Effects of IrO_2/Pt hybrid electrodes on the crystallization and ferroelectric performances of sol-gel-derived Pb(Zr,Ti)O₃ thin film capacitors

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The effects of IrO₂/Pt layered hybrid bottom and/or top electrode structures on the leakage current density versus voltage (J–V), polarization versus voltage (P–V), ferroelectric imprint, and fatigue properties of chemical-solution-derived Pb(Zr_xTi_{1-x})O₃ (PZT, Zr/Ti = 35/65) thin films were investigated. The best P–V and J–V performances were obtained from a capacitor with nonhybrid electrodes (Pt/PZT/Pt capacitor). However, the poor fatigue performance of the capacitor required the adoption of hybrid electrode structures. A thin IrO₂ layer, as thin as 6 nm, which was inserted between top Pt electrode and PZT layer was sufficient for improving the fatigue performance with degradation of the other ferroelectric properties. However, the same layer adopted on the bottom Pt electrode was not effective in improving the fatigue performance with degradation in P–V and J–V properties. This was ascribed to IrO₂ layer dissolution into the PZT layer during the crystallization annealing of the PZT thin film. A thicker IrO₂ layer resulted in more serious degradation.

I. INTRODUCTION

Although a number of experimental and theoretical contributions have been made concerning issues of polarization fatigue, leakage current, imprint, and degradation by forming gas annealing of ferroelectric thin-film devices, 1-3 no clear consensus has emerged regarding their origins or potential solutions. The purpose of this research was to investigate aspects of these degradations which were observed in recent experimental results and to define and suggest various phenomenological explanations and possible solutions. In an approach to address these issues, an extensive series of experiments on the effects of IrO₂/Pt layered hybrid bottom and/or top electrode heterostructures on those degradations were performed. It is well known that the choice of electrode materials used for the lead zirconate titanate (PZT) film has an impact on ferroelectric film quality and device performance. In general, the use of conductive oxide electrodes such as RuO₂, SrRuO₃, IrO₂, or La_{1-x}Sr_xCoO₃ helps to improve the resistance to polarization fatigue for

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PZT.^{4–7} However, these electrodes have generally resulted in larger leakage currents and greater susceptibility to dielectric breakdown than noble metal electrodes. In our early paper,² it was demonstrated that when using such a hybrid electrode system, the film properties are influenced by the thickness/partial coverage of the oxide electrode layers. Therefore, optimization research on the thickness of the IrO₂ electrode layer, which allows excellent fatigue and minimal leakage current values, was performed and the results are presented here.

II. EXPERIMENTAL PROCEDURE

The choice of starting materials and solvent is very important for producing good-quality thin films using the chemical-solution-deposition (CSD) technique. A PZT solution (Zr:Ti = 35:65) was prepared using lead acetate trihydrate [Pb(OAc)_{2.3}H₂O], titanium isopropoxide [Ti(O-i-Pr)₄], and zirconium *n*-butoxide [Zr(O-n-Bu)₄]. Methanol was used as the solvent for all precursors. A 12% excess of lead was added to the precursor solutions to compensate for lead loss during the final annealing process. In the CSD method, the hydrolysis and condensation rate of the solution are important factors that must be controlled to maximize solution stability. In general, to reduce the reactivity of hydrolysis and condensation, a



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complexing or chelating agent is required.⁸ In this study, we used modified alkanolamine as a complexing agent for the PZT solution.

Alkanolamine is used to promote the formation of homogeneous products and improve stability of the solution, by reducing the hydrolysis reaction rate.^{8,9} It does not lead to ester reactions and improves resistance to aging of the solution. In addition, the alcohol– alkanolamine system has excellent dissolving power for many inorganic salts and alkoxides. For example, most of the precursors for Pb-based thin films can be dissolved within 1–5 min in a solution of alcohol–alkanolamine.

