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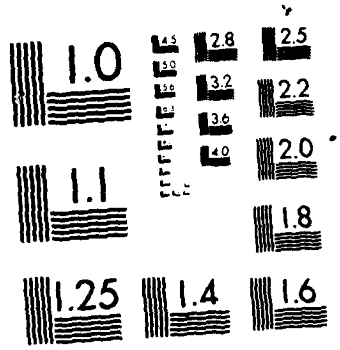

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INFLUENCE OF IONIZING RADIATIONS & ELECTRICAL

OVERSTRESSINGS ON MOS DEVICES:

A COMPARISON

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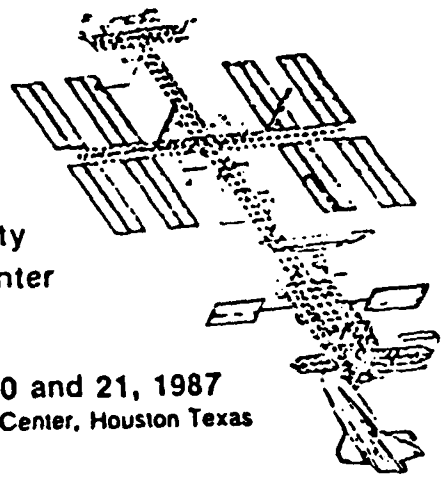

ANALOGOUS INFLUENCE OF IONIZING RADIATIONS AND ELECTRICAL OVERSTRESSINGS: DAMAGE CHARACTERIZATION VIA NOISE PARAMETERS

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Abstract

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Primary mode of failure and/or degradation of MOSFETs due to 'oxide-charge and surface-effects' can result either from ionizing radiations or from electrical overstressings. In either case, the resulting damage can be characterized by a global parametric degradation specified in terms of device noise characteristics. That is, the net effect of charge-trapping and the associated occupation of surface states can be viewed as random/fluctuation phenomena which manifest as the device noise. Thus a common noise model can be prescribed to represent the analogous influence of ionizing radiations and electrical overstressings. Relevant theoretical results and measured data are presented.

INTRODUCTION

The knowledge of common mechanisms involved in the degradation process(es) due to external stimuli, such as ionizing radiations and electrical overstressings, is useful, not only in understanding the interactive physics involved, but also will enable a common hardening technique (process/design) to achieve protection against these stimuli. Such studies will further indicate a one-to-one correlation (in quantifiable terms) between the intensity/magnitude of an ionizing influence and an electrical overstress which may cause the same extent of damage. This equivalence will enable substitution of test method(s) to simulate failure/degradation effects. 'Oxide-charge and surface-effects' [1,2] observed under the influence of ionizing radiations or electrical overstresses result from positive charge build-up in the gate-oxide due to radiation-induced (or EOS-induced) creation of electron-hole pairs; and the trapping of holes at the silicon-to-oxide interface alters the device parameters, namely, the transconductance (g_m), MOS capacitance (C) and the threshold voltage (V_T). To understand the physics of these analogous effects observed, the mode(s) of energy transfer from the invasive external stimulus to the device interior, warrants unique modeling and analysis as discussed in this paper.

Inasmuch as all the degrading device parameters (g_m, C and V_T) are interdependent, the cohesive damage of the device would be assessed by an appropriate function which collectively represents the net physical damage due to external stimulus. It is presently demonstrated that noise characteristics can depict the global representation of stochastical variation [3] in charge-trapping and interface generation due to the external stimuli (ionizing radiations or EOS); relevant noise measurements of degraded devices can also be useful in accelerated test procedures (using equivalent EOS to simulate ionizing radiations) adopted for life-time modeling strategies and in hardening effectiveness evaluation.

OXIDE-CHARGE & SURFACE EFFECTS

A MOS transistor can be looked at as a capacitor with the metal and semiconductor as the plates and the gate-oxide as the dielectric. Under ionizing radiation conditions, the ionization process is illustrated in Fig. 1. At $t^- = 0$ (Fig. 1a), the condition prior to irradiation is shown. At $t = 0$ (Fig. 1b), the ionizing energy is delivered to the oxide, and the electron-hole population is generated. Immediately after ionization, the process of electron-hole recombination will occur, but so will electron transport. But as electron mobility in the oxide at room temperature is approximately 20 cm^2/V-sec, and hole mobility is approximately $2 \times 10^{-5} cm^2$/V-sec, under the applied voltage, any electrons that do not undergo recombination will be swept to the gate and removed in picoseconds, leaving behind the less mobile holes. These holes will begin a transport process toward the silicon-to-oxide interface as shown in Fig. 1e. Some holes will pass into Si, while others will become trapped at defect centers very near the interface of the gate oxide and the bulk silicon.

