Evaluation of reactive ion etching processes for fabrication of integrated GaAs/AlGaAs optoelectronic devices

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Abstract

Reactive ion etching (RIE) was used for the fabrication of GaAs/AlGaAs optoelectronic devices (laser diodes and photodetectors) for optical interconnect applications. Smooth, vertical sidewalls with a smooth surface at the field were obtained after optimizing RIE conditions in BCl3-formed plasma. Accurate in-situ monitoring of the etching process was realized by laser interferometry end-point detection. This led to good process control and reproducibility of the demanding fabrication of the optoelectronic devices. The RIE etching process did not affect the electrical properties of the device by increasing the surface recombination currents. Lasers with etched mirrors exhibited a threshold current density of 970 A cm⁻², which is one of the best values ever reported. The feasibility of a simple technology for the fabrication of optoelectronic circuits, based on a BCl3 RIE process for laser mirror etching, has been demonstrated. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Reactive ion etching; End-point detection; Laser diodes; Multiple quantum wells; Optical interconnects

1. Introduction

A device patterning technology is required for the fabrication of monolithic integrated optoelectronic circuits. Although wet etching [1] has also been examined, dry etching is becoming the most widely used technique for patterning electronic and optoelectronic devices. Dry etching techniques, such as reactive ion etching (RIE) [1,2], reactive ion beam etching [3], chemically assisted ion beam etching [4,5], inductively coupled plasma etching [6] and electron cyclotron resonance plasma etching [7], offer the advantages of anisotropic etching, improved uniformity and in-situ processing when compared with the traditional patterning of devices using wet etching. However, dry etching usually introduces roughness and/or damage to the semiconductor etched surface, which can affect the electrical and optical properties of the devices. The problem is becoming very critical when demanding processing steps are performed, like the formation of mirrors for laser diodes. Even though RIE is the simplest among the aforementioned dry etching techniques, the efforts of making etched mirror lasers have been directed towards the more sophisticated, complex and expensive dry etching techniques [3–7] that use chlorine chemistry processes based on Cl₂ [2–4], mixtures of Cl₂ and BCl₃ [5,6], or Cl₂ and Ar [7].

In this work, we present, for the first time, the fabrication of GaAs/AlGaAs mirrors using a conventional RIE system and an optimized pure BCl₃ process.

2. Experimental procedure

Molecular beam epitaxy (MBE) was used for growing AlGaAs p/i/n laser diodes, with GaAs quantum wells (QWs) in the i-region. For comparison purposes, a GaAs p/i/n structure with 0.5 µm thick i-region was also grown. All structures were grown on n⁺-GaAs substrates. The GaAs test structure was processed as a photodiode using standard photolithographic techniques. The processing procedure involved the follow-
The formation of p-ohmic contacts (Pt/Ti)/Pt/Au, which had ring geometry with 720 μm outer diameter and 520 μm inner diameter, was followed by rapid thermal annealing at 410°C for 1 min. (ii) The formation of mesa (diameter, 720 μm), either by wet etching in CH₃OH:H₃PO₄:H₂O₂ solution or by dry etching in a RIE parallel plate reactor (Vacutec AB) using chlorine-based gases. The RIE system was equipped with Laser Interferometry (900 nm) and charge-coupled device (CCD) camera (Jobin Yvon-Sofie) for in-situ monitoring of the etching process. (iii) The formation of n-ohmic contacts (Ge/Au):Ni/Au, which was followed by rapid thermal annealing at 410°C for 20 s.

The etched-surface morphology of the devices was examined by scanning electron microscope (SEM) and the ideality factor of the diodes was extracted from the dark current–voltage (I–V) characteristics monitored in the Biorad DL4600 Polaron system. Also, the optimized RIE conditions were applied for the realization of edged-mirror lasers, the performance of which was measured using 2.3 μs duration pulses at 20 kHz frequency.

