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Laser Trimming of Emission Wavelength of Quantum Semiconductor Microstructures

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ABSTRACT - Semiconductor wafers with selected regions of different bandgap materials are of interest for the fabrication of monolithically integrated photonic devices. Such wafers have been fabricated by epitaxial growth techniques, typically taking advanatge of the etch- and re-growth process. The regions of a wafer emitting at shorter than as-grown material wavelengths have also been achievable with the quantum well intermixing (QWI) process. Conventional QWI relies on using of a variety of thin film caps, or surface treatments that make the bandgap shifting process difficult to calibrate. Together with a relatively less robust growth technolgy of III-V semiconductors in comparison to, e.g., industrial technology of fabrication of Si-based microstructures, the current QWI techniques have often failed to offer an acceptable level of bandgap blueshifting reproducibility. We have investigated infrared laser based annealing as an alternative bandgap shifting approach designed specifically for trimming of emission wavelength of III-V quantum semiconductor microstructures. The results highlighted in this report illustrate an innovative method of iterative bandgap engineering applied for processing of InGaAs/InGaAsP QW microstructures. The method has the potential for high-precision fabrication of microstructures with almost arbitrary 2D shapes of the QWI material achievable in industrial-size wafers.

1. INTRODUCTION

Selective area bandgap engineering of III-V quantum semiconductor wafers has been the subject of a continuous investigation driven by the application of muti-bandgap wafers in the fabrication of monolithically integrated photonic circuits (MIPCs) [1]. Molecular beam epitaxy and other thin film epitaxial techniques, combined with the etch- and re-growth approach, have frequently been used to fabricate such wafers [2]. However, for industrial-based processes, due to potential cost reduction, it would be attractive to work with the same bandgap wafers fabricated for post-growth bandgap engineering with the quantum well intermixing (QWI) process. The intermixing of the quantum well (QW) and barrier materials can be significantly enhanced in the presence of locally introduced defects. Following the annealing step, this makes it possible to fabricate multi-bandgap QW wafers. Examples of a significant scale post-growth bandgap engineering research can be found in literature addressing processing of QW [3-5] and quantum dot (QD) [6-9] microstructures by conventional QWI methods. Lasers have also been found of interest for QWI, primarily due to the ease with which laser beams can be delivered to selected areas of a semiconductor wafer and introduce intermixing, promoting defects or just locally inducing increased temperature. Bandgap shifting in III-V microstructures has been reported with both pulsed [10-12] and continuous wave (CW) lasers [12-16]. The CW laser appears to be especially attractive due to its potential for direct „writing’ of the QWI (blueshifted) material in a single processing step, i.e., without the need to carry out post-processing annealing that normally is applied following the first QWI step involving deposition of a functional cap layer or surface processing at selected areas. Figure 1 shows an example of an IR Laser Rapid Thermal Annealing (RTA) fabricated array of 9-color GaInAsP/InP QW lasers emitting from λ_0 = 1522 nm (as-grown material) to λ_8 = 1405 nm [17]. This device, fabricated in a 3 mm long bar, is arguably the most advanced MIPC fabricated to date with a laser processing technology. Multi-λ laser arrays fabricated at commercially attractive costs, can find many applications, e.g., in a coarse wavelength division multiplexing (C-WDM) technology [18].

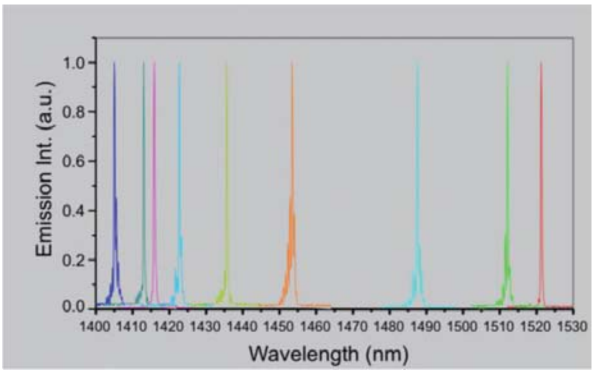

Figure 1: *Emission spectra from a monolithically integrated array of ridge waveguide InP/InGaAs/InGaAsP lasers fabricated by the IR Laser RTA technique [17].*

