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Stretchable AlGaN/GaN High Electron Mobility Transistors

by Randy Tompkins and Nathan Lazarus

NOTICES

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Sensors and Electron Devices Directorate, CCDC Army Research Laboratory

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14. ABSTRACT

Creating electronics able to stretch to conform to soft, highly deformable surfaces such as skin or clothing has opened up new application areas ranging from medical diagnostics and therapy to soft robotics. The wide, direct band gap gallium nitride (GaN) makes it a promising material for the high-power, high-frequency electronic devices necessary for efficiently conditioning wirelessly coupled power in stretchable systems. Since most stretchable electronics are intended to interact with soft biological tissue such as human skin, efficiency, reduction of resistive losses and resulting heat generation become particularly important. Since human skin can stretch up to 100% in certain parts of the body, creating truly stretchable GaN devices becomes necessary for wearable systems. In this work we propose fabricating the first stretchable GaN high electron mobility transistor (HEMT) by fabricating transistors in specialized wavy patterns that are known to reduce the peak mechanical stress during stretching in other material systems.

15. SUBJECT TERMS
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1. Motivation

Creating electronics able to stretch to conform to soft, highly deformable surfaces such as skin or clothing has opened up new application areas ranging from medical diagnostics and therapy to soft robotics.[1] The wide, direct band gap gallium nitride (GaN) makes it a promising material for the high-power, high-frequency electronic devices necessary for efficiently conditioning wirelessly coupled power in stretchable systems. Since most stretchable electronics are intended to interact with soft biological tissue such as human skin, efficiency, reduction of resistive losses and resulting heat generation become particularly important. Since human skin can stretch up to 100% in certain parts of the body, creating truly stretchable GaN devices becomes necessary for wearable systems. In this work we propose fabricating the first stretchable GaN high electron mobility transistor (HEMT) by fabricating transistors in specialized wavy patterns that are known to reduce the peak mechanical stress during stretching in other material systems.[2]

2. Task 1: Mechanical Modeling

Using COMSOL Multiphysics 3.3, we modeled (0001) GaN and (100) silicon (Si) structures in multiple stretchable geometries by solving Hooke's law for continuous media and recording the peak von Mises stress. After applying a 30% strain, we observe up to a 98% reduction in peak stress in GaN as shown in Fig. 1 by going to stretchable geometries compared to the conventional straight geometry and up to a 92% reduction in Si. In addition, GaN is rotationally invariant in plane in the most commonly used crystal growth plane, unlike Si; this results in no change in the peak von Mises stress in GaN with in-plane rotation, whereas a 17% variation was observed in Si for rotations about the [001] direction.[3]

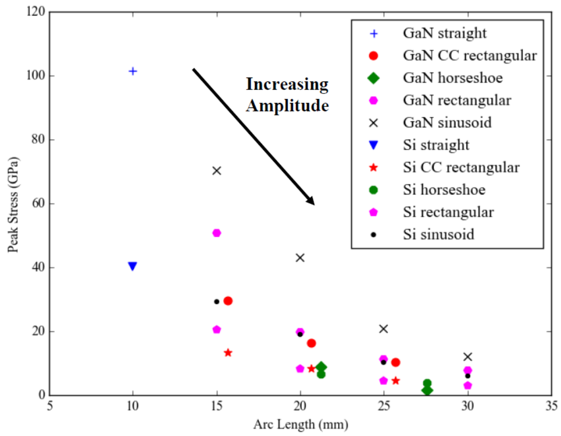

Fig. 1 Plot of peak stress vs. arc length for multiple trace geometries for both (0001) GaN and (100) Si material. Arrow indicates direction of increasing peak-to-peak amplitude.

