Scofield, et. al., Applied Physics Letters **58**, 2782-4 (17 June 1991).

Correlation between preirradiation channel mobility and radiation-induced interface-trap charge in metal-oxide-semiconductor transistors

John H. Scofield, M. Trawick, and P. Klimecky
Department of Physics, Oberlin College, Oberlin, OH 44074

D. M. Fleetwood
Sandia National Laboratories, Albuquerque, NM 87185

We find a strong correlation between preirradiation channel resistance and radiation-induced interface-trap charge in n-channel metal-oxide-semiconductor (MOS) transistors. While it has long been known that the postirradiation mobility of MOS transistors degrades with exposure to ionizing radiation, we believe this is the first time that differences in postirradiation interface-trap charge have been linked to differences in preirradiation device parameters. A simple model is presented that relates the observed variations in preirradiation channel resistance to scattering from defects at the Si/SiO$_2$ interface which may be precursors to the radiation-induced interface-trap charge.

The physics of metal-oxide-semiconductor (MOS) transistors is of considerable importance because of the two-dimensional character of the electronic transport and their pervasive use in modern electronic circuits. Of particular importance for space applications is the susceptibility of MOS transistors to radiation damage. When an MOS transistor is exposed to ionizing radiation, its threshold voltage shifts due to the buildup of interface- and oxide-trap charge, ΔV_{it} and ΔV_{ot} [1]. Tests for radiation hardness involve irradiating a device, and are thus destructive in nature. A previous study has shown that the 1/f noise of transistors *before* irradiation correlates with ΔV_{ot} *after* irradiation [2,3]. In this letter we present evidence which suggests that the carrier mobility of *unirradiated* transistors correlates with ΔV_{it} *after* they are irradiated. Thus, it appears possible to define nondestructive methods to assure the radiation hardness of MOS transistors.

DC-conductance and radiation-hardness measurements were performed on devices from seven wafers [2,3]. These wafers were processed in the same lot, but received different oxidation treatments and postoxidation anneals to vary their radiation hardness [4,5]. For example, some of the wafers received a 30 min, 1100°C N$_2$ anneal immediately after gate oxidation which significantly increases the density of radiation-induced-hole traps in SiO$_2$ [5]. Table I summarizes the properties of the devices used in this study. All measurements were performed at room temperature on $L = (3.45\pm0.10)$ μm long, $W = (16.0\pm0.5)$ μm wide, n-channel transistors with their sources grounded. Uncertainties in oxide thickness (t_{ox}) and threshold voltage (V_T) are 0.5 nm and 10 mV respectively; uncertainties in other quantities are as shown in Table I. Measurements were performed on two or more devices from each wafer. For sufficiently low values of V_d (e.g., < 100 mV), the drain current (I_d) and drain voltage (V_d) were linearly related, i.e., $I_d = gV_d$, where g is the channel dc-conductance. As expected [6], the channel conductance was found to be a linear function of the gate voltage (V_g); that is,

$$g = \beta(V_g - V_T) \tag{1}$$

Note that, for $V_g - V_T = 1$ V, β corresponds to the channel conductance, and β^{-1} the channel resistance. Accordingly, we refer to β^{-1} as the channel "resistance parameter."

Table I: Summary of device properties: wafer number, gate oxide processing, oxide thickness (t_{ox}), *preirradiation*-threshold voltage (V_T), -channel resistance parameter (β^{-1}), and -mobility (μ), and threshold shifts due to oxide- and interface-trap charge (ΔV_{ot} and ΔV_{it}) following irradiation to 100 krad(SiO$_2$).

W#	oxide prep.	t_{ox} (nm)	V_T (V)	β^{-1} (kΩV)	μ (cm^2/V-s)	$-\Delta V_{ot}$ (V)	ΔV_{it} (mV)
21	a	32	0.61	2.77±11%	800±12%	0.20±0.01	120±10
22	a	32	0.70	3.06±10%	768±11%	0.19±0.01	150±10
9	b	32	0.89	3.50± 4%	586± 6%	1.69±0.09	240±40
10	b	32	0.94	3.78± 2%	570± 5%	1.88±0.10	310±30
32	c	48	1.06	4.37± 7%	667± 8%	0.52±0.02	320±20
33	d	48	1.38	5.12± 1%	578± 5%	3.53±0.13	560±20
44	e	60	1.47	5.07± 2%	752± 5%	0.76±0.02	560±30

[a] 15 min, 850°C steam oxide; no postoxidation anneal.
[b] 15 min, 1000°C dry oxide; 30 min, 1100°C N_2 postoxidation anneal.
[c] 30 min, 1000°C dry oxide; no postoxidation anneal.
[d] 30 min, 1000°C dry oxide; 30 min, 1100°C N_2 postoxidation anneal.
[e] 50 min, 850°C steam oxide; no postoxidation anneal.