Despite the advancements with the IR Laser RTA experiments, the limited blueshift amplitude and, especially, the fact that spectral accuracy of the process has often been outside of the range acceptable for the reproducible fabrication of complex integrated photonic devices, make it difficult for Laser RTA to compete with traditional methods of MIPC fabrication [19]. Generally, the limitation of the QWI tuning precision is not specific to the intermixing approach, but rather to the difficult technology of III-V materials. This has prevented the introduction of a bandgap engineering process that would rely on accurate calibration procedures, analogous, e.g., to those known in the CMOS technology of Si-based monolithically integrated devices [20]. It is of practical importance to mention that, for the majority of conventional QW heterostructures designed for manufacturing of photonic devices, the intermixing process leads to blueshifting of the bandgap energy. This has enabled us to propose a method of “laser trimming” of the emission wavelength of QW heterostructures.

In this report, I describe a new technique of iterative bandgap engineering at selected areas (IBESA) that we have developed for trimming the emission wavelength of InGaAs/InGAsP QW microstructures.

2. IR LASER RTA SETUP

The IR Laser RTA setup is schematically illustrated in the left panel of Figure 2. It is equipped with a 150 W 980 nm fiber coupled laser diode (LD) for background heating, and a 30 W TEM$_{00}$ Nd:YAG laser emitting at a wavelength of 1064 nm for selected area heating of semiconductor wafers [21]. A galvanometric scanner (GS) allows to raster the Nd:YAG laser beam over the sample with a controlled velocity of up to 4000 mm/s. An F-Theta lens mounted at the output of the GS head assures that a beam with the same profile is delivered to any site of the wafer’s surface. The temperature of the processed spot is monitored with Mikron M680 fiber optic sensor (Pyrometer) and a custom designed infrared camera (IR-CAM). Another 640 x 480 pixel visible camera (Vis-CAM) operating at 10 Hz is used to monitor the sample’s positioning. With a 0.5 mm diameter of the Nd:YAG laser spot and depending on the amplitude of the blueshift, the fabrication of QWI material could be carried out with a spatial resolution of 100 to 400 μm. Higher spatial resolution processing is feasible with Nd:YAG laser beam delivery system dedicated to deliver spots down to 12 μm in diameter. The IR Laser RTA system allows for processing of up to 2-inch-diameter wafers.

3. IBESA PROCESS

The idea of the IBESA process is to achieve a required bandgap energy at selected areas of the QS wafer by accumulating a series of QWI steps, each designed to induce a small, typically less than 1-2 nm, blue shift. The results of each step are verified by collecting high-resolution PL maps from processed samples. The IBESA cycle is schematically illustrated in Figure 2.

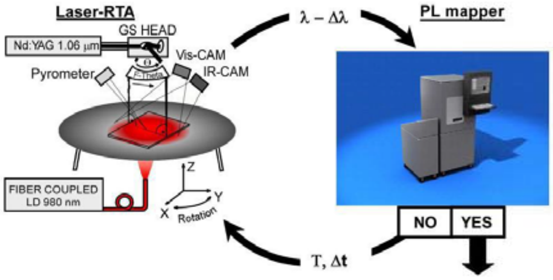

Figure 2: *Schematic idea of the IBESA process designed for laser trimming of emission wavelength of QS wafers [22]. The process is carried out in air. The samples are coated with SIO2, which protects their surface from deterioration (and the operator from As or P vapors).*

The number of IBESA steps can be designed depending on both the required total blueshift and accuracy in achieving a targeted value of bandgap energy (emission wavelength) of a QW microstructure.

