Cell structure and saturation effects of radiation-hardened power VDMOSFET devices under extreme dose X-ray irradiation

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Abstract

In this paper we report radiation effects in radiation-hardened power VDMOSFET devices with different cell structures (stripe-cell and hexagonal-cell) at various irradiation doses of X-ray (45 kV acceleration voltage) by means of DCIV measurements as well as sub-threshold methods, and observed that radiation damages are closely related to cell geometry of the chips. Both radiation-induced oxide charges and interface traps in the chips with stripe cell are smaller than those with hex cell under the same irradiation dose because they have different stresses in the cells. Moreover, the recombination current peaks show a saturation feature when X-ray irradiation dose come to about 4 Mrads (from ~4 to 14.4 Mrads) in the radiation-hardened samples.

1. Introduction

The power vertical double-diffused metal–oxide–semiconductor field effect transistors (VDMOSFETs) have been widely used as an essential component in the power circuits of electronic system [1]. However, ionizing radiation in the metal–oxide–semiconductor (MOS) devices results in build-ups of oxide trap charges and interface traps at the SiO₂/Si interface which may lead to a prompt or delayed failure of the devices [2]. Particularly, catastrophic failure may occur due to single-event current and/or single-event gate rupture when the MOSFETs are operated in a space-based system [3,4]. In the past decades, in order to ensure that the MOSFETs work properly in their extended application many investigations have been conducted in studying physical mechanism involved in the radiation-induced oxide charges and interface traps as well as their processes during and the irradiation and the post-irradiation annealing [5–10]. At the same time great efforts have been taken to develop new technology for improving these devices, which are less sensitive to the radiation effects, for instance, radiation-hardened technology [11,12]. In this communication we report the DCIV studies of
radiation effects on radiation-hardened VDMOS-FET devices with stripe-cell geometry and hexagonal-cell geometry at various X-ray irradiation doses, and find that selection of cell structure is also an important factor to control radiation effects in these devices.

2. Experimental

Two kinds of the power VDMOSFET samples from Fairchild Semiconductor Inc., are as follows: radiation-hardened n-channel VDMOSFET samples with metallic package (TO-205AF) with stripe-cell (FSGL130DX) (denoted as S1 – radiation-hardened stripe cell), and hexagonal cell (FSL13A0DX) (denoted as S2 – radiation-hardened hex cell). Detailed descriptions of these structures were given in [13,14]. The metal packages were cut and removed before irradiation.

The samples were irradiated with X-ray radiation from a Cu-target rotating anode X-ray generator with 45 kV and 10 mA setting. The X-ray dose rate to S1 and S2 was calibrated by Radfet and was equal to 2 krad/s (SiO₂). The irradiated samples were characterized and measured by a direct-current current–voltage (DCIV) method. In the DCIV measurement, a small forward-bias voltage was applied across the PN junction of a gated PN diode since the internal device structure of the power VDMOSFET was similar to a gated PN junction diode [15]. Fig. 1 shows the cross-sectional view of the half-cell of an n-channel VDMOSFET and a schematic of the DCIV measurement set-up. In our cases, a small forward bias, \( V_{PN} \), in the range of 0.1–0.5 V was applied to the PN junction between channel (or body) and drain (or neck), scanning the gate voltage, \( V_{GD} \), and measuring the current through the source with the drain connected to ground. The DCIV data from the lateral gated-diode configuration of the VDMOSFET chip yielded information on the radiation induced trapped oxide charges and on the interface traps at the oxide/Si interface of the drain-side or the “neck” region. In addition, standard sub-threshold current–voltage measurements were also performed for comparison [19].

3. Results and discussions

Fig. 2(a) and (b) shows the DCIV data curves for the radiation-hardened n-channel VDMOSFET devices with a stripe cell geometry and with a hexagonal cell geometry respectively after several doses of X-ray irradiation, 0.6, 1.2, 2.4, 3.6, 7.2, 10.6, 14.4 Mrads. The DCIV data were taken at each of the designated doses after a 10-min time had elapsed at the end of every irradiation step. The DCIV data for those samples exhibit quite different characters: (1) for all irradiation doses DCIV curves of the radiation-hardened hex cell show a prominent two peaks with a broad second peak (Fig. 2(b)) while only one peak can be superficially seen for the radiation-hardened stripe cell (Fig. 2(a)); (2) the DCIV current peaks for both radiation-hardened samples (Fig. 2(a) and (b)) show a saturation behavior at X-ray irradiation doses from 4 M to 14.4 Mrads.

