Evidence That Similar Point Defects Cause 1/f Noise and Radiation-Induced-Hole Trapping in Metal-Oxide-Semiconductor Transistors

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We have found that the $1/f$-noise magnitude of unirradiated metal-oxide-semiconductor (MOS) transistors correlates strikingly with the radiation-induced-hole trapping efficiency of the oxide (f_{OT}). This suggests that the previously unidentified defect that causes $1/f$ noise in MOS transistors is linked to the radiation-induced-hole trap, the "E' center," or to a direct precursor (likely a simple oxygen vacancy) known to be present in SiO_2 before irradiation. We derive a simple equation that relates the noise and f_{OT}.

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Since its discovery in vacuum tubes by Johnson in 1925,[1] the $1/f$ noise of electronic devices has generated intense experimental and theoretical interest.[2] Perhaps the most studied device is the metal-oxide-semiconductor (MOS) transistor. After much debate, it is now generally accepted that the $1/f$ noise of MOS transistors originates in carrier-number and channel-mobility fluctuations caused by the exchange of majority carriers with traps at or near the Si/SiO_2 interface.[2-7] Progress in understanding the *electrical properties* of these defects has been made through studies of the temperature, bias, and time dependences of the fluctuations.[2,7] Still, it has not yet been possible to identify the *microscopic defect(s)* responsible for causing $1/f$ noise in MOS transistors.[2]

Like $1/f$ noise, the response of MOS transistors to ionizing radiation depends on defects at or near the Si/SiO_2 interface. In this Letter, we compare the $1/f$ noise and the radiation response of MOS transistors with oxides that vary widely in radiation-induced-hole trapping efficiency (f_{OT}). We show that techniques to decrease f_{OT} can proportionally decrease the noise of identical, *unirradiated* devices. This suggests that similar defects may cause $1/f$ noise and radiation-induced-hole trapping in MOS transistors, and illustrates that methods to characterize and improve the radiation response of MOS structures can be used to gain new insight into the microscopic origin of $1/f$ noise.

The *n*- and *p*-channel MOS (*n*- and *p*-MOS) transistors used in this study were fabricated in a single device run, in which only gate oxide growth and annealing conditions (Table I) were varied.[8] The 30-min, 1100 °C N_2 anneal performed immediately after gate oxidation in processes *D* and *E* is known to significantly increase the density of radiation-induced-hole traps in SiO_2.[8] Devices from seven wafers (including two each from *A* and *D*) were characterized independently for $1/f$ noise and radiation response.

Two $3\times16\text{-}\mu m^2$ *n*-MOS transistors from each wafer

TABLE I. Wafer process, oxide thickness (t_{ox}), threshold-voltage shifts due to oxide- and interface-trap charge (ΔV_{OT} and ΔV_{IT}) at 100 krad(SiO_2), oxide- and interface-trapping efficiencies (f_{OT} and f_{IT}), and noise level (K) for $3\times16\text{-}\mu m^2$, *n*-MOS transistors. Noise levels are for unirradiated devices.

Wafer	t_{ox} (nm)	ΔV_{OT} (V)	ΔV_{IT} (V)	f_{OT}	f_{IT}	K (10^{-11} V^2)
*A*1[a]	32	−0.19 ± 0.01	0.15 ± 0.01	0.054 ± 0.008	0.043 ± 0.005	7 ± 2
*A*2[a]	32	−0.20 ± 0.01	0.12 ± 0.01	0.057 ± 0.008	0.034 ± 0.005	7 ± 2
B[b]	48	−0.52 ± 0.02	0.32 ± 0.02	0.066 ± 0.009	0.040 ± 0.005	18 ± 3
C[c]	60	−0.76 ± 0.02	0.56 ± 0.03	0.062 ± 0.008	0.045 ± 0.005	22 ± 8
*D*1[d]	32	−1.69 ± 0.09	0.24 ± 0.04	0.48 ± 0.06	0.068 ± 0.009	70 ± 10
*D*2[d]	32	−1.88 ± 0.10	0.31 ± 0.03	0.54 ± 0.07	0.088 ± 0.010	53 ± 11
E[e]	48	−3.53 ± 0.13	0.56 ± 0.02	0.45 ± 0.06	0.071 ± 0.009	130 ± 25

