Chapter 7

Switching Current Study: Hysteresis Measurement of Ferroelectric Capacitors using Current-Voltage Measurement Method

7-1. Introduction

Over the past few decades, various methods for obtaining the electrical polarization loops of ferroelectric capacitors have been reported [24-26, 28-29]; they include the Sawyer-Tower method (STM) [24], virtual ground method (VGM) [25], shunt method [26], constant current (CC) method [28-29] and triangular current (TC) method (See chapter 6). For the Sawyer-Tower and virtual ground methods, a large sensing capacitor and a virtual-ground operational amplifier with an integrating capacitor are utilized in the charge measurement. Additionally, in the shunt method, the sensing capacitor is replaced with a reference resistor (R_{ref}) in the switching current measurement [26]. In the hysteresis loop measurement, the triangular voltage wave is applied to the top electrode of a ferroelectric capacitor and the voltage drop (V_{ref}) across the reference resistor is measured simultaneously to obtain the hysteresis switching current using $I_{switch} = V_{ref} / R_{ref}$. In the retention and fatigue tests, polarization charge can be determined by pulse polarization measurement [27], which applies a pulse sequence to the same architecture of the shunt method. For the CC and TC methods, a constant charging current and a triangular charging current are applied to a specimen and the resulting voltage profiles are recorded simultaneously, to determine its hysteresis loops.

In this chapter, we utilized the current-voltage (I-V) measurement method to determine the hysteresis switching current characteristics and to obtain the polarization-voltage loops of a ferroelectric capacitor. Additionally, a modified poling measurement was utilized to investigate dynamic switching current characteristics and retention properties. Moreover, the switching current characteristics of various depolarized biases were investigated. Furthermore, the temperature effect of switching current characteristics was also addressed.

7-2. Experiments

$Pb(Zr_{0.3}Ti_{0.7})O_3$ (PZT(30/70)) films 250 nm thick were deposited onto Pt(100 nm)/Ta(20 nm)/SiO2(100 nm)/Si substrates by a sol-gel-derived method (See chapters 2 and 5). For the conventional current tester, the measuring mode chosen was generally short, median or long. The default setting for each mode was designed to measure the static current response. The measuring delay, filter delay and integration time are related to each mode and affect the measured current response. Additionally, the range of measured current chosen was often the auto-range or semi-auto-range. The setting of measured range may also influence measuring delay and integration time. The factors (including sweeping delay, measuring delay, integration time and measured range) will influence the measured current response, resulting in a weak switching current response when the sweeping delay and measuring delay were not set to be 0.0 s. The results concerning measured current response for various sweeping delay time are shown in the Fig. 7-1, to clarify the effect of sweeping delay.

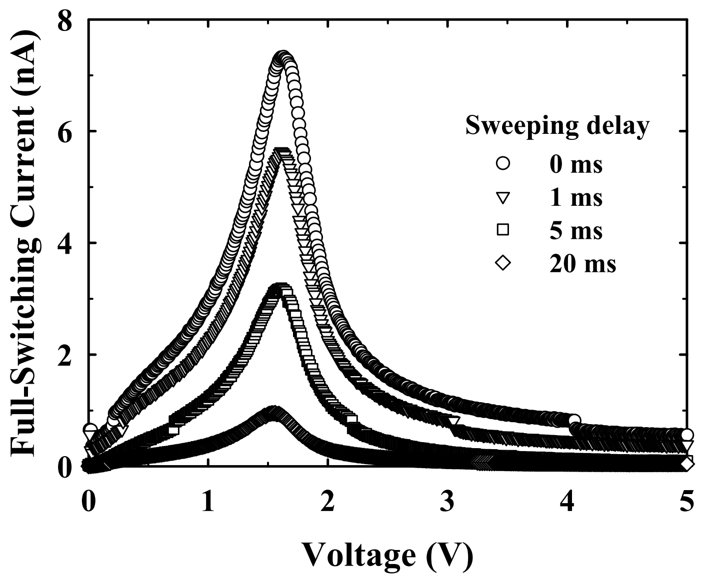

Fig. 7-1 Full-switching current characteristics of ferroelectric films for various sweeping delay time.

In this study, we utilized a Keithley 4200 semiconductor characterization system for the hysteresis switching current measurements. In the measurements, the operation mode chosen was the list sweeping mode. The sweeping delay and measuring delay were set to be 0.0 s and the option for filter delay was disabled. The step voltage was fixed at 0.01 V. The integration time was set to be 0.01 PLC, which is the smallest value of the system, where the PLC is the Power Line Cycles. After estimating the peak switching current affected by the area of ferroelectric capacitors, the measured range chosen was 10 nA. A constant range of measured current yields an almost constant settling time for each voltage step during the switching current measurement. In the measured range of 10 nA, the accuracy of current measurement, in relation to the measured range, was about ±(0.05%*rdg + 1 pA), where rdg is the reading value of measured current. To obtain the hysteresis loops of ferroelectric capacitors, two cycles of triangular voltage profile were applied to a 100 μm × 100 μm capacitor. The hysteresis switching current and time were measured and recorded immediately using this system. Using integral calculus to convert switching current to charge, the polarization-voltage (P-V) curve can be determined. Additionally, the hysteresis loop of the 100 μm × 100 μm capacitor was also measured using a standardized ferroelectric test system RT66A in the virtual ground mode (VGM) to verify the P-V curve.

7-3. Results and Discussions

The experimental procedures were mentioned in the previous section. In the following we will verify the hysteresis loop obtained using the I-V measurement method. This hysteresis loop will also be compared with the results obtained using VG method at slow mode and fast mode. Additionally, the full-switching and non-switching characteristics will be studied using the I-V measurement method. Moreover, the dynamic switching current characteristics and retention property will also be discussed. Furthermore, the de-poling effect of switching current will be characterized. The temperature effect of switching current characteristics will be also addressed.

7-3-1. Verification of hysteresis loops

Figure 7-2 shows a complete cycle of a triangular voltage wave form and hysteresis switching current obtained using the I-V measurement method. The maximum applied voltage was approximately ± 5 V. A single-cycle duration of this measurement was approximately 9.33 s and the sweeping rate (dV/dt) was approximately 2.147 (V/s). It was found that the measured current is maximum when the applied voltage is close to the coercive voltage of the ferroelectric films. These current maxima correspond to the dipole reorientation contribution of the ferroelectric material [48].

For ferroelectric materials, the basic equation of total current $I(t)$ is given by [29]

$$I(t) = A \times \frac{dD(t)}{dt} + I_C = A \times \frac{dP(t)}{dt} + C \times \frac{dV(t)}{dt} + I_C, \quad (1)$$

where $D(t)$ is the dielectric displacement, I_C is the conduction current of the material, A is the area of specimen, t is the time, $P(t)$ is the ferroelectric polarization, C is the parallel plate capacitance, and $V(t)$ is the applied voltage.

