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IRRADIATION EFFECTS ON THE HIGH FIELD BEHAVIOUR OF VERY THIN SILICA LAYERS

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Abstract—Irradiation effects on the electrical characteristics under high field stress of nitrided and non-nitrided very thin silicon oxide films are studied. The generation of new electron traps during constant current stress is increased for irradiated samples. This enhancement is more significant for pure silicon dioxide when compared to nitrided oxide. Further, the correlation between charge to breakdown and traps generation rate during constant current injection is verified and remains valid after irradiation. © 1997 Elsevier Science Ltd

1. INTRODUCTION

The use of commercial VLSI circuits to design radiation hardened systems is very important for the space electronic industry. In this case however the reliability of the circuits is a critical problem because in general radiation constraints which can be found in space are not considered when commercial technologies are optimized. Further, the influence of radiation on MOS integrated circuits is becoming a more general problem as the MOST can be irradiated during processing[1,2].

As far as MOS VLSI circuits are concerned, one of the most important reliability parameters is the quality of the gate insulator. Silicon dioxide nitrided from NH_3, N_2O, NO or a solid polysilicon source[3–5] compared to pure SiO_2 has shown improved electrical properties: reduced interface states generation during high field injection or irradiation, enhanced resistance to dopant or contaminant diffusion. For these reasons it is a widely studied insulator for VLSI applications.

The influence of an ionizing irradiation on the properties of the gate insulator of a MOS transistor has been extensively studied for more than 30 years and much information has been obtained about fixed charges and interface states generation during irradiation[6].

However, modern MOS technologies use ultra-thin insulators (i.e. < 10 nm) which are submitted to high field stresses and/or to carriers injection during operation. Additional parameters such as interface states and electron traps creation during injection and finally breakdown cause concern for reliability in this case.

Little is known about the influence of an ionizing irradiation on the electrical properties of such thin layers[7–9] and the effectiveness of the nitridation upon the radiation sensitivity depends upon the hardness level of the oxide[8]. Further, most articles have been interested in the electrical degradation at low field (radiation-generated positive charges, interface states and neutral centres). However oxide degradation during carrier injection at high field where new interface states and electron traps are generated is also affected by an irradiation and is an important issue. Indeed these conditions apply in EEPROM memories and also during accelerated reliability testing of MOS circuits.

The aim of this article is to study the influence of an ionizing radiation on the high field behaviour of MOS capacitors. New traps and interface states generation during injection and finally breakdown are investigated before and after irradiation in N_2O-nitrided and non-nitrided oxide layers.

2. EXPERIMENTAL

MOS capacitors were processed on ⟨100⟩ oriented *N*-type silicon wafers. The oxide layer has been grown by rapid thermal oxidation (RTO) at 1000°C in dry oxygen up to 7.4 nm or 9.0 nm. Some samples were subsequently nitrided in N_2O for 15 s at 1000°C. Then aluminum has been deposited, annealed at 450°C in forming gas and patterned to form the gate electrode with an area between 10^{-6} cm^2 and 9×10^{-4} cm^2. The first group of devices corresponding to pure thermal oxide layer is called (OX), and the second group corresponding to nitrided oxide is called (NOX).

Irradiation of the wafers has been performed with a ^{60}Co source to a dose of 10 kGy absorbed in the SiO_2 layer. Samples were kept floating during irradiation since measurements were performed at the