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

were irradiated at room temperature to a dose of 100 krad(Si) with $\simeq$1-MeV γ rays from a Co-60 source at a dose rate of $\simeq$1 Mrad(Si)/h. The oxide electric field was 3 MV/cm during exposure. At this electric field and temperature, electrons that escape recombination[9,10] are swept into the gate in picoseconds,[11] and holes are transported via polaron hopping to the Si/SiO_2 interface in microseconds.[9,11] A fraction of these holes, determined by the electric field and the defect density of the *as-processed* SiO_2, are trapped within $\simeq$0.3–10 nm of the Si/SiO_2 interface. Holes remain trapped for milliseconds to years, depending on trap depth and location, before being neutralized via tunneling or thermal activation.[9] Also, interface traps can be created during and after irradiation.[12] Evidence from electron-spin-resonance studies strongly suggests that the radiation-induced-hole trap is an "E' defect" (a trivalent Si center in SiO_2),[9,13] and the interface trap is a "P_b defect" (a trivalent Si center at the Si/SiO_2 interface).[12,13]

Techniques have been developed to distinguish the effects of oxide- and interface-trap charge on the electrical properties of MOS transistors. Here, threshold-voltage shifts due to oxide- and interface-trap charge, $\Delta V_{\rm OT}$ and $\Delta V_{\rm IT}$, were extracted from a comparison of preirradiation and postirradiation current-voltage measurements.[14] Because $\Delta V_{\rm OT}$ and $\Delta V_{\rm IT}$ depend on oxide thickness as well as defect density,[9,12] we define dimensionless oxide- and interface-trapping efficiencies, $f_{\rm OT}$ and $f_{\rm IT}$, as measures of the intrinsic "trappiness" of the oxide and interface. Here $f_{\rm OT}$ is the ratio of the number of holes trapped in SiO_2 to the number of electron-hole pairs created,[9] and $f_{\rm IT}$ is the analogous ratio for interface traps. Values of $f_{\rm OT}$ can be calculated from $\Delta V_{\rm OT}$ with the expression[9]

$$\Delta V_{\rm OT} = -(q/\epsilon_{\rm ox})\kappa_g f_y f_{\rm OT}(t_{\rm ox})^2 D\,. \tag{1}$$

Here $-q$ is the electronic charge, $\epsilon_{\rm ox}$ is the SiO_2 dielectric constant, κ_g is the number of electron-hole pairs generated in SiO_2 per unit dose,[9] f_y is the probability that an electron-hole pair escapes recombination,[9] $t_{\rm ox}$ is the SiO_2 thickness, and D is the dose. Using $f_y \simeq 0.90 \pm 0.05$ (for Co-60 irradiation at 3 MV/cm) and $\kappa_g \simeq (8.1 \pm 0.9)\times 10^{12}$ cm^{-3}rad^{-1}(SiO_2),[10] $f_{\rm OT}$ and $f_{\rm IT}$ (analogously) were calculated for each set of $\Delta V_{\rm OT}$, $\Delta V_{\rm IT}$, and $t_{\rm ox}$ values in Table I. It is important to note the following: (1) A significant number of new defects are *not* introduced into the SiO_2 at this dose and photon energy; instead, precursors to radiation-induced-hole traps are *modified* by hole capture.[9,13,15] (2) Without irradiation or an equivalent destructive test, standard MOS characterization techniques[14] cannot be used to predict $f_{\rm OT}$ or $f_{\rm IT}$. (3) Although other defects have been identified in irradiated SiO_2, E' and P_b centers are the only point defects known to play an important role in MOS response under these irradiation conditions.[9,12,13]

Standard constant-current $1/f$-noise measurements in the linear region of device operation were also performed at room temperature on three or four identical, *unirradiated* 3×16-μm^2 n- and p-MOS transistors from each wafer.[16] The excess-noise power spectral density of the n-MOS transistors, S_V, was found to scale with average drain voltage (V_d), gate voltage (V_g), and frequency (f) as

$$S_V = K(V_d)^2(V_g - V_T)^{-2} f^{-\alpha}\,. \tag{2}$$

Here V_T is the threshold voltage, and $\alpha \simeq 0.95 \pm 0.10$. These dependences are consistent with previous work.[2,5,6] Values of K are listed in Table I.[17]

In Figs. 1 and 2, we compare the $1/f$ noise and the radiation response of these devices. In Fig. 1(a) we illustrate the effect of the 30-min, 110 °C N_2 anneal on $f_{\rm OT}$. Processes A–C, which did not receive the anneal, show $f_{\rm OT} = 0.060 \pm 0.005$. Processes D and E, which received the anneal, show $f_{\rm OT} = 0.49 \pm 0.04$. Hence, the high-temperature anneal increased $f_{\rm OT}$ by nearly an order of magnitude. In Fig. 1(b) we plot the $1/f$ noise levels, K, of identical, unirradiated devices, again as a function of oxide process and thickness. At a given value of $t_{\rm ox}$, processes D and E show roughly an order of magnitude greater noise than A–C. Thus, the anneal increases $f_{\rm OT}$ and K by nearly the same ratio. In Fig. 2 we plot K now as a function of $-\Delta V_{\rm OT}$. One-to-one correlation is