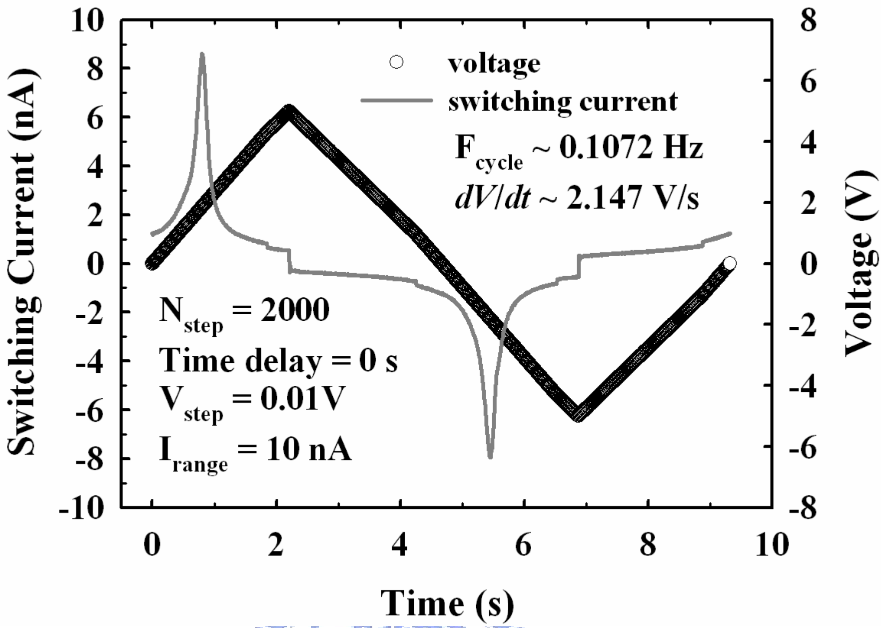

Fig. 7-2 Triangular applied voltage (open circles) and hysteresis switching current (unbroken line) versus time, for 250-nm-thick PZT(30/70) film.

Figure 7-3 shows the discharging current characteristics (I-t) for various holding voltages and its inset displays the leakage current-voltage plot obtained from each I-t curve at a discharging time of 100 s. For the measurements, a positive pulse (+5 V) with a pulse width of 5 ms was first applied to the ferroelectric capacitor to change the initial polarization direction and the remaining procedure was then performed at 0 V for 10 s. Next, I-t measurement was performed at the holding voltage range (from 2.5 to 5 V) to measure discharging current. The leakage current (2.3×10^{-12} A at 5 V) of the insert is negligible relative to switching current (5.5×10^{-10} A at 5 V) and the peak switching current (8.5×10^{-9} A).

In the case of a negligible conduction current (I_C), the total current can be written as $I(t) = A \times dD(t)/dt$ [28-29]. Using $D(t) = (1/A)\int I(t)dt$, the hysteresis loops of can be calculated from the switching current of ferroelectric capacitor.

Figure 7-4 shows the hysteresis plots obtained using the I-V measurement method and virtual ground method operated in the slow mode (~ 5.6 Hz). Additionally, the P-V curve was also measured by the fast mode (~ 56 Hz) of RT66A to verify the data obtained using our method (shown in Fig. 7-5). It was found that the frequency obtained by I-V measurement (~ 0.1 Hz) is lower than that by virtual ground measurement using RT66A (~ 5.6 or 56 Hz). For the I-V measurement method, the coercive voltage $V_C = (V_C^+ - V_C^-)/2$ was about 1.56 V, where V_C^+ and V_C^- are the positive and negative coercive voltages, respectively, obtained from the P-V curve. This value is lower than those measured by the slow mode (1.64 V) and fast mode (1.80 V). This indicates that coercive voltage is dependent on measurement frequency, which is consistent with previously reported results [50].

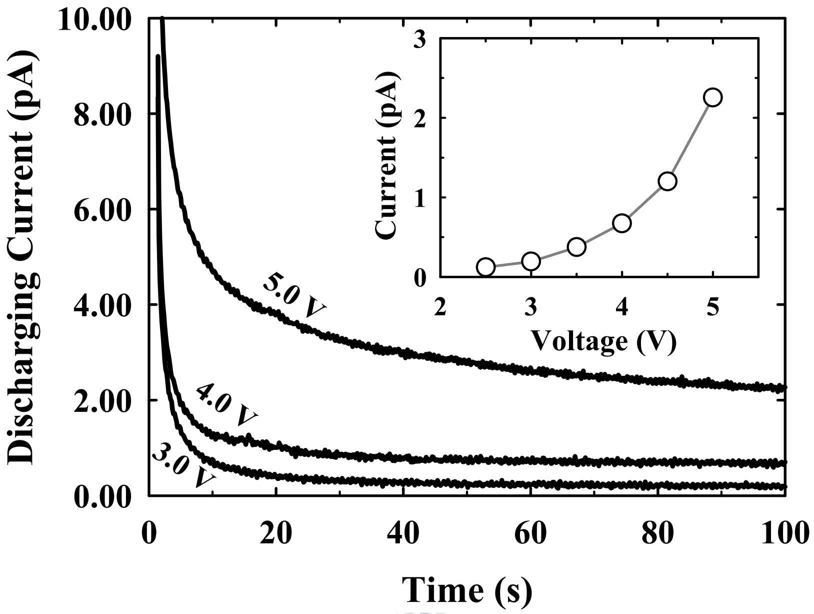

Fig. 7-3 Discharging current (I-t) characteristics for various holding voltages. The inset represents the leakage current-voltage plot obtained from I-t plots at a discharging time of 100 s.

These previously results of the study using the nucleation-controlled model indicates that coercive voltage increases significantly as the measurement frequency exceeds 1 kHz. However, when the frequency is less than 100 Hz, the decrease in coercive voltage becomes smaller and finally coercive voltage saturates at a very low frequency. Additionally, coercive voltages, obtained from our previous studies using the TC method (Chapter 4), remain constant at the very low frequency range from 0.0148 Hz to 1.45 Hz (shown in Fig. 7-6). This trend may be a possible explanation for the similarity between the P-E curves in Fig. 7-5, even though the measuring frequencies and the testing methods are different. The result reveals that the I-V measurement method can also be utilized in hysteresis measurements.

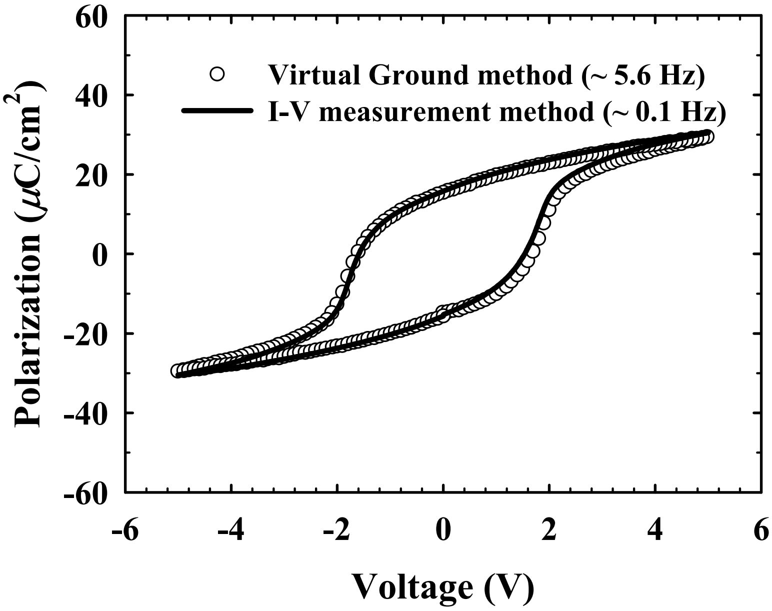

Fig. 7-4 Polarization-voltage (P-V) plots obtained by virtual ground method (open circles) and I-V measurement method (unbroken line). The area of sample was 10^{-4} cm^2. The frequencies obtained by the VG method and I-V measurement method are about 5.6 Hz and 0.1 Hz, respectively.

