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SAND2003-4783
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Printed February 2004

Radiation Aging of Stockpile and Space-Based Microelectronics

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Prepared by
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National Nuclear Security Administration under Contract DE-AC04-94-AL85000.

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Radiation Aging of Stockpile and Space-Based Microelectronics

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Abstract

This report describes an LDRD-supported experimental-theoretical collaboration on the enhanced low-dose-rate sensitivity (ELDRS) problem. The experimental work led to a method for elimination of ELDRS, and the theoretical work led to a suite of bimolecular mechanisms that explain ELDRS and is in good agreement with various ELDRS experiments. The model shows that the radiation effects are linear in the limit of very low dose rates. In this limit, the regime of most concern, the model provides a good estimate of the worst-case effects of low dose rate ionizing radiation.

Acknowledgement

The project team, consisting of Charles E. Hembree, Harold P. Hjalmarson, Peter A. Schultz, James R. Schwank, Marty R. Shaneyfelt and Steven C. Witczak, thanks Carolyn W. Bogdan, Duane J. Bowman, Michael F. Deveney, Arthur H. Edwards, Teresa B. Gutierrez, Thomas R. Mattsson, Albert V. Nunez and Carleton H. Seager for their assistance with this project.

Contents

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1 Introduction

This research project was stimulated by Sandia studies that showed unusually rapid degradation of some integrated circuits (IC's), such as LM185 voltage regulators, when tested at low dose rates. Because these low dose rates are comparable to the intrinsic radation rates, these findings lead to more extensive testing and study (for example, by the Enhanced Surveillance Program). These studies showed that the damage was greatest at low dose rates, and they concluded that these results are consistent with a phenomenon called enhanced low-dose-rate sensitivity (ELDRS) [1, 2, 3]. This phenomenon has important implications for transistors used in low dose-rate environments, such as spacecraft, satellites and nuclear weapons microelectronics. Traditionally, and by specification, the standard testing procedures use higher dose-rates, and thus they would fail to reject certain devices that degrade in a low dose-rate environment.

Several approaches to this problem were undertaken. One approach was to test microelectronic IC's used in low dose-rate environments to determine those which exhibited ELDRS. This time-consuming testing was undertaken at Sandia and other laboratories. At Sandia, such testing continues using Enhanced Surveillance Campaign (ESC) funding. Another approach was to develop a screening test to eliminate new parts that were prone to ELDRS. This became a cooperative effort involving several laboratories [4, 5, 3, 6]. Another approach was to develop a simulation model for the effects of ELDRS; this approach led to a project funded by the Advanced Strategic Computing Initiative (ASCI) to develop a radiation-sensitive device model to use in the massively-parallel circuit simulator Xyce to assess the effects of ELDRS. Finally, another approach, represented by this LDRD, was to develop a physics-based explanation for ELDRS. This approach was appealing because, if successful, it would have several desirable consequences. For example, having a physics-based understanding could help with selecting parts that did not suffer from ELDRS and could help with developing new parts that would not exhibit ELDRS.

From the start, this LDRD project focused on ELDRS with a collaborative experimental-theoretical approach. The main goal was development of an understanding in terms of mechanism for ELDRS. A major motivation for this goal was the fact that testing at the lowest rates, corresponding to stockpile environments, is impossible. Because the unusual dose-rate sensitivity was unexplained, there was a concern that continued increase in sensitivity might be uncovered if testing were done at lower and lower dose rates. This main goal was linked to two other important goals, the development of a SPICE/XYCE model based on the physics mechanism and the development of a procedure to eliminate ELDRS in new devices. In a sense, the first goal, if succesful, would provide capability to assess ELDRS in present stockpile microelectronic devices, and the second goal, if successful, would provide methods to eliminate ELDRS in new stockpile microelectronic devices. This latter goal was linked to a project funded by the Defense Threat Reduction Agency (DTRA) to collaborate on solving the ELDRS problem for spacecraft microelectronics. This collaboration, involving universities, national laboratories and industrial laboratories, was focused on developing new IC's that would not be susceptable to ELDRS.

