Application of an Ultrafast Photonic Technique to Study Polarization Switching Dynamics of Thin-Film Ferroelectric Capacitors

J. Li, H. Liang, B. Nagaraj, W. Cao, Chi H. Lee, *Fellow, IEEE, Fellow, OSA*, and R. Ramesh

***Abstract*—We demonstrate the use of jitter-free ultrafast rise-time electrical pulses generated by a semiconductor photoconductive switch with femtosecond laser illumination to study the fast polarization switching process in fully integrated, ferroelectric PNZT thin-film capacitors. The necessary conditions for high-speed polarization switching detection are presented. The switching behavior for various sizes of capacitors and various rise-times of applied voltage pulses are investigated. Circuit influence on the activation field, α, as well as application of the Inshibashi–Merz model, are discussed.**

***Index Terms*—Ferroelectric capacitor, photoconductive switch, polarization switching, pulse method, ultrafast detection.**

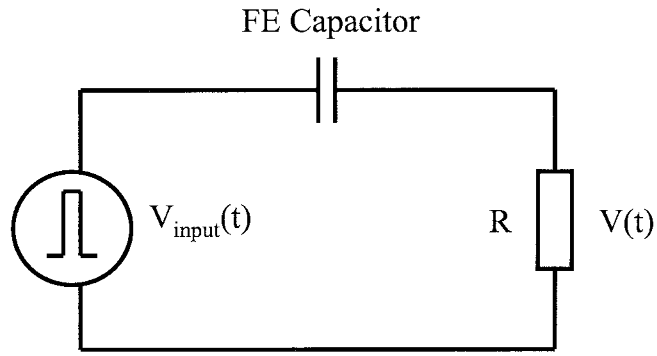

Fig. 1. Equivalent circuit of "pulse method."

I. Introduction

DIFFERENT from linear dielectric materials, ferroelectric materials exhibit a hysterisis loop of polarization as a function of electric field. The application of ferroelectric (FE) capacitors in nonvolatile random-access memories (FeRAMs) is based on the two remnant polarization states and the capability of switching from one state to the other by applying a short voltage pulse [1], [2]. Of importance to the memory application is the device speed, or, in other words, how fast the polarization switching process is.

The polarization switching process is commonly studied by the so-called pulse method with two obvious advantages: 1) it provides a direct measure of the polarization switching time and 2) it can be used for almost all kinds of ferroelectric materials. With the pulse method, Larson *et al.* have reported a polarization switching time of ~390 ps for PZT samples [3], [4]. However, the theoretically predicted intrinsic polarization switching time is ~50 ps [5]–[9]. The measurement of the polarization switching time is hindered by a variety of circuit-related delays such as the rise-time of the input electric pulses, timing jitter, and RC time constant of the circuit. To obtain the intrinsic polarization switching time, the rise-time of the input electric pulse and RC_{FE} time constant must be at least of the same order as the intrinsic switching time. Experimentally, the rise-time of the input electrical pulse, which is the most important limiting factor of the setup, is of great concern. The faster the rise-time, the better the temporal resolution. In fact, the best input electrical waveform for the experiment is a step-function pulse with extremely fast rise-time and constant amplitude thereafter. Such an electric pulse is not easily attainable by electronic means. However, a microwave photonic technique using a photoconductive switch actuated by an ultrashort laser pulse is uniquely suited for producing such a pulse [10], [11]. In this paper, this technique is used with the pulse method to realize the study of the fast polarization switching process. A femtosecond laser triggered experimental setup with time resolution of ~50–100 ps is established to comprehensively investigate the polarization switching behavior of fully integrated $Pb(Nb, Zr, Ti)O_3$ capacitors. A switching time of $t_s = 220$ ps was measured for the smallest capacitor studied. A characteristic switching time $t_0 = 70$ ps was extracted from the Ishibashi–Merz model. Both t_s and t_0 so obtained, to the best of our knowledge, are the smallest among those reported.

This paper is organized as follows. Section II presents circuit simulation of the pulse method, which not only gives rise to the conditions required to obtain the intrinsic polarization switching time but also helps in understanding the experimental results and differentiating between the circuit influences and the intrinsic effects. The detailed experimental setup is described in Section III. The results are presented and discussed in Section IV. Section V gives a conclusion.

II. Simulation

In this section, we take up the subject of numerical analysis of the measurement circuit. The equivalent circuit of the pulse method is shown in Fig. 1. It consists of a pulse generator that provides a positive–positive or negative–positive pulse train, a ferroelectric capacitor under test, and a sampling oscilloscope

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J. Li, H. Liang, W. Cao, and C. H. Lee are with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20742 USA (e-mail: jjli@glue.umd.edu; hliang@glue.umd.edu).

B. Nagaraj and R. Ramesh are with the Materials Research Science and Engineering Center, University of Maryland, College Park, MD 20742 USA.

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with a 50-Ω input impedance. Since the ferroelectric capacitor is a component of the measurement circuit, an understanding of the circuit performance makes it easy to find out what critical circuit parameters will affect the polarization switching process.

By assuming that the capacitor is a linear dielectric capacitor, the ordinary differential equation of the circuit is given by

$$i(t)R + \frac{\int_0^t i(t)dt}{C} = V_{\text{input}}(t) \qquad (1)$$

where $i(t)$ is the current flowing through the oscilloscope, which is represented by a 50-Ω resistor R; $i(t)$ is also the displacement current flowing through the capacitor. C is the capacitance of the dielectric capacitor. $V_{\text{input}}(t)$ is the step-like input electric pulse to the capacitor. The displacement current $i(t)$, which is directly related to the polarization of the capacitor, can be obtained by

$$i(t) = \frac{V(t)}{R} \qquad (2)$$

where $V(t)$ is the output response displayed on the oscilloscope, which is just the voltage drop across the 50-Ω node. The voltage drop across the capacitor is given by

$$V_{\text{cap}}(t) = V_{\text{input}}(t) - V(t) = \frac{\int_0^t i(t)dt}{C}. \qquad (3)$$

Equation (1) can be solved by Laplace transform if $V_{\text{input}}(t)$ is a perfect step function. However, the rise-time of $V_{\text{input}}(t)$ can never be zero. Numerical calculation is required to solve this equation. Simulation is carried out with the Runga–Kutta method. During simulation, the input step-like electric pulse $(V_{\text{input}}(t))$ is mathematically modeled by

$$V_{\text{input}}(t) = A * \exp\left[-\exp\left(-k(x - x_c)\right]\right. \qquad (4)$$

where A controls amplitude, K controls rise-time, and X_c controls position.

