## The Heterogenous Integration of GaN Thin-Film Metal–Semiconductor–Metal Photodetectors Onto Silicon

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Abstract—The heterogeneous integration of GaN thin-film metal-semiconductor-metal (MSM) photodetectors onto a host substrate of SiO<sub>2</sub>–Si is reported herein. Thin-film GaN photodetectors were separated from the lithium gallate (LiGaO<sub>2</sub>) growth substrate using selective etching, and contact bonded onto an SiO<sub>2</sub>–Si host substrate. The thin-film MSMs exhibited a dark current of 13.36 pA and an UV photoresponse at 308 nm of 0.11 A/W at a reverse bias voltage of 20 V. This first demonstration of GaN thin-film device integration onto SiO<sub>2</sub>–Si using a low-temperature integration process, combined with the advances in GaN material quality on LiGaO<sub>2</sub> substrates, enables the integration of GaN devices with Si circuitry for heterogeneously integrated systems.

Index Terms—GaN photodetector, heterogeneous integration, thin-film GaN.

ALLIUM NITRIDE (GaN) materials have been inten- $\mathbf{T}$  sively studied for ultraviolet and blue optical devices, and for high-power and high-temperature electronic devices. As the material quality of GaN has improved, the prospects for heterogeneous integration of GaN devices with host substrates are of interest. The heterogeneous integration of GaN thin-film devices with host substrates such as Si-integrated circuits offers opportunities which include advanced signal processing for integrated UV optical imaging arrays, and advanced packaging and automated tuning for high-power devices. Thus, a great deal of recent research into GaN growth and integration has focused upon achieving device quality GaN epitaxial material concurrent with an integration process. As an example, Wong reported a process to separate thin-film GaN-based device using a laser separation technique that decomposes the interface between the GaN and the sapphire substrate [1], [2].

In this letter, an alternative approach to the heterogeneous integration of GaN onto host substrates is reported. This work utilizes GaN epitaxial material grown on lithium gallate (LiGaO<sub>2</sub>) substrates, which is more closely lattice matched to GaN than sapphire. The process used to separate the thin-film devices from the growth substrate utilizes a simple selective wet chemical etch and bonding process, which are demonstrated in this letter. The test results of the thin-film GaN metal–semiconductor–metal (MSM) photodetectors bonded to

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 $SiO_2$ -Si host substrates reported in this letter shows that the GaN-LiGaO<sub>2</sub> device performance and the low-temperature heterogeneous integration process described herein produces highly competitive integrated device characteristics, as well as the prospect for integration with Si-integrated circuits.

Key to the heterogeneous integration process is the growth of GaN epitaxial layers on lithium gallate (LiGaO<sub>2</sub>) substrates. The most widely used substrates for the growth of GaN epitaxial layers are sapphire (Al<sub>2</sub>O<sub>3</sub>) and SiC [3], [4]. Currently, lithium galate costs  $\sim$ 3 times more than sapphire (with almost no market) and  $\sim$ one to five times less than SiC depending on the crystal quality and doping concentrations needed. Although lithium gallate is still expensive compared to sapphire, the price will drop as the market for LGO grows. Additionally, the inexpensive Czochralski growth technique used to grow LGO is cheaper than competing substrate growth technology with 2-in substrates already demonstrated. <sup>1</sup>

The selection of the substrate strongly influences the quality of the epitaxial nitrides, and thus, the device quality. The large lattice mismatch of GaN films on these substrates imposes constraints on the GaN film quality. The growth of GaN epitaxial layers on lithium gallate (LiGaO<sub>2</sub>) offers distinct advantages toward achieving device quality material and integration. Hexagonal GaN has a lattice mismatch of only -0.19% to the b-axis of LiGaO<sub>2</sub> [5]. The dislocation density of GaN grown on LiGaO<sub>2</sub> is approximately  $2 \times 10^7$  cm<sup>-2</sup> [5], [6], compared to  $10^9-10^{11}$  cm<sup>-2</sup> for direct heteroepitaxial growth approaches for GaN on sapphire. X-ray measurements indicate the high crystalline quality of GaN grown on LiGaO<sub>2</sub>, producing a full-width at half-maximum (FWHM) of 100-180 arcsec for a [00.4] reflection and 200-300 arcsec for a [10.5] reflection. In addition to this small lattice mismatch and device quality material, the most attractive aspect of growing GaN on LiGaO<sub>2</sub> is that the LiGaO<sub>2</sub> substrate can be selectively removed from the GaN epitaxial layer using wet etching, which is a standard microelectronic fabrication process that is well understood, simple, and low cost to implement.