The LDRD project brought together two lines of inquiry to understand the physics of ELDRS. An initial project, using Research Foundation support, had concluded that a hydrogen dimerization mechanism might explain ELDRS [7, 8]. Another project, funded by the DTRA to look at microelectronics in spacecraft and satellites, found that ELDRS often occurred in parts that exhibit two other effects, pre-irradiation elevated thermal stress (PETS) sensitivity and latent interface trap buildup (LITB) [9]. These phenomena seemed to be occurring in similar technologies and were possibly related by underlying physical mechanisms.

2 Project Description and Discussion

This LDRD project utilized information gathered in previous studies of the effects of ionizing radiation on microelectronic devices [10]. It is well known that ionizing radiation generally degrades the performance of Si microelectronic devices by creating interface traps and oxide-trapped charge [11, 10]. The interface traps consist of Si atoms at the interface that failed to bond to the oxide [12]. Such traps act as recombination centers for electrons and holes, and this recombination leads to increased base current in bipolar transistors [10]. The oxide-trapped charge can shift the gate voltage of MOS devices negatively, and it can cause large increases in leakage current [10].

The mechanisms for creating radiation damage have been examined in numerous studies [10]. It is generally agreed that ionizing radiation releases hydrogen that reacts with the interface to create interface traps [13, 14]. The best-accepted model, the two-stage hydrogen model, explains the effects in terms of protons that react with the interface [15, 16]. In this mechanism, radiation creates holes that react with hydrogen source sites to release protons. These protons then migrate to the interface where they react with and release hydrogen from previously passivated traps. Though this process creates interface traps, it does not have an explicit dose-rate dependence.

As noted previously, in certain bipolar devices, the buildup of interface traps has been shown to depend on the dose rate of the radiation source [17, 1]. This leads to enhanced low-dose-rate sensitivity (ELDRS) in these bipolar technologies. Several models have been proposed to explain ELDRS [18, 19, 20, 21, 22, 23]. The most widely accepted model is a space-charge model [18, 19, 22, 23]. In this model, at high dose rates, the space charge of trapped holes slows the migration of protons to the interface, and thus fewer interface traps are produced. However, at low dose rates the space charge is too small to have an effect. As a consequence, this model predicts that approximately twice as many interface traps are produced at low dose rates [23].

2.1 Early Stages

Early in this LDRD project, a hydrogen dimerization mechanism was developed as a competing explanation for ELDRS [8]. In this model, dimerization of hydrogen is included as a possible reaction within the oxide. At low dose rates, it has no effect. However, at high dose rates, when the hydrogen concentration is elevated, this reaction competes with the hydrogen reaction that creates interface states. The initial version of this model was very successful in fitting experimental data. For example, it successfully predicted the temperature dependence of ELDRS data [8]. For these predictions, the model used parameter values that were either guessed or fitted to agree with the ELDRS data. After this initial success, the parameter values were assessed more carefully by making physics-based approximations to each of the reaction rates involving hydrogen and other important species. Electronic structure calculations were also performed for this analysis [24]. As a result, the validity of the parameter values of the dimerization model were gradually improved. However, as the parameters were improved, we found that the model began to disagree with the data because hydrogen diffuses too rapidly through the silica.

Another concern with the initial bimolecular model arose following electronic structure calculations used to test one of the key assumptions of the dimerization mechanism [25]. In this assumption, each of the protons released after irradiation becomes a neutral hydrogen atom by acquiring an electron from the underlying silicon at the silicon-silica interface. This assumption is also used in the well-known two stage hydrogen mechanism [15], and it had an important role in the dimerization model. However, the electronic structure calculations performed on a hydrogen atom near the interface showed that it would lose an electron to the silicon layer if it were near the SiO_2-Si interface, and it would become a proton. By inference, no protons would be converted into neutral hydrogen atoms, in fundamental disagreement with the assumption of the dimerization model.

