Laser-induced bandgap engineering for multicolor detection with a GaAs/AlGaAs quantum well infrared photodetector

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ABSTRACT

Post-growth selective-area laser tuning of quantum well infrared photo-detector (QWIP) material has been investigated as a possible route towards the fabrication of a multicolor low-cost focal plane array device. The method takes advantage of the infrared laser for inducing local temperature of a semiconductor wafer that leads to a spatially selective quantum well intermixing (QWI) process. The wafer consisting of 30-pairs of 6 nm GaAs quantum wells and 35 nm $Al_{0.31}Ga_{0.69}As$ barriers was irradiated by a fast scanning CW Nd:YAG laser beam projecting a total of 12 lines spaced at 0.8 mm. For the chosen pattern, writing scheme and a total power delivered to the sample, a material has been fabricated with 12-regions of distinctly different bandgaps in the range of 790 to 830 nm. Preliminary calculations predict reasonably well the laser-induced temperature profile achieved with a stationary laser beam. However, a more advanced model needs to be developed in order to describe temperature profiles induced with a fast scanning laser beam.

Keywords: quantum well infrared photodetector, multicolor detection, quantum well intermixing, laser processing

1. INTRODUCTION

There has been growing demand for identification of different objects with infra-red (IR) photodetection systems. Two-wavelength IR detection, which has often been used for remote temperature measurements of an object with unknown emissivity [1] has also been explored for identification of some military and civil targets [2]. Highly accurate identification of obscured and camouflaged targets, however, is difficult with only two-color detection and more advanced methods of multiband detection have been proposed and investigated for this purpose [3,4]. Generally, current multispectral systems rely on cumbersome imaging techniques that either disperse the optical signal across multiple IR focal plane arrays (FPA) or use a filter wheel to spectrally discriminate the image focused on a single FPA [5]. Both HgCdTe and GaAs-based technologies have offered the leading edge for IR FPA devices. Advancements in GaAs epitaxial

technologies and attractive properties of GaAs-based quantum well infrared photodetectors (QWIP) have resulted in a significant effort focused on GaAs/AlGaAs QWIP structures and related FPAs. Conventional approaches for 2-color detection typically utilize microstructures comprising stacks of different bandgap materials grown <u>on top of each other</u>. In sequential reading, the different spectral response of such a device is achieved by applying an appropriate bias voltage [6]. In simultaneous reading, different rows of etched microstructures are designed to detect different wavelengths [7]. Multi-bandgap QW material can be obtained by post-growth processing using the quantum well intermixing (QWI) effect. This relatively simple approach has the potential for the fabrication of arrays of multi-bandgap materials aligned <u>next to each other</u> and suitable for simultaneous multiwavelength detection. Recently, red shifting of the QWIP response from 7.7 μm to 8.3 μm has been demonstrated in $GaAs/Al_{0.3}Ga_{0.7}As$ by implementing proton implantation induced QWI [8,9]. Since the high-temperature annealing is a basis of the QWI technique the choice of a laser as a heating source is highly attractive due to the ease with which a laser beam can be delivered to a well-defined spot. Lateral modulation of band levels with a 380-nm period in GaAs/AlGaAs, has been achieved with pulsed-laser heating [10] and laser writing of 70 nm-diameter dots of p-doped GaAs/AlGaAs heterostructures has been reported [11]. Our earlier results have demonstrated the successful use of a CW Nd:YAG laser for writing 100 μm-wide lines of QWI material in InP/GaInAs [12]. We have also demonstrated the feasibility of this approach for writing arrays of two-bandgap material in $GaAs/Al_{0.31}Ga_{0.69}As$ QW microstructures [13]. In this paper, we investigate laser-QWI in $GaAs/Al_{0.31}Ga_{0.69}As$ for maskless fabrication of arrays of multi-bandgap (more than two bandgaps) QWIP microstructures.

2. EXPERIMENTAL DETAILS

The investigated microstructures, which were grown on semi-insulating GaAs by molecular beam epitaxy, consisted of 32 pairs of QW (6 nm GaAs) and barrier (35.3 nm $Al_{0.31}Ga_{0.69}As$) material. Each of the QWs was δ doped with a $9x10^{11}$ cm^{-2} Si spike. Top (411.8 nm) and bottom (771.3 nm) GaAs layers were Si doped to $1.5 x10^{18}$ cm^{-3}. The dimensions of the sample used for writing an array of multi-bandgap material were about 14 mm x 6 mm. The encapsulation with a nominally 200 nm thick layer of SiO_2 was applied to protect decomposition of the sample surface during laser irradiation.