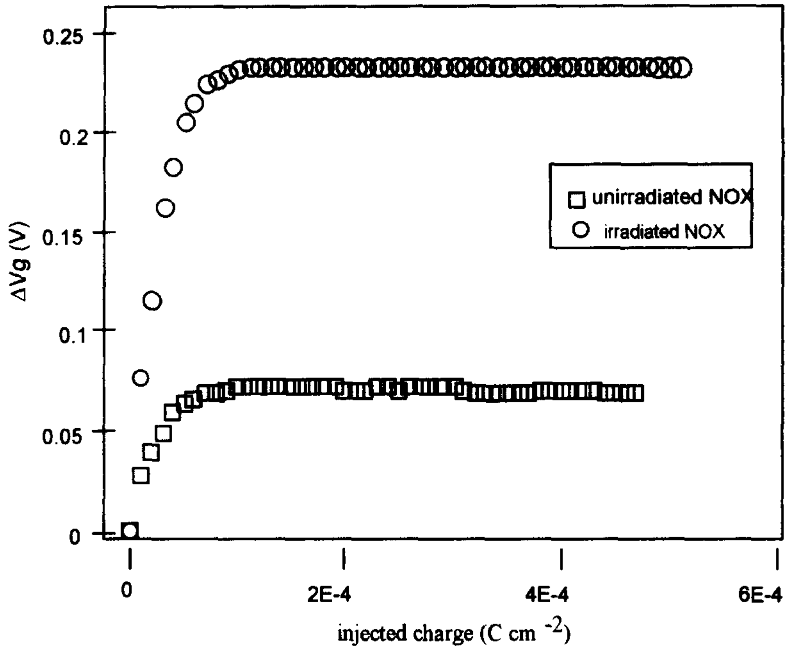

Fig. 1. Voltage shift at low current density before and after irradiation of NOX samples. The current density $J = 10^{-5}$ A cm^{-2} corresponds to a 8 MV cm^{-1} oxide field. The oxide thickness is 9.0 nm.

wafer level. This simulates ionizing radiation exposure during device processing. Although such conditions are not the most stressing they have been shown to induce a degradation of the transistor transconductance[9].

Positive oxide charges (determined from the mid-gap voltage shift) and mid-gap interface state densities have been obtained by capacitance–voltage (CV) measurement using the high–low frequency method[10]. The high frequency CV measurement was performed at 1 MHz using a Boonton capacimeter. The low frequency CV was measured by the quasistatic method (QSM) using a HP4140B picoammeter.

Constant current injection in the Fowler–Nordheim tunneling regime was performed using a Keithley 240 source. The injection was periodically interrupted to perform CV measurements. The bulk electron traps density was studied by monitoring the ΔV_g shift of the gate voltage during constant current injection.

3. RESULTS AND DISCUSSION

3.1. *Before electrical stress*

Positive charges (N_{ot}) and interface states densities (D_{it}) show a very small increase after irradiation. Values of $\Delta N_{ot} = 3$–4×10^{10} cm^{-2} and $\Delta D_{it} = 4$–5×10^{10} cm^{-2} eV^{-1} for a 10 kGy irradiation have been found for the two technologies (OX and NOX) in accordance with the low values already reported for such thin layers[11]. Further, compared to Ref.[9] the nitridation does not change the oxide sensitivity drastically though the irradiation conditions are similar. The studied control samples have however hard oxides and as suggested previously[8] this may be the reason for the small effectiveness of the nitridation.

We have also studied the native and radiation-generated neutral centres. Electrons were injected at low current density ($J = 10^{-5}$ A cm^{-2}) corresponding to an oxide field of about 8 MV cm^{-1}. The voltage shifts ΔV_g have been analyzed in term of a first order kinetics (corresponding to the neutral center filling during injection) to give the effective capture cross-section (σ_{eff}) and density (N_{eff}) of the centres.

Figure 1 shows the evolution of ΔV_g during carrier injection. Saturation of the curves indicates that no additional centres are introduced during injection. As seen in Table 1, the irradiation causes an increase in the effective density of neutral centres with a trapping cross-section of about 10^{-15} cm^2 in both NOX and OX oxides in accordance with previous results[2,12]. Nitrided oxides present a lower density of neutral centres before and after irradiation but the hardening effect of nitridation is very small.

