2

CONF-871032

RADIATION HARDNESS EVALUATION OF THIN FILM FERROELECTRIC CAPACITORS

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ABSTRACT

Ferroelectric capacitor structures have been evaluated in total dose, dose-rate and cosmic ray environments. The capacitors were found to maintain polarization following an exposure of ~5 Mrad(Si), ~1 x 10^{11} rad(Si)/s and ~6 x 10^{6} Cf-252 fission fragments per cm^2. The capacitors show minimal degradation in the P versus E hysteresis curve following ~10 Mrad(Si), ~1 x 10^{11} rad(Si)/s and ~6 x 10^{6} Cf-252 fission fragments per cm^2. In addition, no heavy ion induced hard errors were observed for capacitor bias levels below the intrinsic breakdown voltage of 20 V.

SAND--87-2501C

INTRODUCTION

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A non-volatile semiconductor memory alternative (recently developed by Krysalis Microelectronics Corp.) merges thin film ferroelectric (FE) storage capacitors with complementary metal oxide semiconductor (CMOS) control circuitry. The monolithic memory is capable of greater than 10^{15} erase/write cycles with fast access times (<120 ns) and data retention greater than ten years. The operation of the device is discussed in another paper presented at this conference[1].

This paper presents the results of a preliminary investigation of the radiation hardness of the thin film ferroelectric capacitors used for the non-volatile data storage. A polarized ferroelectric capacitor is read by applying a fixed electric field to the capacitor. If the structure has the same polarization as that produced by the applied electric field, then charge is not released from the the capacitor and the direction of the polarization is unchanged. This state is refered to as P_S. On the other hand, if the applied electric field reverses the polarization, it releases charge and the original capacitor polarization is reversed. This state is refered to as P_R. Since the polarization of the capacitor can be reversed during a read cycle, the capacitor must be re-polarized to the pre-read direction following a read cycle. A non-volatile memory device which must be re-written after being read is known as a destructive read out (DRO) memory device.

The radiation environments used to characterize the capacitors were the following: 1) dose-rate, up to ~1 x 10^{11} rad(Si)/s; 2) total dose, up to ~1 x 10^{7} rad(Si) and 3) exposure to heavy ion fission fragments from a californium-252 fissi

90

foil source.

In addition, a comparison is made between FE capacitor and metal-nitride-oxide-semiconductor (MNOS) capacitor responses to heavy ions exposures. Finally, an estimate is made of the hardness of a 16-kbit RAM fabricated with radiation hardened CMOS peripheral circuitry.

EXPERIMENTAL PROCEDURES

A ferroelectric (FE) material has spontaneous, zero field polarization following the application of an applied electric field. The direction of polarization (P) depends on the direction of the applied electric field and remains after the electric field is removed. The magnitude of the polarization has units of charge per unit area. The zero field residual polarization gives rise to a hysteresis between the polarization (P) and electric field (E) and can be used to store a bit of data (see Figure 1). To evaluate the FE capacitors in the various radiation environments, two types of tests were performed. In the first type of test, the capacitors were set to a given **P** and exposed to one of the radiation environments while the capacitors were shorted. Following the exposure, the capacitors were read to determine if the stored logic state was changed or if the magnitude of the residual **P** was reduced. In the second type of test, the capacitors were continuously cycled during the radiation exposure with a high frequency AC signal. The **P** versus **E** hysteresis curve was periodically recorded (using a 1,2,4,8... time sequence) throughout the test. By comparing the hysteresis responses at each measurement time to those from a device which was not irradiated, any radiation induced degradation in the FE material could be detected.

