GaN Tunnel Switch Diodes

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Tunnel Switch Diodes (TSDs) exhibit a S-shaped IV curve with negative differential resistance. Because of tunneling, they are able to switch between a low-current, high-resistance state (HRS) and a high-current, low-resistance state (LRS) fast, making them promising for high-speed memory [1]. The TSD consists of a thin tunnel barrier on top of a pn junction, [**Fig 1(a)**]. In the HRS state, the barrier allows only a small tunneling current through. When biased beyond a switching voltage the p-layer of the pn-junction depletes from the surface field-effect, and the surface depletion edge reaches the depletion edge of the buried pn diode. This turns the buried diode on, which floods the p-layer with electrons. Much of these electrons become trapped in the top triangular quantum well barrier, self-biasing the device. Since this state is unstable, the drop in electric field moves from p-layer to barrer, with a sudden onset of tunneling current when the TSD reaches the LRS [**Fig. 1(b)**]. Reducing the applied bias reverses this process and the TSD switches back to the HRS state. The switching voltage can be found with $V_s = \frac{qN_A(t_p - x_{dep.})^2}{2\epsilon_{semi}\epsilon_o} + \frac{t_{barrier}\sqrt{2q\epsilon_{semi}N_A\phi_s}}{\epsilon_{barrier}\epsilon_o}$, where N_A is the acceptor doping concentration, x_{dep} is the pn junction depletion width in the p-layer, t_p and $t_{barrier}$ are the thicknesses of the p-layer and tunneling barrier, ϵ_{semi} and $\epsilon_{barrier}$ are the relative dielectric constants of p-layer and the barrier and ϕ_s is the surface potential needed to deplete the p-layer. TSDs were studied in SiO_2/Si and in AlSb/GaSb heterostructures recently [2,3]. Advances in GaN pn-diodes and polarization physics [4] present an exciting opportunity to realize TSDs with new functionality. This work demonstrates GaN homojunction and heterojunction TSDs for the first time.

GaN TSD structures where realized with two different barriers, with energy band diagrams shown in **Figs. 2 (a&b)**. A homojunction TSD was formed by depositing ALD Al_2O_3 barrier layer on a GaN pn diode[**Fig. 2(a)**]. A heterojunction TSD was formed by growing an epitaxial $Al_{0.15}Ga_{0.75}N$ layer on an identical pn diode [**Fig. 2(b)**]. For both TSDs, the p-GaN was 75nm thick with a Mg acceptor doping concentration of $N_A = 2\times10^{18}$ cm^{-3}. The n-GaN was 300nm thick with $N_D=10^{19}$ cm^{-3} Si donor doping. Both barriers were 5 nm in thickness. The above doping and thickness dictate an expected tunnel switch voltage V_S ~3 V.

The devices were grown by plasma-assisted MBE. A plasma source provided the active N, while the metal (Ga, Al) and dopant (Mg, Si) atoms were provided by separate effusion cells. The substrate for both devices was high quality single-crystal bulk n-GaN purchased from Ammono. The MBE growth began at 720 ^oC, and was lowered to 600 ^oC for the p-GaN layer growth. For the heterojunction TSD, the AlGaN barrier was grown immediately following the p-GaN, also at 600 ^oC, without a growth interruption. The epitaxial layers were patterned by optical lithography followed by an RIE etch for isolation mesas ~90nm tall. The Al_2O_3 barrier for the homojunction TSD was then deposited by ALD at 300 ^oC. Top and back contacts were formed by e-beam evaporation of Ti/Au metal stacks.

Fig. 3. shows that both GaN TSDs exhibit a clear S-shaped IV curve at room temperature. The switching voltage in the homojunction ALD barrier TSD ~2 V while for the heterojunction AlGaN barrier TSD its ~3 V. The smaller conduction band offset for the heterojunction TSD (~0.3 eV) versus Al_2O_3/p-GaN (~2 eV) allows for a much larger current density. Prior observations [3] indicate a reduction in V_S upon repeated sweeps. This behavior is indeed seen in the Al_2O_3 barrier homojunction TSD, in **Fig. 3(a).** Regardless of barrier type, every TSD observed till now have switched only a limited number of times before the S-shaped curves loses its NDR and becomes linear. Surprisingly, when measured ~2 weeks later, the TSDs recovered their characteristic S-shaped IV curve indicating the filling of slow traps during switching. **Fig 4.** shows the results of performing IV sweeps on GaN TSDs of varying diameters. The Al_2O_3 barrier homojunction TSD showed S-shaped I-Vs and switching all the way to the maximum device diameter of 690 µm. The heterojunction TSD with AlGaN barrier had the S-shaped switching curve up to ~370 µm [**Fig. 4c**]. The exact degradation mechanisms are not clear yet and warrant future studies.