These calculations led us to reconsider the charge state of the hydrogen released by radiation. Prior to these results, we had assumed that only protons were released during irradiation. An examination of the extensive literature on silica revealed strong support for the release of neutral hydrogen [26, 27, 28]. In fact, earlier experiments had obtained conclusive evidence for the release of neutral hydrogen atoms [26]. Hence, we determined that radiation can release both protons and neutral hydrogen.

Our knowledge that both forms of hydrogen could be involved stimulated much further work. It reinvigorated our interest in the dimerization model, and we developed a revised dimerization model in which both charge states of hydrogen atoms were released by the ionizing radiation. It led to a theoretical effort to postulate source sites and release mechanisms for hydrogen in the oxide. It also led to an experimental effort to find evidence for neutral hydrogen by examining the temperature dependence of the radiation damage, but these experiments led to inconclusive results concerning neutral hydrogen [29].

During the theoretical work, several other discovery experiments were being done primarily to gain information about ELDRS. As stated earlier, the initial experiments showed that PETS and LITB may be associated with ELDRS [9]. Later experiments showed that ELDRS could be eliminated by removing the silicon nitride passivation layer [9, 30]. This layer, present on all bipolar devices, protects the underlying silicon dioxide from contaminants.

The experimental work stimulated new interest in the hydrogen dimerization mechanism for three reasons. One, the silicon nitride passivation layer is well-known to contain very high concentrations of hydrogen. Two, the diffusion of hydrogen and the reactions of hydrogen could be expected to be slow in the silicon nitride layers. This slow diffusion region brought the predictions of the dimerization model back into good agreement with the data. Three, the slow kinetics of the revised dimerization mechanism was consistent with the slow kinetics observed in the LITB measurements.

Further experiments in which other passivation layers were used showed that ELDRS could occur even if silicon nitride was not present [29]. This discovery was very difficult to reconcile with the dimerization model because it is unreasonable to assume that hydrogen diffusion was slow in all these layers.

At this point an alternative model was developed in which hydrogen atoms were retrapped by the source sites. This new model was stimulated by experimental evidence for neutral hydrogen release and an examination of the literature that showed a sublinear dependence on total dose. It led to predictions qualitatively similar to those of the dimerization model [26, 31].

2.2 Final Stage

In the final stage in our project, the experimental work led to an engineering solution to the low dose rate problem [32]. This work was done in collaboration with other research groups as well as the vendor, National Semiconductor Corporation, that produced most of the commerical chips in the low dose rate studies. As discussed previously, the earlier work led to a focus on the passivation layers. In this most recent work, several different types of passivation layers were examined on test chips [32]. As a consequence, a new passivation layer and procedure for making it were found to eliminate the ELDRS problem [32].

Important conceptual advances for the theoretical portion of our project were stimulated by applying the new dimerization mechanism to the passivation layer. One, it again led us to consider the possibility that only neutral hydrogen, not protons, were released during irradiation. Two, it led us to recognize that the essence of the mechanism was bimolecular recombination of two species whose concentrations were controlled by the irradiation. Such bimolecular recombination is also the essence of the dimerization and the hydrogen retrapping models. By induction, we postulated that a variety of bimolecular mechanisms could lead to reduced radiation effects at high dose rates. In contrast to the sublinear dependence at high dose rates, the response would be linear at low dose rates.

The resultant final bimolecular model consists of a suite of mechanisms that have the potential to dominate at high dose rates [33]. This model is in good qualitative agreement with the dose-rate dependent data [32]. To obtain quantitative agreement at high dose rates will require additional information about the bimolecular mechanisms that dominate at high dose rates.

