Field Dependent Dopant Deactivation in Bipolar Devices at Elevated Irradiation Temperatures

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Abstract - Dopant deactivation at 100 °C is measured in bipolar Si-SiO₂ structures as a function of irradiation bias. The deactivation occurs most efficiently at small biases in depletion and is consistent with passivation and compensation mechanisms involving hydrogen.

I. INTRODUCTION

Some applications require that linear integrated circuits be exposed to ionizing radiation at elevated temperatures for extended periods of time. Military specifications for satellite and weapons systems, for example, often require that microelectronics operate reliably at temperatures as high as 125 °C. In addition, high-temperature irradiations have been used to infer degradation mechanisms and simulate low dose rate degradation of bipolar devices[1-4]. This work has resulted in standardized test guidelines, which recommend high dose rate irradiation at 100 °C for the hardness assurance testing of linear circuits[5]. It is known that ionizing radiation can neutralize shallow acceptors in the Si underlying bipolar base oxides[3] and that the neutralization mechanisms occur most efficiently near 100 °C[6]. Although hydrogen is believed to be involved, neither the neutralization mechanisms nor their consequences for device performance are well understood.

In this work, metal-oxide-silicon (MOS) capacitors simulating the base oxide regions of npn bipolar transistors are irradiated at 100 °C over a wide range of biases. Radiation-induced densities of deactivated substrate dopants, oxide trapped charge and interface traps are estimated from high-frequency capacitance-voltage (C-V) curves using a recently introduced charge separation technique[3,7]. The dopant neutralization is found to occur most efficiently at small irradiation biases in depletion corresponding to weak electric fields. The bias dependence is consistent with compensation and passivation mechanisms involving the drift of H⁺ ions in the oxide and Si layers and the availability of holes in the Si depletion region. The results suggest that dopant neutralization may impact hardness assurance test methods that prescribe elevated temperature irradiation. Consequences of the dopant neutralization for transistor gain degradation and sensitivity to oxide trapped charge are discussed.

II. EXPERIMENT

A. Details

The capacitors studied in this work were fabricated in a radiation-hardened bipolar complementary-metal-oxide-silicon process from Analog Devices. The capacitors employ a 55 nm wet thermal oxide and a B-doped Si substrate having a pre-irradiation surface doping concentration of 8 x 10¹⁷ cm⁻³. The dielectric in the capacitors was fabricated similarly to the screen oxide overlying the emitter-base junctions of bipolar transistors from the same process. Approximately 80 of the capacitors were irradiated with a ⁶⁰Co γ-source to 100 krad(SiO₂) over a wide range of gate biases. Consistent with recently implemented test guidelines for bipolar devices[5], all of the irradiations were performed at 10 rad(SiO₂)/s and 100 °C. Pre- and post-irradiation high-frequency (1 MHz) C-V measurements were performed at room temperature by sweeping the gate bias in both directions. The gate bias was ramped at 60 mV/s, which was sufficiently slow to avoid deep depletion. Trends in the C-V characteristics with irradiation bias were independent of the sweep direction. To minimize the dissociation of hydrogen-acceptor pairs by minority carriers, the irradiations and measurements were performed in the dark[8].

B. Charge Separation Technique

Normalized C-V characteristics corresponding to irradiation biases of -11, 0 and +11 V are shown in Fig. 1. The characteristics were obtained by sweeping the capacitors from accumulation to inversion. A pre-irradiation C-V curve is included for comparison. Flatband, midgap and inversion capacitances, computed as a function of the net doping concentration[9], are indicated in the figure for clarity. Follow-
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ing irradiation under any bias (but especially under positive bias), the C-V characteristics undergo a parallel shift due to 
oxide trapped charge and stretchout due to interface traps. In addition, the capacitance measured in depletion and inversion decreases measurably following the 0 V irradiation. This reduction in capacitance is a direct indication of the neutralization of substrate acceptors by hydrogen[3]. In contrast, there is a negligible decrease in the Si capacitance following irradiation under either the positive bias or the negative bias, implying that relatively little dopant neutralization has occurred.

Concentrations of deactivated substrate dopants and radiation-induced densities of net positive oxide trapped charge and interface traps were determined from the C-V characteristics using a recently developed charge separation technique[3,7]. This approach accounts for the neutralization of substrate dopants by hydrogen and is based on the well-known midgap charge separation technique for MOS transistors[10]. Assuming a uniform doping profile, the pre- and post-irradiation net doping concentrations were obtained by iteratively solving[11]

\[ \frac{C_{ox}}{C_{\text{min}}} = 1 + C_{ax} \left[ \epsilon_{Si} \epsilon_{0} q^{2} N_{B} \right]^{\frac{1}{2}} \left[ \ln \left( \frac{N_{B}}{n_{i}} \right) \right]^{\frac{1}{2}}, \]

where \( C_{ax} \) and \( C_{\text{min}} \) are the oxide and minimum capacitances per unit area, \( kT \) is the thermal energy, \( q \) is the electronic charge, \( \epsilon_{Si} \epsilon_{0} \) is the permittivity of Si, \( n_{i} \) is the intrinsic carrier concentration of Si, and \( N_{B} \) is the net concentration of electrically active dopants.

