

Electrical Breakdown in Thin Gate and Tunneling Oxides

IH-CHIN CHEN, STEPHEN E. HOLLAND, STUDENT MEMBER, IEEE, AND CHENMING HU, SENIOR MEMBER, IEEE

Abstract—The breakdown of thin oxides (7.9–32 nm) subjected to high-field current injection is investigated in this study. The physical mechanism of breakdown is found to be localized field enhancement at the cathode interface due to hole trapping. The source of this hole trapping is believed to be impact ionization in the SiO₂. A quantitative model for oxide breakdown based on impact ionization and hole trapping at the cathode is presented and shown to agree well with the experimental $J-t$ and time-to-breakdown, (t_{BD}) results. We observe that $\log t_{BD}$ varies linearly with $1/E$ rather than with E as commonly assumed. The field acceleration factor, i.e., the slope of the $\log t_{BD}$ versus $1/E$ plot, is approximately 140 decades per centimeter per megavolt for the 7.9 nm oxide, with approximately 25 percent of this coming from the field dependence of the impact ionization coefficient and the remainder from the Fowler–Nordheim current dependence on $1/E$. Based on this model, oxide wearout performance might be improved by process changes that reduce interface hole trapping, such as radiation-hard processing, in addition to the reduction of particulate contamination and crystal defects.

I. INTRODUCTION

THE reduction of gate oxide thicknesses is necessary in order to achieve improved MOS device performance for future-generation integrated circuits. The integrity of the SiO₂ is, therefore, a primary concern. In particular, the breakdown of thin gate dielectrics is a major cause of circuit failure, especially for large scale dynamic random access memories [1]. In addition, the rupture of the very thin tunnel dielectrics in nonvolatile E²PROM's is the principal cause of E²PROM's endurance (write/erase cycling) failures. A good understanding of the physical effects resulting from the application of large electric fields applied to thin oxides is needed.

In this paper we report results pertaining to breakdown in thin (7.9–32 nm) SiO₂ gate dielectrics which are subjected to high-field/current stressing. The eventual breakdown is due to the accumulation of trapped holes at the injecting interface which eventually results in the formation of localized high-field/current-density regions [2]. A model based on our results has been developed and is presented here. In addition, we discuss possible implications of our physical model on process improvements.

Manuscript received July 11, 1984; revised October 9, 1984. This work was supported by DARPA under Contract N00039-81-K0251 and by grants from Rockwell International and Advanced Micro Devices.

The authors are with the Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720.

II. OVERVIEW OF SiO₂ BREAKDOWN

Conceptually, the time-dependent dielectric breakdown process may be divided into two stages. During the first, the buildup stage, localized high-field/current-density regions are formed as a result of charge trapping. Eventually, when the local current density or field reaches a critical value, the rapid runaway stage begins during which additional runaway electrical and/or thermal processes result in breakdown. This is shown in Fig. 1. The runaway stage, once reached, is completed in a very short period of time. Hence the time necessary to reach the runaway stage determines the lifetime of the oxide. This paper is concerned with the buildup stage.

The time necessary to complete the buildup stage can be reduced considerably when defects are present. For example, Na⁺ contamination can greatly accelerate the breakdown process [3]–[6], and particulates present on the silicon surface before oxidation have been shown to be a source of localized contamination [7]. Also, crystalline defects in the silicon substrate such as stacking faults can reduce the lifetime of the oxide [8]. In this study, however, we concentrate on the intrinsic breakdown mechanism characteristic of basically gross defect-free devices. It is believed, however, that the basic model to be presented also applies to gross-defect breakdown. The effect of the defects is to modify the model parameters such as oxide thickness, trap density, or a field-enhancement factor.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The devices used in this study were polysilicon-gate MOS capacitors with gate oxide thickness varying from 7.9 to 32 nm. The substrate material was 10–20 $\Omega \cdot \text{cm}$ $\langle 100 \rangle$ p-type. The gate oxide was grown in O₂ at 900 °C with a 10-min nitrogen anneal following oxidation. A post-metallization anneal consisting of 30 min at 450 °C in forming gas was also performed. Bias-temperature (± 4 MV/cm for 15 min at 150 °C) $C-V$ measurements detected essentially no mobile-ion contamination.

The configuration used to stress the devices consisted of, for constant-current stressing, a Keithley 225 current source, a Keithley 610 °C electrometer to monitor the voltage necessary to maintain a constant current, and a

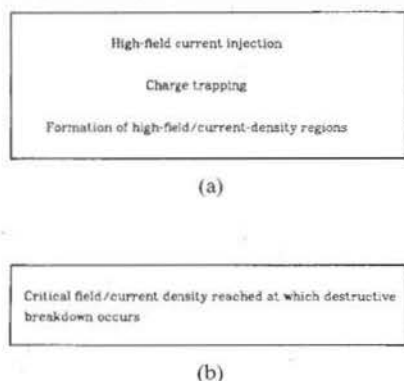


Fig. 1. Conceptual view of the time-dependent dielectric breakdown process. (a) Buildup stage. (b) Runaway stage.

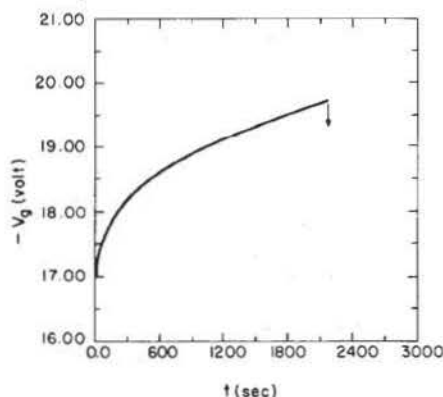


Fig. 2. The gate voltage necessary to maintain a constant current as a function of the stressing time at a constant-current density of 4.8 mA/cm². The gate oxide thickness was 17 nm.

Hewlett-Packard 4140B picoammeter to monitor the current through the device. For constant-voltage stress experiments, the current source is replaced by a Hewlett-Packard 4140B voltage source. All of the instruments are controlled by a Hewlett-Packard 9845C computer.

Current injection eventually results in breakdown of the SiO₂ [9]. This type of stressing roughly emulates the conditions experienced in nonvolatile E²PROM memories, which rely on the tunneling of electrons to and from a floating gate. Thus this type of stressing condition is directly applicable to such devices. It is also a convenient way to characterize the integrity of the gate oxide.