Fig. 2 depicts the shift in the C-V curve associated with the entire process and the resulting permanent shift due to the trapped charge buildup. In the case of the N-channel device, the trapped positive charge will continue to build up and, in effect, make it easier to create the N-channel (inversion layer). This will lower the threshold voltage (Fig. 3). The reversal of threshold shift is caused by the saturation of surface traps and interface state generation at the silicon-to-oxide boundary occurring at higher levels of ionizing radiations. This mechanism of interface state generation is not well understood at this time except for a simple theory that two different crystal structures (silicon and oxide) meet to form an interface having some irregularities, the number of which increases with increased irradiation. In the case of a corresponding P-channel device, the buildup will make it more difficult to create an inversion layer (in an enhancement mode P-channel transistor). The effect of ionizing radiation on a P-channel threshold is shown in Fig. 3. The net effects of ionizing radiation on a MOS device as a function of threshold shifts are therefore: N-channel devices are easier to turn on or can actually become depletion mode; and P-channel devices become more difficult to turn on.

Similar oxide-charge and surface-effects also appear when a MOS structure is subjected to an EOS, say by a (positive) high-voltage at the gate. During the high-voltage pulses, electrons are injected into the gate-oxide via Fowler-Nordheim tunneling from the Si substrate, and some fraction of the injected electrons then create electron-hole pairs in the bulk of the oxide through impact ionization (Fig. 4a). The resulting electrons and holes behave similarly to those generated by ionizing radiation in MOS structures under positive (worst-case) bias (Fig. 4b): Most of the electrons are swept out of the oxide while the holes drift under the positive field toward the oxide-to-silicon interface where they may be removed or trapped. Some of these holes may also cause interface states to be produced. The resulting flatband-voltage shift and interface-state build-up can be depicted as in Fig. 2.

Ionizing radiations or electrical overstressings will also cause carrier mobility degradation because of the presence of trapped charges near the silicon-to-oxide interface and interface generation, of which interface generation is more dominant and it becomes negligible at lower levels of ionizing radiations/EOS. As the stressing levels are increased (about a million rad for ionizing radiations or 9MV/cm for EOS), mobility degradation will affect P and N-channel device performance, with increased interface states being the primary cause of degradation. This mobility degradation can be observed via transconductance (g_m) measurements. Another performance problem induced by ionizing radiations or EOS is the increase in leakage current due to surface effects.

MOSFETs stressed by ionizing radiations or by EOS have the tendency to anneal. Annealing is the time-dependent detrapping of trapped charge at the silicon-to-oxide interface. It is sometimes referred to as a self-healing effect. However, the time constant involved is in the order of minutes to over one year, depending on the extent of damage, design-based on-chip protection and the type of processing. Though the surface states generated are relatively permanent, it can also be annealed with high temperatures (>125° C). Any lattice damage (interstitials, vacancies), however, is irreversible.

Experimental studies indicate that trapping of holes or oxide-silicon interface degeneration does not differ significantly between electrical overstressing and ionizing irradiations [4] despite the fact that holes are transported to the interface rather under high field conditions in EOS phenomenon; whereas, hole transport under ionizing irradiations is not field activated. Hence, it is evident that capture of hole by a trap at the interface is not a strong function of electric field in the oxide.

SINGLE-MODEL REPRESENTATION OF IONIZING RADIATION AND EOS EFFECTS

On the basis of aforesaid discussions, the identical effects observed in MOSFETs when subjected to ionizing radiations or EOS can be summarized as follows: 1) Shift in threshold voltage; 2) Change in oxide-capacitance; 3) Mobility (μ) degradation; 4) Change in transconductance; 5) Increase in leakage current; and 6) Annealing. These various parameters though can represent the degradation (either due to ionizing radiations or due to EOS) independently are, however, interdependent and explicitly related through analytical expressions. Therefore, it is possible to establish a general expression which uniquely represents the cohesive damage, irrespective of the nature of external stimulus. For this purpose the global effect of stochastical variations in charge-trapping and interface generation (under external stimulus) can be considered to model the net physical degradations observed. And as these stochastical fluctuations in the device-interior manifest as the 'device-noise,' the desired modeling can be characterized by appropriate noise parameters of the device.

When a MOS device is subjected to external stress (either ionizing radiations or EOS), the corresponding induction of charge-trapping and generation of interface states can be equivalently represented by an input noise resistance R_N given by [5]

$$R_N \approx C_o N_S (\mu_s/\mu_o)^2 \tag{1}$$

where C_o is a constant, N_S is the surface-state density and μ_s/μ_o refers to the field-effect mobility to low-field mobility ratio. Eqn. (1) indicates that R_N is directly proportional to N_S concurring with the experimental results due to Abowitz, et al [6]. Hence the time-dependent history of N_S as controlled by any external overstressings can be tracked via the assessment of R_N. Further, the field-effect mobility is also dependent on N_S and is therefore linked with g_m and V_T of the device. Explicitly,

$$\frac{\mu_s}{\mu_o} \approx \frac{1}{1+\alpha N_S} \approx \frac{g_m}{g_{mo}} \approx \frac{1}{1+\beta(V_G-V_T)} \tag{2}$$

Here, α and β are constants and g_{mo} refers to the value of g_m under unstressed conditions and V_G denotes the applied gate potential.

