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

E. Aperathitis [a,*], D. Cengher [a], M. Kayambaki [a], M. Androulidaki [a], G. Deligeorgis [a,b], K. Tsagaraki [a], Z. Hatzopoulos [a,b], A. Georgakilas [a,b]

[a] *Microelectronics Research Group, Institute of Electronic Structure and Laser, Foundation for Research and Technology, P.O. Box 1527, 71110 Heraklion, Crete, Greece*

[b] *Physics Department, University of Crete, Heraklion, Crete, Greece*

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 BCl_3-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 BCl_3 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 Cl_2 [2–4], mixtures of Cl_2 and BCl_3 [5,6], or Cl_2 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 BCl_3 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-

* Corresponding author. Tel.: +30-81-394105; Fax: +30-81-394106.

E-mail address: eaper@physics.uoc.gr (E. Aperathitis).

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ing. (i) 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 CH_3OH:H_3PO_4: H_2O_2 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 Cl_2 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 (BCl_3) as etching gas resulted in smooth, vertical sidewalls and no HCl vapours as by-products. The anisotropic etching obtained with a 50 W power BCl_3 RIE recipe (10 mTorr total pressure and 10 sccm BCl_3) gave equal etch rates for GaAs and AlGaAs, and produced smooth sidewalls. By increasing the BCl_3 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 Cl_2 and BCl_3 gases. The addition of Cl_2 in the aforementioned optimized BCl_3 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 BCl_3 was used.

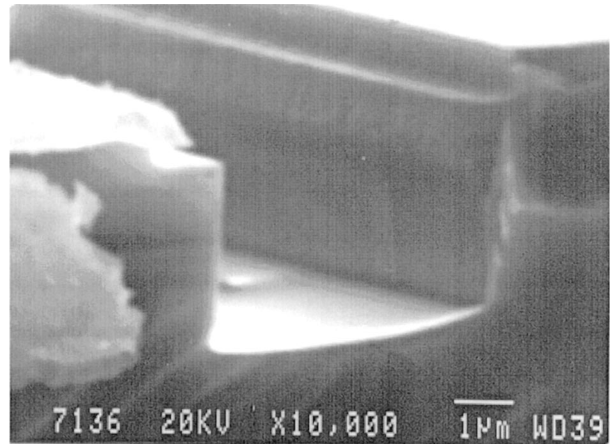

Fig. 1. SEM photograph of two adjacent devices formed by the optimized RIE conditions.

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.

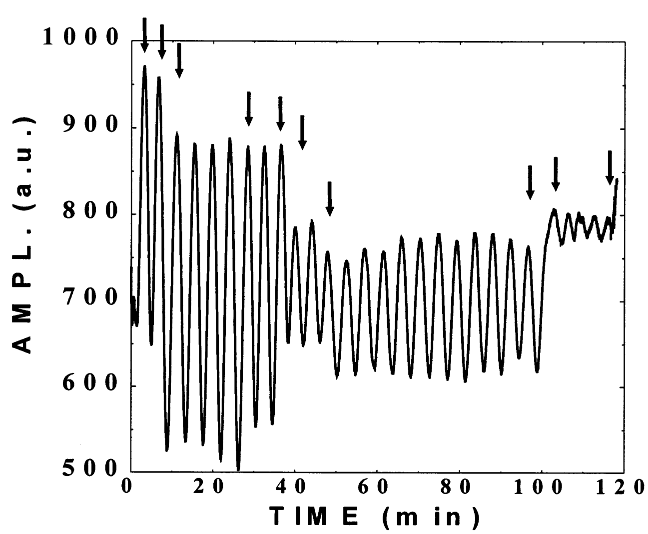

Fig. 2. Laser interferometry signal as a function of etching time for the laser structure of Table 1. The arrows denote heterointerfaces (see Table 1).

Table 1
Details of the laser structure as grown by MBE and as 'seen' by laser interferometry (LI) during reactive ion etching

LASER STRUCTURE AS GROWN BY MBE			LASER STRUCTURE AS "SEEN" BY LI
Layer	Al content	Thickness [μm]	LI Signal peaks
p+ GaAs	0.00	0.15	Peaks 1^{st} – 2^{nd}
p AlGaAs	0.00->0.45	0.1	Peaks 2^{nd} – 3^{rd}
p AlGaAs	0.45	0.6	Peaks 3^{rd} – 7^{th}
p. AlGaAs	0.26	0.24	Peaks 7^{th} – 9^{th}
p AlGaAs	0.26->0.2	0.05	
4x			
AlGaAs/GaAs	0.20 / 0.00	0.0050 / 0.0080	Peaks 9^{th} – 10^{th}
AlGaAs	0.20	0.0050	
n. AlGaAs	0.2->0.26	0.05	Peaks 10^{th} – 12^{th}
n AlGaAs	0.26	0.24	
n AlGaAs	0.26->0.45	0.1	
n AlGaAs	0.45	0.25	Peaks 12^{th} – 23^{rd}
n AlGaAs	0.45	1.30	
n+ AlGaAs	0.45->0.0	0.1	
GaAs buffer layer	0.00	0.1	Peaks 23^{rd} – 24^{th}
GaAs substrate	0.00	400	Last five small peaks

