On the Reduction of Base Resistance in GaN-based Heterojunction Bipolar Transistors

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The high resistivity of p-type GaN presents a significant barrier to the development of bipolar electronic and optoelectronic devices. Specifically with regard to *N-p-n* heterojunction bipolar transistors (HBTs), the resistance of the p-type base manifests itself in three distinct ways: the intrinsic base resistance under the active region of the device, as well as the base access resistance, consisting of contact resistance and extrinsic base resistance. Methods of combating each of these parasitics are presented. A new type of low resistance metal semiconductor contact is proposed and demonstrated, based on strong internal electric fields induced by polarization effects. Results on photoelectrochemical etching as a low damage, dopant selective technique of etching GaN-based HBT structures are presented. Very smooth interfaces and low contact resistances are obtained in GaN/SiC HBT structures. Another etch technique involves crystallographic etching of GaN, producing undercut cross-sections. This enables the use of self-aligned base contacts, further reducing base access resistance. Finally, increasing the conductivity of the p-type material itself is realized by the use of AlGaN/GaN superlattices. Latteral hole conductivity is improved in these structures, but effective electron transport perpendicular to the layers remains to be proven.

INTRODUCTION

Wide band-gap semiconductors including GaN and SiC have proven suitable for high power, microwave electronic devices. Impressive results have been reported specifically for AlGaN/GaN-based HEMTs [1], and SiC MESFETs [2]. Bipolar devices are also attractive for high power electronics due to the inherently greater power density and potentially higher speed. However, it has proven very difficult to achieve high p-type conductivity in GaN films due to the large activation energy of common acceptors. This leads to exceedingly large base resistance in GaN *N-p-n* heterojunction bipolar transistors (HBTs). In this paper, we address the sources of base resistance and provide experimental and theoretical solutions to this problem.

BASE CONTACT RESISTANCE

Low resistance ohmic contacts to p-GaN are difficult to realize owing to the large work function of the semiconductor, as well as the low acceptor ionization efficiency. Specific contact resistances in the 10^{-3} Ω-cm^2 range are typically obtained.

Recently, a new type of metal-semiconductor contact has been proposed, the so-called polarization-enhanced contact. [3] This concept is based upon the large internal electric fields present in thin GaN-based alloys arising from polarization effects. In this contact, the polarization induced electric field enhances that of the space-charge region in a typical tunnel contact, resulting in a shorter tunneling distance for holes, and a decreased contact resistance. This effect is shown schematically in Figure 1.

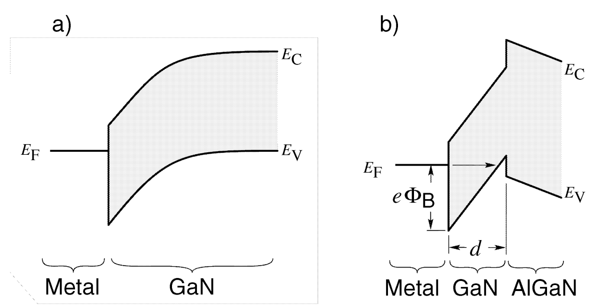

FIG. 1. Band diagrams of a) a traditional metal / p-type semiconductor contact, and b) a polarization enhanced contact .

We consider the case of a thin layer of GaN grown on a layer of AlGaN, where the GaN has an internal electric field due to polarization effects. Assuming a triangular barrier between the metal and the GaN layer, the contact resistance can be calculated analytically [3] with the parameters being the thickness of the GaN layer d, the metal-semiconductor barrier height Φ_B, and the strength of the internal electric field E. Figure 2 shows the minimum GaN layer thickness as a function of electric field required to produce a specified contact resistance.

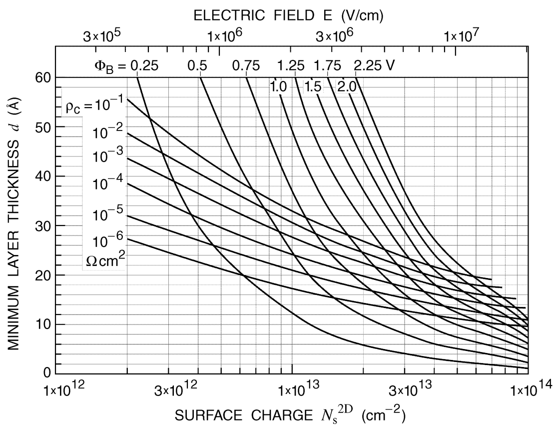

FIG. 2. Calculated specific contact resistance and minimum GaN layer thickness versus polarization induced electric field for barrier heights ranging from 0.25 to 2.25 V.