At low dose rates, the regime of most concern, the theory becomes very simple and dependent on only one parameter, the ”efficiency”. This parameter, whose value cannot exceed unity, bounds the extent of the problem that could be encountered at the lowest dose rates. An examination of data has shown that the largest values of this parameter are associated with problematic devices that exhibit ELDRS.

Finally, the linear version our model has been used to develop an ELDRS-aware model that has been implemented in both the PSPICE and Xyce circuit simulators [34]. Furthermore, a combination of device simulations and PSPICE simulations has been used to determine the value of this parameter for irradiation LM185 IC’s. This work has found that a value of approximately 0.01 can be used to fit radiation degradation for the measured transistors in the LM185. The resultant LM185 similations are in good agreement with the low dose rate data for these devices [34]. This success suggests that our work can be used for successful simulations of bipolar transistor devices to assess circuit reliability in a low dose rate radiation environment.

3 Summary

In this project we used experiments and modeling to develop understanding of the cause of ELDRS. Our experimental work showed that ELDRS can be associated with technology that also exhibits PETS and LITB. We showed that ELDRS is caused by the passivation layer, and we found passivation layers that do not lead to ELDRS.

We developed a general bimolecular theory for the dose-rate dependence of the effects of ionizing radiation on interface traps in microelectronic oxides. In this theory, bimolecular reactions that consume radiolytic species lead to ELDRS. The approximate calculations based on this theory are consistent with earlier experiments that have shown a sublinear dependence on total dose and with ELDRS experiments. Furthermore, this theory can be used to explain the dependence of ELDRS on the types of passivation layer used. However, further work is needed to determine if the theory can predict the dose-rate dependence in terms of measureable parameters that describe the passivation layers. Nevertheless, the theory can be used to define a worst-case test of the radiation hardness of microelectronic devices.

Additional work remains to be done. Our discovery experiments suggested that ELDRS may be caused by the mechanical stress due to the passivation layer or hydrogen introduced by the passivation layer. However, we were not able to perform experiments to determine which, if either, of these effects is the root cause of ELDRS. We were also unable to obtain the material parameter values necessary to do a quantitative simulation of the dose rate dependence. For this reason, we also were unable to perform time-dependent and electric-field dependent simulations of the phenomena.

At the end of the project, we discovered a new effect at low dose rates. At very low total dose, the interface trap density as a function of total dose undergoes a slight increase in its slope after a threshold total dose has been exceeded. This is a small effect that is not included in the simple model obtained in this project; however, it may be present in full numerical simulations in which the effects of electric fields are included.

Finally, the major successes of this project are three-fold. One, the experimental work led to a way to make devices that are not prone to ELDRS. Second, our theoretical work led to a successful model that explains the dose-rate dependence in terms of various bimolecular reactions. Third, the physics-based model indicates that, at low dose rates, the radiation effects are linear and can be represented by one parameter, the efficiency. The resultant low dose rate model has led to successful circuit simulations, and it provides an estimate of the worst-case effects of low dose rates.

4 Publications

The following papers received support from this project.

1. H. P. Hjalmarson, S. C. Witczak, P. A. Schultz, and D. J. Bowman, "A mechanism for enhanced low-dose-rate sensitivity of bipolar transistors," Sandia National Laboratories, Tech. Rep. SAND2000-0530, 2000.

2. M. R. Shaneyfelt, J. R. Schwank, S. C. Witczak, D. M. Fleetwood, R. L. Pease, P. S. Winokur, L. C. Riewe, and G. L. Hash, "Thermal-stress effects and enhanced low dose rate sensitivity in linear bipolar ICs," *IEEE Trans. Nucl. Sci.*, vol. 47, pp. 2539–2545, 2000.

3. M. R. Shaneyfelt, R. L. Pease, J. R. Schwank, M. C. Maher, G. L. Hash, D. M. Fleetwood, P. E. Dodd, C. A. Reber, S. C. Witczak, L. C. Riewe, H. P. Hjalmarson, J. C. Banks, B. L. Doyle, and J. A. Knapp, "Impact of passivation layers on enhanced low-dose-rate sensitivity and pre-irradiation elevated temperature stress effects in bipolar linear ICs," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 3171–3179, 2002.

