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Steep-slope field-effect transistors with AlGaN/GaN HEMT and oxide-based threshold switching device

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Abstract

We report the demonstration of a steep-slope field-effect transistor with AlGaN/GaN MIS-HEMTs employing SiO2-based threshold switching devices in series with the source. The SiO2-based threshold switching devices exhibited steep slope when changing resistance states. The integrated steep-slope transistor showed a low subthreshold swing of sub-5 mV/dec with a transition range of over 105 in the transfer characteristics in both sweep directions at room temperature, as well as the low leakage current (10−5 μA μm−1) and a high IOH/IOFF ratio (>107). Moreover, with the SiO2-based threshold switching devices we also observed a positive shift of threshold voltages of the integrated device. Results from more than 50 transfer characteristics measurements also indicate the good repeatability and practicability of such a steep-switching device, where the average steep slopes are below 10 mV/decade. This steep-slope transistor with oxide-based threshold switching devices can be further extended to various transistor platforms like Si and III–V and are of potential interest for the development of power switching and high frequency devices.

Keywords: gallium nitride, steep slope, Boltzmann limit, threshold switching, transistor

Nowadays, the continuance of Moore’s law has become quite stringent for semiconductor foundries due to the limits of physics and fabrications [1, 2]. Meanwhile, conventional Si based MOSFETs are facing the fundamental limitation of the subthreshold swing (SS) by Boltzmann’s theory [3]. To keep providing faster computing systems for customers in future generation electronics, innovative materials and technologies have been explored extensively. These include III–V compounds [4], two-dimensional (2D) materials [5], topological insulators [6] and neural networks [7].

Recently, researchers proposed to employ tunneling FETs and integrate ferroelectric materials on gate of FETs to realize the steep subthreshold switching [8, 9]. However, the average SS of these devices was larger than 30 mV/decade, which is still unsatisfying. Another effort includes adopting graphene-based resistive switching device to achieve steep slope (sub-10 mV/decade) and low leakage current [10]. It is claimed that this filament transistor can be scaling down to sub-10 nm without sacrificing performance. Nonetheless, the repeatability and homogeneity still remain a critical challenge for such 2D material-based devices.

An alternative approach is to combine phase-change materials with conventional FETs to realize phase-FET or hyper-FET. The metal–insulator–transition (or Mott insulator)
materials such as VO$_2$ and NbO$_2$ are commonly utilized on gate or source electrodes to obtain SS less than 8 mV/dec [11–13]. For example, a GaN-based phase-FET was demonstrated which integrated AlGaN/GaN MOS-HEMT with a VO$_2$ resistor [13]. Nonetheless, the claimed steep-switching occurred at the current saturation region in transfer characteristics and the SS at threshold voltages ($V_{th}$) has not been modulated by VO$_2$. In addition, Mott insulators suffer from thermal instability in high frequency applications. Another effort includes adopting threshold switching device based on Ag and Cu to achieve steep slope (sub-5 mV/decade) and low leakage current [14–16].

In this paper, we implemented SiO$_2$-based threshold switching device with the advanced AlGaN/GaN metal-insulator–semiconductor HEMTs (MIS-HEMTs) on Si substrates and demonstrated a steep-slope transistor (SST). Compared to Mott insulators, SiO$_2$-based resistive random-access memory (RRAM) is favored primarily owing to the low leakage current and compatibility in the back-end-of-line (BEOL) processing in integrated circuits foundries [17–21]. This integrated SS-HEMT device achieved $\sim$5 mV/dec SS with a transition range of over $10^5$ in the transfer characteristics in both scan directions at RT. The $V_{th}$ was also improved significantly. This SS-HEMT also inherited low leakage current ($\sim 10^{-5} \mu$A $\mu$m$^{-1}$) and a high $I_{ON}/I_{OFF}$ ratio ($>10^5$) from the original MIS-HEMTs. These results not only enable this novel transistor architecture to extend to other transistor systems, but also offer considerable possibilities for low-power switching and high frequency applications.

