Anomalous increase in hot-carrier-induced threshold voltage shift in n-type drain extended metal-oxide-semiconductor transistors

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Anomalous increase in positive threshold voltage shift (ΔVT) in n-type drain extended metal-oxide-semiconductor (DEMOS) transistors stressed under high drain voltage and gate voltage is observed. Charge pumping data and technology computer-aided-design simulations reveal that hot-electron injection and trapping in the gate oxide above channel region is responsible for ΔVT. Enhanced impact ionization rate resulted from the presence of large amount of negative oxide charge in channel region is identified to be the main mechanism for anomalous increase in ΔVT. From the results presented in this letter, hot-carrier-induced anomalous increase in ΔVT can become a serious reliability concern in DEMOS transistors. © 2008 American Institute of Physics.

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To reduce chip size and cost in power applications, high-voltage devices integrated into mature complementary metal-oxide-semiconductor (CMOS) process have attracted much attention recently. Among many types of high-voltage devices, drain extended MOS (DEMOS) transistors are extensively used in display drivers. One major reliability concern in DEMOS transistors is hot-carrier reliability because devices are often operated under high drain voltage (Vd) and high gate voltage (Vg).4–7 It has been reported that hot-carrier-induced on-resistance (Ron) degradation is much greater than threshold voltage shift (ΔVT), indicating that hot-carrier-induced damage is mainly located in drift region.4 In this letter, however, anomalous increase in positive ΔVT but small Ron degradation is observed in our DEMOS device stressed under high Vg and high Vd. Charge pumping data reveal that significant ΔVT is attributed to large amount of hot-electron injection and trapping in the gate oxide above channel region. Technology computer-aided-design (TCAD) simulations suggest that enhanced impact ionization (I.I.) rate resulted from the generation of negative oxide charge in channel region is the main mechanism responsible for anomalous increase in ΔVT. The effect of negative oxide charge in channel region on vertical electric field (Ez) of the device is also discussed.

The device investigated in this letter is n-type DEMOS transistor processed by a 0.25 μm CMOS compatible high-voltage technology. Schematic cross section of the device is shown in Fig. 1. The typical operation voltage of the device is 20 V for both Vg and Vd, dc hot-carrier stressing under Vg=20 V and various Vd is carried out at room temperature with the source and bulk terminals connected to the ground. To determine the bias condition in charge pumping measurement, flat-band voltage (Vfb) and threshold voltage (VT) in channel region are obtained from TCAD simulation. Vfb and VT are defined as the Vg when the concentration at Si/SiO2 interface reaches 1014 cm−2 for hole and electron, respectively. From simulation results, Vfb is roughly −0.4 V, while VT is about 1 V. The pulse with high level fixed at 4 V and low level (Vgl) varied from −0.4 to 2 V is applied to the gate under a frequency of 500 kHz. To extract hot-carrier-induced damage in the channel region, charge pumping current (Icp) is measured at source terminal while the drain is floating. From charge pumping data, a method similar to the one proposed by Cheng et al.8 is used to extract hot-carrier-induced oxide charge density (ΔNox) and interface state density (ΔNit) in channel region. The stress tests are periodically interrupted to measure degradation of device parameters (including VT and Ron) and Icp. VT is extracted at Ved=0.1 V, while Ron (=Vd/Icp, Icp is drain current) is measured when Ved=0.1 V and Vg=20 V. In addition to stress tests, two-dimensional TCAD simulations are also performed and I.I. rate and Ez are analyzed to support the proposed degradation mechanism.

When the device is stressed under Vg=26 V and the Vd to produce bulk current (Ib) maximum condition (Vg=9 V) for 5000 s, both ΔVT (1 mV) and Ron degradations (<1%) are small. However, significant ΔVT (VT increases after stress) and some Ron degradations are exhibited when devices are stressed under Vg=20 V with various Vd, as shown in Fig. 2. The time dependence of Ron degradation follows the expected power-law relationship. ΔVT is small

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(<4 mV) during the early stage of stressing (typically between 10^1 and 10^2 s). However, anomalous increase in $\Delta V_T$ is observed after about 10^2 s. To investigate the physical degradation mechanism responsible for $\Delta V_T$, $I_{ot}$ of the device stressed under $V_d=26$ V and $V_g=20$ V is measured and shown in the rightward inset of Fig. 3. Hot-carrier-induced $\Delta N_{ot}$ in channel region is extracted from charge pumping data by

$$\Delta N_{ot} = \Delta V_{fb} C_{ox}/q,$$

where $\Delta V_{fb}$ is stress-induced shift in flat-band voltage and $C_{ox}$ is gate oxide capacitance. The extracted $\Delta N_{ot}$ is shown in Fig. 3 and the time dependence of $\Delta N_{ot}$ is similar to the time dependence of $\Delta V_T$ in Fig. 2. On the other hand, hot-carrier-induced $\Delta N_{ot}$ can be extracted from a properly leftward shift of $I_{cp}$ spectrum by the amount of $\Delta V_{fb}$. The resulting $I_{cp}$ due to $\Delta N_{ot}$ only is shown in the leftward inset of Fig. 3. From the results in Fig. 3, two distinct features are found. First, there is no apparent shift in $I_{cp}$ spectrum (i.e., negligible $\Delta N_{ot}$) during the early stage of stressing (10 s). However, a significant rightward shift in $I_{cp}$ spectrum (i.e., significant negative $\Delta N_{ot}$) is observed when the stressing is long enough (500, 1000, and 5000 s). Second, $I_{cp}$ increase due to $\Delta N_{ot}$ is small, suggesting that $\Delta N_{ot}$ is negligible. Such a result indicates that hot-electron injection and trapping in the gate oxide above the channel region is the main mechanism responsible for positive $\Delta V_T$. The driving force of hot-electron injection is large $E_x$ in the channel region and is discussed in the following paragraph.