4. S. C. Witczak, E. E. King, N. S. Saks, R. C. Lacoe, M. R. Shaneyfelt, G. L. Hash, H. P. Hjalmarson, and D. C. Mayer, "Geometric component of charge pumping current in nMOSFETs due to low-temperature irradiation," *IEEE Trans. Nucl. Sci.*, vol. 49, p. 2662, 2002.

5. A. H. Edwards, P. A. Schultz, and H. P. Hjalmarson, "A mechanism for spontaneous proton generation at the Si-SiO_2 interface," *Phys. Rev. B*, accepted.

6. M. R. Shaneyfelt, R. L. Pease, M. C. Maher, J. R. Schwank, S. Gupta, P. E. Dodd, and L. C. Riewe, "Passivation layers for reduced total dose effects and ELDRS in linear bipolar devices," *IEEE Trans. Nucl. Sci.*, 2003, accepted.

7. H. P. Hjalmarson, R. L. Please, S. C. Witczak, M. R. Shaneyfelt, J. R. Schwank, A. H. Edwards, C. E. Hembree, and T. R. Mattsson, "Mechanisms for radiation dose-rate sensitivity of bipolar transistors," *IEEE Trans. Nucl. Sci.*, 2003, accepted for publication.

References

[1] R. N. Nowlin, E. W. Enlow, R. D. Schrimpf, and W. E. Combs, "Trends in the total-dose response of modern bipolar transistors," *IEEE Trans. Nucl. Sci.*, vol. 39, pp. 2026–2035, 1992.

[2] S. McClure, R. L. Pease, W. Will, and G. Perry, "Dependence of total dose response of bipolar linear microcircuits on applied dose rate," *IEEE Trans. Nucl. Sci.*, vol. 41, p. 2544, 1994.

[3] R. L. Pease, L. M. Cohn, D. M. Fleetwood, M. A. Gehlhausen, T. L. Turflinger, D. M. Brown, and A. H. Johnston, "A proposed hardness assurance test methodology for bipolar linear circuits and devices in a space ionizing radiation environment," *IEEE Trans. Nucl. Sci.*, vol. 44, pp. 1981–1988, 1997.

[4] S. C. Witczak, R. D. Schrimpf, K. F. Galloway, D. M. Fleetwood, R. L. Pease, J. M. Puhl, D. M. Schmidt, W. E. Combs, and J. S. Suehle, "Accelerated tests for simulating low dose rate gain degradation of lateral and substrate PNP bipolar junction transistors," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 3151–3160, 1996.

[5] S. C. Witczak, R. D. Schrimpf, D. M. Fleetwood, K. F. Galloway, R. C. Lacoe, D. C. Mayer, J. M. Puhl, R. L. Pease, and J. S. Suehle, "Hardness assurance testing of bipolar junction transistors at elevated irradiation temperatures," *IEEE Trans. Nucl. Sci.*, vol. 44, pp. 1989–2000, 1997.

[6] R. L. Pease, M. Gehlhausen, J. Krieg, J. Titus, T. Turflinger, D. Emily, and L. Cohn, "Evaluation of proposed hardness assurance method for bipolar linear circuits with enhanced low dose rate sensitivity (eldrs)," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 2665–2672, 1998.

[7] H. P. Hjalmarson, P. A. Schultz, D. A. Bowman, and D. M. Fleetwood, "A unified computational approach to oxide aging processes," in *Multiscale Modelling of Materials*, T. D. de la Rubia, T. Kaxiras, V. Bulatov, N. Ghoniem, and R. Phillips, Eds., vol. 538. Warrendale, PA: Materials Research Society, 1999, pp. 257–262.