The ferroelectric capacitor, which exhibits a hysterisis-type relationship between polarization and electric field as shown in Fig. 2, is of our concern. The simulation of such nonlinear capacitors is realized as follows. From Fig. 2, the polarization reversal process (P^*) consists of both domain polarization switching (ΔP) and linear dielectric polarization change $(P^\wedge)$, which is the charging or discharging of the capacitor. To simplify the analysis, the P^* process can be represented by a simple linear capacitor with capacitance $C_{\text{nonlinear}}$ defined by

$$C_{\text{nonlinear}} = \frac{P^* \cdot A_{FE}}{V_{\text{applied}}}. \qquad (5)$$

The $P^\wedge$ process can be represented by C_{linear} defined by

$$C_{\text{linear}} = \frac{P^\wedge \cdot A_{FE}}{V_{\text{applied}}} \qquad (6)$$

where A_{FE} is the area of the capacitor. Both the P^* and $P^\wedge$ values can be obtained directly from the hysterisis loop in Fig. 2. With $V_{\text{input}}(t)$, $C_{\text{nonlinear}}$, and C_{linear} available, voltage responses corresponding to the P^* and $P^\wedge$ processes, which are represented by $V(t)_{P^*}$ and $V(t)_{P^\wedge}$, can be simulated. The

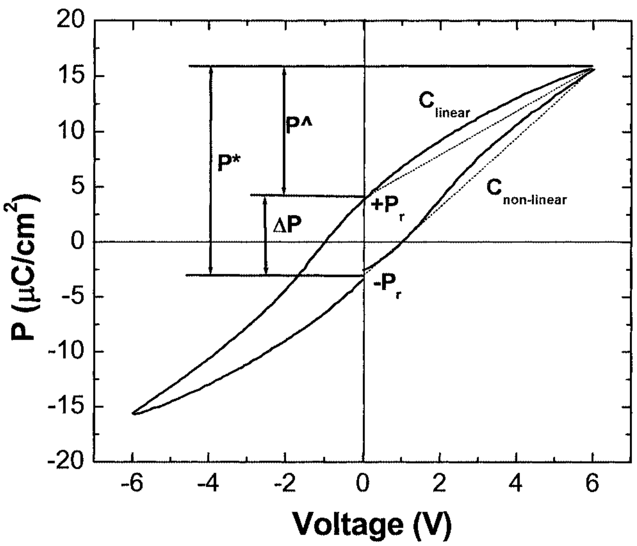

Fig. 2. Hysterisis loop of a thin-film PNZT capacitor. $P^\wedge$ and P^* correspond to the nonswitched and switched polarization changes.

$\Delta V(t)$ response, which corresponds to the domain polarization switching ΔP process, is given by

$$\Delta V(t) = V(t)_{P^*} - V(t)_{P^\wedge}. \qquad (7)$$

In this paper, we are mainly concerned about the $\Delta V(t)$ response, which gives us a way to understand the fundamental physics behind the domain polarization switching of ferroelectric capacitors.

The capacitor area and rise-time of the input electric pulse are two parameters characterizing the measurement circuit. Therefore, simulations were carried out to study their influence on polarization switching, specifically, on the output response $V(t)$. Fig. 3(a) and (b) shows the output responses as a function of time for various capacitances and rise-times, respectively. A response with a longer tail is expected for larger capacitances due to the circuit RC_{FE} time constant, showing the need for small-size capacitors to realize ultrafast polarization switching detection. Similarly a slow rise-time of input pulse corresponds to a slow response. Even with an ultrafast polarization switching process, the slow rise-time makes it impossible to resolve the fast processes that are embedded within. This is exactly the reason that a step-like electric pulse with a fast rise-time is needed. Fig. 3(a) and (b) also shows that the shape of the output response changes with capacitance and rise-time. With increasing rise-time (keep capacitance constant) and decreasing capacitance (keep rise-time constant), the shape of the output response becomes increasingly symmetric. It is important to understand the shape change since it can directly tell when the RC_{FE} effect dominates and when rise-time dominates. In fact, it is the impedance ratio between the capacitor and load resistor, denoted as $B = |(1/j\omega C)/R|$, that influences the shape of the output response. From a circuit point of view, the impact of varying the capacitance on the shape of the output response is the same as that of varying the rise-time. C is the capacitance, R is 50 Ω, and ω is the angular frequency if the applied voltage is sinusoidal. In our case, the applied voltage is a step-like electric pulse with a finite rise-time. It is reasonable

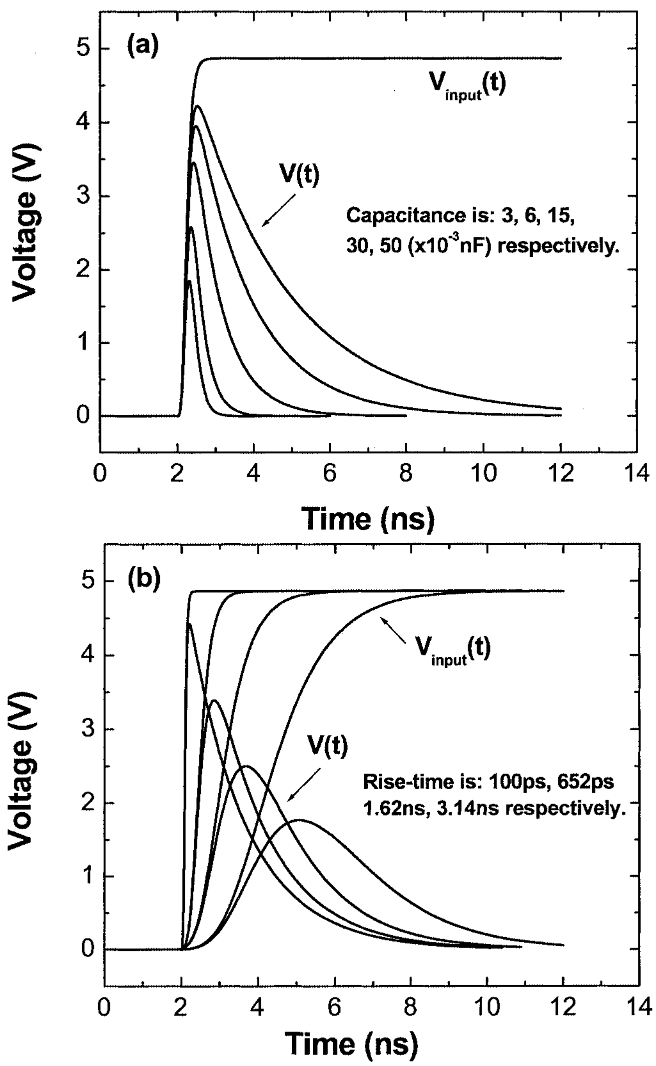

Fig. 3. Simulated output responses $V(t)$ for various (a) capacitor sizes and (b) rise-times of the input electrical pulse $V_{input(t)}$. In (a), the rise-time of the input electric pulse is kept constant at 300 ps. In (b), the capacitance is kept constant at 3e-2 nF.

to use this rise-time information to derive an effective $\omega_{effective}$. In our case, we have used 2π/(rise-time) to represent $\omega_{effective}$. Thus, it is possible to roughly estimate the rise-time required for certain capacitors. Faster rise-times would be a waste for large-size capacitors.

Next, simulations were carried out to study the rise-time dependence of the $\Delta V(t)$ response [defined by (7)] for a certain ferroelectric capacitor. A 22.5 μ × 25 μm^2 PNZT capacitor was chosen for this purpose. The corresponding P^*, $P^\wedge$, $C_{nonlinear}$, and C_{linear} are 28.64 $\mu C/cm^2$, 16.01 $\mu C/cm^2$, 32 pF, and 17.9 pF, respectively. Step-like input electric pulses with 5-V amplitude and various rise-times were used in simulation. Fig. 4 shows the $\Delta V(t)$ responses for various rise-times of input electric pulses. Faster rise-times correspond to faster $\Delta V(t)$ responses. We have observed from Fig. 3 that the rise-time and capacitance will influence the shape of output response $V(t)$. Consequently, the shape of $\Delta V(t)$ will also be influenced.

In conclusion, simulation directly indicates that in order to accurately detect the fast polarization switching process, fast rise-time of input electric pulses and small circuit RC_{FE} time constant are essential.