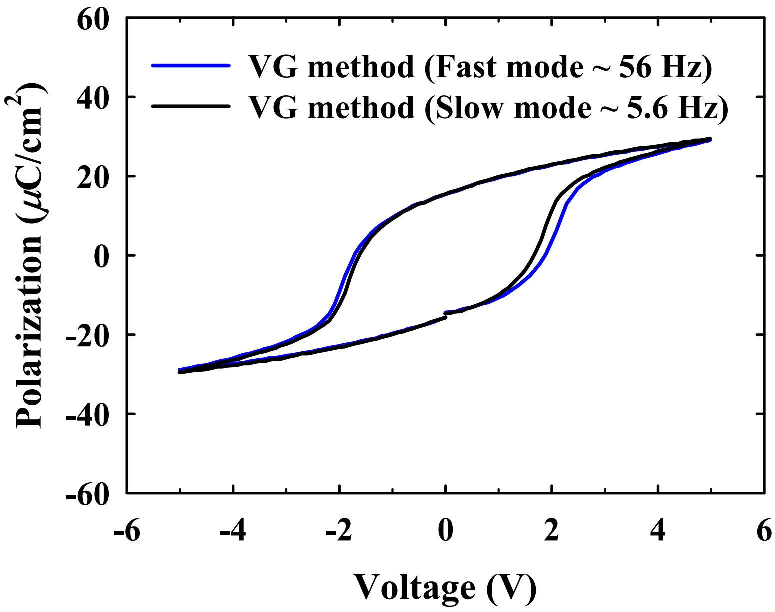

Fig. 7-5 Hysteresis loops of ferroelectric capacitor measured by RT66A. Black line represents the P-V curve measured at slow mode (~ 5.6 Hz). Blue line represents the result measured at fast mode (~ 56 Hz).

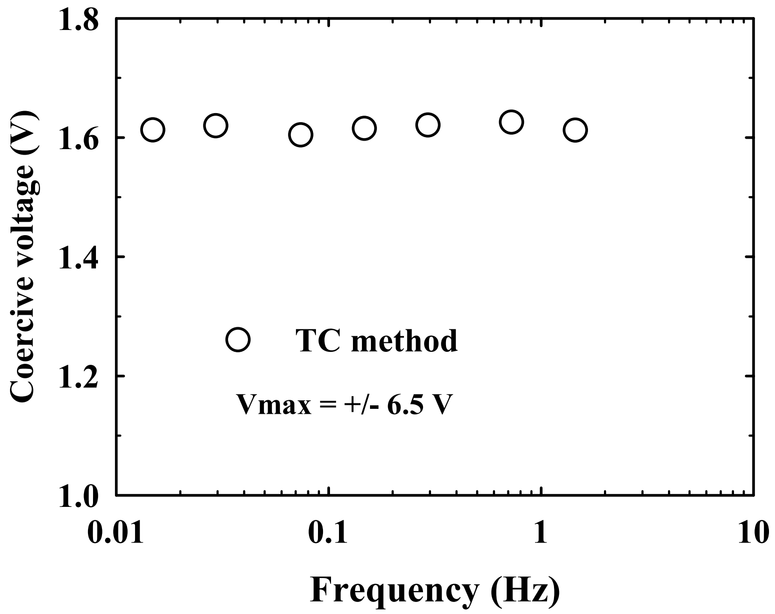

Fig. 7-6 Frequency-dependent coercive voltage plot of ferroelectric capacitor obtained from our previous results using the TC method.

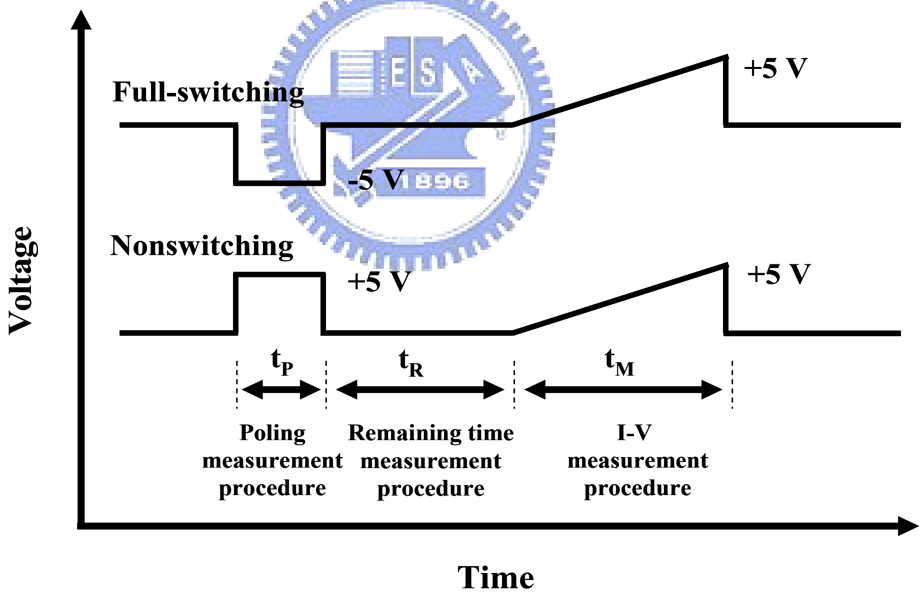

Fig. 7-7 Voltage wave forms for full-switching and nonswitching current measurements. The poling time and remaining time were about 5 ms and 10 s, respectively.

7-3-2. Studies of full-switching and non-switching currents

Figure 7-7 shows two kinds of voltage wave form for switching current versus voltage measurement, which is according to the initial polarization direction of ferroelectric films [40]. One of these wave forms is for the full-switching current measurement and the other is for the nonswitching current measurement. The full-switching and nonswitching currents were measured against and toward an initial polarization direction (poling direction), respectively. In the measurements, the poling time and remaining time were about 5 ms and 10 s, respectively. After the poling time and remaining time measurements, the I-V measurement procedure was performed at the sweeping range (from 0 to 5 V).

In the case of nonswitching current measurement (V_{poling} = +5 V), nonswitching current $I_{ns}(t)$ can be written as $I_{ns}(t) = C \times dV(t)/dt$ and nonswitching charging density P_{ns} can be obtained using the integration of nonswitching current $P_{ns} = 1/A \int I_{ns}(t)dt$. For the full-switching measurement (V_{poling} = -5 V), full-switching charging density can also be obtained using $P_{sw} = \int (I_{ns}(t)/A + dP/dt)\, dt$. The nonvolatile polarization ΔP was thus determined using $\Delta P = P_{sw} - P_{ns}$.

Figure 7-8 shows the switching current characteristics for various poling voltages. For the switching measurement (V_{poling} was changed from 0 to -5 V), the peak switching current increased with poling voltage. Using the integration of full-switching and nonswitching currents, polarization charging densities for various poling voltages were obtained as shown in Fig. 7-9. The nonswitching charging density P_{ns} and full-switching charging density P_{sw} were about 14.01 and 44.185 μC/cm^2, respectively, which are close to the nonswitching charging density (14.22 μC/cm^2) and full-switching charging density (46.43 μC/cm^2) obtained from the hysteresis loops.