Films were spin coated at 4000 rpm for 30 s and subsequently dried at 450 °C for 10 min and 650 °C for 2 min for each layer. The thickness per layer was 125 nm. After two layers were deposited, the coated films were annealed at 650 °C for 30 min in a furnace through a direct insertion method. The final film thickness was 250 nm as measured by scanning electron microscopy. For hybrid electrodes, thin IrO₂ was reactively deposited to three nominal thicknesses, 6, 15, or 30 nm, by reactive sputter deposition. For the electrical measurements, Pt top electrodes have a diameter of 0.2 mm were fabricated by sputtering using a stainless-steel shadow mask. After top electrode fabrication, the capacitors were postannealed at 650 °C for 5 min in air to cure the sputtering damage. Crystallinity, surface microstructure, leakage current, P-V hysteresis, and 1 imprint and fatigue characteristics of the films were investigated using x-ray diffraction (XRD), field emission scanning electron microscopy (FESEM, JEOL, Tokyo, Japan), a Keithley 617 programmable electrometer (Keithley, OH), and an RT 6000S ferroelectric tester (Radiant, NM), respectively. For the measurements of leakage current, a delay time of 3 s was adopted.

III. RESULTS AND DISCUSSION

Figure 1 shows the XRD patterns of the PZT (Zr:Ti =35:65) thin films as a function of IrO₂ thickness on the Pt electrode. The PZT thin film directly deposited on 111oriented Pt shows a highly textured 111 orientation because the activation energy for PZT nucleation is the lowest for heterogeneous nucleation on lattice matched substrates.^{10,11} The film on the 6-nm IrO₂/Pt electrode shows some 100 orientation but has a strong 111 preferred orientation, while the film on the thicker IrO₂/Pt reveals random orientation. It is postulated that the activation energy for nucleation of perovskite PZT is considerably higher than that of growth. Thus, nucleation and crystallization of a single-phase perovskite PZT film is much more difficult to achieve on an oxide electrode than it is on Pt.¹² A large difference between the activation energy for nucleation and growth leads to the formation of rosettes and a two-phase pyrochlore/perovskite



FIG. 1. XRD patterns of the PZT (Zr:Ti = 35:65) thin films grown on IrO₂/Pt hybrid electrodes having different IrO₂ interlayer thicknesses from 0 to 30 nm.

structure. Therefore, it is well known that PZT films on oxide electrodes tend to have a large amount of a nonferroelectric second phase and display a rosette microstructure.⁴ Kwok and Desu reported that whenever the pyrochlore intermediate phase was formed, the pyrochlore to perovskite conversion occurred through an interface controlled transformation and the resultant films were randomly oriented.¹³ As a consistent trend, the XRD patterns of the PZT films grown on IrO_2 show a less textured structure, as shown in Fig. 1, even though peaks from a second phase other than PZT are not detected due to its nanoscale grain size.

Figure 2 shows the FESEM micrographs of the PZT film surfaces having IrO_2 bottom layers with thicknesses of (a) 0 nm, (b) 10 nm, and (c) 30 nm, respectively. The figures clearly show a more non-uniform and rosettelike surface morphology with increasing bottom- IrO_2 layer thickness confirming the XRD results.

More detailed information on the texture evolution and ferroelectric properties of the PZT films depending on the types of the hybrid electrodes can be obtained from composition analysis along the depth direction by Auger electron spectroscopy (AES).

Figures 3(a) and 3(b) show the AES depth profiles of the samples having 6-nm-thick bottom IrO_2 and 30-nmthick IrO_2 layers, respectively. The sputter-etching rate during the analysis was reduced to <10 Å/min considering the small thickness of the IrO_2 layer. Interestingly, the sample that had a 6-nm IrO_2 layer does not show any discernible Ir signal even at the bottom interface whereas the sample having a 30-nm-thick IrO_2 layer clearly shows the existence of the IrO_2 layer between the PZT and the bottom Pt electrode. In the Auger electron energy

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FIG. 2. FESEM micrographs of the PZT film surfaces having IrO_2 bottom layers with the thickness of (a) 0 nm, (b) 10 nm, and (c) 30 nm, respectively.

spectrum, the Ir signal slightly overlaps the Pt signal, so that the Ir signal was not discernible from the background if the intensity is not large enough.

It appears that the IrO_2 layer dissolves into the PZT layer to a certain extent during the crystallization annealing of the PZT layer at 650 °C, so that the 6-nm-thick IrO_2 layer does not exist at the PZT/bottom Pt interface. However, a 30-nm-thick IrO_2 layer remains at that interface due to the larger thickness after the partial dissolution. If all of the 6-nm-thick IrO_2 layer dissolves into the 250-nm-thick PZT layer, the atomic concentration of Ir



FIG. 3. AES depth profiles of the samples having (a) 6-nm-thick and (b) 30-nm-thick bottom IrO_2 layers.

in the PZT layer must be approximately 2% from a simple calculation on the basis of the film thickness ratio. For these overlapping Ir and Pt peaks, the 2% Ir is almost undetectable.