To characterize their radiation response, devices were exposed to 100 krad(SiO_2) in a Co-60 gamma cell at a dose rate of 1 Mrad/h [3]. An oxide electric field of 3 MV/cm was maintained during irradiation. Threshold shifts due to irradiation (ΔV_T) were separated into components ΔV_{ot} and ΔV_{it} using the method of Winokur and McWhorter [1].

Clear correlation between preirradiation channel resistance parameters β^{-1} and threshold shifts due to radiation-induced interface-trap charge, ΔV_{it}, is shown in Figure 1. A similar correlation was not observed between β^{-1} and ΔV_{ot}. All else being equal, both β^{-1} and ΔV_{it} increase with oxide thickness. Thus, variation in t_{ox} accounts trivially for some of the correlation shown in Figure 1. This is not the entire story, however, as devices having similar t_{ox} have different β^{-1} and ΔV_{it} (see Table I). Below we consider the origin of the rest of the correlation, paying close attention to effects associated with t_{ox}.

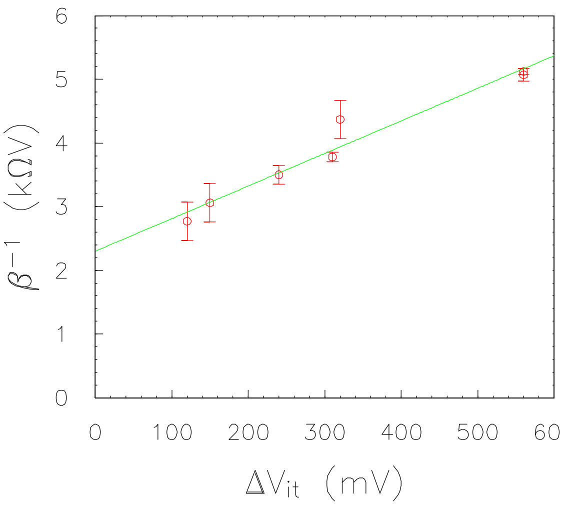

Figure 1 Preirradiation channel resistance parameter (β^{-1}) versus radiation-induced threshold shift due to interface-trap charge (ΔV_{it}).

A number of studies have examined the effects of oxide- and interface-trap charge on carrier mobility in MOS transistors [7-12]. Sun and Plummer have shown that the mobility of (unirradiated) MOS transistors is related to the areal density of oxide fixed charge, Q_f, via the expression

$$(\mu/\mu_0) = (1 + \alpha_1 Q_f)^{-1}, \qquad (2)$$

where μ is the mobility of a device with significant Q_f, μ_0 is the mobility of a device with insignificant Q_f, and α_1 is an empirical constant related to the doping density [8]. Galloway et al. [9] and Sexton and Schwank [10] have shown that a formally similar relationship exists between the mobility, μ_r, of irradiated devices and the radiation-induced interface-trap density, ΔN_{it}, namely

$$(\mu_r/\mu_0) = (1 + \alpha_2 \Delta N_{it})^{-1}, \qquad (3)$$

where α_2 is an empirical constant, and, in this case, μ_0 is the mobility of the unirradiated device. Our data suggest that a similar correlation may exist between the *preirradiation mobility* and *postirradiation interface-trap charge.*

The channel mobility (μ) and resistance parameter (β^{-1}) are related via

$$\beta = \frac{\varepsilon_{ox}}{t_{ox}} \left(\frac{W}{L}\right) \mu, \qquad (4)$$

where ε_{ox} is the oxide dielectric constant [6]. Before irradiation, various scattering mechanisms contribute to the carrier mobility, and hence the channel resistance. Each scattering mechanism has associated with it a component of mobility μ_j. Matthiessen's rule gives the carrier mobility as $\mu^{-1} = \sum_j (\mu_j^{-1})$. The room-temperature mobility of relatively defect-free devices is determined by lattice scattering, ionized-impurity scattering, and "surface" scattering [12]. Lattice scattering, ionized-impurity scattering, and many scattering mechanisms associated with the Si/SiO_2 interface are similar for all devices. Scattering mechanisms common to all devices are represented by μ_0. Variation of the *preirradiation* carrier mobilities indicates that at least one surface-scattering mobility component, μ_p, differs among the devices. We assume that μ_p is inversely proportional to the areal density (n_p) of some "unspecified" interface defect present prior to irradiation, i.e., $1/\mu_p = \gamma n_p$, where γ is the proportionality constant. Thus, the preirradiation mobility may be written as

$$\frac{1}{\mu} = \frac{1}{\mu_o} + \gamma n_p. \tag{5}$$

Prior to irradiation, we assume there exists a density n_{pit} of defects that are "precursors" to the radiation-induced interface trap. (All densities here are per unit gate area.) It is tempting to simply suggest that the postirradiation ΔV_{it} is proportional to n_{pit}. However, just as we normalized out the effects of device geometry by expressing the channel resistance variations in terms of μ, so we must normalize out the effects of device geometry and radiation dose on ΔV_{it}.