3. Experimental results and discussion

3.1. RIE conditions optimization

One of the most demanding process for the fabrication of etched mirrors on GaAs/AlGaAs structures by RIE is the process that will yield anisotropically etched walls as well as similar etch rates for GaAs and AlGaAs for obtaining smooth etched mirrors. The anisotropic and smooth etching of chlorine-based gases was examined both on GaAs and AlGaAs layers as well as on the structures used in this work.

The use of pure Cl₂ gas (3 sccm, 5 mTorr, 75 W) resulted in faster etching of GaAs over AlGaAs by 1.5 times, with rough sidewalls. A further increase in total pressure and power resulted not only in increased etch rate, but also in the formation of HCl vapours in the chamber. The use of boron trichloride (BCl₃) as etching gas resulted in smooth, vertical sidewalls and no HCl vapours as by-products. The anisotropic etching obtained with a 50 W power BCl₃ RIE recipe (10 mTorr total pressure and 10 sccm BCl₃) gave equal etch rates for GaAs and AlGaAs, and produced smooth sidewalls. By increasing the BCl₃ flow from 0.2 to 2 sccm and then to 10 sccm, the ratio of AlGaAs to GaAs etch rate was reduced from 1.35, to 1.20 and then to 1.05, respectively. Similar results were obtained by reducing the power to 25 W. Typical mirrors obtained are shown in the SEM photographs of Fig. 1. The etch rate was 23.5 nm min⁻¹, whereas the selectivity of the photoresist mask over the etched material was 1:50. No improvement was achieved by using mixtures of Cl₂ and BCl₃ gases. The addition of Cl₂ in the aforementioned optimized BCl₃ recipes resulted in alternate rough and smooth sidewall regions, attacking, at the same time, the photoresist mask with higher rate than that obtained when only BCl₃ was used.

The laser interferometry with the CCD camera, with which the RIE system was equipped, was used as an in-situ method of etch-rate determination as well as heterolayer identification, end-point detection and observation of the quality of the surface morphology on the field [8,9]. A typical example is shown in Fig. 2, where the laser interferometry signal is plotted as a function of etching time during the optimized etching process for the formation of mirrors in the p/i/n laser structure seen in Fig. 1. Table 1 presents the structure layers as grown by the MBE as well as the structure layers as ’seen’ by the laser interferometry (L.
The optimized RIE conditions were applied for the fabrication of laser diode and waveguide photodetector, both having the same MBE structure. The structure is that presented in Table 1. Such a fully processed optoelectronic configuration is shown in the micrograph of Fig. 3, where the RIE-etched mirror of the photodetector can be seen. The performance of a p/i/n AlGaAs laser diode with 4 QWs in the i-region and with RIE-etched mirrors was examined. The device had a 10 μm wide ridge, a 250 μm length and around 3 μm deep etched mirrors. The optical emitted power as a function of injected current density of the laser diode is seen in Fig. 4. The threshold current density was 970 A cm$^{-2}$.

The value of 970 A cm$^{-2}$ is one of the best values ever reported for dry-etched mirrors [6,7] and indicates that good-quality lasers can be fabricated by a simple and low-cost RIE system using pure BCl$_3$ gas.

### 4. Conclusions

Reactive ion etching was used for the fabrication of GaAs/AlGaAs optoelectronic devices (photodetectors and laser diodes). Smooth, vertical sidewalls with a smooth surface at the field were obtained after optimizing RIE conditions in BCl$_3$-formed plasma. Accurate in-situ monitoring of the etching process was realized by laser interferometry, which could be used for end-point detection. This led to good process control and reproducibility for the fabrication of the optoelectronic devices.

GaAs p/i/n test photodiodes, with mesa fabricated by RIE or wet etching, exhibited similar ideality factors,
indicating that RIE etching does not affect the electrical properties by increasing the surface recombination currents.

An optimized BCl₃ RIE process was developed for the fabrication of smooth and vertical facets. Lasers with etched mirrors exhibited a threshold current density of 970 A cm⁻², one of the best values ever reported.

This work has demonstrated the feasibility of the RIE process, based on BCl₃, for laser mirror etching and for the fabrication of optoelectronic circuits.

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References