Fig. 2 shows the voltage needed to maintain a constant current as a function of the stressing time for a 17-nm oxide stressed at a current density of 4.8 mA/cm². The gate voltage increases with time until breakdown, at which time the gate voltage necessary to maintain a constant current drops suddenly, to a value of a few volts. There was no ambiguity in the use of this criterion to determine the time at breakdown. The increase in gate voltage necessary to maintain a constant current is due to electron trapping in the SiO₂ [9]–[11]. In addition, traps are believed to be generated as a result of the high-field stress. This trap generation explains the nonsaturating behavior of the gate voltage versus time plot. Thus electron trapping occurs throughout the buildup stage.

It is tempting to conclude, and the recent prevalent view seems to be, that oxide breakdown is a result of electron trapping [9], [12]. Evidence for positive charge generation during the high-field stressing, however, has also been presented [2], [13]–[15]. Positive charge generated by impact ionization in the SiO₂ has long been associated with breakdown [16]–[19]. Essentially, in the impact-ionization model the breakdown process is a result of a current instability due to cathode field enhancement resulting from holes generated in the oxide via impact ionization. We now briefly describe some recent experiments supporting the impact ionization model.

A convenient parameter to characterize breakdown due to charge injection is the "charge-to-breakdown" Q_{BD} , given by (for the constant-current case)

$$Q_{BD} = \int_0^{t_{BD}} J dt = J t_{BD} \text{ C/cm}^2 \quad (1)$$

where J is the current density in amperes per square centimeter (A/cm²), and t_{BD} is the time necessary for breakdown, i.e., the time to complete the buildup stage.

In order to separate out the effects of trapped electrons and trapped positive charges on breakdown, devices were stressed to approximately 90 percent of Q_{BD} and then annealed at high temperatures to detrapp the electrons. The I – V and C – V characteristics of such a device are shown in Fig. 3. This device was stressed at a current level of +6.7 mA/cm² to +18 C/cm² (substrate injection, V_g positive), and then thermally annealed at 450 °C. The gate oxide thickness was 32 nm. Shown in Fig. 3 are the pre-stress, post-stress, and post-stress/anneal characteristics. The anneal succeeded in removing the electrons which were trapped during the constant-current stress. This can be seen by comparing the gate-injection I – V characteristics before and after stress/anneal. The post-stress/anneal gate-injection I – V characteristic has essentially completely recovered to its pre-stress value (Fig. 3(c)). The slight shift of the I – V curve to the left is due to the presence of positive charge which was not annealed. This positive charge can also be seen in the post-anneal quasi-static C – V characteristics. However, the most dramatic change in the device characteristics after stressing and annealing is the increased current and lowered slope of the post-stress/anneal substrate-injection I – V characteristics (Fig. 3(b)). This interface was the cathode (injecting interface) during the constant-current stress.

We attribute this I – V characteristic to the trapping of holes near the cathode, which increases the electric field there resulting in enhanced current injection. The I – V characteristic in SiO₂ is described by the Fowler–Nordheim equation

$$J = AE_c^2 e^{-B/E_c} \quad (2)$$

where E_c is the cathode electric field and A and B depend on the electron effective mass and the barrier height at the cathode. Specifically, B is given by

$$B = 8\pi(2m^*)^{1/2} \phi_B^{3/2} / (3hq) \quad (3)$$

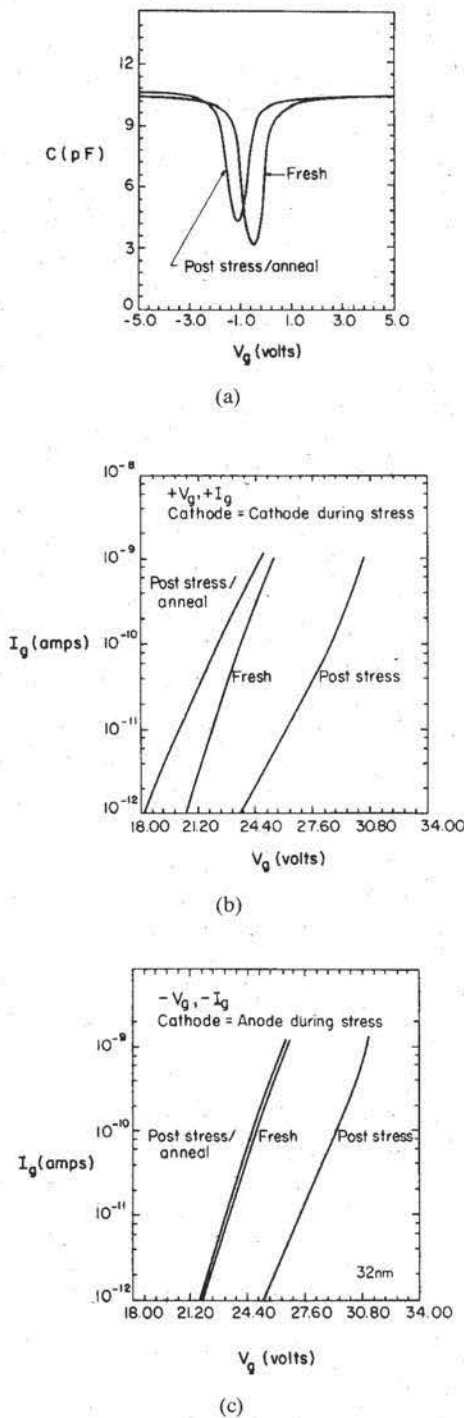


Fig. 3. The before-stressing and post-stressing/annealing C - V and I - V characteristics of a device stressed to $+18 \text{ C/cm}^2$ at 6.7 mA/cm^2 (substrate injection). (a) Quasi-static C - V measurement. (b) Substrate-injection I - V measurement. (c) Gate-injection I - V measurement.

where m^* is the electron effective mass, ϕ_B is the barrier height at the cathode, h is Planck's constant, and q is the electronic charge. Thus the slope of the I - V characteristic (on a semi-log plot) is

$$\frac{d \ln J}{dV} = \frac{2}{E_c} + \frac{B}{E_c^2} \quad (4)$$

and is dependent on E_c . Hence a lower slope implies a

higher E_c , assuming that the conduction mechanism after stressing and annealing can still be described, at least qualitatively, by the Fowler-Nordheim equation. In the next section we present a more exact model for the I - V characteristics after stressing. Image force barrier lowering is neglected in this work. Hartstein and Weinberg have shown both experimentally and theoretically that image force barrier lowering is negligible for the case of tunneling in SiO_2 [20]–[22].

