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Photo-enhanced chemical etched GaN LED on silicon substrate

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ABSTRACT

In this study, GaN LEDs grown with an intermediate DBR on a Si substrate were chemically etched by 3 M KOH solution under UV light illumination. After 60 min of KOH etching, the hexagonal etch pits and randomized embossments were clearly imaged by SEM and AFM. The etch pits were generated at the threading dislocations, which are common for lattice mismatched growth of GaN on Si. The photoluminescence intensity at 380 nm was enhanced by approximately 21% after PEC etching. The enhanced PL intensity indicated that the generated etch pits and embossments increased the surface area, and effectively increased light scattering effects by randomizing the light rays and increasing the number of scattering events.

1. Introduction

Presently, GaN-based light-emitting diodes (LEDs) are commercially available with low power consumption and high light output [1–3]. For the mass production of GaN-based LEDs, large substrates (up to a 300 mm diameter wafer) are essential to lower the production cost at all stages of processing. Due to the absence of a commercial GaN substrate, GaN LEDs are typically grown on sapphire or SiC that is much smaller than 300 mm in diameter. Therefore, GaN LEDs grown on Si substrates hold great promise for use by the semiconductor industry for low-cost large-area GaN epitaxy [4,5]. GaN grown on Si substrates typically contains many defects that originate from the lattice mismatch and difference in thermal expansion coefficients [6,7]. In addition to the advantage in production cost, the integration of Si and GaN is essential to manufacture optoelectronic integrated circuits (OEIC), that monolithically integrats optical elements and electronic circuits. OEIC is considered to be a solution to the stray capacitance and inductance that appear at the connected regions. Many studies have reported that OEIC is necessary to solve the interconnect bottleneck [8,9].

The current roadblock to high brightness LEDs is the low light extraction efficiency, which is the inability to harvest a significant fraction of photons generated in semiconductor to the ambient. According to Snell's law, the light escape angle (light cone) is approximately 24° between GaN and air; from this viewpoint, the photons emitted towards the escape cone can be extracted to air. The photons out of the escape angle would suffer from total internal reflection (TIR) [10]. Several methods have been used to enhance the light extraction efficiency, including photo enhanced chemical etching (PEC etching), the formation of a photonic crystal, patterning using the stamping method, and the use of anodic aluminum oxide [11–14]. Among these, PEC etching has been shown to be an effective etching method as it does not require any kind of electron-beam (in lithography) or plasma (in dry etching), which can damage the LED structure [15]. Furthermore, PEC etching is simple and compatible with advanced Si microelectronics, where the etching conditions can be easily controlled by the concentrations of the etchant, temperature, and lamp power. However, there has been no study on the surface texturing of GaN LEDs grown on Si substrate using PEC etching. In this study, we examined the morphology of PEC etched GaN LED surfaces and evaluated the increase in light extraction efficiency under various fabrication conditions after PEC etching.

2. Experimental

Metalorganic chemical vapor deposition was employed to deposit single quantum-well LED devices with an underlying AlN/AlGaN DBR on Si(1 1 1) substrates. Two-inch Si wafers were cleaned via a modified Radio Corporation of America process followed by an *in situ* H_2 bake. An Al seed layer was deposited prior to the onset of NH_3 flow to protect the Si surface from nitridization. A 45.3 nm AlN/42.7 nm GaN superlattice was deposited at 1005 °C and 50 Torr. A GaN SQW-LED was deposited at 1020 °C and 150 Torr directly on the Bragg reflector. The LED structure consisted of a 200 nm GaN:Si, a 20 nm/10 nm/20 nm AlGaN:Si/GaN-undoped/AlGaN:Mg SQW, and a 125 nm GaN:Mg layer structure. The n- and p-type doping was accomplished with disilane and Cp_2Mg, respectively.

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GaN LEDs on Si substrates were etched using a 3 M KOH solution at room temperature. The KOH solution was stirred at 500 rpm and exposed to UV light (mercury lamp) during the etching process. The Si substrate was coated with an electro-resist polymer to avoid wet-etching of the Si substrate by the KOH solution. After 60 min of KOH etching, LED samples were dipped in deionized water for 5 min for rinsing. A Scanning Electron Microscope (SEM) and an Atomic Force Microscope (AFM, Veeco) were used to characterize the etched surface and morphology. In addition, a focused ion beam (FEI company, NOVA 200) was employed to investigate the depth and shape of the etch pits. Photoluminescence (PL) measurements were taken at room temperature and used to examine the enhancement of light extraction efficiency. A pump source with a wavelength of 325 nm (from a He–Cd laser, Kimmon Koha Co. Ltd.) was used for PL spectroscopy.

