GaN-on-Si membranes for power device applications: Stress evolution throughout fabrication

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Keywords: GaN, transistors, stress, membrane, power devices

The effect of local substrate and buffer layer removal in GaN-on-Si membrane structures is explored with respect to residual stress and out-of-plane displacement. Contact profilometry showed good agreement with the COMSOL Multiphysics® model, which was used to infer mechanical stress throughout the membrane fabrication process. Out-of-plane displacement up to 40 µm for a membrane with a diameter of 10 mm was observed, and found to be either convex, concave or a mixture of both simultaneously, depending on the 3-dimeonsional membrane geometry. The results provide a guide for design of vertical GaN-on-Si transistors, and highlight the trade-off between device size and the effects of residual stress and out-of-plane displacement.

INTRODUCTION

Vertical GaN transistors are promising candidates for next generation power electronic applications including transportation, communication and power distribution, offering exceptional power density and on-resistance at breakdown voltages >1200 V [1]. Technology transfer from native GaN substrates to affordable, sustainable non-native substrates such as Si is critical to ensuring maximum impact in mass market applications, though this introduces significant technical challenges, with breakdown voltage in initial attempts limited to <1000 V due to breakdown along threading dislocations and material defects [2]. This work explores the effect of local substrate and epitaxial layer removal on mechanical stress in a GaN-on-Si membrane structures, with a view to enhancing breakdown field in the active GaN layer by removal of material with high dislocation density, facilitated through use of a buried n+GaN drain contact layer (Fig. 1(a)).

METHODOLOGY

The COMSOL Multiphysics package® was used to model mechanical stress in 3-dimensional GaN-on-Si membrane structures (Fig. 1(b)), with a layer stack of Si substrate (200 µm), AlN nucleation layer (150 nm), AlGaN strain relief layer (4.5 µm) and GaN drift layer (1.6 µm). Initially, a planar GaN-on-Si platform is modelled (with no local substrate removal), with in-built strain already present due to the large difference in thermal expansion coefficients between the Si substrate and epitaxially grown III-nitride materials, and the requirement for high growth temperatures [3]. A cylindrical volume was then defined in the center of the sample (Fig. 1(b)) and the effect of removing material from the Si substrate side on mechanical deformation and localized residual stress was observed using the thermal stress module. The solid mechanics boundary conditions consist of two symmetry conditions to reduce the model size (i.e. only a quarter of the sample is simulated with the cylinder axis in the center) and two fixed point conditions at the edges of the cylinder on the symmetry plane to prevent the model from

