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Film Quality Dependence of Adaptive-Learning Processes in Neurodevices Using Ferroelectric PZT Films

E. Tokumitsu, R. Nakamura, K. Itani, and H. Ishiwara

Precision and Intelligence Laboratory, Tokyo Institute of Technology
4259 Nagatsuta, Midori-ku, Yokohama 227, JAPAN

Partial switching in ferroelectric $PbZr_xTi_{1-x}O_3$ (PZT) thin films has been studied for the adaptive learning metal-ferroelectric-semiconductor field effect transistor (MFSFET) applications. Particularly, the effects of film quality on adaptive-learning processes in ferroelectric PZT thin films are discussed. Dimensionality of the ferroelectric domain growth is estimated 1.3 for sol-gel grown PZT films and 2.2 for vacuum-evaporated materials. It is shown that this discrepancy results in the difference of the adaptive-learning processes. It is also demonstrated that the learning process in PZT films can gradually proceed by applying the short input pulses.

1. INTRODUCTION

We have previously proposed an "adaptive learning" metal-ferroelectric-semiconductor field-effect transistor (MFSFET) as a key-device for the future neural network systems[1]. In this application, the gate insulator is composed of a ferroelectric film. Here, we define the term "adaptive-learning" processes as (i) a function in which device properties can be changed partially or totally after the device has processed a certain number of usual signals, and (ii) a function in which the device properties can be restored to the initial state by usual or reset signals. In adaptive-learning MFSFETs, positive and negative input pulses can be used to realize these two functions. It is important that the duration of input pulses be shorter than the switching time to reverse the polarization partially. By partially switching the polarization of the ferroelectric gate insulator, we can precisely control the threshold voltage and the source-drain resistance and maintain these even after the input pulses are turned off, because of the remanent polarization of the ferroelectric gate insulator.

We have already reported that the polarization of sol-gel grown PZT films can be gradually reversed by applying short positive pulses and can be restored to the initial state by applying short negative pulses[3], demonstrating the "adaptive-learning" processes in ferroelectric PZT films. We have also reported that PZT films with good crystalline and electrical properties can be grown by dual-beam vacuum evaporation technique[3]. However, partial switching characteristics in vacuum-evaporated PZT films have not been reported.

In this paper, we report the details of "adaptive-learning" processes, namely gradual polarization change, in PZT thin films prepared by either sol-gel or vacuum evaporation method. Particularly, effects of PZT film quality on the adaptive-learning processes have been discussed.

2. SAMPLE PREPARATION

PZT thin films were prepared by either sol-gel or vacuum evaporation technique on $Pt/Ti/SiO_2/Si$ or Pt/MgO substrates. Typical thickness of the PZT films was 200-300 nm. In the sol-gel technique, thin films of PZT were spin-coated, dried at 150 ℃ for 10 min, and consolidated at 400 ℃ for 20-60 min. After the desired thickness was obtained by repeating the above process, the sample was annealed at 600-800 ℃ for 90 sec to 60 min in an oxygen ambient. The Zr composition in PZT thin films was 0.52.

Vacuum evaporation system used in this work consists of a deposition chamber with an electron-beam gun and an alumina crucible. An oil diffusion pump with a liquid nitrogen trap and a turbo-molecular pump were used to obtain a background pressure less than 1×10^{-5} Pa. PbO powder and ZrO_2 /TiO_2 pellets were used as source materials. Since the vapor pressure of PbO is much higher than that of ZrO_2 and TiO_2, PbO was evaporated from heated crucible, while electron-beam gun was used for evaporation of ZrO_2/TiO_2. PZT films were prepared at 600-650 ℃. Zr/Ti molar fraction ratio of the pellet was fixed to (65/35), which results in Zr molar fraction of 0.3-0.4 in the deposited PZT films.

X-ray diffraction measurements were employed to characterize crystalline quality of the PZT films. It was found from X-ray diffraction patterns that the PZT film by sol-gel technique at 800 °C was polycrystalline, exhibiting perovoskite orientations of PZT at (110), (100), (111), and (211). On the other hand, only PZT(001) and (002) peaks were observed for the vacuum evaporated films.

To measure the electrical characteristics, Pt or Au top electrodes (200 μm in diameter) were evaporated at room temperature to form MFM (metal-ferroelectrics-metal) capacitor structures. We intentionally used large top electrodes to obtain a long switching time, which make it easy to measure the partial switching characteristics when short pulses are applied. The measurement circuit for switching responses consists of a programmable pulse generator which drives a MFM capacitor in series with 50 Ω resistor.

