well region, blue-shifting ceases. This saturation of the blue-shift can be observed above 120 nm as shown in
Fig. 8. Output power and voltage plotted as a function of current for a seven quantum well device.

Fig. 9. DC extinction of a 175 micron long EAM for three wavelengths. Wavelengths measured are: 1545 nm (squares), 1553 nm (circles), 1562 nm (diamonds).

B. Active/Passive Fabry-Perot BRS Lasers

An important parameter in the SGDBR device is the modal loss in the mirror and phase sections at the gain peak of the active region. Not only does the modal loss in these regions have a large effect on the un-tuned output power of the device, but also, plays a large role in determining the power ripple in the tuning band. Using active/passive devices, where the passive region is composed of intermixed quantum wells, the modal loss of the intermixed quantum wells, used in the mirror and phase sections, can be extracted. This is done by plotting the differential efficiency of the active/passive device as a function of passive region length. The method is described in [1]. Fig. 6 shows the experimental data with the theoretical fit for regions shifted to the band-edge for both the tuning and EAM sections. The tuning and EAM region modal loss was computed to be 5.1 cm$^{-1}$ and 8.0 cm$^{-1}$, respectively.

C. Carrier Induced Tuning

In order to cover the full tuning range in our SGDBR design, the front mirror must continuously tune 7 nm by a carrier-induced change in refractive index.

Using the method described in [1], the tuning of a 7 quantum well sample was measured. The results of this measurement are shown in Fig. 7, where we have demonstrated over 7 nm of continuous tuning at 1550 nm, which translates to a modal group index change of 1.7%. This is sufficient to demonstrate the full tuning range of the SGDBR device.

D. SGDBR Laser

The SGDBRs, incorporating a centered quantum well active region, and fabricated using QWI to render three band-edges, exhibit low threshold current and high output power.
Operating in continuous-wave mode, the power output versus the applied bias was measured for a 7-quantum-well SGDBR. As shown by Fig. 8, the SGDBR produces more than 20 mW of output power with a 100 mA bias on the gain section. The threshold current was measured to be 10.4 mA, with a slope efficiency of 31%.

E. EAM Extinction and Bandwidth

In this section we report the data obtained from the 175 μm long EAM at 1553 nm with –4 volt DC bias.

We have characterized the intermixed material in terms of loss, tuning, gain, and absorption, and found that the intermixed MQW active region provides the desired performance in each section of the widely tunable SGDBR/EAM device.

The QWI process described is general in its application and can be used to monolithically integrate a number of devices each with a unique band edge.

REFERENCES


