Selective area bandgap engineering of InGaAsP/InP quantum well microstructures with an infrared laser rapid thermal annealing technique

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ABSTRACT

Fabrication of wafers with built-in areas of different bandgap materials is of paramount importance for the technology of monolithically integrated devices. Numerous approaches have been proposed and investigated in literature to address this problem especially in III-V based-semiconductor microstructures. We report on an innovative technique of post-growth selective area bandgap engineering of InGaAsP/InP quantum well (QW) microstructures that is based on infrared laser rapid thermal annealing (Laser-RTA). The method makes use of a 150 W 980 nm laser for background heating of wafers to just below the threshold for quantum well intermixing (QWI) temperatures. Another infrared source, a 30 W TEM00 Nd:YAG laser, is used to increase the temperature above the QWI threshold that leads to the fabrication of different bandgap material. The Laser-RTA technique allows for a significant reduction in the risk of damaging the surface of a semiconductor wafer heated to high temperature with one laser source. Also, it has the potential to fabricate almost arbitrary shaped lines of bandgap engineered material. For the investigated GaInAsP/InP QW microstructures, we have achieved bandgap shifts in excess of 200 nm. We discuss advantages that the proposed Laser-RTA technique offers in the fabrication of monolithically integrated photonic devices.

Keywords : Quantum well intermixing, laser-induced bandgap engineering, laser direct writing, laser rapid thermal annealing, photoluminescence, InGaAsP/InP quantum well heterostructures

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1 INTRODUCTION

Selective area bandgap engineering of quantum semiconductor heterostructures is the subject of intense investigations due to the potential of this approach in the fabrication of advanced devices and, in particular, photonic integrated circuits (PICs). The challenge is to develop a manufacturing technology capable of cost-attractive delivery of photon emitters and PICs comprising lasers, modulators, waveguides and other active photonic devices. For quantum well (QW) and quantum dot (QD) microstructures, spatially selective intermixing of the QW (QD) and barrier materials, known as quantum well (dot) intermixing (QWI/QDI), has become one of the most investigated methods for selective-area bandgap engineering [1-3]. The common QWI techniques have been based on impurity-induced diffusion [4-6], ion implantation [7] and impurity free vacancy diffusion [8]. Additionally, transient melting of multiple layers by pulsed laser irradiation [9] has been demonstrated to be effective for QWI. Laser annealing has also been used to introduce encapsulant Si into the epitaxial layers and stimulate impurity-induced disordering [10]. Pulsed Nd:YAG laser (λ=1064nm) irradiation through a dedicated mask has been reported to allow the carrying out of the QWI process with lateral resolutions of about 25 μm [11] and 3 μm [12]. All conventional QWI techniques, due to the difficult to control multi-step approach, suffer from a lack of accuracy, which is one of the reasons limiting their industrial applications. Infrared continuous wave (CW) laser has been demonstrated to be an attractive tool for one-step QWI, yielding material that is of high electrical and optical quality [13]. Early results have indicated the feasibility of this approach for writing quantum boxes [14]. However, with the exception of a 4-line array of the QWI material demonstrated in GaAs/AlGaAs samples [15] this approach has not been explored for industrial size wafer level processing.

Our preliminary 3D finite element method (FEM) calculations have indicated the feasibility of a CW laser approach for wafer level bandgap engineering [16, 17]. Here, we report on the results of selective area QWI in GaInAs/GaInAsP microstructures obtained with a CW laser rapid thermal annealing (L-RTA) technique that has been developed for wafer level processing.

2 EXPERIMENTAL SETUP

The experimental setup consists of two infrared laser irradiation sources: a fiber pigtailed (1mm core, NA=0.22) CW GaAs/AlGaAs laser diode (LD), which operates at 980 nm and delivers power of up to 150 W and the second laser source, which is a CW Nd:YAG TEM00 laser operating at 1064 nm and delivering power of up to 30 W. The diameter of the LD spot on the sample can be regulated, typically, between 2 and 25 mm. The role of the LD is to increase the wafer background temperature to near the QWI threshold. A galvanometric scanner (GS) allows to raster the Nd:YAG laser beam over the sample with controlled velocity of 1-4000mm/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 surface. The diameter of the Nd:YAG laser spot used in these experiments was 0.5 mm, but with a special beam delivery optics it is possible to decrease the irradiation spot down to 12 μm in diameter. A low-resolution, custom designed IR camera (IR-CAM) with 640x480 pixels was used to map the semiconductor wafer's temperature. The IR-CAM, which was equipped with narrow band filters to eliminate 980 and 1064 nm radiation from the processing lasers, could collect radiation from the whole 2 inch diameter wafer at the rate of 4 Hz. The minimum temperature that could be monitored with this instrument was about 350 °C. Temperature measurements of the Nd:YAG laser irradiated spots were carried out with a 2-channel fiber optic pyrometer (MIKRON M680). The pyrometer allowed collecting radiation from circular areas of 0.4 and 0.7 mm in diameter. Transient temperature behavior at selected spots irradiated with the laser was carried out at the rate of 10 Hz. The minimum temperature that could be monitored with the pyrometer was about 438 °C assuming the InP material emissivity equal 0.7. The processed samples were held in a room ambient environment. The processed samples were located above a 9 mm x 12 mm opening in a graphite wafer and they were backside irradiated with a 25 mm diameter LD beam.

