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EMPIRICAL RELIABILITY MODELS OF RETENTION FAILURES IN A FERROELECTRIC MEMORY DEVICE USING $SrBi_2(Ta,Nb)_2O_9$

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The temperature dependence of retention failures in a 288-bit ferroelectric memory device using $SrBi_2(Ta,Nb)_2O_9$ was studied. The retention times until failure occurred were fit to a model having a relationship of $\log(\log t_f)$ vs. $1/T$ for the period of infant mortality and to the Arrhenius model having the form of $\log t_f$ vs. $1/T$ for the period of random failures, where t_f is the time to failure and T is the temperature. The activation energy was found to be 0.35 eV for infant failures and 1.15 eV for random failures. This paper discusses possible causes for the different activation energies.

Keywords: ferroelectric memory, retention, Bi-layered perovskite, $SrBi_2(Ta,Nb)_2O_9$

INTRODUCTION

Ferroelectric memory devices using Bi-layered perovskites such as $SrBi_2Ta_2O_9$ (SBT) and $SrBi_2(Ta,Nb)_2O_9$ (SBTN) have become an important class in nonvolatile memories because of their fatigue-free nature exceeding 1 x 10^{12} read/write cycles and superior retention properties to those of other ferroelectric materials such as $PbZrTiO_3$ (PZT).[1-4] As typical requirements for nonvolatile memories, a charge stored in a ferroelectric memory capacitor must be preserved for more than 10 years over a wide range of temperatures. The storage temperature without electrical bias typically ranges from -10 to 70 °C for consumer applications and between -40 and 85 °C for industrial applications.

Nonvolatile ferroelectric memories retain stored charges as remanent polarization charges in ferroelectric capacitors. The remanent polarization in PZT capacitors decreases as temperature rises and eventually collapses at the Curie temperature. In addition, remanent polarization tends to decrease with time.[5,6] Therefore the temperature dependence of data retention is a potential reliability concern for ferroelectric memory devices. In this paper, we report on the temperature dependence of retention failures in a 2.43V programmable 288-bit ferroelectric memory device using SBTN. We establish reliability models that can predict the data retention life of SBTN memories. Statistical results yielded by the temperature-accelerated retention testing of SBTN memories are fully interpreted with the models.

MODELING OF RETENTION FAILURE

When the remanent polarization $P(t)$ decays with time t at a constant decay rate of $1/\tau$, the exponential dependence of $P(t)$ is

$$P(t) = P_0 e^{-\frac{t}{\tau}} \quad , \qquad (1)$$

where $P_0 = P(0)$. When the relationship in Eq.(1) is drawn on a $\log P(t)$ vs. t plot, $1/\tau$ yields a slope showing polarization decay behavior. Let us assume here that a memory device fails in a retention test when $P(t)$ of a memory capacitor reaches a specific value of P_f, which gives the lower limit of remanent polarization whose charge is detected by the sense amplifier. We then have this expression for the time to failure t_f:

$$t_f = \tau \ln\left(\frac{P_0}{P_f}\right) \tag{2}$$

In Eq.(1), $1/\tau$ can be regarded as the specific decay rate determined by the polarization decay mechanism. The temperature dependence of the rate constant is then expressed by

$$\frac{1}{\tau} = \frac{1}{\tau_0} e^{-\frac{E}{kT}} , \tag{3}$$

where E is the specific activation energy, k is the Boltzmann constant, T is the absolute temperature, and $\tau = \tau_0$ at $E/kT = 0$. Combing Eqs.(2) and (3), we obtain the following relationship between the temperature and the time to failure:

$$\ln t_f \propto \frac{E}{kT} \tag{4}$$

This relationship is commonly referred to as the Arrhenius reaction model and it is adequate as far as Eq.(1) is relevant to the decay process. However, the actual decay process for long periods of time is described well by the empirical form of [7-9]:

$$P(t) = P_0 - m \ln\left(\frac{t}{t_0}\right) , \tag{5}$$

where t_0 is a characteristic time at which the linear behavior of $P(t)$ begins with respect to ln$t$, P_0 is the polarization at $t = t_0$, and m is the slope of the curve in a $P(t)$ vs. ln$t$ plot. Let us assume here that a memory device will definitely fail when the $P(t)$ of a memory capacitor reaches a specific value of P_f We obtain this expression for the time to failure t_f:

$$\ln\left(\frac{t_f}{t_0}\right) = \frac{1}{m}(P_0 - P_f) \tag{6}$$

If the slope m can be regarded as the rate constant of the decay in remanent polarization in Eq.(5), it should have a form such as

$$m = m_0 e^{-\frac{E}{kT}} , \tag{7}$$

where $m = m_0$ at $E/kT = 0$. From Eqs.(6) and (7), we obtain the following relationship between the temperature and the time to failure:

$$\ln\left[\ln\left(\frac{t_f}{t_0}\right)\right] \propto \frac{E}{kT} . \tag{8}$$

