Optics & Laser Technology 51 (2013) 36–42

Contents lists available at SciVerse ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

UV laser induced selective-area bandgap engineering for fabrication of InGaAsP/InP laser devices

Mohammad Kaleem [a,*], Xin Zhang [a], Yuan Zhuang [a], Jian-Jun He [a], Neng Liu [b], Jan J. Dubowski [b]

[a] State Key Laboratory of Modern Optical Instrumentation, Department of Optical Engineering, Zhejiang University, Hangzhou 310027, China
[b] Laboratory for Quantum Semiconductors and Photon-based BioNanotechnology, Interdisciplinary Institute for Technological Information (3IT), Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1

ARTICLE INFO

Article history:
Received 21 November 2012
Received in revised form
12 March 2013
Accepted 16 March 2013
Available online 21 April 2013

Keywords:
Quantum well intermixing
Photonic integration
Semiconductor laser

ABSTRACT

Large bandgap blueshifts in III–V quantum semiconductor microstructures are achievable with UV-laser induced quantum well intermixing (QWI). We report on the application of the UV-laser QWI technique to investigate bandgap engineering of a compressively strained InGaAsP/InP quantum well laser microstructure. The attractive performance of the technique, determined by the ability of a laser to generate point defects, has been demonstrated with bandgap blueshifts reaching 142 nm, with enhancement of photoluminescence intensity. We have also investigated this technique for post-growth wafer level processing designed for the fabrication of laser diodes.

1. Introduction

Integrated optics promises components which will extend the bandwidth and/or switching capabilities of fiber optics communications and provides very rapid information processing between active devices interconnected through low loss waveguides. Integration of devices offers significant improvements in mechanical stability and reliability, as well as device miniaturization [1]. The realization of photonic integrated circuits (PICs) requires spatially selective control over the local optical and electrical characteristics of the multiple quantum well (MQW) material. Many monolithic fabrication techniques have been developed. Selective regrowth and selective area epitaxy are two promising techniques. However, the regrowth techniques require expensive facilities such as metal–organic vapor phase epitaxy (MOVPE) during the fabrication process and yields are usually low. Selective area epitaxy using silica masking allows regions with different bandgaps to be realized across a wafer in a single growth step, but such an approach does not allow complete control of the bandgap in two dimensions [1]. Post growth quantum well intermixing (QWI) is an attractive alternative method to engineer the bandgap of quantum well (QW) semiconductors in which the absorption edge is permanently changed by intermixing the wells and barriers.

Numerous QWI techniques have been developed in the past decades, such as impurity-induced disordering (IID), impurity-free vacancy disordering (IFVD) [1,2], ion implantation induced disordering (IIID) [3,4], argon plasma induced disordering [5] and plasma induced damage during the deposition of sputtered SiO_2 [6]. UV-laser induced disordering (UVLID) QWI technique is one of the promising methods reported in the literature [7–13]. In this technique, point defects are created near the surface of quantum well (QW) chip by UV-laser irradiation, and the diffusion of these point defects downward to the QW region in the rapid thermal annealing (RTA) process leads to large bandgap energy shifts. A top sacrificial layer of InP (e.g. 500 nm thick) is commonly used to serve as a reservoir for laser generated point defects. The exchange of group V species e.g., P and As, and group III species, e.g., Ga and In causes change of potential barrier height and the well width. This leads to blueshifts of the optical absorption edge and formation of a different bandgap QW material. This post-growth wafer level fabrication of multibandgap QW material facilitates active and passive components to be integrated monolithically at relatively reduced costs.

It is known that the absorption of UV-laser radiation by solids can induce disruption to the lattice and lead to the intermixing effect. The bond strength of InP is lower than the bond strength of InGaAs [13]. Thus, by using an InP top sacrificial layer we can achieve higher concentration of point defects with even low UV-laser fluences in the sacrificial layer while the InGaAs surface remains undamaged which is necessary for the fabrication of photonic devices on the QWI altered material. The resulting material can have high optical and electrical quality.