From Eqns. (1) and (2), the following relation can be obtained:

$$\frac{\Delta R_N}{R_N} \approx \frac{\Delta g_m}{g_m}\left[2 - \frac{1}{1-\frac{\Delta V_T}{V_T} \quad \frac{1}{(V_G-V_T)\beta}}\right] \tag{3}$$

The constant β has the approximate values of 0.138 and 0.308 for the N-channel and P-channel MOSFETs, respectively [4]. More generally, V_G can be expressed in terms of the electric field across the gate-oxide, namely, E_G. That is, $V_G = E_G t_{ox}$, where t_{ox} is the gate-oxide thickness. While E_G refers to the electric field intensity corresponding to an electrical overstress (EOS) phenomenon, it is possible to establish an equivalent E_G to represent the ionizing radiation dosage, which produces the same extent of degradation expressed via noise parameter of eqn. (3). Let D_I be the dosage delivered (or, absorbed dosage) to an oxide-gate, which through ionization process creates a hole density (area density) of Q_R equal to $K_I t_{ox} D_I F(E_G)$ where K_I is the infinite field ionization coefficient [4] equal to 1.22 x 10^{-6} C $CM^{-3}rad^{-1}$ (SiO_2) and $F(E_G)$ is the E-field dependent charge-yield parameter [4] with approximate value of 0.83 at E_G = 1MV/cm. If the same hole-density of Q_R has to be stimulated by an electrical overstress phenomenon (via high field injection of electron current density through Fowler-Nordheim tunneling by the gate-oxide field-intensity, E_G), the corresponding current density (j) can be expressed (by neglecting space-charge effects) as equal to AE_G^2 exp $(-B/E_G)$ where A and B are constants. The best estimates of [4] A and B are 2×10^6 amperes/$(MV)^2$ and 238 MV/cm, respectively. Therefore EOS-equivalent of Q_R can be written as

$$Q_R\ (EOS) = j\alpha\ t_{ox}\ \Delta t \qquad (4)$$

where α is the probability per unit length that an injected electron will create an electron-hole pair and is equal to α_o exp $(-H/E_G)$ where $\alpha_o \approx 6.5 \times 10^{11}\ cm^{-1}$ and H~ 180MV/cm [4].

Further, Δt in eqn. (4) specifies the duration of EOS event. Assuming that lightning function of the form $e_1(t) = E_G\ [\exp(-Ct)-\exp(-Dt)]$ to represent the transient electrical overstressing, the duration, Δt is given by

$$\Delta t = [(D-C)/CD]\ [\exp\ (-Ct_m)-\exp(-Dt_m)]^{-1} \qquad (5)$$

where t_m is the rise-time of the transient equal to $\ln(D/C)/(D-C)$. The values of C and D can be explicitly specified for a given type of EOS event, such as human-body ESD model, etc., and are dependent on the peak value of the stressing potential, V_G.

Combining eqn. (4) and eqn. (5), the equivalent dosage D_I can be expressed as

$$D_I = \alpha_o\ A\ E_G^2\ [(D-C)/CD]\ [\exp(-Ct_m)-\exp(-Dt_m)]^{-1}\exp\ [-(H+B)/E_G] \qquad (6)$$

Hence, using approximate values for the parameters discussed previously, the expression for D_I reduces to

$$D_I \approx 10^{24}\ (V_G/t_{ox})^2\exp(-418\ t_{ox}/V_G)\Delta t(V_G) \qquad (7)$$

where V_G is expressed in MV, t_{ox} in cm and Δt is functionally dependent on V_G.

Considering a typical electrical overstressing due to an electrostatic discharge (ESD) of subcatastrophic level (say V_G = 50V peak) from a finger tip (Fig. 5) across a gate-oxide of thickness 30 nm over a pulse-duration, Δt = 10n sec, the corresponding equivalent radiation dosage is approximately equal to 36 M rad (SiO_2). That is, this ESD event would introduce as many holes into the oxide as a 36 M rad (SiO_2) of ionizing radiation.

RELATIVE NOISE PERFORMANCE UNDER EOS AND IONIZING IRRADIATIONS

For a given injected electron fluence ($Q_I = j\Delta t$), the relative damage introduced in the MOSFET by an EOS and an ionizing radiation can be estimated as follows: By virtue of one-to-one equivalence between the magnitude of EOS and ionizing dosage, the relative damage expressed, say, in terms of threshold shift $\Delta V_T/V_T$ can be written as a linear proportionality relation of the form $\Delta V_T(EOS)/V_T = K\ \Delta V_T(RAD)/V_T$ where K is a constant.

Considering the results due to Boesch and McGarrity [4], for a given amount of injected electron fluence ($1.9 \times 10^{-5} C/cm^2$), the theoretical and experimental results corresponding to high field stressing of 9MV/cm) and ^{60}Co irradiation (10^4 rad SiO_2) on a t_{ox} = 1000 Å MOS structure, the value of K is found to be approximately equal to 2.3; or, in general, K>1. Hence, using the linear relation between $\Delta V_T(EOS)/V_T$ and $\Delta V_T(RAD)/V_T$, it can be shown that $\Delta R_N(EOS)/R_N$ is nearly equal to $(4/3)\Delta R_N(RAD)/R_N$. In other words the damage, manifesting as the device noise under EOS injecting a given amount of electron fluence into the gate, is approximately 25% more, for the same extent of electron fluence injected by a radiation source. Typical noise parameter ($\rho = \dfrac{\Delta R_N/R_N}{\Delta g_m/g_m}$) variations as functions of radiation dosage for a P and N channel MOSFETs are shown in Figs. 6 and 7. Corresponding variations of threshold voltage, V_T are also depicted in Figs. 6 and 7, from which it can be observed that the noise parameter follows the trend of V_T variations(s).