For example, to obtain a contact resistance of $1x10^{-5}$ Ω-cm^2 given a barrier height of 0.5 V, it is necessary to have a 20 Å GaN layer with an internal field of greater than $2x10^6$ V/cm.

We have demonstrated contact resistances as low as $9x10^{-4}$ Ω-cm^2 using Ni contacts deposited on p-type AlGaN/GaN superlattice structures. These SL structures have 200 Å period, and are terminated in a 100 Å GaN layer, consistent with the polarization-enhanced contact structure outlined above. In addition, we have experimental evidence of strong internal fields resulting in a shift of the photoluminescence spectra attributed to the quantum confined Stark effect (QCSE).[4] While it is difficult to determine whether this low contact resistance is due to polarization-enhancement, as deposited Ni contacts to the SL structures are observed to be ohmic, which is very atypical of bulk p-GaN layers.

PHOTOELECTROCHEMICAL ETCHING

Fabrication of HBTs typically involves the formation of double mesa structure, which exposes the base and collector regions for contact metalization. In the GaN materials system, this is usually performed with some type of dry etch technique. However, two problems are frequently encountered specifically with HBT structures. First, the etch selectivity between emitter and base can be very poor for both AlGaN/GaN and GaN/SiC emitter-base junctions. This makes it difficult to stop the etch precisely at the emitter-base junction, which is especially important for thin base layers. [5] The second problem with dry etching is the effect of ion damage at the surface. For etched p-GaN surfaces, contact resistance is observed to degrade significantly as compared to unetched results. For the GaN/SiC system, ion damage contributes to large leakage currents between emitter and base. Techniques such as emitter regrowth have been shown to alleviate this problem [6], but add significant complexity to the device fabrication. Clearly, a low damage, dopant selective etch technique is highly attractive for HBT fabrication.

In order avoid these problems, we have chosen to utilize photoelectrochemical (PEC) etching. This technique uses a weak electrolyte as part of an electrochemical cell. Ultra-violet light is used to create electron-hole pairs inside the semiconductor. Assuming a pinned surface potential and the resulting band bending at the surface, holes are forced toward the surface in an n-type semiconductor and toward the bulk in a p-type semiconductor. This is shown schematically in Figure 3.

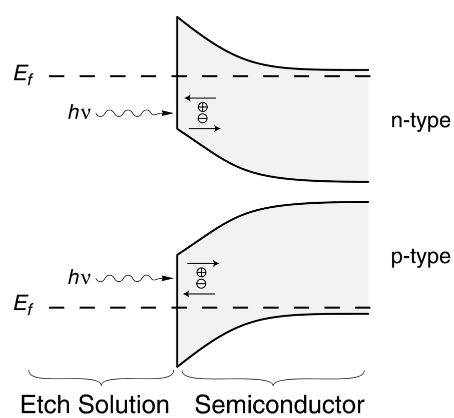

FIG. 3. Band diagram of the electrolyte-semiconductor interface showing band bending effects on photo-generated electron-hole pairs.

Excess holes at the surface are essentially broken chemical bonds, making the semiconductor susceptible to the etch solution. Excess electrons at the surface tend to strengthen the bonds, resisting the etchant. Therefore high dopant selectivity can be achieved with PEC etching. The following sections discuss results obtained with PEC etching of GaN/SiC and AlGaN/GaN HBT structures.

PEC ETCHING OF GaN/SiC-BASED DEVICES

Photoelectrochemical etching was used to form the emitter mesa in a GaN/SiC (4H) *N-p-n* HBT structure. The emitter ohmic metal (Ti/Al/Ni/Au) was used as the mask for the etch process. UV illumination was provided by a Hg arc lamp at an intensity of approximately 10 mW/cm^2. The etch solution consisted of a 0.04 M aqueous solution of KOH. During the etch process, a 1.0 V bias was applied between a gold cathode in the solution and the GaN sample. A profilometer trace of the etch result is shown in Figure 4. In the figure, the etch through the base to the n-SiC collector has been completed using fluorine-based RIE.

