An Investigation of Anode Hole Injection-Induced Abnormal Body Current in n-Channel HfO₂/TiN MOSFETs

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ABSTRACT This paper investigates an anode hole injection (AHI)-induced abnormal body current (abn IB) in n-channel HfO₂/TiN MOSFETs. Traditionally, body current is independent of gate voltage during initial electrical characteristic measurements. Nevertheless, in this paper, the opposite is found in our experiment. Therefore, two different measurement techniques are employed, with the body current attributed to electrons in the inversion layer under the grounded source/drain. This indicates that the dominant mechanism is AHI rather than electron tunneling from the valence band. Moreover, the abn IB is dominated by tunneling mechanisms because it is independent of temperature.

INDEX TERMS Body current, anode hole injection, MOSFET.

I. INTRODUCTION

As metal oxide semiconductor field-effect transistors (MOSFETs) scale down, traditional SiO₂-based dielectrics are only a few atomic layers in thickness, resulting in increased gate leakage current, increased power dissipation, and reduced performance. To overcome these problems, conventional SiO₂ gate dielectrics are being replaced by high-k dielectric, specifically HfO₂ gate dielectric [1]. In addition, high-k gate dielectrics can be integrated with strained silicon, a silicon-on-insulator (SOI) structure, and fin field-effect transistor (FinFET) devices [2]–[4]. At present the FinFET is one promising structure because of its excellent overall performance as well as the gate control ability which suppresses short-channel effects. In this letter, we investigate the anode hole injection-induced abnormal body current (abn IB) in n-channel HfO₂/TiN MOSFETs. In general, body current is an indicator of reliability and can be used to predict the lifetime of a device, as the impact ionization current is generated near the drain side when the device is operated in the saturation region [5]. In addition, when the transistor is turned off and \( V_{GD} < -1 \text{V} \), the generation of electron-hole pairs is caused by band-to-band tunneling (BTBT), and the body current and drain current increases are termed gate-induced drain leakage (GIDL) current [6]. However, the abnormal body current we note operates in the linear region, unlike the case explained above. Further details will be explained later.

II. EXPERIMENT

The HfO₂/TiN n-FinFETs used in this letter were fabricated by 16 nm technology with a gate-last process. To begin, high quality 1 nm thermal oxide was grown as an interfacial layer for the core device. Then 2 nm of HfO₂ dielectric was deposited by atomic layer deposition (ALD). Furthermore, after the deposition of the HfO₂, the process was divided into two parts: one group was annealed at high temperature in N₂ ambient (normal devices), while the other was not annealed (abnormal current devices). Finally, work function metal (WFM) layers of TiN were deposited by ALD. In this work, the dimensions of devices were width = 154 nm and...
length = 20, 38, 60, 80, and 100 nm. Figure 1(a) shows the structure of a FinFET device. A cross-section of corresponding point A to A’ in this FinFET 3D structure is shown in Figure 1(b). All experimental curves were measured using an Agilent B1500 semiconductor parameter analyzer and a Cascade M150 probe station.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the drain current-gate voltage ($I_D - V_G$), gate current-gate voltage ($I_G - V_G$), and body current-gate voltage ($I_B - V_G$) log-scale curve at the linear region measurement for abnormal current/normal devices. $I_G - V_G$ and $I_B - V_G$ electrical characteristics under grounded and floating S/D operations for (b) abnormal current device and (c) normal device. (d) IB-VS/D electrical characteristics under floating gate operation.

FIGURE 2. (a) $I_D - V_G$, $I_G - V_G$, and $I_B - V_G$ log-scale curve at linear region measurement for abnormal current/normal devices. $I_G - V_G$ and $I_B - V_G$ electrical characteristics under grounded and floating S/D operations for (b) abnormal current device and (c) normal device. (d) IB-VS/D electrical characteristics under floating gate operation.

To further investigate the mechanism of abnormal $I_B$, we investigate models used in previous reports [7]–[10], which have proposed that the significant tunneling current components of the poly-Si gate are hole tunneling from the valence band (HVB), electron tunneling from the valence band (EVB), and electron tunneling from the conduction band (ECB), as shown in Figure 3(a). One of these gate leakage currents is likely to be the main cause of abnormal $I_B$. First, the HVB model can be eliminated because the TiN metal gate has fewer holes in the FinFET structure. Second, the band diagram of EVB indicates the electrons tunnel from the valence band of the Si substrate to the TiN metal gate. The remaining holes collect in the substrate. The EVB model may, then, explain the cause. Third, Figure 3(b) shows the electrons tunneling from the inversion layer to the metal gate (anode), and generating electron-hole pairs by impact ionization at the HfO$_2$/metal interface; these holes can then inject to the body (cathode); this model is similar to anode hole injection (AHI) [8], which corresponds to ECB in previous reports [7]. The EVB and AHI mechanisms generate holes that contribute to body current; however, an important difference between the EVB and the AHI model.
is the source of electrons. In the EVB model, the electrons come from the valence band, but the electrons come from the conduction band under the AHI model. Therefore, two operation conditions which can be used to distinguish the different sources of electrons are floating (GB) and grounded (GSDB) source/drain (S/D) operations, schematics of which are shown in Figure 3(c) and (d). Because the S/D cannot supply sufficient electrons to the inversion layer under GB operation, the gate leakage current becomes insignificant, as shown in Figure 2(b). Similarly, the $I_B$ is negligible in this operation. In contrast, both currents show very pronounced increases under GSDB operation. These results demonstrate that the origin of abnormal $I_B$ can be attributed to the electrons in the inversion layer rather than the electron-hole pairs separated in the valence band of the substrate. Consequently, the AHI model is confirmed to be the dominant mechanism contributing to abnormal $I_B$.