Richeboeuf, J. Yvon-Sofie, private communication) and these layers are denoted by the arrows above the interferogram of Fig. 2. The signal shape is an indication of the interface quality of the MBE-grown structure, the constant etch rate during etching through the structure down to and/or into the substrate, and consequently very good end-point detection control. Interferograms like that shown in Fig. 2 ensure the smooth surface morphology on the field during the whole etching process time.

3.2. Electrical characterization

The damage that might have been introduced during dry etching was examined by monitoring the I–V characteristics of three p/i/n GaAs diodes that had their mesa formed differently. The mesa of diode P274DE1 was formed using the optimized RIE processed of 10 sccm BCl_3, 10 mTorr total pressure and 25 W power. The mesa of diode P274DE2 was formed using the same RIE process but at 50 W power, which reduced the etch rate by almost one-half of that of diode P274DE1 and thus increased, almost twice, the etching time. The etching process of these devices was monitored using the laser interferometry end-point detection system. The third diode, P274WE, was performed by wet etching. The saturation current for all three diodes, deduced from the I–V curves, was between 3×10^{-12} and 5×10^{-12} A. The best ideality factor, $n=1.96$, was obtained for the P274DE2 diode, whereas the other two diodes showed almost the same ideality factor, which was 2.04 for P274DE1 and 2.01 for P274WE. The almost 4% difference in the ideality factor values of the diodes clearly demonstrates that RIE does not introduce any surface damage that can drastically affect the electrical properties of the device through increased surface recombination currents.

3.3. Laser diode characterization

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,

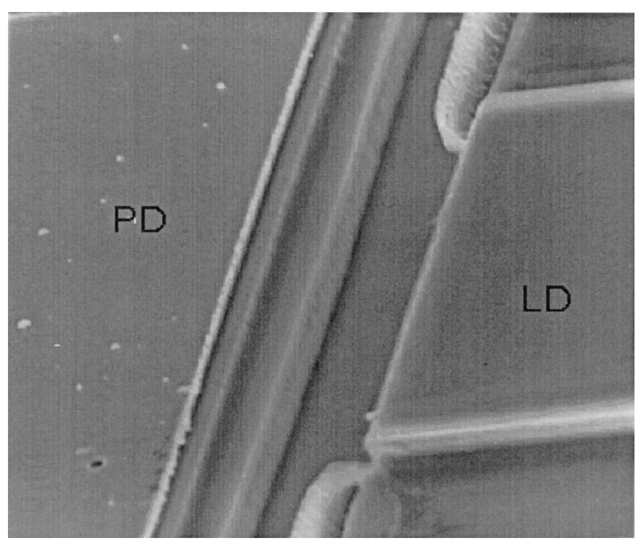

Fig. 3. SEM photograph of a laser diode (LD) next to a waveguide photodetector (PD) with RIE-edged mirrors. The distance between the mirrors is 5 μm.

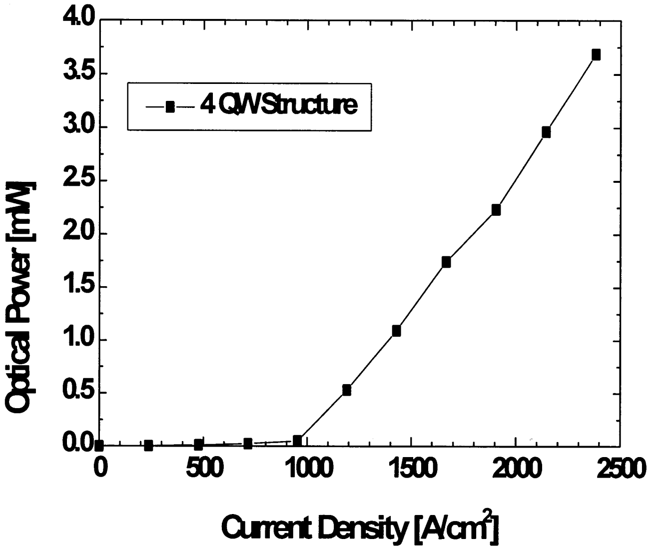

Fig. 4. Measured emitted power as a function of current density of a 4-QW laser diode, with RIE-etched mirrors.

indicating that RIE etching does not affect the electrical properties by increasing the surface recombination currents.

An optimized BCl_3 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 BCl_3, for laser mirror etching and for the fabrication of optoelectronic circuits.

Acknowledgements

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