Room temperature photoluminescence (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 array detector. The PL mapping was carried out with a 10 μm step-resolution.

The InGaAs/InGaAsP microstructure consisted of 5 QWs (6 nm thick InGaAs) and 4 barriers (10 nm thick InGaAsP) material. The topmost QW was coated with approximately 10 nm thick barrier material of InGaAsP and a 70 nm thick InP cap. Both the QWs and barriers were n-type (Si doped at 8x17 cm^{-3}). The microstructure was grown on a 0.375 mm thick InP wafer.

The InGaAsP/InP samples used for determination of the transient temperature behavior and that were used for writing an array of parallel lines of the QWI material had dimensions of 10 mm x 14 mm x 0.375 mm. Samples were capped with PECVD 270 nm thick SiO_2 layers on the polished (front) side, and with 740 nm SiO_2 on the back side. The SiO_2 caps prevented the wafers from decomposition and served as antireflection coatings leading to the increased coupling efficiency of the irradiating lasers on a carbon plate with an opening of 9 x 12 mm. Optical reflection measurements carried out for InGaAsP/InP wafer at 1064 nm have shown that the reflected power decreased from 37 % for a bare wafer down to 10 % for the InGaAsP/InP wafer coated with 264 nm thick SiO_2 layer.

3 RESULTS

3.1 Temperature profiles

To model the L-RTA temperature profiles induced in InGaAsP/InP sample, we carry out calculations for a SiO_2 coated InP wafer ($\varepsilon = 0.7$). Such an approximation is quite reasonable given that the thickness of this wafer (375 μm) significantly exceeds that of the total QW microstructure grown on its top (< 1 μm). Figure 1 presents the experimental and calculated transient temperature behaviour at the center of the InGaAsP/InP wafer irradiated with a CW Nd:YAG laser at 1.7 W and backside heated with a 41 W radiation from a CW 980 nm laser diode. It is worth noticing that the Laser-RTA technique allows for an almost instantaneous increase of the temperature. Also, because it is the wafer that is heated directly, after switching off the laser the temperature to the background decreases very quickly. This behaviour is well reproduced by our 3D FEM calculations. Figure 2 shows temperature profiles along the longer axis of the 10 mm x 14 mm InP sample induced with a 41 W LD (24 mm diameter spot) and a moving spot (0.5 mm) of the 1.2 W Nd:YAG laser. The results have been

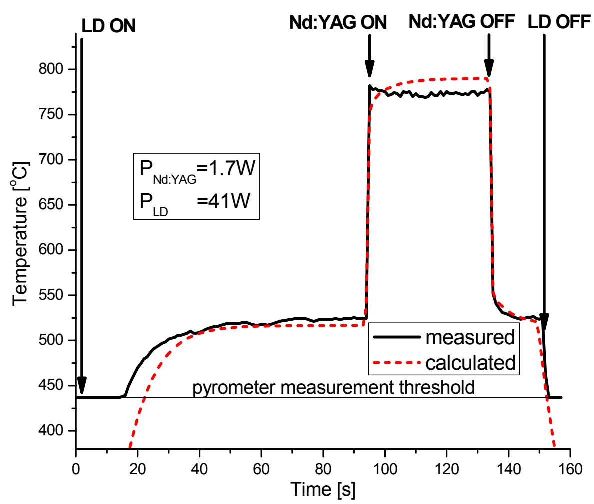

Figure 1 Transient temperature behavior at the center of the InGaAsP/InP wafer irradiated with a CW Nd:YAG laser at 1.44 W and backside heated with a 42 W radiation from a CW 980 nm laser diode. Experimental and calculated results are shown by the solid and broken lines, respectively.