The annealing was carried out with a CW Nd:YAG laser operating at the wavelength of 1064 nm. The near-Gaussian laser beam of 0.8 mm in diameter was slightly focused to achieve a 0.6 mm diameter spot on the sample. Zones of different bandgap materials were created by projecting a 12-line temperature pattern with the beam that was scanned in a zigzag manner, from left to right, using an x-y galvanometric mirror system. The laser beam was scanned at 5 cm/s and the total irradiation time was 80 sec. Test measurements of laser-induced sample temperature were monitored with an infrared pyrometer equipped with optical fiber and a focusing lens, which allowed for collecting the signal from an estimated area of 2 mm in diameter. The average surface temperature induced with the laser beam of power density of 1 W/mm^2 was about 840 ^{o}C (measured for a 3 mm diameter laser spot).

QW photoluminescence (PL) maps were collected at room temperature using an infrared Fourier transform spectrometer PL mapping system, which was equipped with a 980 nm laser diode excitation source. The measurements were carried out with a 10-μm laser spot and in 20 μm steps.

Temperature simulations were obtained by using a 3-dimensional finite element method [14]. Calculations were carried out for a 14 x 6 x 0.375 mm piece of a GaAs wafer assuming the material parameter as listed in Table 1.

Table 1. Material (GaAs) parameters used in the calculations of laser induced temperatures.

Specific heat	Density	Thermal conductivity	Coefficient of absorption at 1064 nm	Reflectivity at 1064 nm
325 J/kg·K	5316 kg/m^3	56 W/m· K	1000 m^{-1}	0.35

## 3. RESULTS AND DISCUSSION

Following the irradiation with a stationary laser beam, and for irradiation times exceeding 10-20 sec, formation of a zone of intermixed material occurred at temperatures exceeding 800 ^{o}C. Figure 1 shows a QW PL map (a) and a plot of the QW PL peak position across the sample (b), which was irradiated for 90 sec with a laser beam delivering power of 1 W/mm^2 [13]. A material with slowly changing bandgap energy is represented by four grey-scale zones. From the center, each of the zones corresponds to the QWI material blue shifted to ~ 795, 805, 812 and 822 nm, respectively, while the as-grown material is characterized by PL peak at ~ 832 nm. The QW PL peak wavelength as a function of the position on the sample, along the longer axis running through the center of the laser-annealed spot is shown in Fig. 1b. From this more quantitative

a)   b)
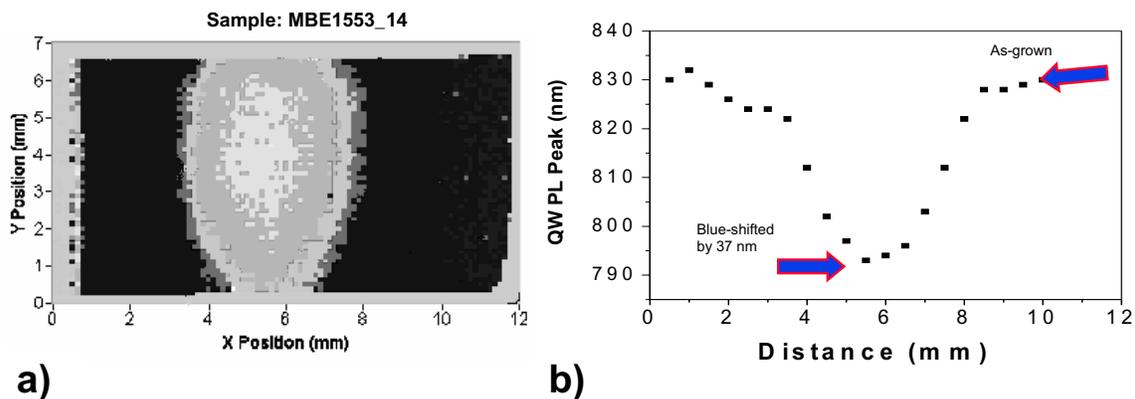
FIG. 1. Quantum well photoluminescence map (a) and QW PL peak position across the sample (b) that was irradiated for 90 sec with a laser beam delivering power of 1 W/mm^2. The contour lines in Fig. 1a) have been plotted for the wavelength increment of 8 nm [13].