From the shift of the C - V characteristics we estimate that the trapped hole density affecting the C - V measurement is $\approx 3.6 \times 10^{11} \text{ cm}^{-2}$. This is, however, much too small to cause the observed slope lowering. In addition, a uniform field enhancement necessary to cause the observed decrease in slope would result in an extremely large increase in current due to the strong dependence of J on E_c . From these considerations we conclude that the substrate-injection conduction following stressing and annealing is localized in a very small fraction of the oxide area (approximately 1 part in 10^6 of the total area). Because of the strong dependence of J on E_c , this localized component dominates over the current flowing in the remainder of the oxide area where the field enhancement is much smaller. Localized conduction has been observed previously, both in Na^+ -contaminated devices [3] and clean oxides [23], and in devices known to have stacking faults in the underlying silicon substrate [8].

We then studied the effect of this field enhancement and electron trapping on breakdown. After annealing, the devices were subjected to further constant-current stressing both with and without annealing, and both with the same current as the initial stress and with the reversed polarity. When the polarity of current injection is unchanged, the cathode during the final stress has already experienced field enhancement as a result of the initial stress. When the polarity of current injection is reversed after annealing, however, the cathode during the final stress has not undergone any significant field enhancement as evidenced by the recovery of this I - V characteristic in Fig. 3.

The results of this experiment are shown in Table I. In Table I, + refers to substrate injection (gate positive) and minus to gate injection. The current density was 33 mA/cm^2 in this experiment and the gate oxide thickness was 32 nm . Q_i is the initial charge per unit area injected into the oxide before annealing, and Q_{BD} is the additional charge necessary for breakdown after annealing. One observes from Table I that if the polarity of the current is unchanged after annealing, the device breaks down very quickly (row 2). Furthermore, the annealing steps in row 2 detrapped the electrons trapped during the initial stress (Fig. 3) but did not increase the final charge-to-breakdown. Obviously, there is no direct link between electron trapping and breakdown. If the polarity is reversed after annealing, however, then a much longer time to breakdown (equivalent to larger Q_{BD}) after annealing is observed (row 3). Thus the field enhancement, which occurs mainly at the cathode interface, has a dominant effect on the breakdown, and we conclude that oxide breakdown is due to positive

TABLE I
ADDITIONAL CHARGE PER UNIT AREA NECESSARY FOR
BREAKDOWN Q_{BD} AS A FUNCTION OF THE INITIAL CHARGE PER
UNIT AREA INJECTED INTO THE OXIDE Q_i AND THE ANNEALING
TEMPERATURE

(Note: $-$ refers to electron injection from the polysilicon gate, and $+$ refers to injection from the silicon substrate ($J = 33 \text{ mA/cm}^2$).)

	Initial $Q_i \text{ C/cm}^2$	Final $Q_{BD} \text{ C/cm}^2$		
		No Anneal	350°C Anneal	450°C Anneal
1	0	-19.1	-16.3	-18.8
2	-17.0	-1.4	-0.8	-1.2
3	-17.0	+15.4	+13.9	+16.2

charge trapping at the cathode in localized areas, which become localized high-field/current-density regions. When the local current density reaches a critical value, the runaway process quickly brings the oxide to destructive breakdown. While the data are for the 32-nm samples, we have observed similar results with the thinner 13-nm samples.

The most likely source of this positive charge is holes generated by impact ionization in the SiO_2 . This conclusion is based on the similarity of the trapping and annealing characteristics of the positive charge with that observed in radiation experiments [2]. Previous experiments by Shatzkes and Av-Ron [13], and more recently by Nissan-Cohen *et al.* [14], [15] offer strong evidence for impact ionization in SiO_2 , and in fact high-field current injection leading to positive charge trapping has been proposed as a nonradiative technique to electrically measure the radiation sensitivity of MOS dielectrics [24], [25].

Thus the following picture for breakdown in SiO_2 subjected to high-field current injection based on the impact-ionization model is shown in Fig. 4. Electrons are injected from the cathode into the SiO_2 via Fowler-Nordheim tunneling. Some of these electrons gain sufficient energy to cause impact ionization in the SiO_2 . A fraction of the generated holes in the SiO_2 are then driven by the field back toward the cathode, where some are trapped. A localized component of trapped holes results in localized field enhancement and conduction, which further accelerates the local hole trapping and eventually results in breakdown and thermal destruction when the localized current density reaches a critical value.

Thus the model for breakdown presented here is very similar to the impact-ionization models reported earlier [13], [16]–[19]. There are, however, several important differences. First of all, the previous models do not include the effects of electron trapping and trap generation. While we rule out electron trapping as the cause of breakdown, we cannot neglect the effects of electron trapping on the internal fields in the oxide. Electron trapping lowers the cathode field for the case of a constant-voltage stress which in turn lowers the current, resulting in effect a negative feedback situation. Previous models consider only recombination of some of the generated holes with injected electrons as a means of limiting the increase in the cathode field which eventually results in breakdown [13], [17], [18].

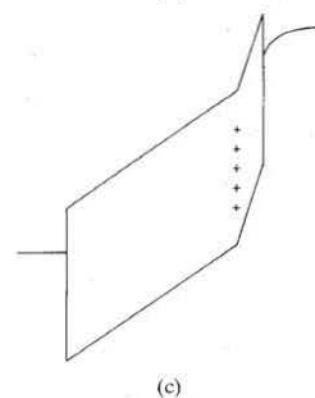
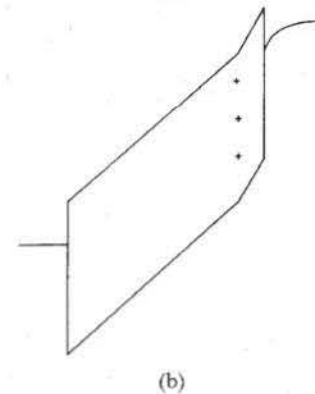
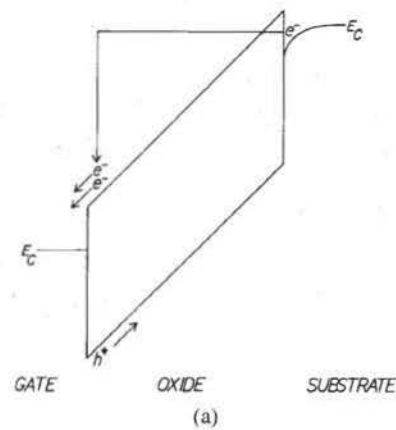


Fig. 4. Breakdown in SiO_2 due to high-field current injection. (a) Electron injection from the cathode results in some of the electrons gaining sufficient energy to create hole-electron pairs in the SiO_2 . Some of the generated holes are driven to the cathode. (b) Hole trapping in local areas at the cathode increases the cathode field. (c) Localized high densities of trapped holes result in the formation of localized high-field/current-density regions, causing positive feedback eventually resulting in breakdown.

