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Improvement of *n*-GaN Schottky diode rectifying characteristics using KOH etching

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KOH etch was investigated as a means to improve the $I-V$ characteristics of Schottky diodes on *n*-type GaN grown by molecular-beam epitaxy on sapphire, or on hydride vapor phase epitaxy templates. Atomic force microscopy images and $I-V$ characteristics are presented. After etching as-grown films in molten KOH, Schottky diodes on *c*-plane GaN had orders of magnitude reduction in reverse leakage current. The best devices had leakage currents less than 10^{-12} A (10^{-8} A/cm^2) at -5 V, and ideality factors of 1.04. Measurements on several different sample structures indicate a correlation between surface roughness and saturation current, and an improvement in ideality factor when etched in KOH. Phosphoric acid was also investigated, but did not result in significant improvements in $I-V$ characteristics.
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The III-nitrides are a rapidly evolving family of materials, poised for a wide range of commercial applications. Numerous studies detail distinctive defects associated with growth by molecular-beam epitaxy (MBE), metalogranic chemical vapor deposition (MOCVD), or hydride vapor phase epitaxy (HVPE).[1–3] Most of the structural defects in the III-nitrides result from the lack of native GaN substrates.[4] The current state of barrier formation on GaN is under heavy investigation by numerous groups to identify and correct the sources of nonidealities in the metal–semiconductor junction.[5–7] Defects in the III-nitride films, which can be scattering centers, traps, or both in nearly any device,[8,9] cause device degradation,[3] and can be responsible for premature device failure.[10,11]

Wet chemical etching is traditionally used as a method to determine the defect density and for device fabrication in GaN. Methods for correcting surface perturbations have been investigated by numerous groups.[12–16] The etches used in this study attack the defective regions in the material, which may be electrically active. Moreover, the etches preferentially attack off *c*-planes of GaN, notably smoothing the nominally *c*-plane surface.

The MBE GaN samples chosen for this study were selected based on the variety of samples having a different appearance, defect structure, and as-grown $I-V$ characteristics. The control group consisted of diodes on as-grown material deposited on sapphire or HVPE GaN and the experimental groups were fabricated on etched material. Phosphoric (H_3PO_4) acid and potassium hydroxide (KOH) were used as the etchants in the experimental group for one structure (SVT889), and only KOH as the experimental group for the other eight structures. SVT750 is a MBE film on *c*-plane sapphire and SVT889 is MBE GaN on HVPE GaN.

Etching times were chosen on a case-by-case basis using atomic force microscope (AFM) images to gauge surface quality, with the target surface characterized by deep etch pits and a large area of smooth *c*-plane. Samples were placed in the heated etches, 210 °C for KOH (85% by weight pellets) and 160 °C H_3PO_4 (85% by weight solution), and then rinsed in deionized water.

An AFM in tapping mode was used to determine the surface roughness and crystallographic faces. The surface roughness was measured with a Digital Instruments Nanoscope, both overall, and between etch pits. Schottky diodes were then formed on the etched surfaces.

The fabrication procedure for both as-grown and etched samples is the same and is as follows. The samples were cleaned in acetone, methanol, and deionized water, in respective order. Aqua regia (1:3 HNO_3:HCl) was then used to remove the oxide layer from the surface of the sample. Optical lithography was used to define the contact area, which was 125 μm for the opening and 75 μm for the Schottky contact, with ohmic contact covering the *c*-face of the sample. The Ti/Al/Ti/Au (300 Å/1000 Å/300 Å/150 Å) metallization was deposited using electron beam (for Ti and thermal evaporation (for Al and Au), and a standard lift-off process was used to pattern the contacts. The contacts were annealed at 900 °C for 1 min by rapid thermal annealing in nitrogen ambient. Ni/Au (300 Å/750 Å) metallization was then deposited and patterned to form Schottky contacts.

AFM images for SVT750 are presented as an example of an MBE film grown on sapphire [Fig. 1(a)], and then etched for 60 s in molten KOH [Fig. 1(b)]. The as-grown surface is rough, with a high density of hillocks ($\sim 9\times10^8$ cm^{-2}). After etching, the surface becomes extremely flat with a low density of etch pits ($\sim 1.5\times10^8$ cm^{-2}), and some large-

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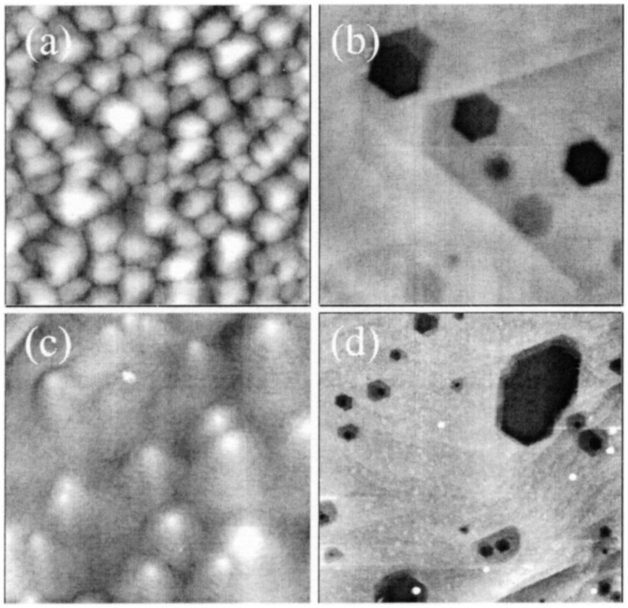