Assuming charge neutrality of the interface traps when the Fermi energy is at midgap[12], densities of radiation-induced oxide trapped charge and interface traps, respectively, were estimated from

\[ \Delta N_{ax} = \frac{C_{ax}}{q} \left[ \left( V_{mg} - V_{mg}^{0} \right)_{\text{post}} - \left( V_{mg} - V_{mg}^{0} \right)_{\text{pre}} \right], \]

and

\[ \Delta N_{it} = \frac{C_{ax}}{q} \left[ \left( V_{so} - V_{so}^{0} \right)_{\text{post}} - \left( V_{so} - V_{so}^{0} \right)_{\text{pre}} \right], \]

where \( V_{mg} \) is the midgap voltage, \( V_{so} = V_{\text{inv}} - V_{mg} \) is defined as the stretchout between the inversion and midgap voltages, the subscripts pre and post refer to the measurement time relative to radiation exposure, and the superscript 0 denotes an ideal value assuming the absence of oxide defects.

Theoretical values for the midgap and inversion voltages, respectively, were evaluated at \( V_{mg}^{0} = V_{G}^{0}(\phi_{s} = \phi_{f}) \) and \( V_{inv}^{0} = V_{G}^{0}(\phi_{s} = 2\phi_{f}) \), where[13]

\[ V_{G}^{0}(\phi_{s}) = \phi_{s} + \frac{1}{C_{ax}} \left( \frac{kT}{q} \ln \left( \frac{N_{B}}{n_{i}} \right) \right) \]

describes the ideal relationship between the gate bias, \( V_{G} \), and the surface potential, \( \phi_{s} \), and the Fermi potential is defined as

\[ \phi_{f} = \frac{kT}{q} \ln \left( \frac{N_{B}}{n_{i}} \right). \]

**C. Mechanisms for Dopant Neutralization**

Fig. 2 shows the concentration of acceptors neutralized near the Si surface as a function of irradiation bias. Vertical dashed lines define regions of bias corresponding to accumulation, depletion and inversion prior to irradiation. Each region exhibits a distinct behavior with respect to dopant neutralization. The neutralization is most significant for irradiation biases in depletion. Within this range, the dopant deactivation is a strong function of bias, peaking near 1 V. At peak efficiency, approximately 25% of the electrically active dopants near the Si surface are neutralized by radiation exposure. By comparison, the concentration of neutralized dopants is small for irradiation biases in accumulation and inversion and increases moderately with bias in inversion.

This bias dependence is consistent with compensation and mechanisms described in physically based models elsewhere[14,15]. Considerable evidence exists to suggest that the neutralization of Si acceptors by hydrogen occurs primarily through two mechanisms. In the case of acceptor passivation[14], \( \text{H}^{0} \) can deactivate \( \text{B}^{+} \) through the reaction

\[ \text{B}^{+} + \text{H}^{0} + \text{h}^{+} \rightarrow (\text{BH})^{0}, \]

where \( \text{h}^{+} \) represents a free hole. In the passivating state, the hydrogen atom occupies a bond-centered position along a <111> axis between a substitutional B site and a neighboring Si atom.

In the case of acceptor compensation[15], electron-hole pair recombination occurs when \( \text{H}^{0} \) donates an electron to the Si conduction band. The hydrogen and boron then bond ionically according to

\[ \text{B}^{+} + \text{H}^{0} + \text{e}^{-} + \text{h}^{+} \rightarrow (\text{BH})^{0}, \]

where \( \text{e}^{-} \) represents a free electron. In (6), the presence of a hole is required, whereas, in (7), the Coulombic attraction of ions can occur in a region free of carriers. For either mechanism, the result is a reduction in the net concentration of
electrically active dopants and a decrease in the semiconductor capacitance.

The bias dependence can be explained in terms of H⁺ drift in the oxide and Si layers and the concentration of holes available in the Si depletion region. The H⁺ ions required for compensation originate in the oxide from well-known mechanisms involving hole transport[16] or trapping[17]. Compensation of the substrate dopants is minimal for negative irradiation biases, because relatively few of these H⁺ ions are able to transport to the Si depletion region. Under small positive biases, increased drift of the H⁺ ions drives (7) forward. Since some of the H0 atoms required for acceptor passivation result from reactions involving H⁺ near the Si-SiO₂ interface, (6) is similarly affected by bias. These reactions include the neutralization of H⁺ ions by substrate electrons[18] and the dissociation of H₂ molecules[19] residual to the formation of interface traps. Above sufficiently positive biases (≥ 1 V in these capacitors), the rate of (6) decreases with bias as the Si surface becomes depleted of holes. The reduction in acceptor neutralization in this regime may also imply that an increasing number of H⁺ ions drift out of the depletion region before they are able to react with substrate dopants. In addition, acceptor passivation may be reduced at large biases (of either sign) due to a reduction in the formation of excitons necessary to liberate H0 atoms from OH groups in the oxide[20].