4. QW MICROSTRUCTURE: COMPOSITION AND DIAGNOSTICS

We investigated a QW microstructure grown by metal-organic vapor phase epitaxy on a 0.375 mm thick InP substrate covered with a 1.5 µm thick InP buffer layer [22]. The microstructure comprised five 6 nm thick InGaAs QWs separated by 10 nm thick InGaAsP barriers. The active region was Si doped at 8 x 10^{17} cm^{-3} and capped with a 20 nm-thick InGaAsP, 40 nm InP, 6 nm InGaAs etch stop layer and a 30 nm thick InP layer. The capping was p-type doped at $5x10^{17}$ cm^{-3}. The room-temperature QW PL emission wavelength from this microstructure was at 1550 nm. Typical dimensions of samples used in this study were 10 mm x 12 mm. The as-grown wafer was coated with plasma-enhanced-chemical-vapor-deposition 50 and 500 nm thick SiO_2 layers on the front (polished) and back (unpolished) sides of the wafer, respectively. The SiO_2 caps prevented the wafers from high-temperature decomposition in the atmospheric environment. Before Laser-RTA processing, the samples were cleaned, sequentially, with OptiClear, acetone, isopropyl alcohol, and finally rinsed with deionized water. A test experiment revealed that the investigated InGaAs/InGaAsP microstructure could be blue-shifted by 230 nm in a single 30-second irradiation step at 780 ºC [23]. The results reported here were obtained with the intermixing and background temperatures of 760 and 550 ºC, respectively.

Room temperature PL measurements were carried out with a commercial mapper (Philips PLM-150) using an Nd:YAG laser (λ = 532 nm) as an excitation source and an InGaAs detector array. The PL mapping was performed with 1 nm and 10 µm spectral and spatial resolutions, respectively.

Based on an edge detection algorithm, custom LabVIEW image recognition software was developed for precise repositioning of samples returning from PL mapping measurements. The software interfaced VIS-CAM and the XYZ-R motorized stage allowed sample reinstallation within 5-µm translational and 0.05-deg rotational accuracies. We developed this approach to take advantage of the IR Laser RTA and industrial PL mapper setups available in our laboratory. However, it is feasible to combine these two techniques within one environment where a processed sample/wafer would remain immobilized until the completion of the IBESA process.

5. RESULTS

Figure 3a shows a PL wavelength peak map of a fragment of the sample irradiated with the Nd:YAG laser beam in 20 sites for different periods of time. The conditions of the irradiation at A1-A4 and B1-B4 sites and the achieved blueshifts are given, respectively, in the „Step 1 processing time' and „Peak wavelength' columns of Table 1. It can be seen that the 30 sec irradiated spots A3 and B1 have been blueshifted by 70 nm from the initial 1550 nm. Their diameter is approximately 280 µm. Figure 3b compares the PL spectrum of the center of the A3 spot with that of the as-grown material, both obtained under nominally the same excitation conditions. A decreased PL intensity of the A3 site is related to the reduced quantum confinement of the intermixed QWs. It is worth mentioning that for small blueshifts ($\delta\lambda \leq$ 50 nm) the opposite effect was observed, with a slightly increased PL intensity of the intermixed material. A reduced concentration of grown-in defects following the annealing step, before the reduced confinement starts to dominate the QW PL emission intensity, could explain such a behavior. Sites A1, A2 and A4 show the QW material emitting at 1488, 1492 and 1504 nm, while site B2 emits at 1484 nm and sites B3 and B4 at 1497 nm.

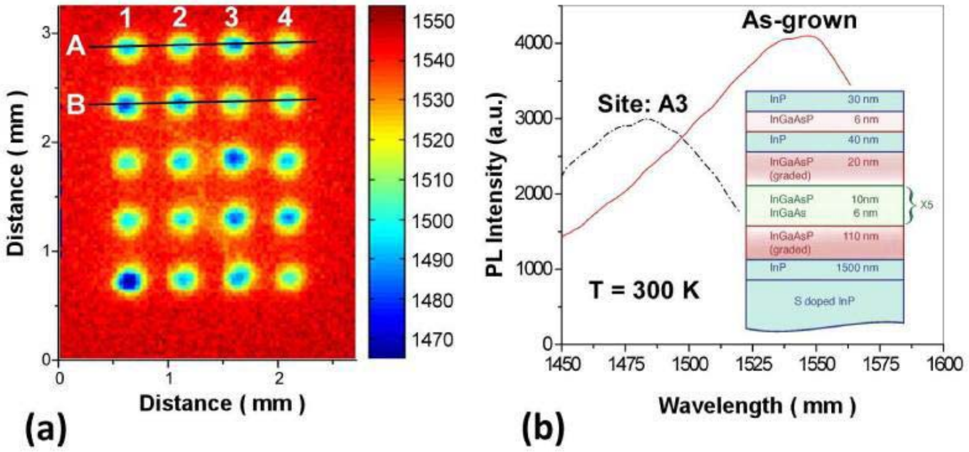

Figure 3: *Photoluminescence (PL) peak wavelength map of an InGaAs/InGaAsP QW wafer with 20 sites of QWI material fabricated by IR Laser-RTA (a), and PL spectra of the as-grown and 70 nm blueshifted (site A3) materials (b) [22]*