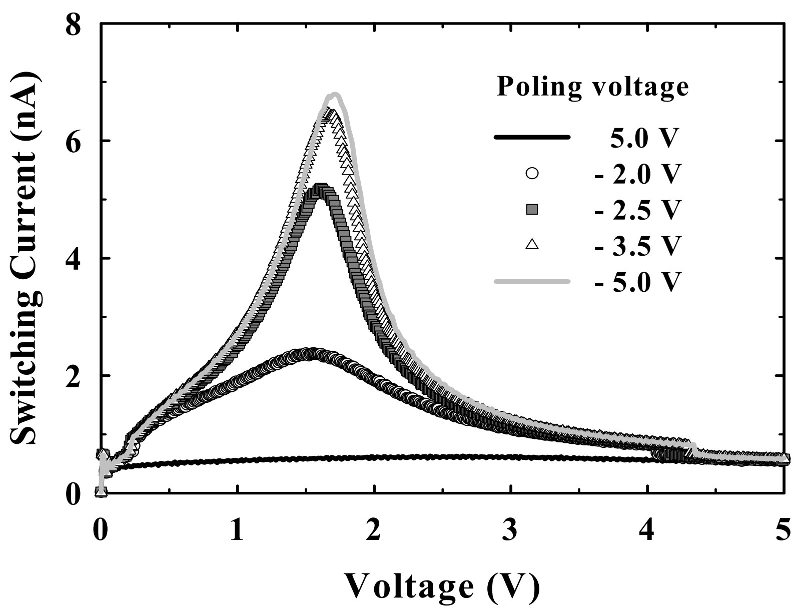

Fig. 7-8 Switching current characteristics of ferroelectric capacitor for various poling voltages.

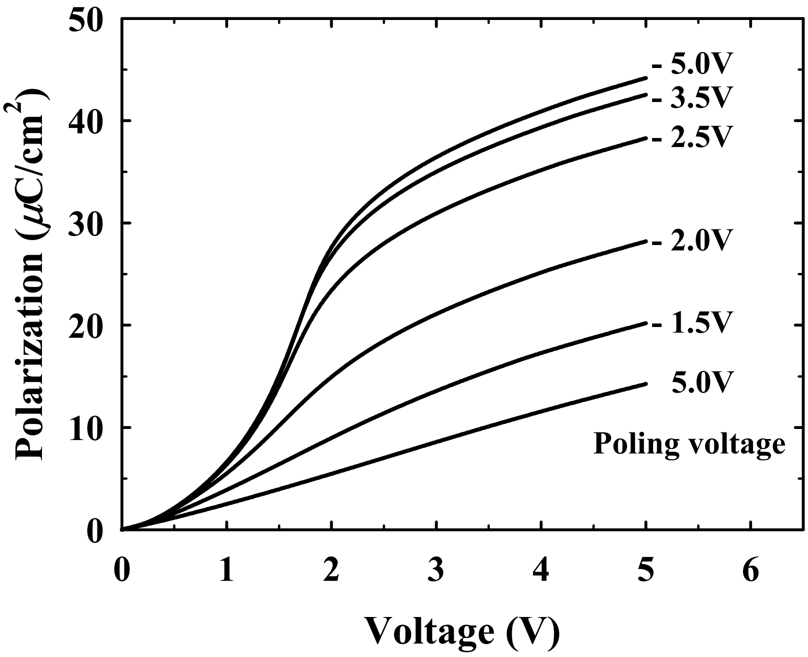

Fig. 7-9 Polarization charge density of ferroelectric capacitor for various poling voltages. The full-switching density and nonswitching charge density are about 44.185 and 14.01 μC/cm^2, respectively.

By combining nonswitching and full-switching current measurements, the retention property of a ferroelectric capacitor can be determined by adjusting remaining time t_R. To construct the nonvolatile polarization ($\Delta P^+ = P_{sw}^+ - P_{ns}^+$ and $\Delta P^- = P_{sw}^- - P_{ns}^-$) of a ferroelectric film, four parameters (i.e., P_{sw}^+, P_{ns}^+, P_{sw}^-, P_{ns}^-) must be measured using nonswitching and full-switching current measurements, where P_{sw}^+ is the positive full-switching charging density, P_{ns}^+ is the positive nonswitching charging density, P_{sw}^- is the negative full-switching charging density, and P_{ns}^- is the negative nonswitching charging density. For each parameter, the time of nonswitching or full-switching current measurement is composed of poling time t_{Poling}, remaining time t_R, and the time of I-V measurement (ranging from 0 to 5 V) t_M. The total time t_T for obtaining nonvolatile polarization (ΔP^+ and ΔP^-) is about $t_T \approx 4 \times (t_R + t_M)$ as poling time is neglected.

7-3-3. Study of dynamic switching current in retention duration

To improve the efficiency of retention measurement, modified voltage wave forms (Fig. 7-10) were introduced to investigate the retention property of the ferroelectric capacitor. The

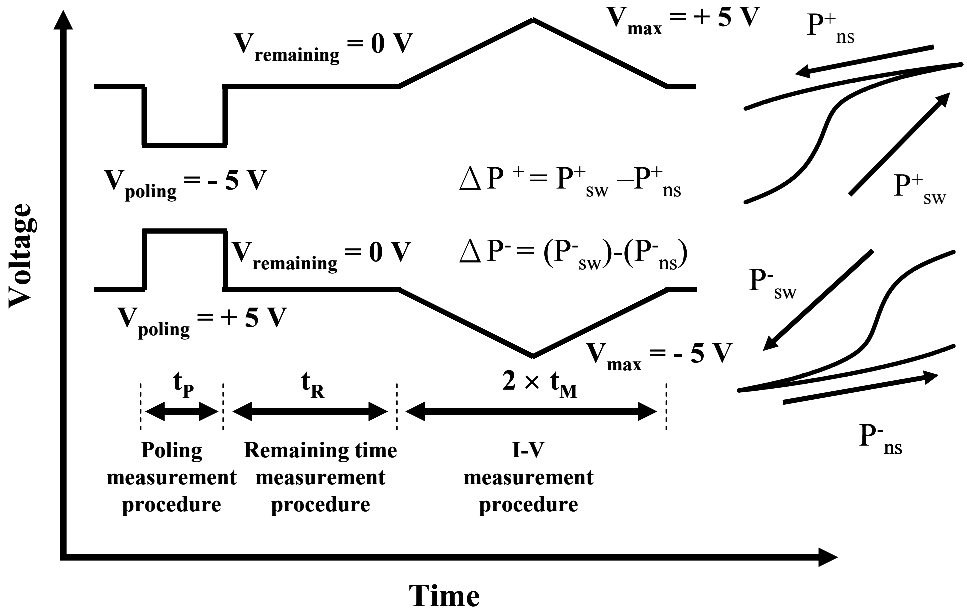

Fig. 7-10 Voltage wave forms for retention polarization measurements. The poling time was about 5 ms and the remaining time was changed from 1 s to 3000 s.

voltage wave form is composed of the poling measurement procedure, remaining time measurement procedure and I-V measurement procedure. In the I-V measurement procedure, voltage was first ranged from 0 to 5 V then immediately back to 0 V. The time of this I-V measurement procedure was about $2\times t_M$. Using the testing profile, the switching charging density (P_{sw}^{+}) and nonswitching charging density (P_{ns}^{+}) can be obtained simultaneously. The total time (t_T) for obtaining nonvolatile polarization (ΔP^{+} and ΔP^{-}) was about $t_T \approx 2\times(t_R+2\times t_M)$, which is shorter than that in § 7-3-2.

