FOCUSED ION BEAM ETCHING OF GaN

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ABSTRACT

We have investigated the use of focused ion beam (FIB) etching for the fabrication of GaN-based devices. Although work has shown that conventional reactive ion etching (RIE) is in most cases appropriate for the GaN device fabrication, the direct write facility of FIB etching – a well-established technique for optical mask repair and for IC failure analysis and repair – without the requirement for depositing an etch mask is invaluable. A gallium ion beam of about 20nm diameter was used to sputter GaN material. The etching rate depends linearly on the ion dose per area with a slope of $3.5\times10^{-4}\mu m^3/pC$. At a current of 3nA, for example, this corresponds to an etch rate of $1.05\mu m^3/s$. Good etching qualities have been achieved with a side wall roughness significantly below 0.1μm. Changes in the roughness of the etched surface plane stay below 8nm.

INTRODUCTION

Tremendous effort has been made in recent years in developing GaN-based devices due to their wide spectrum of potential applications ranging from short-wavelength light emitters and lasers, solar-blind detectors to high temperature devices [1–4]. GaN-based devices reported to date have mostly been fabricated using reactive ion etching (RIE) [5]. RIE-etched side walls, however, often suffer from a significant surface roughness, which is a major concern, e.g., for laser diodes since optical losses in the laser end mirrors increase the threshold current. Because of the difference in the cleavage plane between GaN (1100) and the commonly used sapphire substrate (1102) it is difficult to achieve flat cleaved end mirrors. The development of improved etching techniques is therefore essential to enhance the performance of GaN-based devices [6–8]. Furthermore, it will be necessary to find etching techniques which allow the fabrication of GaN on the nanometer scale for the development of novel device structures,, e.g., for integrating laser diodes with wavelength selective electro-absorbers [7].

Focused ion beam (FIB) etching is not only the most promising technique for the fine patterning of GaN-based devices, but also for improving the quality of laser facets. A focused gallium ion beam of 5-20nm size is used in FIB to sputter material. The direct write facility of focused ion beam (FIB) etching – a well-established technique for optical mask repair and for IC failure analysis and repair – without the requirement for depositing an etch mask is invaluable. This allows the nanometer scale fabrication of nitride devices. Focused ion beam (FIB) etching has also great potential for the post-processing of devices and has been successfully applied to achieve polarization control in red GaAs-based vertical cavity surface emitting lasers (VCSELs) [9,10]. In this report, we determine basic parameters for the FIB-etching of GaN. We investigate the quality of FIB-etched GaN structures using atomic force microscopy and scanning electron microscopy.

EXPERIMENT

GaN layers, 1.2µm thick, were grown by metalorganic vapor phase epitaxy (MOCVD) on sapphire substrates. The layers were unintentionally n-doped with a carrier concentration of $6\times10^{17}cm^{-3}$ and a carrier mobility of $360cm^2/Vs$. Patterns were etched in the GaN layer using a focused gallium ion beam of 20nm diameter size. The instrument used comprises an FEI focused gallium ion gun with a magnetic sector mass analyser, a Thornley Everhard secondary electron detector and peripheral components. It enables the user to capture an image of the sample at high magnification using the scanned focused ion beam and secondary electron detector, and then to delineate or import arbitrary patterns in two dimensions to be etched into the specimen with the same beam.

Furthermore, an integrated mass spectrometer, a double-focusing electric and magnetic sector unit, can be used to provide secondary ion mass spectrometry (SIMS) analysis, and so the instrument can be employed as an analytical tool in its own right, or the SIMS detector can be used to provide end-point detection during etching, particularly on devices with multi-layered structures. The spatial resolution of the system is below 100nm at 50pA; the main component limiting the available resolution being noise and vibration. The spectral resolution of the SIMS detector is $M/\Delta M=2000$.

The fabricated samples were investigated using an atomic force microscope from TopoMetrix and a JEOL-6400 scanning electron microscope to determine the etch depth and surface roughness of the fabricated GaN structures.

