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Total-Dose Degradation of Thin Film Ferroelectric Capacitors[1]

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Abstract

The effects of total-dose ionizing irradiation on $PbO-ZrO_2-TiO_2$ ferroelectric capacitors have been studied in detail. It is shown that significant total-dose degradation of ferroelectrics can occur at dose levels greater than 1 Mrad(Si).

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Summary

Applications exist for circumvention, erasable/programmable, and other nonvolatile memories that can operate at high speeds in severe radiation environments. Ferroelectric memories can function at high speeds and, on the basis of preliminary work, have been claimed to exhibit high tolerance to total-dose radiation, transient upset, neutrons, and single event upset [1]. However, the application of thin film ferroelectrics to nonvolatile memories is relatively new. Little is known about the properties and mechanisms governing retention, aging, and radiation hardness of thin film ferroelectric devices. Previous studies of the radiation hardness of ferroelectrics resulted in mixed conclusions. Wrobel et al. [2] showed that devices cycled during irradiation exhibited little or no degradation to dose levels up to 10 Mrad(Si). On the other hand, work by Scott et al. [3] showed that, for other bias conditions and processes, ferroelectric devices can fail to retain charge at much lower total-dose levels.

In this work we explore in detail the total-dose radiation hardness of $PbO-ZrO_2-TiO_2$ (PZT) ferroelectric capacitors. The devices used in this study were obtained from two different suppliers (noted here as A and B). Capacitors were irradiated and annealed postirradiation with varying bias conditions to determine the effects of bias and the mechanisms governing radiation-induced degradation of ferroelectric capacitors. Two key parameters measured were the remanent polarization, P_r, and the retention polarization (the polarization remaining after irradiation or due to time alone), R. P_r is a parameter characterizing the intrinsic switching properties of a ferroelectric, i. e. the polarization available in switching from positive to negative bias. R is a practical circuit parameter that gives the amount of stored polarization charge after irradiation that can be sensed in a memory during reading. The results show that, under some bias conditions, substantial radiation-induced degradation of ferroelectrics can occur at dose levels greater than 1 Mrad(Si). Possible mechanisms for the observed results are discussed.

One method used in this study to characterize P_r and R was a pulsed voltage technique. This technique consisted of two + 5 V pulses followed by two - 5 V pulses. A typical measured waveform for the pulsed voltage test is shown in Figure 1. This curve was taken with the ferroelectric capacitor polarized prior to measurement with a - 5 V pulse. To measure the loss of polarization during irradiation (the decrease in R), the pulsed voltage test was always the first measurement taken after irradiation. Note that R is not necessarily equal to $2P_r$. In general, R normalized to its preirradiation value decreased faster during irradiation than P_r normalized to its preirradiation value. Besides the pulsed voltage measurements, standard hysteresis curves were also taken at frequencies from 1 kHz to 300 kHz. A typical hysteresis curve is shown in Figure 2. The curve was taken during cycling using a programmable waveform generator and digitizer. The ferroelectric signal was measured across a 10 nF integrating capacitor. Parameters routinely extracted from the hysteresis curves were P_r, the saturation polarization, P_s, and coercive field, E_c. The highest frequency used for these tests was 300 kHz. At higher frequencies the ferroelectric capacitor (100 μm x 100 μm) caused significant loading of the applied signal, preventing the use of frequencies greater than 300 kHz. In general, the variation in P_r during irradiation measured using the hysteresis curves was in qualitative agreement with the variation in P_r measured using the pulsed voltage technique. The radiation sources used in this work were a 1.1 MeV Co-60 gamma cell at a dose rate of 225 rad(Si)/s and a 10 keV x-ray source at a dose rate of 3300 rad(Si)/s. For simplicity and for comparison to previous data, the dose is shown here in units of rad(Si). The correlation between rad(Si) and the dose of interest, rad(PZT), will be discussed in the full text. For all tests, control devices were measured in parallel using the same bias and polarization conditions as the irradiated devices to determine the degradation in performance due to time and/or cycling alone.

