Observation of latent reliability degradation in ultrathin oxides after heavy-ion irradiation

John S. Suehle,[a] Eric M. Vogel, and Peter Roitman
Semiconductor Electronics Division, National Institute of Standards and Technology, Gaithersburg, Maryland 20899

John F. Conley, Jr.[b] and Allan H. Johnston
NASA Jet Propulsion Laboratories, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109

Bin Wang and Joseph B. Bernstein
Center for Reliability Engineering, University of Maryland, College Park, Maryland 20742

C. E. Weintraub
Department of Electrical Engineering, North Carolina State University, Raleigh, North Carolina 27695

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Constant voltage time-dependent-dielectric-breakdown distributions were obtained for both unirradiated and irradiated 3.0 and 3.2 nm thick SiO_2 films subjected to ^{60}Co gamma irradiation and heavy ions of 823 MeV ^{129}Xe (linear energy transfer = 59 MeV-cm^2/mg). The gamma irradiation had no effect on oxide lifetime. The heavy ion irradiation substantially reduced oxide life even though the devices were biased at 0.0 V during irradiation. The reduction of oxide lifetime under constant-voltage stress conditions was a strong function of the heavy ion fluence. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1448859]

The effects of ionizing radiation on ultrathin oxides (t_{ox} < 4 nm) is becoming a concern, particularly due to the recent observations of radiation-induced leakage current (RILC) and radiation-induced soft breakdown (RSB) in oxides after gamma and heavy ion irradiation.[1–11] RILC has been observed for heavy ions, x-rays, and electrons with relatively low linear energy transfers (LETs) between 10 and 40 MeV-cm^2-mg^{-1}. RILC has been modeled as inelastic trap-assisted-tunneling due to neutral oxide defects and was found to be very similar to stress-induced-leakage current (SILC) observed after constant voltage stress.[5–7] RSB, however, has only been observed for higher LET ions and is characterized by higher leakage currents and gate current noise.[2–4,8–11] In this case, the leakage path is believed to be due to a permanent conductive filament as a result of a breakdown event[10] and has recently been modeled as a quantum point contact.[11]

Despite the large number of studies detailing the immediate effects of ionizing radiation on thin oxides, there are few results on any degradation of the long-term reliability of ultrathin oxides due to latent defects. Earlier work did not show any latent reliability effects as a result of precursor ion damage.[3] Gamma irradiated samples also did not show a decrease of time to breakdown, although a slight increase in the breakdown time was noted after a low-temperature anneal.[12] In one study, an increase in the number of extrinsic failures (early failures) of the thin oxide lifetime distribution was observed,[13] however, the intrinsic lifetime was not changed after gamma, electron, and neutron irradiation. In this work, constant voltage breakdown distributions were obtained for both unirradiated and irradiated 3.0 nm thick SiO_2 films subjected to 823 MeV ^{129}Xe (LET = 59 MeV-cm^2/mg) heavy ion irradiation. The results indicate that the heavy ion irradiation substantially reduced intrinsic oxide life. The reduction of lifetime under constant-voltage stress conditions was a strong function of the heavy ion fluence.

Two different sets of *p*-substrate test capacitors were used in this study. The first set was supplied by a commercial facility and had a thermally grown oxide thickness of 3.2 nm and a device area of 1×10^{-3} cm^2. The second set was fabricated using conventional field oxide isolation on *p*-type silicon substrates. The devices from the second set had an oxide thickness of 3.0 nm and areas of 10^{-4} and 4×10^{-4} cm^2. Both sets were fabricated with polysilicon gate electrodes and interconnected to probe pads with aluminum metallization. The devices from each set had equivalent intrinsic reliability as exhibited by similar charge-to-breakdown (Q_{bd}) versus gate voltage characteristics. The oxide thickness was determined by high frequency capacitance vs voltage curves with quantum simulation of substrate quantization and poly depletion effects included.[14]

The 3.2 nm thick samples were subjected to gamma irradiation using the National Institute of Standards Technology (NIST) gamma cell source that provided a dose rate of approximately 6.5 kGy/h. Gamma irradiation was concluded after a total dose of 300 kGy (Si). The 3.0 nm thick samples were subjected to heavy ion irradiation at the Texas A&M University Cyclotron using 823 MeV ^{129}Xe (LET = 59 MeV-cm^2/mg) with a total fluence up to 1×10^8 ions/cm^2. Exposures were conducted at normal incidence with the capacitor gates tied to ground (V_g = 0.0 V). Constant voltage

[a]Electronic mail: john.suehle@nist.gov
[b]Presently with: Sharp Laboratories of America, 5700 NW Pacific Rim Blvd., Camas, WA 98607.