Table 1. Effective capture cross-sections and densities of native and irradiation created neutral traps for OX and NOX devices

	Effective capture cross-section σ_{eff} (cm^2)	Effective density N_{eff} (cm^{-2})
OX		
Unirradiated	5.6×10^{-15}	4.40×10^{11}
Irradiated	4.5×10^{-15}	8.20×10^{11}
NOX		
Unirradiated	7.0×10^{-15}	1.65×10^{11}
Irradiated	6.4×10^{-15}	5.56×10^{11}

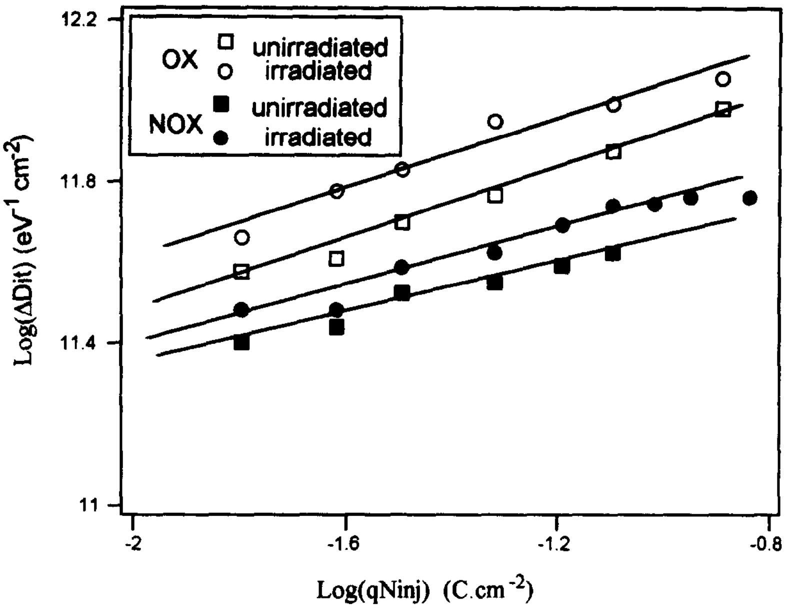

Fig. 2. Interface state density created during injection as a function of the injected charge (qN_{inj}) for OX and NOX samples. The injected oxide field is 10 MV cm^{-1}, and the oxide thickness is 7.4 nm.

3.2. During high field carriers injection

The capacitors were electrically stressed at a constant current corresponding to an electric field higher than 10 MV cm^{-1}. The densities of injection-generated interface states and electron traps were measured as mentioned before and the charge injected at breakdown was recorded.

3.2.1. Interface-states generation. The interface-states density at mid-gap is represented as a function of the injected charge on Fig. 2 before and after irradiation for OX and NOX samples. The density of the injection-generated interface states (ΔD_{it}) is described by the relationship[13]:

$$\Delta D_{it} = \beta(qN_{inj})^{\alpha} \quad (1)$$

where β and α are constants and N_{inj} is the density of injected carriers.

After electron injection, all irradiated samples have presented more interface states than unirradiated ones and the tendency for a smaller sensitivity of nitrided oxide to interface states generation[14] is also valid for irradiated samples. In Table 2 α and β values determined by the best fit of the data on Fig. 2 using eqn (1) are given. It can be seen that α is irradiation independent and relatively higher for pure silicon oxides compared to nitrided ones. Following the interface state generation model[13] results in Table 2 suggest that the irradiation slightly modifies the density of precursor centers only.

Table 2. α and β parameters determined for two oxide fields in irradiated and unirradiated samples

	10 MV cm^{-1}		11 MV cm^{-1}	
	α	β	α	β
OX				
Unirradiated	0.44	2.3×10^{12}	0.56	3.0×10^{12}
Irradiated	0.43	3.0×10^{12}	0.53	4.0×10^{12}
NOX				
Unirradiated	0.32	1.0×10^{12}	0.38	1.0×10^{12}
Irradiated	0.35	1.3×10^{12}	0.36	1.5×10^{12}

3.2.2. Electron trapping. As usually done[15,16], the time evolution of ΔV_g has been analyzed in terms of electron trapping during injection by native (as fabricated) or radiation-induced (for irradiated samples) traps with a first order trapping kinetics, and by electron traps creation and immediate filling during injection following a linear law. A small positive trapping observed at the earlier time has been neglected (about 5% to the total negative charge in this study).