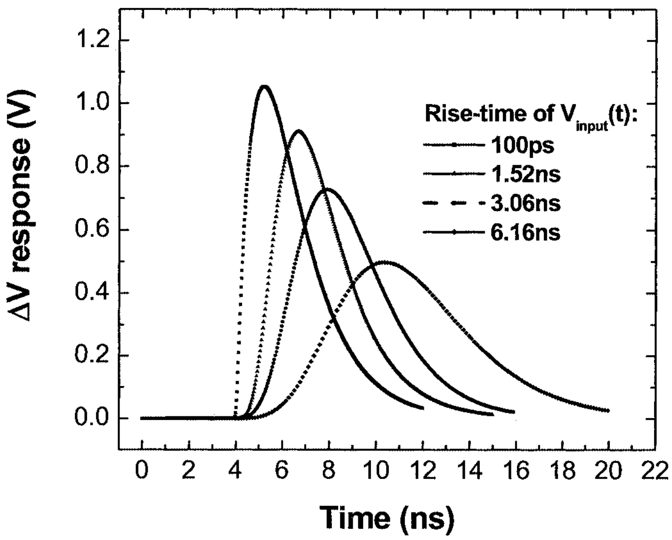

Fig. 4. Simulated $\Delta V(t)$ responses for various rise-times of input electric pulses.

III. Experimental Arrangement

With the ~50 ps theoretically estimated polarization switching time, a setup with time resolution of at least the same level is required. Since rise-time of input electric pulse is a limiting factor, approaches to generate step-like pulse with less than 50-ps rise-time are essential. In our experiment, a semiconductor photoconductive switch was used as a fast "pulse generator" to produce step-like pulse with fast rise-time as short as ~50–100 ps and amplitude up to 10 V. The resistance of the photoconductive switch in its dark state (or high resistance state), without laser illumination, is ~ 100 kΩ to the order of MΩ. With laser illumination, the electron-hole pairs are generated and the switch is in its conductive state, with a resistance of a few Ω. Thus a voltage pulse is generated. Theoretically the rise-time of the voltage pulse should be in the picosecond region. In practice, it usually only reaches the subnanosecond region. The rise-time depends on laser power, bias, etc. A Si photoconductive switch is chosen to generate the step-like pulse because the carrier lifetime in Si is on the order of microseconds. Constant amplitude voltage pulse after turn-on enables one to systematically study the polarization switching process for ferroelectric capacitors of different sizes. Si switches with interdigitated fingers are patterned in coplanar transmission-line structures with 50-Ω characteristic impedance in order to transmit high-frequency signal with little dispersion. Another issue worth mention is the effects of the dynamics of the photoconductive switch on final experimental results. Basically, the capacitance of the Si switch is very small (on the order of tens of fF) compared to that of the ferroelectric capacitor (on the order of tens of pF); and what we are concerned with is just the step-like electric pulse generated by such a switch, which already includes the influence from the switch's time-varying capacitance and time-varying conductance. Therefore, in this case, the dynamics of the Si switch will not affect experimental results.

The detailed experiment arrangement is shown in Fig. 5. A conventional pulse generator is used to produce the writing pulse that sets the ferroelectric device to the stable positive

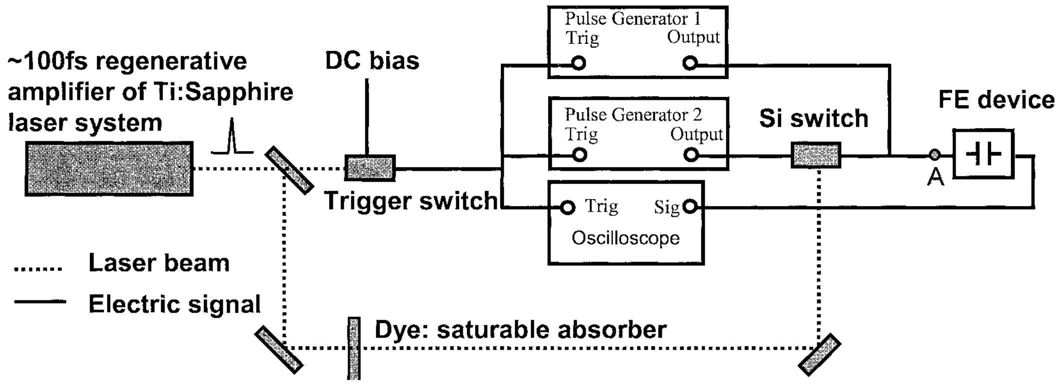

Fig. 5. Experimental setup.

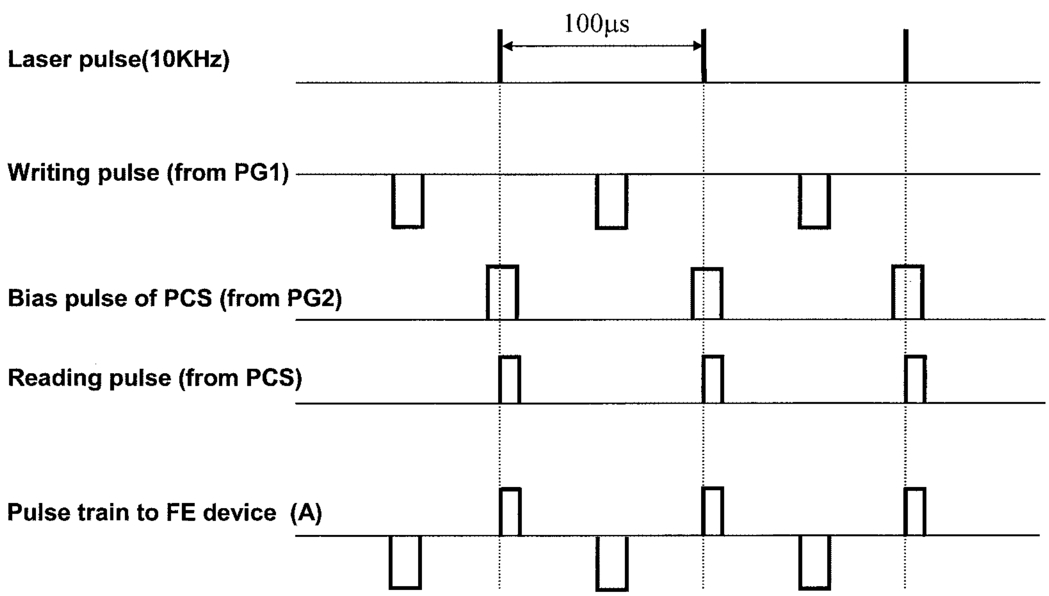

Fig. 6. The time sequence of each pulse train.

or negative polarization state by applying positive or negative square pulses. Electric pulses with $\sim$7 ns rise-time, 8 V amplitude, and 1 μs duration are used as the writing pulse. Femtosecond laser pulses from the regenerative amplifier of a Ti:Sapphire laser system (repetition rate $=$ 10 KHz, laser pulse width $\sim$100 fs) illuminate the Si switch to produce a reading pulse with fast rise-time, sufficiently large amplitude, and long duration. The bias of the Si switch is provided by another conventional pulse generator. The delay between the two pulse generators is controlled such that the writing pulses sit in the middle of the reading pulses. The output pulse train to the ferroelectric device is the combination of the writing and reading pulse trains. The new pulse train can be a sequence of negative–positive pulses or positive–positive pulses. A negative–positive pulse sequence applied to the ferroelectric device produces a switched response $V(t)_{P^*}$, while a positive–positive sequence gives the nonswitched response $V(t)_{P^\wedge}$. By subtracting the nonswitched response from the switched response, $\Delta V(t)$ response is obtained, which gives information depending only on the domain polarization switching ΔP. An HP54750A digitizing oscilloscope with a time resolution of $\sim$20 ps is used to monitor the output polarization switching response. The input impedance of the oscilloscope is 50 Ω, which is impedance-matched to the transmission line to make sure that there is no signal reflecting back to the setup. Fig. 6 shows the timing sequence of each pulse train. All instruments are synchronized by a low jitter trigger signal generated by a photodiode.