After the integration of the half-hysteresis switching current, the full-switching charging density P_{sw} (43.45 μC/cm^2), the nonswitching charging density P_{ns} (14.14 μC/cm^2) and nonvolatile charging density ΔP (29.31 μC/cm^2) can be determined. These values are consistent with those in § 7-3-2. The result indicates that the testing profile can be utilized in the retention polarization measurements. Figures 7-11(a) and 7-11(b) show the positive half-hysteresis switching current characteristics and the P-V plots of the ferroelectric capacitor for various remaining times. The remaining time ranged from 1 to 3000 s and the remaining voltage was fixed at 0 V. As can be seen from the switching current-voltage and P-V plots, the position of peak switching current and the positive coercive voltage of hysteresis loops increased with remaining time t_R. A similar behavior was also found in the

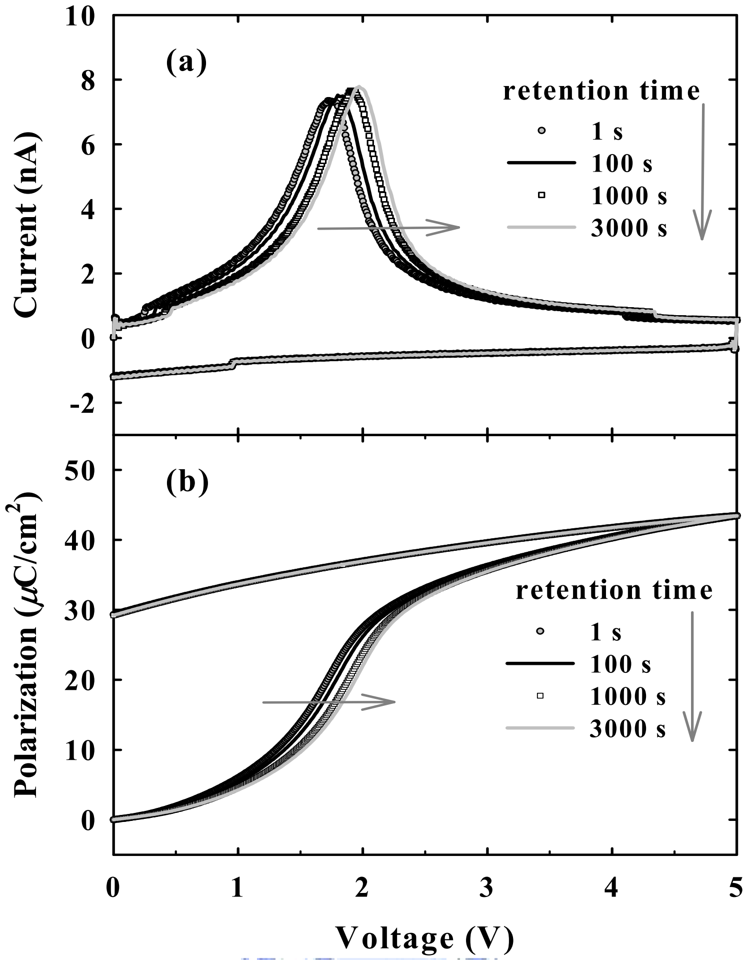

Fig. 7-11 (a) Positive half-hysteresis switching current characteristics and (b) its polarization-voltage (P-V) plots, for various remaining times.

negative half-hysteresis switching current-voltage and P-V plots (Fig. 7-12). These behaviors may be due to the redistribution of space charges with the time after the poling procedure [51], resulting in an increased coercive voltage as remaining time increased. The retention polarization property obtained from these measurements is shown in Fig. 7-13. The result indicates that the nonvolatile polarization of PZT(30/70) capacitor is nearly independent of remaining time at 25 ^{o}C. Additionally, the retention polarization measurement was also performed using RT66A to verify measured results obtained by the I-V measurement method. The pulse widths of the write pulse and read pulse were about 2 ms and the amplitudes of both pulses were about 5 V. Using pulse polarization measurement, nonvolatile polarization can be obtained and the results are also shown. A satisfactory agreement was found between nonvolatile polarization measured using RT66A and that obtained by the I-V measurement method. The results indicate that the I-V measurement method can also be utilized in the retention polarization measurement using the testing profile of Fig. 7-10.

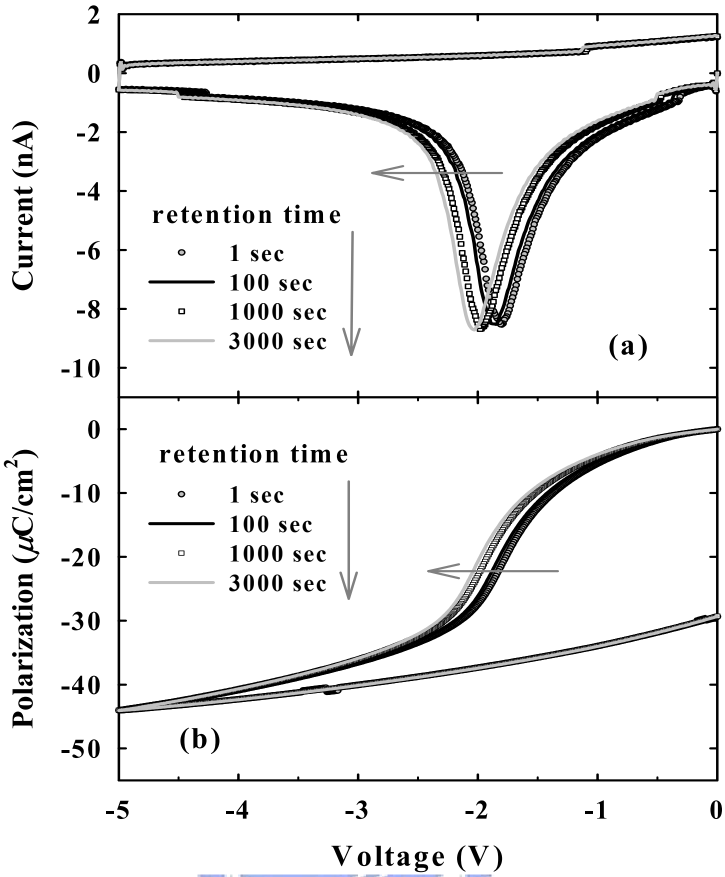

Fig. 7-12 (a) Negative half-hysteresis switching current characteristics and (b) its polarization-voltage (P-V) plots, for various remaining times.

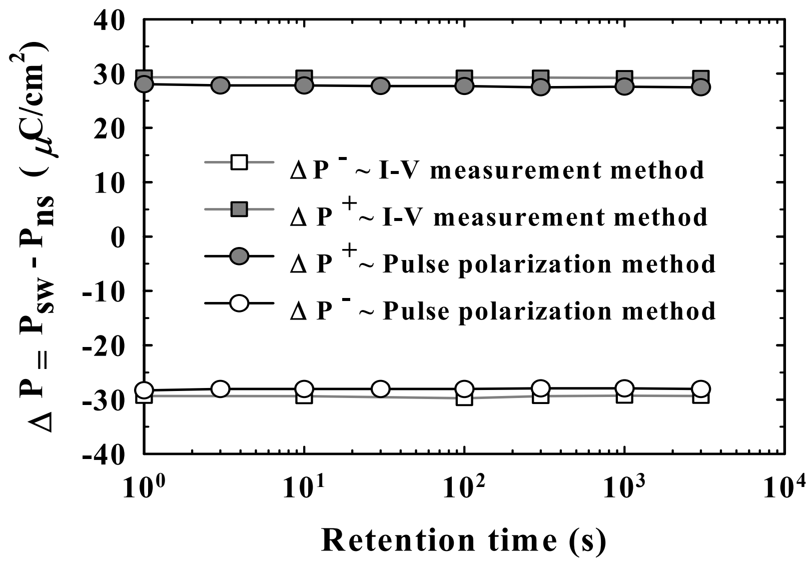

Fig. 7-13 Nonvolatile polarization (ΔP^{+} and ΔP^{-}) versus remaining time plot (retention property) obtained by I-V measurement method and pulse polarization method, for 250-nm-thick PZT(30/70) film.