RESULTS AND DISCUSSION

Square patterns of about 7µm size were etched in the 1.2µm-thick-GaN layer by FIB at different Ga-ion doses. Figure 1 displays the secondary-electron image of the specimen after

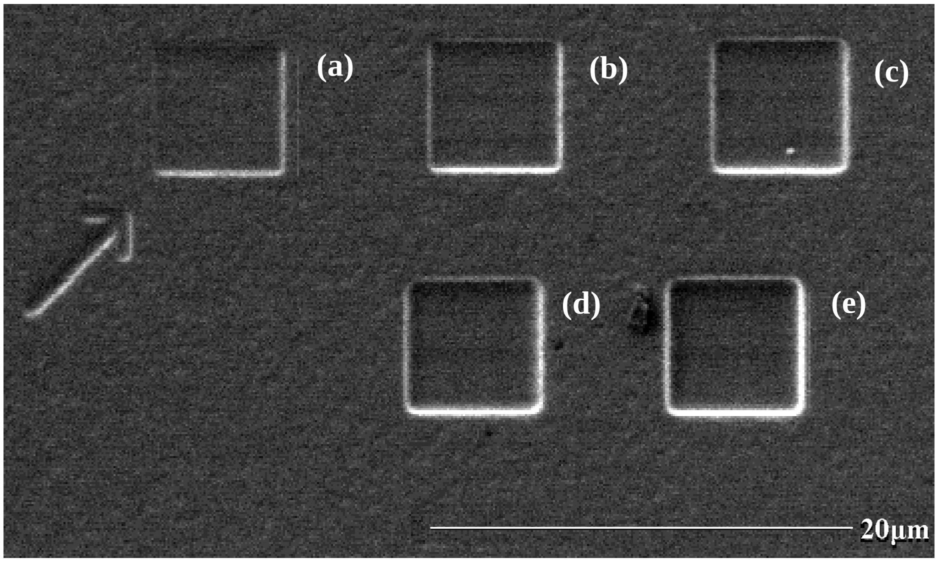

Figure 1: Focused ion beam (FIB)-etched pattern in GaN layer, fabricated using Ga-ion doses of (a) 500, (b,d) 1000, (c) 1500, and (e) $2000pC/\mu m^2$.

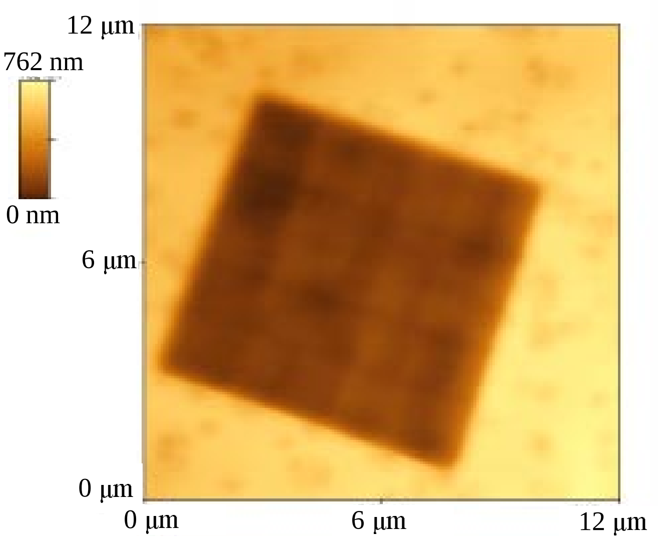

Figure 2: Atomic force microscopy (AFM) image of FIB-etched structure in GaN.

the etching, obtained while scanning the Ga-ion beam over the sample surface at a very low dose. The individual square patterns were etched with ion doses of: (a) 500pC/μm^2, (b,d) 1000pC/μm^2, (c) 1500pC/μm^2, and (e) 2000pC/μm^2. The pattern (b) and (d) were etched at a different current, 1nA and 3nA, respectively. Note that no etch mask is necessary for the etching. The pattern is written directly onto the specimen by scanning the 20nm-wide gallium ion beam over the sample surface. This direct write facility of focused ion beam (FIB) etching is illustrated by the etched arrow on the left side of Figure 1. The etched lines of the arrow are less than 1μm wide. The achievable minimal line width is only limited by the diameter of the gallium ion beam and the vibrational stability of the FIB-instrument.

