Characterization of Strained AlGaN/GaN HEMTs on CMP-thinned Si Substrates

Marko J. Tadjer[1,a], Travis J. Anderson[2], Andrew D. Koehler[2], Jordan D. Greenlee[3],
Karl D. Hobart[2], Fritz J. Kub[2]

[1]American Society for Engineering Education, Washington DC, 20036, USA.
[2]United States Naval Research Laboratory, Washington DC, 20375, USA.
[3]National Research Council, Washington DC, 20001, USA.
[a] marko.tadjer.ctr@nrl.navy.mil

Keywords: wide bandgap, GaN, HEMT, CMP, substrate, strain, degradation, wafer bow, Hall effect

Abstract

The effect of substrate thinning on the characteristics of AlGaN/GaN high electron mobility transistors (HEMTs) on Si substrates was studied. Wafers of AlGaN/GaN on 575 µm thick 4-inch (111) Si substrates were thinned to 200 µm and 150 µm. The increase in strain, measured by wafer curvature interferometry and Raman spectroscopy, was inversely proportional to final substrate thickness. However, the Lehighton-measured sheet resistance remained stable on the thinned HEMT structures. Shallow cracks in the AlGaN barrier and increased sheet resistance after Ohmic contact annealing showed that high temperature processing induced relaxation detrimental to the heterostructure. The resulting transistors therefore exhibited relatively low drain current density.

INTRODUCTION

III-Nitride high electron mobility transistors (HEMTs) on large area, low cost Si substrates have attracted much attention from the commercial RF device community due to steady advances in epitaxial growth, material quality, and device performance. However, higher resistivity and thermal conductivity SiC substrates have proven superior for HEMT power applications. To improve the breakdown voltage and thermal profiles of GaN-on-Si HEMTs, techniques such as localized etching of the Si substrate in the access region or transfer of the III-N epitaxial layers onto alternative substrates such as quartz and diamond have been reported [1-3]. Azize has studied the effect of gradual backside substrate dry plasma etching on the AlGaN/GaN heterostructure [4]. While an increase in 2DEG carrier density (N_{SH}) was reported when the substrate was thinned from 500 to 350 µm, a plastic deformation of the structure occurred when the substrate thickness was further reduced to 150 um, evidenced by cracks in the GaN epi and reduced electrical performance. In this work, we quantify the influence of chemical mechanical polishing on the substrate-induced strain and HEMT performance. We further address the possibility for minimizing performance degradation by post-CMP localized substrate etching.

EXPERIMENTAL

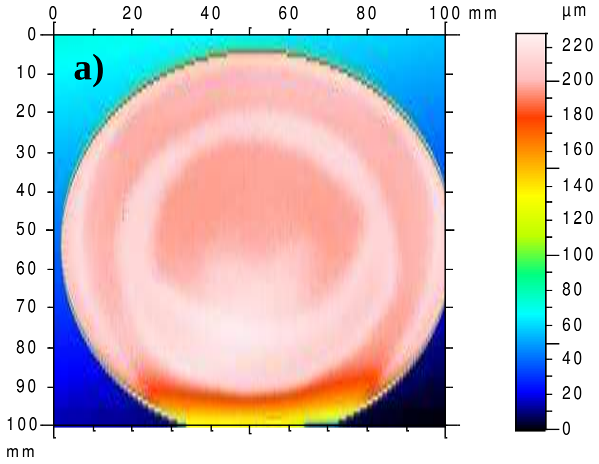
Four-inch wafers of commercially available $Al_{0.27}Ga_{0.73}N$/GaN HEMT structures grown by metalorganic CVD on 575 µm thick (111) Si substrates were thinned by backside grinding and chemical-mechanical polishing (CMP) to 200 µm and 150 µm. HEMT devices were processed on samples diced from the 200 µm thick wafer. Standard sample handling and fabrication methods were employed: Cl-plasma mesa etching, Ti/Al/Ni/Au Ohmic contacts alloyed by rapid-thermal annealing, Ni/Au gate lift-off, followed by a 100 nm thick plasma-enhanced CVD SiN passivation and 220 nm thick Ti/Au contact pads.

RESULTS AND DISCUSSION

The average sheet resistance (R_{SH}), measured by a non-contact Lehighton instrument over the entire wafer, increased by less than 5% in both cases (Table I).

TABLE I. COMPARISON OF ALGAN/GAN HEMTS AS A FUNCTION OF SUBSTRATE THICKNESS AND HIGH TEMPERATURE ANNEALING.