The unintentionally doped (0001) GaN MSM photodetector on (001) LiGaO<sub>2</sub> was grown using plasma-assisted radio frequency molecular beam epitaxy. Fig. 1(a) shows a schematic cross-sectional view of the epitaxial layer. Five periods of a  $Al_{0.4}Ga_{0.6}N$ –GaN superlattice were deposited as a part of the nucleation layer, followed by a 1- $\mu$ m thick unintentionally

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Pt/Au 1µm GaN AlGaN/GaN superlattice GaN nucleation layer LiGaO2

(a) (b)

Fig. 1. (a) Schematic cross section of the GaN MSM photodetector, and (b) photomicrograph of an interdigitated GaN MSM.



Relative 2- $\theta$  Angle (arcsec)

(a)

(b)

Fig. 2. (00.4) X-ray reflection scan of GaN. The measured FWHM is 130 arcsec. (10.5) reflection is shown in the inset (FWHM  $\sim$  300 arcsec).

doped GaN epitaxial layer. We have found Li diffusion to be controllable during the growth by incorporating appropriate gettering layers. Li is incorporated as a substitutional impurity, and thus, is immobile after the growth [5], [7]. The gettering layer can be pure AlGaN or AlGaN–GaN supperlattices. Secondary ion mass spectroscopy (SIMS) profiles show that the Al containing layer effectively blocks Li outdiffusion from the LiGaO<sub>2</sub> growth substrate.

The structural quality of the film was measured using X-ray rocking curves recorded with a Bede QC2 double axis diffractometer equipped with a Cu tube. The FWHM values of the film from X-ray diffraction measurements were 130 arcsec for the (00.4) plane reflection [Fig. 2(a)] and about 300 arcsec for the (10.5) reflection [Fig. 2(b)]. The electrical characterization by Hall effect measurement was not possible due to the high resistivity of the sample. The background free-carrier concentration was conservatively estimated to be below  $10^{15}$ /cm<sup>3</sup> based on the flat-band voltage [8].

Metal-semiconductor-metal (MSM) photodetectors were fabricated and tested before and after thin-film integration. The interdigitated finger MSM devices used for all measurements were 47  $\mu$ m long, with 2- $\mu$ m finger width and 5- $\mu$ m finger Fig 3. GaN thin-film MSM detector bonded onto SiO2-Si host substrate.

spacing, and a detection area of  $50 \times 50 \ \mu m^2$ . A photomicrograph of an onwafer GaN–LiGaO<sub>2</sub> MSM is shown in Fig. 1(b). The devices were fabricated using standard photolithography to pattern photoresist with a subsequent metallization, and liftoff process to define metal Schottky metal contacts on the GaN. The Schottky contacts were 500 Å Pt/2000 Å Au, deposited using electron beam evaporation. A cleaning step used to remove the oxide on the GaN surface using hydrofluoric (HF) acid for 1 min and warm ammonium hydroxide (NH<sub>4</sub>OH) for 15 min prior to the metallization lowered the MSM dark current by several orders of magnitude.

The thin-film integration process began on the GaN–LiGaO<sub>2</sub> grown sample. Mesas in the GaN were patterned using a photoresist mask and dry etching in a plasma therm inductively coupled plasma (ICP) system using Cl<sub>2</sub>–BCl<sub>3</sub>–Ar gases with flow rates of 8 sccm/12 sccm/5 sccm operating at a 500 W plasma power, 90 V dc bias, and a substrate holder temperature of 15 °C Under these conditions, the etch rate of the GaN ranged from 2000 Å–2400 Å per minute, while the etch rate of the LiGaO<sub>2</sub> substrate was approximately <10 Å/min. Thus, the mesa etch stops at the GaN–LiGaO<sub>2</sub> growth interface. The GaN mesas were then coated in Apiezon W (black wax) to protect and support the GaN mesas during the subsequent LiGaO<sub>2</sub> substrate removal process.

