Integration of $Ba_xSr_{1-x}TiO_3$ Thin Films with AlGaN/GaN HEMT Circuits

Hongtao Xu, Nadia K. Pervez, Peter J. Hansen*, Christopher Sanabria, Likun Shen, Stacia Keller, Umesh K. Mishra, and Robert A. York
Department of Electrical and Computer Engineering
*Materials Department, College of Engineering
University of California, Santa Barbara, California 93106
E-Mail: hongtao@engineering.ucsb.edu

ABSTRACT:
AlGaN/GaN HEMTs have attracted considerable interest as power devices in microwave applications, promising greater than a tenfold increase in power-density as compared with GaAs devices. Similarly, $Ba_xSr_{1-x}TiO_3$ (BST) thin films have been investigated for microwave circuit application because of their high dielectric constants, high tunability, relatively low loss, and fast switching speed. BST-based varactors are especially attractive for high-power RF circuits since they can sustain relatively large AC fields at low average DC fields, unlike diode technologies. Additionally, due to its high dielectric constant, BST is a candidate for very compact MMIC DC blocking capacitors, promising a 100-fold reduction in capacitor area as compared with SiN and SiO_2 capacitors. In this paper, we will provide a valid method of process integration for future active GaN circuit design and fabrication using BST capacitors. A C-band MMIC oscillator in GaN HEMT technology has been designed with BST capacitor as DC blocking capacitors.

I. INTRODUCTION

AlGaN/GaN HEMTs have been developed as power devices in microwave applications. Many research groups have demonstrated microwave circuits employing high speed, high power and low noise GaN HEMT devices [1]-[3]. $Ba_xSr_{1-x}TiO_3$ (BST) thin films have been investigated as a potential low cost voltage tunable element for microwave circuit application because of their high tunability, relatively low loss, and fast switching speed. BST has shown great promise in applications as tunable RF and microwave components, such as phase shifters, tunable filters, tunable matching networks and voltage-controlled oscillators [4]-[6]. Additionally, due to its high dielectric constant, BST is a candidate for compact MMIC DC blocking capacitors. Our objective is to integrated BST capacitors with GaN devices in RF and microwave circuits.

When the BST capacitor process was initially integrated with the GaN HEMT process, several issues need to be considered. First, during the BST sputtering process, the AlGaN 2DEG channel was damaged by the plasma. Second, both HEMT and BST devices require high temperature processes, which adversely impacted each other. Electrodes containing Au contacting the BST film could not sustain the rapid thermal annealing (RTA) required for the ohmic contacts of the HEMT. In this paper, we will show our solutions to these problems, providing a valid method of process integration for future active GaN circuit design and fabrication using BST capacitors.

II. DEVICE FABRICATION

The HEMT devices tested were grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrates. The epitaxial structure consisted of a semi-insulating Fe-doped GaN base layer [7], followed by a 290 Å thick $Al_{0.35}Ga_{0.65}N$ barrier layer. The room temperature sheet

0-7803-7904-7/03/$17.00 ©2003 IEEE.

electron concentration and Hall mobility were ~1.5×10^{13} cm^{-2} and ~1170 cm^2/Vs, respectively. The HEMT device fabrication started with ohmic contact formation. Ti/Al/Ni/Au (200/1500/375/500 Å, respectively) were evaporated and annealed at 870 °C for 30 seconds in N_2. Device mesa isolation was then performed using a Cl_2 reactive ion etch (RIE). TLM measurements showed an average contact resistance of 0.4 Ω·mm, and a sheet resistance R_{sq}≈370 Ω/□. The gate contact was formed by evaporating Ni/Au/Ni (300/2500/500 Å, respectively). The final processing step was a 170 nm PECVD Si_3N_4 passivation layer, which has been shown to eliminate DC to RF dispersion [8, 9]. The gate width and length on all the devices tested were 2x75 μm, and 0.7 μm, respectively.