Fully integrated, $Pt/(La_{0.5}Sr_{0.5})CoO_3/\ Pb(Nb_{0.04}Zr_{0.28}Ti_{0.68})\ O_3/(La_{0.5}Sr_{0.5})CoO_3/Pt$ ferroelectric capacitors with a thickness of 200 nm were used in this study. Details of the growth and long-term properties are reported elsewhere [12]. The bond pads were wire bonded and the device was inserted into 50-Ω microstrip transmission lines for minimum dispersion.

Due to high-speed transmission lines and the high-bandwidth sampling oscilloscope, the time resolution of this setup depends only on the rise-time of the electric pulse generated by the Si switch, which could be $\sim$50–100 ps. Our experiment establishes the capability for detecting fast polarization switching of ferroelectric capacitors. A $\sim$220 ps polarization switching time was obtained for a 4.5 $\times$ 5.4 μm capacitor. Modeling of the switching transients using the Merz–Ishibashi model [5], [6], [13]–[15] yields a characteristic switching time of 70 ps. Moreover, systematic study of polarization switching processes becomes possible.

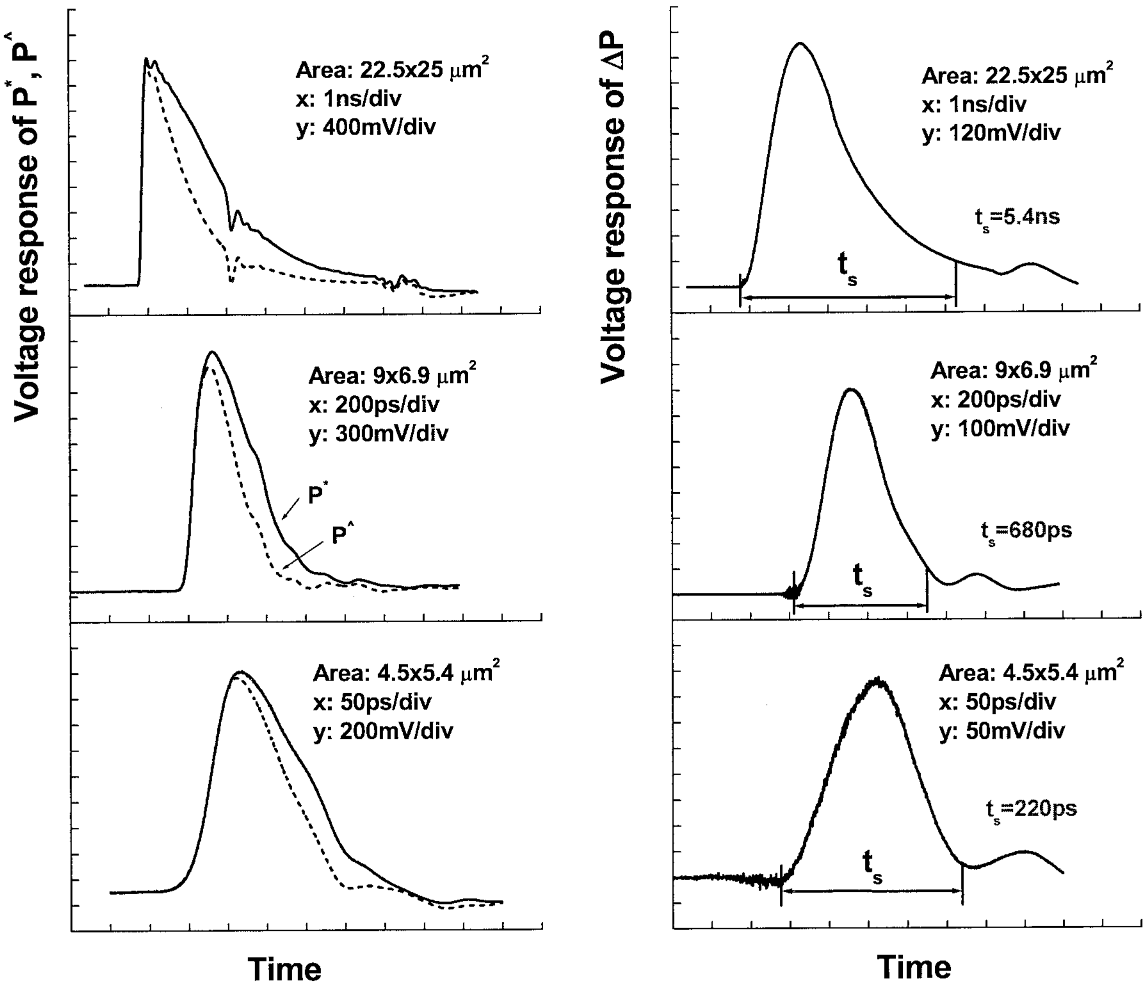

Fig. 7. Voltage responses of P^*, $\mathrm{P}^\wedge$, and $\Delta\mathrm{P}$ processes for various capacitor areas.

IV. Experimental Results

In this section, we report experimental results with the above setup. Our intention is not only to obtain the most "accurate" intrinsic polarization switching time but also to investigate the influence of circuit parameters, specifically the rise-time of the input electric pulse and the capacitor size on the polarization switching process. Fig. 7 shows the voltage responses corresponding to the polarization switching (P^*) and nonswitching $(\mathrm{P}^\wedge)$ cases, and $\Delta\mathrm{P}$ for ferroelctric capacitors with various areas. The polarization switching time $\mathrm{t_s}$, which is defined as the time from the onset point to the point that is 90% down from the maximum, is ~220 ps for the smallest 4.5 × 5.4 μm capacitor. The corresponding applied input electrical pulse, which is generated by a Si switch with a rise-time (10–90%) of 66 ps, is shown in Fig. 8. The fact that the measured switching time $\mathrm{t_s}$ is larger than the rise-time of the input electric pulse suggests that the time resolution of our setup is sufficient for this size capacitor. With the decrease of capacitor area, the $\Delta\mathrm{P}$ response time decreases because of $\mathrm{RC_{FE}}$ limitation. The shape of the P^*, $\mathrm{P}^\wedge$, and $\Delta\mathrm{P}$ responses varies just as expected by simulation with various sizes of capacitors.

An important fundamental question is the limit of domain polarization switching speed in thin-film ferroelectrics. If we assume that the domain walls propagate with a field dependent speed $\mathrm{v} = \mu\mathrm{E}$ and a mobility of $\sim 2.4 \times 10^{-4}\ \mathrm{m^2/Vs}$ [16], then the intrinsic polarization switching time in a 200-nm PNZT film is ~70 ps at 6 V. The experimentally obtained $\mathrm{t_s}$ is inevitably convoluted with circuit parameters. How to extract intrinsic polarization switching time from $\mathrm{t_s}$ is of great interest. The Ishibashi–Merz model is commonly used as a bridge between the experimental data and the intrinsic switching time. In

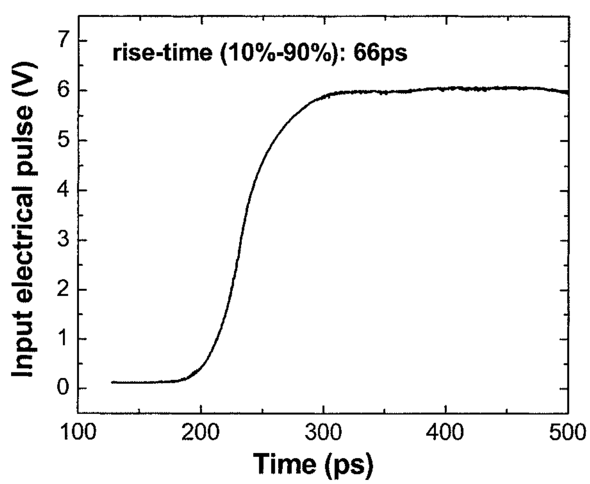

Fig. 8. Input 6-V electric pulse for the 4.5 × 5.4 mm capacitor.