Will radiation hardening concurrently improve static-protection or vice versa? The observed similarities suggest the possibility of formulating a one-to-one equivalence of modeling of radiation damage versus EOS effects from which it can be extrapolated that any scheme that is implemented (either via processing or via design methods) to prevent/reduce radiation-induced (deleterious) effects may also subdue the influences of EOS effects. In other words radiation hardening schemes (process/design) with a few optimization changes may provide dual protection to prevent/reduce gate-oxide damages arising from ionizing radiations or from EOS. In order to achieve effective dual protection through optimization of process/design techniques, basic research is required to determine this ionization radiation-to-EOS equivalence so that the common-to-both type of damages(s) in the gate-oxide can be effectively prevented through optimization procedures.

CONCLUSIONS

This work provides a basic insight into the problem of a comparative study relating ionizing radiations and EOS effects on MOS devices. The results indicate a strong correlation between the two effects cited, which suggests the feasibility of designing common countermeasures, as well as adopting substitutions in the analysis and/or simulation techniques.

ACKNOWLEDGEMENT

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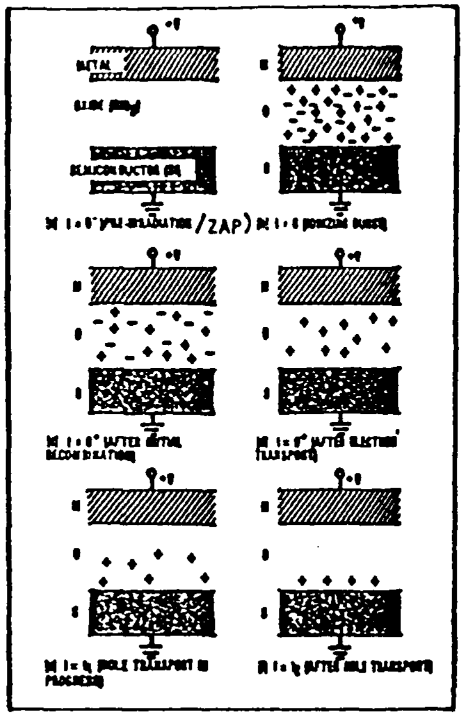

FIG. 1 CARRIER TRANSPORT MECHANISM

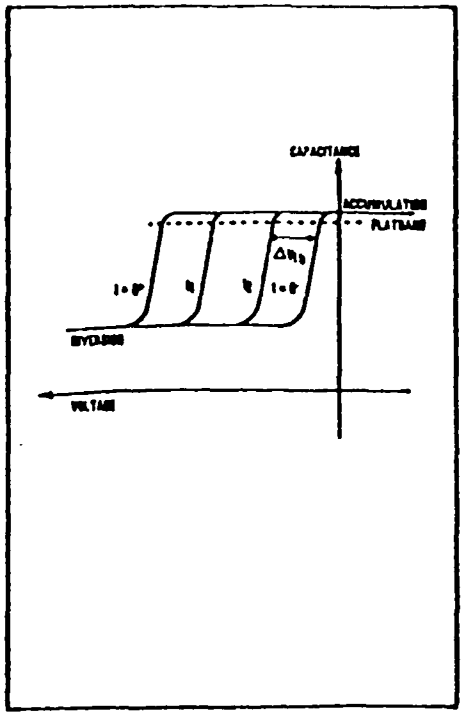

FIG. 2 C-V CURVES FOR CONDITIONS IN FIG. 1

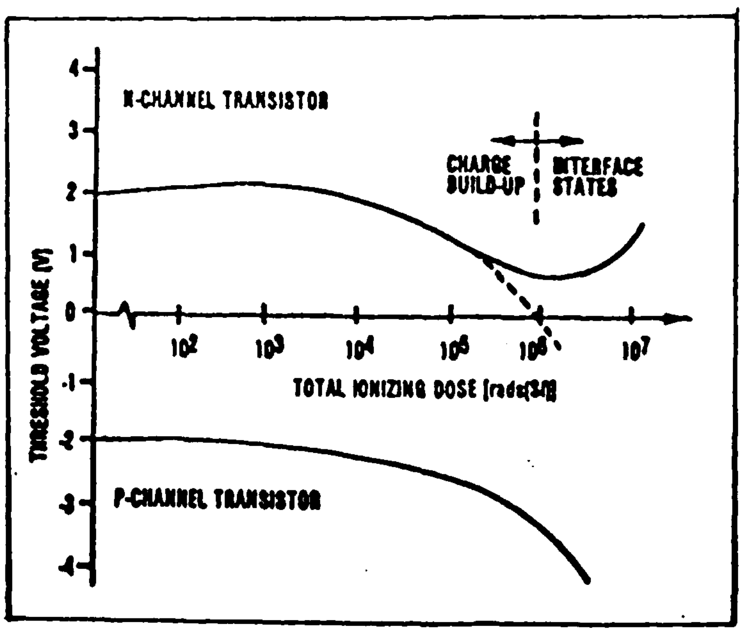

FIG. 3 RADIATION EFFECTS ON P AND N CHANNEL MOSFETS.