The hydrogen transport arguments related to acceptor deactivation are reflected in the densities of radiation-induced oxide trapped charge and interface traps plotted in Figs. 3(a) and 3(b). The densities represent averages obtained from capacitance sweeps in both directions. The bias dependencies of ANo and ANδ are consistent with well-known hydrogen[16] and trapped hole[21] models for radiation-induced interface trap formation, where a moderately positive E-field aids the transport of H⁺ ions and holes to the Si-SiO₂ interface. Above ~ 11 V, ANo and ANg decrease with bias due to a reduction in capture cross-sections for hole traps near the Si-SiO₂ interface[22]. This reduction in the buildup of oxide defects coincides with a moderate increase in the neutralized acceptor concentration over the same range of biases. The correlation of the two suggests that the increase in acceptor passivation at large positive biases is due to an increased number of H⁺ ions and holes reaching the Si depletion region.

A closer examination of radiation-induced damage at peak efficiency in the dopant deactivation provides additional insight into the involvement of hydrogen. A 100 krad(SiO₂) exposure creates ~ 4.4 x 10¹² ehp / cm² in the 55 nm base oxide[23]. Under the field corresponding to a 1 V irradiation bias, ~ 25 % of these electron hole pairs survive recombination[24], leaving ~ 1.1 x 10¹² ehp / cm² to do damage via transport and trapping events. Since the maximum Si depletion width following 1 V irradiation is ~ 45 nm, (1.9 x 10¹⁷ cm⁻²)(450 x 10⁻⁸ cm) = 8.5 x 10¹¹ Si acceptors / cm² are neutralized at this bias. Assuming every surviving hole releases one hydrogen atom in the oxide, it follows that 8.5 x 10¹¹ cm² / 1.1 x 10¹² cm² = 75 % of the hydrogen contributes to the neutralization of dopants. Similarly, 4.0 x 10¹⁰ cm⁻² / 1.1 x 10¹² cm² = 35 % of the hydrogen contributes to interface trap formation. These quantities imply that the dopant neutralization is effectuated by hydrogen that generates interface traps as well as hydrogen that does not.

III. IMPLICATIONS FOR GAIN DEGRADATION

The radiation response of these capacitors suggests that dopant neutralization may be critical for linear circuits operated at elevated temperatures and impact hardness assurance techniques that prescribe high-temperature testing[5]. The potential for dopant neutralization is heightened by the fact that E-fields in many bipolar base oxides are weak. The consequences of dopant neutralization for gain degradation
would depend on the device geometry and polarity considered[3]. In a npn device, acceptor neutralization would exacerbate radiation-induced gain degradation by increasing the back-injection of electrons into the emitter and enhancing the emitter sensitivity to oxide trapped charge. As acceptors are neutralized, recombination in the emitter would increase due to spreading of the depletion region. In an npn device, the deactivation of base acceptors would similarly enhance gain degradation through depletion region spreading and increased series resistance in the base. Such enhancement, however, would be moderated by increased electron injection into the base. The full paper will provide a detailed discussion of the implications of dopant neutralization for bipolar gain degradation supported by numerical simulations.

IV. SUMMARY

This work provides insight into physical mechanisms contributing to radiation-induced dopant neutralization in bipolar devices. Consistent with recently implemented guidelines for the hardness assurance testing of linear circuits[5], Si-SiO₂ structures fabricated in a bipolar process were irradiated at 10 rad(SiO₂)/s and 100 °C as a function of bias. Densities of deactivated dopants, oxide trapped charge and interface traps induced by the radiation were estimated from high-frequency C-V curves using a recently introduced charge separation technique[3,7]. The dopant neutralization occurs most efficiently at small irradiation biases in depletion corresponding to weak electric fields. The bias dependence is consistent with compensation and passivation mechanisms involving the drift of H⁺ ions in the oxide and Si layers and the availability of holes in the Si depletion region. Since the neutralization of Si dopants by hydrogen occurs most efficiently near 100 °C[6], and electric fields in bipolar base oxides are generally weak, dopant neutralization may impact hardness assurance test guidelines. Consequences of the dopant neutralization include a direct reduction in transistor gain and increased device sensitivity to oxide trapped charge.

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