Executive Summary

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1. **Title of the Project:** Development of Gallium Nitride (GaN) Based Technology Platform for THz Applications

2. **Date of Start of the Project:** 01.10.2021.

3. **Aims and Objectives:**
   1. To pursue disruptive and translational approaches for addressing fundamental roadblocks in developing Gallium Nitride (GaN) based technology platform for THz applications.
   2. Demonstration of GaN based THz Devices.

4. **Significant achievements (not more than 500 words to include List of patents, publications, prototype, deployment etc):** In the previous report, we showed the results of scaled GaN RF HEMTs and fabricated a device with gate lengths of 300 nm and drain source distance of 4.3 µm. The devices showed a maximum current of 1 A/mm, transconductance (g_m) of 200 mS/mm, and f_T of 35 GHz. However, scaling of devices leads to lower breakdown voltages, short channel effects and degraded current collapse behavior due to increase in the channel electric field. Thus, efficient distribution of the electric field is important. Considering these problems, a unique high-k passivation was developed to increase gate control while also improving the

distribution of the electric field. We created a unique high k ternary oxide, $Al_xTi_{1-x}O$, with this goal in mind. The p-type character of the oxide aids in the effective redistribution of the channel electric field, improving breakdown voltage and lowering current collapse, while the high-k property aids in achieving good gate control reducing the short channel effects. We have investigated the various reliability challenges faced in GaN-on-Si HEMTs and proposed device design guidelines to mitigate these reliability issues, resulting in many important publications. These studies are in line with the RF technology and can be used as guidelines to improve the performance and robustness of GaN-on-Si RF HEMTs. Following is the list of key publications.

1. Soni and M. Shrivastava, "Implications of Various Charge Sources in AlGaN/GaN Epi-Stack on the Drain & Gate Connected Field Plate Design in HEMTs," in IEEE Access, vol. 10, pp. 74533-74541, 2022, doi: 10.1109/ACCESS.2022.3190484.
2. R. Roy Chaudhuri, V. Joshi, S. Dutta Gupta and M. Shrivastava, "Observations and Physical Insights Into Time-Dependent Hot Electron Current Confinement in AlGaN/GaN HEMTs on C-Doped GaN Buffer," in IEEE Transactions on Electron Devices, vol. 69, no. 12, pp. 6602-6609, Dec. 2022, doi: 10.1109/TED.2022.3213627.
3. R. R. Chaudhuri, A. Gupta, V. Joshi, R. R. Malik, S. D. Gupta and M. Shrivastava, "Impact of Channel Electric Field Profile Evolution on Nanosecond Timescale Cyclic Stress-Induced Dynamic RON Behavior in AlGaN/GaN HEMTs—Part II," in IEEE Transactions on Electron Devices, doi: 10.1109/TED.2023.3300652.
4. R. R. Chaudhuri et al., "Unique Lattice Temperature Dependent Evolution of Hot Electron Distribution in GaN HEMTs on C-doped GaN Buffer and its Reliability Consequences," 2023 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2023, pp. 1-5, doi: 10.1109/IRPS48203.2023.10118255.
5. S. Dutta Gupta, V. Joshi, R. R. Chaudhuri and M. Shrivastava, "Unique Gate Bias Dependence of Dynamic ON-Resistance in MIS-Gated AlGaN/GaN HEMTs and Its Dependence on Gate Control Over the 2-DEG," in IEEE Transactions on Electron Devices, vol. 69, no. 3, pp. 1608-1611, March 2022, doi: 10.1109/TED.2022.3144378.
6. V. Joshi, S. D. Gupta, R. R. Chaudhuri and M. Shrivastava, "Interplay of Device Design and Carbon-Doped GaN Buffer Parameters in Determining Dynamic in AlGaN/GaN HEMTs," in IEEE Transactions on Electron Devices, vol. 69, no. 11, pp. 6035-6042, Nov. 2022, doi: 10.1109/TED.2022.3209635.

7. V. Joshi, R. Roy Chaudhuri, S. Dutta Gupta and M. Shrivastava, "Physical Insights Into Electron Trapping Mechanism in the Carbon-Doped GaN Buffer in AlGaN/GaN HEMTs and Its Impact on Dynamic On-Resistance," in IEEE Transactions on Electron Devices, vol. 70, no. 6, pp. 3011-3018, June 2023, doi: 10.1109/TED.2023.3269409.
8. M. A. Mir, V. Joshi, R. R. Chaudhuri, M. A. Munshi, R. R. Malik and M. Shrivastava, "Dynamic Interplay of Surface and Buffer Traps in Determining Drain Current Injection induced Device Instability in OFF-state of AlGaN/GaN HEMTs," 2023 IEEE International Reliability Physics Symposium (IRPS), Monterey, CA, USA, 2023, pp. 1-6, doi: 10.1109/IRPS48203.2023.10117664.
9. M. A. Munshi et al., "Understanding Temperature Dependence of ESD Reliability in AlGaN/GaN HEMTs," 2023 45th Annual EOS/ESD Symposium (EOS/ESD), Riverside, CA, USA, 2023, pp. 1-5, doi: 10.23919/EOS/ESD58195.2023.10287745.
10. M. A. Mir et al., "On The Role of Stress Engineering of Surface Passivation in Determining the Device Performance of AlGaN/GaN HEMTs," 2024 IEEE International Reliability Physics Symposium (IRPS), Grapevine, TX, USA, 2024, pp. 1-5, doi: 10.1109/IRPS48228.2024.10529406.
11. M. A. Mir, V. Joshi, R. R. Chaudhuri, M. A. Munshi, R. R. Malik and M. Shrivastava, "Physical Insights Into the Drain Current Injection-Induced Device Instabilities in AlGaN/GaN HEMTs," in IEEE Transactions on Electron Devices, vol. 71, no. 9, pp. 5251-5257, Sept. 2024, doi: 10.1109/TED.2024.3427097.
12. R. R. Malik et al., "Interplay of Surface Passivation and Electric Field in Determining ESD Behaviour of p-GaN Gated AlGaN/GaN HEMTs," 2023 45th Annual EOS/ESD Symposium (EOS/ESD), Riverside, CA, USA, 2023, pp. 1-7, doi: 10.23919/EOS/ESD58195.2023.10287740.

5. **Concluding remarks:** Now that mm-W characteristics have been achieved, further focus will be on the remaining objectives which include:

THz operation: Optimization of the high k dielectric is required further in addition to scaling of the device to achieve THz operation.

Contact Optimization: Contact resistance should be low to enhance the drive current, the current contact resistance is $R_C = 0.7$ Ω-mm, however for RF applications, R_C of < 0.5 Ω-mm is desirable. To achieve low RC different metal stacks will be used, AlGaN barrier recess depth will be varied, and annealing temperature will be optimized.

Reliability study: After meeting the targeted specifications of millimeter wave GaN-on-Si RF devices, they will be subjugated to standard and novel DC and RF stress scenarios emulating the situations the devices face in real circuit applications. This will be done to study the failure points and reliability bottlenecks of the device. Further computational modelling of the experiments will be done to gain better physical insights into the failure mechanisms. Based on the results design guidelines will be proposed to mitigate the failures and enhance device performance. The device design will be implemented to make the device more robust and achieve a reliable and high-performance GaN-on-Si RF HEMT for THz devices.