Demonstration of GaN HyperFETs with ALD VO_2

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Owing to strong electron-electron interactions, transition metal oxide materials can exhibit multiple phases with vastly different electronic, magnetic, structural, and thermal properties. Reversible control of the transitions between these phases by electronic means can give rise to completely novel devices which can provide new functionalities and help to overcome limits of traditional semiconductor devices [1, 2]. VO_2 is a transition metal oxide material that exhibits a metal-insulator transition (MIT) at a temperature of ~67 C [3]. Recently, by coupling VO_2 to the source of traditional semiconductor MOSFET devices, hybrid-phase-transition-FET (hyper-FET) devices were demonstrated [4]. These HyperFETs showed steep switching slope less than the room-temperature Boltzmann switching limit of ~60 mV/dec [4]. GaN based electronics has emerged as an enabler of high-speed and high-power RF and microwave electronics [5], and is currently being investigated intensively for next-generation high-voltage power electronics [6,7], as well as steep-switching based low-power digital electronics [8]. In this work, we combine ALD-grown VO_2 with III-Nitride high-electron mobility transistors (HEMTs) to realize GaN-VO_2 HyperFETs, demonstrating steep-switching behavior in a platform that is amenable to integration and scaling.

For this study, VO_2 thin films of 35nm thickness were grown on c-plane Sapphire substrates using atomic layer deposition (ALD) with Tetrakis-ethylmethylamino-Vanadium [TEMAV] and Ozone as precursors. The as-deposited VO_2 films were amorphous, but crystallize upon annealing. Using optical photolithography these films were patterned into resistors of 100μm width and lengths varying from 4μm to 20μm into a transmission line measurement (TLM) pattern as shown in Fig. 1(a). These VO_2 resistors show a ~1000X decrease in resistance as the VO_2 undergoes MIT beyond ~70C as shown in Fig. 1(b). The transition temperature is quite close to the bulk value of ~67C [3]. The MIT in the VO_2 resistors can also be driven by direct current injection as shown in Fig. 1(c). The voltage corresponding to MIT increases with resistor length, whereas the critical current injection necessary is roughly constant for all measured resistors (~1.3-1.5 mA). For a given resistor, the MIT voltage increases as temperature is lowered below ~67C. To keep the transition voltage lower, we loaded the source of GaN HEMT with the 4μm length VO_2 resistor kept at 60C.

The HEMTs used in this study were fabricated on AlGaN/GaN epilayers grown on (111) Si wafers [7]. Ti/Al/Ni/Au ohmic contacts were deposited using e-beam evaporation followed by rapid thermal annealing in N_2 atmosphere at 850C. After mesa-isolation etch, the room temperature mobility and 2-dimensional electron gas density for these epilayers was 1660 cm^2/V-s and 7.6 x 10^{12} cm^{-2} respectively. A 40nm Ni/100nm Au gate metal stack was deposited using e-beam evaporation. A 50μm wide HEMT with gate length of 3μm, gate-drain distance 4μm and gate-source distance 2μm was used to realize the GaN HyperFET. The measured I_{DS}-V_{GS} transfer characteristics and I_{DS}-V_{DS} characteristics of this control GaN HEMT device at 60C is shown in Fig. 2.

To realize the HyperFET, a 4μm length VO_2 resistor was connected to the source of AlGaN/GaN HEMT as shown in Fig. 3(a). The measured I_{DS}-V_{GS} and subthreshold slope characteristics of the GaN HyperFET at 60C are shown in Fig. 3(b)-3(d). In the transfer characteristics, the hyper-FET shows hysteresis depending on the voltage scan direction, accompanied by a steep slope with increasing V_{GS} associated with electric field-induced MIT in VO_2. The subthreshold-slope at the MIT transition point is ~59 mV/dec, lower than the Boltzmann limit of ~66 mV/dec at 60C (Fig. 3(d)). Below the MIT transition point, the drain current in the GaN HyperFET is lower than the control HEMT because of the large VO_2 resistance in its insulating state acting in series with the HEMT. We also observe a steep increase in the drain current in the I_{DS}-V_{DS} scans. At low drain biases, a large gate leakage is observed because of the Schottky gate, which can be removed using a gate oxide or regrown contacts [7] in future devices.

In summary, we have demonstrated GaN HyperFETs using ALD deposited VO_2 with steep switching behavior beyond the Boltzmann switching limit. Apart from low-power digital electronics, the GaN HyperFET is expected to enable innovations in RF and power electronics. This work is supported in part by the Center for Low Energy Systems Technology (LEAST), one of the six SRC STARnet centers sponsored by MARCO and DARPA, and ONR MURI programs monitored by Dr. Paul Maki, and Dr. Brian Bennett.