FIG. 1. AFM image of (a) as-grown (75-nm vertical scale) and (b) KOH-etched surface (25-nm vertical scale) of SVT750 sapphire substrate with GaN MBE overgrowth. AFM image of (c) as-grown (5-nm vertical scale) and (d) H_3PO_4 (7.5-nm vertical scale) etched surfaces of SVT889 HVPE substrate with GaN MBE overgrowth. The MBE GaN grown on HVPE template and etched in KOH was similar in appearance to (b). Images are 4 μm^2.

scale hexagonal terraces ($\sim 2.5\times 10^8$ cm^{-2}). For SVT889, [Fig. 1(c)], the as-grown surface has a spiraled terrace density of about 5×10^8 cm^{-2}, attributable to screw dislocations. Molten KOH etching for 5 min (not pictured) removed the hillocks, exposed a flat *c*-plane with some well-defined hexagonal pit formation ($\sim 5\times 10^7$ cm^{-2}), created a uniform step terrace across the surface, and left small diameter column density of $\sim 1.25\times 10^8$ cm^{-2}. H_3PO_4 etching for 7 min [Fig. 1(d)], left small columns ($\sim 1.25\times 10^8$ cm^{-2}), and formed irregularly shaped pits in the surface with a density of $\sim 5\times 10^8$ cm^{-2}.

The $I-V$ curves for SVT750 and SVT750 KOH [Fig. 2(a)], show the potential of KOH etching in improving the $I-V$ characteristics. Although the as-grown sample did not have a linear region for parameter extraction, the KOH etch improved the ideality factor to 1.04 and the saturation current is drastically reduced to 2.3×10^{-10} A/cm^2. Sample SVT889 (HVPE substrate with GaN overgrowth by MBE), showed slight improvement in ideality factor and degradation in saturation current when etched in H_3PO_4, but improvements for both values when etched in KOH prior to device fabrication [Fig. 2(b)]. The ideality improved from 1.52 as-grown to 1.06 KOH, averaged from five devices. In the H_3PO_4 sample's forward bias curve, there is a noticeable kink, evidence of a variance in transport dynamics, around 1 V that is absent from both the as-grown and KOH-etched samples. The saturation current increased from 1.3×10^{-5} A/cm^2 as-grown to 5.2×10^{-3} A/cm^2 for H_3PO_4, and decreased to 5.7×10^{-10} A/cm^2 for KOH etching. The values for the KOH-etched samples are comparable to those presented in literature.[17–24]

The surface roughness, excluding the etch pits, for all of the samples presented in Fig. 3, decreased after etching, except for one of the MBE structures (SVT429); the open symbol denotes after etching surface roughness. Figure 3(a) demonstrates a ubiquitous improvement in ideality factor when etching in KOH, whereas Fig. 3(b) establishes a correlation between surface roughness and saturation current. Since SVT429 became rougher when etched, the improvement in ideality factor and degradation in saturation current support the argument for multiple causes of poor device quality. The device improvement could be the result of several effects of the etchant. One possible effect of the etchant is removal of defects through physical or chemical isolation, such as oxidation. A conducting defect would appear as a parallel current path, thereby increasing the slope under reverse bias. Another explanation in diode improvement lies in the surface's reduced number of facets. Each facet of the crystal, representing different crystalline orientation, has different states associated with its surface structures and kinetics, leading to a locally specific surface barrier height. For SVT750 and SVT889 the surface roughness disregarding etch pits decreased with etching and the ideality factor and saturation current improved. AFM techniques beyond tapping mode AFM could provide measurements helpful in resolving the true nature of barrier and conductivity non-uniformity.[25,26] Results from a previous topology and charge investigation by atomic and electric force microscopy