Following irradiation, ΔV_{it} is related to the radiation-induced interface trap density ΔN_{it} via $\Delta V_{it} = q\Delta N_{it}/C_{ox}$, where $C_{ox} = \varepsilon_{ox}/t_{ox}$ is the gate capacitance per unit area and -q is the electronic charge. We further assume that

$$\Delta N_{it} = \kappa_g f_y D t_{ox} f_{it}, \tag{6}$$

where κ_g is the number of electron-hole (e-h) pairs produced per unit dose, f_y is the probability that an e-h pair escapes recombination, D is the radiation dose, and the "interface-trap generation efficiency" f_{it} is the number of interface traps created per radiation-induced e-h pair. Values of f_{it} can be calculated from ΔV_{it} [3,13,14] via

$$\Delta V_{it} = (q/\varepsilon_{ox})\kappa_g f_y D (t_{ox})^2 f_{it}. \tag{7}$$

Note that f_{it} is a dimensionless measure of the interface-trap buildup, as desired. It is assumed that f_{it} is proportional to the precursor defect density, i.e. $f_{it} = \sigma n_{pit}$, where σ is a proportionality constant.

Finally, we assume that the defects responsible for the variation in preirradiation mobility are related to those that give rise to the radiation-induced interface traps. Specifically, we assume that $n_p = \lambda n_{pit}$ [15]. This leads to the final expression that relates the preirradiation mobility μ to the interface-trap buildup efficiency f_{it},

$$\frac{1}{\mu} = \frac{1}{\mu_o}(1 + \alpha\, f_{it}), \tag{8}$$

where $\alpha = \lambda\gamma\mu_o/\sigma$ is a combination of the various proportionality constants. Figure 2, a plot of $1/\mu$ versus f_{it}, verifies the linear dependence predicted by Eq.(8). The carrier mobility, in the absence of precursor-defect-related scattering, may be extracted from the vertical intercept of Figure 2. Our data give a value of $\mu = 960\ \mathrm{cm}^2/\mathrm{V\text{-}s}$, quite reasonable given the doping of these devices, $4 \times 10^{16}\mathrm{cm}^{-3}$ [16].

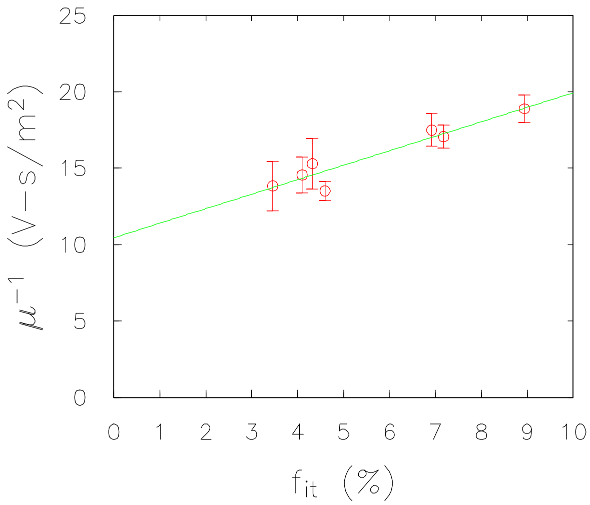

Figure 2: Preirradiation inverse channel mobility (μ^{-1}) versus interface-trapping efficiency (f_{it}). Values of f_{it} are derived from ΔV_{it}.

We also note in Table I that a correlation exists between the preirradiation values of V_T and the postirradiation ΔV_{it} for these devices. This suggests either that (1) the precursor defects that lead to radiation-induced interface-trap charge in these devices may be associated with negative fixed oxide charge, which has reduced the channel mobility via Eq.(2), or (2) some of the precursor defects were *already* converted to interface traps during the device processing. While further work is required to determine whether either of these is the case, to our knowledge *neither* of these possible connections between preirradiation transistor characteristics and radiation-induced interface-trap charge has been demonstrated previously.

