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Thermal annealing of lattice-matched InGaAs/InAlAs Quantum-Cascade Lasers

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ABSTRACT

We describe the evolution of optical power, threshold current, and emission wavelength of a lattice-matched InGaAs/InAlAs Quantum-Cascade Laser (QCL) emitting at 13 µm grown by gas-source molecular-beam epitaxy under thermal annealing. Pieces from the same 2-in wafer were annealed at 600 °C, 650 °C, or 700 °C for 1 h; one control piece remained unannealed. No change in threshold current and emission wavelength was observed. The slope efficiency and maximum emission power increase for the 600 °C anneal, but higher annealing temperatures resulted in degraded performance. This result stands in contrast with the observation that strain-compensated structures cannot withstand annealing temperature of 600 °C. Useful information for post-growth processing steps and the role of interface roughness in QCL performance are obtained.

1. Introduction

Quantum Cascade Lasers (QCLs) are the most widely used lasers emitting in the mid-infrared region up to the THz region because their emission wavelengths can be directly engineered by way of the structure design. Strain-compensated materials are used to reach the short-wavelength limit of radiation emission around 3 µm while lattice-matched InGaAs/InAlAs system is the most common material system used for QCLs emitting up to the reststrahlen band. In order to improve the thermal conductance — and therefore performance — of QCLs, etched laser stripes are regrown with electrically insulating InP to allow simultaneous electrical insulation and thermal conductance [1,2]. This step can be carried out using either Molecular Beam Epitaxy (MBE) or Metalorganic Chemical Vapor Deposition (MOCVD). It was demonstrated, however, that the temperatures necessary for MOCVD are incompatible with strain-compensated structures that have a low thermal budget [1]. We propose in this paper to determine the thermal budget of lattice-matched QCL to obtain information about the technologies available for regrowth of InP. Rapid thermal annealing has been used in Quantum Well Infrared Photodetectors (QWIP) to shift the wavelength. It shows a 100 cm^{-1} red-shift on an GaAs/AlGaAs structure for an annealing at 900 °C for 30 s [3]. However, to the best of the knowledge of the authors, a post-growth annealing experiment on a lattice-matched InGaAs/InAlAs to InP Quantum Cascade Laser with temperatures as mentioned in this paper has not yet been conducted.

2. Experiment

A Quantum-Cascade Laser was grown by gas-source molecular beam epitaxy (GSMBE) with all components lattice-matched to the InP substrate following the same active region as in [4]. The lattice mismatch was measured by high resolution X-ray diffractometry and was shown to be below 0.1%. The measured periodicity of the active region strays from the nominal periodicity by at most 2% (worst case scenario, limited by our XRD measurement). The gain region consists of 70 periods of lattice-matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ grown at 400 °C on a 2 in InP:S wafer ($2 \times 10^{17}\ \text{cm}^{-3}$). Immediately below and above the gain region are waveguide layers, each being 360 nm of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$. An upper cladding layer of 2.5 µm InP:Si ($3 \times 10^{17}\ \text{cm}^{-3}$) was followed by 0.6 µm of lattice-matched $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$: Si ($1 \times 10^{19}\ \text{cm}^{-3}$) to act as a plasmon surface. Finally a contact of 0.1 µm of highly doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$: Si ($5 \times 10^{19}\ \text{cm}^{-3}$) was grown. Except for the gain region, the growth temperature was 480 °C. The optimal growth temperature of 400 °C for the active region was derived after [5] where it shows the best results in terms of power and threshold current. The wafer was then cleaved into 4 quarters. One of them acts as reference (480A) while the other three underwent an annealing of 1 h with a temperature ramp of 10 °C/min up to 600 °C (600B), 650 °C (650C), and 700 °C (700D) inside the MBE growth chamber. No rapid thermal annealing was used. Prior to annealing, both sides of the quarters were capped with about 100 nm of sputtered SiO_2 that acts as protective layer to avoid desorption of group V elements during the annealing. After annealing, those 4 quarters were

