Laser-induced selective area tuning of GaAs/AlGaAs quantum well microstructures for two-color IR detector operation

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Selective area laser annealing of GaAs/Al$_x$Ga$_{1-x}$As quantum well infrared photodetector (QWIP) material has been investigated as a possible route towards the fabrication of two-color low-cost focal plane array devices. Tuning of the wavelength response of the material has been achieved as a consequence of the quantum well intermixing (QWI) effect. A 90 s irradiation with a continuous wave Nd:yttrium–aluminum–garnet laser, at the peak temperature of 850 °C, resulted in the 40 nm blueshift of the QW photoluminescence peak from 832 to 792 nm. This corresponded to the 0.7 μm redshift of the wavelength response of the investigated QWIP microstructure in the 8 μm optical absorption region. The amplitude of this shift is consistent with the literature data obtained for similar material processed directly by rapid thermal annealing (RTA) or by a two-step process involving particle implantation and RTA. We have examined the laser-QWI approach for direct writing of arrays of a two-band gap material. The preliminary results indicate the feasibility of this approach for fabricating linear arrays with a period of 0.8 mm.
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I. INTRODUCTION

Two-wavelength infrared (IR) detection is of significant interest for both military and civil applications. Imaging at two wavelengths allows more accurate identification of targets obscured by fumes, fog, and fires.[1,2] Also, two-wavelength detection of a remote target with unknown emissivity makes possible accurate measurements of its surface temperature. 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 focal plane arrays (FPAs). A monolithically integrated two-color QWIP eliminates the need for beam splitters and other optical components required for dual band systems based on dedicated FPA. Conventional approaches for two-color detection typically utilize microstructures comprising stacks of different band gap materials grown on top of each other. In sequential reading, the different spectral response of such a device is achieved by applying an appropriate bias voltage.[3] In simultaneous reading, different rows of etched microstructures are designed to detect different wavelengths.[4] In addition to complicated growth of different band gap materials, either sequential or simultaneous reading has its own drawbacks, such as compromised reading speed or compromised optical fill factor of the device. Multi-band gap QW material can be obtained by postgrowth processing using the quantum well intermixing (QWI) effect. This relatively simple approach has the potential for the fabrication of arrays of two-band gap materials aligned next to each other and suitable for simultaneous two-color detection. Recently, read shifting of the QWIP response from 7.7 to 8.3 μm has been demonstrated in GaAs/Al$_{0.3}$Ga$_{0.7}$As by implementing proton implantation induced QWI.[5] Since high-temperature annealing is the 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[6] and laser writing of 70-nm-diam dots of *p*-doped GaAs/AlGaAs heterostructures has been reported.[7] Our early results have demonstrated the successful use of a continuous wave (cw) Nd:yttrium–aluminum–garnet (YAG) laser for writing 100-μm-wide lines of QWI material in InP/GaInAs.[8] It has been claimed that laser-based QWI could make it possible to modify band gap structure of III–V QW materials on a lateral scale better than 25 μm.[9] In this article, we investigate laser QWI in GaAs/Al$_{0.31}$Ga$_{0.69}$As for maskless fabrication of arrays of two band gap QWIP microstructures. The potential practical advantage of this approach would be in providing a flexible and less expensive method of manufacturing multicolor QWIP FPA.

II. EXPERIMENTAL DETAILS

The investigated microstructures, which were grown on semi-insulating GaAs by molecular beam epitaxy, consisted of 32 pairs of QWs (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 $9\times10^{11}\ \mathrm{cm}^{-2}$ Si spike. Top (411.8 nm) and bottom (771.3 nm) GaAs layers were Si doped to $1.5\times10^{18}\ \mathrm{cm}^{-3}$. A typical dimension of a sample used in this experiment was about 11