7-3-4. Switching current characteristics for various depolarized biases

As reported elsewhere [40], the peak switching current becomes smaller with increasing delay time and the switching charge density obtained from leakage current density is about ten times larger than that from remanent polarization. It was speculated that the phenomenon arises following the switching of space charge.

To study the phenomenon of space charge switching, the voltage wave forms were designed to measure the switching current properties for various depolarized biases, as shown in Fig. 7-14. A negative pulse (-5 V) was first applied to change the initial polarization direction. Next, another positive pulse (from 0.5 to 5 V) was utilized to depolarize the ferroelectric films. A measurement procedure was then performed to determine the half-hysteresis switching current characteristics. Between procedures, a remaining time measurement procedure was inserted. The remaining time and remaining voltage were about 10 s and 0 V, respectively.

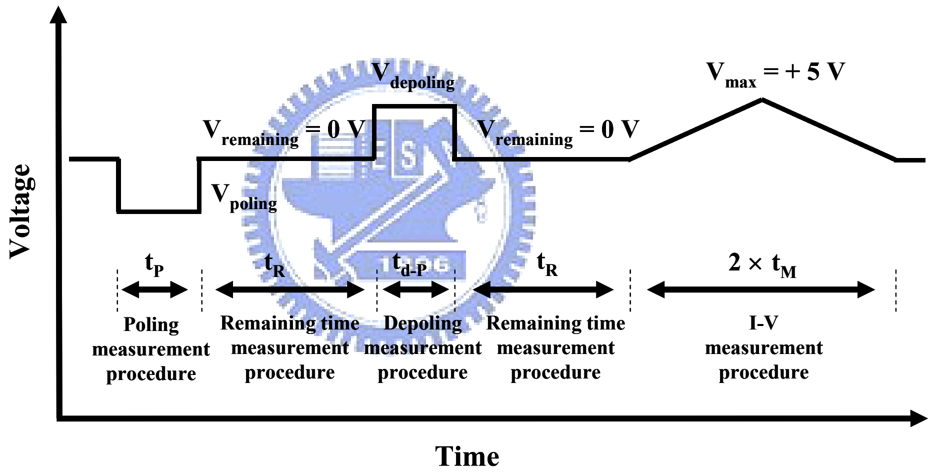

Fig. 7-14 Voltage wave forms of depolarization measurement. The poling time and remaining time were about 5 ms and 10 s, respectively.

Figure 7-15 depicts the switching current characteristics for various depoling voltages. The figure shows that the peak switching currents are almost identical and only a slight decrease in switching current is found in the low-voltage region as the depoling bias of about 1 V is less than the coercive voltage. Additionally, the switching current at such a low-voltage region (< 0.7 V) is almost close to that obtained using a depoling bias of 5 V. This indicates that the slight decrease in switching current may be attributed to the reversible component of polarization charge or the switching of space charge during the depoling procedure. When the depoling bias is close to the coercive voltage, an obvious reduction in the peak switching current is observed and the peak of switching current moves to the high-voltage region with increasing depoling bias. This peak almost disappears as depoling bias exceeds 2.5 V even though the depoling time is about 5 ms.

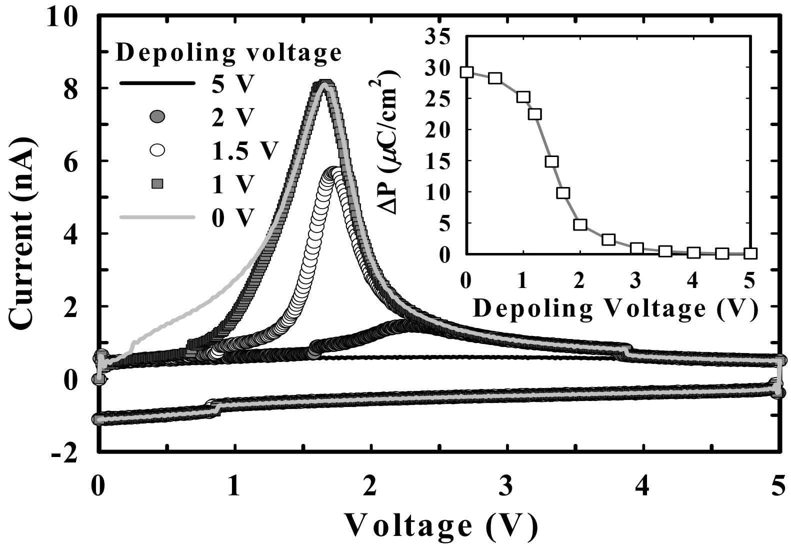

Fig. 7-15 Switching current characteristics for various depoling voltages, for 250-nm-thick PZT(30/70) film. The inset represents nonvolatile polarization (ΔP) versus depoling voltage plot.

The inset in Fig. 7-15 shows the relevant result of nonvolatile polarization calculated from the half-switching current plots. It was found that the polarization states are partially reversed as the depoling voltage is smaller than coercive voltage and the polarization charge density decreases markedly with increasing depoling bias. When the depoling voltage exceeds 3.5 V, the polarization states of ferroelectric films are nearly reversed, which is consistent with the fact that the hysteresis loops of the PZT(30/70) capacitor saturate as the applied voltage exceeds 3.5 V.

7-3-5. Temperature effect of switching current characteristics and P-V loops

To study the temperature effect of switching current, the I-V measurements for various temperatures were performed. The measurement temperature was changed from root temperature (~ 20 ^{o}C) to 125 ^{o}C. The measuring delay was about 1 s. To avoid the destruction of ferroelectric property of PZT capacitor, the applied bias of the I-V measurement was from 0 to 4 V. The relevant results are shown in Fig. 7-16. As can been seen, the leakage current at the bias of 4V increased with the measurement temperature. At such a high temperature of 125 ^{o}C, the conduction current is no longer negligible, which may result in the shape-distortion of P-V curve. Figure 7-17 depicts the switching current characteristics for the