Electron trapping, however, will also tend to decrease the cathode field for the case of constant-voltage stressing and cannot be neglected. In addition, electron trapping will increase the field near the anode for both constant-current stressing and constant-voltage stressing. This will result in an increase in hole generation due to the strong field dependence of the impact-ionization coefficient. These points are elaborated on in the next section.

Also, most of the previous models neglect hole drift in the oxide [13], [17], [18]. Our results, however, show that holes are indeed driven to the cathode where a fraction are trapped (Fig. 3). In addition, the dominant hole trapping in terms of the enhancement of the cathode field occurs in

localized areas, which was not included in the previous models. This effect could be important when one considers the possibility of oxide lifetime improvement as a result of improvements in the processing of the oxide. This is discussed further in Section V. In the next section the quantitative model is presented.

IV. THE QUANTITATIVE MODEL

There is no qualitative difference between constant-current and constant-voltage stressing. Only constant-voltage stressing, however, will be simulated here, simply because constant voltage stressing is the more popular method of stressing the gate oxide.

The oxide sample is subdivided into two types of oxide areas connected in parallel, the weak area and the robust area. The localized weak area is very small in total size and highly susceptible to hole trapping near the cathode (the weak area could also be areas of thinner oxide leading to similar simulation results). The robust area is much larger in relative size and not susceptible to localized hole trapping near the cathode. The areas of these two types of capacitors are denoted by A_w and A_r , respectively. The area ratio A_w/A_r has been estimated to be in the order of 10^{-6} from the data presented in Fig. 3. What follow are the descriptions of the weak and robust oxides and the charges associated with each. For the sake of simplicity, all the charges are assumed to be sheet charges located at their respective centroids.

A. Weak Oxide Area

The band diagram associated with this type of oxide is shown in Fig. 5(a). The definitions of the terms are as follows:

- Q_{ot}^+ is the density of trapped holes near the cathode (C/cm^2);
- x_p is the centroid of Q_{ot}^+ ;
- $Q_{ot,w}^-$ is the density of trapped electrons in the oxide;
- x_n is the centroid of $Q_{ot,w}^-$, which is $\approx 0.6 T_{ox}$ for 13-nm oxide [11];
- $E_{c,w}$ is the cathode field;
- $E_{m,w}$ is the field between $x = x_p$ and $x = x_n$;
- $E_{a,w}$ is the anode field, i.e. the field between $x = x_n$ and $x = T_{ox}$;
- T_{ox} is the oxide thickness; and
- T_t is the tunneling distance.

Since the voltage across the oxide is constant, by Gauss's Law it can be shown that

$$E_{c,w} = \frac{V_{ox}}{T_{ox}} - \left(1 - \frac{x_n}{T_{ox}}\right) \frac{Q_{ot,w}^-}{\epsilon_{ox}} + \left(1 - \frac{x_p}{T_{ox}}\right) \frac{Q_{ot}^+}{\epsilon_{ox}} \quad (5.1)$$

$$E_{m,w} = E_{c,w} - \frac{Q_{ot}^+}{\epsilon_{ox}} \quad (5.2)$$

$$E_{a,w} = E_{m,w} + \frac{Q_{ot,w}^-}{\epsilon_{ox}} \quad (5.3)$$

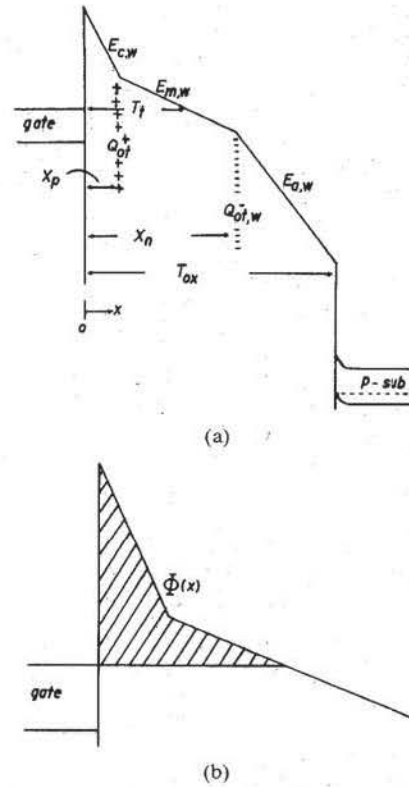


Fig. 5. (a) Energy-band diagram for the weak area oxide susceptible to hole trapping near the cathode. For a fixed oxide voltage V_{ox} , both Q_{ot}^+ and $Q_{ot,w}^-$ will affect the cathode field. (b) Potential barrier at the cathode. With Q_{ot}^+ located within the tunneling distance the potential barrier is no longer triangular.

where V_{ox} is the potential drop across the oxide, and ϵ_{ox} is the permittivity of SiO_2 .

As shown in Fig. 5(b), with Q_{ot}^+ located near the cathode the barrier (shaded region) is no longer triangular. Therefore the Fowler–Nordheim equation (2) cannot be applied directly, and the tunneling probability must be calculated for this barrier shape.

It can be shown that the current density for this type of barrier can be expressed as (Appendix)

$$J_w = AE^2 e^{-KH} \quad (6)$$

where A and $K = 8\pi(2m^*)^{1/2}/3hq$ are the two constants of Fowler–Nordheim equation

$$H = \frac{3}{2} \int_0^{T_t} \sqrt{\Phi(x)} dx \quad (7)$$

and E is obtained from the following equation:

$$E = \frac{\Phi_B^{3/2}}{H} \quad (8)$$

Once $J_w(t)$ is determined, $Q_{ot,w}^-$ can be determined by using the electron trapping model of Liang and Hu [11] (although any empirical electron-trapping model may be used), i.e.,

$$Q_{ot1}^- = qN_{op} \left(1 - e^{-\int_0^t \sigma_g J dt/q}\right) + \int_0^t g(J) J(t) dt - \frac{qg(J)}{\sigma_g} \left(1 - e^{-\int_0^t \sigma_g J dt/q}\right) \quad (9)$$

where N_{op} is the pre-existing trap density ($\#/cm^2$), $g(J)$ is the generation rate which can be determined from the slope of a V_g versus F plot for constant-current stressing where F is the fluence, i.e., the number of electrons per unit area injected into the oxide, σ is the capture cross section for the pre-existing traps, and σ_g is the capture cross section for the generated traps. The value of g at $J = -10 \text{ mA/cm}^2$ is determined to be 7×10^{-8} experimentally. The values for σ and σ_g are taken from [11, Fig. 4]. The functional dependences on J for these parameters are also obtained from [11]. Not shown in Fig. 5 is any positive charge trapped in the anode region. This positive charging has been observed and studied in detail [10], [13]–[15]. While this charge is not included explicitly in the model, its effects are included in the electron trap generation rate g which is a measure of the net charge trapped in the oxide. This also implicitly includes any effects due to field emission of trapped charges.