Previous published work [8,12,13] demonstrated blueshifts up to 130 nm using unstrained InGaAs/InGaAsP QW laser structure. In this paper we report superior experimental results with wavelength blueshifts as large as 142 nm in compressively strained InGaAsP/InP QW laser structure using the combination of UV-laser irradiation process and rapid thermal annealing treatment. We show that the

* Corresponding author. Tel.: +86 131 736 55579.
E-mail address: kaleemmuk@yahoo.co.uk (M. Kaleem).

0030-3992/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlastec.2013.03.012

photoluminescence (PL) intensity can be enhanced with reduced linewidth under certain UV irradiation conditions, possibly due to the change of strain distribution in the QW that alters the band structure and enhances the Fermi occupation factor. By using a thick InP sacrificial layer that is removed after UV irradiation and RTA, little surface damage was observed which might affect the device performance. Preliminary results on the application of the UV-laser QWI technique for laser device fabrication are also presented.

2. UV laser QWI in InGaAsP/InP microstructures

The investigated sample of InGaAsP/InP laser structure contains five 1% compressively strained $In_{0.8}Ga_{0.2}As_{0.8}P_{0.2}$ QWs with unstrained 1.25Q InGaAsP barriers. From the surface the layers are a 0.5 μm Zn-doped (10^{18} cm^{-3}) InP sacrificial layer, 0.2 μm Zn-doped (10^{19} cm^{-3}) $In_{0.53}Ga_{0.47}As$ cap, 1.5 μm Zn-doped (10^{18} cm^{-3}) InP cladding, 0.004 μm Zn-doped (4×10^{17} cm^{-3}) 1.3Q InGaAsP etch-stop layer, 0.15 μm Zn-doped (4×10^{17} cm^{-3}) InP cladding, five repeats of 10 nm undoped InGaAsP barrier (λ_g = 1.25 μm) and 5.5 nm undoped $In_{0.8}Ga_{0.2}As_{0.8}P_{0.2}$ QW which are sandwiched by two 0.06 μm InGaAsP step-graded index separate confinement layers with the bandgap wavelength λ_g varying from 1.05 μm to 1.25 μm, and 1.5 μm Si-doped (2×10^{18} cm^{-3}) InP buffer on Si-doped (4×10^{18} cm^{-3}) InP substrate.

A fragment of the InGaAsP/InP wafer was irradiated with a KrF laser (ProMaster OPTEC, ATLEX 300i, λ = 248 nm) delivering 22 ns pulses of fluence in the range of 50–200 mJ/cm^2. The sample was irradiated at room temperature and at normal incidence to the surface. The pulse repetition rate was 10 Hz. The laser beam was not homogenized and the spots of almost rectangular shape were created on the sample surface without using a mask. The *X–Y–Z* positioning of the sample was controlled by a computer. This UV-laser setup allowed for the processing of the same sample at numerous sites, each measuring approximately 600×500 μm^2. After being exposed to the laser, the samples were annealed in a nitrogen atmosphere using an RTA furnace operating at 750 °C for 120 s. During the RTA processing, samples were placed between two Si wafers to prevent desorption of the group V elements. Since numerous sites of the same sample could be processed with different laser parameters, the annealing conditions were the same for different spot sites. The possible damage generated during the UV-laser process was investigated before and after RTA treatment.

The bandgap shifts induced by the above UV-laser procedure were measured using room temperature photoluminescence (PL) measurements. The photoluminescence mapper using a Nd:YAG (yttrium aluminum garnet) laser (λ = 1064 nm) was used as an excitation source along with a photo-detector array built in a spectrum analyzer. The under observation sample was placed on a computer-controlled *x–y* stage, which was moved in 17.5 μm steps. With the computer software collecting data as a function of the *x–y* position, a two dimensional map for the peak wavelength and intensity was measured. For each spot, we first measured the wavelength at the peak position of the UV-laser beam profile and then looked at the corresponding intensity of the same point in the same spot. This procedure is repeated for each spot. The PL spectral peak corresponds to the QW electron–hole recombination peak, which for the as-grown material is obtained at 1553 nm.