[8] H. P. Hjalmarson, S. C. Witczak, P. A. Schultz, and D. J. Bowman, "A mechanism for enhanced low-dose-rate sensitivity of bipolar transistors," Sandia National Laboratories, Tech. Rep. SAND2000-0530, 2000.

[9] M. R. Shaneyfelt, J. R. Schwank, S. C. Witczak, D. M. Fleetwood, R. L. Pease, P. S. Winokur, L. C. Riewe, and G. L. Hash, "Thermal-stress effects and enhanced low dose rate sensitivity in linear bipolar ICs," *IEEE Trans. Nucl. Sci.*, vol. 47, pp. 2539–2545, 2000.

[10] T. P. Ma and P. V. Dressendorfer, Eds., *Ionizing Radiation Effects in MOS Devices and Circuits*. New York, NY: John Wiley and Sons, 1989.

[11] H. L. Hughes, "Historical perspective," in *Ionizing Radiation Effects in MOS Devices and Circuits*, T. P. Ma and P. V. Dressendorfer, Eds. New York, NY: Wiley, 1989, pp. 47–86.

[12] P. M. Lenahan and P. V. Dressendorfer, "Hole traps and trivalent silicon centers in metal/oxide/silicon devices," *J. Appl. Phys.*, vol. 55, pp. 3495–3499, 1984.

[13] C. M. Svensson, "The defect structure of Si-SiO_2 interface: A model based on trivalent silicon and its hydrogen compounds," in *The Physics of SiO_2 and Its Interfaces*, S. T. Pantelides, Ed. Elmsford, NJ: Pergamon Press, 1979, pp. 328–332.

[14] N. S. Saks and D. B. Brown, "The role of hydrogen in interface trap creation by radiation in MOS devices – a review," in *The Physics and Chemistry of SiO_2, and the Si-SiO_2, Interface*, C. R. Helms and B. E. Deal, Eds. New York, NY: Plenum Press, 1993, pp. 455–463.

[15] F. B. McLean, "A framework for understanding radiation-induced interface states in SiO_2 MOS structures," *IEEE Trans. Nucl. Sci.*, vol. NS-27, pp. 1651–1657, 1980.

[16] P. S. Winokur, H. E. Boesch, Jr., J. M. McGarrity, and F. B. McLean, "Two-stage process for buildup of radiation-induced interface states," *J. Appl. Phys.*, vol. 50, pp. 3492–3494, 1979.

[17] E. W. Enlow, R. L. Pease, W. E. Combs, R. D. Schrimpf, and R. N. Nowlin, "Response of advanced bipolar processes to ionizing radiation," *IEEE Trans. Nucl. Sci.*, vol. NS-38, pp. 1342–1351, 1991.

[18] D. M. Fleetwood, S. L. Kosier, R. N. Nowlin, R. D. Schrimpf, J. R. A. Reber, M. DeLaus, P. S. Winokur, A. Wei, W. E. Combs, and R. L. Pease, "Physical mechanisms contributing to enhanced bipolar gain degradation at low dose rates," *IEEE Trans. Nucl. Sci.*, vol. 41, pp. 1871–1883, 1994.

[19] D. M. Fleetwood, L. C. Riewe, J. R. Schwank, S. C. Witczak, and R. D. Schrimpf, "Radiation effects at low electric fields in thermal, SIMOX, and bipolar-base oxides," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 2537–2546, 1996.

[20] R. K. Freitag and D. B. Brown, "Study of low-dose-rate radiation effects on commercial linear bipolar ICs," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 2649–2658, 1998.

[21] S. C. Witczak, R. C. Lacoe, D. C. Mayer, D. M. Fleetwood, R. D. Schrimpf, and K. F. Galloway, "Space charge limited degradation of bipolar oxides at low electric fields," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 2339–2351, 1998.