3. SWITCHING CHARACTERISTICS

First, we studied switching characteristics with varying the input voltage. Figure 1 shows reversal switching current responses of vacuum-evaporated PZT films when the input pulse voltage was varied from 1 to 5 V. The applied pulse sequence consists of a reset pulse of -5V, following a double read pulse with various voltages as shown in the inset of the figure. It is seen that the switching time becomes shorter as the input pulse voltage increases. A similar responses were observed for PZT films prepared by the sol-gel technique. The reversal current response can be expressed by the following formula[4,5],

$$j = 2P_r n/t_s \, (t/t_s)^{n-1} \exp[-(t/t_s)^n], \qquad (1)$$

where P_r, t_s, and n mean remanent polarization, switching time, and dimensionality factor, respectively. By fitting the experimental data shown in Fig. 1 with the above formula, we found that the dimensionality factor, n, was 2.2 for vacuum evaporated PZT films, while that for the sol-gel PZT was 1.3. This indicates that ferroelectric domains in sol-gel PZT grow one-dimensionally or grains are small enough to prevent the two-dimensional growth of ferroelectric domains.

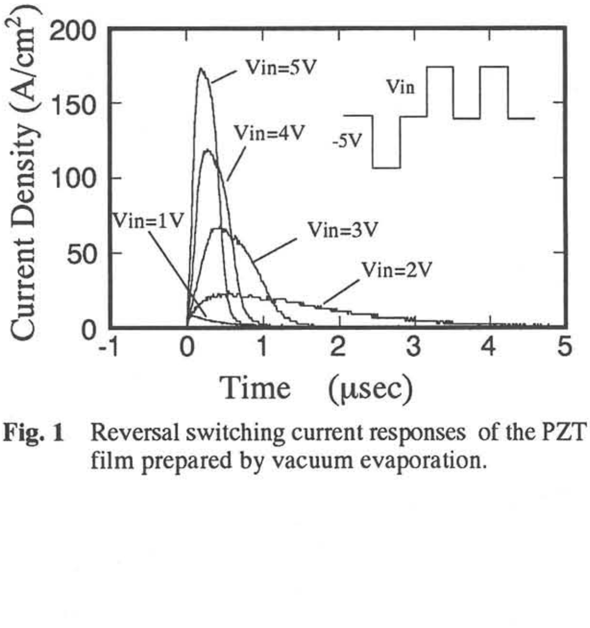

Fig. 1 Reversal switching current responses of the PZT film prepared by vacuum evaporation.

On the other hand, planar growth is believed to take place in vacuum-evaporated PZT films. Hence, the discrepancy in dimensionality factor n is due to the difference in crystalline quality of the PZT films.

By integrating the current response, the reversed polarization can be estimated as a function of the time as shown in Fig. 2. When the input voltage is 5 V, the reversed polarization increases rapidly and saturates at 62 μC/cm^2, which corresponds to $2P_r$. For a smaller pulse voltage, the polarization increases more gradually and saturates at a lower value, indicating the switching time t_s is larger for a smaller input voltage. Figure 3 shows the total reversed polarization as a function of input voltage. Open triangles and solid circles show the polarization changes for sol-gel and vacuum-evaporated PZT films respectively. The reversed polarizations in this figure are normalized by the polarization obtained for an input voltage of 5V. It is seen that the reversed polarization increases with the input voltage for both cases. The change is more rapid for the PZT films prepared by vacuum evaporation.

Figure 4 shows the polarization change by a 5V-pulse for sol-gel and vacuum evaporated PZT films.

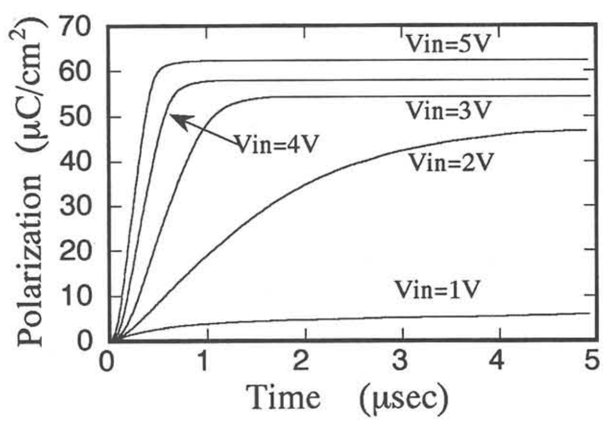

Fig. 2 Reversed polarization as a function of the time for the vacuum evaporated PZT film.

