High-k Nanolaminate Gate Dielectric for SLCFET Amplifiers with Improved Frequency Performance and Breakdown Voltage

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Abstract

The Superlattice Castellated Field Effect Transistor (SLCFET) is emerging as a technology platform for RF front ends. High performing SLCFET RF amplifiers can be integrated with previously developed world-class SLCFET RF switches on the same wafer. This paper reports the first-time demonstration of a high-k gate dielectric (Al_2O_3/TiO_2 nanolaminate) on a SLCFET amplifier with improved performance. The nanolaminate gate dielectric achieved almost double the breakdown voltage as compared to the POR (low-k) gate dielectric, enabling higher voltage operation. Additionally, a unity power gain frequency f_{max} = 160 GHz was achieved, the highest reported for a SLCFET device.

INTRODUCTION

The Superlattice Castellated Field Effect Transistor (SLCFET), comprised of a stacked superlattice of AlGaN/GaN two-dimensional electron gases (2DEGs) and a three-dimensional castellated T-gate, is a promising candidate for emerging RF GaN transistor technology. For an RF switch, the high-charge density stacked superlattice provides reduced sheet resistance with minimal off-capacitance penalty, resulting in low-loss RF switches with figure of merit F_{CO} > 1.8THz [1-2]. For RF amplifiers, the increased charge density has enabled high power density and efficiency up to Ka band [3-4]. Additionally, W-band operation was achieved by careful device scaling and management of device parasitic resistance and capacitance [5]. Scaling of the process of record (POR) low-k gate dielectric thickness improved transconductance, therefore frequency performance improved with thinner gate dielectric. The effectiveness of reducing gate dielectric (low-k) thickness highlights the importance of the gate dielectric for continued scaling and triggered the feasibility study of using high-k gate dielectrics on the SLCFET amplifier. This manuscript reports the demonstration of an Al_2O_3/TiO_2 nanolaminate high-k gate dielectric on the SLCFET amplifier to improve device frequency performance and breakdown voltage.

DISCUSSION

Al_2O_3/TiO_2 nanolaminate composites are multi-layer films, realized by periodically alternating deposition of Al_2O_3 and TiO_2. Al_2O_3/TiO_2

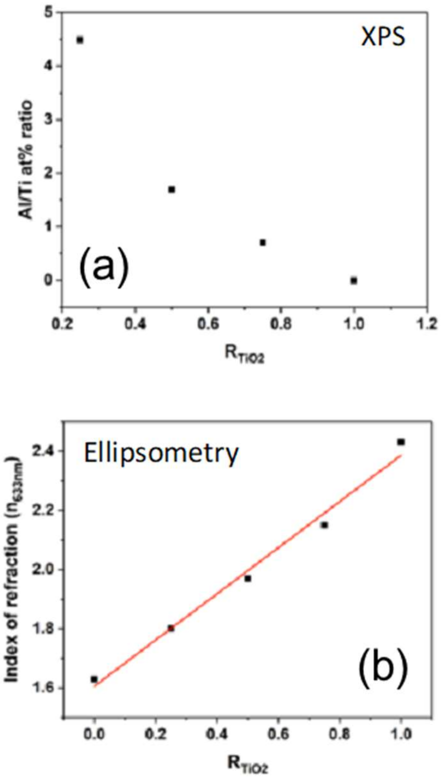

Fig. 1: (a) XPS and (b) ellipsometry material properties of nanolaminate films with different TiO_2/Al_2O_3 ratios.

TABLE 1. PROPERTIES OF NANOLAMINATES WITH VARYING AL_2O_3 TO TIO_2 RATIOS DEPOSITED ON SI WAFERS.

R_{Al2O3}:R_{TiO2}	Temp. (°C)	Thickness (nm)	Dielectric Constant	Hysteresis (mV)	J @ 10V (A/cm^2)
3:1	250	23.7	8.9	700	10.1×10^{-3}
1:1	250	22.8	13.4	400	3.7×10^{-3}
1:3	250	21.4	18.1	300	3.3×10^{-3}
0:1	200	22.3	21.1	20	2.9×10^{-3}
0:1	300	18.0	24.4	2	2.7×10^{-3}

TABLE 2. PROPERTIES OF NANOLAMINATES WITH A 1:3 AL_2O_3 TO TIO_2 RATIOS DEPOSITED ON GAN WAFERS.