Assuming that the centroid of the negative charge is in the middle of the oxide[16,17] the trapping rate r can be written:

$$r = 2C_{ox}\frac{d[\Delta V_g(t)]}{d[qN_{inj}]} \quad (2)$$

where C_{ox} is the oxide capacitance.

Figure 3 shows the variation of r with the injection field E_{ox}, for irradiated and unirradiated OX and NOX devices. An exponential dependence for the trapping rate with E_{ox} is shown in accordance with previous results[15]:

$$r = r^{\circ}\exp(E_{ox}/E^{\circ}) \quad (3)$$

with a field parameter E° and prefactor r° summarized in Table 3. While the constant E° is not irradiation sensitive, an enhancement of the prefactor r° is observed after irradiation. This is more significant for pure dioxide compared to nitrided one. Results in Fig. 3 correspond to an increase of the

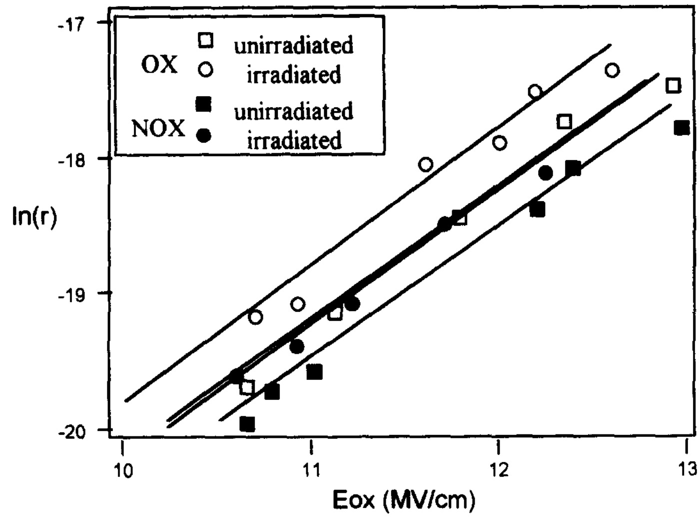

Fig. 3. Electron trapping rate r as a function of the oxide field during injection at different constant current for OX and NOX devices before and after irradiation.

trapping rate for irradiated devices of about 30% and 15% for OX and NOX samples respectively.

Because the capture cross-section and the re-emission probability are closely related with the structure of the traps, we have attempted, according to the dynamic balance model[15], to study the irradiation effect on the trapping–detrapping characteristics relative to the injection created traps. In order to measure the effective capture cross-section of newly created traps, a charge of $4.8\,C\ cm^{-2}$ has been injected at high field ($11\ MV\ cm^{-1}$) to create these new traps and then, after interruption, a small charge $3\times10^{-4}\ C\ cm^{-2}$ was injected to fill them at a constant current density of $10^{-5}\ A\ cm^{-2}$ corresponding to a lower field ($8.5\ MV\ cm^{-1}$)[15,18]. The effective capture cross-section is determined from the filling law which exhibits first order kinetics. A value of about $10^{-15}\ cm^2$ has been found for all irradiated and unirradiated samples (OX and NOX). The trapping rate may be expressed as[15,18]:

$$r = N_p\sigma_p h_g \tag{4}$$

where N_p is the density of precursor centres, σ_p is the cross-section for the generation of a trapping centre from a precursor and h_g is the occupancy factor of the generated centre. The invariance of the effective capture cross-section tends to show that new traps created during FNT stress may be the same in both irradiated and unirradiated devices. In this case, the factor h_g in eqn (2) is not modified by the irradiation.

As a consequence, the enhancement of the trapping rate observed for irradiated devices is caused by an increase of the density N_p of precursor defects and/or of the cross-section σ_p.