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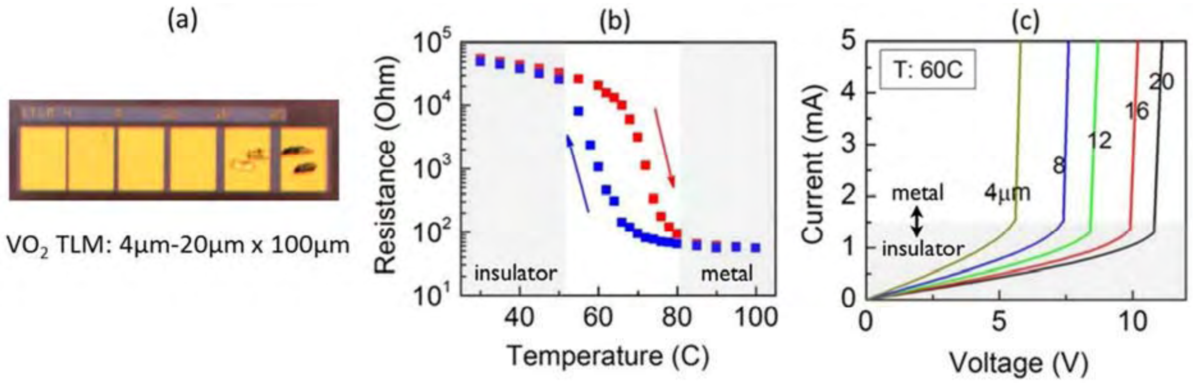

Fig.1 (a) TLM pattern fabricated on 35nm VO_2 thin films on Sapphire, (b) Temperature dependent resistance of 20μm long and 100μm wide VO_2 resistors showing ~3 orders decrease because of the insulator to metal transition, (c) Electric field driven insulator to metal transition in VO_2 resistors at 60C as a function of resistor length, transition voltage increases with resistor length whereas transition current is ~1.3-1.5 mA for all resistors.

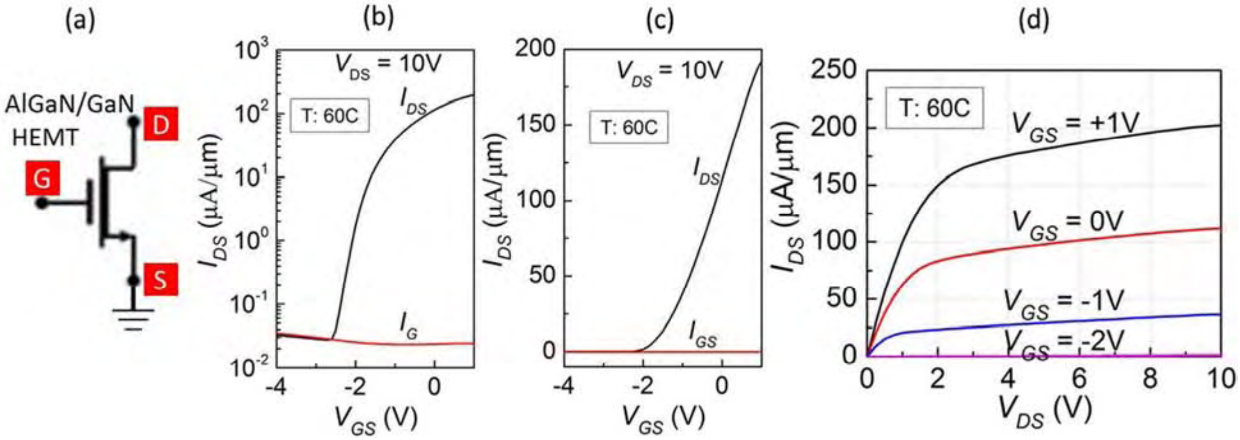

Fig.2 (a) Circuit symbol for the standalone AlGaN/GaN HEMT device, (b,c) I_{DS}-V_{GS} transfer characteristics, (d) I_{DS}-V_{DS} characteristics of the HEMT device at 60C.

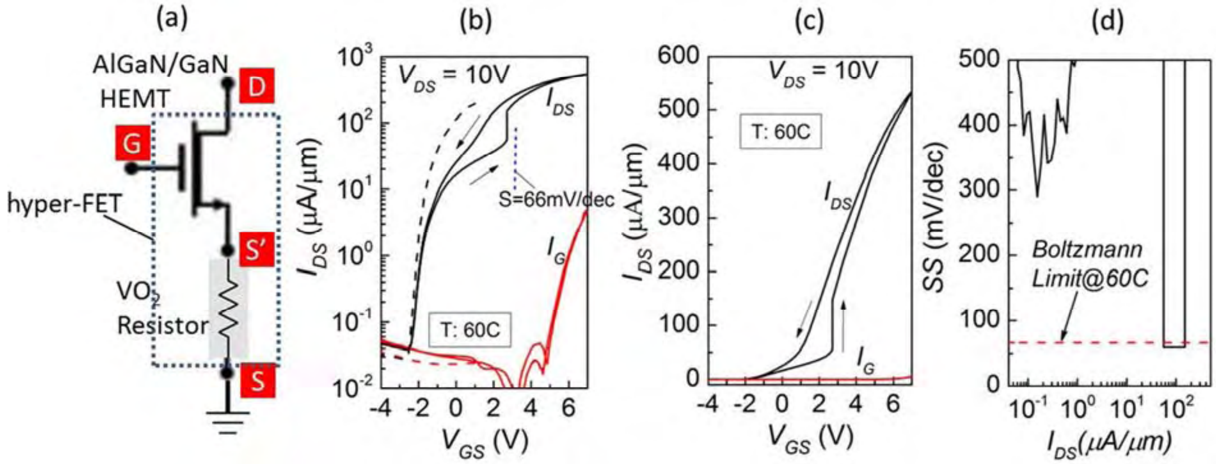

Fig.3 (a) Schematic circuit diagram of the VO_2 resistor loaded GaN HEMT device or hyper-FET, (b,c) I_{DS}-V_{GS} transfer characteristics, (d) Subthreshold slope of the hyper-FET device at 60C. Transfer characteristics of the standalone HEMT device shown in Fig. 2(b) are reproduced as dashed lines in Fig. 3(b) for comparison (with $V_{DS'}$ = 10V).