Prior to the QW intermixing, we take a thermal stability test with the as-grown sample to determine the blueshift induced by the RTA-only process. The InGaAsP/InP MQW laser sample exhibits bandgap shifts at temperatures as low as 660 °C. The bandgap shift increases rapidly with increasing anneal temperature. The observed bandgap blueshift for RTA-only sample is about 23 nm at 750 °C. It goes up to 30 nm at temperatures above 770 °C. The PL intensity tends to decrease and the peak broadening is observed after the RTA treatment. The thermal interdiffusion is believed to be responsible for the change of the confinement profile and strain distribution in the MQW structure. Furthermore, it is possible that the diffusion of both the dopants (Zn) and surface chemical defects also contributed to the decrease of PL intensity.

Fig. 1 shows the wavelength and intensity map of the PL spectra for QW sample after the combination of UV-laser irradiation and RTA procedures. The PL maps were measured after removing the sacrificial layer and the InGaAs cap layer. For clarity, each spot site of each row is marked with letters and the corresponding data is presented in Table 1. It can be seen clearly that a noticeable large blueshift is achieved with even 50 pulses of UV-laser irradiation. The formation of an array of clearly distinguishable sites of multiple bandgap material took place following the combination of UV-laser irradiation and RTA treatment. Spots were not uniform due to the fact that the UV-laser beam used in this experiment was not uniform.

Table 1 gives the detailed information about the laser irradiation conditions, the achieved blueshifts, the peak PL intensity and the full width at half maximum (FWHM) for each spot shown in Fig. 1. The first three spots (A1–A3) in the first row exhibit wavelength shift of nearly 100 nm. The wavelength shift of about 122 nm is achieved in the 2nd row 1st column spot (A4) of the sample. Similarly, even larger wavelength shift is achieved in the 4th row and onwards which suggests that wavelength shift tends to increase as the UV-laser energy and number of pulse doses increase. The wavelength blueshift is more uniform at greater number of pulses. However, we observe that at maximum wavelength shift, the intensity is slightly reduced. Fig. 1b presents the intensity map of the same sample after UV-laser processing and RTA treatment. The peak intensity of the as-grown sample is 1.92 nW while its linewidth (FWHM) is 93.4 nm. For the RTA-only region, the peak intensity decreases to 1.7 nW while the linewidth is increased to 109 nm. The intensity of the first three spots A1–A3 in the 1st row of the sample is about 2.3–2.7 nW which is much higher than that of the as grown sample as well as the RTA-only region. The linewidth ranges from 75.7 to 80.6 nm, which is also much narrower. Similarly, the 2nd row intensity of all five spots (A4 and B1–B4) is between 2.0 and 2.7 nW which is again much higher and narrower than that of the as grown sample and RTA-only region. Since two spots in the 2nd row overlapped they were repeated in the last row marked as A4⁎ and B1⁎. On average, almost all the rest of the spots exhibit intensity higher than that of the as grown sample and the RTA-only region. We did not use extended parameters of UV-laser energy and the number of pulses knowing that it would lead to the saturation of the wavelength shift and can damage the InGaAs surface which can degrade the performance of photonic devices [11,12]. The compressively strained InGaAsP/InP QW laser structure used here is different from unstrained QW structure in previously reported work [8,13]. The structure used in this experiment also has a thicker sacrificial layer of 500 nm (Zn-doped), and thus a larger reservoir for generating large number of point defects. By using a thick InP sacrificial layer which is removed after UV irradiation and RTA, little surface damage was observed which may affect the device performance.

Examples of 3D PL wavelength and intensity maps have been shown in Figs. 2 and 3 for A1 and B1′ spots, respectively. We can see that most of the PL emission from these spots is located near 1.46–1.47 μm. However, fragments of the central portion of those spots emit at a less blueshifted wavelength of ~1.51 μm. For instance, the maximum and minimum PL intensity of the A1 spot illustrated in Fig. 3b is, respectively, about 2.7 nW and 0.8 nW. This non-uniform distribution of the blueshift amplitude and the intensity within the spot is a finger print of the non-uniform