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Optimization of AlGaN/GaN current aperture vertical electron transistor (CAVET) fabricated by photoelectrochemical wet etching

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AlGaN/GaN current aperture vertical electron transistor (CAVET) was fabricated and optimized for band gap selective photoelectrochemical wet etching. The large polarization induced voltage offset (around 2.5–4 eV) observed in the first generation CAVET was reduced to 0.7 V in this structure by employing a δ Si doping layer buried 60 Å below the $In_{0.03}Ga_{0.97}N$ (60 nm thick) and bottom GaN interface to screen the polarization fields. Other sample structures were studied to achieve an aperture with both good undercut etching and a small voltage offset. It was clearly demonstrated that etch selectivity in the GaN/InGaN/GaN undercut structures was influenced by hole confinement and the chemical activity of the N-face GaN. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1806281]

There have been many reports of high-frequency and high-power electronic devices fabricated from III-nitride materials.[1,2] A limitation to the high-frequency operation of GaN-based high electron mobility transistors has been the attendant dc-rf dispersion, believed to originate from the presence of traps at the surface.[3,4] A number of approaches have been used to remove this dispersion, including surface passivation,[5] capping with *p*-type GaN (Ref. 6) as well as incorporating thick UID (unintentionaly doped) GaN on top of the AlGaN/GaN structure.[7] We have previously reported on a vertical electronic devices, the current aperture vertical electron transistors (CAVET), which is shown schematically in Fig. 1. The aperture is formed using either regrowth[8] or selective lateral etching[9] a sacrificial InGaN layer using photoelectrochemical (PEC) wet etching. In the CAVET, the high field region is not at the surface but in the bulk[9] minimizing the effect of surface traps. The device includes a two-dimensional (2D) electron gas (2DEG) formed between the AlGaN and GaN layers. Two sources were patterned on each side of the gate and the drain was set on the bottom. The current in the 2DEG flows downward through the current aperture and is modulated by the gate above. The 60 nm thick, unintentionally doped $In_{0.03}Ga_{0.97}N$ layer formed the original aperture layer that was selectively eleched by PEC etching, using a GaN filter to illuminate the sample with only long-wavelength light.[9] The $I-V$ characteristics of that first-generation device are shown in Fig. 2(a), which reveals the large voltage offset. We had earlier made the correlation between the barrier introduced by the built-in piezoelectric field through the undoped InGaN layer shown in Fig. 2(b), and the voltage offset observed in the $I-V$ characteristics shown in Fig. 2(a). The current-voltage characteristics of the first etched aperture CAVET were satisfactory but also displayed a rather large voltage offset ranging from 2.5 to 4 V [refer to Fig. 2(a)]. This paper describes the development of the second-generation etched CAVET, with substantial reduction of the voltage offset from 2.5–4 to 0.7 V. The improvements required the simultaneous modification of the device structure in tandem with the optimization of the selective PEC etch process used to define the aperture.

In redesigning the CAVET structure, several approaches were used to decrease the polarization-induced barrier through different ways of *n*-type doping of the InGaN and surrounding materials while maintaining the etch selectivity.

The fabrication process for the CAVET has been described in our earlier paper.[10] The PEC etch process initially used is also the same as described previously: the etchant is 0.004M KOH, the illumination source is a 1000 W Xe lamp, and a GaN template grown on sapphire substrate was interposed between the Xe lamp and the sample, acting as a filter to achieve the band gap-selective etching between InGaN and GaN. In order to minimize the piezoelectric-induced barrier to electron flow at the InGaN–GaN interface, two initial material modifications were explored. The first modification was to uniformly Si dope ($\sim 1 \times 18\ \mathrm{cm}^{-3}$) the 60 nm thick $In_{0.03}Ga_{0.97}N$ layer, attempting to screen the effects of the piezoelectric field. That band diagram, simulated with a 1D schrodinger-Poisson solver is shown in Fig. 3(a): the barrier height in the conduction band was decreased from 0.7 (for the UID InGaN layer) to around 0.3 eV. The second modification reduced the thickness of the undoped InGaN layer from 60 to 30 nm, resulting in a reduction of the barrier height from 0.7 to around 0.5 eV, as shown in Fig. 3(b). The band diagram simulations indicated that these modified

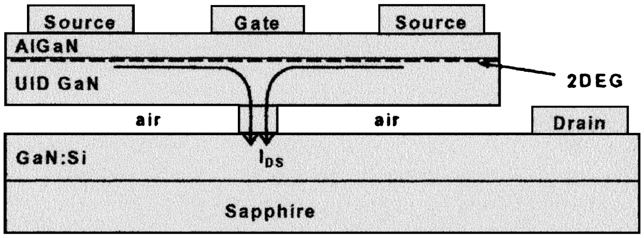

FIG. 1. Schematic illustration of the CAVET structure.