The AlGaN/GaN device epilayers for the MIS-HEMTs were grown by the metalorganic chemical vapor deposition (MOCVD) on Si substrates. Trimethylgallium (TMGa) and trimethylaluminum (TMAI) were used as the precursors for Ga and Al, respectively, and ammonia (NH$_3$) was the source for N. The carrier gas is H$_2$. As showed in figure 1(a), the heterostructure consists of a highly resistive GaN buffer layer grown on a Si substrate, a 100 nm GaN channel layer, a 1 nm AlN interlayer, a 28 nm Al$_{0.25}$Ga$_{0.75}$N barrier layer, and a 2 nm GaN-cap layer. A 20 nm Si$_3$N$_4$ layer grown by low-pressure chemical vapor deposition (LPCVD) serves as the gate dielectrics and a passivation layer. The LPCVD-grown Si$_3$N$_4$ layer was deposited at 780 °C with ammonia (NH$_3$) flow of 280 sccm, a SiH$_2$Cl$_2$ flow of 70 sccm, and a deposition rate of 3.5 nm min$^{-1}$ [22].

The AlGaN/GaN HEMTs were fabricated using the conventional photolithography. The wafer was cleaned in acetone and isopropyl alcohol under ultrasonic, and then dipped briefly in hydrochloric acid before metal depositions. Planar device isolation was achieved by multi-energy fluorine-ion implantation [23]. The LPCVD-Si$_3$N$_4$ in the source/drain contacting area was etched away by reactive ion etching. Ohmic contacts for source and drain regions were formed by e-beam evaporation of Ti/Al/Ni/Au (20/130/50/150 nm) and annealed at 890 °C for 30 s in N$_2$ ambient. Then gate metals were deposited by e-beam evaporation with Ni/Au (50/150 nm) and lift-off process. The gate-to-source space, the gate-to-drain space, the gate width, and the gate length are 4, 15, 100, and 4 $\mu$m, respectively. After the MIS-HEMT fabrication, a 2D electron gas density of $\sim 1 \times 10^{13}$ cm$^{-2}$ and electron Hall mobility of $\sim 1800$ cm$^2$ V$^{-1}$ s$^{-1}$ were measured at room temperature. More details on device fabrications can be found in references [23–26]. The circuit symbols for MIS-HEMT device denoting the source (S), gate (G) and drain (D) terminals are illustrated in figure 1(a).

Threshold switching devices with a metal-insulator–metal (MIM) structure were then fabricated on the source contacts of the MIS-HEMT, as showed in figure 1(a). Figure 1(b) shows the MIM structure including a 12 nm Ti bottom electrode (BE), a 12 nm SiO$_2$ switching layer and a 15 nm Ag top electrode, sequentially deposited by e-beam evaporation without interrupting the vacuum. Each MIM cell is circular with a diameter of 30 $\mu$m. No thermal annealing was conducted afterwards. The finial devices were denoted SS-HEMT. More details on the deposition and fabrication of SiO$_2$-based threshold switching cells can be found in [27]. DC characterizations of oxide-based threshold switching devices were carried out using a Keithley 2400 sourcemeter.
resistive switching processes at current compliance of 5 and 7.5 μA for device switching to size discontinuous conductive fire reducing surface roughness of source electrodes and optimized using a Keithley 4200-SCS parameter analyzer. All ON/OFF transfer curves of the MIS-HEMTs and SS-HEMTs were performed at three different current compliances (I_{CC}) of 5 μA (in red) and 7.5 μA (in blue). The scan was taken at a sequence of 1-2-3-4, as labeled in the figure 2. For each current compliance, ~30 cycles were conducted to ensure the device repeatability and endurance. Threshold switching devices will go from a high resistance state (HRS) to a low resistance state (LRS) or ‘ON’ state at a threshold voltage (V_{TH}). All V_{TH} values are marked in the figure 2. For I_{CC} = 7.5 μA, V_{TH}^H and V_{TH}^L represent the threshold voltages of MIM device switching to ‘ON’ and ‘OFF’ states, respectively.

and transfer curves of the MIS-HEMTs and SS-HEMTs were performed using a Keithley 4200-SCS parameter analyzer. All measurements were performed at room temperature.