The bottom IrO_2 thickness-dependent phase evolution behavior shown in Fig. 1 can now be more clearly understood. For the case of the PZT layer on the 6-nm-thick IrO_2 layer, the initial crystallization must occur on the IrO_2 layer, which results in a non-highly 111-textured structure. However, as crystallization proceeds, the IrO_2 coverage on the Pt layer decreases due to dissolution of the IrO_2 layer and thus crystallization occurs on the Pt surface, which produces a highly 111-textured film. However, for the cases of 15- and 30-nm-thick IrO_2 layers, the full coverage of the layer on the Pt electrode precludes direct contact of the PZT layer with the Pt resulting in a nontextured structure. The more random nature of the PZT film on the 30-nm-thick IrO_2 layer than that on

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the 15-nm-thick IrO_2 layer suggests that the absolute amount of dissolved Ir in the PZT also have some influence on the crystallization behavior.

This thickness-dependent presence of the IrO_2 layer greatly influences the P-V as well as the J-V and fatigue properties.



FIG. 4. J-V curves of PZT thin films having different IrO₂ layer thicknesses at the bottom electrode interface.

Figure 4 shows the J-V curves of PZT thin films with different IrO₂ layer thicknesses at the bottom electrode interface. The PZT thin films on the Pt and 6-nm-IrO₂/Pt hybrid electrode show an excellent leakage current density, which is in the order of 10^{-7} – 10^{-8} A/cm² up to 10 V, while the films on the thicker IrO_2 (15 and 30 nm) bottom hybrid electrode reveal a higher leakage current density $(10^{-5}-10^{-6} \text{ A/cm}^2)$ with increasing IrO₂ layer thickness. Even though a rigorous conduction mechanism study was not performed in this study, from our previous study,¹⁴ the conduction of this 250-nm-thick PZT film must be a interface limited one (such as Schottky emission and tunneling) combined with bulk limited one (such as space charge limited). Especially, the PZT/ IrO₂ contact must have a lower potential barrier height than that of the PZT/Pt contact due to the smaller work function of IrO₂, resulting in a more bulk limited conduction behavior. Therefore, the increase in the leakage current with increasing IrO₂ thickness for the cases of 15- and 30-nm-thick film appears to be either due to an increase in the defect charge density by larger dissolution of Ir or to the formation of a conducting second phase. In general, PZT on an oxide electrode has two known pyrochlore-type secondary phases.^{15–17} The first



FIG. 5. P-V hysteresis loops of PZT filsm with four different electrode stacks (a) Pt/PZT/Pt, (b) Pt top/6-nm-IrO₂/PZT/Pt, (c) Pt/PZT/6-nm-IrO₂/Pt bottom, and (d) Pt top/6-nm-IrO₂/PT/6-nm-IrO₂/Pt bottom as a function of maximum applied voltage from 2 to 5 V.

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FIG. 6. P-V hysteresis loops of PZT thin films with four different electrode stacks (a) Pt/PZT/Pt, (b) Pt/PZT/15-nm-IrO₂/Pt bottom, (c) Pt top/15-nm-IrO₂/PZT/15-nm-IrO₂/Pt bottom, and (d) Pt/PZT/30-nm-IrO₂/Pt bottom as a function of maximum applied voltage from 2 to 5 V.

is an insulating PZT pyrochlore [Pb₂(Zr,Ti)₂O_{7-x}]. However, this type of pyrochlore would not cause the high leakage currents, because it has a high resistivity of about 10^{10} – 10^{11} Ω -cm The second pyrochlore-type phase is a PZT pyrochlore-related conducting phase (specifically for RuO₂, PZT pyrochlore-ruthenate [Pb₂(Ru,Zr,Ti)₂O_{7-x}] or lead ruthenate $(Pb_2Ru_2O_{7-x})$. This would produce a high conduction path, and its lattice constant is very similar to PZT pyrochlore. It is, therefore, more likely that this phase is responsible for the high leakage current of the PZT films on the oxide electrode/Pt hybrid structure. This is consistent in that the films on thicker IrO₂/Pt would produce much more of the PZT pyrochlore-related conducting phase. It is assumed that PZT pyrochlore or PbO is more reactive with IrO_2 than it is with PZT perovskite and therefore forms a conducting phase very easily like in the case of RuO2. Furthermore, the increased surface roughness (Fig. 2) with the increasing bottom-IrO₂ thickness also contributes to the increased leakage current density.