A 3000Å BST thin film was grown on an AlGaN/GaN substrate with 3000Å of electron-beam evaporated Pt that was pre-patterned by liftoff as a bottom electrode for an MIM capacitor. The BST films were deposited using RF magnetron sputtering. The film growth conditions were optimized for tunability and microwave loss performance; typical growth conditions for a ~3000 Å $Ba_{0.5}Sr_{0.5}TiO_3$ film are a substrate temperature of 700 °C, base pressure of 50 mTorr (90 sccm Ar/10 sccm O_2), and RF power of 150 W on two 3" targets. Pt/Au top electrodes were evaporated followed by a BST etch in 1:1 buffered HF:DI water. The BST capacitors were passivated by a 3000 Å SiO_2 film to prevent contamination during subsequent processing. This passivation layer also functions as an insulating layer beneath the overpass bridge, which connects the top electrodes to a high-conductivity interconnect metal layer.

In this work, both BST capacitors and HEMT devices were fabricated on the same samples. A schematic cross-section of the process and a completed parallel plate capacitor and HEMT device is shown in Fig. 1.

III. RESULTS AND DISCUSSION

Reference HEMT devices were fabricated without incorporating the BST film process as an experimental control sample. The HEMT devices were subjected to I-V characterization. Pulsed I-V measurement at 200 ns shows the drain current density reaches 1.37 A/mm for V_{gs}=0 V.

BST capacitors were first fabricated directly on the AlGaN surface before the HEMT process. Following the BST deposition, the BST was selectively removed and HEMT devices were fabricated in the area where the BST film was completely removed. In Fig 2, pulsed I-V curves measured at 200 ns on both a control HEMT and a HEMT exposed to the plasma during BST growth are compared. Exposure to the plasma decreased the current density by 28 % and decreased the magnitude of the pinch-off voltage from -7.5 V to -6 V. Further investigation showed that both the sheet electron concentration and Hall mobility are decreased due to plasma damage in the HEMT structure during the BST sputtering [10]. To avoid this damage, a barrier layer is required to protect the 2DEG during BST growth. A thin SiO_2 layer was introduced for this purpose. Because of the stability of group III-nitrides, the SiO_2 layer should not react with the AlGaN. Since it can be wet etched uniformly by the same etchant (buffered HF) as the BST film, the choice of a SiO_2 buffer layer is compatible with both the GaN HEMT and BST capacitor processes.

Based on these initial findings, a 3000 Å S_iO_2 layer was evaporated on the HEMT device area after bottom electrodes of the BST capacitors were pre-patterned. Following the BST deposition, both the SiO_2 and BST films were etched away from the HEMT device area using buffered HF during the BST pattern definition. In Fig 3, pulsed I-V curves at 200 ns on both a control HEMT and a HEMT protected by SiO_2 were compared. The performance of the HEMT was not degraded by exposure to the BST deposition. A 3000 Å sacrificial SiO_2 layer efficiently protects HEMT's 2DEG channel. Additionally, the pinch off voltage did not change and the average ohmic contact resistance was the same as the control devices, indicating that the SiO_2 did not react with the AlGaN during the approximately 3 hour high temperature BST deposition.

While the sacrificial SiO_2 layer solved one problem, another problem in the integration is that the source/drain annealing causes a reduction in the BST capacitors' breakdown voltage. Before the source/drain annealing, the BST capacitors could sustain the application of more than a 20 V bias, but after the annealing the capacitors broke down at 3 V. Even for BST devices with pure Pt top electrodes, the breakdown voltage was still as low as 7 V. Devices with such low breakdown voltage cannot be used in high power microwave GaN HEMT circuits. To avoid this problem, the sequence of process steps was rearranged. Source and drain ohmic contacts were fabricated first, followed by the ebeam evaporation of a 3000 Å SiO_2 film. The BST capacitors were made following the completion of these two steps, with HEMT device mesa isolation and gate metallization following the BST capacitor fabrication. The complete process flow is depicted in Fig 1.