R_{Al2O3}:R_{TiO2}	Al_2O_3 Recipe	TiO_2 Recipe	Temperature (°C)	Thickness (nm)	Dielectric Constant	Hysteresis (mV)
1:3	Original	Original	250	10.1	31.1	300
1:3	Optimized	Original	250	10.5	29.2	150
1:3	Optimized	Optimized Ar/O_2	250	11.1	31.4	50
1:3	Optimized	Optimized O_2	250	11.3	34.8	150

nanolaminate composites were deposited on Si wafers for process development with a single cycle resulting in a thickness of 1 Å per Al_2O_3 cycle and 0.55 Å per TiO_2 cycle. As shown by X-ray photoelectron spectroscopy (XPS) in Fig. 1a, the composition of the nanolaminate film can be varied by changing the ratio of TiO_2 to Al_2O_3 monolayers deposited. The nanolaminate material properties, such as index of refraction, are also varied according to composition, or the ratio of TiO_2 to Al_2O_3, shown in Fig. 1b.

Al_2O_3/TiO_2 nanolaminates were deposited on Si wafers varying the ratios of Al_2O_3 to TiO_2 cycles (R_{Al2O3}:R_{TiO2}), as shown in Table 1. The nanolaminate film properties degrade for gate dielectric applications with increasing Al_2O_3 concentration, however, the work function of Al_2O_3 is more desirable than TiO_2. This is shown by the dielectric constant decreasing, hysteresis measured by capacitance-voltage measurements increasing, and leakage current increasing with increasing Al_2O_3 concentration in the

Al_2O_3/TiO_2 nanolaminate films. A 1:3 ratio recipe of $Al_2O_3:TiO_2$ nanolaminate was selected to be further optimized on GaN substrates, to keep the Al_2O_3 content low compared to the TiO_2. As shown in Table 2, the dielectric constant of the nanolaminate films are significantly higher when deposited on GaN, as opposed to Si substrates. The Al_2O_3 and TiO_2 recipes were optimized by in-situ ellipsometry measurements to determine the optimal pulse/purge and flow conditions. For comparison, the TiO_2 recipe was optimized with either an Ar/O_2 or O_2 plasma, which previously have been shown to yield different phases, crystallinity and density of TiO_2 [6].

For SLCFET amplifier device fabrication, the process flow was modified from the SLCFET baseline flow to avoid high temperature thermal budget exposure to the dielectric. Fig, 2 shows a measured I_d-V_g and I_d-V_d curve of a device with the nanolaminate gate dielectric. Fig. 3 shows the measured breakdown voltage improvement of the nanolaminate compared to the POR low-k dielectric. The nanolaminate gate dielectric enhanced the breakdown voltage from ~50 V to ~80 V. The higher breakdown voltage enables higher drain voltage operation (V_D) to improve gain, output power, efficiency, and impedance matching for SLCFET amplifiers and MMICs.

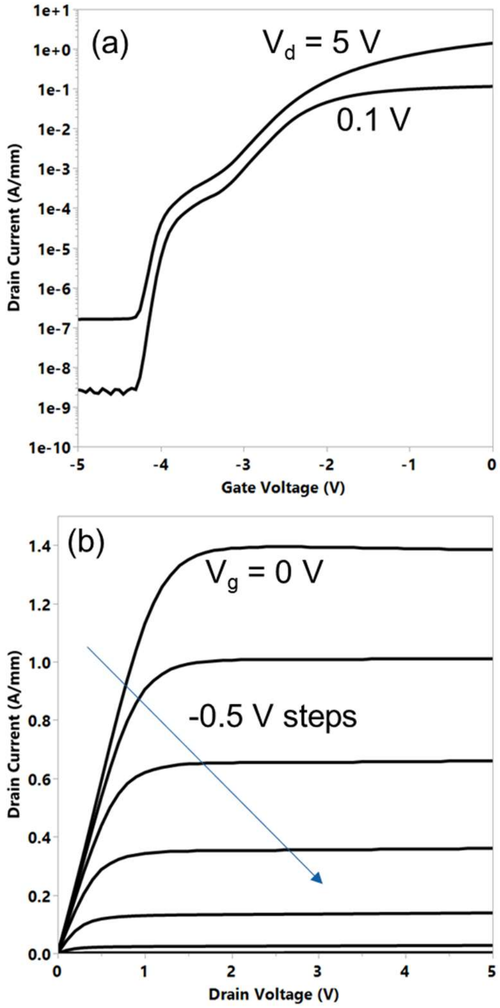

Fig. 2: (a) I_d-V_g and (b) I_d-V_d of a SLCFET amplifier device with Al_2O_3/TiO_2 gate dielectric.