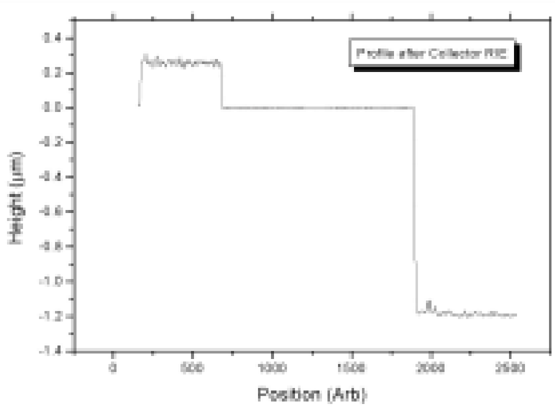

FIG. 4. Etch profile of a GaN/SiC HBT structure after PEC base mesa etch and collector mesa RIE.

The resulting surface is very smooth (smoother than the unprocessed GaN epitaxial surface) and appears specular under the optical microscope. Etching is complete after approximately 20 minutes, but can be extended much longer due to the good selectivity.

Contacts to the exposed p-SiC surface were formed using e-beam deposited Ti/Au metalization. The I-V characteristic of the contacts before and after high temperature (800 ºC) anneal is shown in Figure 5.

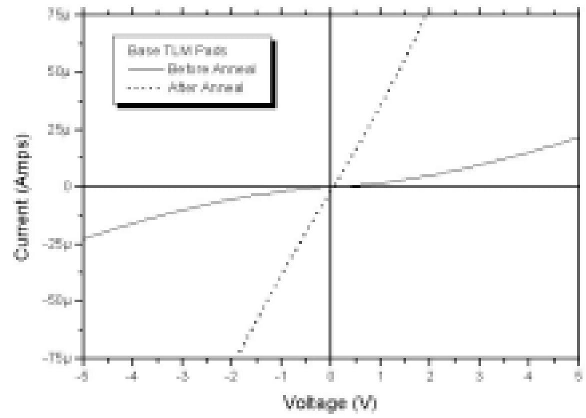

FIG. 5. I-V characteristic of Ti/Au contacts to PEC-etched p-SiC before and after high temperature anneal.

It is evident that as-deposited contacts are slightly rectifying but become linear after anneal. The specific contact resistance of this base metalization scheme was measured using the TLM method. The measured resistance as a function of contact pad separation is shown in Figure 6.

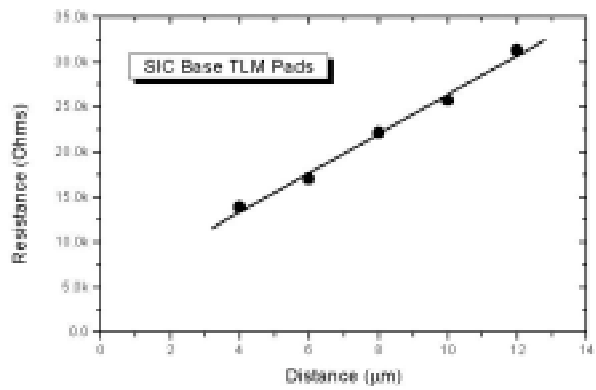

FIG. 6. Resistance vs. contact spacing for Ti/Au TLM pads deposited on PEC-etched SiC surface.

Using this measurement, specific contact resistance was calculated to be approximately 2.5×10^{-5} Ω-cm^2, which is an acceptable result for p-SiC.

PEC ETCHING OF ALL GaN-BASED DEVICES

The same PEC etch process outlined above for the GaN/SiC system has been applied to AlGaN/GaN *N-p-n* devices. The GaN epi-layers investigated were grown on 6H SiC substrates by MBE. In this case, the best etch results were obtained without external bias applied to the system. Figure 7 shows the profile of an emitter mesa formed with PEC etching.

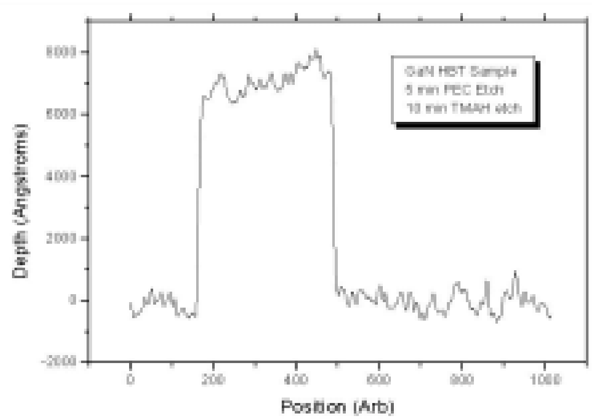

FIG. 7. PEC-etch profile of all-GaN HBT structure.