Figure 4(a) and (b) shows $I_G - V_G$ and $I_B - V_G$ curves under different $V_D$ in abnormal current devices. It can be clearly observed that $I_G$ and $I_B$ become smaller with increasing $V_D$. The reduction of the vertical electric field near the drain side leads to the reduction of electrons tunneling from the inversion layer, as shown in Figure 4(c). In other words, the lateral electric field becomes stronger so that the electrons tend to drift into drains. Therefore, the generation of electron-hole pairs by electron impact ionization at the HfO$_2$/metal interface is also reduced. In addition, when these abnormal current devices are operated under the condition of large $V_D$ measurement, the electrons undergo impact ionization on the drain side, as shown in Figure 4(d). In conclusion, the impact ionization occurs at the gate when abnormal current devices are operated in the linear region and the impact ionization occurs at the drain when abnormal current devices are operated in the saturation region.

Figure 5(a) shows $I_G - V_G$ and $I_B - V_G$ at different temperatures for $V_D = 0$V. It is clear that $I_G$ and $I_C$ increase significantly with increasing temperature. However, they have insignificant changes after a $V_T$ correction for different temperatures, as shown in the inset of Figure 5(a). In general, the dominant mechanism of $I_G$ is Poole-Frenkel ($I_P$) in the hafnium oxide rather than the tunneling ($I_T$) mechanism in the silicon oxide [11]. Because the Poole-Frenkel current path and tunneling current path are in series, the current fitting is dominated by the smaller one. Therefore, the $I_G$ and $I_B$ are dominated by tunneling mechanism because they are independent of temperature. Accordingly, the HfO$_2$ has more bulk traps, resulting in the tunneling mechanism ($I_{P-F} > I_T$), as confirmed by current fitting.

To further verify that the HfO$_2$ has more bulk traps in the abnormal current devices than the normal devices, we performed measurements of the reliability of positive bias stress (PBS) [12]. Thus, we define device failure criteria as 50mV $V_T$ shift, the lifetime for the device to reach this degradation value. Figure 5(b) shows the lifetime during PBS at $V_G = V_T + V_{stress}$ with $V_{stress} = 1.5V \sim 1.9V$ and $1.7V \sim 2.1V$ for abnormal current/normal devices, respectively. Clearly, the lifetime of the abnormal current devices is 3 orders of magnitude shorter than that of the normal devices. Consequently, many bulk traps in HfO$_2$ lead to the abnormal body current. Because the electron can easily tunnel from the inversion layer to the metal gate and generate electron-hole pairs by impact ionization at the HfO$_2$/metal interface, these holes can easily tunnel to the body.

Figure 5(c) shows that $I_B$ has a linear relationship to channel length, which is measured by grounded source, drain, and body at $V_G = 1.4V$ for different channel lengths. Because the abnormal $I_B$ is caused by the AHI model, longer channel...
lengths lead to a larger body current. Furthermore, the AHI model-induced hole current has a linear dependence on the electron current tunneling from the inversion layer, as shown in Figure 5(d), with the $I_S + I_D$ indicating the electron tunneling current from the inversion layer. The $\Delta I_B$ is obtained by subtracting the GB component from the GSDB of $I_B$, which is the pure hole current induced by AHI model. These results provide further proof that the AHI model indeed exists and is the dominant mechanism contributing to abnormal body current in n-FinFETs. However, it is worth noting that since metal has no energy gap, holes are not easily generated in metal. Therefore, impact ionization is more likely to occur at the HfO$_2$/metal interface. Previous reports have indicated that doping TiO$_2$ with nitrogen will reduce the bandgap [13], [14]. In contrast, we believe that TiN will be oxidized to TiON at the HfO$_2$ gate stack, resulting in a small bandgap at the interface. However, it is difficult to verify this model with simulation, so we use sputtering to deposit a layer of TiN thin film on a dummy wafer under a trace oxygen atmosphere at thicknesses of 2.59, 5.02, and 10.75 nm. After deposition of the thin films, the $E_g$ values measured by the N&K analyzer [15] were 1.41, 1.59, and 1.71 eV, respectively, as shown in Table 1. This also corresponds to the voltage at which the body current rises significantly in the $I_B - V_G$ diagram, which is approximately 1.1 V, as shown in Figure 4 (b). After the flatband voltage correction, according to the formula $V_G - V_{fb} = V_{ox} + 2\phi_B$, the $V_{ox} + 2\phi_B$ value is approximately 1.6 to 1.9 V. This voltage difference causes the electrons to gain energy, which is sufficient for generation of electron-hole pairs by electron impact ionization at the HfO$_2$/TiN interface.

### TABLE 1. The $E_g$ of TiON thin films of different thicknesses as measured by the N&K analyzer.

<table>
<thead>
<tr>
<th>TiON Thickness (nm)</th>
<th>$E_g$(eV)</th>
<th>Goodness of Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.59nm</td>
<td>1.41</td>
<td>0.9957</td>
</tr>
<tr>
<td>5.02nm</td>
<td>1.59</td>
<td>0.9963</td>
</tr>
<tr>
<td>10.75nm</td>
<td>1.71</td>
<td>0.9974</td>
</tr>
</tbody>
</table>

### IV. CONCLUSION

In this letter, different measurement techniques demonstrate that the abnormal $I_D$ is dominated by the AHI model. Additionally, $I_G$ and $I_B$ exhibit the tunneling mechanism because they have insignificant changes after a $V_T$ correction for different temperatures. Therefore, the HfO$_2$ has more bulk traps, resulting in the tunneling mechanism ($I_{P-F} > I_T$). Finally, the $V_{ox} + 2\phi_B$ value approximates the TiON bandgap, demonstrating that impact ionization occurs at the HfO$_2$/metal interface.

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### REFERENCES


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