[22] R. J. Graves, C. R. Cirba, R. D. Schrimpf, R. J. Milanowski, A. Michez, D. M. Fleetwood, S. C. Witczak, and F. Saigne, "Modeling low-dose-rate effects in irradiated bipolar-base oxides," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 2352–2360, 1998.

[23] S. N. Rashkeev, C. R. Cirba, D. M. Fleetwood, R. D. Schrimpf, S. C. Witczak, A. Michez, and S. T. Pantelides, "Physical model for enhanced interface-trap formation at low dose rates," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 2650–2655, 2002.

[24] P. A. Schultz and P. J. Feibelman, unpublished; for a description of the method see: P. J. Feibelman, Phys. Rev. B, 35, pp. 2626–2646, 1987.

[25] A. H. Edwards, P. A. Schultz, and H. P. Hjalmarson, "A mechanism for spontaneous proton generation at the Si-SiO_2 interface," *Phys. Rev. B*, accepted.

[26] K. L. Brower, P. M. Lenahan, and P. V. Dressendorfer, "Defects and impurities in thermal oxides on silicon," *Appl. Phys. Lett.*, vol. 41, pp. 251–253, 1982.

[27] D. L. Griscom, "Diffusion of radiolytic hydrogen as a mechanism for the post-irradiation buildup of interface states in SiO_2-on-Si structures," *J. Appl. Phys.*, vol. 58, pp. 2524–2533, 1985.

[28] D. L. Griscom, D. B. Brown, and N. S. Saks, "Nature of radiation-induced point defects in amorphous SiO_2," in *The Physics and Chemistry of SiO_2 and the Si-SiO_2 Interface*, C. R. Helms and B. E. Deal, Eds. New York: Plenum Press, 1988, pp. 287–297.

[29] S. C. Witczak, E. E. King, N. S. Saks, R. C. Lacoe, M. R. Shaneyfelt, G. L. Hash, H. P. Hjalmarson, and D. C. Mayer, "Geometric component of charge pumping current in nMOSFETs due to low-temperature irradiation," *IEEE Trans. Nucl. Sci.*, vol. 49, p. 2662, 2002.

[30] M. R. Shaneyfelt, R. L. Pease, J. R. Schwank, M. C. Maher, G. L. Hash, D. M. Fleetwood, P. E. Dodd, C. A. Reber, S. C. Witczak, L. C. Riewe, H. P. Hjalmarson, J. C. Banks, B. L. Doyle, and J. A. Knapp, "Impact of passivation layers on enhanced low-dose-rate sensitivity and pre-irradiation elevated temperature stress effects in bipolar linear ICs," *IEEE Trans. Nucl. Sci.*, vol. 49, pp. 3171–3179, 2002.

[31] P. S. Winokur, "Radiation-induced interface traps," in *Ionizing Radiation Effects in MOS Devices and Circuits*, T. P. Ma and P. V. Dressendorfer, Eds. New York, NY: John Wiley and Sons, 1989, ch. 4, pp. 193–255.

[32] M. R. Shaneyfelt, R. L. Pease, M. C. Maher, J. R. Schwank, S. Gupta, P. E. Dodd, and L. C. Riewe, "Passivation layers for reduced total dose effects and ELDRS in linear bipolar devices," *IEEE Trans. Nucl. Sci.*, 2003, accepted.

[33] H. P. Hjalmarson, R. L. Please, S. C. Witczak, M. R. Shaneyfelt, J. R. Schwank, A. H. Edwards, C. E. Hembree, and T. R. Mattsson, "Mechanisms for radiation dose-rate

sensitivity of bipolar transistors," *IEEE Trans. Nucl. Sci.*, 2003, accepted for publication.

[34] C. H. Hembree, H. P. Hjalmarson, A. Nunez, M. Deveney, C. Bogdan, and D. Bowman, "Enhanced surveillance campaign: Experimental and simulation studies of enhanced low-dose-rate sensitivities of bipolar transistors," SNL, Tech. Rep., 2004, in preparation.

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