Consequently, the temperature dependence of the time to data retention failure in ferroelectric memories has a linear relationship between log(logt_f) and $1/T$.

EXPERIMENTAL

Device Fabrication

For the present experiment, we designed a 288-bit serial memory incorporating SBTN cell capacitors with Pt electrodes. The capacitor size is

5x5 μm^2. Each memory cell is comprised of two transistors and two capacitors (*2T/2C*) with the cell size of 182 μm^2. The 288-bit memory is organized into 18 rows by 16 bits. A typical access time of the memory is 230 ns at 5 V and room temperature. The ferroelectric memory cells were fabricated on silicon wafers with CMOS circuits using advanced ferroelectric process technologies.[10] Finished wafers were electrically tested to insure the full functionality of each memory die, then conformable dies were mounted in plastic package parts after sawing.

Testing Procedure

Prior to baking for the retention test, a test data pattern was programmed (written) into each test memory part at 2.43 V and 75 °C, a programming voltage that is low enough, and a temperature chosen to be the maximum for use in consumer applications. The programmed parts were then baked at the high temperatures of 125, 150, and 175 °C for the required periods of time up to 2,000 hrs. The baked parts were cooled to 75 °C, and then their data integrity and functionality were tested. Test pulses for reading data were 2.43 V. Any memory part with failing bits was rejected. Ten test parts were prepared for each test condition of temperature and bake time. Since destructive read-out is essential for the *2T/2C* ferroelectric memory, each part was tested only once for its retention measurement to ignore past history effects such as imprint.

RESULTS

The distribution of times to failure obtained from the temperature-accelerated retention test was approximated to a lognormal distribution, as shown in Fig.1. This approximation is valid for describing that retention failures are certain to occur after a threshold in remanent polarization P_f is reached. In this figure, the cumulative failures apparently increase as baking temperature is elevated, and tend to be saturated with time. The saturation of cumulative failures with time indicates a decrease in failure rate with time, and suggests that candidates for retention failure are exhausted within a certain retention time. Accordingly, the linear fitting of data to a lognormal distribution is allowed while the cumulative percent failure is building up.

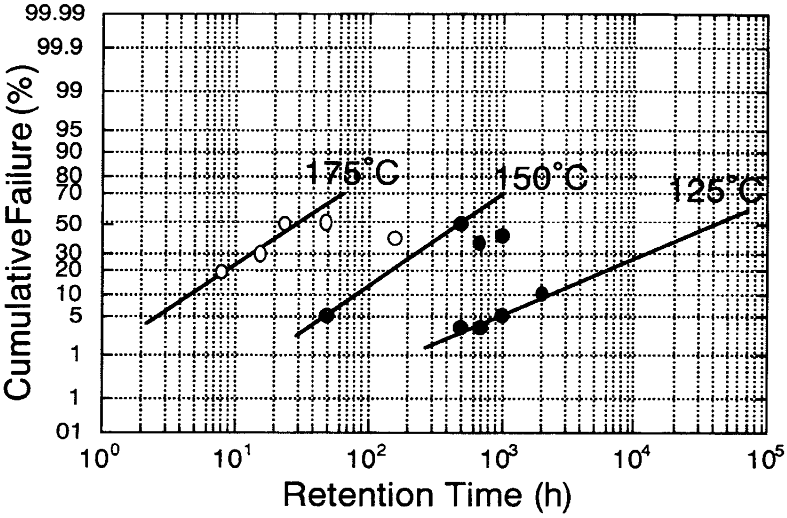

FIGURE 1 A lognormal plot of cumulative failures *vs.* storage time for retention dada of 288-bit memory parts for a write voltage of 2.43V.