3. Task 2: Electrical Characterization Study

To examine the effect of device geometry on electrical performance, we performed standard IV tests for HEMT device structures fabricated on GaN films grown on rigid sapphire substrates in wavy stretchable designs. The study compared contact angle, location of devices along the sinusoid, and gate length. In all cases to within experimental uncertainty of 7%–10%, device properties were the same. Thus, we conclude in going from conventional to stretchable geometries electrical properties of devices are not compromised.[4]

4. Task 3: Stretchable HEMT Fabrication

A schematic of our fabrication process is shown in Fig. 2. Initially, HEMT devices are fabricated in serpentine geometries using our standard process shown in Fig. 3a. An Inductively Coupled Plasma (ICP) etch is then done to expose the Si substrate (Fig. 3b). The sample is then mounted to glass slides using epoxy with two Ti/Au-coated sapphire wafers. The sample is then wire bonded (Fig. 3c). Approximately 50 cycles of XeF$_2$ are then used to release the GaN devices (Fig. 3d). Sylgard 184 is then poured at one end of the sample to embed the devices. In the final step, the sample is flipped over on its backside, and approximately 1000 cycles of XeF$_2$ are used to remove the backside Si substrate. An optical microscopy image of the final fabricated devices is shown in Fig. 3e along with the I$_{ds}$-V$_{ds}$ IV curve before and after embedding (Fig. 3f).

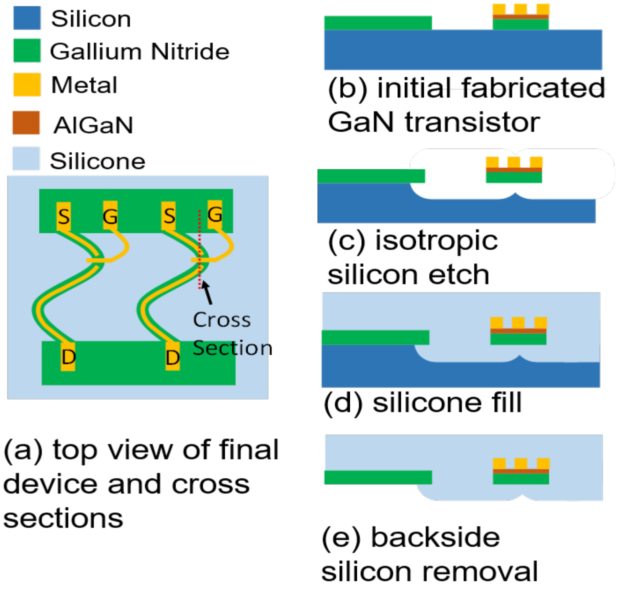

Fig. 2 Process flow for fabricating stretchable AlGaN/GaN HEMTs

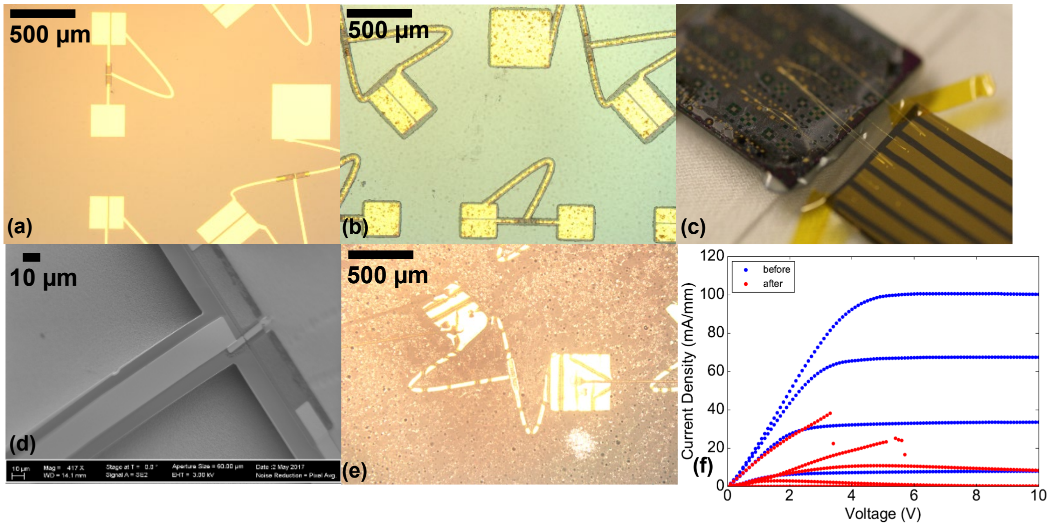

Fig. 3 (a) Fabricated AlGaN/GaN HEMTs in stretchable geometries. (b) Post-ICP etch with exposed Si substrate. (c) Wire-bonded devices. (d) Released AlGaN/GaN HEMT post-XeF_2 etching. (e) Fully embedded AlGaN/GaN HEMT post-Si substrate removal. (f) I_{ds}-V_{ds} curve of stretchable HEMT device both before and after embedding in Sylgard 184.