Thus the density of trapped holes near the cathode is given by

$$Q_{ot}^+ = \eta \int_0^t J_w(t) (M_w - 1) dt \quad (10)$$

where η is the trapping efficiency and M_w is the multiplication factor in the weak area, which can be expressed as

$$M_w = \frac{1}{1 - \int_{T_i}^{T_{ox}} \alpha(E) dx} \approx 1 + \int_{T_i}^{T_{ox}} \alpha(E) dx \quad (11)$$

where $\alpha(E)$ is the impact ionization coefficient. η implicitly includes the effects of recombination of generated holes with injected electrons. More exact modeling of the dynamics of recombination can be found in references [13], [14], [17]–[19]. $\alpha(E)$ has the form

$$\alpha(E) = \alpha_0 e^{-H/E} \quad (12)$$

with $H = 78 \text{ MV/cm}$ and $\alpha_0 = 3.3 \times 10^6$ at room temperature [25]. We have also found H and α_0 to be in this range [26]. The η factor is a parameter to be adjusted. In our charge sheet model, $\int_{T_i}^{T_{ox}} \alpha dx$ can simply be expressed as

$$\int_{T_i}^{T_{ox}} \alpha dx \approx \alpha(E_{m,w})(x_n - T_i) + \alpha(E_{a,w})(T_{ox} - x_n). \quad (13)$$

B. Robust Oxide Area

For the robust oxide, the situation is similar but simpler. The only difference is that there is no localized hole trapping near the cathode. The band diagram associated with these areas is shown in Fig. 6. The symbol definitions should be self-explanatory. Equations (5)–(14) still apply after obvious modifications (change of subscript and setting Q_{ot}^+ to zero).

We simulated the time evolution by subdividing the time scale into small intervals. The charges that influence the electric field are taken from the previous time interval. After the new J_w and J_r are determined, the additional charges built up within the new time interval can be

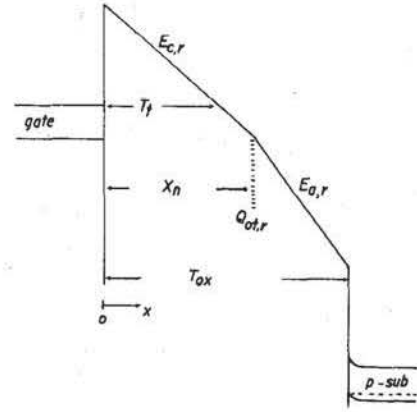


Fig. 6. Energy-band diagram for the region without localized cathode hole trapping (robust area). For a fixed oxide voltage V_{ox} , electron trapping Q_{ot}^- will decrease the cathode field and therefore reduce the current.

calculated. The total current density J_{total} is

$$J_{total} = \frac{1}{A_w + A_r} (A_w J_w + A_r J_r) \quad (14)$$

and breakdown is arbitrarily defined as the time when J_{total} increases by a factor of more than ten in one time interval. The t_{BD} results are insensitive to the definition as J_{total} increases rapidly within a very short time just prior to breakdown.

In this simulation, the only adjustable parameters are x_p and the η factor. η is process dependent for the case of uniform trapping of holes generated by ionizing radiation [24], [25], [27]. Values of η , however, have not been reported for the case of localized hole trapping. In addition, the trapping efficiency is expected to become smaller as more charge is trapped due to saturation effects [28]. In our case, x_p is chosen to be 20 nm from the cathode, and η is chosen to be a constant value of 10^{-5} .

Fig. 7 shows the $\log J_{total}$ versus t plots for constant voltage stressing at $V_g = -16.5$ and -16.0 V ($T_{ox} = 13 \text{ nm}$). As can be seen, the calculated result follows the experimental curve quite closely. The discrepancy in t_{BD} is not much larger than the observed sample to sample variations. Although the statistical nature of t_{BD} cannot be modeled by a single event, these figures do show that the simulation result does in general follow the experiment. In particular, the reduction of J due to electron trapping is well modeled. Fig. 8 shows the time-to-breakdown t_{BD} versus average field E_{ox} for the 13-nm-thick oxide samples. The time-to-breakdown is predicted quite well by the model. We believe that the discrepancy is mainly due to the imperfection of (12).

From the preceding discussion, it is not difficult to see that (11) is the key process that determines the lifetime of the oxide. If we assume that the amount of Q_{ot}^+ needed to cause runaway is the same for different gate voltages, then the lifetime t_{BD} should be inversely proportional to the product of J_w and $(M_w - 1)$. Since both J_w and $(M_w - 1)$ have the $e^{-\text{const}/E}$ dependence, t_{BD} can be expected to

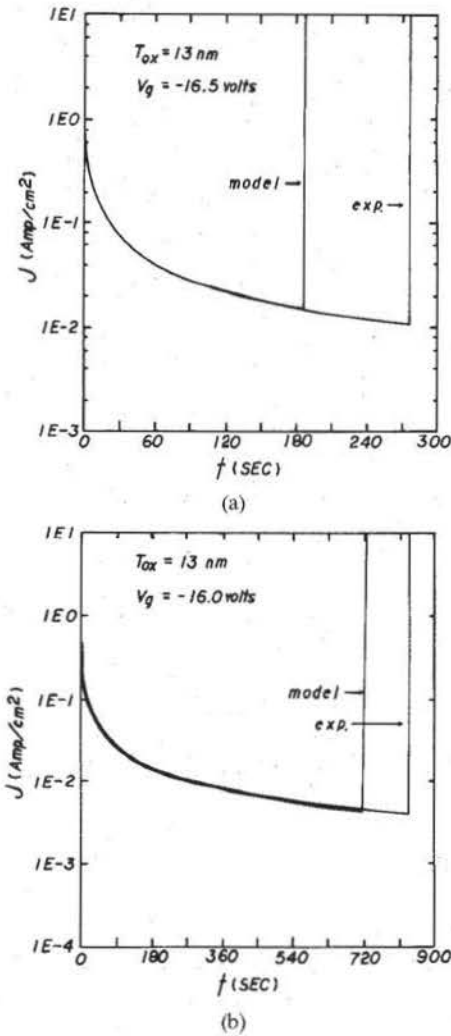


Fig. 7. $\log J_{\text{total}}$ versus t for V_g equals -16.5 V and -16.0 V ($T_{\text{ox}} = 13$ nm). The monotonic decrease in current is mainly due to electron trapping. The current in the weak area is not significant initially but eventually becomes the dominant component.