description, it can be seen that the material bandgap changed most rapidly, from 822 to 795 nm, in the 2 mm long central portion of the laser-irradiated site. The characteristic oval shape of the zone of the QWI material is related to non-uniform heat dissipation along the shorter axis of the sample. This dimension was only two times greater than the diameter ($\phi = 3$ mm) of the laser spot used in this experiment. The profile of the QWI material fabricated with a laser is expected to be a signature of the laser beam and the method used for achieving temperature requited for the intermixing. For the sample that was irradiated for a total of 80 sec with a fast scanning laser beam (a 0.6-mm-diameter spot) projecting a 12-line pattern, a monotonic decrease of the QD PL peak wavelength was observed from 830 nm for as-grown material (both ends of the sample) to near 790 nm in the center of the sample. Figure 2 shows QD PL peak positions observed along the longer axis of the sample for its center and the right half region. Seven minima at 785, 787, 791, 795, 803, 816 and 824 nm can be distinguished in this plot. The 0.8 mm distance between the minima corresponds to the inter-line spacing that was chosen for the laser written pattern. Although the amplitude of the QW PL peak oscillations is not well preserved across the sample, it varies between 3 and 10 nm, this result demonstrates the feasibility of direct laser writing of multi-bandgap QWI material. In the investigated case, 6 pairs of lines with different bandgap material have been fabricated following a 80 sec exposure to the laser radiation. It is reasonable to expect that significantly narrower lines of the QWI material, as well as more arbitrary patterns should be achievable with more advanced schemes of sample heating and dedicated in-line diagnostics.

The results of temperature profile simulation obtained for the irradiation conditions as described for Fig. 1 are shown in Figure 3. The maximum temperature of 820 °C has been calculated in the center of the laser spot (Fig. 3a), which is in a reasonable agreement with the measured value of 840 °C. The calculations reproduce also reasonably well the elongated shape of the heat zone related to the rectangular shape of the sample (compare with Fig. 1a). We were not able, however, to reproduce the temporal behavior of the sample temperature. As shown in Fig. 3b, the temperature calculated in the center of the laser irradiated zone (solid line) increases continuously to reach the maximum at 90 sec, i.e., at the end of the irradiation. However, the measured temperature (broken line) reached the minimum within the first 10-15 sec, and it
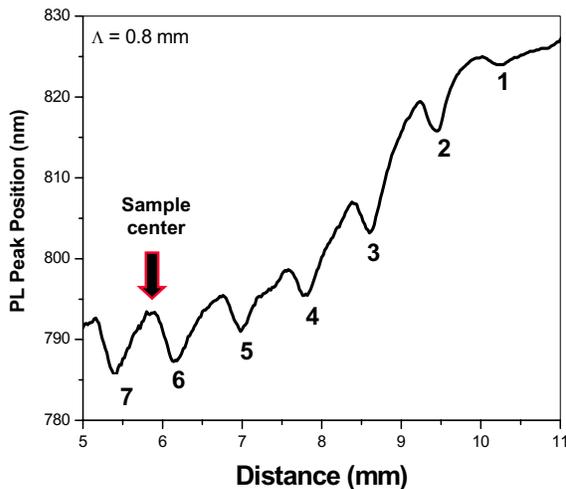
FIG. 2. Quantum well PL peak position measured across the sample irradiated with a fast scanning laser beam that was used to generate a 12-line pattern.
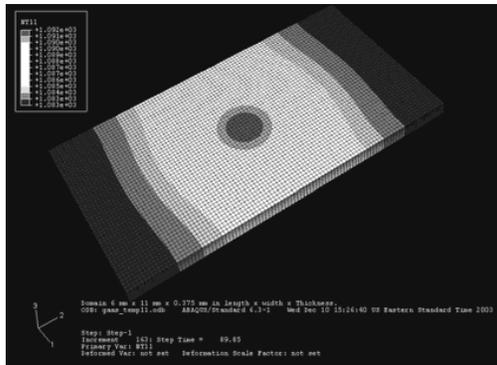
a)
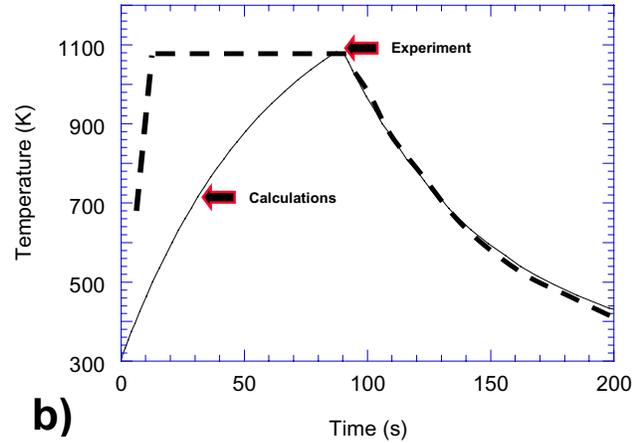
b)