The GaN epitaxial layer is impervious in terms of practical etch rate to most wet chemical acid solutions, thus, removal of the LiGaO<sub>2</sub> substrate from the GaN epitaxial layer is highly selective. The sample was immersed in  $HF: H_2O(1:10)$  for approximately 2 h to remove the LiGaO<sub>2</sub> substrate. The etch rate of the LiGaO<sub>2</sub> substrate in HF: H<sub>2</sub>O (1:10) is approximately 4.5  $\mu$ m/min. The mesas embedded in the Apiezon W were bonded to the SiO<sub>2</sub> (9000 Å) coated Si substrate through contact bonding. The Apiezon W is then dissolved with trichloroethylene, leaving the thin-film devices bonded to the SiO<sub>2</sub>-Si host substrate. Fig. 3 is a scanning electron microscope picture of a 170  $\mu$ m × 90  $\mu$ m mesa, 1- $\mu$ m-thick GaN thin-film MSM photodetector bonded to a SiO<sub>2</sub>-Si substrate. Notable in this procedure is the low temperature of the process, which predicts the successful implementation of this approach for integration with Si CMOS circuitry.



1000

800

600

400

200

0

-200

Intensity (A.U.)



Fig. 4. Dark I-V (a) characteristics and (b) responsivity of GaN MSM before and after bonding.

The dark current and photoresponse of the GaN MSMs before and after bonding were measured. A Keithley 617 electrometer was used to measure the current–voltage (I-V) performance of the MSM detector. A 250-W tungsten lamp was used for photoresponse measurements. The light from the source was colliminated and focused onto the MSM using calcium fluoride lenses. A laser line filter at 308 nm (with a bandwidth of 10 nm) was used to filter the incident optical beam. The optical system utilized in this study was calibrated with an ultraviolet enhanced calibrated Si photodetector and a Newport 1853 optical power meter.

The measured dark currents and responsivities for the onwafer MSMs and the thin-film MSMs after bonding to the SiO<sub>2</sub>–Si host substrate are shown in Fig. 4. The dark currents of 0.58 pA at 5 V and 11.46 pA at 50 V onwafer degrade slightly to 0.63 pA at 5 V and 13.36 pA at 50 V after bonding, as shown in Fig. 4(a). This degradation is within the error tolerance of the measurements. The 10-V low bias dark current of 1.01 pA of the thin-film GaN MSM detector is comparable to the best reported low bias dark current of 0.8 pA at 10 V for onwafer MSMs with similar area and finger spacing, but with a 4  $\mu$ m thick GaN layer [9]. The best reported 1- $\mu$ m-thick GaN

onwafer MSM had a dark current of approximately 50 pA at 10 V [9]. Also notable is that this thin-film device exhibits no reverse bias breakdown up to 100 V.

The measured responsivity values of the thin-film GaN MSM, with no antireflection coating, of 0.11 A/W at 20 V and 0.22 A/W at 50-V reverse bias conditions before bonding, decreases to 0.09 A/W and 0.22 A/W, respectively, at the same bias condition after thin-film processing and bonding, as shown in Fig. 4(b). These results are competitive with the best reported responsivity results, which are for a 4- $\mu$ m-thick antireflection coated GaN onwafer MSM with a responsivity of 0.15 A/W at a 20-V bias condition [9].

In summary, the fabrication, heterogeneous integration onto a  $SiO_2$ -Si host substrate, and characterization of a GaN thin-film MSM photodetector is reported. The dark current before and after bonding is competitive, and does not change significantly after integration. The responsivity is slightly decreased after bonding, but is competitive with onwafer devices. This first demonstration of GaN thin-film device integration using simple selective chemical etching, contact bonding, and low-temperature processing for integration predicts the successful heterogeneous integration of GaN thin-film devices with Si-integrated circuitry for advanced heterogenous integrated systems, which include GaN materials and devices.

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