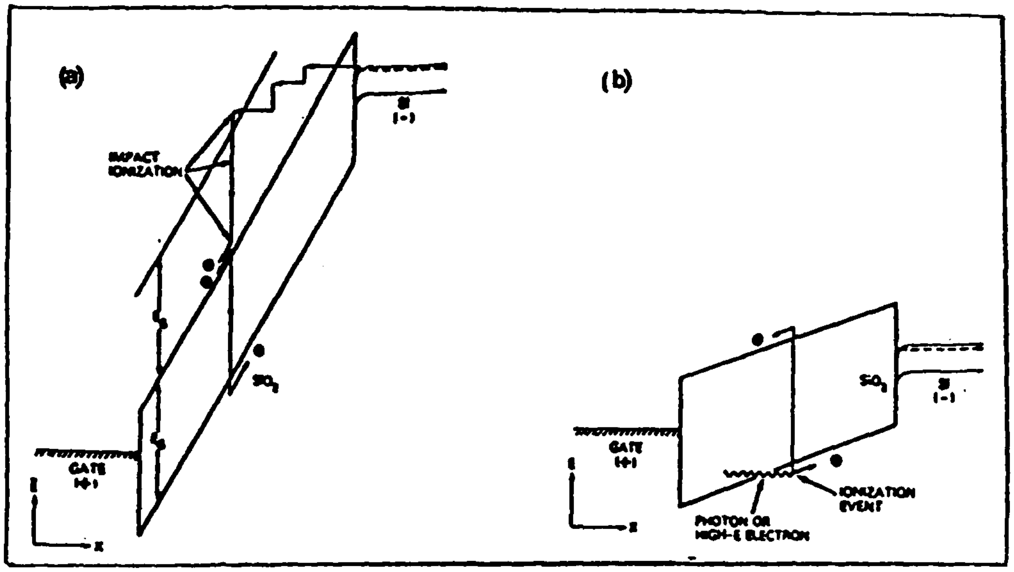

FIG. 4 CREATION OF ELECTRON - HOLE PAIRS DUE TO: (A) HIGH-FIELD INJECTION AND (B) IONIZING RADIATION

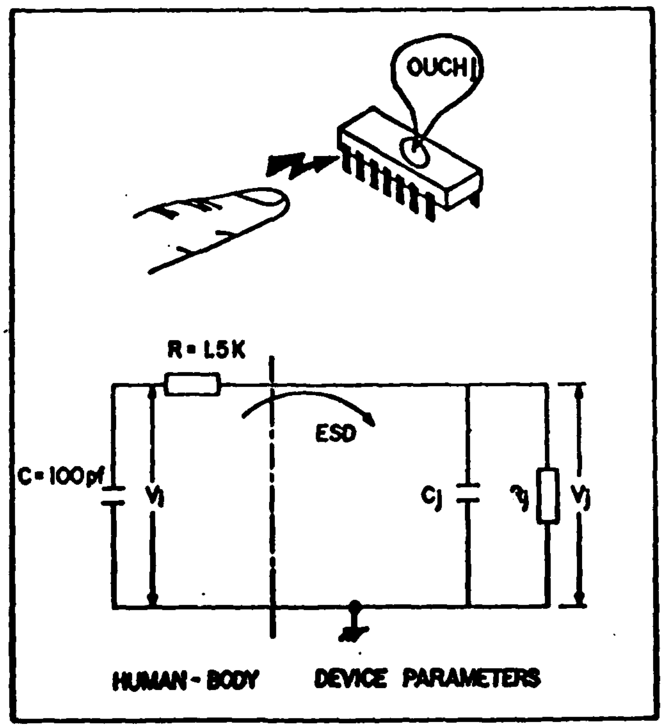

FIG. 5 ESD: HUMAN-BODY MODEL

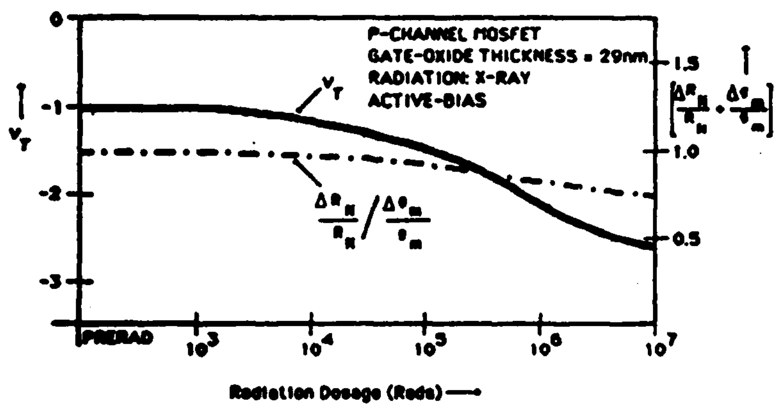

FIG. 6 RADIATION DOSAGE VERSUS THRESHOLD VOLTAGE (V_T) AND NOISE PARAMETER ($\Delta R_N/R_N + \Delta g_m/g_m$)