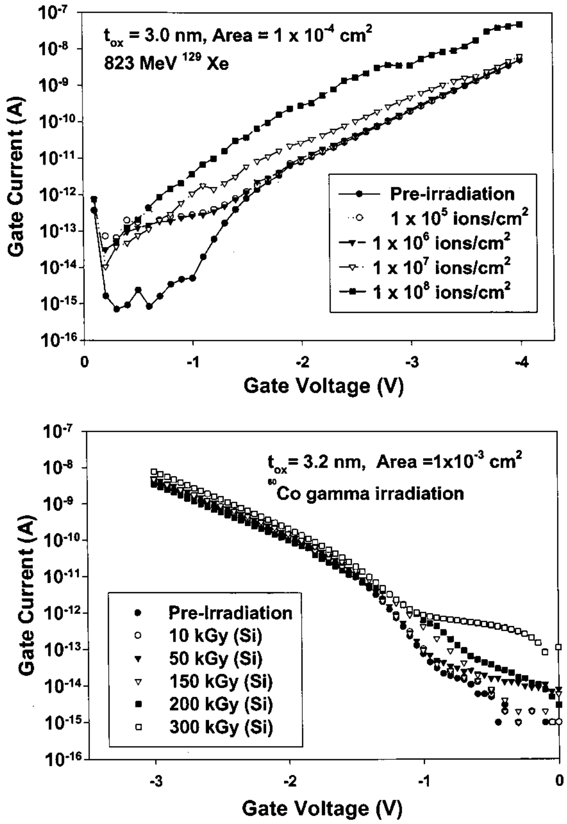

FIG. 1. (Top plot) Current versus voltage characteristics of 3.0 nm thick SiO_2 test capacitors measured before and after heavy ion irradiation. The characteristics are shown for a fluence of 1×10^5 ions/cm^2, 1×10^6 ions/cm^2, 1×10^7 ions/cm^2, and 1×10^8 ions/cm^2. Characteristics shown for the fluence of 1×10^7 ions/cm^2 and 1×10^8 ions/cm^2 indicate the device has experienced soft breakdown. (Bottom plot) Current versus voltage characteristics of 3.2 nm thick SiO_2 test capacitors measured before and after ^{60}Co gamma irradiation. The oxide conduction increases as a function of total dose.

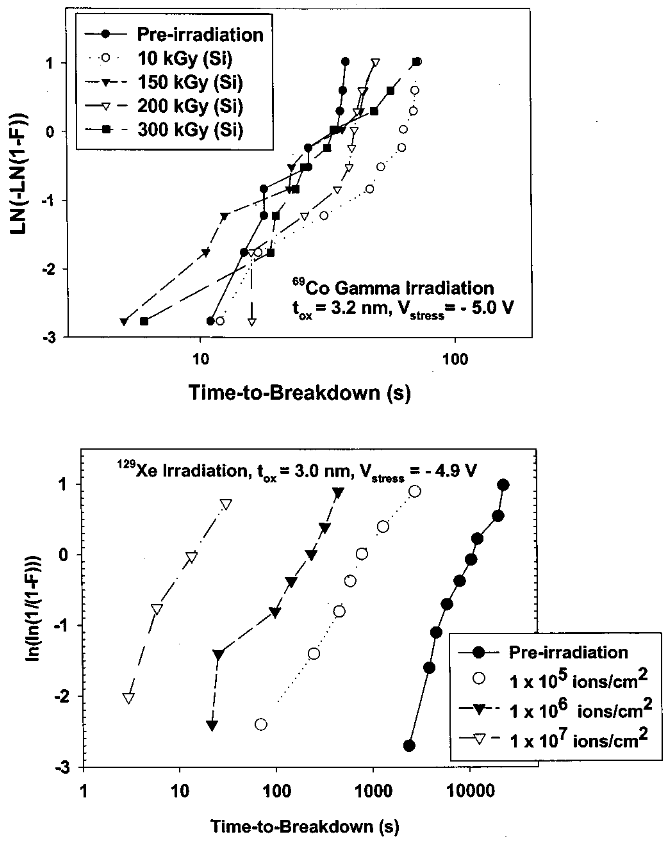

FIG. 2. (Top plot) Weibull lifetime distributions of test capacitors subjected to constant voltage TDDB tests ($V_{stress} = -5.0$ V) following gamma irradiation. Note that there is no statistical differences in the lifetime distributions following a total dose of 300 kGy (Si). (Bottom plot) Weibull lifetime distributions of test capacitors subjected to constant voltage TDDB tests following heavy ion irradiation. The plot shows distributions obtained for a stress condition of -4.9 V and a device area of 1×10^{-4} cm^2. Oxide life is significantly reduced as the heavy ion fluence is increased.

time-dependent dielectric breakdown (TDDB) tests were performed at a gate voltage of -4.9 and -5.0 V. The initial breakdown event, either hard or soft, was defined as the end of oxide life. The failure distributions of devices subjected to heavy ion exposure and gamma irradiation were then compared to un-irradiated devices.