Increasing the gallium-ion dose results in an increasing etch depth in the GaN layer as seen Figure 1. Atomic force microscopy (AFM) images were recorded from the various square patterns to determine the etch depth as function of ion dose. Figure 2 shows an AFM image of the etched pattern (e) of Figure 1. The determined etch depth as function of gallium ion dose per area is displayed in Figure 3. The etching rate depends linearly on the gallium-ion dose with a slope of 3.5x10^{-4}μm^3/pC. At a current of 3nA, for example, this corresponds to an etch rate of 1.05μm^3/s. We note that the etching rate shows a minor dependence on the gallium-ion currents used. Figure 3 shows the results obtained at a low gallium-ion current. Increasing the current from 1nA to 3nA at a constant dose of 1000 pC/μm^2 in Figure 1 (b,d), i.e., decreasing the etch time, results in an decrease in the etching rate by about 10-20%. The underlying mechanism is currently not known and is part of ongoing investigations.

Figure 4 shows the change in the RMS roughness of the GaN surface after etching, i.e., inside the etched square pattern in Figure 1, as function of the gallium ion dose, determined from the AFM images to evaluate the quality of the FIB etching of GaN. The RMS surface roughness increases up to gallium ion doses of 1000pC/μm^2, however, saturates at higher ion doses. Note that the RMS roughness of the GaN layer is only 8nm larger after the FIB etching at a dose of 2000pC/μm^2 than on the as-grown sample (RMS=17nm).

Figure 5 shows a scanning electron microscopy image of an edge of a deep square pattern etched by FIB at a gallium-ion dose of 3000pC/μm^2 at a current of 3nA. The image allows us to estimate the obtained side wall roughness achievable with FIB. The side wall roughness stays

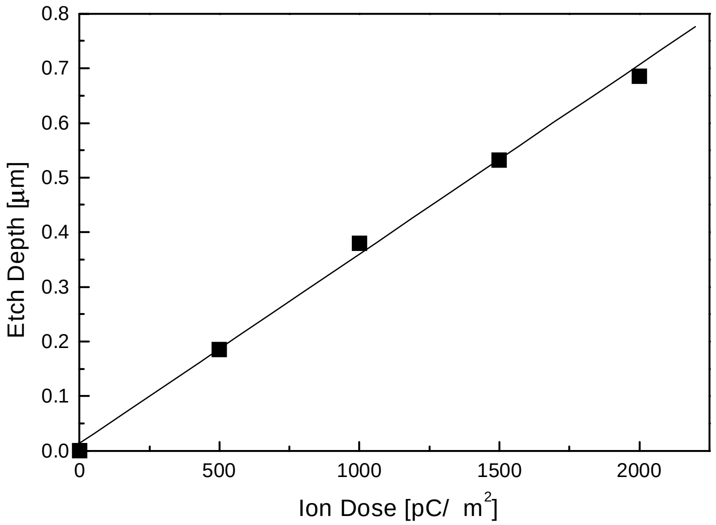

Figure 3: Etch rate as function of gallium ion dose.