behave similarly, i.e.,

$$t_{\text{BD}} \approx \frac{c}{J_w(M_w - 1)} \approx c^* e^{(B+H)/E} \quad (15)$$

where B and H are the exponential factors in the F-N current (2) and impact-ionization coefficient (12) respectively, and c and c^* are constants independent of E . This equation implies that $\log t_{\text{BD}}$ versus $1/E$ should be a straight line, more so than $\log t_{\text{BD}}$ versus E , which is widely postulated to be a straight line in the literature [29]–[31]. Klein and Solomon have also derived a very similar equation for the time-to-breakdown [18]. To our knowledge, however, this field dependence of t_{BD} has not been experimentally observed.

Fig. 9(a) shows the t_{BD} versus E_{ox} and versus $1/E_{\text{ox}}$ plots for a 7.9-nm tunneling oxide, where E_{ox} is the average oxide field defined as $E_{\text{ox}} = V_{\text{ox}}/T_{\text{ox}}$. The solid lines are obtained from the model. As can be seen, a more nearly linear relationship between $\log t_{\text{BD}}$ and $1/E_{\text{ox}}$ can be observed over a wide range of t_{BD} . Furthermore, Fig.

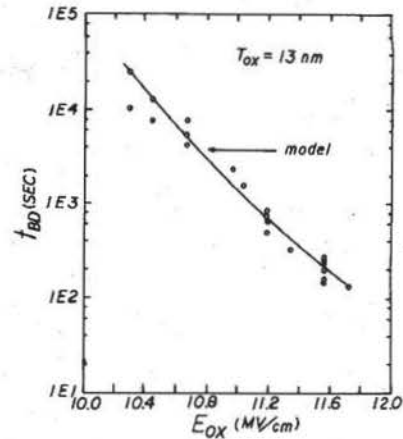


Fig. 8. Time-to-breakdown t_{BD} versus average field $E_{\text{ox}} = V_{\text{ox}}/T_{\text{ox}}$ for constant voltage stressing ($T_{\text{ox}} = 13$ nm). The solid curve is the result of the model.

9(b) is the $\log(1/\eta\alpha)$ versus $1/E_{\text{ox}}$ plot [26], and Fig. 9(c) is the $\log(1/J)$ (Fowler–Nordheim current) versus $1/E_{\text{ox}}$ plot. As can be seen, the slope in Fig. 9(a), 140 decades per centimeter per megavolt is approximately the sum of the slopes in Fig. 9(b) (40 decades per centimeter per megavolt) and Fig. 9(c) (110 decades per centimeter per megavolt), as predicted by (15).

V. DISCUSSION

One key result that we have presented is the likely role of interface hole trapping in the SiO_2 breakdown process. Further evidence for the role of the interface in breakdown is the fact that Q_{BD} for substrate injection is about 20 percent higher than Q_{BD} for gate injection [2]. Thus from the standpoint of breakdown, the polysilicon- SiO_2 interface is weaker than the Si-SiO_2 interface. This effect has also been observed by Van der Schoot and Wolters [32].

Thus, we believe that any improvement in the breakdown characteristics will require an improvement in the interface properties. In particular, according to our model, hole trapping at the interfaces must be minimized. Hole trapping in SiO_2 has been studied extensively because of its role in the degradation of MOS devices exposed to ionizing radiation. As a result of these studies, “radiation-hard” processes have been developed [33]–[35]. In general, radiation hardness has been achieved by minimizing the temperature at which the gate oxide is grown, and by minimizing the temperature for all post-oxidation processing steps.

However, while radiation-hard processing is known to reduce the uniform component of hole trapping, it is only a hope that it will also reduce the localized hole trapping. The uniform component of positive charge, which is responsible for the post-stressing/annealing $C-V$ shift in Fig. 3, anneals in a similar manner to what has been observed for radiation-induced positive charge [2], [36]–[38]. This is to be expected since in both cases, we believe, the positive charge is trapped holes. The density of positive charge remaining decreases as a function of the annealing temperature. The localized component of positive charge,

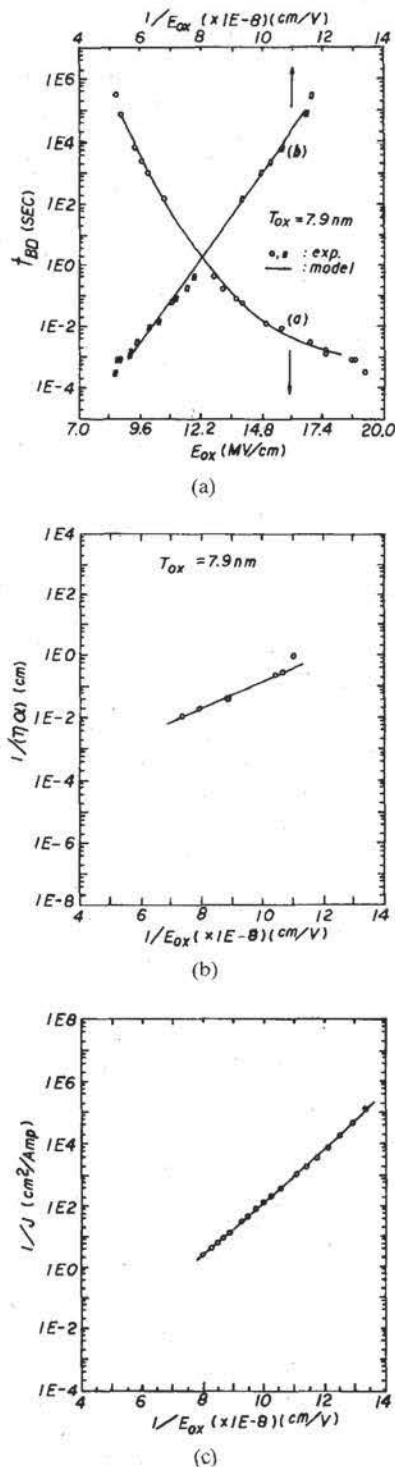


Fig. 9. (a) $\log t_{BD}$ versus E_{ox} and $1/E_{ox}$ for the 7.9-nm tunneling oxide. $\log t_{BD}$ follows a linear relationship with $1/E_{ox}$, not E_{ox} as hitherto assumed. (b) $\log 1/\eta\alpha$ versus $1/E_{ox}$ for the 7.9-nm tunneling oxide. The slope corresponds to the H factor of α ($\alpha = \alpha_0 e^{-H/E}$). (c) $\log 1/J_{total}$ versus $1/E_{ox}$ for the same tunneling oxide. The slope in the figure is approximately equal to the B factor of the Fowler-Nordheim current. ($J = AE^2 e^{-B/E}$)

however, does not seem to be affected significantly by the anneal, as can be seen in Table 1. The Q_{BD} for the case without polarity reversal (row 2) is basically insensitive to temperature over this temperature range. Since the localized and uniform hole traps exhibit different thermal de-

trapping characteristics, they may respond differently to radiation-hard processing also. Nevertheless, we recommend investigating the hypothesis that radiation-hard processing could improve the time-dependent breakdown quality of the oxide as well.

