IMPROVEMENT OF HOT-CARRIER RESISTANCE AND RADIATION HARDNESS OF n MOSFETs BY IRRADIATION-THEN-ANNEAL TREATMENTS

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Abstract—The improvement of hot-carrier resistance and radiation hardness in n -channel MOSFETs by a novel technique is studied. This technique includes a Co-60 (1 M rad) irradiation and a subsequent anneal in N_2 at 400°C for 10 min. The hot-carrier-induced instability and the radiation-induced degradation in MOSFETs are examined from the shifts of threshold voltage, transconductance, and drain current. It is observed that the sample after irradiation-then-anneal treatment shows more resistance to hot carrier and radiation damage than that without treatment. The effects are explained by a model involving strain relaxation induced near the SiO_2/Si interface by irradiation.

1. INTRODUCTION

The hot-carrier-induced device degradation is important to the long-term reliability of MOSFETs. The degradation is due to the increase of the internal electrical field as a result of device scaling or from the use of high power supply voltage. Several approaches have been reported which reduce the degradation[1–4]. Some make changes in device structures, and others add additional process steps during device fabrication. Degradation due to radiation damage is also important to MOSFETs. There are strong needs for radiation-hardened MOSFETs in space-satellite and nuclear-plant applications. Several approaches to improve the radiation hardness have been investigated in recent years[5–7]. Generally, workers have employed variations in fabrication[5,6] or designed new structures[7].

Recently, we have found that both the hot-electron-induced degradation and the radiation-induced degradation in MOS capacitor devices can be dramatically improved by repeated irradiation-then-anneal (ITA) treatments [8,9]. These improvements can be explained by a bond strain gradient model[10]. Briefly, it is known that the larger the SiO_2/Si interface strain, the worse the hot carrier and radiation hardness of the oxide insulator[3,8,9]. We believe that irradiation may release the interface strain and that the radiation-induced damage can be suitably annealed out[8,9]. Therefore the ITA treated MOS capacitors should become more hot-carrier and radiation-hard than those without ITA treatment. Since the ITA treatment needs no change in the device fabrication process, it should be useful in practice.

In this work, the ITA treatment was applied to n -channel MOSFETs for reducing hot-carrier and

radiation-induced degradation. Interestingly, it is found that the ITA-treated MOSFET devices yield smaller shifts in threshold voltage, transconductance, and drain current during hot-carrier stressing than the control devices. Also, it is found that the radiation-induced change of the drain current in the ITA-treated MOSFET is smaller than that for a control device. Therefore, the ITA treatment is useful for MOSFETs in the improvement of hot-carrier resistance and radiation hardness.

2. EXPERIMENTAL

The n -channel MOSFETs (channel length $L = 30 \mu m$, channel width $W = 400 \mu m$) used in this study were fabricated on (100)-oriented p -type silicon wafers with a resistivity of 4–10 Ωcm . It is noted that the long-channel MOSFETs discussed in this work are important to industry application since they are still prone to hot-electron-induced degradation in analog circuits where a 10 V power supply is employed[11]. After standard cleaning, wet oxides of 7000 Å were formed at 1000°C for 180 min. The source/drain regions were then defined by photolithography. The source and drain were formed by ion implantation ($5 \times 10^{15}/cm^2$, 100 keV) and were then annealed at 900°C for 30 min to activate the implants. After the oxide of the active regions was removed, 320 Å gate oxide was grown at 950°C for 20 min. Finally, after Al(1% Si) metallization and patterning, the devices were postmetallization annealed in N_2 at 350°C for 10 min.

The ITA treatment was performed after sample preparation. This ITA treatment was performed by a Co-60 irradiation with a total dose of 10^6 rad (SiO_2) then an anneal in N_2 at 400°C for 10 min. Note that the MOSFET devices were not biased during

irradiation and the dose rate of irradiation was about 100 rads (SiO_2)/s in this work. The MOSFETs with and without (control) ITA treatment were compared. The channel-hot-carrier (CHC) stressing experiments were performed by using an Hp4145 semiconductor parameter analyzer[12]. The stressing condition was decided according to the well known bell-shaped curve of substrate current I_{SUB} as a function of gate voltage V_G under a certain fixed drain voltage V_D . Figure 1 shows the I_{SUB} vs V_G curve of an n MOSFET at $V_D = 15$ V. A V_G of 5.8 V was chosen according to the maximum value of substrate current shown in Fig. 1. In this work, the CHC stressing experiments were performed at $V_D = 15$ V and $V_G = 5.8$ V. The source voltage V_S and the substrate bias were set to 0 V. Note that since both of the I_{SUB} and the maximum channel electric field E_{MAX} are important to the characterization of hot-carrier-induced device degradation in long channel MOSFETs[11,13], they should be of the same condition for each stress experiment. The threshold voltage shift ΔV_{TH} , the percentage degradation of transconductance $\Delta G_M/G_{M0}$, and the percentage degradation of drain current $\Delta I_D/I_{D0}$ were recorded during stressing. In this work, the data of measurements and characterization were acquired after 0, 10, 30, 70 and 150 min of stressing.