Wafer/ Sample	Thickness µm	R_{SH} Ω/sq.	ΔR_{SH} %	$E_{2,GaN}$ cm^{-1}	$\Delta\sigma_{XX}$ GPa	Bow µm
A	575	480.6	-	567.03	-	41
B	200	501.7	4.3	567.31	0.81	220
B+RTA	200	1289	168	567.49	1.33	-
C	150	504.2	4.9	567.52	1.42	314



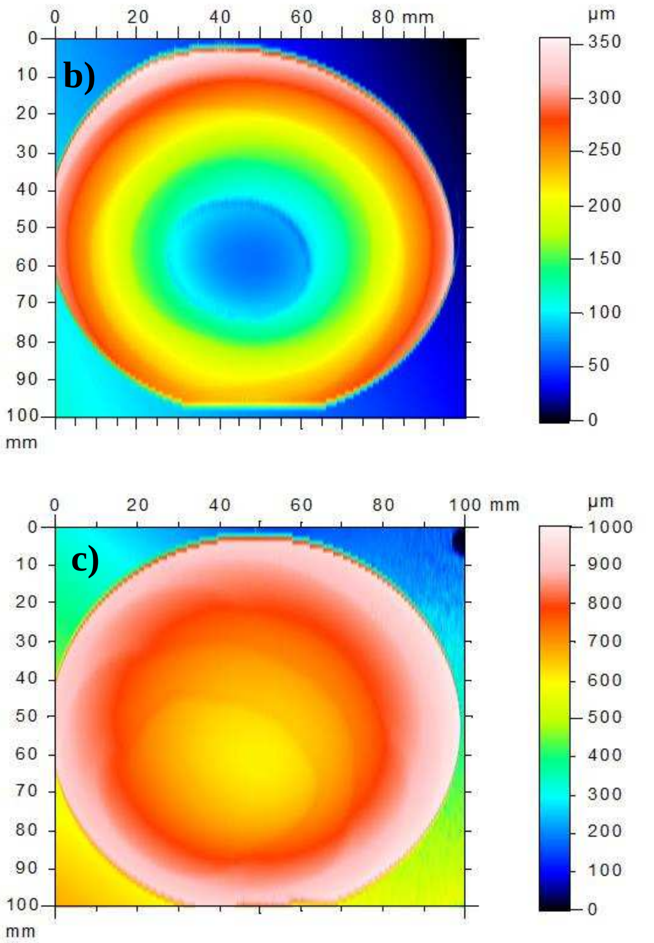


Fig. 1. Bow profiles of a) wafer A (575 µm thick Si substrate), b) wafer B (200 µm thick Si substrate), and c) wafer C (150 µm thick Si substrate).

From the maps in Fig. 1, the bow parameters of wafers A, B, and C were measured to be concave with values of 41 µm, 220 µm, and 314 µm, respectively. The Raman frequency of the GaN buffer E_2 phonon line, stimulated using a 532 nm green laser, was used to calculate the additional in-plane stress caused by substrate thinning for each wafer [5]. Fig. 2a shows the E_2 phonon lines for wafers A and C. The blue shift in the E_2 phonon line of wafer C, relative to that of wafer A, indicated additional compressive stress. For wafers B and C, this additional stress was calculated to be 0.83 and 1.42 GPa, respectively.

An additional sample from wafer B (200 µm thick) was subjected to the conditions of the Ohmic contact rapid thermal annealing process (850 °C, 30 sec., N_2). A further increase in both R_{SH} and compressive stress were observed (Fig. 2b, Table I). Therefore, substrate thinning and subsequent annealing introduced compressive stress in the substrate, which counteracted the tensile strain in the AlGaN barrier, reducing the piezoelectric polarization and N_{SH}, resulting in increased R_{SH}.