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mm×6 mm. The encapsulation with a nominally 200-nm-thick layer of SiO_2 was applied to protect decomposition of the sample surfaces 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 either shaped with the use of an optical expander to give a ~3-mm-diam spot on the sample, or it was slightly focused to achieve a spot of 0.6 mm in diameter. The laser irradiating beam was the only source of heat delivered to the sample. Consequently, due to both the heat dissipation and surface damage threshold (~2 W/mm^2), the sample average temperature could not be repeatably raised to near 700 °C (required for the intermixing process) with laser spots smaller than 0.6 mm in diameter. Sample temperature was monitored with an infrared pyrometer using a focusing lens, which gave an estimated 2-mm-diam detection area. The average surface temperature induced with the laser beam of power density of 1 W/mm^2 was about 840 °C. A stationary and expanded laser beam was used to fabricate a single zone of the intermixed material with its band gap slowly changing across the sample. In order to fabricate zones of alternating band gap materials, a slightly focused laser beam was used to ''write'' periodic temperature patterns using a set of galvanometric mirrors. The two band gap material structure consisted of an array of 12 lines, which were spaced at 0.8 mm. The lines were written at a speed of 5 cm/s for a total exposure time of 80 s.

QW photoluminescence (PL) maps were measured with an infrared Fourier transform spectrometer (FTIR) based room-temperature PL mapping system equipped with a 980 nm laser diode excitation source. The measurements were carried out with 100 and 10 μm spot diameters in normal and high-resolution modes, respectively.

The absorption measurements were carried out with a FTIR BOMEM MB-100 at room temperature. Samples were mounted in a holder that could be adjusted to achieve the irradiation at the Brewster angle. Light was incident onto the sample through a 250-μm-wide slit. A polarizer was used in front of the holder to provide *p*-polarized light used in the measurements.

The PL and intersubband energies were calculated from solutions of the Schrödinger equation, taking into account band nonparabolicity, and assuming a Fickian quantum well interdiffusion model. The IR intersubband transition energies were calculated using an average interdiffusion profile obtained from fitting the PL data.

III. RESULTS AND DISCUSSION

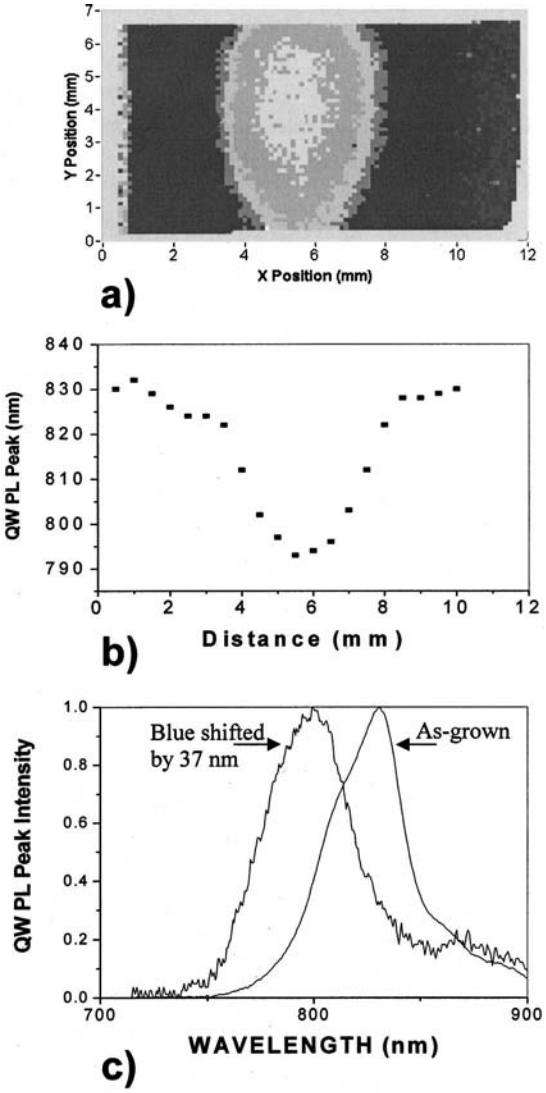

FIG. 1. Quantum well photoluminescence map (a), QW PL peak position across the sample (b), and a comparison between QW PL spectra for as-grown and the most blueshifted materials (c). The sample was irradiated for 90 s with a laser beam delivering power of 1 W/mm^2. The contour lines in Fig. 1(a) have been plotted for the wavelength increment of 8 nm.