3.2.3. Breakdown. Intrinsic breakdown of ultra-thin silica layer (say <10 nm thick) where electron energy cannot reach the threshold of impact ionization[19] has been attributed to either holes or electron trapping[20], interface states generation[21] or defect generation[22] caused by electron injection. It has been shown[22] that breakdown can be correlated with the trap generation rate.

Figure 4 shows the charge injected at breakdown as a function of $d(\Delta V_g)/d(qN_{inj})$ for irradiated and unirradiated samples. It is important to note that in our results, we verify the correlation between oxide degradation and generation of new traps. As in Ref.[22], the charge injected to breakdown can be represented by a relationship in the form:

$$Qbd = \alpha\left[\frac{d(\Delta V_g)}{d(qN_{inj})}\right]^{\beta} \tag{5}$$

where the parameter β is not modified by the irradiation and α is only decreased by less than 12% for OX devices so that eqn (5) is also valid after irradiation with unchanged parameters. Higher trap generation leads to lower breakdown charge. Then, as proposed in Ref.[22], trap generation appears as a good monitor for oxide degradation and consequently breakdown even in irradiated oxides. Further, results in Fig. 4 tend to show that nitrided oxides are less affected, compared to pure oxides, by a 10 kGy gamma irradiation.

Table 3. E° and r° values for irradiated and unirradiated samples

	E° (MV cm^{-1})	r°
OX		
Unirradiated	1.04	3.14×10^{-14}
Irradiated	1.01	4.92×10^{-14}
NOX		
Unirradiated	0.94	1.17×10^{-14}
Irradiated	0.98	2.46×10^{-14}

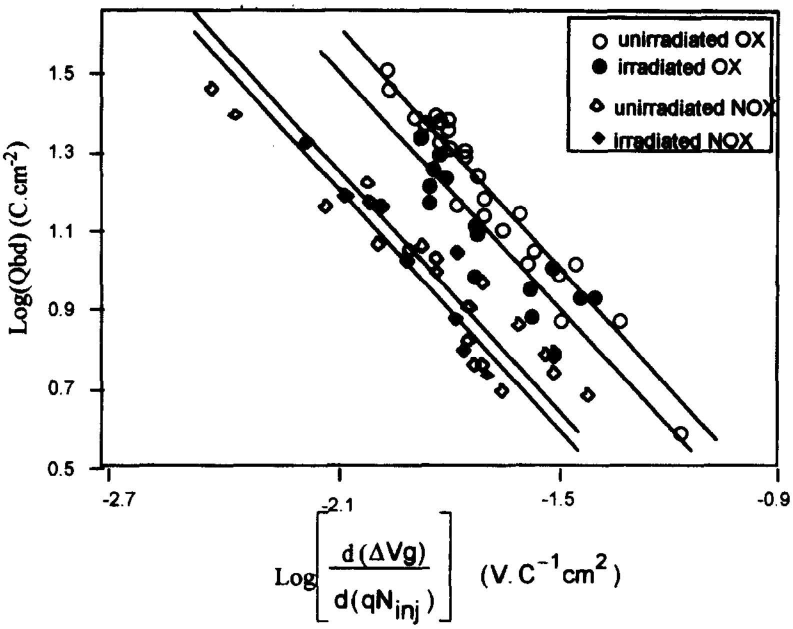

Fig. 4. Charge to breakdown as a function of $d(\Delta V_g)/d(qN_{inj})$ before and after irradiation of NOX and OX devices. This figure includes results obtained during injection at current densities of 3×10^{-1} A cm^{-2} and 3×10^{-2} A cm^{-2}.

4. SUMMARY

Silica layers 7.4 nm and 9.0 nm thick have been irradiated with a dose of 10 kGy. The oxide is a hard one with respect to the radiation-generated positive charge and interface states and after irradiation the density of neutral centres is substantially increased. It is shown that irradiated devices exhibit a substantial enhancement of both the interface states and electron traps generation rates during constant current stress.

Finally, the charge to breakdown is slightly decreased after irradiation and remains correlated with the electron trap generation with the same empirical relationship as before irradiation.

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