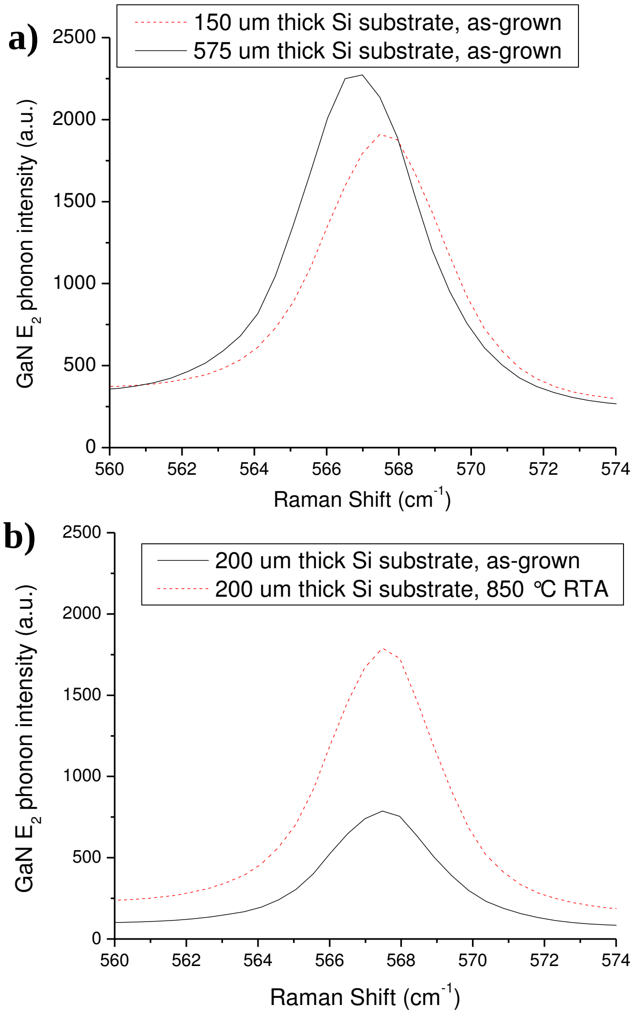


Fig. 2. Raman spectra of the GaN E_2 phonon lines for a) wafer C before and after thinning to 150 µm, and b) a sample from wafer B before and after an 850 °C, 30 sec. anneal in N_2 atmosphere.

Surface morphology of the AlGaN/GaN heterostructures was evaluated by atomic force microscopy (AFM). Substrate thinning by did not significantly change the rms roughness of the unprocessed material (Fig. 3a). However, upon annealing the contacts, shallow cracks in the AlGaN barrier layer were observed (Fig. 3b), which supported the increased stress indicated by the E_2 phonon blueshift (Fig. 2b) and sheet resistance (Table I).

The DC current-voltage characteristics are presented in Fig. 4. Hall measurements indicated a reduction in N_{SH} by about a factor of 3 to ~$3x10^{12}$ cm^{-3}, consistent with the increase in R_{SH} measured on the RTA-annealed control sample (Table I).

While RTA-induced R_{SH} degradation can be avoided either by Ohmic contact deposition prior to substrate thinning or employing a nonalloyed Ohmic metallization process, the presented experiment confirms the fragility of

AlGaN/GaN heterostructures caused by the large thermal mismatch to (111) Si.

