GaN-based laser diode with focused ion beam-etched mirrors

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Abstract

GaN-based MQWs-SCH laser diodes (LDs) with Fabry–Perot resonator mirrors fabricated by focused ion beam (FIB) etching were demonstrated for the first time. The diodes show lasing by pulsed current injection at room temperature with a lasing wavelength near 410 nm. FIB etching of the mirrors significantly reduced the threshold current from 1.25 to 0.75 A. In addition we studied the dependence of I-L characteristics on the successive rotation of the etched mirror of a single device and found a strong angular dependence. A similar study of the tilting angle revealed a very weak variation. © 1999 Published by Elsevier Science S.A. All rights reserved.

Keywords: GaN-based laser diode; Focused ion beam etching; Fabry–Perot resonator mirrors

1. Introduction

Plenty of effort has been paid to fabricate nitride-based laser diodes (LDs) [1–12] for the application of short wavelength coherent light sources. The application of nitrides, however, is not limited to light emitters but nitrides can also be used to realize wavelength selective electroabsorbers (EA) [13]. We recently found that GaN based multi-quantum wells (MQWs) show a strong quantum confined Stark effect (QCSE) [14] and can be controlled by a variable bias voltage. Therefore, the integration of a LD with such an EA will lead to the realization of new functional optical modulators based on nitrides. In order to realize such novel devices, it is profitable to establish a fine patterning fabrication technique on a nanometer scale for nitride-based semiconductors in order to integrate the LD and the EA in an identical epitaxial wafer. Focused ion beam (FIB) etching is one of the most suitable methods for the fabrication of such fine patterns. This has recently been demonstrated in GaN epilayers [15].

Very recently, we demonstrated the first nitride-based MQWs separate confinement heterostructure (MQWs-SCH) LD with FIB etched mirrors [16]. In this paper the dependence of the current vs. light output power (I-L) characteristics of the same LD chip on the rotation angle and tilting angle of the FIB etched mirrors is reported.

2. Experiments and results

The MQWs-SCH LD structure was grown by organometallic vapor phase epitaxy on a sapphire (0001) substrate. The structure consists of a low temperature deposited 30 nm AlN buffer layer, 5 μm n-type GaN:Si, a 0.6 μm Al0.07Ga0.93N:Si cladding layer, an 80 nm n-GaN:Si optical waveguide layer. Next comes the active layer, an 80 nm p-GaN:Mg optical waveguide layer, a 0.6 μm p-Al0.07Ga0.93N:Mg cladding layer and a 0.1 μm p-GaN:Mg contact layer. The free electron concentrations of all Si doped layers is $1 \times 10^{18}$ cm$^{-3}$, while free hole concentrations at RT of p-waveguide layer and p-cladding layer are $3 \times 10^{17}$ cm$^{-3}$ and that of the p-contact layer is $1 \times 10^{18}$ cm$^{-3}$. The active layer consists of five pairs of 2 nm Ga0.85In0.15N well layers embedded in 4 nm Ga0.95In0.05N barrier layers. The active MQW layer was topped by 20 nm p-Al0.15Ga0.85N:Mg. A 5 μm wide ridge was formed by chlorine based reactive ion etching (RIE). The cavity length is 500 μm after cleaving. The widths of the p-electrode and the n-electrode were 3
and 200 μm, respectively. Au/Ni was used as the p-electrode, while Al/Ti was used for the n-electrode. After cleaving the wafer along the (1100) plane of the sapphire, FIB etching was performed. Fig. 1 schematically shows the structure of the LD and the FIB etching process. FIB etching was done with a focused Ga⁺ ion beam accelerated at 30 kV.

In this study, three consecutive steps in the FIB process have been performed. In the first step, both side edges were etched over an area of 32 × 10 μm with an ion beam current of 4.7 nA. In the second step, areas of 32 × 1.2 μm were etched with a reduced ion beam current of 650 pA. Finally, in the third and finest etch step, areas of 32 × 1.2 μm were etched with a current of 131 pA. The etching time for the first and the second step was about 15 min, while that of the third step was 60 min. In order to realize vertical etching, the structure should be tilted 2° away from the ion beam. In this paper, a tilting angle θ of 2° is defined as θ = 0°. The roughness of the mirror planes was measured by AFM. The as cleaved root mean square roughness was 3 nm and could be significantly reduced by the FIB process to a value of 0.6 nm. This value is significantly better than typical RIE results. A SEM image of the final side edge of the MQWs-SCH LD after FIB etching is shown in Fig. 2. No facet coating was performed.

The characteristics of the MQWs-SCH LD were measured at RT under pulsed current conditions with a pulse width of 400 ns and a repetition rate of 500 Hz. Fig. 3 shows the I-L characteristic of the MQWs-SCH LD before and after FIB etching. By the improved mirror quality the threshold current could be reduced significantly from 1.25 to 0.75 A in the same device. Fig. 4 shows the emission spectra of the MQWs-SCH LD with FIB etched mirrors for variable driving currents below (0.96 * I_th), at and above (1.15 * I_th) the threshold current. Above threshold, lasing occurred at around 410 nm.

In order to characterize the dependence of the I-L characteristics on the mirror orientation two sample sets were prepared by progressive etching of the same devices. In the first set the rotation angle around the (0001)-axis (φ) was varied and in the second set the tilting angle around the cleaved edge (θ) was varied. Only one mirror was changed while the other remained fixed at φ = θ = 0°.

While the initial processing was performed in all three steps, the variation of the angles φ and θ was performed only under the conditions of the third step.
In order to eliminate device-to-device variations measurements and etching for each set were performed alternatingly on the very same device. In the result we find a strong variation of the threshold current on the rotation angle (Fig. 5). In contrast to the rotation angle, there is only a very little dependence of the threshold current on the tilting angle (Fig. 6). This directly reflects the fact that there is no optical waveguiding of the lasing mode within the plane of the layered structure.

3. Summary

A GaN-based MQWs-SCH LD with Fabry–Perot resonator mirrors fabricated by FIB etching was demonstrated for the first time. Lasing at 410 nm is observed under pulsed current injection at room temperature. By reducing the mirror roughness to 0.6 nm RMS in a FIB etch process and perfect alignment of the mirrors the threshold current could be significantly reduced from 1.25 to 0.75 A. The orientation of the mirror planes was optimized by studying the I-L characteristics as a function of mirror rotation and tilting. Successive etching and measurements were performed on the same device in order to eliminate device variations. We find a strong dependence of the threshold current on the in-plane rotation angle. On the contrary, only a very little dependence is observed for tilting angles up to 5°. By means of the FIB process an excellent control over the parallel alignment of Fabry–Perot mirrors is possible. Therefore, the FIB process is quite promising for the fabrication of future nitride-based novel optical integrated nano-scale devices within an identical wafer.
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