To investigate the radiation-induced device degradation, the device parameters are examined before and after Co-60 (1 M rads) irradiation. The values of ΔV_{TH} , $\Delta G_M/G_{M0}$, and $\Delta I_D/I_{D0}$ are compared between the ITA treated and the control (without ITA) samples. It is known that the smaller the device parameter shift, the better the radiation hardness. Note that the threshold voltage V_{TH} is obtained from the extrapolated value of I_D vs V_G curve at $V_D = 0.1$ V. The transconductance G_M is the maximum slope of I_D vs V_G curve at $V_D = 0.1$ V. For I_D

Fig. 1. I_{SUB} vs V_G at $V_D = 15$ V.

Fig. 2. Stress time dependence of threshold voltage shift ΔV_{TH} .

measurements, two conditions are compared: (1) linear region, $V_D = 0.1$ V, $V_G = 5$ V; and (2) saturation region, $V_D = 5$ V, $V_G = 5$ V.

3. RESULTS AND DISCUSSION

Figure 2 shows the ΔV_{TH} as a function of CHC stressing time for a control and an ITA treated MOSFETs. It is observed that the magnitude of ΔV_{TH} is substantially reduced for the ITA treated sample. Similarly, the $\Delta G_M/G_{M0}$ as a function of CHC stressing time was also examined and was shown in Fig. 3. The magnitude of $\Delta G_M/G_{M0}$ is also reduced for the

Fig. 3. Stress time dependence of transconductance percentage degradation $\Delta G_M/G_{M0}$.

ITA treated sample. It is clear that the ITA-treated MOSFET is more resistant to the hot-carrier induced degradation than the control device. It is known that both ΔV_{TH} and ΔG_M account for the hot-carrier induced interface trap generation[14]. Therefore, the results in both Figs 2 and 3 show that the generation of interface traps is suppressed in ITA treated oxides. Figure 4 shows the dependence of $\Delta I_D/I_{D0}$ in the linear region on the hot-carrier stressing time. It also clearly shows that the ITA-treated n MOSFET is more resistant to hot-carrier induced degradation than the control device. Similarly, the dependence of $\Delta I_D/I_{D0}$ in the saturation region on the hot-carrier stressing time is also examined, as shown in Fig. 5. The improvement is quite clear for the ITA treated sample. It is known that I_D depends on V_{TH} and G_M . Since ΔI_D is reduced, it is believed that ΔV_{TH} or ΔG_M must also be reduced. This is consistent with the fact that the ITA treatment can reduce the generation of interface traps induced by hot-carrier stressing as described above. Since the stability of I_D is one of the most important electronic characteristics of MOSFET device performance, the ITA treatment is a useful method to improve the hot carrier resistance of MOS-based integrated circuit (IC).

Figure 6(a) shows the I_D vs V_D curves for a control sample before and after Co-60 (1 M rads) irradiation. As can be seen from this figure, the radiation damage is serious in the control sample since the I_D is decreased significantly after irradiation. The value of ΔV_{TH} , $\Delta G_M/G_{M0}$, and $\Delta I_D/I_{D0}$ (linear region) for this sample due to irradiation are 0.63 V, -24% and -27%, respectively. Figure 6(b) shows the I_D vs V_D curves for an ITA treated sample before and after irradiation. Obviously, the radiation-induced decrease in I_D is reduced. The values of ΔV_{TH} ,

Fig. 4. Stress time dependence of drain current percentage degradation $\Delta I_D/I_{D0}$ in linear region.

Fig. 5. Stress time dependence of drain current percentage degradation $\Delta I_D/I_{D0}$ in saturation region.

$\Delta G_M/G_{M0}$, and $\Delta I_D/I_{D0}$ (linear region) for this sample due to irradiation are 0.2 V, -19% and -10%, respectively. They are much smaller than those shown in Fig. 6(a). Thus it is evident that the radiation hardness can be significantly improved by the ITA treatment. It is noted that the I_D - V_D curves before irradiation in Fig. 6(a) and (b) are not completely identical. The V_{TH} s for the control and the ITA treated samples before irradiation are -1.35 V and -1.14 V, respectively. There is little difference among them. This is mainly due to the fact that the anneal treatment used in this work does not completely remove the radiation-induced damage in n MOSFETs. Further study of the choices of the total dose and anneal temperature used in the ITA treatment is worthwhile. However, from the results observed above, we can at least conclude that the ITA treatment is an efficient method to reduce the hot-carrier and radiation-induced degradation in n MOSFETs.

It is hypothesized that the improved hot-carrier resistance and radiation hardness are due to the relaxation of the Si/SiO₂ interface strain after ITA treatment. According to the bond-strain gradient model[10], a reduced bond strain gradient leads to an increased oxide hardness. The ionizing radiation breaks a strained bond leaving an Si⁺ site and a nonbridging oxygen center that could migrate toward the SiO₂/Si interface to form interface traps. Therefore, we believe that radiation releases the interface strain, although it introduces interface traps and positive charges near the SiO₂/Si interface. Since most of the radiation-induced positive charge and interface traps can be annealed out[15], the SiO₂/Si interface strain will suitably be reduced by ITA treatment. This therefore gives an improved interfacial property for MOSFETs.

Fig. 6. I_D vs V_D characteristics before and after Co-60 (1 M rads) irradiation for (a) the control sample and (b) the ITA treated sample.

4. CONCLUSIONS

It is shown that the hot-carrier resistance and radiation hardness are much improved by ITA treatment. The improvements have been explained by the SiO_2/Si interface strain relaxation. Since this treatment is performed after sample preparation, it is suitable for most of the MOSFET applications. With the present trend of device size scaling down, it is worthwhile to apply this method to submicron channel length devices.

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