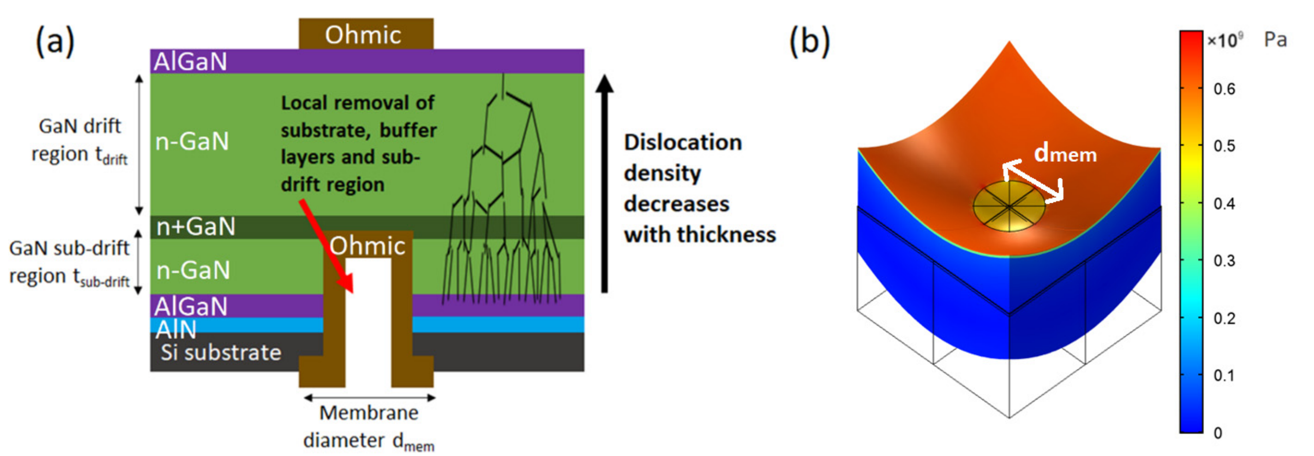

Fig. 1. (a) Cross-section schematic and (b) 3D stress model of GaN-on-Si membrane.

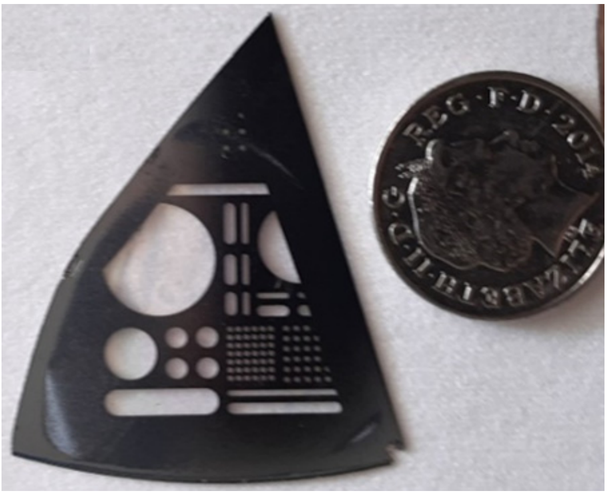

Fig. 2. GaN-on-Si membranes (full Si substrate removal only) of varying shapes and sizes with a 10 pence coin for scale.

sliding in the *z*- direction. For the thermal stress model, the strain reference temperature is defined as 1150°C and the ambient temperature is defined as 25°C. The model was compared with experimental measurements using planar GaN-on-Si samples, characterized using contact profilometry, with model material properties taken from literature sources or extrapolated using Vegard's law when necessary [4]. Membrane bow was calibrated through measurement of out-of-plane displacement of circular membranes of varying diameter fabricated using a modified Bosch deep Si plasma etch (Fig 2, with more details of the fabrication process in [5]).

RESULTS AND DISCUSSIONS

Residual mechanical stress at the center of a 2 mm diameter membrane throughout the membrane formation process (assuming damage-free layer removal by optimized etch processing [5, 6]) is shown in Fig. 3. Initially (i), the thick Si substrate is relaxed, with residual stress distributed across the III-nitride epilayers according to their relative thickness and mechanical properties. This stress is redistributed as the substrate is locally thinned (ii), with a progressive decrease in the AlGaN strain relief layer and GaN drift layer correlating with an increase in the AlN nucleation layer and remaining Si substrate of similar magnitude. Following complete local removal of the substrate and thin AlN growth nucleation layer (iii), stress in the AlGaN and GaN layers rises gradually as the total membrane thickness is further reduced, with stress in the GaN layer tending to its initial value prior to local substrate removal as it is thinned further. It is noted that stress in the GaN and AlGaN layers does not exceed initial values, in contrast to that of the AlN and Si substrate layers. In all cases the yield stress of each material is not exceeded, explaining the apparent high mechanical stability despite thickness/diameter ratios exceeding 1000. In contrast,