Since the relaxation process of remanent polarization is supposed to be associated with early retention failures,[7,8] it was advisable to employ the model following Eq.(8) for infant failures. Figure 2 shows the temperature dependence of the times to 50% cumulative failure for the infant failure regime. The fitting of a straight line in Fig.2 yielded an activation energy of 0.35 eV. It was also possible to describe the temperature dependence of time to 50% cumulative failure with the Arrhenius model. In this case the activation energy was determined to be 2.2 eV. However this energy value is so far over the tested temperatures as to induce no thermally activated failures. It is therefore natural to adopt the former model for infant failures. The good linearity of the fitting in Fig. 2 supports the belief that the decay in remanent polarization during the infant failure period is governed by the logarithmic law for decay time.

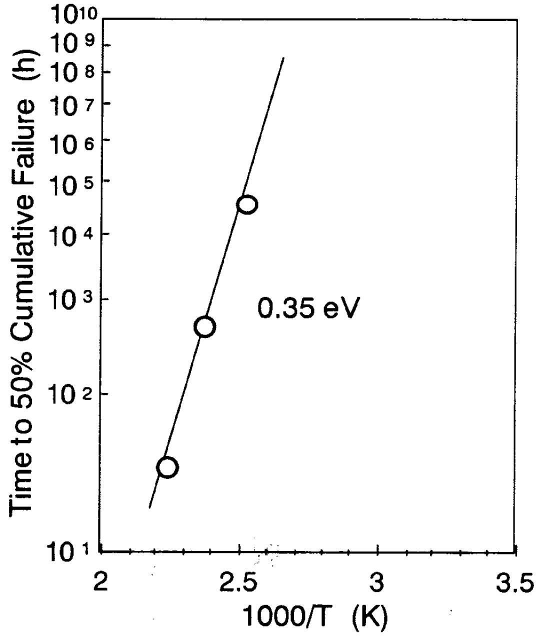

FIGURE 2 A plot of the log of the log of times to 50% cumulative failure *vs.* $1/T$, showing a straight line with an activation energy of 0.35 eV.

Random failures appear in the saturated regime in Fig.1. The time to failure in the random failure period was calculated using the χ^2 distribution, where infant failures were not included in the failure rate calculation. Figure 3 shows the temperature dependence of the mean time between failures (MTBF), whose behavior is characterized by a constant failure rate and fit to the Arrhenius model using Eq.(4). The fitting of the model in Fig. 3 shows a straight line with an activation energy of 1.15 eV. This relationship can be used to predict the failure rate at specified temperatures other than the test temperatures. The extrapolation of the line predicts 1 FIT at 27 °C and 198 FITs at 70°C, where 1 FIT is a unit of failure rate equal to 10^{-9} h^{-1}. These failure rates are low enough for nonvolatile memory applications.

DISCUSSION

As we demonstrated, there are two different mechanisms for memory retention failures. Infant failures with an activation energy of 0.35 eV appear for the beginning of baking. After a while, the retention failure is dominated by a random failure mechanism with an activation energy of 1.15 eV. A possible explanation for the two different activation energies follows.

The value of activation energy for infant failures is quite similar to the depth of electron and hole traps in Bi-layered perovskites.[11] Trap states are spatially distributed in the ferroelectric memory capacitor. During a bake, trapped carries such as electrons and holes can be activated thermally and transported toward preferential dipoles to screen or neutralize the polarization charge. But because there is a finite number of carriers surrounding a dipole, the reduction in remanent polarization is saturated when the redistribution of carriers for charge screening or neutralization surrounding the dipole is established. Since the occurrence of infant failures is saturated within a finite time, this mechanism can be accelerated by temperature to effectively screen infant failures.

