72

SAND 98-0709C
SAND-98-0789C
SPACE CHARGE LIMITED DEGRADATION OF BIPOLAR OXIDES
AT LOW ELECTRIC-FIELDS

RECEIVED

CONF-980705--MAR 25 1998

S. C. Witzcak¹, R. C. Lacoe¹, D. C. Mayer¹, D. M. Fleetwood², R. D. Schrimpf³ and K. F. Galloway³

OSTI

¹Electronics Technology Center, The Aerospace Corporation, Los Angeles, CA 90009-2957

²Department 1332, Sandia National Laboratories, Albuquerque, NM 87185-1083

³Department of Electrical and Computer Engineering, Vanderbilt University, Nashville, TN 37235

ABSTRACT

Concentrations of low-field hydrogen transport through irradiated bipolar oxides are estimated from dopant passivation measurements. Metastably trapped charge reduces oxide degradation at high dose rates by inhibiting the transport of hydrogen ions.

I. INTRODUCTION

Radiation-induced degradation of many types of bipolar transistors[1,2] and circuits[3] is more severe following low dose rate exposure than following high dose rate exposure. Since microelectronic devices in space are generally subjected to low dose rate irradiation, this complicates the hardness assurance testing of linear circuits and can lead to an overestimation of device lifetime in space. Previous work examining the physical mechanisms responsible for this dose rate effect has focused primarily on oxide trapped charge[4,5]. Reduced net positive oxide trapped charge densities at high dose rates and zero bias have been attributed to space charge effects from slowly transporting holes trapped metastably at O vacancy complexes[4,5]. Decreasing the dose rate or increasing the irradiation temperature leads to an increase in net positive oxide trapped charge near the Si-SiO₂ interface by reducing these space charge effects.

In this work, concentrations of hydrogen transport through two types of bipolar oxides are estimated from dopant passivation measurements in MOS capacitors. For unbiased irradiations, hydrogen passivation of substrate acceptors is greatly reduced at high dose rates compared to that at low dose rates or elevated temperatures. Consistent with other widely accepted models[6], it is argued that fewer interface traps are formed by high dose rate irradiation under zero bias, because fewer H⁺ ions can drift to the Si-SiO₂ interface and react with trap precursors. Similar to hole transport in these oxides, drift of the H⁺ ions is inhibited at high dose rates by space charge accumulated in the oxide bulk.

II. EXPERIMENT

A. DETAILS

Hydrogen transport through irradiated bipolar oxides was characterized via measurements of dopant passivation and/or compensation in the underlying Si as a function of dose rate and irradiation temperature. Hydrogen is known to neutralize many types of shallow acceptors (especially B) in Si primarily through two mechanisms[7,8]. In the case of acceptor passivation, atomic H⁰ can deactivate B by occupying a bond-centered position between a substitutional B site and a neighboring Si atom along a <111> axis[7]. In the case of acceptor compensation, H⁰ can donate an electron to the Si conduction band (becoming H⁺) and complex directly with a B⁻ ion through Coulombic interaction[8]. In either case, the result is a reduction in the net concentration of electrically active impurities and a decrease in the semiconductor capacitance.

Acceptor neutralization was observed in MOS capacitors from Analog Devices' RBCMOS and RF25 processes through high-frequency (1 MHz) C-V measurements. Capacitors and transistors from both of these processes were shown previously to be sensitive to dose rate[1,2,4,5]. Both capacitor types employ wet thermal oxides grown on B-doped Si substrates. The oxides were subjected to similar ion implant and high-temperature anneal steps known to create oxygen vacancies and vacancy complexes[9]. The RBCMOS capacitors have an oxide thickness of 55 nm and a pre-irradiation surface doping of $8 \times 10^{17} \text{ cm}^{-3}$. The oxide thickness and pre-irradiation surface doping of the RF25 capacitors are 570 nm and $2 \times 10^{16} \text{ cm}^{-3}$, respectively. All capacitors in this work were

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DTIC QUALITY INSPECTED 1

MASTER

19980529 071

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

irradiated under zero bias with ^{60}Co γ -rays. The C-V measurements were performed by sweeping the capacitors from inversion to accumulation at a ramp rate of 60 mV/s.