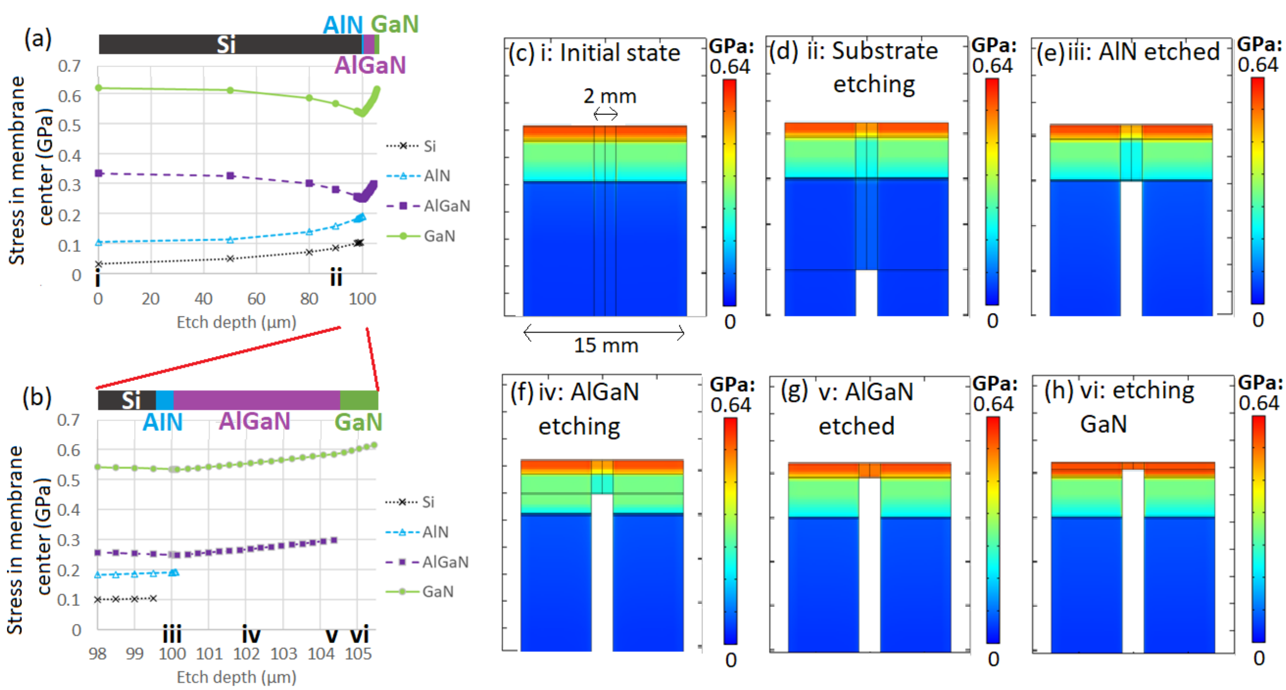

Fig. 3. (a) Residual stress in 2 mm GaN-on-Si membrane structures following local removal of the Si substrate and subsequent AlN, AlGaN and GaN epilayers. (b) shows the same but focused on the III-nitride epilayers. Residual stress maps of cross sections of membranes throughout the removal process, corresponding to points i-vi in (a) and (b), are shown in (c)-(h).

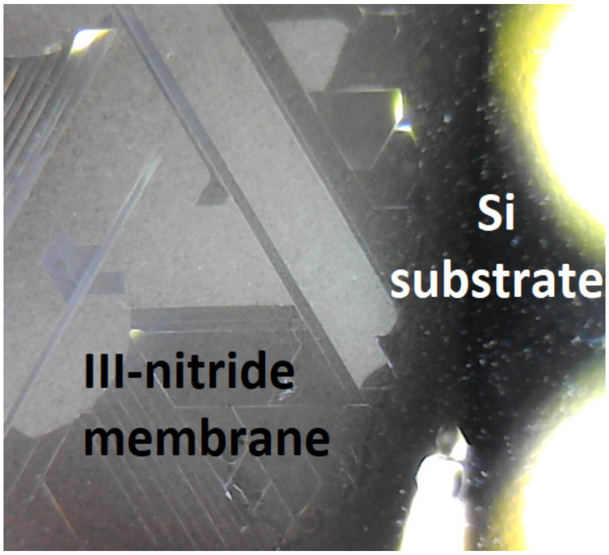

Fig. 4. GaN-on-Si membranes with sharp corners cracking during fabrication, with the hexagonal shape characteristic of the wurtzite GaN crystal structure.

membranes with geometries featuring sharp corners (unlike the curved shapes shown in Fig. 2) were more susceptible to cracking along crystallographic planes during membrane fabrication and subsequent processing [6, 7] (Fig. 4), suggesting increased localized stress associated with geometric discontinuities, to be a focus of future work.