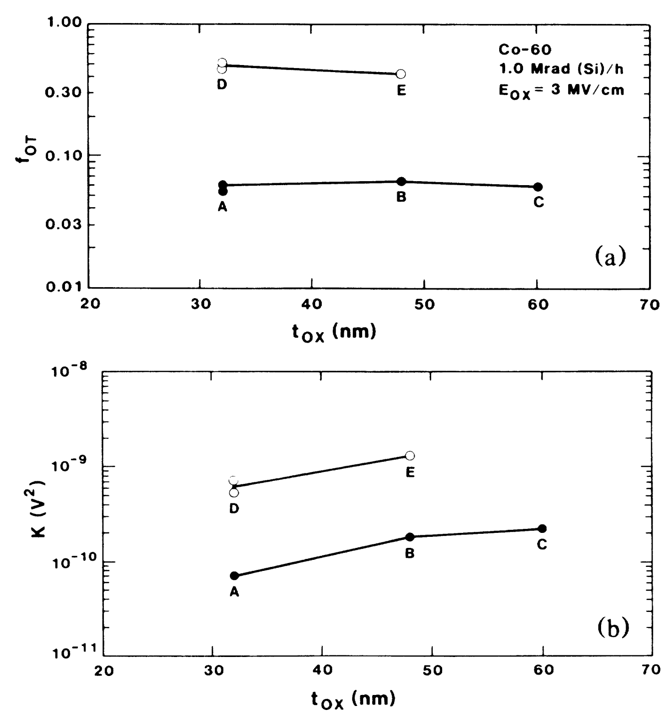

FIG. 1. (a) Radiation-induced-hole trapping efficiency, $f_{\rm OT}$, and (b) Noise level, K, as a function of oxide thickness and processing. Processes D and E received a 30-min, 1100 °C N_2 anneal known to increase $f_{\rm OT}$. Noise levels are for unirradiated devices. Lines are guides to the eye.

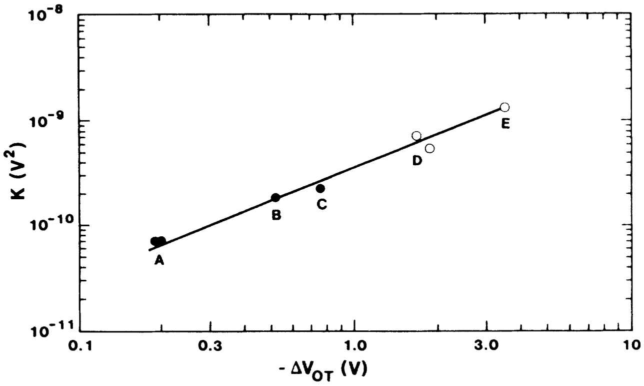

FIG. 2. Noise level, K, as a function of $-\Delta V_{OT}$ for processes A–E. Noise levels are for unirradiated devices. The line is a least-squares fit, with unity slope.

clearly observed. (The dependence on f_{OT} is discussed below.) Similar correlation is not found between K and ΔV_{IT}. For example, note in Table I that transistors made with processes C and E show similar ΔV_{IT}, but their noise levels differ by a factor of $\simeq 6$. Thus, the noise of unirradiated MOS transistors is evidently more sensitive to (precursors to) radiation-induced-hole traps than (precursors to) interface traps.

Similar correlation is obtained for p-MOS transistor noise and ΔV_{OT}; further, the noise of p-MOS transistors is comparable to that of n-MOS devices on the same wafer.[17] Following the work of McWhorter[3] and extensions,[2,4–7] we attribute the p-MOS noise to the exchange of majority carriers (holes) with hole traps. Hole capture and emission lead to changes in the number of carriers in the channel, and in the channel mobility, and thus to noise. Correlation between f_{OT} and $1/f$ noise is therefore very natural for p-MOS transistors.