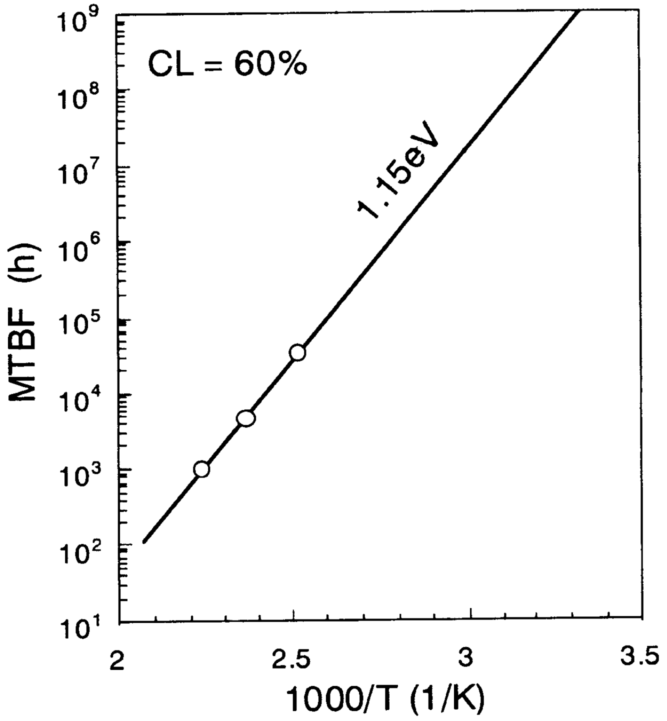

FIGURE 3 Mean time between failures *vs.* temperature. The MTBFs were calculated using the χ^2 distribution with a 60% confidence level.

The mechanism for random failures can be attributed to the motion of oxygen vacancies and/or ionic impurities in the ferroelectric because the activation energy obtained is about 1 eV. These mobile charges may cause the occasional charge compensation or neutralization of oriented dipoles with a certain reaction rate, thereby resulting in a loss of polarization charge. The retention failure rate during the random failure period is therefore determined by the reaction rate of the mobile charges with dipoles.

CONCLUSION

We studied the temperature dependence of retention failures in a 288-bit $SrBi_2(Ta,Nb)_2O_9$ memory programmable at 2.43 V. The temperature dependence of infant retention failures was fit to an empirical reliability model having the form of $\log(\log t_f) \propto 1/T$. This approximation resulted in an activation energy of 0.35 eV. Since the activation energy for infant failures is similar to that of electron and hole traps in Bi-layered perovskites, we believe that the infant retention failures are associated with the electrons and holes in shallow traps. The random failures, on the other hand, exhibit a low failure rate with the relatively high activation energy of 1.15 eV. We therefore suppose the random failure mechanism is caused by the random reactions of oxygen vacancies and/or ionic impurities with oriented dipoles. The Arrhenius model predicted random failure rates of 1 FIT at 27 °C and 198 FITs at 70°C for the 288-bit $SrBi_2(Ta,Nb)_2O_9$ memory.

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References

[1.] T. Mihara, H. Watanabe, C. A. Paz de Araujo, J. Cuchiaro, M.

Scott, L. D. McMillan, *Proc. 4th Int. Symp. Integr. Ferroelectr.*, Monterey, CA, p.137 (1992).

[2.] C. A. Paz de Araujo, J. D. Cuchiaro, L. D. McMillan, M. C. Scott, and J. F. Scott, *Nature*, **374**, 627 (1995).

[3.] P. C. Fazan, *Integr. Ferroelectr.*, **4**, 247 (1994).

[4.] W. Kinney, *Integr. Ferroelectr.*, **4**, 131 (1994).

[5.] T. D. Hadnagy and D. J. Sheldon, *Integ. Ferroelect.*, **4**, 217 (1994).

[6.] D. J. Sheldon, *Integr. Ferroelectr.*, **8**, 185 (1995).

[7.] N. E. Abt, *Proc. 3rd Int. Symp. Integr. Ferroelectr.*, Colorado Springs, CO, p.404, 1991.

[8.] J. M. Benedetto, R. A. Moore, and F. B. McLean, *J. Appl. Phys.*, **75**, 460 (1994).

[9.] T. Mihara, H. Yoshimori, H. Watanabe, and C. A. Paz de Araujo, *Jpn. J. Appl. Phys.*, **34**, 2380 (1995).

[10.] Y. Shimada, Y. Nagano, E. Fujii, M. Azuma, Y. Uemoto, T. Sumi, Y. Judai, S. Hayashi, N. Moriwaki, J. Nakane, T. Otsuki, C. A. Paz de Araujo, and L. D. McMillan, *Integr. Ferroelectr.* **11**, 229 (1995).

[11.] J. Robertson, C. W. Chen, W. L. Warren, and C. D. Gutleben, *Appl. Phys. Lett.*, **69**, 1704 (1996).