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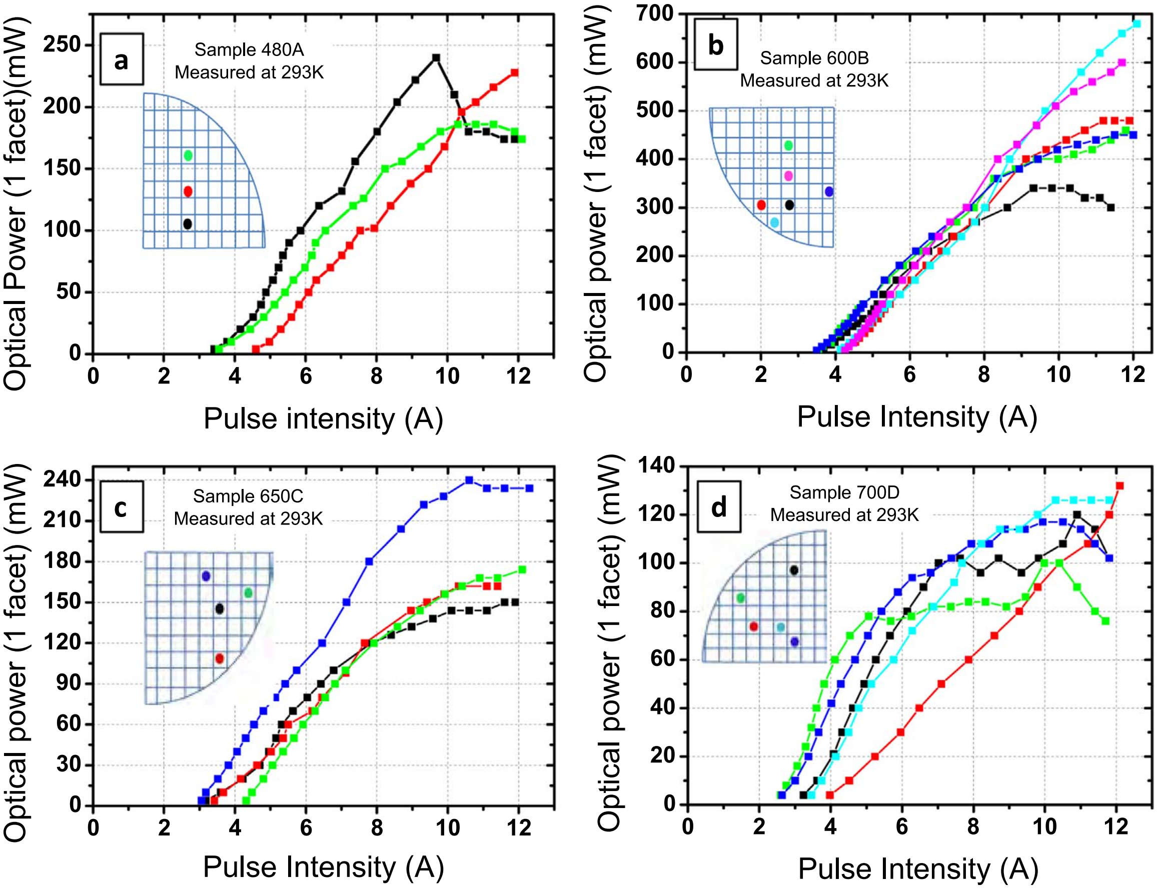

Fig. 1. Peak optical power per facet measured with a RL-3610 Laser Power Meter at room temperature (293 K) with a duty cycle of 0.1% for control quarter (a), quarter annealed at 600 °C (b), quarter annealed at 650 °C (c) and quarter annealed at 700 °C (d). In the inset, for each graph, the relative positions of the measured stripes on the quarter wafer are displayed.

processed into laser stripes of 50 μm × 2.2 mm after removal of the SiO_2 capping layers by a solution of buffered hydrofluoric acid (HF). We opened a 30 μm window on top of the stripe with a negative photoresist which acts as an insulator during the deposition of galvanic indium by electrodeposition. Lasers from different locations on the quarters were characterized in terms of optical emission power (*L–I*), threshold current density, and emission wavelength to ensure uniformity of the results. For the *L–I* measurement the laser strips were driven with 100-ns current pulses at 10 kHz repetition rates. Optical emission spectra for a current of 8.5 A were recorded at room temperature using a Fourier Transform Infrared spectrometer (FTIR) from Bruker (EQUINOX 55). The stripe widths were measured with a scanning electron microscope, allowing an accurate determination of the threshold current densities. The facets of the laser remained as cleaved throughout the experiment.

3. Characterization

The peak *L–I* curves (Fig. 1) show reasonably good uniformity for each quarter. The maximum optical power was recorded for lasers annealed at 600 °C with a maximum peak optical power of 680 mW per facet. The optical power seems to have benefited from the annealing up to 600 °C since almost a twofold increase is recorded with respect to the reference quarter. For annealing temperatures higher than 600 °C, however, the performance is lower than the reference level. The lowest peak optical power is obtained with the 700 °C annealed ones with a decrease of roughly 50% compared to the reference. The threshold currents (Fig. 2), on the other hand, remain unchanged; the small variations observed can be explained by slight variations of stripe width and length. Finally the emission wavelength is not affected by the annealing with all spectra centered at 13 μm (Fig. 3). The shape of the spectra represents various longitudinal modes (e.g., various intersubband transitions) which occur with increasing current, clearly visible on the 650 °C anneal.

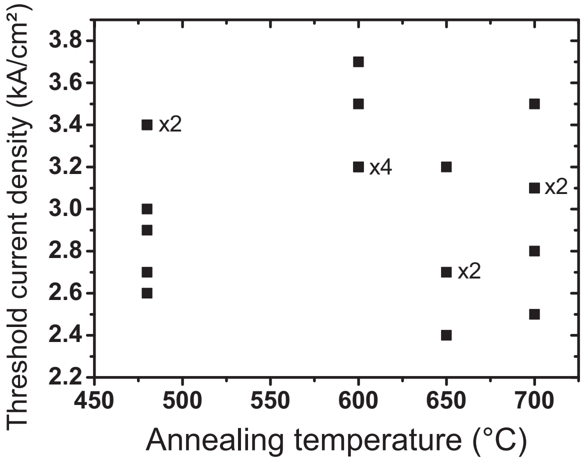

Fig. 2. Threshold current densities measured at room temperature for several stripes for each quarter wafer. The indicators “x4″ or “x2″ indicate the number of points merged at the same value.

4. Analysis

Prior to the experiment, a red shift of the emission wavelength was expected due to material interdiffusion at the interfaces of the quantum