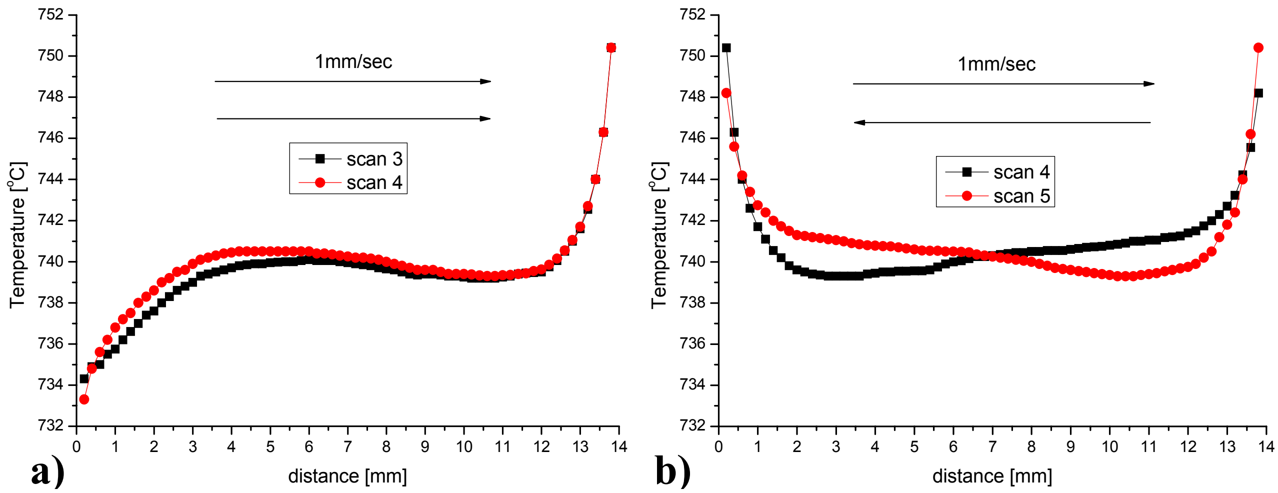

Figure 2 Temperature profiles along the center of an InP sample induced with a 41 W 980 nm LD (24 mm diameter spot) and a spot (0.5 mm) of the 1.2 W Nd:YAG laser moving in one direction (a), and in two directions (b).

plotted for scans repeated in one direction (Fig. 2a) and two directions (Fig. 2b). A one-direction scan indicates that one of the sample edges will be underheated, while the other overheated. Scanning in two directions will result in a more uniform average temperature in the center of the sample. Therefore, we chose the two-direction scan mode in our study of the process of direct laser writing of the lines of the QWI material.

3.2 Experimental results

Figure 3a presents the dependence of the blueshift on the L-RTA induced temperatures at eleven points of the InGaAsP/InP QWI material. Each point has been irradiated for 30 sec with the standard (0.5 mm diameter) Nd:YAG laser beam. During the processing the background temperature was maintained at 550 ^{o}C with the LD irradiation. An example of the profile of the QWI material achieved for the spot annealed at near 780 ^{o}C is shown in Fig. 3b. The 230 nm blueshift can clearly be seen, while the width of the spot is near 300 μm. This indicates that only top portion of the Nd:YAG Gaussian beam induced temperature exceeding the threshold value for QWI. Figure 4 presents a photoluminescence map of a 3 mm x 10 mm fragment of the InGaAsP/InP QW microstructure with five clearly distinguishable lines of the QWI material. The sample's temperature was maintained at 620 °C with the LD delivering 49 W to a 24 mm diameter spot. The lines of the QWI material have been written sequentially with the Nd:YAG laser delivering power of 1.2W. The scanning speed of the laser spot was 1 mm/s. The lines of the QWI material have been