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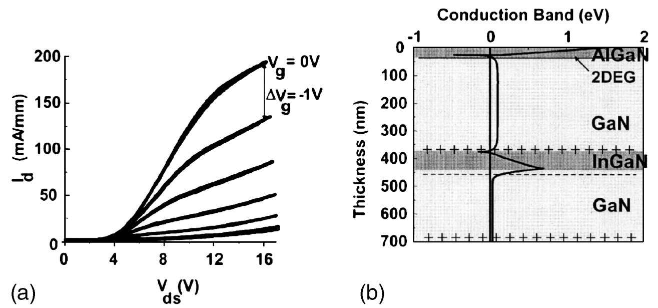

FIG. 2. (a) $I-V$ characteristics of first-generation CAVET; (b) Conduction band diagram of CAVET with UID 60 nm InGaN/layer.

CAVET structures should have provided the reduction in offset voltage that was sought. To a first approximation, the band gap-selective PEC etch process used to produce the first CAVET device should have been appropriate for the selective etching of these newly-engineered apertures. However, both structures showed a dramatic degradation of the selectivity and surface smoothness obtained for the PEC etching of the aperture layer. The uniformly Si-doped 60 nm InGaN layer showed a very rough etch morphology [Fig. 3(c)] and evidence of attack of the GaN overlayer (i.e., loss of selectivity). Figure 3(d) shows a much poorer quality undercut etching in the thinner (30 nm instead of 60 nm thick) InGaN. The difficulties in selective etching of the thin aperture layer may have in part been due to mass transport limitations of the etchant and etch products through such a narrow channel. It appeared that the more controlled method of barrier lowering was through Si doping of the aperture layer, and we decided to pursue this approach further.

The uniform Si doping of the InGaN layer clearly modified the selectivity achievable with the PEC etch process and no well-controlled undercut etching could be achieved. In order to introduce "screening" charge into the material while simultaneously minimizing the impact on the selectivity of the etch process, a δ–doped Si layer was introduced at and near to the lower InGaN–GaN interface [see Fig. 4(a)]. Hall measurements of test structures allowed us to determine that the δ–doped Si layer provided an electron sheet charge density of around $6\times\ 12\ \mathrm{cm}^{-2}$. Figure 4(b) shows simulations of the conduction band for δ-doped layers placed at varying distances d from the InGaN-GaN interface. As the placement of the doping layer is moved from the interface itself of 10 nm away from the interface, within the GaN underlayer, the conduction band barier increases. As expected, placing the δ-doped layer at the InGaN–GaN interface is the ideal electrical design for the CAVET aperture with no barrier existing in the conduction bad as the charge is fully screened. Unfortunately, the PEC etch profile of the fully screened structure is poor, as shown in Fig. 4(c). But, Fig. 4(d) shows dramatic improvement in etch selectivity that results by using a 60 nm thick InGaN layer with the δ-doped Si layer located 6 nm from the InGaN–GaN interface. This structure was used to from the CAVET device whose $I-V$ characteristics are shown in Fig. 5; the voltage offset has clearly been reduced from 2.5 to 4 V in the first generation CAVET to 0.7 V here. For this device, $I_{\max}\sim 0.32$ A/mm, and the transconductance $g_m \sim 70$ ms/mm.

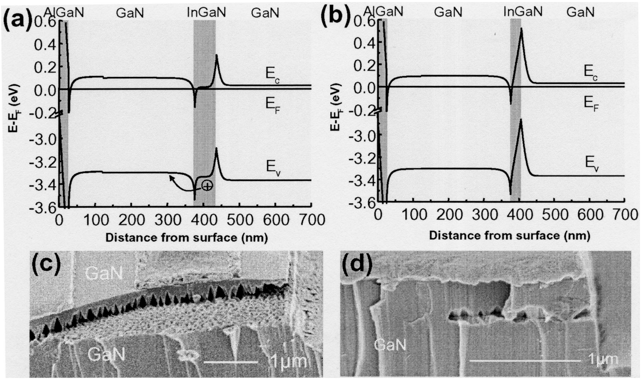

FIG. 3. (a) Band diagram of sample with uniformly Si doped, 60 nm thick InGaN; (b) Band diagram of sample with 30 nm thick UID InGaN, (c) SEM image of sample with uniformly Si doped, 60 nm thick InGaN; (d) SEM image of sample with 30 nm thick UID InGaN.

We now explain the etch selectivity dependence of the various studies. The answer has in the band diagram and, in particular, the valence band. Analysis of our experiments suggests several important features of the match between material structure and etch process.

(1) "Hole transfer": etch rates in PEC etching are augmented by the creation of photogenerated holes that enhance the oxidation and hence etching of the material. Although holes may be selectively generated in a lower band gap material, a particular band structure may favor the "transfer" of those holes of different regions of the material, hence facilitating etching in those regions. Figure 6 compares the hole confinement in the InGaN region between UID InGaN and uniformly Si doped InGaN. In the uniformly doped InGaN material, the holes generated in region 1 (InGaN region) may be able to tunnel through the region 2 (top GaN region) since the InGaN layer has higher hole energy compared to the top GaN layer. These holes in region 2 can contribute to the etching of the overlying GaN. This might also explain the dramatically different etch morphologies resulting from the different placements of the δ-doped layer from the InGaN–GaN interface, shown in Fig. 4(c) and 4(d). Figure 4(b) shows that better hole confinement was predicted when the δ Si doping layer was moved into bottom GaN, resulting in the undercut shown in Fig. 4(d).