5. Conclusion/Future Work

We have fabricated AlGaN/GaN HEMT devices in stretchable geometries and fully embedded in a Sylgard 184 polymer to enhance stretchability. Results show that fully embedded devices retain electrical characteristics with a slight reduction in drain current. In addition, results from the electrical characterization study show that through proper device design, devices in stretchable geometries retain their electrical properties compared to conventional devices. Modeling results show that in going to serpentine geometries, the peak stress can be reduced as much as 98%. Future work includes simultaneous mechanical and electrical testing of fabricated stretchable GaN devices currently in progress.

6. References

1. Rogers JA, et al. Science. 2010;327:1603.
2. Lazarus N, et al. IEEE Trans. on Electron Devices. 2015;62:2270.
3. Tompkins RP, et al. ECS Trans. 2016;72(5):89–95.
4. Tompkins RP, et al. Solid State Electron. 2017;136:36 – 42.

Appendix. Publications, Presentations, and Awards

A.1 Publications

1. Tompkins RP, et al. Solid State Electron. 2017;136:36 – 42.
2. Tompkins RP, et al. ECS Trans. 2016;72(2):89–95.
3. Mahaboob I, et al. Influence of mask material on the electrical properties of selective area epitaxy GaN microstructures. J. Vac. Sci. B (accepted).
4. Mahaboob I, et al. Role of mask material in influencing electrical properties of selective area epitaxially grown GaN microstructures. J. Electron. Mat. (submitted).

A.2 Presentations

1. Curtis SM, Tompkins RP, Nichols B, Kierzewski I, Lazarus N. Micro-raman spectroscopy for stress mapping of crystalline stretchable semiconductors. University of Kiel, Kiel, Germany, 2017.
2. Curtis SM, Wang H, Tompkins RP, Lazarus N. Effect of mechanical anisotropy in gallium nitride and silicon for stretchable electronics. Poster: Mid Atlantic Micro-Nano Alliance (MAMNA) Spring 2017 Symposium. Johns Hopkins Applied Physics Laboratory, Laurel, MD, 2017.
3. Mahaboob I, Marini, J, Hogan K, Rocco E, Shadi Shahedipour-Sandvik F, Tompkins RP, Lazarus N. Design and Bottom-up development of stretchable geometry AlGaN/GaN high electron mobility transistors. Electronic Materials Conference, South Bend, IN, 2017.
4. Tompkins RP, et al. Mechanical modeling and electrical characterization of AlGaN/GaN HEMTs in stretchable geometries. 2016 ISDRS, Bethesda, MD, 2016. INVITED
5. Lazarus N, Tompkins RP. High performance stretchable power electronics. 2016 ISDRS, Bethesda, MD (2016). INVITED
6. Tompkins RP, et al. Electrical properties of AlGaN/GaN HEMTs in stretchable geometries. 58th Electronic Materials Conference, Newark DE, 2016.
7. Tompkins RP, et al. Mechanical analysis of stretchable AlGaN/GaN high electron mobility transistors. 229th ECS meeting, San Diego CA, 2016.
8. Mahaboob I, Marini J, Hogan K, Tompkins RP, Lazarus N, Shahedipour-Sandvik S. Development of stretchable geometry AlGaN/GaN HEMTs with selective epitaxial growth technique. IWN 2016, Orlando, FL, 2016.

A.3 Awards

1. Tompkins RP, Lazarus N. co-advisors University of Maryland, S M Curtis Master's Defense, April 12, 2018.
2. Curtis SM. First Place in the U.S Army Research Lab's (ARL) Sensors and Electron Devices Directorate Summer Student Oral Presentation: Branch, Division, and Directorate Undergraduate Winner, July 2017.
3. Curtis SM. Second Place Poster Award Mid-Atlantic Micro-Nano Alliance (MAMNA) Spring 2017 Symposium, April 2017.

List of Symbols, Abbreviations, and Acronyms

GaN	gap gallium nitride
HEMT	high electron mobility transistor
ICP	Inductively Coupled Plasma
Si	silicon

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