We mentioned earlier that this type of high-field stressing was applicable to E^2 PROM's. In particular, the threshold-window closing observed after a sufficient number of write and erase cycles have been performed is due to electron trapping, and we believe the oxide breakdown in these devices is also described by our model. While we have studied the "intrinsic" breakdown of basically defect free oxides, it is reasonable to assume that the "early" breakdowns are caused by the same mechanism of hole generation and trapping. In this case the "weak oxide area" is weak because of a particularly high density of hole traps or large hole capture cross section at a local spot, or because of thinner oxide thickness or lower effective barrier height at time zero due to particulate contamination, crystalline defects or interface asperities in the silicon. In fact, we suspect that all three causes contribute to the early breakdowns in different oxide samples. The quantitative model presented in this paper, after straightforward modifications, should be applicable to these early breakdowns as well.

VI. SUMMARY

We have presented evidence which suggests that hole trapping in localized areas at the cathode is responsible for breakdown in SiO_2 films which have been subjected to high field current stress. The holes are believed to be generated by impact ionization. A quantitative model describing the charge buildup stage of the breakdown process has been presented and found to agree with experiments. Specifically, it is shown that although electron trapping occurs throughout the stressing experiment, it is not responsible for oxide breakdown. Localized hole trapping enhances the cathode field and increases the local current density, hence further accelerating the local hole trapping. This process eventually causes the local current density to reach a critical value to cause destructive thermal breakdown.

It appears that the thinner tunneling oxides in E^2 PROM's break down by the same mechanism as the thicker gate oxides. While electron trapping is responsible for the threshold window closing, the tunneling oxide breakdown is due to hole trapping. A quantitative model for $J-t$ and time-to-breakdown (t_{BD}) is presented. Excellent agreement was obtained between the model and experiments. Both the model and experiment suggest that $\log t_{BD}$ varies linearly with $1/E$ rather than E as widely postulated. This fact is especially clear with thinner samples for which data over a larger range of E can be collected. For a 7.9-nm oxide the field acceleration factor for t_{BD} is approximately 140 decades per centimeter per megavolt of which approximately 25 percent is contributed by the field dependence of the impact ionization coefficient

and the additional 75 percent is due to the Fowler–Nordheim current dependence on $1/E$.

While data has been presented only for “intrinsic” breakdown of basically defect-free oxides, it is reasonable to assume that “early” breakdowns occur at local sites where hole trap density or trap cross section is large, or where the oxide thickness or effective barrier height is low due to particulate contamination or silicon crystalline defects. Both the physical and the quantitative models should be applicable to early failures.

Reduction of the densities of particulates and material defects will obviously be helpful. Our model suggests that any process changes that reduce hole trapping at the interface should be helpful, too. Radiation-hard processing is an obvious candidate.

APPENDIX

The tunneling probability for an electron with energy $\mathcal{E}$ is

$$D(\mathcal{E}) \approx e^{-2 \int_0^T k(\mathcal{E}) dx} \quad (\text{A1})$$

where $k(\mathcal{E})$ is the wave vector within the oxide, and can be approximated by

$$k(\mathcal{E}) = \frac{2\pi}{h} \sqrt{2m^*(q\Phi(x) - \mathcal{E})} \quad (\text{A2})$$

where $\Phi(x)$ is the potential barrier profile, m^* is the effective mass, and h is Planck's constant. Therefore, the tunneling probability is mainly determined by the following integration:

$$G = \int_0^T \sqrt{\Phi(x)} dx \quad (\text{A3})$$

Here $\mathcal{E}$ is set to zero, i.e., the tunneling is from the conduction band edge of the cathode. For a triangular barrier with barrier height φ_B and field E , the above integral becomes

$$G = \frac{2}{3} \frac{\varphi_B^{3/2}}{E} \quad (\text{A4})$$

If the preceding two cases has the same tunneling probability, then

$$\frac{\varphi_B^{3/2}}{E} = \frac{3}{2} G \quad (\text{A5})$$

This is the factor that we put into the Fowler–Nordheim equation, and the effective field E can also be determined this way.