Following irradiation with a stationary laser beam, formation of a zone of intermixed material occurred at temperatures above 800 °C and for irradiation times exceeding 10–20 s. Figure 1 shows a QW PL map (a), a plot of the QW PL peak position across the sample (b) and a comparison between PL spectra for as-grown and the most blueshifted material (c) obtained from a 12 mm×6 mm wafer irradiated for 90 s with a laser beam delivering power of 1 W/mm^2. A material with slowly changing band gap energy with four characteristic zones can clearly be identified in Fig. 1(a). From the center, each of the zones corresponds to the QWI material blueshifted to ~795, 805, 812, and 822 nm, respectively. The characteristic oval shape of the zone of the QWI material is related to nonuniform heat dissipation along the shorter axis of the sample, which was comparable to the laser spot diameter (ϕ=3 mm) used in this experiment. 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, which is shown in Fig. 1(b), provides a more quantitative description of the intermixed material. It can be seen that the band gap of the intermixed material changed most rapidly, from 822 to 795 nm, in the 2-mm-long central portion of the laser-irradiated site. This corresponds to a band gap gradient of about 13 nm over the 1 mm distance. The observed profile is a signature of the laser beam used for the irradiation and a more confined region of the

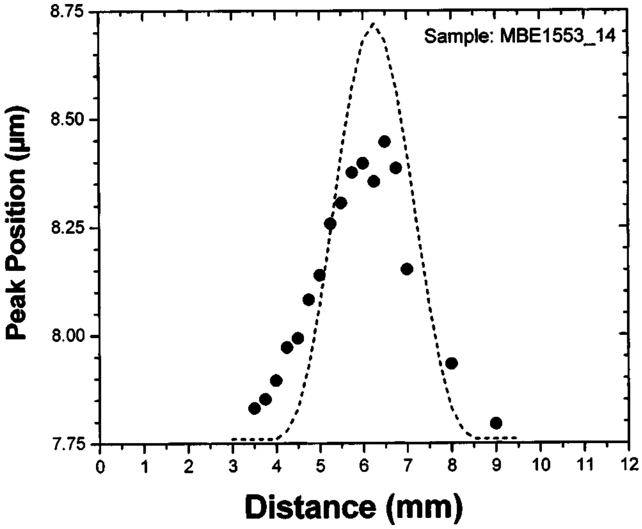

FIG. 2. Position of the intersubband absorption peak across the sample discussed in Fig. 1. The dotted line represents calculated values of the intersubband peak position obtained for interdiffusion coefficients used to fit the PL data.

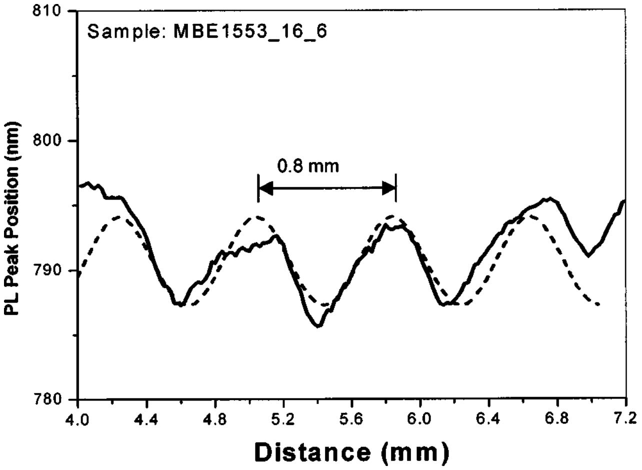

FIG. 3. Quantum well photoluminescence peak position (solid line) measured across the sample irradiated with a laser beam used to write a series of parallel lines. The calculated positions of the quantum well photoluminescence peaks for interdiffusion coefficients changing between 1.44 and 1.0 nm have been shown by the dotted line.