In the simplest sketch, the $1/f$ noise of n-MOS transistors is similarly attributed to electrons interacting with "electron traps." That the n-MOS transistor noise in Fig. 2 correlates strikingly with radiation-induced-*hole* trapping seems somewhat surprising, since deep-level electron traps in SiO_2 are typically thought to be associated with different defects than are the hole traps.[13,15,18] Still, electron-trap levels have been associated with E' defects after irradiation,[9,15] and with a precursor to the E' center[19] known to be present in SiO_2 before irradiation.[9,15] Much evidence suggests that this precursor is a simple oxygen vacancy in SiO_2.[9,13,15,19] The strong experimental correlation between K and f_{OT} therefore suggests that the noise of both n- and p-MOS transistors may be associated with these vacancies, or with closely related defects present in proportional numbers. Consistent with this interpretation, we note that, unless special precautions are taken in fabrication, the E' center is by far the dominant defect in MOS radiation response. This presumably reflects the large number of oxygen vacancies in "standard" MOS oxides,[8,20] and may indicate that much of the $1/f$ noise observed in MOS transistors is associated with oxygen vacancies in SiO_2.

To quantitatively explore the link between K and f_{OT}, we assume that (1) defects with similar average, effective capture cross sections, σ_t, are responsible both for the noise and the radiation-induced-hole trapping, and (2) the preirradiation noise, S_V, is proportional to the density of oxide traps, which is in turn proportional to f_{OT}/σ_t. We incorporate these assumptions into the noise model developed by Christensson, Lundstrom, and Svensson (CLS).[5,6] It is assumed in this model that (near the Si/SiO_2 interface) oxide traps are distributed uniformly in energy and space, and the noise results from carrier-number fluctuations only.[2–7] With these simplifying assumptions, we find that[21]

$$K = \frac{q^2 kT f_{OT} t_{ox}^2}{LW\sigma_t \epsilon_{ox}^2 E_g \ln(t_{max}/t_{min})} . \qquad (3)$$

Here k is the Boltzmann constant and T is the temperature, L is the channel length and W is the width, E_g is the SiO_2 band gap ($\simeq 9$ eV),[9] and t_{max} and t_{min} are presumed "cutoff" times of the noise process.[2,5,6] The factor of kT/E_g appears because only traps within $\simeq kT$ of the Fermi level contribute to the noise, while traps in the entire SiO_2 band gap contribute to f_{OT}. Note from Eq. (1) that the dependence of K on $f_{OT}t_{ox}^2$ implies that $K \propto -\Delta V_{OT}$, consistent with Fig. 2. Although the CLS model clearly ignores factors important to a complete description of the noise process, e.g., changes in channel mobility that accompany trapping and detrapping events and variations of the trap distribution in space and energy,[2,7,9] we feel that Eq. (3) can provide insight into the connection between the noise and f_{OT}. For example, we may use Eq. (3) to provide an order-of-magnitude estimate of σ_t. Using values of K, t_{ox}, and f_{OT} from Table I, and assuming that $t_{max}/t_{min} \simeq 10^{12}$ (because of the logarithm, the exact value is not critical), we find that $\sigma_t \simeq (4.0 \pm 0.5) \times 10^{-13}$ cm^2. This agrees well with typical capture cross sections found for hole traps and for electron capture at Coulomb-attractive sites in SiO_2 in radiation effects and avalanche injection studies (10^{-12}–10^{-14} cm^2),[9,18] showing that Eq. (3) is consistent with the idea that similar point defects cause $1/f$ noise and radiation-induced-hole trapping in MOS transistors.

In summary, we find that methods to decrease the radiation-induced-hole trapping efficiency of SiO_2 can decrease the $1/f$ noise of unirradiated devices proportionally. This suggests that the defect that causes $1/f$ noise in MOS transistors is linked closely to the radiation-induced-hole trap, the E' center, or to a direct precursor (likely an oxygen vacancy) known to be present in as-processed SiO_2. To our knowledge, this is the first time that the $1/f$ noise of MOS transistors has been linked to a point defect with known microstructure. We conclude that comparative studies of $1/f$ noise and radiation effects can provide new insight into the microscopic origin of the $1/f$ noise of MOS transistors.

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[21]Here we have simply replaced the areal density of traps that contribute to the noise process in Eq. (1) of Ref. 6 with the equivalent density of traps, $(kT/E_g) f_{\mathrm{OT}}/\sigma_t$, inferred to contribute to the noise process under the assumptions stated in the text. Note that f_{OT} and σ_t can be measured *independently* of noise measurements (e.g., Ref. 9). This approach extends and corrects the preliminary model in Ref. 16. The form of Eq. (3) is not significantly affected by the CLS-model presumption that carriers interact with traps via tunneling, while recent evidence (Refs. 2 and 7) favors thermal activation.