Figure 3 shows the radiation-induced degradation in R, normalized to its preirradiation value, for ferroelectric capacitors obtained from supplier A. The devices were irradiated using both the Co-60 and x-ray sources with the electrodes shorted. The devices were polarized prior to irradiation with a - 5 V pulse. These two radiation sources were used to determine the difference in radiation-induced degradation between low- and high-energy radiation sources. Note that

within part-to-part variation the same degradation is observed for the Co-60 and x-ray irradiations. This is likely coincidental. One expects [4] more dose enhancement due to the platinum electrodes of the ferroelectric capacitors for the low-energy x-ray irradiations. On the other hand, at low electric fields, one expects [5] a higher charge yield for the Co-60 irradiations. The same degradation for the 10 keV x-ray and 1.1 MeV Co-60 sources suggests that the radiation-induced degradation is not due to displacement effects, which should be minimal for the low-energy x-ray irradiations. The longest time associated with the irradiations (the 14 Mrad(Si) Co-60 data point) is ~ $6x10^4$ s. At $6x10^4$ s, the reduction in R for nonirradiated control devices with the electrodes shorted for the same time duration was 10 to 15 %. Thus, most of the degradation is due to radiation. The large degradation in R, approximately 55 % at 3 Mrad(Si), is substantially more radiation-induced degradation than observed by Wrobel et al. [2].

The effects of a postirradiation biased anneal on the radiation-induced degradation is shown in Figure 4 for ferroelectric capacitors obtained from supplier A. Figure 4 is a plot of R normalized to its preirradiation value versus dose. The capacitors were irradiated with the Co-60 source with the electrodes shorted. Immediately after irradiation some devices were stressed for 1000 s with a 10 V DC bias and other devices were stressed with 10^8 cycles with a 10 V sine wave at a frequency of 30 kHz. Note that for the DC postirradiation bias, R recovered to 85 % of its preirradiation value. The recovered value is close to the degradation in R due to time alone (for nonirradiated devices). Thus, almost 100 % of the radiation-induced degradation has annealed. For the AC bias postirradiation, R recovered to 60 % of its preirradiation value. The AC cycling was stopped at 10^8 cycles. Additional cycles began to cause nonradiation-induced cycling damage. As will be discussed below, irradiation also does not appear to affect the cycling damage.

The partial recovery of R postirradiation by cycling suggests that cycling during irradiation may result in less degradation in R (or P_r). This is shown in Figure 5. Figure 5 shows P_r versus time for nonirradiated cycled control devices and for devices cycled during irradiation. The devices were cycled to 10^8 cycles with a 20 Vp-p sine wave at a frequency of 33 kHz. The devices were irradiated at 3300 rad(Si)/s with the x-ray source. Note that the cycling was stopped when the irradiation was completed. Within part-to-part variation, no difference is observed between the nonirradiated control devices and the devices cycled during irradiation. Thus, by cycling the devices during irradiation, no radiation-induced degradation in P_r is observed. This is consistent with the observations of Wrobel et al. [2]. Summarizing the results of Figures 3 to 5, we note that the bias during irradiation can significantly affect the radiation-induced degradation of ferroelectric capacitors.

A computer program has been developed [6] to model the hysteresis curves for varying charge trapping and leakage configurations. The results of Figures 3 to 5 are consistent with charge trapping in the ferroelectric material. The model can be used to determine the effects of different charge distributions on the hysteresis curves. The results of the modelling and their implications on the mechanisms for the radiation-induced degradation will be discussed at the conference. It is interesting to note that ferroelectric capacitors obtained from supplier B showed no radiation-induced degradation at dose levels up to 14 Mrad(Si). However, during even a short biased anneal, the leakage current through the oxide increased dramatically (> 10 μA at 10 V). The leakage path through the ferroelectric may have provided a path for the radiation-generated charge to dissipate, thereby limiting the radiation-induced degradation.