The membrane fabrication process results in an out-of-plane displacement of the membrane in response to the redistribution of mechanical stress. Circular membranes with 0.5 mm diameter show a local concave out-of-plane displacement of less than 100 nm following Si substrate removal (Fig. 5(a)). The model demonstrates a similarly small value of bow which increases following further removal of III-nitride epilayers. Underestimation of the exact value of bow by the model is attributed to uncertainties in the absolute dimensions of the 3-dimensional structure. As the membrane diameter is increased to 1 mm the displacement becomes convex, subsequently increasing sharply to a maximum displacement of 40 µm for a membrane diameter of 10 mm (Fig. 6). The profile of the out-of-plane displacement for the 10 mm diameter membrane is shown in Fig. 5(b). It is notable that while the displacement at the membrane center is strongly convex, there is a relatively small (~2 µm) concave displacement at the border region close to the remaining Si substrate. For circular membranes this feature lacks radial symmetry, and similar features with alternating convex and concave bow were observed in the elongated membrane shapes shown in Fig. 2. While the precise nature of such features is still under investigation, it is noted that the model predicts a reduction in the maximum out of-plane-displacement as the membrane thickness is reduced following removal of the AlGaN strain relief and AlN nucleation layers (Fig. 5), with a concave displacement in the membrane center compensating a convex displacement at the edge.

The capacity for stress compensation by local deformation in GaN-on-Si contrasts and complements previous results on GaN-on-diamond membrane structures [5, 7]. While diamond layers can be deposited on GaN membranes by chemical vapour deposition at high temperature, the resultant deformed GaN-on-diamond membrane is dependent upon the initial stresses and deformation of the membrane; since the diamond has a low thermal expansion coefficient and high mechanical rigidity, the membrane is effectively held in its deformed state. The presented work demonstrates that the structural deformations can be anticipated prior to diamond growth and

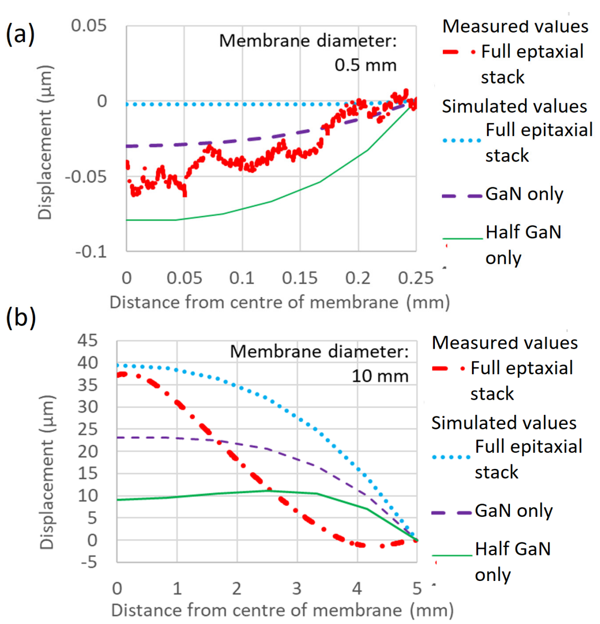

Fig. 5. Local out-of-plane displacement in circular GaN-on-Si membranes with diameter (a) 0.5 mm and (b) 10 mm following substrate removal, with the simulated effect of further layer thinning also shown.

