Demonstration of GaN HyperFETs with ALD VO₂

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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]. VO₂ is a transition metal oxide material that exhibits a metal-insulator transition (MIT) at a temperature of ~67°C [3]. Recently, by coupling VO₂ 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 VO₂ with III-Nitride high-electron mobility transistors (HEMTs) to realize GaN-VO₂ HyperFETs, demonstrating steep-switching behavior in a platform that is amenable to integration and scaling.

For this study, VO₂ 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 VO₂ 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 VO₂ resistors show a ~1000X decrease in resistance as the VO₂ undergoes MIT beyond ~70°C as shown in Fig. 1(b). The transition temperature is quite close to the bulk value of ~67°C [3]. The MIT in the VO₂ 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 ~67°C. To keep the transition voltage lower, we loaded the source of GaN HEMT with the 4µm length VO₂ resistor kept at 60°C.

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 N₂ atmosphere at 850°C. After mesa-isolation etch, the room temperature mobility and 2-dimensional electron gas density for these epilayers was 1660 cm²/V-s and 7.6 x 10¹² 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 60°C is shown in Fig. 2.

To realize the HyperFET, a 4µm length VO₂ 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 60°C 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 VO₂. The subthreshold-slope at the MIT transition point is ~59 mV/dec, lower than the Boltzmann limit of ~66 mV/dec at 60°C (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 VO₂ 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 VO₂ 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.

Fig. 1 (a) TLM pattern fabricated on 35nm VO\textsubscript{2} thin films on Sapphire, (b) Temperature dependent resistance of 20\textmu m long and 100\textmu m wide VO\textsubscript{2} resistors showing ~3 orders decrease because of the insulator to metal transition, (c) Electric field driven insulator to metal transition in VO\textsubscript{2} resistors at 60\textdegree C 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 60\textdegree C.

Fig. 3 (a) Schematic circuit diagram of the VO\textsubscript{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 60\textdegree C. Transfer characteristics of the standalone HEMT device shown in Fig. 2(b) are reproduced as dashed lines in Fig. 3(b) for comparison (with \( V_{DS} = 10 \text{V} \)).