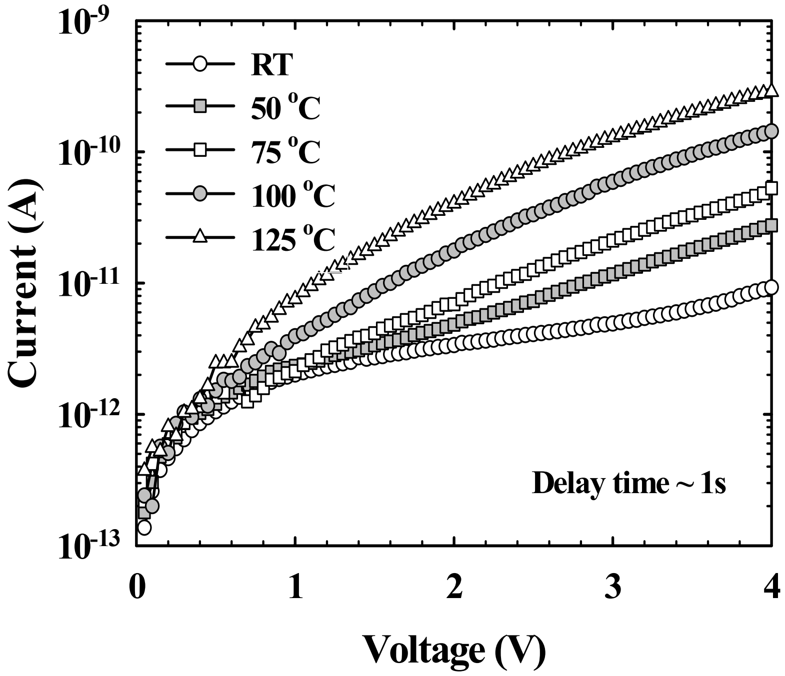

Fig. 7-16 Leakage current characteristics measured at various temperatures, for 250-nm-thick PZT(30/70) film. The delay time of this measurement was about 1 s.

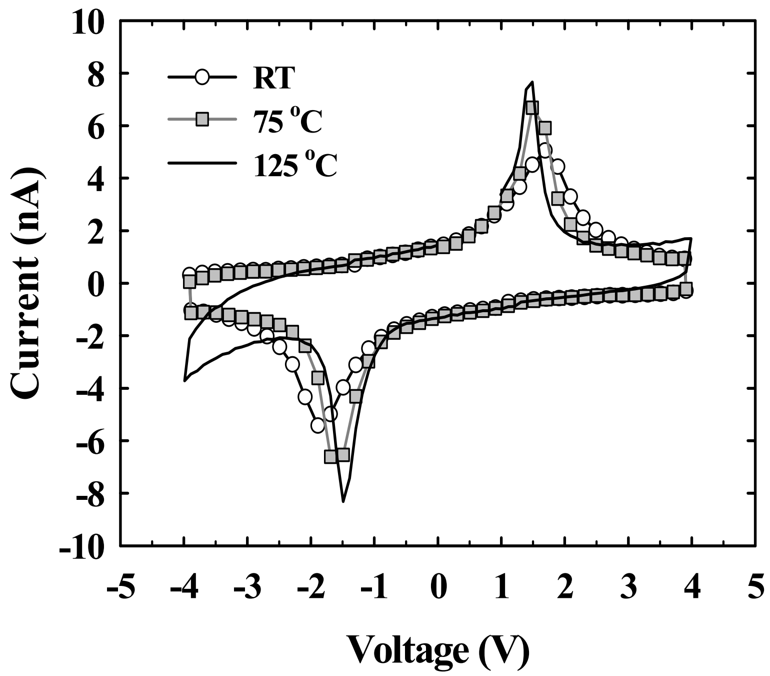

Fig. 7-17 Switching current characteristics measured at various temperatures, for 250-nm-thick PZT(30/70) film.

PZT capacitor measured at various temperatures. As temperature increased, a considerably increase in switching current appears at high-voltage region and the position of peak current region moves to low-voltage region. This movement of the current peak indicates that the coercive voltage of PZT capacitor reduced with increasing the measurement temperature.

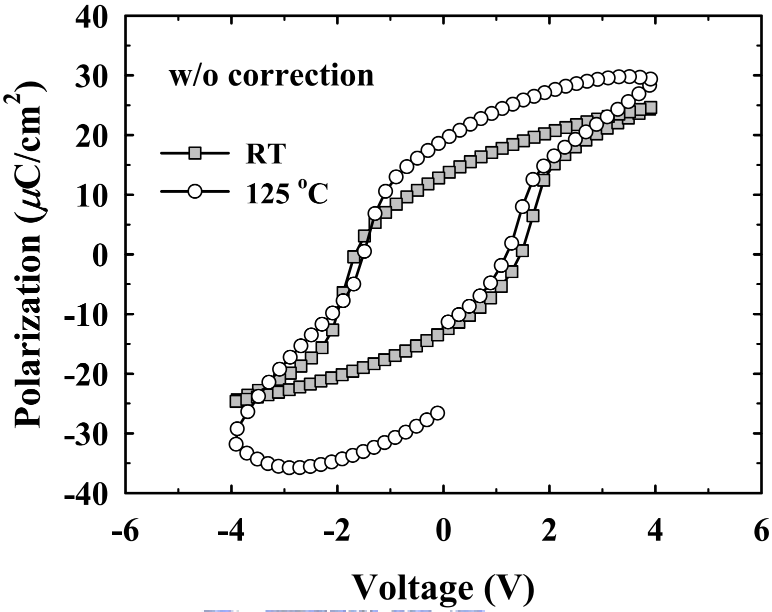

Fig. 7-18 Polarization-Voltage loops obtained at various measurement temperatures, for 250-nm-thick PZT(30/70) film.

Figure 7-18 shows the P-V curves measured at various temperatures. As can be seen, the shape-distortion exhibits in the P-V curve of the PZT capacitor measured at 125 °C. Additionally, an enlarged remnant polarization was also found, which could be misleading. To study further the temperature effect of the remnant polarization, a test profile was designed to perform the non-switching measurement, as shown in Fig. 7-19(a). Using the same settling parameter of hysteresis measurement (Fig. 7-19(b)), the non-switching current characteristics were obtained. The relevant results are shown in Fig. 7-20. For comparison, the hysteresis switching characteristics are also shown in this figure.

Using $q^i(t,V) = I_s^i(t_1^i,V) \times \Delta t_1^i - I_{ns}^i(t_2^i,V) \times \Delta t_2^i$, the effect of conduction current and linear capacitance can be eliminated to yield a corrected P-V curve. The results concerning $q^i(t,V)$ are shown in Fig. 7-21, where $q^i(t,V)$ is the product of the difference in time (Δt) and the currents ($I_s^i(t_1^i,V)$ or $I_{ns}^i(t_2^i,V)$), $I_s^i(t_1^i,V)$ is the full-switching hysteresis current, $I_{ns}^i(t_2^i,V)$ is the non-switching current, t is the time, and V is the voltage. By exploiting $Q(V) = \sum q^i(t,V)$, the polarization charge can be obtained to construct the corrected P-V curves. Figure 7-22 shows the result concerning the corrected P-V curves measured at different temperature. It was found that ferroelectric hysteresis loops of PZT capacitor measured at different temperature are virtually the same and that only a reduced coercive voltage exhibits in the corrected P-V curves as measurement temperature increased.