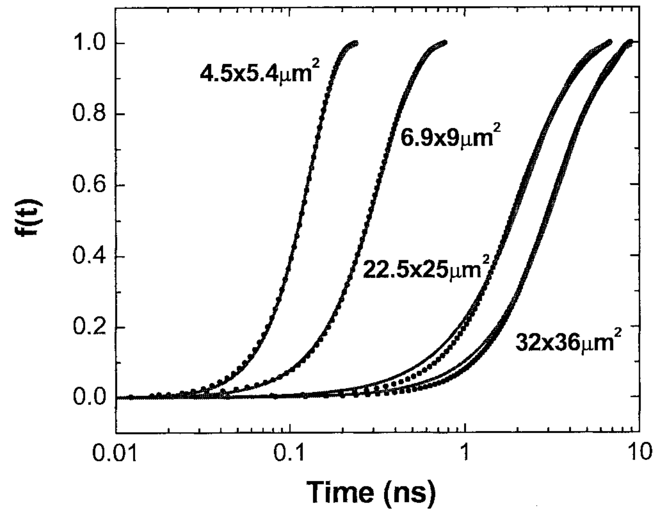

Fig. 9. Plots of measured (dot line) and fitted (solid line) $f(t)$ curves for various capacitor areas.

this model, the switching process can be described in terms of a classical solid-state phase transformation involving nucleation and growth of reverse domains [5], [6], [13]–[15]. The volume fraction of the domains switched as a function of time is given by

$$f(\text{switched}) = 1 - \exp\left[-\Phi(E)\Psi(t)\right] \qquad (8)$$

where $\Phi(\mathrm{E})$ represents the field dependence and $\Psi(\mathrm{t})$ represents the time dependence of the switching process. Combining the Merz model with that of Ishibashi yields

$$f(\text{switched}) = 1 - \exp\left[-\exp\left(-\frac{\alpha}{E}\right)\left(\frac{t}{t_0}\right)^n\right] \qquad (9)$$

where $\mathrm{t_0}$ is called the characteristic switching time. In theory, $\mathrm{t_0}$ represents the time at which 63% polarization has been switched with infinite applied electric field. Being roughly equal to 63% of intrinsic switching time, $\mathrm{t_0}$ is also an intrinsic parameter. n is the dimensionality of the nucleating domain.

$\Delta\mathrm{P}$, which represents the switched polarization, can be obtained by integrating the experimentally obtained current transient $\Delta\mathrm{i(t)}$, where $\Delta\mathrm{i(t)} = [\mathrm{V(t)_{P^*}} - \mathrm{V(t)_{P^\wedge}}]/50\,\Omega$, as shown in (10)

$$\Delta P(t) = \frac{\int_0^\infty \Delta i(t)dt}{A_{FE}} \qquad (10)$$

and $\mathrm{A_{FE}}$ is the area of the capacitor. If the total switched polarization is $\mathrm{P_{total}}$, then f can be expressed as

$$f(\text{switched}) = \frac{\Delta P(t)}{P_{\text{total}}}. \qquad (11)$$

In other words, $f(t)$ is a plot of the normalized fraction of switched domain as a function of time.

Fig. 9 shows the plots of $f(t)$ and the corresponding fit curves using the Ishibashi–Merz model for different capacitor sizes. Using the above model, we extracted the $\mathrm{t_0}$ and dimensionality n values from $f(t)$. Fig. 10(a) and (b) shows the dependence of $\mathrm{t_s}$, $\mathrm{t_0}$, and n on capacitor size. Both $\mathrm{t_s}$ and $\mathrm{t_0}$ decrease linearly with area, illustrating the $\mathrm{RC_{FE}}$ time limitation.

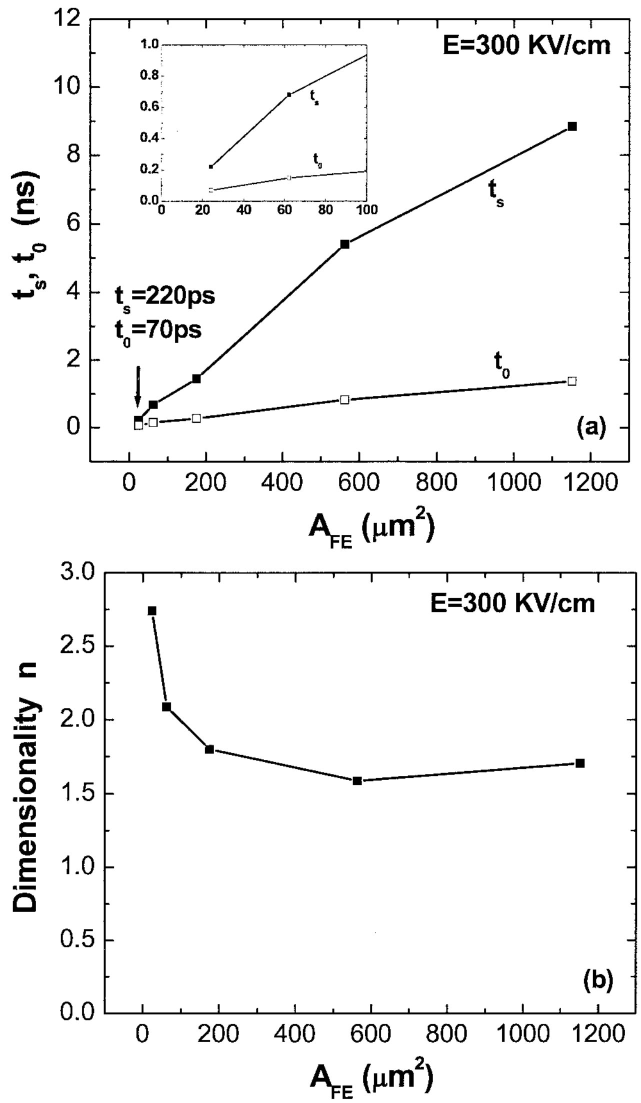

Fig. 10. (a) Polarization switching time $\mathrm{t_s}$, characteristic switching time $\mathrm{t_0}$. (b) n as a function of capacitor area. The inset shows the front part of (a).

A 500-kV/cm activation field [12] is used in fitting the experimental data, which yields a $\mathrm{t_0}$ value of 70 ps and an n value of 2.7 for the 4.5 $\times$ 5.4 μm capacitor, suggesting the three-dimensional growth of the reverse domain. The fitting parameter $\mathrm{t_0}$, which is intrinsic, should not be a parameter depending on capacitor area. However, our data show that $\mathrm{t_0}$ varies with capacitor area, although this change is less than that of $\mathrm{t_s}$. The reason for this discrepancy could be that the circuit factors in the polarization switching process are not considered by the Ishibashi–Merz model. Fig. 10(b) also shows that n varies with the capacitor area. Is this variation intrinsic or circuit parameter related? We will discuss this question shortly.