Figure 1 shows typical postirradiation current–voltage (I_g-V_g) characteristics for the devices subject to 823 MeV ^{129}Xe ions (top plot) and gamma irradiation (bottom plot) as a function of dose. There was a 0.0 V bias applied during the irradiation. The oxide conduction increased following the irradiation as observed in previous studies.[2,3,9,10,11] In some cases, especially after higher heavy ion fluences, some of the devices experienced soft breakdown.[3,9,10,11] An example of post soft breakdown conduction is shown in the top plot for the 1×10^7 and 1×10^8 ions/cm^2 fluence. Post soft breakdown gate leakage current usually increased by over an order of magnitude at gate voltages greater than -2.0 V and exhibited noisy or random fluctuations. Oxide conduction after gamma irradiation also increased as a function of total dose. Note that the change of the leakage current after a total dose of 300 kGy gamma irradiation was similar to that observed for the heavy ion irradiation at a fluence of 1×10^6 ions/cm^2 (approximately two orders of magnitude increase at $V_g = -0.5$ V). Soft breakdown was not observed in devices subjected to gamma irradiation. Only devices that did not experience soft breakdown were subjected to subsequent TDDB testing.

The top plot of Fig. 2 shows Weibull failure distributions as a function of total dose for the devices subjected to a constant voltage stress of -5.0 V following gamma irradiation. Note that there is no statistical shift in the failure time even after a total dose of 300 kGy (Si). The bottom plot of Fig. 2 shows Weibull failure distributions for devices subjected to a -4.9 V constant voltage stress following heavy ion irradiation doses of 1×10^5 ions/cm^2, 1×10^6 ions/cm^2, and 1×10^7 ions/cm^2. Most of the devices that received a dose of 1×10^8 ions/cm^2 experienced soft breakdown, and there were not enough devices to test for statistically significant results. Figure 2 shows that for a fluence of 1×10^5 ions/cm^2, the intrinsic TDDB life decreased by over an order of magnitude. This fluence corresponds to about approximately 10 ion "hits" for the 10^{-4} cm^2 test capacitors and an equivalent gamma total dose of only about 1 Gy. The intrinsic TDDB life dramatically decreases as the fluence is increased. The experiment was repeated (not shown) for different size capacitors (4×10^{-4} cm^2) and for a different stress voltage (-4.7 V), and a similar reduction in oxide life was observed.

The level of RILC ($V_g = -0.5$ V) induced after 300 kGy of gamma irradition and after a fluence of 1×10^6 ^{129}Xe ions/cm^2 was observed to be similar. It is interesting that the intrinsic reliability degradation effect observed for heavy ion irradiation was not observed for devices subjected to ^{60}Co gamma irradiation, even after a total dose of 300 kGy (Si). Earlier work[7] and thermal annealing experiments[14] have indicated that neutral electron traps similar to those that are responsible for SILC under constant voltage stress are most likely responsible for the increase in oxide conduction following ionizing radiation. We assume that the density of these traps are similar in the both the gamma and heavy ion irradiated samples since the postirradiation leakage currents are similar in magnitude. However, oxide lifetime is significantly reduced in the heavy ion irradiated samples indicating that an additional wear-out defect generation mechanism is operative. One possible explanation is that the damage tracks produced by heavy ion strikes may produce weaker areas in the oxide film where defect generation is enhanced during constant voltage stress. The eventual early breakdowns would occur in these weakened areas. The energy loss per angstrom is much greater for heavy ions than for ^{60}Co, resulting in the production of highly energetic electrons and holes. Because of these much higher energy electrons, the same physical mechanisms responsible for wear-out under constant voltage stress may be operative under heavy ion bombardment but not in gamma irradiation.

In this letter, it was shown that in addition to radiation-induced leakage current and radiation–induced soft breakdown, heavy ion irradiation can significantly degrade the intrinsic reliability of ultrathin gate oxides. The lifetime degradation was observed for devices with zero gate voltage applied, suggesting that even powered down circuits may be at risk for long-term missions in ionizing radiation environments.

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