On the other hand, for the case of the 6-nm-thick IrO_2 layer, complete dissolution of the layer causes the contact property to be similar to that of PZT/Pt resulting in almost the same low leakage current level as that of the

the sample without the IrO_2 interlayer. This is because the contact barrier height increases to that of Pt/PZT and the interface suppresses the leakage current flow.

Figure 5 shows the P-V hysteresis loops of PZT films with four different electrode stacks (Pt/PZT/Pt, Pt top/6-nm-IrO₂/PZT/Pt, Pt/PZT/6-nm-IrO₂/Pt bottom, and Pt top/6-nm IrO₂/PZT/6-nm-IrO₂/Pt bottom) as a function of the maximum applied voltage from 2 to 5 V. It can be seen that the loop shapes for the films on the four different electrode stacks are almost same, while the remanent polarization (P_r) values are slightly different. The measured $P_{\rm r}$ values of the PZT thin films crystallized on bare Pt electrode are similar $(2P_r \text{ of }$ 60 μ C/cm² at 5 V), regardless of the top electrode structures. The PZT thin films grown on IrO2/Pt hybrid electrode reveal a somewhat smaller P_r value $(2P_r)$ of 48 μ C/cm² at 5 V) when compared to the films on Pt. The data presented above are entirely consistent with the fact that the P_r values of the PZT films depend on the film orientation and microstructure, which in turn appear to be substantially affected by the bottom electrode structure and materials. Other possible factors which can affect the polarization behavior of PZT capacitors include the presence of second phases or localized inhomogeneous crystallization of the PZT films as discussed above.

Figure 6 shows the P-V hysteresis loops of PZT thin films with thicker IrO₂ (15 and 30 nm)/Pt top and bottom hybrid electrodes for further evidence. It is observed that the hysteresis loop shapes and P_r values are affected only by the bottom electrode. The P_r values become smaller with increasing the IrO₂ bottom electrode thickness, whereas the P_r values are not affected by the top electrode structure, clarifying the above hypothesis. Regardless of the top IrO₂ thickness, both the P_r values and loop shapes of these films on Pt are almost consistent with those of the films with the Pt top and bottom electrodes.

Figure 7 shows the imprint behavior or thermally induced voltage shifts (ΔV) of the PZT thin films with four different electrode stacks. The capacitors were stored under the $-P_r$ state at 150 °C for 5000 s. In general, the evaluation standard for imprint is the voltage shift in the hysteresis loop. The development of a voltage shift in thin films left in a given polarization state for an extended period of time can be induced by heating the capacitor after poling to a positive/negative remanence ($\pm P_r$) or by heating the capacitor under an applied saturating voltage (dc bias). This method is very effective in understanding the phenomena because it is related to the internal bias field effects previously reported in bulk ceramics. It is reported that this voltage shift arises from asymmetric behavior of ferroelectrics induced by an the asymmetric distribution of charge trapping and/or charged defect and/or defect complexes.^{18–21} Possible factors affecting the voltage shift are thermally generated or field injected carriers and the alignment of defect dipoles, all of which appear to be thermally activated. In an integrated device, if the shift is large enough, the coercive voltage becomes too large in one direction to be switched by the programming voltage.

It is observed that the voltage shifts of the PZT thin films slightly increases with increasing IrO₂ thickness. The measured ΔV values of the PZT thin films are between 0.52 and 0.57 V, as shown in Fig. 6. This trend of voltage shifts can be accounted for if the trapped charge is not confined to the film/electrode interface but is distributed over a wider area near the interface region.²² The slight increase in ΔV with IrO₂ thickness might be due to the increase in the amount of injected charge during the imprint test or the increased defect density as a result of IrO₂ dissolution.