Fig. 11 shows the dependence of the nonswitched polarization $(\mathrm{P^\wedge})$, switched polarization $(\mathrm{P^*})$, and their difference $\Delta\mathrm{P}$ on capacitor size. Since calculation of polarization has already taken into account the area, the $\Delta\mathrm{P}$ value should be the same. However, there is an obvious decrease of polarization for the 4.5 $\times$ 5.4 μm capacitor. The reason for this could be that the effective area of this capacitor is much smaller than expected. Conversely, it is quite possible that there is a real decrease in

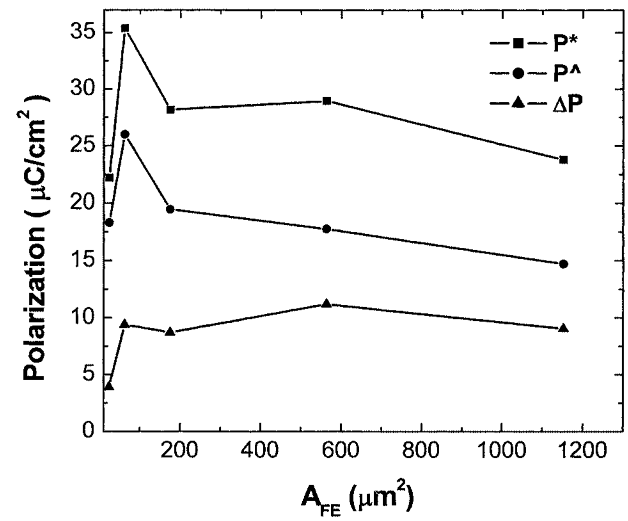

Fig. 11. Nonswitched polarization $(P^\wedge)$, switched polarization (P^*), and the difference between P^* and $P^\wedge$ (ΔP) as a function of capacitor area.

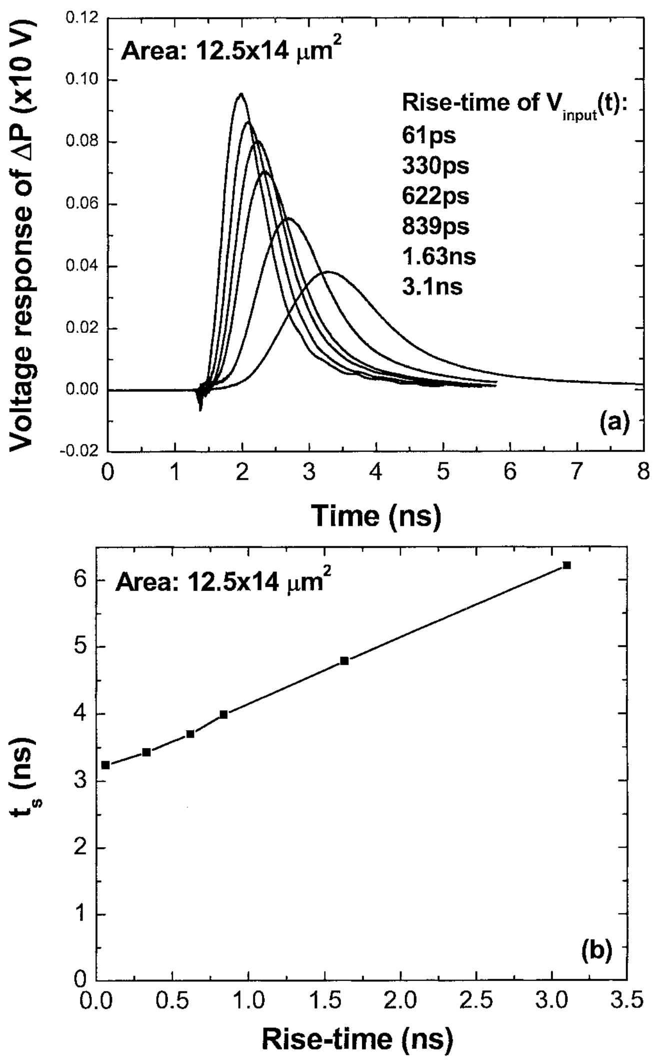

Fig. 12. (a) Voltage responses of the ΔP process for various rise-times of input electric pulses. (b) Polarization switching time t_s as a function of rise-time.

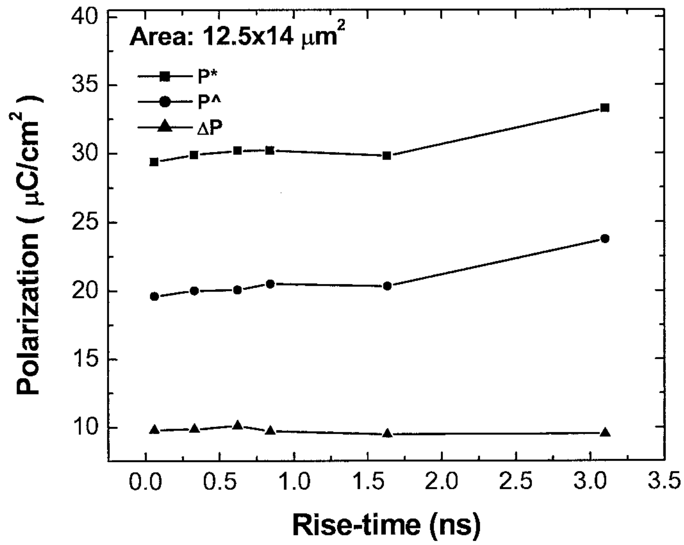

Fig. 13. Nonswitched polarization $(P^\wedge)$, switched polarization (P^*), and the difference between P^* and $P^\wedge$ (ΔP) as a function of rise-time of input electric pulse.

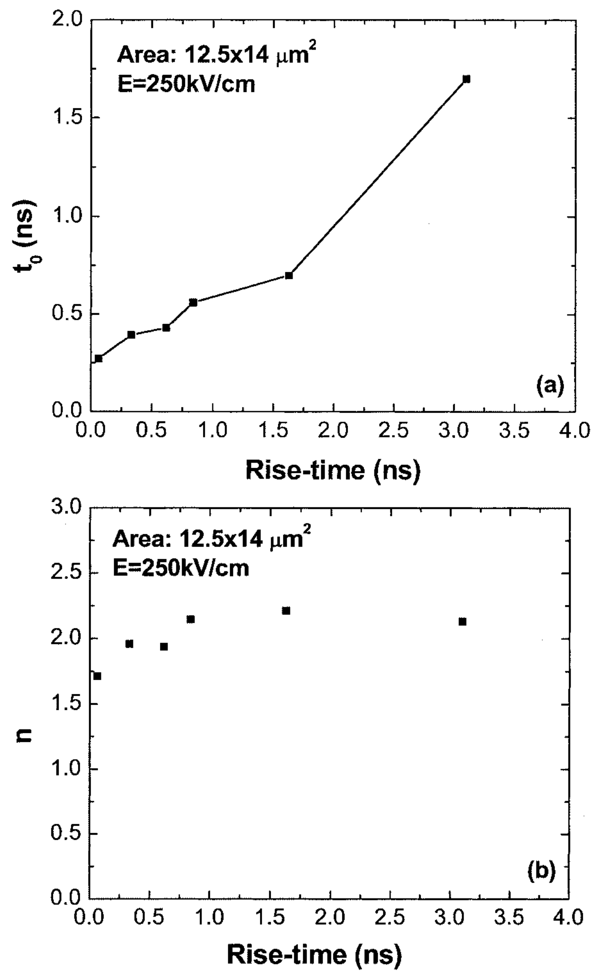

Fig. 14. (a) Characteristic switching time t_0 and (b) dimensionality n as a function of rise-time of input electric pulse.

switched polarization due to processing damage, which is likely to be more impacting at smaller sizes.