The effect of the heater ramp rate was also investigated. When the heater ramp rate was 50 °C/min, the ohmic contact resistance increased from 0.4 Ω·mm to 0.9 Ω·mm after BST deposition. In addition, the source and drain contacts appeared cracked, delaminated and discolored. As shown in Fig 4. The thermal mismatch between the ohmic contact metals and SiO_2 layer could account for both the metal and SiO_2 layers cracking during the rapid temperature change due to the heater ramping. Through cracks in the SiO_2 layer, the souce and drain contact metals are exposed to O_2 from the sputtering ambient and oxidized. Oxidized metals are etched and delaminated in the buffered HF during the BST etch. Ohmic contacts protected by intact SiO_2 are not harmed by the buffered HF.

With a slower heater ramp rate (20 °C/min) durings BST deposition, no cracks, delamination, or significant discoloration was observed on the source and drain ohmic contacts. The average ohmic contact resistance was 0.4 Ω·mm both before and after the BST deposition. A C-V measurement performed on BST capacitors manufactured with the integrated GaN/AlGaN HEMT-BST process. (Fig. 5.) The capacitance density at 0V bias is 14.3 fF/μm^2 and the tunability is 3.3:1 with a 20 V bias. The 1MHz zero-bias Q factor of this film was 85.

A C-band MMIC oscillator in GaN HEMT technology has been designed, fabricated and characterized with $Ba_xSr_{1-x}TiO_3$ (BST) film capacitors integrated as DC block capacitors. The layout of the oscillator is shown in Fig. 6. The lumped LC resonator works with the common gate HEMT to generate negative resistance. The oscillator, based on AlGaN/GaN HEMT with 0.7 μm gate length and 200 μm gate width, delivers 20.7 dBm output power when bias at Vds=15 V and Vgs=-2.5V, with DC-to-RF efficiency of 12.5%. Phase noise was measured to be -105 dBc/Hz at 100 kHz offset from 5 GHz carrier.

IV. CONCLUSION

In this paper, a new method has been developed to incorporate BST thin film capacitors in microwave circuits based on GaN HEMTs. A 3000 Å sacrificial SiO_2 layer protects the AlGaN surface and 2DEG from plasma damage. Reduction of the heater ramp rate to 20 °C/min during BST growth mitigates damage to the source and drain ohmic contacts, such as cracking and delamination. Using BST thin films, varactors and small area DC blocking capacitors can be integrated into GaN HEMT microwave circuits. High voltage (>20 V) operation and compatibility with a monolithic process are other advantages realized in this work. Compact GaN MMIC circuits, such as power amplifiers, oscillators and VCOs, can be implemented with the integration of BST film to the GaN/AlGaN process.

REFERENCES

[1] Y. Chung, C. Y. Hang, S. Cai, Y. Qian, C. P. Wen, K. L. Wang, and T. Itoh, "AlGaN/GaN HFET power amplifier integrated with microstrip antenna for RF front-end application," IEEE Trans Microwave Theory and Techniques, vol. 51, no. 2, pp. 653 -659, Feb. 2003.

[2] V. Paidi, S. Xie, R. Coffie, B. Moran, S. Heikman, S. Keller, A. Chini, S. P. DenBaars, U. K. Mishra, S. Long, and M. J. W. Rodwell, "High linearity and high efficiency of class-B power amplifiers in GaN HEMT technology," IEEE Trans Microwave Theory and Techniques, vol. 51, no. 2, pp. 643 -652, Feb. 2003.

[3] V. Kaperm, V. Tilak, H. Kim, R. Thompson, T. Prunty, J. Smart, L. F. Eastman, and J. R. Shealy, "High power monolithic AlGaN/GaN HEMT oscillator," Gallium Arsenide Integrated Circuit (GaAs IC) Symposium 24th Annual Technical Digest, pp. 251 -254, 2002.

[4] B. Acikel, T. R. Taylor, P. J. Hansen, J. S. Speck, and R. A. York, "A new high performance phase shifter using $Ba_xSr_{1-x}TiO_3$ thin films," IEEE Microwave and Wireless Components Lett., vol. 12, no. 7, pp. 237-239, July 2002.