Figure 8 shows the AES depth profile results of the top-Pt/6-nm-IrO₂/PZT/Pt sample. It is clearly observed that the 6-nm-thick IrO₂ layer remained at the top interface



FIG. 7. Voltage shifts (ΔV) of the PZT thin films with four different electrode stacks (a) Pt/PZT/Pt, (b) Pt top/6-nm-IrO₂/PZT/Pt, (c) Pt/PZT/ 6-nm-IrO₂/Pt bottom under the remanence and 150 °C for 5000 s.

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even after the top electrode annealing. This is because the top 6-nm-thick IrO_2 layer was formed after the PZT crystallization annealing was completed and received only short heat treatment. It appears that the noncrystalline, gel-state PZT more easily reacts with IrO_2 than the well-crystallized PZT film.

Figure 9 shows the fatigue properties of the PZT thin films with four different electrode stacks. When cycled with 5 V and a 500-kHz squared wave pulse, the Pt/PZT/ Pt capacitors show an abrupt polarization decrease after the 10^7 cycles as expected, whereas the PZT capacitors with both top and bottom 6-nm-IrO₂/Pt hybrid electrodes and only a top 6-nm-IrO₂/Pt hybrid electrode exhibit an



FIG. 8. AES depth profile results of the top-Pt/6-nm-IUrO $_2$ /PZT/Pt sample.



FIG. 9. Fatigue properties of the PZT thin films with four different electrode stacks.

almost flat fatigue profile up to 10^9 cycles. The fatigue performance of the PZT capacitor having only top 6-nm-IrO₂/Pt hybrid electrode is slightly better than that having the both top and bottom hybrid electrodes. It has been shown by many researchers that fatigue of PZT thin films can be substantially alleviated by use of conductive oxide such as RuO₂, IrO₂, SrRuO₃, or hybrid electrodes, incorporated only in both top and bottom electrodes.^{4–6} However, our results indicate that a high polarization endurance behavior with fatigue cycles can be obtained even on asymmetrical Pt top/6-nm-IrO2/PZT/Pt capacitors as shown in Fig. 9. Recently similar results have been presented for asymmetrical top SrRuO₃/PZT/Pt and Pt/SrRuO₃/PLZT/Pt by Cross et al. and Stolichinov et al.^{7,23} It was claimed that in an asymmetrical top hybrid electrode system, the physical mechanisms of polarization switching depend on the driving voltage amplitude. The polarization switching endurance under a high amplitude is governed only by the top SrRuO₃ interface, whereas the degradation properties of the bottom Pt interface do not play an important role. On the contrary, for driving voltage amplitudes lower than 80 kV/cm, the Pt-interface induced degradation is a limiting factor for the fatigue performance. On the basis of these results, they suggested that the fatigue of switching polarization of PZT film capacitors is controlled by the interfaces, and the most probable fatigue mechanism is related to the inhibition of the near-interfacial nucleation of the opposite domains by the entrapped mobile carriers. This suggestion is well matched to our results presented here. However, the use of only a bottom 6-nm-IrO₂/Pt is less effective in improving PZT fatigue resistance than that of top 6-nm-IrO₂/Pt hybrid electrode. This difference can be accounted for by the fact that the bottom 6-nmthick IrO₂ layer does not exist anymore after the crystallization annealing of the PZT layer, as shown in Fig. 3, whereas the top 6-nm-thick IrO₂ layer is still there, as shown in Fig. 8, and acts as a nucleation site for reverse domain formation.

IV. CONCLUSION

An optimization study on the layer sequence and thickness of IrO_2/Pt layered hybrid electrode structure on the *J*–*V*, *P*–*V*, ferroelectric imprint, and fatigue properties of chemical-solution-derived PZT thin films were performed. Even though the best *P*–*V* and *J*–*V* performances were obtained from capacitors having nonhybrid electrodes (Pt/PZT/Pt capacitor), poor fatigue performance of the capacitor required the adoption of hybrid electrode structures. A thick IrO_2 layer (>10 nm) badly affects the crystallization behavior of the PZT layer generating a nontextured structure with a rough surface morphology and smaller P_r values. A thin IrO_2 layer, as thin as 6 nm, inserted between the top Pt electrode and the PZT layer



was sufficient for improving the fatigue performance without any degradation in the other ferroelectric properties. However, the same layer adopted on the bottom Pt electrode was not effective in improving the fatigue performance with degradation in P-V and J-V properties due to the dissolution of the IrO₂ layer into the PZT layer during the crystallization annealing of the PZT thin films. Therefore, it was determined that the thermal and chemical stabilities of the oxide electrode layer are critically important in improving the fatigue performance by adopting the oxide electrode layer. The adoption of the conducting oxide layer in the top electrode stack, rather than the bottom electrode, is much more effective eliminating the degradation in crystallinity, texturing, P-V, and J-V behaviors. The thickness of the top oxide layer could be reduced to 6 nm, which is good for high-density integrated devices.