Devices have also been irradiated with a - 5 V bias and open circuited. The devices irradiated open circuited resulted in approximately the same degradation as the devices irradiated short circuited. However, the devices irradiated with a - 5 V bias resulted in less degradation. This is different than the results of Scott et al. [2]. Scott concluded that devices shorted during irradiation resulted in more degradation than both devices irradiated open circuited or with a -5 V applied bias. The difference between this work and that of Scott's may be due to different process conditions. Also, Scott's conclusions were based on pass/fail tests at a single dose level. One must use a large sample size in a pass/fail test, as performed by Scott, to obtain a high confidence level. It is possible that the failures observed by Scott were due to part-to-part variation, and not due to bias. By measuring the parametric degradation as a function of dose, one can more straightforwardly determine the effects of bias on radiation hardness.

In summary, the effects of total-dose ionizing radiation on ferroelectric capacitors have been studied in detail. It has been shown that, for some process conditions, significant radiation-induced degradation can occur in ferroelectric capacitors at dose levels greater than 1 Mrad(Si). It is likely that the degradation is due to radiation-induced trapped charge. This charge can easily be dissipated after irradiation by applying a positive bias, or prevented during irradiation by irradiating with an AC bias (if compatible with actual use). We have presented in the summary a sample of the results obtained. The details of the work and a discussion of the possible mechanisms for the radiation-induced degradation will be presented at the conference. The effects of changing dose rate will also be discussed.

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References

1. G. C. Messenger and F. N. Coppage, "Ferroelectric Memories: A Possible Answer to the Hardened Nonvolatile Question," IEEE Trans. Nuc. Sci., NS-35, 1461 (1988).
2. T. F. Wrobel, J. A. Bullington, and L. J. Schwee, "Radiation Hardness Evaluation of Thin Film Ferroelectric Capacitors," GOMAC Digest of Papers, 13, 267 (1987).
3. J. F. Scott, C. A. Araujo, H. B. Meadows, L. D. McMillan, and A. Shawabkeh, "Radiation Effects on Ferroelectric Thin-Film Memories: Retention Failure Mechanisms," J. Appl. Phys., 66, 1444 (1989).
4. D. M. Long, D. G. Willard, and J. Wallace, "Dose Enhancement Effects in Semiconductor Devices," IEEE Trans. Nuc. Sci., NS-29, 1980 (1982).
5. T. R. Oldham and J. M. McGarrity, "Comparison of ^{60}Co Response and 10 keV X-Ray Response in MOS Capacitors, IEEE Trans. Nuc. Sci., NS-30, 4377 (1983).
6. S. L. Miller and J. R. Schwank, "Device Modelling of Ferroelectric Capacitors," (to be published).

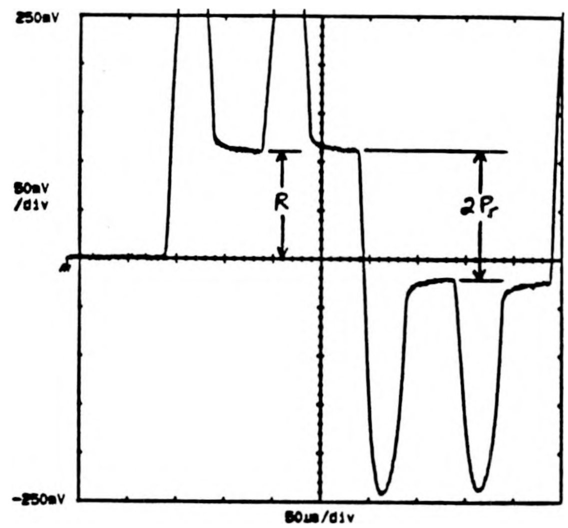

Figure 1: Measured pulsed voltage waveform. Noted in the figure are the points corresponding to R and P_r.

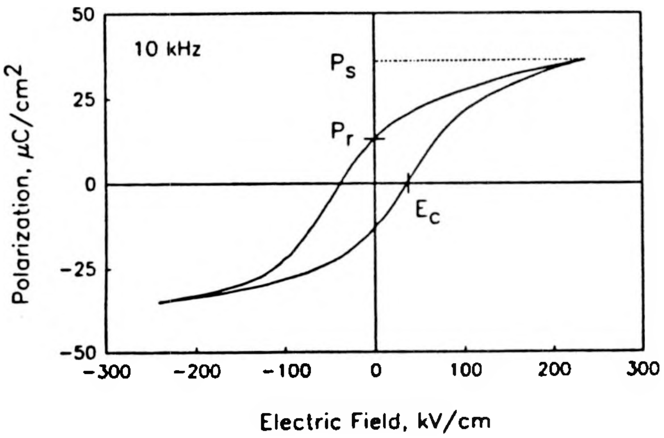

Figure 2: Hysteresis curve for a ferroelectric capacitor. Noted in the curve are the points corresponding to P_r, P_s, and E_c.