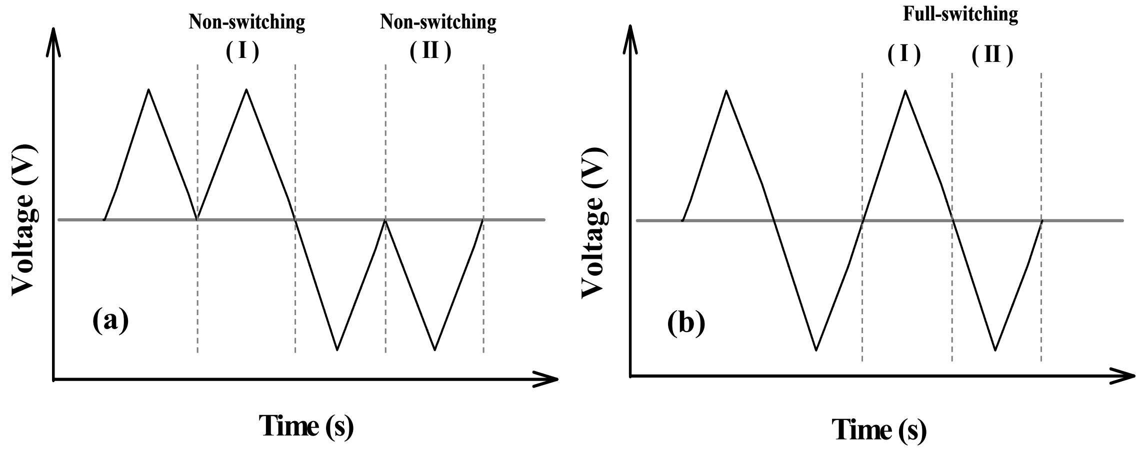

Fig. 7-19 Testing profiles for (a) non-switching hysteresis current characteristic and (b) full-switching hysteresis current characteristic.

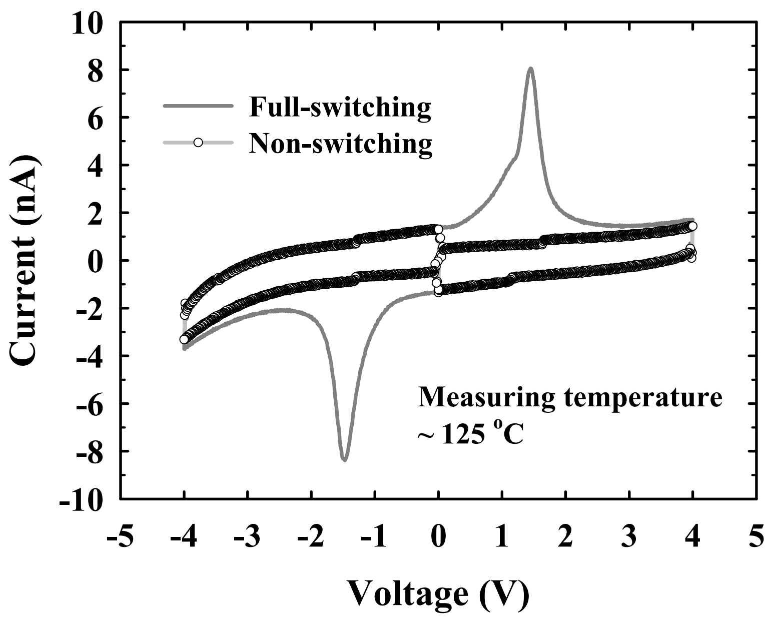

Fig. 7-20 (a) Full-switching hysteresis current characteristics and (b) non-switching hysteresis current characteristics measured at the temperature of 125 °C, for 250-nm-thick PZT(30/70) film.

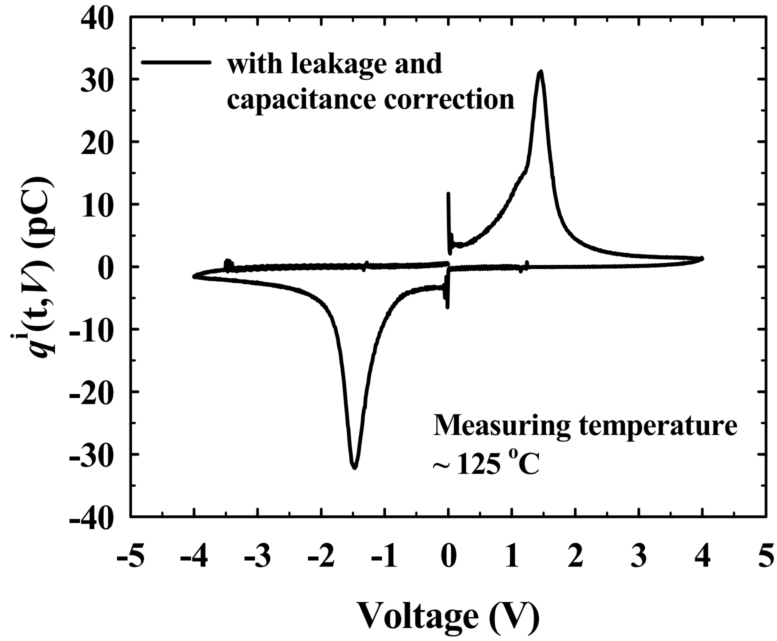

Fig. 7-21 $q^i(t,V)$ - voltage plot of ferroelectric capacitor obtained at the measurement temperature of 125 °C, for 250-nm-thick PZT(30/70) film.

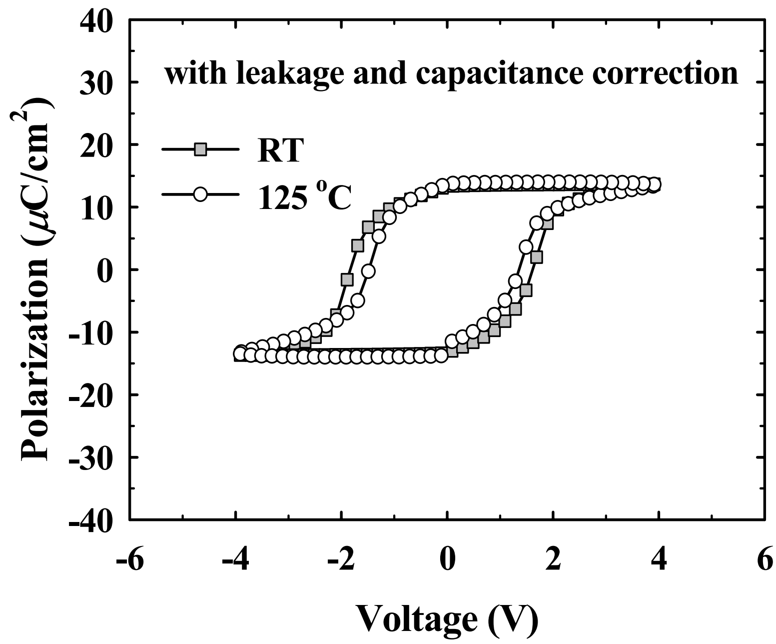

Fig. 7-22 Corrected ferroelectric hysteresis loops measured at various temperatures, for 250-nm-thick PZT(30/70) film.

7-4. Summary

In this chapter, the current-voltage (I-V) measurement method was applied to determine the hysteresis switching current characteristics of ferroelectric capacitors to obtain the polarization-voltage (P-V) loops. The similarity between the P-V curves obtained by the virtual ground and I-V measurement methods implies that the I-V measurement method can also be utilized in the hysteresis measurements. The full-switching and nonswitching current characteristics were investigated using two kinds of poling measurement. The nonvolatile polarization (ΔP) calculated from the poling measurements is consistent with that obtained from P-V loops. Additionally, the dynamic switching current characteristic and the retention property of PZT(30/70) capacitor were also investigated by the modified poling measurements. An increased coercive voltage of half P-V curves was observed as remaining time increased. Moreover, the depolarized characteristics of ferroelectric capacitors and the phenomenon of space charge switching were also investigated using another modified poling profile. Furthermore, the temperature effect of switching current characteristics of ferroelectric capacitor was also discussed and the corrected P-V loops were constructed using the I-V measurement method. The findings indicate that the I-V measurement method constitutes an approach for investigating ferroelectric properties.