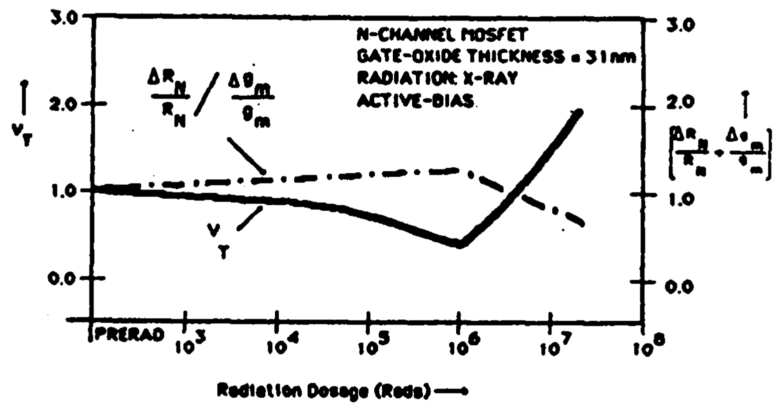

FIG. 7 RADIATION DOSAGE VERSUS THRESHOLD VOLTAGE (V_T) AND NOISE PARAMETER ($\Delta R_N/R_N + \Delta g_m/g_m$)

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NOTE

NOISE CHARACTERISTICS OF IONIZING-RADIATION STRESSED MOSFET DEVICES

INTRODUCTION

It has been known for years that ionizing radiations can change the electrical properties of solid state devices, leading to possible system failure [1]. In particular, gamma rays, X-rays and neutron bombardment have proven most harmful. Among the LSI devices, MOS circuits are highly sensitive to damages under critical radiation environments. The primary failure mode and/or degradation of MOSFETs resulting from ionizing radiations is due to the 'oxide-charge and surface-effects,' [2], occurring in the gate-oxide and/or field-oxide regions. The effects of ionizing radiations are mainly threshold voltage shift and channel mobility degradation caused by the creation of electron-hole pairs and trapping of holes at the Si-SiO_2 interface [2]. The net effect of charge-trapping and the associated occupation of surface states can also be viewed as a random/stochastical phenomenon which can be characterized by a global noise parameter. Such a representation/model will be useful to study the noise performance of the device under radiation environments as indicated in the present work.

NOISE-MODEL

The global effect of 'oxide-charge and surface-effects' described above can manifest as the device noise which can be quantitatively represented by a noise-model as described below:

Following the analysis by Leventhal [3], the effect of charge-trap induction and generation of interface states can be equivalently represented by an input noise resistance R_N given by

$$R_N = C \left(\frac{\mu_S}{\mu_o}\right)^2 N_S \tag{1}$$

where C is a constant of proportionality and N_S is the surface-state density; μ_S/μ_o refers to the field-effect mobility to low field-effect mobility ratio. Further, inasmuch as field-effect mobility is also dependent on N_S and is, therefore, linked with the device transconductance (g_m) and the threshold voltage (V_T) [4,5], the following relation can be obtained [6] from eqn. 1. (Note the typographical errors in [6]: eqns. 1 and 3 of [6] should read as eqns. 1 and 2 of the present paper, respectively.)

$$\frac{\Delta R_N}{R_N} = \frac{\Delta g_m}{g_m} \left[2 - \frac{1}{1 - \dfrac{\Delta V_T}{V_T} \cdot \dfrac{1}{(V_G - V_T)\beta}}\right] \tag{2}$$

where ΔV_T is the threshold-voltage shift and β is a constant, approximately equal to 0.138 and 0.308 for the N-channel and P-channel MOSFETs, respectively [5].

The quantity V_G in eqn. 2 represents an 'equivalent gate-potential' which would inject the same electron-fluence into the gate equal to that injected by the ionization irradiation. V_G can also be expressed in terms of an 'equivalent electric field' across the gate-oxide, namely E_G. That is, $V_G = E_G t_{ox}$, where t_{ox} is the gate-oxide thickness.

This equivalent electric stress parameter E_G, can be specified explicitly in terms of the radiation dosage, D, assuming that, over a duration of Δt, the effect of E_G or D is to inject the same extent of electron fluence, namely $j\Delta t$, where j is the current density. Hence, relevant analysis yields,

$$D \simeq A\, E_G^2\, \Delta t\, \exp(-B/E_G) \qquad (3)$$

where A and B are constants approximately equal to 10^{24} and 418, respectively [7], if E_G is expressed in MV/cm. Thus for a given dosage level of D, using eqns. 2 and 3, the noise performance of the device can be decided quantitatively.