Similarly, a study was also carried out on the effect of the rise-time of input electric pulse on the polarization switching process. The rise-time was varied by using cable delay lines with various lengths. The dispersion of the cables will stretch the rise-time of input electric pulse; therefore a longer cable results in a slower rise-time. Fig. 12(a) shows the voltage transients of the ΔP process for various rise-times of input electric

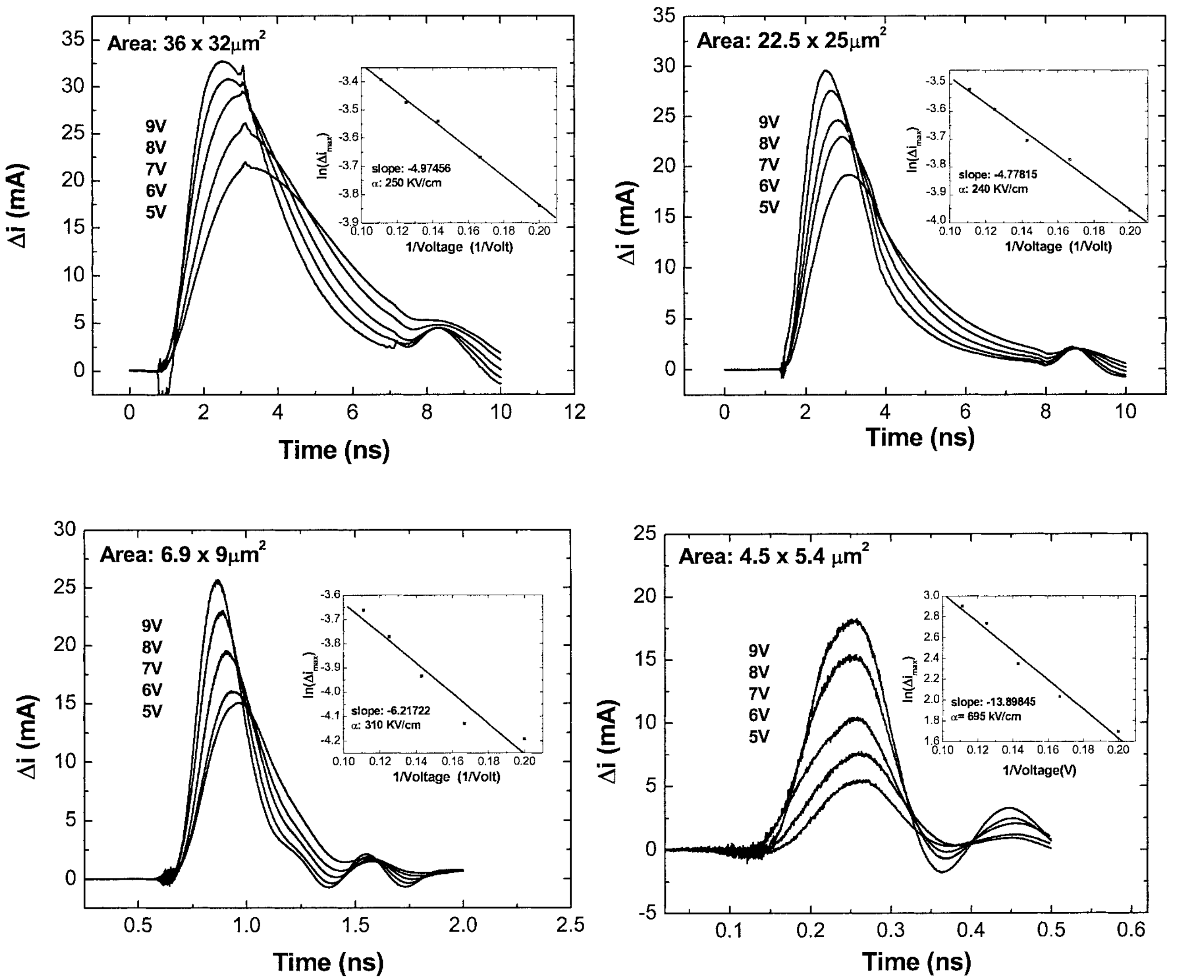

Fig. 15. Current responses of $\Delta \mathrm{P}$ processes for various amplitudes of input electric pulses for various capacitor areas. The inset shows the plot of $\Delta \mathrm{i}_{\max}$ versus $1/V$ for each capacitor.

pulses. Fig. 12(b) shows the polarization switching time $\mathrm{t_s}$ as a function of rise-time of input electric pulse for a 12.5×14 μm ferroelectric capacitor. The curves are very similar to what is expected from simulation. It clearly shows that for the capacitor with such an area, faster or even zero rise-time of input electric pulse will not yield intrinsic switching time. The time resolution of the experimental setup is completely limited by the circuit $\mathrm{RC_{FE}}$. Fig. 13 shows the nonswitched polarization $(\mathrm{P}^\wedge)$, switched polarization (P^*), and their difference $\Delta\mathrm{P}$ as a function of the rise-time of the input electric pulse for this capacitor. No matter how much the rise-time is, the $\Delta\mathrm{P}$ value should be constant since the polarization switching is an integration process. This point is clearly illustrated in Fig. 13, in which the lines are relative flat. The rise-time dependent data were fitted to the Ishibashi–Merz model to extract the characteristic switching time $\mathrm{t_0}$ and dimensionality n, as shown in Fig. 14(a) and (b). The rise-time indeed influences the n value and $\mathrm{t_0}$ value, suggesting the circuit parameters will influence the reliability of this model. Therefore, the changing of n with capacitor area, as shown in Fig. 14(b), may also be influenced by circuit parameters. The fact that both decrease of rise-time and increase of capacitor area give rise to the same trend on n value further proves the circuit impact on n value since we already explained in simulation that the decrease of rise-time and increase of capacitor area have the same effect on the impedance of the capacitor. From another point of view, changing the rise-time and capacitor area causes the change of impedance ratio B that defines the shape of the P^* and $\mathrm{P}^\wedge$ responses, and hence that of the $\Delta\mathrm{P}$ response. Different shapes of $\Delta\mathrm{P}$ voltage responses will have different dimensionality n since n is a shape factor in fitting. Therefore, changing of circuit parameters results in different n values. One thing for sure is that the smaller the capacitor size and the faster the rise-time of the input electric pulse, the more reliable the fitted values of $\mathrm{t_0}$ and n will be.