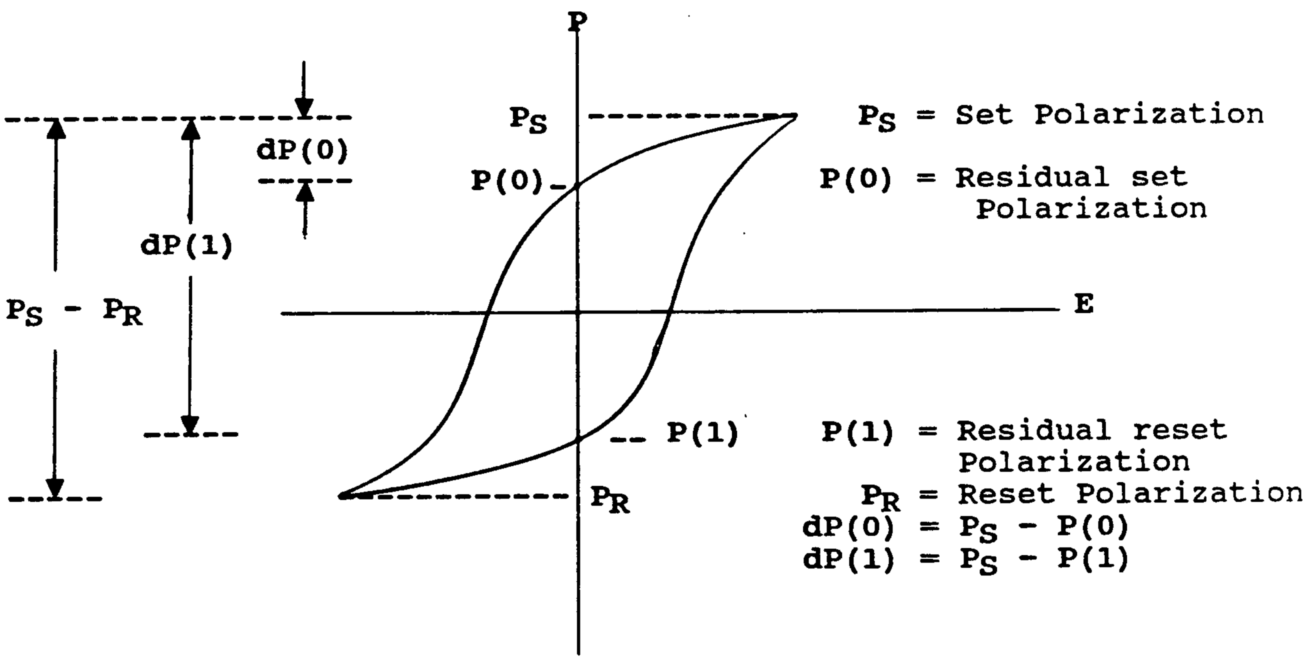

Figure 1. The hysteresis loop of a ferroelectric capacitor.

The dose rate tests were performed with a Febatron 705 flash X-ray source calibrated with a PIN photo-diode and TLDs. The pulse width was measured to be ~30 ns. Various dose-rates were obtained by varying the distance from the Bremsstrahlung converter.

The total dose tests were performed with a Shepherd model 81-22, Co-60 source. The source was calibrated with calcium fluoride TLDs and all exposures were done inside a lead/aluminum shield box as per MIL-STD-883, Method 1019.3.

The heavy ion exposure tests were performed using a Cf-252 fission fragment (FF) source. Californium is an artificial element which undergoes spontaneous fission. The average heavy fragment (mass number ~142) has ~80 MeV of energy and the average light fragment (mass number ~106) has ~104 MeV of energy. Because of the high rate of energy loss of these particles, even in air, the tests were performed in a vacuum. The range of the FFs in the ferroelectric material was calculated to be ~8.5 x 10^{-4} cm. This distance is large compared to the thickness of the ferroelectric capacitor structure, ~ 0.6 x 10^{-4} cm, which includes the upper electrode metal thickness.

EXPERIMENTAL RESULTS

Dose-rate

No loss of stored data was observed following dose rate exposures to ~1 x 10^{11} rad(Si)/s with a pulse width of ~30 ns. No degradation in **P** versus **E** was observed following dose-rate exposures from ~1 x 10^{7} to ~1 x 10^{11} rad(Si)/s. These data are summarized in the Table.