TEST STUDIES & CONCLUSIONS

Variations of the noise parameter $\frac{\Delta R_N}{R_N} / \frac{\Delta g_m}{g_m}$ corresponding to a P-channel and an N-channel MOSFETs as functions of the radiation dosage (X-ray), are depicted in Figs. 1 and 2. Also shown in Figs. 1 and 2 are the threshold voltage shifts in the P- and N-channel MOSFETs [8]. The results on noise parameter presented in Figs. 1 and 2 are calculated via eqns. 2 and 3, using the available data on threshold voltage shifts versus radiation dosage [8]. From the results shown, the following can be inferred:

1. Damage introduced by ionizing radiations in a semiconductor device (such as MOSFET) can also be characterized by the noise performance of the device.

2. The noise parameter, as a function of radiation dosage tends to track closely the variation of V with respect to the dosage level. This is true for both P- and N-channel MOSFETs (Figs. 1 & 2). The percentage shift in the magnitude of noise parameter, for a given level of radiation dosage is, however, less than the corresponding percentage shift in the threshold voltage. Referring to Fig. 1 , (P-MOS) for a dosage level of 10^7 rad (Si), V_T shifts by 170%, whereas the noise parameter changes only by 26%. Similarly in Fig. 2 (N-MOS), V_T shifts for 10^6 and 10^7 rad (Si) are -52% and +42%, respectively. However, the corresponding noise parameter shifts are +28% and -8%, respectively. Thus, for a given level of irradiation, the variation in V_T is more overwhelming than changes in noise performance.

3. Nevertheless, in low noise applications of the device, the influence of ionizing radiations should be duly accounted for in the system design as noise performance degradation is inevitable as a result of radiation-induced oxide effects. While 'single event' upsets due to ionizing radiation usually cause concern in digital circuits, noise performance degradation due to cumulative/total ionizing irradiations may require specific attention in linear devices. Especially, as the device is stressed repeatedly, the device damage (noise performance degradation) will cumulatively increase. Such endochronic degradation response would be detrimental for low-noise system operation. The present analysis is useful in the relevant studies.

4. The simple model presented here provides a quantitative approach to determine the noise performance of a MOSFET ionizing irradiations. The relevant calculations are useful to determine the extent of radiation hardening required to achieve a given level of lov noise performance of the device under ionizing radiation environments. And, noise monitoring can serve as an adjunct support to conventional V_T and C_{ox} estimations adopted in hardness assurance efforts.

5. The present vork models only the effect(s) of ionizing radiations on the device-noise. Should the geometrical parameters (such as the channel length) change, the transconductance vould be significantly affected (especially in short-channel devices) and the relevant noise-model vill be more involved. Related studies are in progress.

6. It can be shown that $\Delta g_m/g_m = \Delta V_T/(V_G-V_T)$. Hence, the noise-parameter profiles of Figs. 1 and 2 vill remain the same (except for a scale-factor) if the noise-parameter is normalized vith respect to threshold-voltage shift.

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CAPTIONS FOR THE DIAGRAMS

Fig. 1 Threshold voltage and noise parameter versus total radiation dosage (P-Channel MOSFET).

Fig. 2 Threshold voltage and noise parameter versus total radiation dosage (N-Channel MOSFET).