Figure 2 shows the representative resistive switching curves of the Ag/SiO_{2}/Ti oxide-based threshold switching devices at two different current compliances (I_{CC}) of 5 μA (in red) and 7.5 μA (in blue). The scan was taken at a sequence of 1-2-3-4, as labeled in the figure 2. For each current compliance, ~30 cycles were conducted to ensure the device repeatability and endurance. Threshold switching devices will go from a high resistance state (HRS) to a low resistance state (LRS) or ‘ON’ state at a threshold voltage (V_{TH}). All V_{TH} values are marked in the figure 2. For I_{CC} = 7.5 μA, V_{TH}^H and V_{TH}^L are ~3.7 V for positive scans and ~1.8 V for negative scans. In contrast for I_{CC} = 5 μA, V_{TH}^H are ~3.2 V and ~2.8 V. In addition, the ON state switched back to OFF state when the voltage sweeps back to a low level (V_{TH}^L = 1.5 V for I_{CC} = 7.5 μA and V_{TH}^L = 2.5 V for I_{CC} = 5 μA). The rectifying ratio of ~10^2 can be further enhanced with smaller MIM devices due to the inverse proportional relation between HRS and device size [16]. The device performance can be improved by reducing surface roughness of source electrodes and optimizing fabrication process. The possible threshold switching mechanism is proposed as the formation of unstable or even discontinuous conductive filaments at low compliance currents. More details on resistive switching mechanisms of the SiO_{2}-based threshold switching devices can be found in [28, 29].

Figure 3(a) illustrates the I_D–V_{GS} transfer characteristics of the stand-alone AlGaN/GaN MIS-HEMTs at drain voltages (V_{DS}) from 3 to 9 V and gate voltages (V_{GS}) from −14 to 4 V in both linear and logarithmic scales. The threshold voltage for HEMT (V_{th}), defined as the voltage at a current of 10^{-2} μA μm^{-1}, was determined as −12.28 V at a V_{DS} of 6 V in the forward scan. In addition, the hysteresis of V_{th} values between forward and backward scans is also obtained from figures 2(b) and (c). The hysteresis of V_{th} (∆V_{th}) is defined by the following equation: ∆V_{th} = V_{th}^f (backward) − V_{th}^f (forward). The ∆V_{th} can originate from the acceptor-like trap states in the Si_{3}N_{4}/GaN interface [30, 31]. At V_{DS} = 6 V, a low ∆V_{th} of 0.22 V was observed due to a high quality interface between GaN and Si_{3}N_{4} grown by LPCVD [23]. It is also noteworthy that hysteresis ∆V_{th} has a tendency to reduce as V_{DS} increases. This can be ascribed to the fact that fewer electrons would be captured by those aforementioned trap states when V_{DS} increases and then the electrical stress between gate and drain (V_{GD}) reduces. The saturation drain current (I_{D}) at V_{GS} = 4 V and V_{DS} = 9 V is 515 μA μm^{-1}. The ON/OFF ratio of over 10^7 was also achieved in this stand-alone AlGaN MIS-HEMT device.

Figures 3(b) and (c) show the I_D–V_{GS} transfer characteristics of integrated SS-HEMT at V_{DS} from 5 to 10 V for both forward scans and backward scans in logarithmic scales. The steep-subthreshold-switching behaviors were clearly observed in both scan directions. This steep slope switching occurs at a high current range from ~10^{-2} μA μm^{-1} to more than 10^6 μA μm^{-1}, indicating a high ON/OFF ratio of more than 10^7. This large current transition range of over 7 decades is 100 times greater than previous report on Ag/TiO_{2}-Based steep-slope transistor [32]. All subthreshold-switching values are below 5 mV/dec. In addition, the drain current (I_{D}) was suppressed in the SS-HEMT compared to the stand-alone MIS-HEMT. This can be ascribed to the additional source resistance from the SiO_{2}-based threshold switching devices, leading to the reduction of the actual bias applied on the drain and thus the decrease of the drain current. For instance, at V_{GS} = 3 V and V_{DS} = 9 V, the drain current was 432 μA μm^{-1} for SS-HEMT device while it was 513 μA μm^{-1} for the stand-alone MIS-HEMT. This suppressed I_{D} phenomena is also consistent with previous reports on steep-slope transistors, such as AlGaN phase-FET with VO_{2} [13], a Si MOSFET with NbO_{2} on gate [11] and a Si MOSFET with atom switch devices based on Ag and Cu [16]. On the other hand, a positive shift in V_{th} values was observed in both scan directions compared to the stand-alone HEMT in figure 3(a). This trend is also consistent with previous work on steep-switching transistors [11–16, 32]. This shifting V_{TH} can be attributed to the intrinsic low leakage current and high resistance of SiO_{2}. SiO_{2} has a huge bandgap of ~9.0 eV. This leads to the lower leakage current, larger current transition and smaller SS in our demonstrated steep-slope transistors. Once the threshold switching device is switched on, the integrated transistor will immediately rectify to the current saturation mode since the stand-alone HEMT is already turned on given the same gate voltage. In comparison, TiO_{2} and other oxides typically have a relatively small bandgap between 3.0 and 6.0 eV. The leakage current or OFF current would be higher in transfer characteristics (I_D–V_{GS} measurements) and such steep-threshold-switching performance would be less pronounced if these oxides are adopted in our design. More details will be discussed in the later section.
Figures 3. The $I_D-V_{GS}$ transfer characteristics of (a) the stand-alone AlGaN/GaN MIS-HEMTs in both logarithmic (left) and linear (right) scales, and the integrated steep-slope AlGaN/GaN HEMTs (SS-HEMT) for (b) the forward scan and (c) the backward scan in logarithmic scales.