[5] D. Kim, Y. Choi, M. G. Allen, J. S. Kenney, and D. Kiesling, "A wide bandwidth monolithic BST reflection-type phase shifter using a coplanar waveguide Lange coupler," IEEE MTT-S International Microwave Symposium Digest, vol. 3, pp. 1471 -1474, 2002.

[6] A. Tombak, F. T. Ayguavives, J.-P. Maria, G. T. Stauf, A. I. Kingon, and A. Mortazawi, "Tunable RF filters using thin film barium strontium titanate based capacitors," IEEE MTT-S International Microwave Symposium Digest, 2001, vol. 3, pp. 1453 -1456.

[7] S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "Growth of Fe-doped semi-insulating GaN by metalorganic chemical vapor deposition," Appl. Phys. Lett., vol. 81, pp. 439–441, 2002.

[8] R. Vetury, N.-Q. Zhang, S. Keller, and U. K. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaN/GaN HFETs," IEEE trans. Electron Devices, vol. 48, no. 3, pp. 560-566, Mar. 2001.

[9] B. M. Green, K. K. Chu, E. M. Chumbes, J. A. Smart, J. R. Shealy and L. F. Eastman, "The effect of surface passivation on the microwave characteristics of undoped AlGaN/GaN HEMTs," IEEE Electron Device Lett., vol. 21, no. 6, pp. 268-270, June 2000.

[10] P. J. Hansen, L. Shen, Y. Wu, Y. Terao, S. Heikman, D. Buttari, S. P. DenBaars, R. A. York, J. S. Speck, U. K. Mishra, "AlGaN/GaN Metal Oxide Heterostructure Field Effect Transistors Using Barium Strontium Titanate," presented at the International Workshop on Nitride Semiconductors, Aachen, Germany, July 2002.

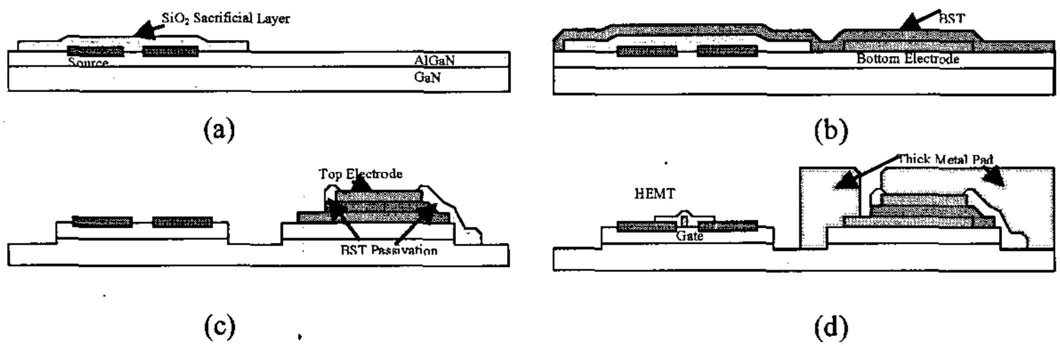

Fig. 1. Process flow
(a) Source/drain ohmic contacts with SiO_2 sacrificial layer.
(b) Prepatterned bottom electrodes and BST film deposition.
(c) BST pattern etch, top electrodes, mesa isolation and BST film passivation.
(d) Gate metallization, HEMT passivation and thick metal pad.

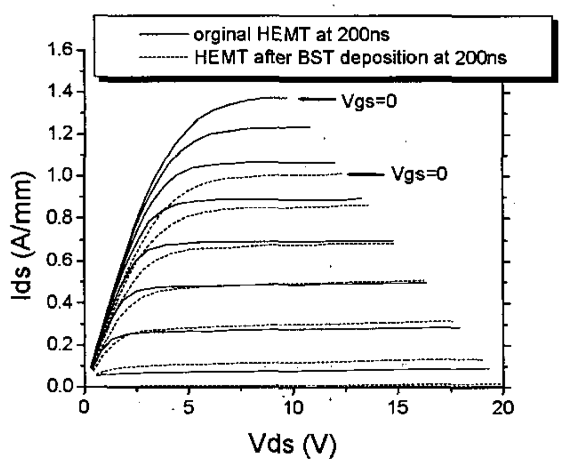

Fig. 2. 200 ns pulsed I-V for HEMT device with BST deposition compared to control device.