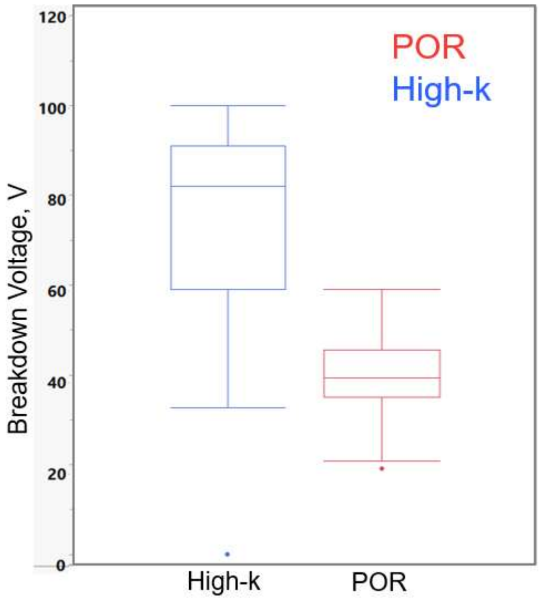

Fig. 3: Measured breakdown voltage on SLCFET amplifier comparing nanolaminate high-k and POR gate dielectrics.

Fig. 4 shows measured unity power gain frequency f_{max} and unity voltage gain frequency f_T extracted from small signal s-parameter measurements at a drain voltage of 5 V for SLCFET amplifier devices comparing the high-k (nanolaminate) and the POR gate dielectric. This is the highest reported f_{max} value for SLCFET amplifier to date [4-5,7]. As a comparison, the best POR gate dielectric performance for the same gate process and gate length is shown in red [4]. The measured gate length of the devices was 180-190 nm. Fig. 5 shows load-pull measurements at 94 GHz and V_{ds} = 10V of a device with high-k nanolaminate gate dielectric. The device shows an output power of 3.1 W/mm, normalized to active

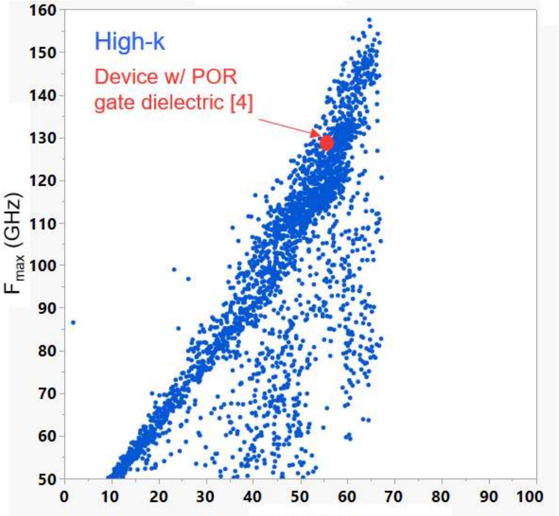

Fig. 4: f_{max} vs. f_t for the high-k nanolaminate (blue) compared to the best prior POR performance (red).

current carrying width, with a peak power-added-efficiency (PAE) of 23%.

CONCLUSIONS

We report first time demonstration of a high-k gate dielectric on a SLCFET amplifier device with the highest reported f_{max} and almost double the breakdown voltage compared to the POR gate dielectric. It is anticipated that the high-k nanolaminate gate dielectric will further enable gate length scaling without sacrificing breakdown voltage and further improve the gain, frequency, and power performance of the device. Combining SLCFET RF amplifier and the already established world-class switch (F_{co} = 1.8 – 2.5 THz) enables a new platform for wideband, reconfigurable RF front-ends.

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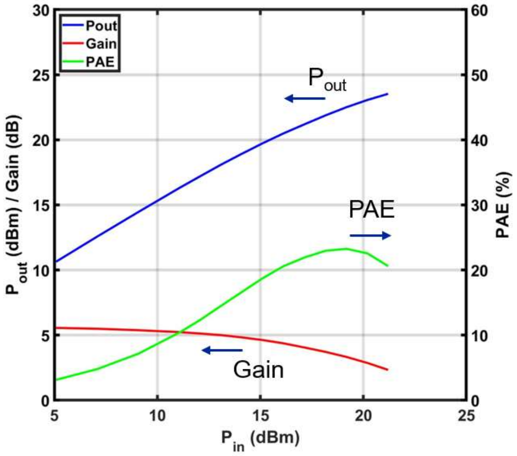

Fig. 5: Load pull measurement at 94 GHz and V_{ds} = 10 V for a device with Al_2O_3/TiO_2 nanolaminate gate dielectric.

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