Table 1: *Irradiation time and resulting PL peak wavelength emission from InGaAs/InGaAsP QW heterostructures processed by a 3-step IBESA technique [22].*

Point #	Step 1 processing time (s)	Peak wavelength (nm)	Step 2 processing time (s)	Peak wavelength (nm)	Step 3 processing time (s)	Peak wavelength (nm)
A1	27	1488	-	-	4.5	1479
A2	25	1492	3	1485	2	1480
A3	30	1480	-	-	-	1480
A4	20	1504	9	1486	2	1481
B1	30	1480	-	-	-	1480
B2	28	1484	-	-	1.8	1481
B3	23	1497	4	1486	2.1	1481
B4	23	1497	4	1486	2.1	1481

To illustrate the IBESA approach, we requested that all the sites from both rows A and B would emit at 1480 nm, i.e., at the same emission wavelength as A3 and B1. This required additional blueshift amplitudes from 9 to 23 nm. As it can be seen in Table 1, the targeted 1480 nm emission wavelength was achieved following additional two-step processing at A2 and A4, and one-step at A1. Similarly, the targeted 1480 nm emission from the B series sites has been achieved following additional one- or two-step-processing.

These results demonstrate a highly reproducible process capable of controlling the emission wavelength of InGaAs/InGaAsP QW microstructures, between 1550 and 1480 nm. Depending on the application of the investigated material, however, this tuning range could easily be extended to 1320 nm. We note that the wavelength tuning precision of ±1 nm observed in this current experiment is limited by the relatively low spectral precision of room-temperature PL spectra.

As an illustration of the potential of the IR Laser RTA technique in writing arbitrary contours of the QWI material, Figure 4 shows a PL map of a GaInAs/GaInAsP QW sample that was irradiated with the GS controlled position of the Nd:YAG laser beam writing a letter "S". This „watermark' was obtained following 400 passes of the 1.2 W Nd:YAG spot moving at 50 mm/s (4 sec dwell time). The background temperature of the sample during this experiment was maintained at 620 °C [21]. This result was obtained with a conventional IR Laser RTA technique, but it should be pointed out that with this approach, a variety of 2D QWI microstructures could be fabricated with a constant blueshifting amplitude or a position-dependent bandgap by applying the IBESA technique.

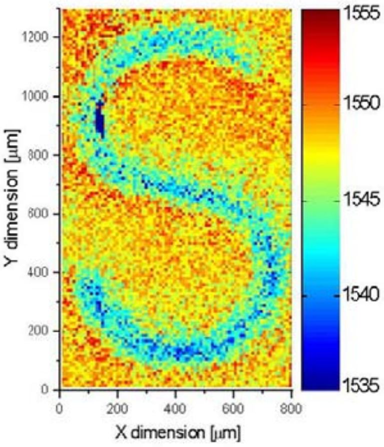

Figure 4: *Photoluminescence map of the IR Laser RTA fabricated S-shape 'water mark' in an InGaAsP/InP QW sample [21].*

6. SUMMARY AND PERSPECTIVES

We have investigated infrared laser based annealing as an alternative bandgap shifting approach designed specifically for trimming the emission wavelength of III-V quantum semiconductor microstructures. The results highlighted in this report illustrate an innovative method of iterative bandgap engineering applied for processing of InGaAs/InGaAsP QW microstructures. The method has the potential for high-precision fabrication of microstructures with almost arbitrary 2D shapes of the QWI material achievable in industrial-size wafers. Also, for arrays of quantum dots separated by the distance exceeding diameter of a thermal zone induced in the IR Laser RTA process (1-10 µm), the IBESA method could be used for trimming of emission wavelength of individual quantum dots.

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