To explain the anomalous increase in $\Delta V_T$, normalized I.I. rate (i.e., $|I_b/I_d||$,$I_b/I_d$ is bulk current) for the device stressed under $V_d=26$ V and $V_g=20$ V is analyzed. As shown in Fig. 4, $|I_b/I_d|$ is close to unity during the early stage of stressing. However, $|I_b/I_d|$ rapidly increases as the stress time is longer than 10^2 s. In addition, Fig. 4 reveals that $|I_b/I_d|$ and $\Delta V_T$ have a similar anomalous increasing behavior, indicating that the anomalous increase in $\Delta V_T$ is related to enhanced I.I. rate. To identify the mechanism responsible for enhanced I.I. rate, the effect of negative $\Delta N_{ot}$ on the magnitude of I.I. rate and $E_x$ is examined by TCAD simulations. Figures 5(a) and 5(b) show I.I. rate (where the impact ionization model proposed by Selberherr is used in simulation) and $E_x$ (along the dot line in the inset) under $V_d=26$ V and $V_g=20$ V for devices with or without the presence of $\Delta N_{ot}$ in the channel region. The origin of $x$ axis in Fig. 5(b) is the location of $p^+n^+$ junction and $\Delta N_{ot}$ is uniformly distributed between $x=-0.8$ $\mu$m and 0 (where electron injection probability is significant) in simulations. The amount of $\Delta N_{ot}$ is varied from small ($5 \times 10^{10}$ cm^{-2}) to large ($7 \times 10^{11}$ cm^{-2}). The simulated $\Delta V_T$ is less than 4 mV when

FIG. 2. (Color online) $R_{on}$ degradation shows the expected power-law relationship. $\Delta V_T$ is small during the early stage of stressing; however, anomalous increase in $\Delta V_T$ is observed after about 10^2 s.

FIG. 3. (Color online) Hot-carrier-induced $\Delta N_{ot}$ in the channel region is extracted. $I_{cp}$ data measured at various stress time are presented (rightward inset). The $I_{cp}$ spectrum due to $\Delta N_{ot}$ only is also extracted (leftward inset).

FIG. 4. (Color online) During stressing, $|I_b/I_d|$ and $\Delta V_T$ show a similar anomalous increasing behavior, indicating that the anomalous increase in $\Delta V_T$ is related to enhanced $|I_b/I_d|$.

FIG. 5. (Color online) Simulated (a) I.I. rate and (b) $E_x$ under $V_d=26$ V and $V_g=20$ V for the devices with or without the presence of negative $\Delta N_{ot}$ in channel region. I.I. rate and $E_x$ are almost identical when small $\Delta N_{ot}$ is present. I.I. rate is greatly enhanced but $E_x$ is reduced when large $\Delta N_{ot}$ is present.

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\( \Delta N_{ot} = 5 \times 10^{10} \text{ cm}^{-2} \), while simulated \( \Delta V_T \) is about 47 mV when \( \Delta N_{ot} = 7 \times 10^{11} \text{ cm}^{-2} \). The relationship between \( \Delta V_T \) and \( \Delta N_{ot} \) is similar in simulation and measurements when the above simulated \( \Delta V_T \) results are compared to \( \Delta V_T \) and \( \Delta N_{ot} \) data in Figs. 2 and 3. As shown in Fig. 5(b), large positive \( E_y \) (favors for electron injection into SiO\(_2\)) in the channel region is identified to be the main mechanism responsible for the anomalous increase in \( \Delta V_T \). The gradual saturation behavior in \( \Delta V_T \) when \( \Delta V_T \) is significant is attributed to the reduction of \( E_y \). The results presented in this letter indicate that the anomalous increase in \( \Delta V_T \) may become a serious concern and should be taken into consideration in evaluating hot-carrier reliability of DEMOS devices.

In summary, hot-carrier-induced anomalous increase in \( \Delta V_T \) in DEMOS transistors stressed under high \( V_d \) and high \( V_g \) is examined. Hot-electron injection and trapping in the gate oxide above channel region causes positive \( \Delta V_T \). Enhanced I.I. rate during stressing resulted from the presence of large \( \Delta N_{ot} \) is identified to be the main mechanism responsible for the anomalous increase in \( \Delta V_T \). The gradual saturation behavior in \( \Delta V_T \) when \( \Delta V_T \) is significant is attributed to the reduction of \( E_y \). The results presented in this letter indicate that the anomalous increase in \( \Delta V_T \) may become a serious concern and should be taken into consideration in evaluating hot-carrier reliability of DEMOS devices.

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