The correlation between the preirradiation values of β^{-1} and the postirradiation values of ΔV_{it}, illustrated in Figure 1, is strongly reminiscent of the relation between preirradiation 1/f noise and the postirradiation oxide-trap charge established previously [2,3]. Conceptually, it is useful to write the preirradiation channel resistance parameter, $\xi \equiv \beta^{-1}$, of a given device as $\xi(t) = \xi_0 + \delta\xi(t)$. Here ξ_0 is the time-average of the resistance parameter, determined primarily by phonon scattering and scattering from impurities at or near the Si/SiO$_2$ interface [4,5,11]. The fluctuating portion, $\delta\xi(t)$, arises because changes in the occupancy of defects at or near the interface change the number of charge carriers in the channel at a given time, and also cause the defect-related scattering rates to vary with time. Previous work has strongly suggested that the low-frequency excess (1/f) noise of MOS transistors (e.g., below 1 kHz) primarily reflects carrier-defect interactions with oxide traps that are more than a few monolayers from the interface [2,3,17-19]. (Of course, at significantly higher frequencies there is also information in $\delta\xi(t)$ that bears on defects at or much nearer the interface.) Therefore, prior to irradiation, there appears to be information in ξ_0 which may allow one to predict the postirradiation interface-trap charge (Figure 1), and information in low-frequency components of $\delta\xi(t)$ which allows one to predict the postirradiation oxide-trap charge. Thus, the interaction of the current with defects present before irradiation may contain a significant amount of information that could enable one to predict the radiation response of MOS transistors via channel resistance and 1/f noise measurements, without the need for destructive testing of the device.

The authors would like to thank Nathan Schwadron for assistance in setting up the noise-measuring apparatus and M.R. Shaneyfelt, P.J. McWhorter, F.W. Sexton, and P.S. Winokur for useful discussions. The work was supported by the U.S. Department of Energy.

---

1. P.J. McWhorter and P.S. Winokur, *Appl. Phys. Lett.* **48**, 133 (1986); D.M. Fleetwood, *Appl. Phys. Lett.* **55**, 466 (1989).
2. J.H. Scofield, T.P. Doerr, and D.M. Fleetwood, *IEEE Trans. Nucl. Sci.* **NS-36**, 1946 (1989).
3. D.M. Fleetwood and J.H. Scofield, *Phys. Rev. Lett.* **64**, 579 (1990).
4. P. S. Winokur, E.B. Errett, D.M. Fleetwood, P.V. Dressendorfer, and D.C. Turpin, *IEEE Trans. Nucl. Sci.*, **NS-32,** 3954 (1985).
5. J.R. Schwank and D.M. Fleetwood, *Appl. Phys. Lett.* **53**, 770 (1988).
6. S.M. Sze, *Physics of Semiconductor Devices, 2nd edition* . (John Wiley & Sons, New York, 1981), p.441.
7. C.T. Sah, T.H. Ning, and L.L. Tschopp, *Surf. Sci.* **32**, 561 (1972).
8. S.C. Sun and J.D. Plummer, *IEEE Trans. Electron Dev.* **ED-27**, 1497 (1980).
9. K.F. Galloway, M. Gaitan, and T.J. Russell, *IEEE Trans. Nucl. Sci.* **NS-31**, 1497 (1984).
10. F.W. Sexton and J.R. Schwank, *IEEE Trans. Nucl. Sci.* **NS-32**, 4461 (1985).
11. F.B. McLean and H.E. Boesch, Jr., *IEEE Trans. Nucl. Sci.* **NS-36**, 1772 (1989).
12. S. Selberherr, W. Hänsch, M. Seavey, and J. Slotboom, *Archiv für. Elektronik Übertragungstechnki* **44**, 161 (1990).
13. For the irradiation conditions and devices employed in this study (Ref.3), $\kappa_g = (8.1 \pm 0.9) \times 10^{12}$ cm^{-3} rad^{-1}(SiO$_2$), $f_y = (0.90 \pm 0.05)$, and D = 100 krad(SiO$_2$). Equation (5) is valid only for doses low enough that ΔV_{it} is approximately linear with D (D < 1 Mrad(SiO$_2$) for these devices).
14. D.M. Fleetwood, P.S. Winokur, and J.R. Schwank, *IEEE Trans. Nucl. Sci.* **NS-35**, 1497 (1988).
15. In fact, n_p and n_{pit} may be identical, i.e., $\lambda = 1$. Further work is required to determine whether n_p and n_{pit} are identical or simply proportional.
16. S.M. Sze, Physics of Semiconductor Devices, 2nd edition. (John Wiley & Sons, New York, 1981), p.29.
17. M.B. Weissman, *Rev. Mod. Phys.* **60**, 537 (1988).
18. M.J. Kirton and M.J. Uren, *Adv. Phys.* **38**, 367 (1989).
19. T.L. Meisenheimer and D.M. Fleetwood, *IEEE Trans. Nucl. Sci.* **NS-37**, 1696 (1990).