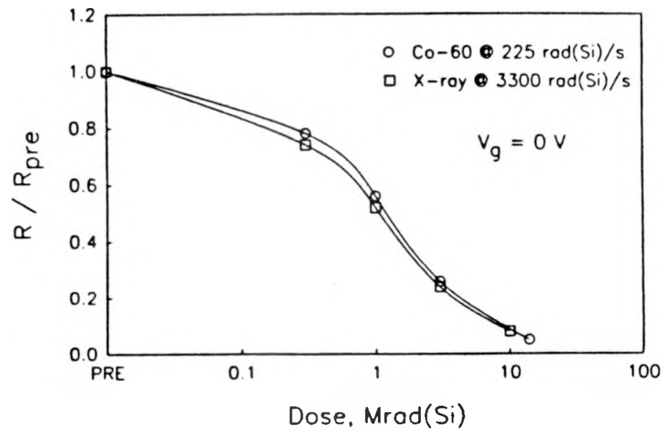

Figure 3: Radiation-induced degradation in the normalized value of R for capacitors irradiated with a Co-60 and x-ray source with the electrodes shorted.

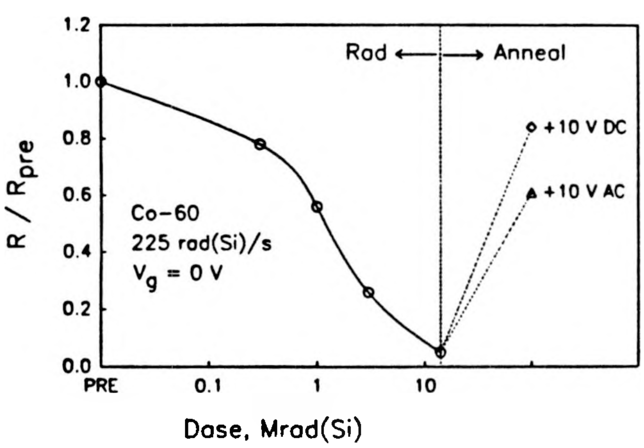

Figure 4: The effect of a postirradiation biased anneal on the normalized value of R. The capacitors were irradiated with a Co-60 source and annealed using either a 10 V DC bias or with a 10 V 30 kHz sine wave.

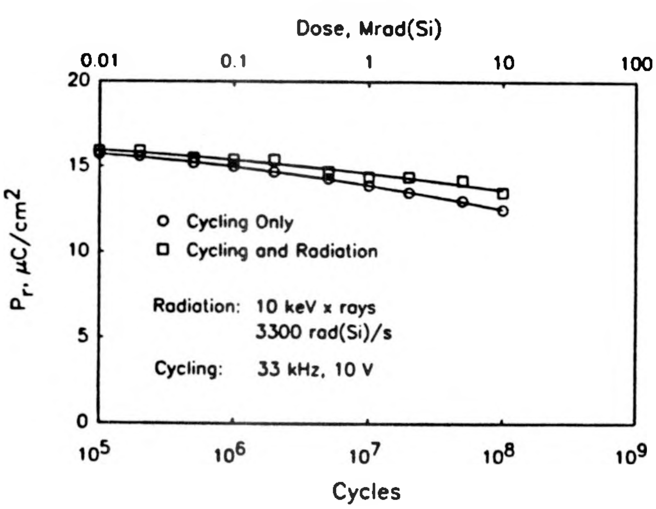

Figure 5: The effect of cycling during irradiation on P_r. Shown in the figure is P_r for nonirradiated and irradiated cycled devices. The capacitors were irradiated with a x-ray source and cycled with a 10 V 33 kHz sine wave.