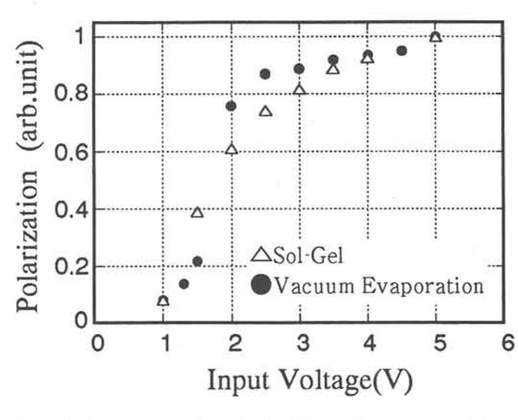

Fig. 3 Total reversed polarizations for various input voltages. Open triangles and solid circles show polarizations for sol-gel and vacuum-evaporated PZT films, respectively.

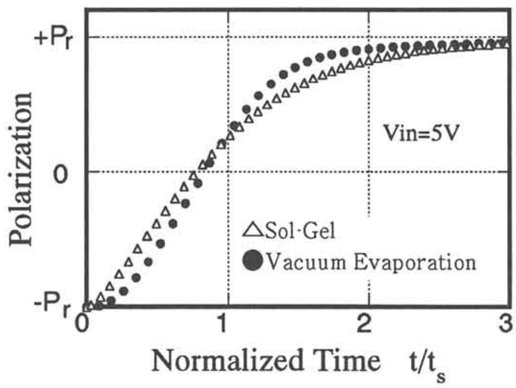

Fig. 4 Measured polarization change as a function of time for sol-gel and vacuum-evaporated PZT.

In this figure, time is normalized by the respective switching times t_s for both PZT films. These curves correspond to the adaptive learning processes as the number of applied pulses is increased. It is found that in sol-gel grown PZT films, the learning process proceeds from the beginning and relatively long time (many pulses) is necessary to reach the completely-learned condition ($+P_r$). On the other hand, if the vacuum-evaporated PZT films are used, the learning process does not proceed at the beginning and then the polarization rapidly changed from $-P_r$ to $+P_r$. This can be explained by the difference of dimensionality factor, n, because the polarization change can be given by

$$P=P_r\{1-2\exp[-(t/t_s)^n]\}. \qquad (2)$$

Next, to confirm the adaptive-learning process in PZT films, we studied partial switching when short pulses are applied (PFM : pulse frequency modulation). The durations of each pulse are 50 and 100 nsec. Figure 5 shows the polarization change of vacuum-evaporated PZT films as a function of total pulse width. It is clearly seen that the polarization gradually changes by applying positive pulses. The polarization change by a single pulse (PWM : pulse width modulation) is also plotted for comparison. The polarization reversed by a single pulse changes from $-P_r$ to $+P_r$. When the pulse duration is 100 nsec, the polarization change reversed by many short pulses agrees with the curve obtained for a single pulse. On the other hand, the polarization change by 50 nsec pulses is not so large. The reversed polarization tends to saturate at $0.8P_r$, which suggests the limited learning capability when short pulses are employed. This is probably because the actually applied voltage to the MFM capacitor is small for short input pulses because of the CR time constant of the measurement circuit. The increase of the polarization at the beginning by 100 nsec pulses is more rapid than that by 50 nsec pulses. This supports the above explanation, because the switching time becomes larger for a smaller input voltage as previously shown in Fig. 3.

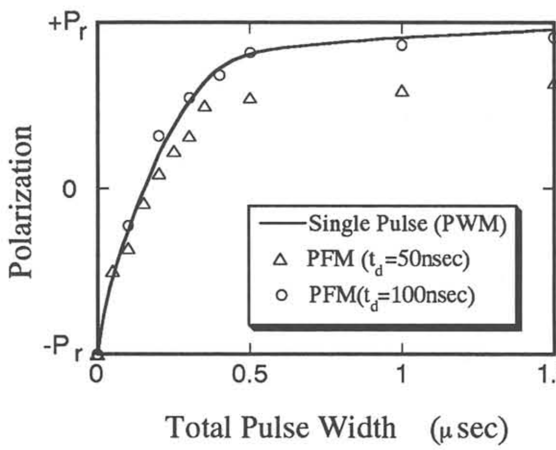

Fig. 5 Polarization change due to partial switching when a single pulse (PWM) and many short pulses (PFM) are applied.

We also found that when the input pulses decreased to 3V, the polarization change is small, which can be explained by the voltage dependence of P_r as shown in Fig.3. Furthermore, it was also confirmed that the polarization which was partially reversed by the positive pulses can be restored to the initial state by applying the several negative pulses.

4. CONCLUSION

We have studied the effects of film quality on adaptive-learning processes in ferroelectric PZT thin films. PZT films were prepared by the sol-gel or vacuum evaporation techniques. It was found that the dimensionality, n, of the domain growth was 1.3 for sol-gel grown PZT films and 2.2 for vacuum-evaporated materials. This difference leads to the different "learning-curve" of adaptive learning MFSFETs.

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