B. EFFECT OF DOSE RATE ON DOPANT PASSIVATION

A representative set of C-V curves for an RBCMOS capacitor irradiated to several total doses is shown in Fig. 1. The irradiation was performed at room temperature and a dose rate of 0.1 rad(Si)/s. Following irradiation, the C-V characteristics undergo a parallel shift due to net positive oxide trapped charge and a (small) stretchout due to interface traps. In addition, the capacitance measured in depletion and inversion decreases commensurately with dose. This decrease in capacitance is a direct indication of hydrogen passivation and/or compensation of acceptor impurities in the Si substrate[7,8].

In Fig. 2, C-V curves are shown for RBCMOS capacitors irradiated to 400 krad(Si) at dose rates of 0.1 and 294 rad(Si)/s. A pre-irradiation C-V curve is included for comparison. The radiation-induced decrease in capacitance is less dramatic at the high dose rate than at the low dose rate, implying decreased hydrogen transport into the Si substrate at the high rate. Furthermore, the decrease in capacitance occurs over a wide range of gate biases, indicating that hydrogen neutralization of acceptors occurs within the entire depletion region.

In Figs. 3(a) and 3(b), changes in minimum capacitances at room temperature are examined as a function of total dose for RBCMOS and RF25 capacitors irradiated at several dose rates. Corresponding changes in the net doping concentrations, computed from the ratios of minimum and oxide capacitances[10], are shown on the right ordinate axes. The net doping changes provide lower bounds on the amount of hydrogen transport, since it is assumed that not all of the hydrogen entering the Si passivates acceptors[7]. Each data point represents an average of data taken on several capacitors, where the capacitances are normalized by gate area to account for different capacitor sizes. For either capacitor type, the net concentration of electrically active dopants decreases monotonically with total dose. For a given dose, the net doping concentration changes less dramatically with increasing dose rate, indicating that the amount of hydrogen entering the Si substrate is reduced at the high dose rate.

C. EFFECT OF IRRADIATION TEMPERATURE ON DOPANT PASSIVATION

Representative C-V curves for RBCMOS capacitors irradiated at three temperatures between 25 and 100°C are shown in Fig. 4. Each of the capacitors received a total dose of 800 krad(Si) at a dose rate of 294 rad(Si)/s. A C-V curve for an unirradiated capacitor is included for comparison. The magnitude of the radiation-induced change in inversion capacitance increases markedly with temperature. This decrease in capacitance suggests that hydrogen transport through the base oxide is accelerated at elevated irradiation temperatures. Because the stability of B-H complexes in Si is temperature dependent[7], it is expected that some of the capacitance reduction at elevated temperatures results from an improved efficiency in the B neutralization process. A comparison of these data with results from thermal activation studies of hydrogenated B-doped Si[11] suggests that the majority of acceptor neutralization in these samples is due to increased hydrogen transport.

Fig. 5 shows changes in the minimum capacitance per unit area as a function of total dose, where irradiation temperature is a parameter. Similar to before, the corresponding changes in net doping concentration are shown on the right ordinate axis. At any irradiation temperature, the net concentration of electrically active dopants decreases monotonically with total dose. For any given dose, the reduction in net doping concentration grows more dramatic with increasing temperature due to accelerated hydrogen transport. Levels of hydrogen transport inferred from the passivated dopant concentrations at 100°C and the high dose rate are quantitatively similar to those ascertained at 0.1 rad(Si)/s and room temperature.

III. DISCUSSION

The strong dependence of hydrogen transport on dose rate and irradiation temperature in these oxides allows us to provide a more complete physical model for mechanisms contributing to dose rate dependent degradation. At low dose rates, the degradation of bipolar oxides essentially follows the usual models for irradiated MOS oxides[6] with the exception that charge transport is considera-

bly slower. Due to material work function differences, radiation-induced holes transport slowly through O vacancy complexes (such as E_g' centers) to the Si-SiO₂ interface[4,5], where a fraction of them are captured by deep traps and contribute to changes in the Si surface potential. H⁺ ions, coincidentally produced by the cracking of H₂ at broken bond hole traps[12], drift by similar retarded interactions to the Si-SiO₂ interface, where they eventually react with trap precursors to form interface traps. This mechanism for interface trap buildup is similar to one suggested elsewhere for latent interface traps in MOS devices having high O vacancy densities[13].

