Laser-based Bandgap Engineering of Quantum Semiconductor Wafers

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Abstract: Both laser-RTA (rapid thermal annealing) and UV excimer laser technologies have been investigated for post-growth bandgap engineering of quantum well and quantum dot wafers. The results indicate that this approach has the potential to offer industrially attractive solutions.

Keywords: quantum well intermixing, laser annealing, iterative bandgap tuning, Nd:YAG, excimer laser

1. Introduction

Selective area bandgap engineering of quantum semiconductor wafers is the subject of intense investigation due to the potential of this approach in the fabrication of advanced photonic devices and, particularly, monolithically integrated photonic circuits (MIPCs) [1]. The challenge is to develop an innovative manufacturing technology capable of cost-attractive delivery of MIPCs. A growth/etch/regrowth is the most obvious and frequently employed procedure for that purpose [2]. However, the relatively low manufacturing yield of the same bandgap energy wafers faces an additional challenge related to the added complexity of the growth/etch/regrowth process. 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), offers solutions that are potentially attractive for the manufacture of MIPC-allowing semiconductor wafers. For the period up to 2000, a review of the results reporting the use of the QWI technology for the fabrication of MIPCs can be found in [3]. Since then, a steady number of publications on QWI-made MIPCs has been reported every year as shown e.g., in [4, 5] and references therein. In addition, there has been observed a growing number of reports discussing the intermixing phenomena in QD microstructures [6-9]. Lasers are highly attractive for the post-growth processing of QW and QD wafers due to the ease with which they can modify surface properties and/or temperature of wafers at selected sites. Early results reported both CW and pulse IR laser induced QWI in GaInAsP/InP microstructures. In most cases, these were single-step, $\lambda_0 \rightarrow (\lambda_0 - \Delta\lambda_1)$ bandgap engineering results obtained on individual samples [Marsh]. Processing of industrial size wafers, with bandgap shifted by $\Delta\lambda_1$, $\Delta\lambda_2$, $\Delta\lambda_3$, etc., at selected sites, has yet to be demonstrated.

In 2002, we reported on the IR laser fabrication of a 3 mm long bar comprising a series of nine GaInAsP/InP QW lasers emitting from λ_0 = 1525nm (as-grown material) to λ_8 = 1460 nm [10]. To the best of our knowledge, this was an example of the most advanced MIPC fabricated to date with laser technology. A multi-λ laser emitting device, if fabricated at a commercially attractive cost, could find applications, e.g., in a coarse wavelength division multiplexing (C-WDM) technology [11]. To explore further the IR laser QWI approach for industrial applications, we have developed a new Laser-Rapid Thermal Annealing (Laser-RTA) technique [12].

In 2003, we reported that irradiation of QW semiconductors with UV laser pulses could be used to modify surface properties of the QW microstructure cap and, following RTA step, this could lead to selected area bandgap engineering [13]. The significance of this invention for industrial applications is that it is compatible with wafer level processing by excimer lasers that, for some time already, have been implemented in the manufacturing process of electronic circuits.

This paper highlights the progress we have recently achieved in the area of IR and UV laser based technologies for QW/QD intermixing, and the perspectives of this approach for manufacturing of industrially viable MIPCs.

2. Iterative Bandgap Engineering At Selected Areas Of Semiconductor Wafers

Achieving targeted values of the bandgap energy in selected areas of a QW wafer with a post-growth QWI technique requires a series of experiments to a) describe the characteristics of the process and b) calibrate the parameters of the process with respect to the properties of a QW/QD wafer. Fig. 1a shows a PL map of the 2.5 mm x 10 mm fragment of the InGaAsP/InP QW sample that was processed with a Laser-RTA technique [12]. Five lines of the QWI material can easily be distinguished from the background of the as-grown material emitting at 1552 nm. The maximum blue-shifted amplitudes observed for each line of the QWI material are at 1535 ±1 nm, as illustrated by the cross-sectional PL scan in Fig. 1b. This illustrates that, for the same

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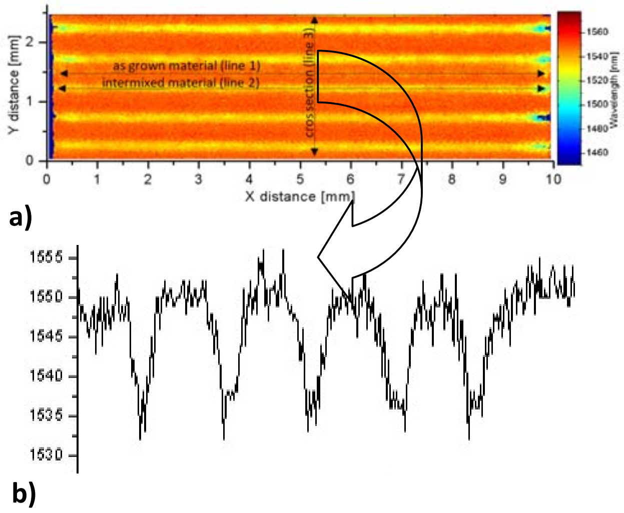

Fig. 1. Photoluminescence map of a series of lines of the QWI material fabricated with the Laser-QWI technique (a) and a cross-section PL scan indicating amplitude of the QWI process (b) [12].

QW wafer, the Laser-RTA technique achieves excellent reproducibility of the annealing conditions. However, due to changing wafer-to-wafer properties, normally, it is difficult to reach targeted values of blue shifts with precision better than 5-10 nm. To address this problem, we have applied the Laser-RTA technique for iterative bandgap engineering at selected areas (IBESA) achieved in a series of steps, each designed for blueshifting not exceeding 2 nm. Collecting PL maps after each step allows verifying the results of intermixing and tune (if necessary), laser power and/or time of irradiation to achieve PL emission at a targeted wavelength. Specially developed image recognition software was implemented to be able relocate the sample returning from the PL mapping back to the original position. Fig. 2 shows an example of IBESA applied for tuning emission wavelength from 4 sites of a InGaAsP/InP QW wafer [14].

a) b)

Fig. 2. Cross-section PL scan through four sites each emitting at different wavelength (a), and the PL scan through the same set of sites, following the 2-step IBESA processing, illustrating the achieved PL emission at 1483 nm [14].

3. Excimer Laser Quantum Well Intermixing Photolithography

Excimer lasers are attractive for QWI as they can be used to pattern wafers in numerous sites with different doses of radiation required for generation of intermixing-enhancing defects. Fig. 3 shows an example of the QWI photolithography process carried out for a GaInAsP/InP QW wafer irradiated with an ArF excimer laser [15].

Fig. 3. Photoluminescence map of a multi-bandgap GaInAsP/InP QW wafer achieved by irradiation with an ArF laser projecting different masks (2.5X demagnification). The as-grown material emits at 1534 nm. The 'fleur-de-lys' and 'maple leaf' sites emit at 1409 nm and the 'S' site at 1470 nm [15].

It should be noted that, depending on the laser and processed QW microstructure, an excimer laser irradiation could be used to suppress the intermixing in selected areas, as reported in [16].

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