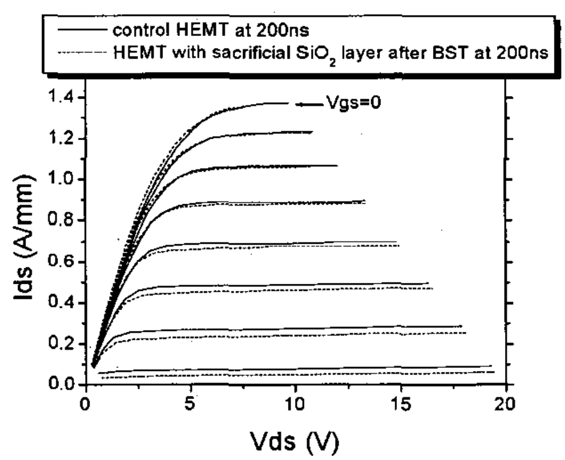

Fig. 3. 200 ns pulsed I-V for HEMT device protected by sacrificial SiO_2 with BST deposition compared to control device.

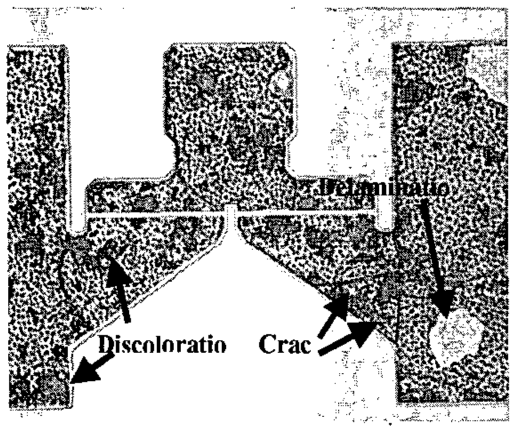

Fig. 4. Photograph of source and drain ohmic contacts after BST deposition with heater ramp rate of 50°C/sec.

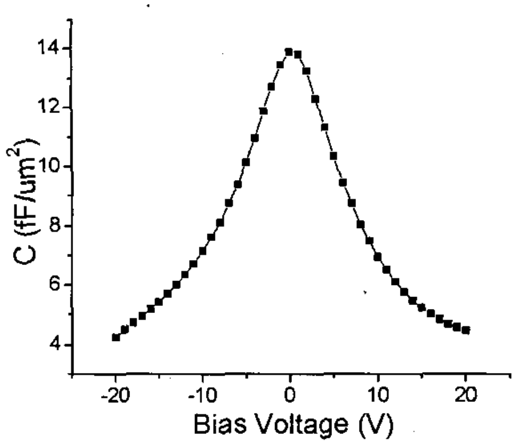

Fig. 5. C-V measurement of BST Capacitor

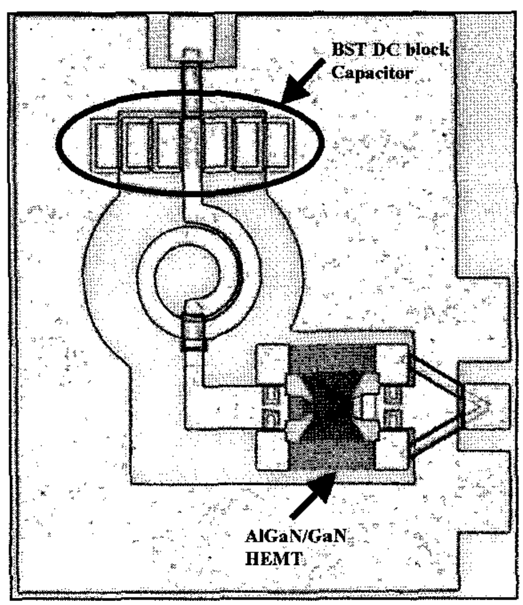

Fig. 6. the photograph of the 5 GHz GaN HEMT oscillator with BST DC block