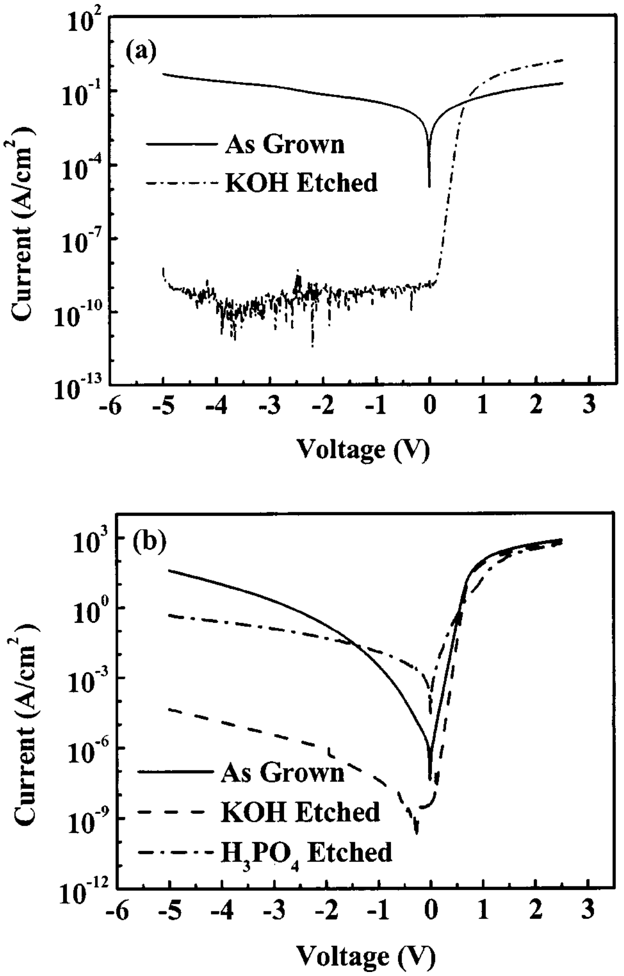

FIG. 2. $I-V$ curves for (a) SVT750 sapphire substrate with GaN MBE overgrowth as-grown and etched diodes; (b) SVT889 HVPE substrate with GaN MBE overgrowth as-grown and etched diodes.

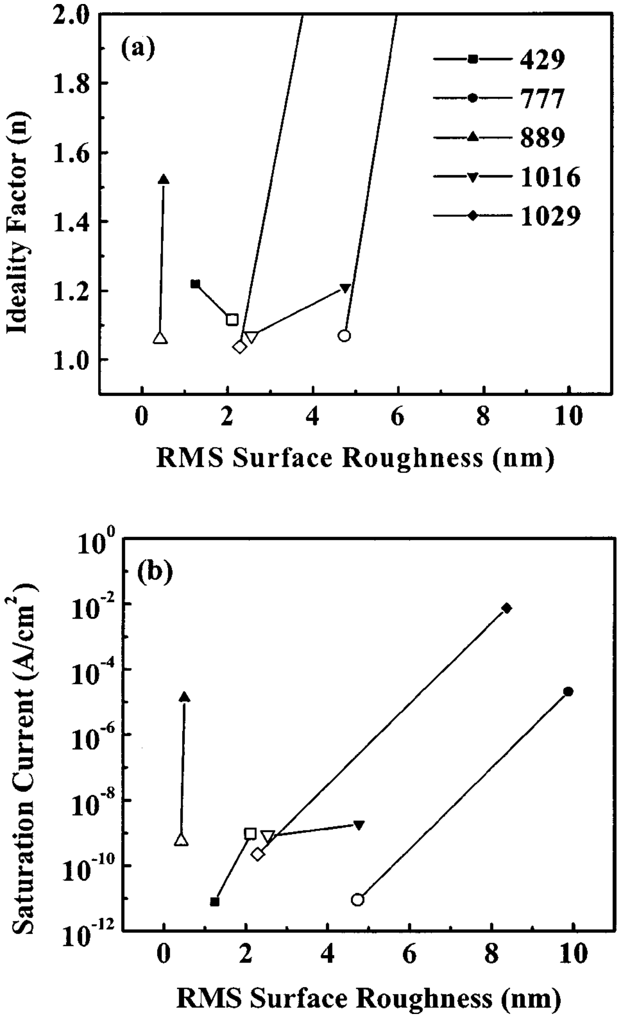

FIG. 3. Surface roughness versus (a) ideality factor and (b) saturation current presented for five samples. Other samples' characteristics did not yield a region for parameter extraction. Open symbols denote measurements after KOH etching and closed symbols are as-grown.

studies suggest that barrier perturbations could partially be a result of charge distribution around surface structures.[27]

The KOH etching process was found to reduce the surface roughness and expand defects to hexagonal pits. A leakage current reduction of 8.5 orders of magnitude can be seen in MBE sample SVT750 at −5 V when comparing the as-grown sample to the KOH-etched sample. For SVT750, KOH etching, an ideality factor of 1.04 was measured, and the saturation current was measured to be 2.3×10^{-10} A/cm^2, noting that the as-grown sample did not even have a linear region for parameter extraction. HVPE template-grown MBE GaN (SVT889), showed similar improvement, although this is better starting material. SVT889 saturation current reduced from 1.3×10^{-5} to 5.7×10^{-10} A/cm^2, for KOH etching, and increased to 5.2×10^{-3} A/cm^2 for H_3PO_4 etching. The ideality factor for the as-grown sample was 1.52, the KOH etch ideality factor equaling 1.06, and the best H_3PO_4 etch ideality factor equaling 1.43, noting H_3PO_4 generally degraded the ideality factor. The data presented shows a correlation between surface roughness and saturation current values. In samples etched in KOH, the saturation current fell when the surfaces became smoother. The ideality factor improves regardless of surface roughness. The reduction in saturation current is attributed to the etchant planarizing the surface, while the improvement in ideality factor is attributed to the passivation and removal of defective regions of material by molten KOH etching.

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