REFERENCES

- [1] C. R. Barrett and R. C. Smith, “Failure modes and reliability of dynamic rams,” in *IEDM Tech. Dig.* (Washington, DC), Dec. 1976.
- [2] S. Holland, I. C. Chen, T. P. Ma, and C. Hu, “On physical models for gate oxide breakdown,” *IEEE Electron Device Lett.*, vol. EDL-5, p. 302, Aug. 1984.
- [3] T. H. DiStefano, “Dielectric breakdown induced by sodium in MOS structures,” *J. Appl. Phys.*, vol. 44, p. 527, Jan. 1973.
- [4] S. I. Raider, “Time-dependent breakdown of silicon dioxide films,” *Appl. Phys. Lett.*, vol. 23, p. 34, July 1973.
- [5] C. M. Osburn and D. W. Ormond, “Sodium-induced barrier-height lowering and dielectric breakdown on SiO_2 films on silicon,” *J. Electrochem. Soc.*, vol. 121, no. 9, p. 1195, Sept. 1974.
- [6] S. P. Li, E. T. Bates, and J. Maserjian, “Time-dependent MOS breakdown,” *Solid-State Electron.*, vol. 19, p. 235, 1976.
- [7] J. R. Monkowsik and R. T. Zahour, “Failure mechanism in MOS gates resulting from particulate contamination,” in *Proc. Int. Rel. Phys. Symp.*, p. 244, Apr. 1982.
- [8] P. S. D. Lin, R. B. Marcus, and T. T. Sheng, “Leakage and breakdown in thin oxide capacitors-correlation with decorated stacking faults,” *J. Electrochem. Soc.*, vol. 130, no. 9, p. 1878, Sept. 1983.
- [9] E. Harari, “Dielectric breakdown in electrically stressed thin films of thermal SiO_2 ,” *J. Appl. Phys.*, vol. 49, no. 4, p. 2478, Apr. 1978.
- [10] C. S. Jenq, T. R. Ranganath, C. H. Huang, H. S. Jones, and T. L. Chang, “High-field generation of electron traps and charge trapping in ultra-thin SiO_2 ,” in *IEDM Tech. Dig.* (Washington, DC), p. 388, Dec. 1981.
- [11] M. S. Liang and C. Hu, “Electron trapping in very thin thermal silicon dioxides,” in *IEDM Tech. Dig.* (Washington, DC), p. 396, Dec. 1981.
- [12] W. K. Meyer and D. L. Crook, “Model for oxide wearout due to charge trapping,” in *Proc. Int. Rel. Phys. Symp.*, p. 242, Apr. 1983.
- [13] M. Shatzkes and M. Av-Ron, “Impact ionization and positive charge in thin SiO_2 films,” *J. Appl. Phys.*, vol. 47, no. 7, p. 3192, July 1976.
- [14] Y. Nissan-Cohen, J. Shappir, and D. Frohman-Bentchkowsky, “High field current induced-positive charge transients in SiO_2 ,” *J. Appl. Phys.*, vol. 54, no. 10, p. 5793, Oct. 1983.
- [15] —, “Determination of SiO_2 trapped charge distribution by capacitance-voltage analysis of undoped polycrystalline silicon-oxide-silicon capacitors,” *Appl. Phys. Lett.*, vol. 44, no. 4, p. 417, Feb. 1984.
- [16] J. J. O'Dwyer, “Theory of high field conduction in a dielectric,” *J. Appl. Phys.*, vol. 40, no. 10, p. 3887, Sept. 1969.
- [17] T. H. DiStefano and M. Shatzkes, “Impact ionization model for dielectric instability and breakdown,” *Appl. Phys. Lett.*, vol. 25, no. 12, p. 685, Dec. 1974.
- [18] N. Klein and P. Solomon, “Current runaway in insulators affected by impact ionization and recombination,” *J. Appl. Phys.*, vol. 47, no. 10, p. 4364, Oct. 1976.
- [19] I. Kashat and N. Klein, “Current runaway in insulators affected by impact ionization and drift,” *J. Appl. Phys.*, vol. 48, no. 12, p. 5217, Dec. 1977.
- [20] Z. A. Weinberg and A. Hartstein, “Photon assisted tunneling from aluminum into silicon dioxide,” *Solid State Commun.*, vol. 20, no. 3, p. 179, 1976.
- [21] A. Hartstein and Z. A. Weinberg, “On the nature of the image force in quantum mechanics with application to photon assisted tunneling and photoemission,” *J. Phys. C: Solid State Phys.*, vol. 11, p. L469, 1978.
- [22] —, “Unified theory of internal photoemission and photon-assisted tunneling,” *Phys. Rev. B*, vol. 20, no. 4, p. 1335, Aug. 1979.
- [23] C. M. Osburn and N. J. Chou, “Accelerated dielectric breakdown of silicon dioxide films,” *J. Electrochem. Soc.*, vol. 120, no. 10, p. 1377, Oct. 1973.
- [24] H. E. Boesch and J. M. McGarrity, “An electrical technique to measure the radiation susceptibility of MOS gate insulators,” *IEEE Trans. Nucl. Sci.*, vol. NS-26, p. 4814, Dec. 1979.
- [25] M. Knoll, D. Braumig, and W. R. Fahrner, “Comparative studies of tunnel injection and irradiation on metal oxide semiconductor structure,” *J. Appl. Phys.*, vol. 53, no. 10, p. 6946, Oct. 1982.
- [26] I.-C. Chen, S. E. Holland, and C. Hu, “Characterization of impact ionization in thin SiO_2 ,” to be published.
- [27] F. B. McLean, H. E. Boesch, Jr., and J. M. McGarrity, “Hole transport and recovery characteristics of SiO_2 gate insulators,” *IEEE Trans. Nucl. Sci.*, vol. NS-23, p. 1506, Dec. 1976.
- [28] R. Freeman and A. Holmes-Siedle, “A simple model for predicting radiation effects in MOS devices,” *IEEE Trans. Nucl. Sci.*, vol. NS-25, p. 1216, 1978.
- [29] D. L. Crook, “Techniques of evaluating long term oxide reliability at wafer level,” in *Proc. Int. Rel. Phys. Symp.*, p. 444, Apr. 1978.
- [30] E. Anolick and G. Nelson, “Low field time dependent dielectric integrity,” in *Proc. Int. Rel. Phys. Symp.*, p. 8, Apr. 1979.
- [31] D. L. Crook, “Method of determining reliability screens for time dependent dielectric breakdown,” in *Proc. Int. Rel. Phys. Symp.*, p. 1, Apr. 1979.
- [32] J. J. van der Schoot and D. R. Wolters, “Current induced dielectric breakdown,” in *Conf. Proc. Insulating Films On Silicon*, p. 270, 1983.

- [33] K. G. Aubuchon, "Radiation hardening of PMOS devices by optimization of the thermal SiO₂ gate insulator," *IEEE Trans. Nucl. Sci.*, vol. NS-18, p. 117, Dec. 1971.
- [34] G. F. Derbenwick and B. L. Gregory, "Process optimization of radiation-hardened CMOS integrated circuits," *IEEE Trans. Nucl. Sci.*, vol. NS-22, p. 2151, Dec. 1975.
- [35] K. G. Aubuchon, H. T. Peterson, and D. P. Shumake, "Radiation-hardened CMOS/SOS LSI circuits," *IEEE Trans. Nucl. Sci.*, vol. NS-23, p. 1613, Dec. 1976.
- [36] J. M. Aitken, "Annealing of radiation-induced positive charge in MOS devices with aluminum and polysilicon gate contacts", *J. Electron. Mat.*, vol. 9, no. 3, p. 639, 1980.
- [37] A. Reisman and C. J. Merz, "The effects of pressure, temperature, and time on the annealing of ionizing radiation induced insulator damage in n-channel IGFET's," *J. Electrochem. Soc.*, vol. 130, no. 6, p. 1384, June 1983.
- [38] M. Shimaya, N. Shiono, O. Nakajima, C. Hashimoto, and Y. Sakakabara, "Electron beam induced damage in poly-si gate MOS structures and its effect on long-term stability," *J. Electrochem. Soc.*, vol. 130, no. 4, p. 945, Apr. 1983.
-