(2) Greater chemical "reactivity" of N-face GaN. Our recent studies have revealed the much more rapid etch rates of N-face GaN, compared to Ga-face GaN subject to the same etch conditions. Experiments have shown that finite etching of N-face GaN can take place in the absence of illumination,[11,12] and that the resulting etch morphology is strongly crystallographic in nature, producing a rough etched surface. Thus, band gap-dependent photocontrolled etch selectivity is reduced if the N-face GaN can etch without the presence of light. Insofar as the (nonilluminated) vertical etching to top GaN (with exposed N-face) becomes comparable to the photoinduced lateral etching (within InGaN sacrificial layer), the control of the etch and resulting etch morphology will be

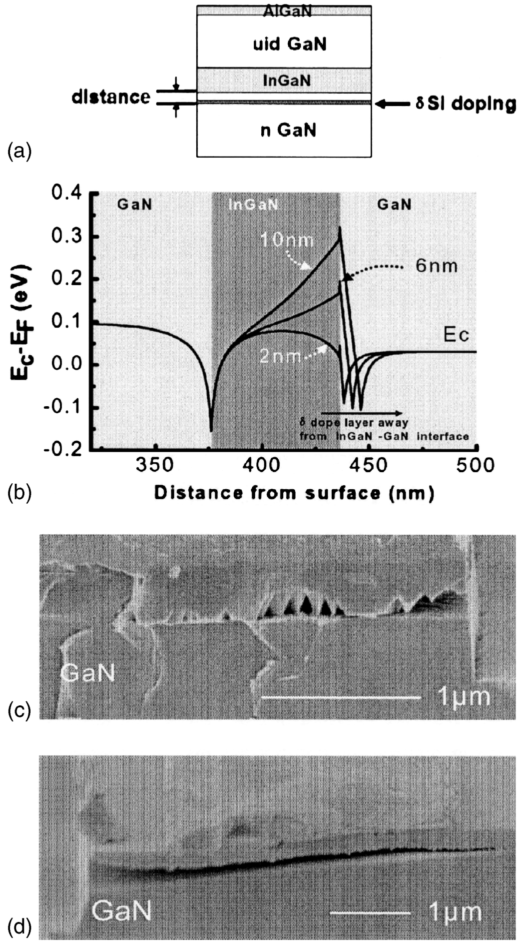

FIG. 4. (a) Schematic illustration of CAVET structure with δ Si doping layer set at and near to the lower InGaN–GaN interface; (b) Band diagram of conduction band for δ-doped layers placed at varying distances d from the lower InGaN–GaN interface. (c) SEM of etch morphology of δ-doped Si layer at the lower InGaN–GaN interface. (d) SEM of etch morphology of δ-doped Si layer located 6 nm from the lower InGaN–GaN interface.

changed and it becomes difficult to achieve the smooth, deep, selective undercut etching. Therefore, both the hole confinement and the chemically reactive N-face GaN property can influence the PEC undercut etching behavior within the GaN material of GaN/InGaN/GaN structure dramatically.

In conclusion, we have substantially reduced the voltage offset of the etched aperature CAVET device. Device improvement required the carefully coupled redesign of the device band structure and the understanding of the interaction of band structure with the PEC etch mechanism. A strategic placement of a δ-doped Si layer 6 nm from the InGaN–GaN interface resulrted in a highly selective, smoothly etched aperture with a low voltage offset. Hole confinement and N-face GaN etch property were observed to affect the PEC undercut etching behavior of GaN/InGaN/GaN structure. Other strategies for PEC etching, such as using different electrolytes, including HCl, $H_2SO_4H_2O_2/H_2O$ are under exploration to achieve good selective undercut etching.

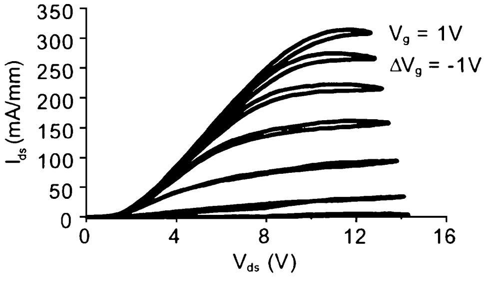

FIG. 5. $I-V$ characteristics of second-generation CAVET with voltage offset decreased to 0.7 V.

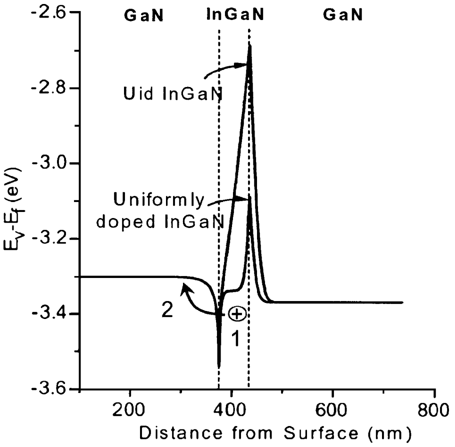

FIG. 6. Schematic demonstration of hole confinement in InGaN region between UID InGaN and uniformly Si doped InGaN.

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