3. Results and discussion

It is known that alkaline-solution etching of the GaN surface is highly dependent on the orientation of growth surface. In the *c*-plane polar GaN structure, KOH-etched nitrogen-face-GaN forms hexagonal pyramids when exposed to a base solution. This is in contrast to gallium-face-GaN, which is chemically more stable than nitrogen-face-GaN [5,16,17]. In the case of an *a*-plane $(1\,1\,\bar{2}\,0)$ non-polar GaN structure, KOH etching created triangular pillars and v-shape pits along the [0 0 0 1] direction [18].

Fig. 1 shows a schematic of the LED structure with inverse hexagonal truncated cone shape etch pits. Fig. 2 displays a SEM image of the etch pits after 60 min of PEC etching; the insetted figure shows a further magnified image of one etch pit. These types of etch pits can originate from screw dislocations, mixed

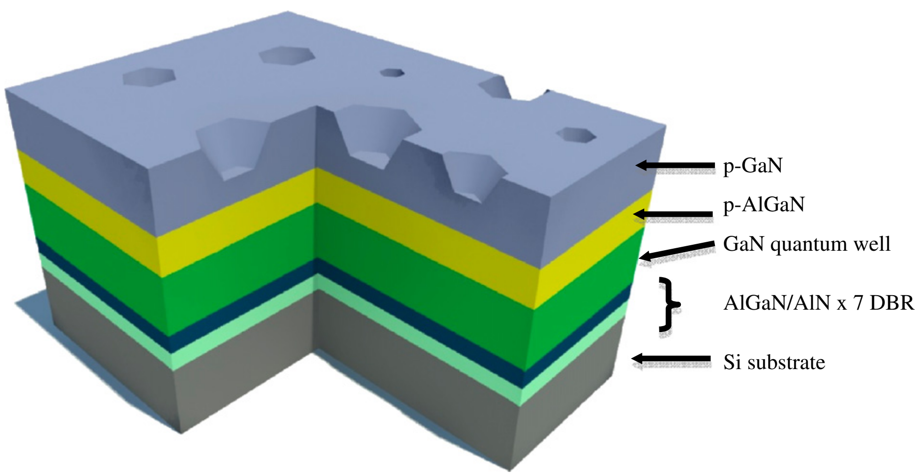

Fig. 1. Schematic structure of PEC-etched GaN LED.

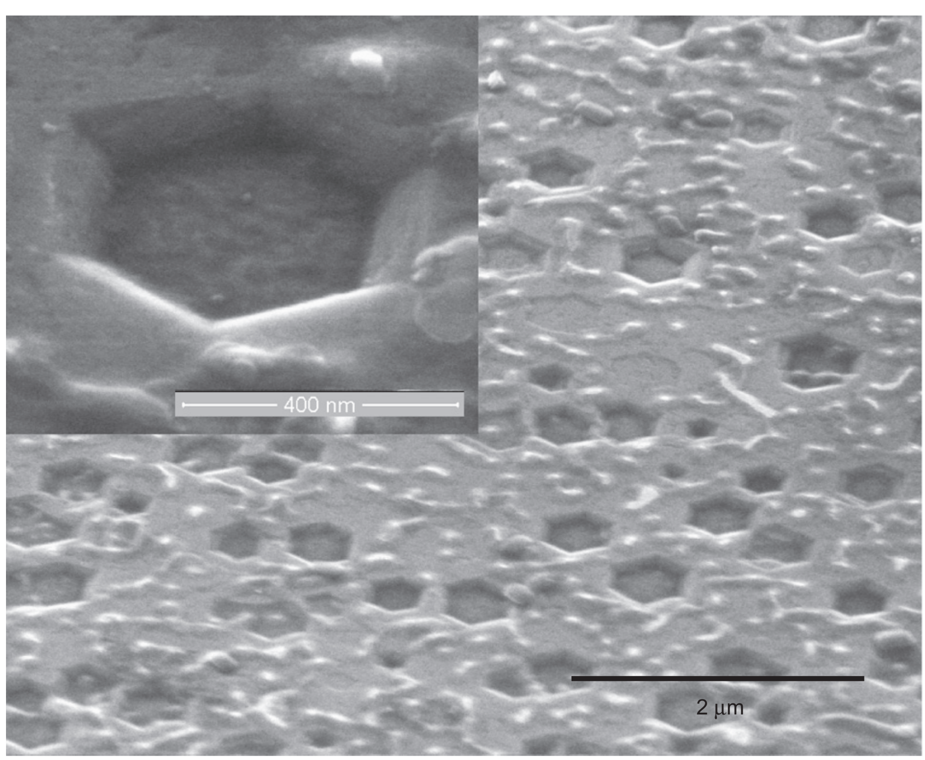

Fig. 2. SEM image of PEC-etched GaN surface for 60 min.