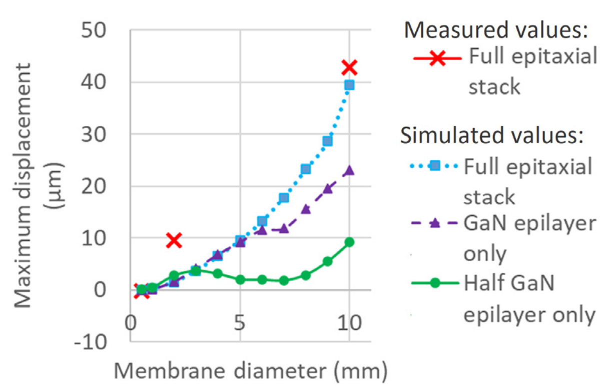

Fig. 6. Maximum out-of-plane displacement of GaN-on-Si membranes of different diameters following substrate removal, with the simulated effect of further layer thinning also shown.

strategies to minimize this bow can and are currently being investigated through modelling. Additionally, this work has positive implications for large area GaN-on-Si power devices, with implementation of buried n+GaN embedded epitaxial contact layers (Fig. 1(a)) in recently demonstrated 20 µm thick GaN-on-Si epitaxial structures [8] enabling optimal design to achieve maximum voltage blocking capability without mechanical failure during fabrication and operation. The effect of top-side device fabrication processes on pre-fabricated GaN-on-Si membrane structures, such as metal deposition and annealing, are not expected to induce mechanical failure (providing membrane sharp corners avoided), as stress values are expected to remain below yield values for curved membrane geometries. However, the localized out-of-plane displacement is likely to introduce additional challenges to lithographic, etch and deposition processes in the fabrication of power devices with sub-µm features, which typically require planar surfaces for high resolution and good uniformity. As such it is advisable to fabricate devices on planar GaN-on-Si wafers prior to large-area membrane formation, with thick photoresist sufficient to protect against the ambient plasma environments used to etch the Si substrate [5] and subsequent III-nitride epilayers [6] for back-end electrical contact as in Fig. 1(a). Subsequent work will further investigate the mechanisms underpinning the alternating orientation of displacement within a single membrane, and explore techniques to minimize maximum displacement through optimisation of the 3-dimensional membrane geometry, including corner-smoothing to reduce peak stress and implementation of more complex structures.

Conclusions

The effect of local substrate removal on residual stress and mechanical displacement in GaN-on-Si structures was investigated. Membranes undergo out-of-plane displacement in response to the redistribution of local stress during the fabrication process, resulting in concave bow for small circular membranes and net convex bow for large membranes, to a total of 40 µm for a diameter for 10 mm. For circular membranes stress remains below critical values and mechanically stable structures with aspect ratios exceeding 1000 were realized. Alternating concave and convex regions within the same membrane were observed, with the model suggesting such compensation of maximum displacement may be exploited through optimisation of membrane design.

Acknowledgements

This project has been supported by Engineering and Physical Sciences Research Council (EPSRC) under program Grant GaN-DaME (EP/P00945X/1). J. A. Cuenca is an EPSRC Postdoctoral researcher.

References

[1] Y. Zhang et al., IEEE Elec. Dev. Lett. 40(1), 75 (2019)

[2] S. Benedorfer et al., : J. Appl. Phys. 127, 015701 (2020)

[3] J. A. Cuenca et al., Carbon 174, 647 (2021)

[4] W. Liu et al., J. Appl. Phys. 97, 073710 (2005)

[5] M. Smith et al., AIP Advances 10, 035306 (2020)

[6] M. Smith et al., Appl. Surf. Sci. 521, 146297 (2020)

[7] D. Field at al., ACS Appl. Mater. Interfaces. 12(48) 54138 (2020)

[8] A. Tanaka et al., Adv. Mater. 29(38) 1702557 (2017)