In conclusion, GaN homojunction and heterojunction TSDs have been realized for the first time. Both TSDs show the characteristic S-shaped NDR near the designed 3 V. Homojunction TSDs with ALD Al_2O_3 barriers showed signs of repeatable back-to-back switching. The GaN TSDs retain S-shaped NDR at room temperature for several sized diodes. Because the TSD's S-shaped NDR behavior is purely electronic by tunneling and not due to the slower movement of vacancies, mechanical changes or domain wall movement, it is expected to play a significant role in realizing memories, or low-power switch/memory hybrids in combination with transistors. This work is supported by the Center for Low Energy Systems Technology (LEAST), of the six SRC STARnet centers sponsored by MARCO and DARPA, and a ONR MURI THz program monitored by Dr. Paul Maki.

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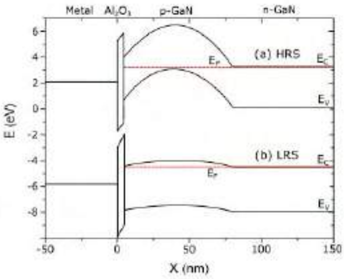

Fig. 1. Energy band diagram explaining the operation of Tunnel Switch Diode (TSD). (a) The HRs where the current is low due to the p-GaN barrier. (b) The LRD with the pn diode turned on and carrier tunneling.

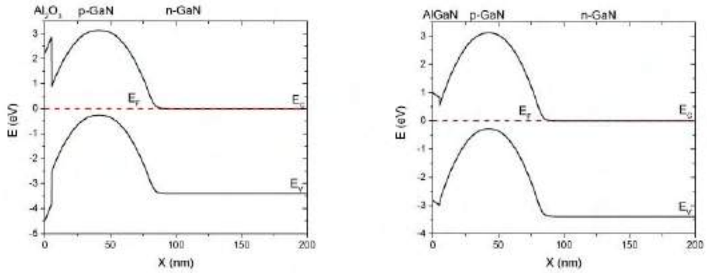

Fig. 2. (a) Energy band diagram of the GaN TSD with an Al_2O_3 barrier. (b) Energy band diagram of the GaN TSD with an epitaxial $Al_{0.15}Ga_{0.75}N$ barrier. The low (15%) Al composition prevents the formation of a polarization-induced 2DEG in the p-GaN, but causes zero-bias depletion.

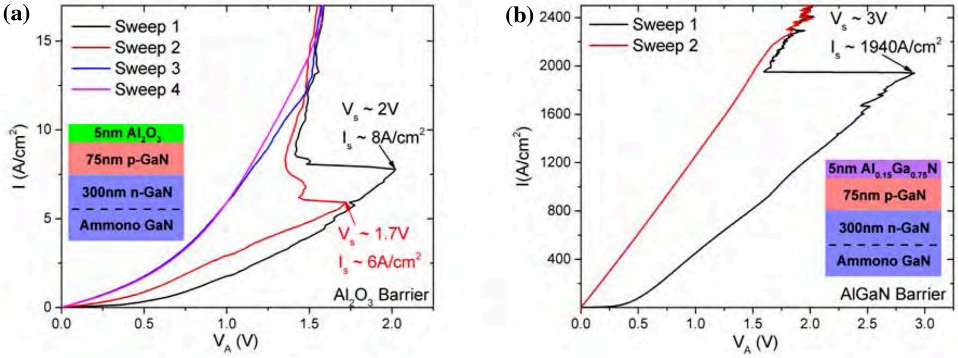

Fig. 3. Measured IVs showing S-shaped NDR curves at 300K for the homojunction and heterojunction GaN tunnel switch diodes. (a) Using an Al_2O_3 barrier in a homojunction TSD leads to limited repeated switching. (b) The AlGaN barrier heterojunction TSD allows a higher current, but with less repeatable switching.

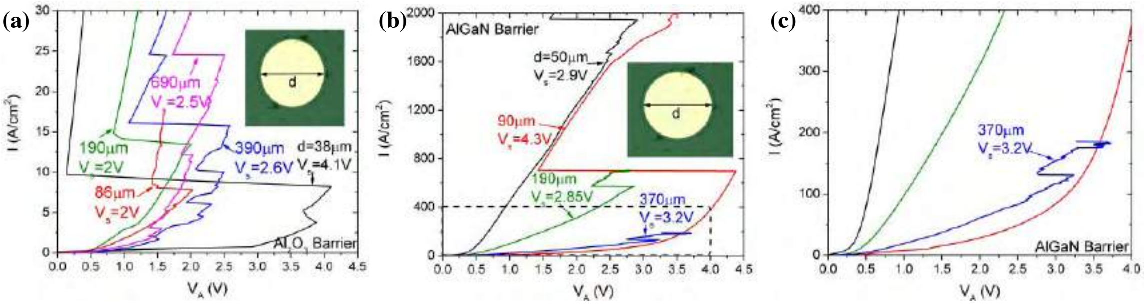

Fig. 4. IV curves for different diode diameters. (a)Homojunction tunnel switch diodes with Al_2O_3 barrier. S-shaped NDR and switching is seen for every diameter size. (b) Heterojunction TSDs with AlGaN barrier. No switching was observed for diodes bigger than 370 μm diameter. (c) Zoom in of the dashed rectangle in Fig. 4b, showing the muted switching of the 370 μm tunnel switch diode.