Figure 4. The extracted subthreshold swing (SS) as a function of the drain current ($I_D$) for the integrated steep-switching AlGaN/GaN HEMTs (SS-HEMTs) at $V_{DS}$ = (a) 5 V, (b) 6 V, (c) 7 V, (d) 8 V, (e) 9 V and (f) 10 V, and (g) the stand-alone AlGaN/GaN MIS-HEMTs at $V_{DS}$ = 6 V. (h) shows the summary of the SS values at a function of the applied drain voltages $V_{DS}$ of the SS-HEMT and the stand-alone HEMT at $V_{DS}$ = 6 V. All data displayed in black indicated the forward scan and the red for the backward scan. Grey dash lines indicate the subthreshold swing limit at room temperature for traditional transistor.

Figures 4(a)–(h) show the extracted SS as a function of the drain current for the integrated SS-HEMTs at $V_{DS}$ = (a) 5 V, (b) 6 V, (c) 7 V, (d) 8 V, (e) 9 V and (f) 10 V in both scan directions, and (g) for the stand-alone AlGaN/GaN MIS-HEMTs at $V_{DS}$ = 6 V. For the MIS-HEMT device, the SS values were much higher than the Boltzmann limit of 60 mV/dec at RT and the minimum values were $\sim$ 85 mV/dec in the forward scan and $\sim$ 80 mV/dec in the backward scan, respectively. With the integration of silica-based threshold switching devices, the steep subthreshold switching occurs at
an abrupt transition range of drain current, which is higher than 5 orders of magnitude in forward scans (see figures 4(a)–(f)). Figure 4(h) shows the summary of SS values at a function of applied drain voltage $V_{DS}$. Starting from $V_{DS}=5$ V, the SS-HEMT exhibited the steep-subthreshold-switching behavior and dropped dramatically to 1.94, 1.79, 1.47, 1.47, 1.49 mV dec$^{-1}$ at $V_{DS}=5$, 6, 7, 8, 9 and 10 V in the forward scans. In backward scans, SS values were still far smaller than the Boltzmann limit of 60 mV dec$^{-1}$ at RT, i.e. 1.81 mV/dec, 1.49 mV/dec, 2.96 mV dec$^{-1}$, 2.04 mV dec$^{-1}$, 2.04 mV dec$^{-1}$ and 1.90 mV/dec at $V_{DS}=5$ V, 6 V, 7 V, 8 V, 9 V and 10 V, respectively. It is worth pointing out that in the steep-slope ranges, SS values are comparable in both scan directions. However, this is not a general case for measurement results of more than 50 times. SS values in backward scans are generally larger than in the forward scans, which has previously been observed in the steep-switching AlGaN phase-FET with VO$_2$ [13]. This can be attributed to the fact that more electrons are accumulated in the SiO$_2$-based threshold switching devices during sweeping of $V_{GS}$ from negative to positive range. Future work on characterizing the switching performance of this type of integrated AlGaN/GaN SS-HEMTs will be conducted to investigate the modulation capability.

