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Fabrication of novel quantum cascade lasers using focused ion beam (FIB) processing.

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Abstract: Focussed ion beam (FIB) processing has been applied to the fabrication of novel InP-based cleaved coupled cavity (CCC) quantum cascade lasers (QCL). Gas assisted etching using XeF2 has been shown to significantly reduce the redeposition of sputtered material onto the mirror surfaces during final milling. For the unprocessed laser a broad spread of lasing peaks are observed between 9.72µm to 9.78µm at a current of 380mA (1kA/cm-2). After FIB processing, substantial side mode suppression is observed on applying a current of 20mA (100A/cm-2) to the short section and the main lasing peak is observed at 9.77µm.

1. Introduction

Recent years have seen spectacular advances in the performance and functionality of III-V semiconductor quantum cascade lasers (QCLs). QCLs have been shown to operate over an unprecedented wavelength range (λ~3.5µm to >100µm), with high temperature, continuous wave operation at mid-infrared wavelengths for InP-based QCLs. The potential of such devices is significant with applications ranging from chemical sensing to free-space optical communications. It has been recently demonstrated that InP based QCL devices can be successfully grown by metal-organic vapour phase epitaxy (MOVPE) [1] [2]. The design of the MOVPE grown devices in this current study have been tailored to give a room temperature emission wavelength around 10.3µm, which corresponds to the absorption line in the infrared spectra of ethene gas, hence providing the potential for ethene gas detection applications. The device is based on a double phonon resonance design [3], with the following four-well active regions

$$\frac{81}{72}/20/35/23/38/65/94/95/58/20$$ (thickness in Å), where the first layer is the injection barrier. The numbers in bold type refers to Al0.52In0.48As barriers and normal type to In0.53Ga0.47As quantum wells, and these compositions are lattice matched to InP. There are 35 repeats of the active regions with appropriate bridging regions linking them together. They are embedded within a doped InP waveguide and grown on an n+ doped InP substrate. The emission from the laser device described above has relatively ‘broad’ lasing features as lasing occurs at several longitudinal modes in the laser cavity. In order for the device to be used for gas sensing applications, it is necessary for it to work under single mode operation. One way to achieve single mode
operation is to make a so called cleave-coupled cavity (CCC) device, which enables a controllable selection of laser modes [4] [5]. This can be achieved by cutting a laser cavity into 2 non-equivalent sections with an air gap between the two sections. The 2 laser segments are electrically isolated, and by providing different drive currents and pulse delays for an individual segment, mode selectivity and tuneable emission can be achieved. In this report, we present the application of focused ion beam (FIB) milling to the fabrication of self-aligned cleaved coupled cavity ridge lasers for single mode operation. We provide an account of the FIB fabrication procedure, subsequent device performance and material characterisation via scanning electron microscopy (SEM) and cross-sectional scanning transmission electron microscopy (STEM).

2. Experimental
FIB processing was performed using an Orsay-Physics CANION 31M plus ion column with a liquid Ga+ ion source operating at 30 keV. Precision milling was achieved using a RAITH ELPHY Quantum Universal SEM/FIB Nanolithography System. A template mask was overlaid onto a FIB captured image and the exact position of the trench defined on the laser ridge. In this instance a trench 10µm wide by 32µm (perpendicular to the laser ridge) and 8µm deep was required with two sections of 365µm and 925µm either side of the air gap respectively. Coarse milling was first of all performed to within ~1µm of the desired dimensions, with the specimen inclined perpendicular to the incident ion beam, using a probe current of ~250pA a dwell time of 5ms and a 0.1µm step size. Each mirror face was then milled in turn by alternating the scan direction using a reduced dwell time of 1ms and step size of 0.05µm. An additional specimen tilt of ±2° was applied at this stage to ensure the final mirror facets were parallel and perpendicular to the surface. Gas assisted etching was also performed during the intermediate and polishing stages using a xenon difluoride precursor. The gas was introduced to the specimen surface using a capillary needle with the chamber pressure maintained at 8x10⁻⁵ mbar. Polishing of the mirror faces was achieved using a lower probe current of ~50pA in addition to the introduction of XeF₂ with typical dwell time and step size of 0.05ms and 0.025µm respectively. Finally, the two sections of the device were electrically isolated by milling a ~1.5µm wide trench through the remaining gold contact. The milling procedures were monitored in real time via a FEGSEM operating at 15 keV. Further structural characterisation was performed in a JEOL 2010F FEGTEM operating in STEM mode. Electron transparent samples were prepared by the FIB ex-situ lift-out technique [6]. For optical characterisation of the device, the sample was soldered onto a copper block heat sink using indium paste and mounted into a liquid helium cooled cryostat. The emission measurements were performed using a FTIR spectrometer with liquid nitrogen cooled MCT detector.