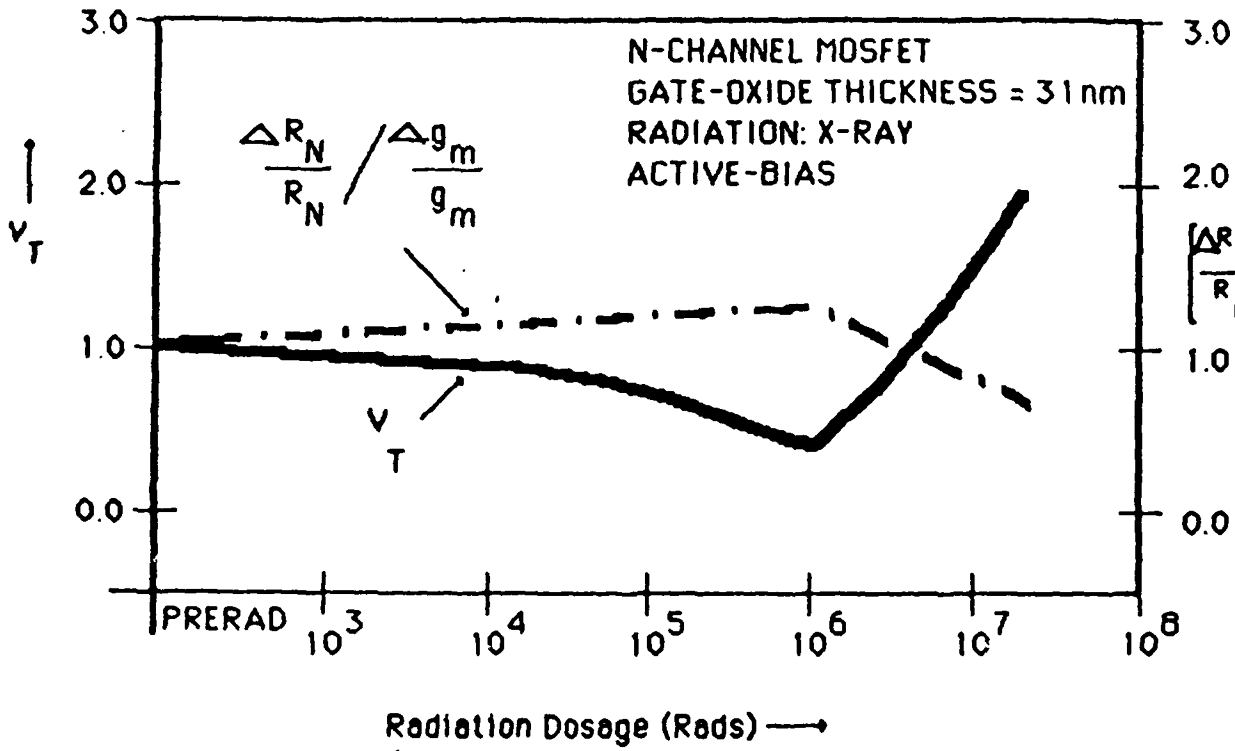

FIG. 2 THRESHOLD VOLTAGE (V_T) AND NOISE PARAMETER ($\Delta R_N / R_N \div \Delta g_m / g_m$)

VERSUS RADIATION DOSAGE

N-CHANNEL MOSFET

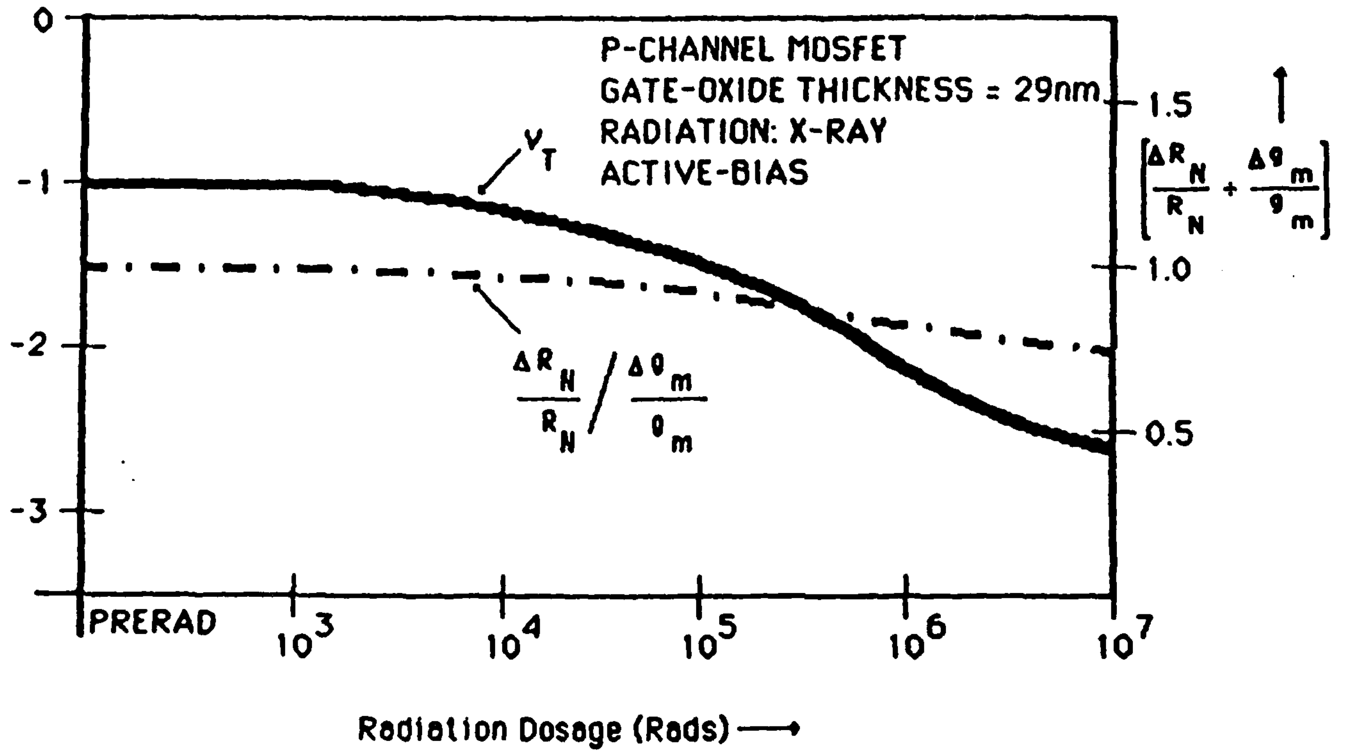

FIG. I THRESHOLD VOLTAGE (V_T) AND NOISE PARAMETER ($\Delta R_N / R_N \div \Delta g_m / g_m$)

VERSUS RADIATION DOSAGE

P-CHANNEL MOSFET

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