In order to confirm the repeatability of the steep-slope HEMT device, we performed $I_{DS}$–$V_{GS}$ measurements on multiple devices for more than 50 times. Summary of $V_{SS}$ values (defined as the gate voltage where the steep slope transition occurs) at a function of applied drain voltages $V_{DS}$ in the SS-HEMT and the summary of SS values at a function of applied drain voltages $V_{DS}$ are shown in the figures 5(a) and (b), respectively. For each sweep direction of each drain voltages $V_{DS}$, more than 10 $I_{DS}$–$V_{GS}$ curves were chosen to calculate the statistical distribution of $V_{SS}$ and SS values. We can see that a positive shift in all subthreshold gate voltages where the steep slope transition occurs ($V_{SS}$) compared to those in a normal stand-alone HEMT device ($\sim -12.5$ V). In addition, $V_{SS}$ in backward scans are generally more negative than these in forward scans. This can be accounted for electron accumulation in both MIM and HEMT devices during sweeps. As for SS ranges shown in figure 5(b), SS appears to be more stable at around 2–5 mV dec$^{-1}$ as $V_{DS}$ increases. Future work on achieving better stability of SS and device can be incorporating GaN-based threshold switching devices [24] and improving fabrication process.

The proposed threshold switching mechanisms are concluded as follows: with the SiO$_2$ threshold switching device on the source of a HEMT, the original gate voltage $V_{GS}$ is composed of 2 parts: $V_{GS}$ and $V_{SS}$ (see figure 1(c)). The $V_{SS}$ ($\sim-0$ V) is equal to the condition where Ag electrode was applied a positive voltage, namely $V_{SS}>0$, since this is a depletion-mode HEMT and steep switching occurs at a negative $V_{GS}$. There are three possible device operation scenarios:

1. As $V_{GS}<V_{th}$ of HEMT [$V_{th}$ (HEMT) $\sim-12$ V], the integrated HEMT behaves like a stand-alone HEMT and the device was turned off;
2. As $V_{th}<V_{GS}<0$, at a certain level of $V_{GS}$, $V_{SS}$ will exceed the $V_{th}$ of the SiO$_2$ threshold switching device [$V_{th}$ (MIM)]. Then conductive filaments form between top and BEs. As the MIM device turns to LRS, the integrated transistor (HEMT in this case) will immediately rectify to the current saturation region and the steep switching occurs. This is due to the similar resistance states for both for SiO$_2$ MIM structure and HEMT since the OFF current is in the range from $10^{-9}$ to $10^{-7}$ A for SiO$_2$ MIM structure while the OFF current of HEMT is lower than $1 \times 10^{-8}$ A (this is the detection limit of the setup-up).
3. As $V_{GS}$ sweep back, $V_{SS}$ will exceed the $V_{th}$ (MIM) at another certain level of $V_{GS}$. Then conductive filaments break, the MIM device turns to HRS, the steep switching occurs, and the transistor turns off.

In summary, we implemented the SiO$_2$-based threshold switching devices on the improved AlGaN/GaN MIS-HEMTs
on Si substrates and demonstrated a steep-slope transistor. This integrated SS-HEMT device achieved ~5 mV/dec SS with a current transition range of over 105 in the transfer characteristics in both scan directions at RT. It also inherited low leakage current (~10−5 μA μm −1) and a high IDSS/IOFF ratio (>105) from the MIS-HEMTs. Advantages of SiO2-based threshold switching devices include intrinsic low leakage current, facile fabrication process, CMOS-compatible and controllable switching properties. Further engineering approaches can be adopted to fabricate the steep-slope transistor with desired switching behavior. For example, an enhancement-mode GaN HEMT, III–V transistors and even Si FinFETs can also be integrated with such SiO2-based threshold switching devices. In addition, OFF current level can be further reduced by laterally scaling down the size of MIM structure. Therefore this novel transistor design harnesses the unique properties of facile and CMOS-compatible SiO2-based threshold switching devices and promises numerous performance advantages over conventional three-terminal transistors.

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References

[6] Kong D et al 2011 Ambipolar field effect in the ternary topological insulator (Bi0.5Sb1.5)2Te3 by composition tuning Nat. Nanotechnol. 6 705–9
[9] Salahuddin S and Datta S 2008 Use of negative capacitance to provide voltage amplification for low power nanoscale devices Nano Lett. 8 405–10