In order to obtain more information about the radiation damages from these DCIV data, we have analyzed all DCIV data by resolving a second current peak by subtracting from the overall
DCIV data, the primary current peak fitted with a Gaussian function and bulk current $I-V$ portion fitted with an exponential function. Fig. 3 shows an example of such fittings to the DCIV current curves for two above-mentioned samples with the same X-ray irradiation dose of 3.6 Mrads. Each overall DCIV curve can be decomposed into three components: $I_b$ – the bottom current level is the bulk current of the forward-biased PN diode without any influence from the surface recombination, $I_{p1}$ and $I_{p2}$ – the two DCIV current peaks appear possibly due to two different types of recombination centers and belong to radiation-induced recombination currents. Each of these currents may be caused by two different interface traps located at the oxide–Si interface in the drain region of the VDMOSFET since the increase of the current peak $\Delta I_P$, is proportional to the increase of the interface trap density $\Delta N_{IT}$ [16],

$$\Delta I_P \approx \frac{q A_G n_i (\pi/4) \sigma_0 \theta_{th} \Delta N_{IT}}{\exp(qV_{PN}/2kT)},$$  

(1)
here $A_G$ is the gate area, $n_i$ is the intrinsic doping concentration, $\sigma_0$ is the average capture cross section, $\theta_{th}$ is the thermal velocity, $\Delta N_{IT}$ is the increase of interface trap density and $V_{PN}$ is a small forward applied bias across the PN junction.

Fig. 3(a) and (b) presents DCIV curves and their resolved components for the two radiation-hardened chips with different cell geometries, respectively. The following features can be seen: firstly, the peak values of the two current curves, $I_{p1}$ and $I_{p2}$ for these two chips are more or less similar (for instance, $I_{p1} = 0.0651$ mA for the stripe cell and 0.0642 mA for the hex cell; $I_{p2} = 0.0537$ mA for the former and 0.062 mA for the latter), indicating that the two chips have nearly the same concentration of the interface traps. From Eq. (1), we also obtain that the interface trap density for S1 peak 1 under same dose irradiation is only 11 times of the interface traps density is increased for S2 peak 1 under same dose irradiation of 3.6 Mrads. Secondly, the peak positions, $V(I_{p1})$ and $V(I_{p2})$ are shifted quite differently for the two radiation-hardened chips after the X-ray irradiation with the same dose. $V(I_{p1}) = 12.05$ V for the stripe cell is less than half of that for the hex cell ($= 26.10$ V) Thirdly, the second component of the current curve, $I_{p2}$ for the stripe cell exhibits a Gaussian-like distribution with the width of $W(I_{p2}) = 6.30$ V while that for the hex cell has a broadly asymmetric hump with the width of $W(I_{p2}) = 19.10$ V, the former is nearly one third of the latter. Moreover, the shift for the S1 chip is $V(I_{p2}) = 7.07$ V whereas the shift of the S2 chip $V(I_{p2}) = 15.80$ V. Therefore, it is quite certain that the differences of DCIV parameters between the two radiation-hardened VDMOSFET devices come from their different geometrical structures of the cells.

Recently, Jie et al. have studied the effect of interface trapped charge on DCIV curves, and observed that the stress-induced oxide charge shifts the DCIV peaks while the stress-induced interface trap charge causes a spread in the DCIV peaks for pMOSFETs when hot-carrier stress is introduced [17,18]. In our situation the $V(I_{p1})$, $V(I_{p2})$ and $W(I_{p2})$ for the stripe cell structure are much smaller than those for the hex-cell structure at the same irradiation condition. These indicate that the density change of the trapped oxide charges in the hex cell is much larger than that in the stripe cell after the irradiation, and the density of interface trap charges responsible for peak 1 for the hex cell is almost the same as that for stripe cell

Table 1
Two current peaks, $I_{p1}$, $I_{p2}$ and the shifts, $V(I_{p1})$, $V(I_{p2})$ as well as the widths, $W(I_{p1})$, $W(I_{p2})$ decomposed from the DCIV data as a function of the X-ray irradiation dose for the three samples: S1 – radiation-hardened stripe cell and S2 – radiation-hardened hex cell (S2), in sequence

<table>
<thead>
<tr>
<th>Dose (Mrads)</th>
<th>$I_{p1}$ (mA)</th>
<th>$V(I_{p1})$ (V)</th>
<th>$W(I_{p1})$ (V)</th>
<th>$I_{p2}$ (mA)</th>
<th>$V(I_{p2})$ (V)</th>
<th>$W(I_{p2})$ (V)</th>
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<td>0</td>
<td>3.8870e−5</td>
<td>−1.59</td>
<td>0.37</td>
<td>1.7259e−5</td>
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<td>0.0254</td>
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<td>−6.84</td>
<td>3.50</td>
<td>0.0268</td>
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<tr>
<td>2.4</td>
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<td>0.0537</td>
<td>−7.07</td>
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<td>0.0617</td>
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</tr>
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<td>10.8</td>
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<td>−16.70</td>
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because of the same amount of current level for peak 1, whereas that responsible for peak 2 for hex cell is much larger than that for stripe cell. Why is this so? In the hexagonal geometry, a large and contiguous portion of poly-silicon is punctuated into many hexagonal regions of poly-silicon. Within these regions, p-body and n<sup>+</sup> sources are diffused. However, stripe geometry has many rectangular portions of poly-silicon surrounded by a large and contiguous p-body region diffused into and beneath the poly-silicon. The lateral drain-voltage fields are suppressed at the stripe corners but are significantly increased at the hex corners.