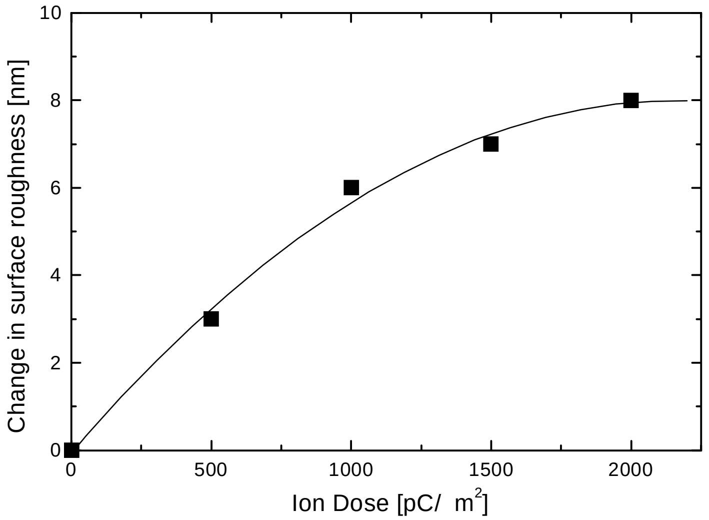

Figure 4: Change in the root mean square (RMS) of the GaN surface roughness after the FIB etching.

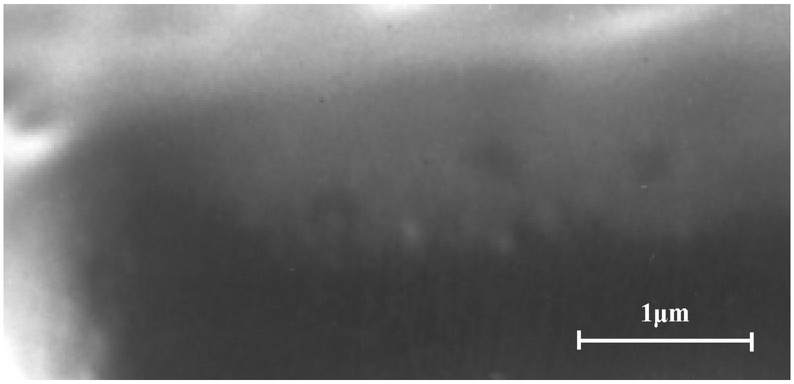

Figure 5: Scanning electron microscopy images of FIB-etched edge.

well below 0.1μm. This result is very promising for use of FIB etching for the fabrication of smooth GaN laser facets. Note that the pattern shown in Figure 5 was etched at a high gallium ion current. The result can even be improved by lowering the current. A large beam current results in an increased gallium beam diameter, a reduced spatial resolution and therefore a reduced etch quality. A closer examination of Figure 5 shows consistently rounded top edges (top of Figure 5). Reducing the Ga-ion current significantly improves the etching quality as indicated in Figure 1 when comparing the pattern (b) and (d) fabricated at a current of 1nA and 3nA, respectively.

The good quality of the FIB-etched GaN surfaces as well as of the side walls illustrates that FIB-etching is well suited for the fabrication of GaN-based devices. The achieved surface roughness and side wall roughness is comparable or better than etching results obtained with reactive ion etching (RIE) reported in the literature [11]. The superiority of FIB for the fabrication of GaN laser diode end facets has recently been illustrated by Mack *et al.* [8]. FIB-post-processed GaN laser diodes showed a reduction in the threshold current, i.e., reduced optical losses in the end facet mirrors. The direct write facility of FIB is invaluable for the fabrication of nanometer size features in GaN (see e.g. Figure 1).

CONCLUSIONS

We have demonstrated the great potential of focused ion beam (FIB) etching to fabricate GaN-based devices. Parameters for the FIB etching of GaN were determined. The etching rate increases linearly with ion dose with a slope of $3.5\text{x}10^{-4}\mu\text{m}^3/\text{pC}$. The obtained side wall roughness stays well below 0.1μm. The direct write facility of FIB was demonstrated. Arbitrary nanometer scale features were etched in a GaN film. Since FIB etching is intrinsically a serial process, FIB etching is slower than high-density plasma etching techniques. However, the high etching quality of FIB as well as its high versatility makes FIB etching highly attractive for the post-processing of GaN-based devices where only a small area has to be modified.

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