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REFERENCES

- M. Dawber and J.F. Scott, Appl. Phys. Lett. **76**, 1060 (2000);
 M. Dawber and J.F. Scott, Appl. Phys. Lett. **76**, 3655 (2000).
- S-H. Kim, J.G. Hong, S.K. Streiffer, and A.I. Kingon, J. Mater. Res. 14, 1018 (1999).
- A. Tagantsev, Presented in the 12th International Symposium on Integrated Ferroelectrics, Aachen, Germany, 12–15, 2000 (unpublished).
- O. Auciello, K.D. Gifford, and A.I. Kingon, Appl. Phys. Lett. 64, 2873 (1994).

- I.S. Chung, J.K. Lee, W.I. Lee, C.W. Chung, and S.B. Desu, in *Ferroelectric Thin Films*, edited by B.A. Tuttle, S.B. Desu, R. Ramesh, and T. Shiosaki (Mater. Res. Soc. Proc. **361**, Pittsburgh, PA, 1995), pp. 249–254.
- R. Ramesh, H. Gilchrist, T. Sands, V.G. Keramidas, R. Haakenaasen, and D.K. Fork, Appl. Phys. Lett. 63, 3592 (1993).
- J. Cross, M. Fujiki, M. Tsukada, K. Matsuura, and S. Ontani, Jpn. J. Appl. Phys. Lett. 38, L448 (1999).
- S-H. Kim, C.E. Kim, and Y.J. Oh, Thin Solid Films **305**, 321 (1997).
- 9. Y. Takahashi and J. Yamaguchi, J. Mater. Sci. 25, 3950 (1990).
- G.J. Willems, D.J. Wouters, H.E. Maes, and R. Nouwen, Integr. Ferroelectr. 15, 19 (1997).
- C.J. Kim, D.S. Yoon, Z.T. Jiang, and K.S. No. J. Mater. Sci. 32, 1213 (1997).
- H.N. Al-Shareef, K.R. Bellur, O. Auciello, and A.I. Kingon, Ferroelectrics 152, 85 (1994).
- 13. C.K. Kwok and S.B. Desu, J. Mater. Res. 8(2), 339 (1993).
- J.C. Shin, J. Park, C.S. Hwang, and H.J. Kim, J. Appl. Phys. 86, 506 (1999).
- H.N. Al-Shareef, K.R. Bellur, O. Auciello, and A.I. Kingon, Thin Solid Films 256, 73 (1995).
- J.M. Longo, P.M. Raccah, and J.B. Goodenough, Mater. Res. Bull. 4, 191 (1969).
- H.N. Al-Shareef, K.D. Gifford, M.S. Ameen, S.H. Rou, P.D. Hren, O. Auciello, and A.I. Kingon, Ceram. Trans. 25, 97 (1992).
- 18. G. Arlt and H. Neumann, Ferroelectrics 87, 109 (1988).
- B.H. Park, S.J. Hyun, C.R. Moon, B.D. Choi, J. Lee, C.Y. Kim, W. Jo, and T.W. Noh, J. Appl. Phys. 84, 4428 (1998).
- W.L. Warren, D. Dimos, G.E. Pike, and K.V. Vanheusden, Appl. Phys. Lett. 67, 1689 (1995).
- S-H. Kim, D-S. Lee, C.S. Hwang, D-J. Kim, and A.I. Kingon, Appl. Phys. Lett. 77(19), 3036 (2000).
- S-H. Kim, H-J. Woo, J. Ha, C.S. Hwang, and A.I. Kingon, Appl. Phys. Lett. 78, 2885 (2001).
- 23. I. Stolichnov, A. Tagantsev, N. Setter, J. Cross, and M. Tsukada, Appl. Phys. Lett. **74**, 3552 (1999).