In Merz's studies on single crystals of barium titanate, he introduced a parameter, called the "activation field (α)," which indicates the ease of polarization switching. The activation field can be calculated from the switching transients with different input electrical pulse amplitudes, as described by

$$\ln(\Delta i_{\max}) = \ln i' - \alpha d \frac{1}{V} \tag{12}$$

in which $\Delta \mathrm{i}_{\max}$ is the maximum value of $i(t)$, V is the amplitude of the applied bias voltage, and d is the thickness of the

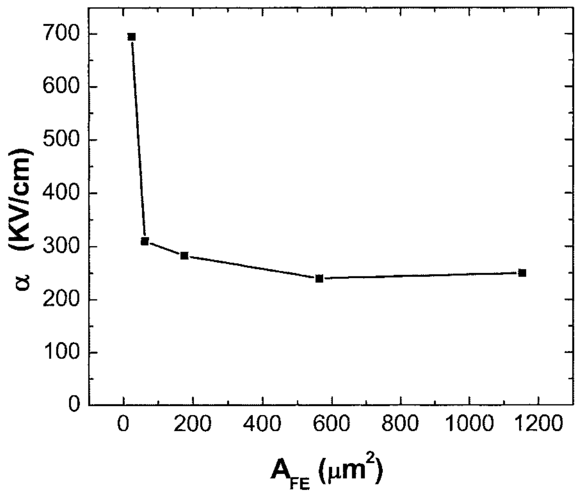

Fig. 16. Activation field α as a function of capacitor area.

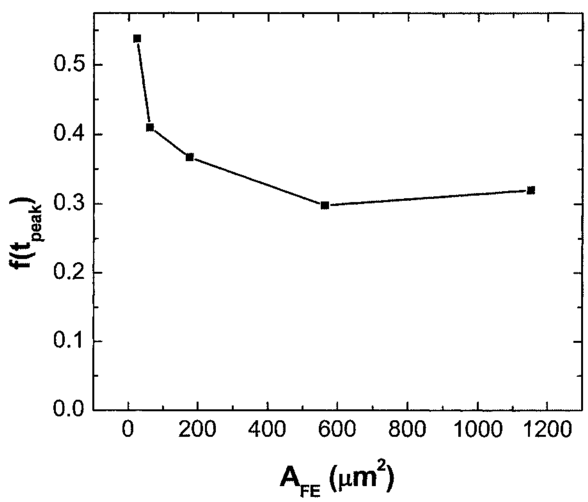

Fig. 17. $f(t_{peak})$ as a function of capacitor area.

film. The slope of the linear fit of $\ln(\Delta i_{max})$ as a function of $1/V$ yields the activation voltage αd. By dividing by the thickness d, the activation field is obtained.

Fig. 15 shows the current responses of the ΔP process for various pulse voltages for different capacitor sizes. The inset shows the logarithm of Δi_{max} as a function of the pulse voltage, showing a linearly fitted line. Fig. 16 shows the activation field α as a function of capacitor area. Clearly, α has the trend to increase with the decrease of capacitor size. Still it is possible that the change in α is due to the change of the shape of the ΔP response for various size capacitors. An interesting point is that when we compare the curves of α, n, and $f(t_{peak})$ as a function of capacitor area (Figs. 16, 10(a), and 17, respectively), we find that they show a similar trend. t_{peak} is the time when the ΔP transient is at a maximum value. $f(t_{peak})$ represents the percentage of polarization that has been switched at time t_{peak}, which is also related to the shape of ΔP. It shows that α is not extremely robust.

V. Conclusion

In summary, a setup capable of studying fast polarization switching processes in ferroelectric capacitors is developed with a time resolution as small as ~50–100 ps by using a semiconductor photoconductive switch as a fast "pulse generator" to produce jitter-free step-like electrical pulses with fast rise-times. Simulation of the "pulse method" is carried out to study the circuit impact on the experimentally obtained data. The application of the Ishibashi–Merz model on the polarization switching study is discussed. Experimental data show that the activation field α varies with the capacitor area. With the smallest size capacitor available for current study, an experimentally measured switching time $t_s = 220$ ps was obtained. From these data, the characteristic switching time $t_0 = 70$ ps can be deduced using the Ishibashi–Merz model. Both the t_s and t_0 values obtained are the smallest among those reported. These results point to the need for generating a step function pulse with a rise-time even smaller than 66 ps with a capacitor area less than 4.5 $\times$ 5.4 μm in order to obtain absolute intrinsic switching time.

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J. Li received the B.S. and M.S. degrees from Tsinghua University, Beijing, China, in 1993 and 1996, respectively. She is pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Maryland, College Park.

Her current researches focus on application of ultrafast laser to study fast dynamic processes in materials such as superconductor, ferroelectrics, and polymer.

H. Liang received the B.S. and M.S. degrees from Tianjin University, China, in 1993 and 1996, respectively. He is currently pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Maryland, College Park.

His current researches focus on nonlinear optical imaging using near-field microscopy and studying fast dynamic process in materials.

B. Nagaraj received the Ph.D. degree in materials science from the Indian Institute of Science, Bangalore, in 1976.

Her doctoral work was on interface electrical characterization of semiconductor devices. She is currently a Research Associate in the Department of Physics and Materials Science, University of Maryland, College Park. Her current research interests include ferroelectric and wide bandgap semiconductor device physics, interface characterization, and reliability.

W. Cao, photograph and biography not available at the time of publication.

Chi H. Lee (F'91) received the Ph.D. degree from Harvard University, Cambridge, MA, in 1968.

He is currently a Professor of electrical engineering at the University of Maryland, College Park. His research has involved all aspects of ultrafast lasers, from generation, characterization, and measurements to a wide range of applications. His group was the first to observe picosecond photoconductivity effect in GaAs (1972). He is also a pioneer in ultrafast optoelectronics and microwave photonics. He has published more than 200 papers in these areas.

Prof. Lee is a Fellow of the Optical Society of America (OSA) and the Photonic Society of Chinese American. He was Chairman of the Technical Committee on Lightwave Technology in the IEEE Microwave Theory and Techniques (MTT) Society. He was the Program Cochair of the Topical Meeting on "Picosecond Electronics and Optoelectronics" in 1985 and 1987. He was the General Cochair of the International Meeting on "Microwave Photonics" in 1998. He was Chairman of the 2003 LEOS Summer Topical Meeting on Photonic Time/Frequency Measurement and Control (PTFMC), 14–16 July 2003, Vancouver, BC, Canada, and Chairman of the Microwave Photonics Technical Committee of LEOS.

R. Ramesh received the Ph.D. degree in materials science from the University of California, Berkeley, in 1987.

He is a Distinguished University Professor at the University of Maryland, College Park. His thesis work led to the identification of the reversal mechanism in Fe-Nd-B magnets and the subsequent design of permanent magnets with superior performance. As a Staff Scientist at the Lawrence Berkeley Laboratory from 1987 to 1988, he carried out pioneering research on high-temperature superconductors and was responsible for the identification of the 110K superconducting phase in the bismuth cuprate system. He joined Bellcore in 1989 and initiated research in several key technology areas, including ferroelectric nonvolatile memories. He has extensive experience in the integration of ferroelectric and other metal oxide thin films with Si technology. His work in this area has led to the identification of metallic oxide electrodes as attractive electrode materials in the fabrication of both nonvolatile and volatile memory capacitors. He has also demonstrated a very novel method of growth of highly oriented metal oxides on Si substrates using layered perovskites as templates. In 1994, he initiated research into the area of colossal magnetoeresistive oxide thin films and heterostructures. His work in the areas of transmission electron microscopy and materials science of high-temperature superconductors, growth mechanisms in oxide thin films, pulsed laser deposition of ferroelectric and magnetic oxide thin films, and information storage technologies is recognized worldwide. He has more than 250 publications, 15 patents issued, and 11 patents pending.

Dr. Ramesh is a Fellow of the American Physical Society. He received the Humboldt Senior Scientist Prize from the Alexander von Humboldt Foundation in 2001 for his pioneering work on the fundamental nanoscale science of size scaling in ferroelectric thin films; and the A. James Clark College of Engineering Faculty Outstanding Research Award.