TABLE OF
DOSE-RATE RESULTS

Sample Number	Dose Rate (rad(Si)/s)	Dose (rad(Si))	**P** (μC/cm^2)	$P_S - P_R$ (μC/cm^2)	Flash X-Ray Pulse Width (ns)
7155B	-	-	2.52	14.0	-
	9.4 x 10^{6}	0.28	2.16	14.1	30
	6.8 x 10^{7}	2.03	2.47	14.2	30
	2.7 x 10^{8}	8.14	2.33	13.9	30
	1.0 x 10^{9}	30.0	2.46	14.0	30
	1.2 x 10^{10}	373	2.34	14.0	30
	6.0 x 10^{10}	1800	2.30	14.0	30
	1.2 x 10^{11}	3600	2.20	14.1	30
7152C	-	-	7.61	15.0	-
	1.2 x 10^{11}	3600	7.47	15.0	30

Total dose

No data loss was observed following an exposure of ~4.5 x 10^6 rad(Si). No additional degradation in the average P was observed following an exposure of ~1 x 10^7 rad(Si). Some degradation in P is normal following the ~10^{12} cycles associated with the 18 hour total dose exposure. Therefore, to determine the effect of the radiation, a comparison was made with non-irradiated, cycled capacitors. In both cases, P degraded from ~7.5 $\mu C/cm^2$ to ~3 $\mu C/cm^2$.

Heavy ion exposure.

No heavy ion induced degradation of P was detected for a FF fluence of ~6 x $10^6/cm^2$ with a static gate bias of 8 V. This represents an average of ~350 hits per capacitor during a test sequence. No polarization loss was detected following a FF fluence of ~8 x $10^6/cm^2$ with the capacitors shorted during the exposure. No heavy ion induced dielectric breakdown was observed at gate bias levels below 20 V. Dielectric breakdown is normally observed in these devices at bias levels above 20 V without heavy ions. No loss of data was observed after a FF fluence of ~8 x $10^6/cm^2$.

DISCUSSION

One interesting effect observed for the FE capacitors was the lack of heavy ion induced hard-errors (HIIHEs) below the intrinsic breakdown voltage of the device. Hard-errors (HEs) have been observed in both MNOS and high voltage MOS devices exposed to cosmic-ray environments[2]. Hard errors are observed in MNOS structures at bias levels well below the nominal bias required to write the device. These errors have been attributed to current conduction through the high temperature ion track leading to a permanent high conductance path through the dielectric. The high conductance path is a result of high temperature diffusion of high conductance material through the dielectric. In Wrobel's study, a material dependent threshold electric field was found that was a function of the ion energy deposition per unit path length. Below the threshold electric field, no permanent damage was observed. If the HIIHE threshold electric field in FE devices is above the intrinsic breakdown of the FE material, then no failure threshold electric field would be observed. Such an explanation is consistent with the data.

It can be seen from the data presented above, that FE capacitors have very high tolerance to total dose and dose-rate radiation environments. These capacitors, merged with radiation hardened CMOS decoding circuitry, should produce a non-volatile random access memory (RAM) limited only by the CMOS hardness.

It is difficult to analyzes the potential hardness of such an integrated structure without the details of the specific circuit topology and the radiation parametric variation of the CMOS decoding circuitry. However, some useful estimates can be made based on existing data for CMOS devices. Winokur et. al.[3] have shown that in n-channel devices short term threshold voltage shift produced from trapped holes are about -1 V for for a 1 x 10^5 rad(Si) exposure. At long times the threshold shift is caused from interface states and results in a positive ~0.5 V shift. If the RAM sense amplifiers and decoding circuitry can be designed to be insensitive to shifts of this magnitude, then it should be straightforward to design a FE memory that is both hard to ~10^5 rad(Si) and immune to severe cosmic-ray space environments.

SUMMARY

In summary, FE memory capacitors are immune to IIHE which make them a good choice for space environment. In addition, the total dose and dose-rate radiation hardness of FE capacitors has been demonstrated. The hardness level of a nonvolatile memory produced by merging radiation hardened CMOS technology with the FE capacitors should be limited by the hardness of the CMOS peripheral circuitry.

REFERENCES

1. J. T. Evans, W. D. Miller and J. A. Bullington, "Ferroelectrics: A New Non-Volatile Technology," this conference.

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