Fig. 3. Calculated temperature profile in a 11 x 6 x 0.375 mm GaAs sample irradiated for 90 sec with a 3 mm diameter laser spot delivering the power of 1 W/mm^2 (a), and a comparison between the calculated temporal behaviour of temperature in the center of the laser irradiated zone (solid line) and temperature determined experimentally (broken line).
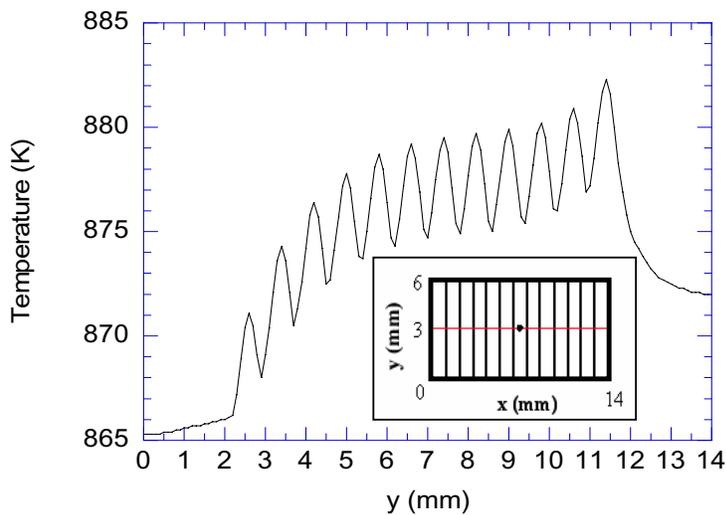
Fig. 4. Temperature profile calculated along the longer axis crossing the center of the sample. A 12-line pattern has been simulated for a spot running in a zigzag fashion from left to right.

remained constant afterward. The most probable reason for this discrepancy is that the calculations assumed a temperature-independent coefficient of absorption. Figure 4 shows the temperature profile calculated along the longer axis running through the center of the sample for the case where a 12-line pattern was generated by irradiating it with a laser spot running in a zigzag fashion. The results correspond to the last irradiation cycle, thus, they show the maximum values of temperatures induced with the laser. The agreement with experimental results of QWI (see Fig. 3) is not adequate. The calculated average temperature of the sample increases from the left to right side (direction of the scan). However, the experimental results indicate it should reach a maximum in the center of the sample where we observed the maximum bandgap blue shift. Also, the QWI results suggest that the overall temperature was reduced at both ends of the longer axis of the sample, while calculations indicate that this took place only at the left end of the sample. Finally, the maximum temperature predicted by the current simulation is about 883 K (610 °C), which is well below temperatures required for inducing the QWI process. Clearly, a more developed model is required for dynamic simulating of laser-induced temperature profiles.

4. CONCLUSIONS

We have investigated Nd:YAG laser-induced quantum well intermixing for maskless and selective area modification of the bandgap of GaAs/$Al_{0.31}Ga_{0.69}$As quantum well infrared photodetector microstructures. An array of 12 lines of the QWI material has been 'written' by fast scanning a slightly focused laser beam for a total of 80-sec exposure time. The most blue-shifted material was characterized by the QW PL peak emission at near 785 nm, which was shifted from the initial wavelength of ~ 830 nm. Other lines of the QWI material were characterized by emissions at 787, 791, 795, 803, 816 and 824 nm. These results demonstrate the feasibility of direct laser writing of multi-bandgap QWI material for manufacturing of a multicolor QWIP photodetector device. Preliminary calculations of laser-induced temperature with a stationary laser beam are in a reasonable agreement with experimental results. However, a more advanced model needs to be developed in order to predict temperature patterns induced with a fast scanning laser beam.

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