In one case, we have a positive radius of curvature, whereas in the other case, we have a negative radius of curvature. It should be pointed out that the poly-silicon width for a stripe is constant throughout, which results in constant neck width, whereas the neck width varies for a hexagonal structure (maximum neck width occurs at the hexagonal corners) [13]. In other words, the stress in the hex geometry is obviously stronger than in the stripe one, which can determine those parameters discussed above because the shape of the current peak can be distorted by areal non-uniformity of oxide charge $Q_{OT}$ and interface trap.

![Graphs showing two current peaks and their shifts](image)

**Fig. 4.** (a) Two current peaks, $I_{p1}$, $I_{p2}$ and (b) their shifts, $V(I_{p1})$, $V(I_{p2})$ as well as (c) their widths, $W(I_{p1})$, $W(I_{p2})$ decomposed of the DCIV data as a function of the X-ray irradiation dose for the three samples, and (d) the increase of density of interface traps $\Delta N_{IT}/N_{IT}$ with irradiation dose variation for both of samples.
density $D_{IT}$ \[16\], probably indicating that $Q_{OT}$ and $D_{IT}$ caused by radiation in hex cell are much more non-uniform than those in strip cell. Therefore, both stress-induced oxide charge and part of the stress-induced interface trapped charge in the radiation-hardened stripe cell (S1) caused by X-ray irradiation are smaller than those in the radiation-hardened hex cell (S2).

Based on the above analyses, we further consider the radiation effects on DCIV curves of these two kinds of VDMOSFET devices at various X-ray irradiation doses. Table 1 lists all parameters $I_{p1}$, $V(I_{p1})$, $W(I_{p1})$, $I_{p2}$, $V(I_{p2})$ and $W(I_{p2})$ obtained from the DCIV data of these samples (S1 and S2) at seven irradiation doses of 0.6, 1.2, 2.4, 3.6, 7.2, 10.8 and 14.4 Mrads, respectively. Fig. 4 plots the values of these parameters and $\Delta N_{IT}/N_{IT}$ calculated from peak currents by using Eq. (1) as a function of X-ray irradiation doses. From Fig. 4 and Table 1 we can obtain: (1) $I_{p1}$, $I_{p2}$, $V(I_{p})$ and $W(I_{p})$ for the radiation-hardened samples (S1 and S2) increase as the irradiation dose increases at low doses (less than 7.2 Mrads), and then become saturated at $\sim$7.2 Mrads, and even slowly decrease at higher doses afterwards, but in general, the values of these DCIV parameters for the sample with the hex cell geometry (S2) are higher than those for the sample with the stripe cell geometry (S1). This is particularly true for $V(I_{p1})$ and $W(I_{p2})$ which rise very fast at low irradiation doses and

![Fig. 5. Standard sub-threshold measurement (a) for S1, (b) for S2, and (c) increase of density of interface traps extracted from sub-threshold curve $\Delta V_{th}$ with irradiation dose variation.](image_url)
then become saturated and remain basically unchanged at even higher level; (2) densities of two different kinds of interface traps corresponding to the two recombination current peaks increase at different speed under the same X-ray dose rate. These results demonstrate that up to a certain irradiation level, the radiation-induced oxide charges as well as the radiation-induced interface traps in radiation-hardened samples show a saturation property and do not change much when higher irradiation dose is applied. By then, the radiation-hardened VDMOSFET devices are not sensitive to the radiation effect. Comparing the two radiation-hardened chips, all DCIV parameters for the stripe cell geometry shows a better behavior than those for the hex cell geometry as far as the resistance to radiation damage is concerned. This may be one of the reasons that the radiation-hardened power VDMOSFET devices with stripe cell geometry has better radiation performance in dealing with catastrophic failure caused by single-event burnout (SEB) and/or single-event gate rupture (SEGR) when they are operated in space environment [13].

In addition, a standard sub-threshold $I-V$ measurement is performed on both of the radiation-hardened samples under each X-ray dose. Fig. 5(a) and (b)) shows sub-threshold curves while 5(c) describes $\Delta V_{th}$, which is directly proportional to the density of interface traps at various X-ray irradiation doses [19]. The extracted data in Fig. 5(c) also support the saturation behavior we have observed in the above DCIV curves, demonstrating that the radiation-hardened devices with stripe cell geometry are superior to those with hex cell geometry since less interface traps can be generated during X-ray irradiation process.

In conclusion, we have studied radiation effects on radiation-hardened power VDMOSFET devices with stripe-cell geometry and hexagonal-cell geometry at various irradiation doses of X-ray (45 kV acceleration voltage) by means of DCIV measurement and sub-threshold methods, and found that both cell geometry of the chips and radiation-hardened treatment strongly influence the radiation effects on the devices. (1) The oxide charges and interface traps in the radiation-hardened stripe cell are much smaller than those in the radiation-hardened hex cell under the same irradiation dose. (2) The recombination currents show a saturation when X-ray irradiation dose comes to about 4 Mrads (from $\sim$3.6 to 14.4 Mrads) in both of the radiation-hardened samples. However, a detailed study of radiation effects on different cell geometries as well as thickness of oxide layer for radiation-hardened chips is necessary in order to fully understand mechanism of these effects and improve their property for practical uses.

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References