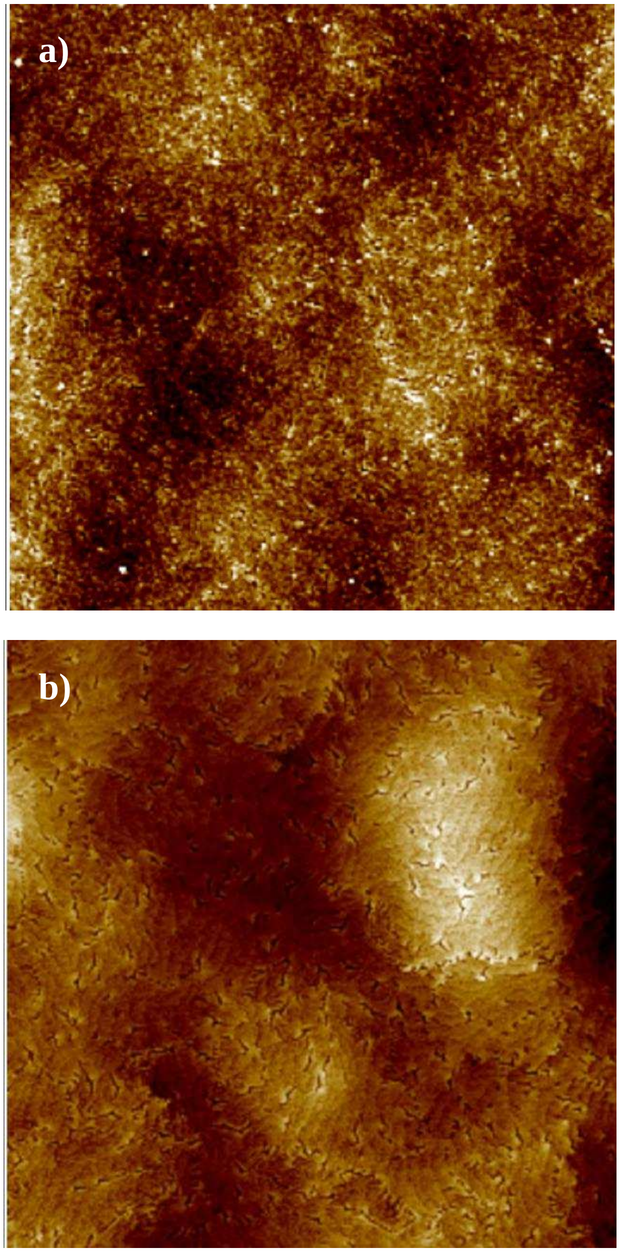


Fig. 3. Atomic force microscope images of the AlGaN surface of a sample from wafer B a) before and b) after an 850 °C, 30 sec. anneal in N_2 atmosphere. Each image covers a 5x5 µm surface area.

CONCLUSIONS

The effect of Si substrate thinning on the electrical characteristics and surface morphology of AlGaN/GaN HEMTs was presented. Raman spectroscopy indicated the introduction of additional compressive stress in the structure, which counteracted the piezoelectric-induced tensile stress in the III-nitride and caused the sheet resistance to increase and the HEMT drain current to decrease. Cracks in the AlGaN surface were observed as well, similarly to the work of Azize, indicating the possibility of partial plastic relaxation in the heterostructure.

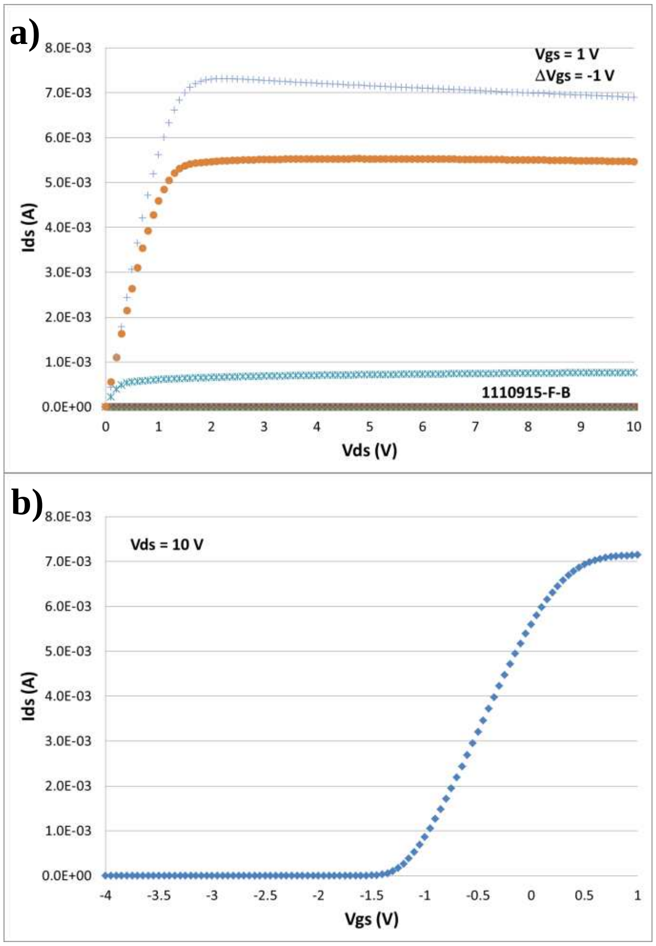


Fig. 4. a) I_{DS}-V_{DS} characteristics of HEMTs fabricated on samples from wafer B, CMP-thinned to 200 µm. b) I_{DS}-V_{GS} (V_{DS} = 10 V) characteristics of HEMTs fabricated on samples from wafer B (200 µm thick).

ACKNOWLEDGEMENTS

M.J.T. acknowledges support from the American Society for Engineering Education NRL Postdoctoral Fellowship program. J.D.G. acknowledges support by the National Research Council. The authors are grateful to the NRL Nanoscience Institute Staff for processing support. Research at NRL was supported by the Office of Naval Research.

REFERENCES

[1] N. Herbecq, et al., Appl. Phys. Express 7, 034103 (2014).
[2] B. Lu and T. Palacios, IEEE Electr. Dev. Lett., vol. 31, no. 9, pp. 951-953, 2010.
[3] K.D. Chabak, et al., IEEE Electr. Dev. Lett., vol. 31, no. 2, pp. 99-101, 2010.
[4] M. Azize and T. Palacios, J. Appl. Phys. 108, 023707 (2010).
[5] M. Kuball, Surface and Interface Analysis, vol. 31, no. 10, pp. 987-999, 2001.