3. Results and Discussion
An overview of the device structure is presented in figure 1(a) showing a bright-field (BF) STEM cross-section through a portion of the upper contact region with the relative position of the QCL multi-layer region labelled “A”. A higher magnification BF-STEM image of part of the QCL multi-layer structure is given in figure 1(b) with the active and bridging regions indicated. Thickness measurements of the active and bridging regions were found to be uniform across the whole layer structure and were in good agreement with the nominal growth parameters. An SEM image of the completed FIB milled trench is shown in figure 2(a). Figure 2b shows a comparison of emission spectra of the pre FIB processed Fabry-Perot (FP) laser with the CCC device. For the FP laser, lasing peaks are observed between 9.72µm to 9.78µm at current of 380mA (1kA/cm²). By applying the same current density to the long section and no current through the short section (spectrum ii in figure 2b), the lasing peaks are found to span across similar range as the FP laser. However, the most intense lasing mode is red-shifted to ~9.73µm, hence, the short section with no applied bias acts as a passive laser mode selector. Substantial side mode suppression (10dB) is observed when applying 20mA (100A/cm²) of current (density) to the short section (spectrum iii in figure 2b), and the main lasing peak is observed at 9.77µm. The side mode suppression can be explained by the fact that
the threshold gain of each laser mode and the effective mirror loss of the cavity can be modulated by varying the bias applied to the short cavity section [5].

Figure 1. (a) STEM (BF) image of a portion of the contact region showing the relative position of the QCL layer structure “A”. (b) Detail of part of the QCL structure with one period of the active and bridging regions labelled.

For the present double phonon sample design, inter-sub-band photocurrent measurements have shown that, the emission wavelength of the long section and absorption wavelength of the short section differ by ~60meV. Consequently, changing the absorption in the short section (by passing current through it) does not significantly affect the loss in this section as the emission from the long section only overlaps the tail of the absorption in the short section. It is expected that larger effects on the CCC emission properties can be achieved by using a QCL design where the emission and the absorption wavelengths are closer in energy.

Figure 2. (a) SEM image of the completed FIB milled CCC device. (b) Emission spectra for: (i) F-P laser (380mA, 1kA/cm^2) (ii) the long section only (280mA, 50ns pulse at 10kHz, J~1kA/cm^2) and (iii) showing side mode suppression after applying a current of 20mA (J~100A/cm^2) (continuous mode) to the short section.

One disadvantage of FIB processing of deep parallel-sided trenches is the undesirable re-deposition of sputtered material from one surface to another during final polishing. Such phenomenon results in the uneven build up of debris over the previously clean surfaces as illustrated in figure 3(a). However, the
application of XeF₂ gas assisted etching can significantly reduce these artefacts as shown in figure 3(b). Although the effect of surface roughness on device performance was not specifically assessed in this current work it is believed that for the devices in question, the unipolar nature of QCLs limits surface recombination effects and the long wavelength of the emission would minimises scatter due to etch ‘roughness’.

Figure 3. Cross-section through the QCL device illustrating the difference in quality of the initially clean mirror surface after the adjacent surface has been milled (a) by conventional ion milling showing the mottled surface due to re-deposition, (b) with XeF₂ gas assisted etching (all other milling parameters constant).

4. Conclusions
We have demonstrated the successful fabrication of InP based cleaved coupled cavity quantum cascade laser using focused ion beam milling. The use of XeF₂ gas assisted milling has been shown to radically reduce the re-deposition of sputtered material from adjacent surfaces onto the finished mirrors during final polishing. For the unprocessed laser a broad spread of lasing peaks are observed between 9.72µm and 9.78µm at a current of 380mA (1kA/cm²). After FIB processing, substantial side mode suppression is observed on applying a current of 20mA (100A/cm²) to the short section and the main lasing peak is observed at 9.77µm.

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