QWI material could be expected for a smaller laser spot. The QW PL peak at ~832 nm characterizes the as-grown material. A comparison between QW PL peaks for the most blueshifted and as-grown materials, which is shown in Fig. 1(c), indicates that the full width at half maximum of the QW PL peak has increased from the initial 76 meV to about 96 meV for the most blueshifted ($\delta\lambda=37$ nm) material. Some of that increase can be explained by the reduced quantum confinement in the QWI material. Calculations of the PL peak position in the intermixed material indicate that the 37 nm blueshift corresponds to an interdiffusion length of 1.05 nm. The increased defect concentration level in the intermixed material and/or nonuniform intermixing due to the temperature gradient in depth of the sample are other possible sources responsible for the QW PL peak broadening. The structural changes could also be responsible for the reduced intensity of the blueshifted PL signal as indicated by the noisier spectrum in Fig. 1(c). Additionally, the laser beam of excessively high power could generate surface defects, which act as PL quenching nonradiative recombination centers.

Figure 2 shows the position of the intersubband absorption peak observed in the sample discussed in Fig. 1. The experimental points (full circles) show a redshift from 7.75 μm (as-grown material) to near 8.5 μm in the center region of the sample. The dotted line represents calculated values of the intersubband transitions obtained for the PL data fitted interdiffusion coefficients. It can be seen that the predicted maximum redshift is near 8.75 μm, which exceeds the measured values by about 0.25 μm. It appears reasonable to link this discrepancy with the limited (250 μm) lateral resolution of the IR absorption measurements. However, increased concentration of defects and nonuniform well-to-well intermixing in the processed material could also lead to such a discrepancy.

The QW PL peak position measured across the sample that was irradiated with a laser beam writing an array of 0.8 mm spaced lines is shown in Fig. 3 (solid line). Four minima at near 785–790 nm indicate location of the lines of the most band gap shifted material. The band gap gradient achieved in this case is about 17 nm/mm. Energy level calculations for the 47 nm blueshifted GaAs/$Al_{0.31}Ga_{0.69}As$ QWIP microstructure suggest that the interdiffusion coefficient is about 1.44 nm, i.e., it represents a modest 25% smearing of the QW-barrier interface. The dotted line in Fig. 3 represents calculated values of the QW PL peak position obtained for interdiffusion coefficients changing between 1.44 and 1.0 nm. The relatively small amplitude of the QW PL peak oscillations (~10 nm) is the result of excessive temperature reached by the nonirradiated material located between the lines. Reducing the spot size of the laser-writing beam and introducing the back heating of the sample could further increase the amplitude, and the related band gap gradient to beyond 17 nm/mm.

IV. CONCLUSIONS

We have investigated Nd:YAG laser-induced quantum well intermixing for maskless selective area modification of the band gap of GaAs/$Al_{0.31}Ga_{0.69}As$ quantum well infrared photodetector microstructures. A 37 nm blueshift of the band gap energy has been induced following a 90 s irradiation with cw power of 1 W/mm^2. This corresponded to a 0.75 μm redshift of the intersubband absorption energy. An array of 0.8 mm period lines of the band gap shifted material has been written by fast scanning a slightly focused laser beam for a total of 80 s exposure time. The most blueshifted material was characterized by the QW PL peak emission near 785 nm, i.e., a 47 nm tuning range was achieved in the single processing step. The amplitude of the periodically oscillating blueshift was only 10 nm, but reducing the spot size of the laser-writing beam and introducing the back heating of the sample could further increase this amplitude. It remains to be demonstrated to what extent modified properties of the processed GaAs/$Al_{0.31}Ga_{0.69}As$ QWIP microstructure could be offset by the gain in the increased functionality and integration level of a device fabricated from such material.

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