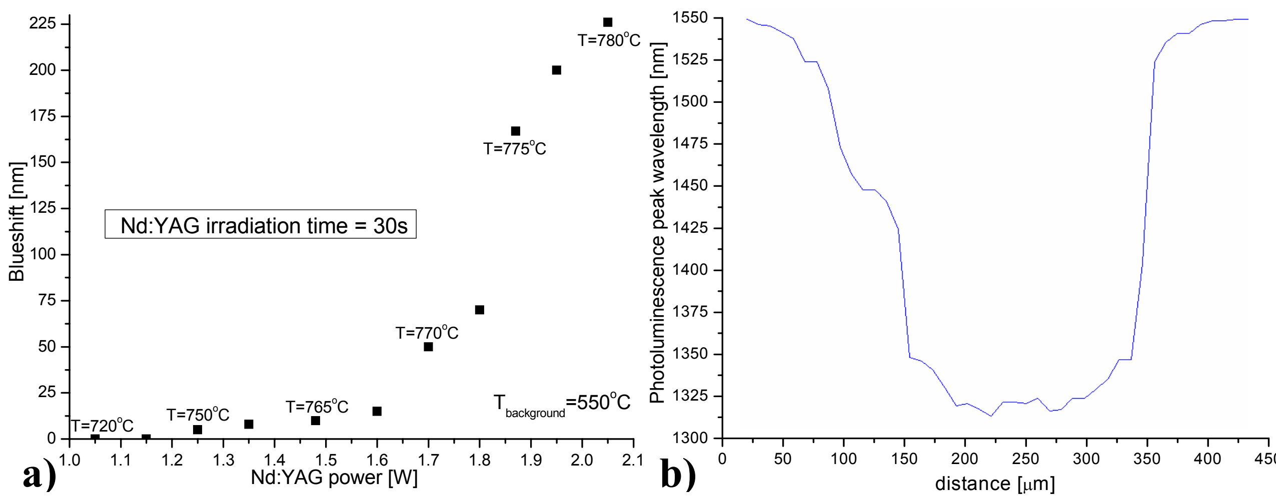

Figure 3 Dependence of the blueshift on the power of the Nd:YAG laser irradiating for 30 sec eleven points of the InGaAsP/InP QW heterostructure a), and a profile of the QWI site that was blueshifted by 230 nm b).

blue-shifted by approximately 15 nm with respect to the 1552 nm emission from the as grown material. Each line, which was fabricated following 20 double passes, is approximately 300 μm wide. The PL peak position in the middle of the QWI line is 1538 ± 5 nm, which compares to 1552 ± 4 nm for the scan across the as-grown material. As predicted by the FEM calculations (Fig. 2b), both edges of the sample have been overheated and show the increased blue-shift amplitude of the QWI material. We expect that the effect of overheating the sample edges could be avoided by using a variable speed Nd:YAG laser beam. This approach will be investigated in our future experiments. The maximum blue-shifted amplitudes that have been observed for each line of the QWI material are at 1535 ±1 nm. This illustrates that the L-RTA technique achieves excellent reproducibility of the annealing conditions.

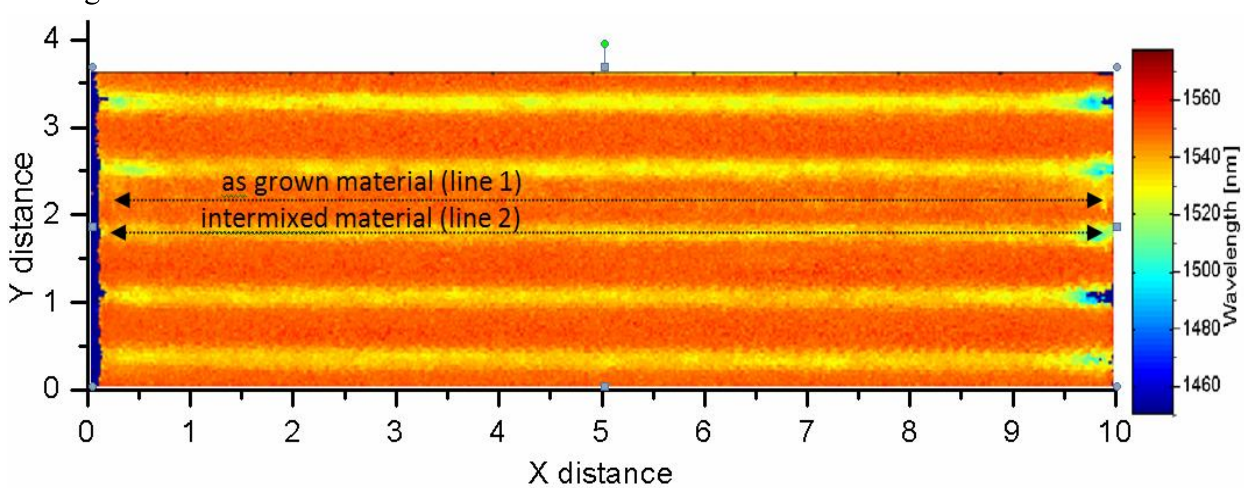

Figure 4 Photoluminescence map of an L-RTA processed InGaAsP/InP QW sample with 5 lines of the intermixed material.

4 CONCLUSIONS

We have developed an innovative Laser Rapid Thermal Annealing (L-RTA) technique for selective area intermixing of QW wafers. The approach is based on the application of a 150 W 980 nm LD and a 30 W TEM00 Nd:YAG laser for simultaneous heating of the back and front sides of the wafer, respectively. The L-RTA technique allows generating the heating rates of semiconductor wafers significantly exceeding those achieved with conventional RTA techniques. The dynamics of the L-RTA process and the ability to anneal arbitrary shape patterns, e.g., lines and circles, are well described using 3D FEM approximation and commercial (COMSOL) software. We have investigated the L-RTA technique for QWI of InGaAsP/InP QW microstructures. With a Nd:YAG laser beam focused to 0.5 mm, an array of 5 lines of the QWI InGaAs/InGaAsP material with its bandgap blue shifted by 15 nm has been successfully fabricated in a 10 mm x 14 mm sample. Each line of the QWI material is approximately 300 μm wide. It is expected that the L-RTA technique will find applications in fine-tuning of the emission wavelength at selected areas of QW and QD wafers.

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