At high dose rates under zero bias, the accumulation of space charge in the oxide significantly alters the transport of both radiation-induced holes and H⁺ ions. As the space charge accumulates, it eventually dominates the localized electric-fields in the oxide and prevents a portion of newly created holes and/or H⁺ ions from ever reaching the Si-SiO₂ interface. As a consequence, radiation-induced densities of interface traps and positive oxide trapped charge are reduced. In addition, space charge in the oxide can increase the number of compensating electrons in the bulk, leading to a further reduction in Si surface potential[4,5]. At sufficiently elevated irradiation temperatures, significant amounts of space charge do not accumulate in the oxide bulk due to the accelerated transport of holes and H⁺ ions[5,14].

Trends in the transport of hydrogen observed in these oxides support the use of high dose rate irradiation at elevated temperatures to simulate low dose rate degradation of bipolar circuits and devices[1,2]. In addition, these results suggest that dopant passivation in the p-type emitters of pnp bipolar transistors may be an important mechanism for radiation-induced current gain degradation previously not considered.

ACKNOWLEDGMENTS

The authors are indebted to M. DeLaus and A. Martinez of Analog Devices, Inc. for furnishing the test devices. The authors acknowledge L. Cohn of the Defense Special Weapons Agency, R. L. Pease of RLP Research, Inc. and P. Winokur of Sandia National Laboratories for technical discussions of this work. Work performed at The Aerospace Corporation is supported by the U.S. Air Force Space and Missile Center under Contract No. F04701-93-C-0094. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94A85000.

REFERENCES

- [1] 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, *IEEE Trans. Nucl. Sci.*, 43, 3151, 1996.
- [2] 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, *IEEE Trans. Nucl. Sci.*, 44, 1989, 1997.
- [3] A. J. Johnston, C. I. Lee and B. G. Rax, *IEEE Trans. Nucl. Sci.*, 43, 3049, 1996.
- [4] D. M. Fleetwood, S. L. Kosier, R. N. Nowlin, R. D. Schrimpf, R. A. Reber, M. DeLaus, P. S. Winokur, A. Wei, W. E. Combs and R. L. Pease, *IEEE Trans. Nucl. Sci.*, 41, 1871, 1994.
- [5] D. M. Fleetwood, L. C. Riewe, J. R. Schwank, S. C. Witczak and R. D. Schrimpf, *IEEE Trans. Nucl. Sci.*, 43, 2537, 1996.
- [6] T. R. Oldham, F. B. McLean, H. E. Boesch, Jr. and J. M. McGarrity, *Semicond. Sci. & Technol.*, 4, 986, 1989.
- [7] C. P. Herrero, M. Stutzmann and A. Breitschwerdt, *Phys. Rev. B*, 43, 1555, 1991.
- [8] P. J. H. Denteneer, C. G. Van de Walle and S. T. Pantelides, *Phys. Rev. B*, 39, 10809, 1989.
- [9] P. M. Lenahan and P. Dressendorfer, *J. Appl. Phys.*, 55, 3495, 1984.
- [10] B. E. Deal, A. S. Snow and C. T. Sah, *J. Electrochem. Soc.*, 112, 308, 1965.
- [11] J. I. Pankove, *J. Appl. Phys.*, 68, 6532, 1990.
- [12] R. E. Stahlbush, A. H. Edwards, D. L. Griscom and B. J. Mrstik, *J. Appl. Phys.*, 73, 658, 1993.
- [13] D. M. Fleetwood, M. J. Johnson, T. L. Meisenheimer, P. S. Winokur, W. L. Warren and S. C. Witczak, *IEEE Trans. Nucl. Sci.*, 44, 1810, 1997.
- [14] M. R. Shaneyfelt, J. R. Schwank, D. M. Fleetwood and P. S. Winokur, *IEEE Trans. Nucl. Sci.*, 45, No. 3, 1998.

Fig. 1. Effect of total dose on the C-V characteristics of the RBCMOS capacitor.

Fig. 2. Effect of dose rate on the C-V characteristics of the RBCMOS capacitor.

Fig. 3(a). Effect of dose rate on the net doping concentration of the RBCMOS capacitor.

Fig. 3(b). Effect of dose rate on the net doping concentration of the RF25 capacitor.

Fig. 4. Effect of irradiation temperature on the C-V characteristics of the RBCMOS capacitor.

Fig. 5. Effect of irradiation temperature on the net doping concentration of the RBCMOS capacitor.

M98005033

Report Number (14) SAND -- 98 - 0709C

CONF - 980705 --

Publ. Date (11) 1998 03

Sponsor Code (18) DOE/MA ; ~~DOE~~ USAF, XF

LJC Category (19) UC-900 ; UC-000 , DOE/ER

DOE