The result shows considerable residual roughness at the AlGaN/GaN interface. However, the roughness is comparable in magnitude to the roughness of the unprocessed sample itself. Therefore, it is difficult to determine whether the etch process has caused the roughness, or if the heterojunction is not well defined.

I-V characteristics of Ni TLM pads deposited on PEC etched p-GaN surfaces exhibit diode-like behavior, which we attribute to localized shorting of the base-collector junction under the contacts. Further work must be done with epi-wafers exhibiting much less roughness.

SELF-ALIGNED BASE METAL

The use of a self-aligned base contact is another fabrication technique that could realize a large reduction in base access resistance. This process is widely used for HBT fabrication in other materials systems, and often involves anisotropic etching of the emitter to achieve an undercut cross-section. This enables deposition of the base contact without a mask, and thus the base contact-to-emitter distance can be much less than the limit imposed by optical lithography. Recent demonstration of crystallographic wet chemical etching of GaN has shown the ability to create undercut profiles. [7] An example of such an etch is shown in Figure 8.

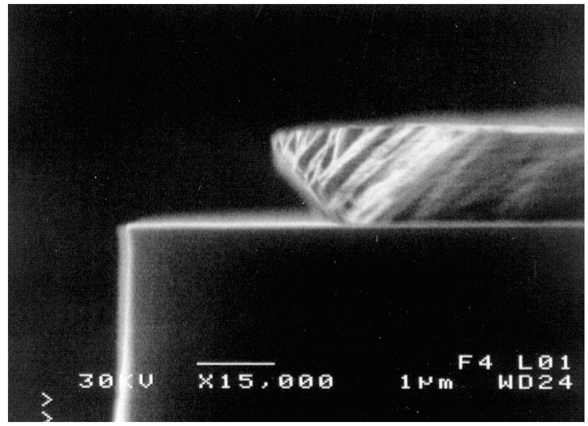

FIG. 8. SEM micrograph showing undercut anisotropic etching of GaN grown on a sapphire substrate.

The procedure is a two step process, with one etch establishing depth (possibly RIE or PEC), and the second creating the undercut profile. We have observed undercut planes using heated (~80ºC) tetramethyl ammonium hydroxide (TMAH) and tetraethyl ammonium hydroxide (TEAH). These etchants do not create etch pits on the surface, and have negligible etch rate in the vertical direction. They are also observed to clean residual roughness left behind by the first etch step. We are currently working to apply this etch technique to device applications.

SUPERLATTICE DOPING

Increasing the acceptor activation efficiency is a fundamental approach toward decreasing resistance of p-GaN. Modulation of the valance band edge in wide band gap semiconductors was originally proposed as a method of increasing ionization of deep acceptors. [8] This modulation can be realized using a AlGaN/GaN superlattice, as shown in Figure 9,

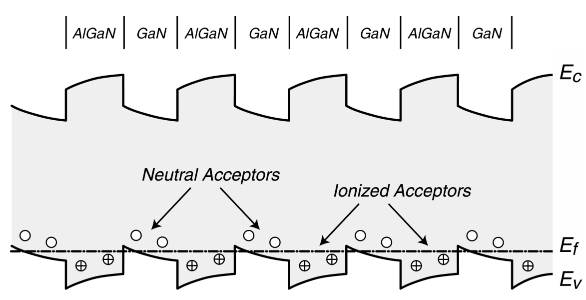

FIG. 9. Band diagram of an AlGaN/GaN superlattice showing ionized acceptors in the barriers and neutral acceptors in the wells.

Recent experimental results have shown the conductivity of such structures to be around one order of magnitude greater than bulk p-GaN layers [9,10]. This increase has been attributed to both tunneling and polarization effects.

The use of such material in the base of a GaN HBT could potentially improve base resistance. Holes traveling parallel to the SL layers from the active device area to the base contact would see a decreased resistance over bulk material. However, injected electrons traveling toward the collector (and hence perpendicular to the SL layers) could be trapped by the quantum wells, significantly decreasing the base transport factor. Hot electron transport, where electrons are injected from a wide-gap base into the base at an energy exceeding the conduction band edge energy of the superlattice, could in theory enable efficient transport across the base layer.

CONCLUSIONS

The sources of base resistance in GaN-based heterojunction bipolar transistors have been examined and solutions presented ranging from novel fabrication techniques (PEC and crystallographic etching) to the use of AlGaN/GaN superlattice structures. A new type of metal-semiconductor ohmic contact has been proposed and demonstrated. Each of these concepts has the potential to decrease base resistance in GaN-base *N-p-n* heterojunction bipolar transistors.

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