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| Induction | | | | | | | | | | | | of | | | ferroelectricity | | | | | | | | | | | | in | | | | nanoscale | | | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | films | | | | | on | | Pt | | | | | | | | | | | | | | | | | |
| electrode | | | | | | | | | | | | without | | | | | | | | | post-annealing | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Bo-Ting | | | | | | | Lin, | | | | | Yu-Wei | | | | | | Lu, | | | | Jay | Shieh∗,Miin-Jang | | | | | | | | | | | | | | | | Chen∗ | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| a | r | ticle | | | | | | | | | | in | | | f | o | | | | | | | a | | | | b | stract | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Article | | | history: | | | | | | | | | | | | | October | | | | 2016 | | | Largestable | | | | | | | | | | | | ferroelectricity | | | | | | | | | innanoscale | | | | | | | undoped | | | | | | zirconia | | | | (ZrO2)thinfilmsprepared | | | | | | | | | | | | | without | | | | post- | |
| Received | | | | 30 | | July | | | 2016 | | | | | | | annealing | | | | | | | | | | has | | | been | | | | | demonstrated | | | | | | | forthefirsttime.Remanent | | | | | | | | | | | | | | | polarizations | | | | | | upto12�Ccm−2were | | | | | | | | | | |
| Received | | | | in | | revised | | | | | form | | | 21 | | obtained | | | | | | | | intheas-deposited | | | | | | | | | | | | | ZrO2 thinfilms | | | | | | | | | prepared | | | | byremote | | | | | plasma | | | | | atomic | layerdeposition | | | | | | | | at300◦C | | | |
| Accepted | | | | | 22 | October | | | | | | 2016 | | | |
| substrate | | | | | | | | | temperature | | | | | | | | | | onthePtelectrode. | | | | | | | | | Ferroelectric | | | | | | | | crystallization | | | | | | | ofthefilms | | | | | wasachieved | | | | | | without | | |
| Available | | | | | online | | | | xxx | | | | | | |
| post-annealing, | | | | | | | | | | | | | | whichishighly | | | | | | | | | beneficial | | | | | | totheapplication | | | | | | | | | ofthefilmsinnon-volatile | | | | | | | | | | | | | memories | | | | | and |
| Keywords:  Zirconia  Ferroelectricity | | | | | | | | | | | | | | | | | | | | | | | ultralow-power | | | | | | | | | | | | | | | nanoelectronics. | | | | | | | | | Theexistence | | | | | | | | | oftheferroelectric | | | | | | | | orthorhombic | | | | | | | | phase | | | with | noncen- | | | |
| trosymmetric | | | | | | | | | | | | | spacegroupPbc21 intheas-deposited | | | | | | | | | | | | | | | | | | | | | | ZrO2 thinfilms | | | | | | | wasconfirmed | | | | | | | | byhigh-resolution | | | | | | |
| transmission | | | | | | | | | | | | electron | | | | | | | microscopy. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
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| **1.** | **Introduction** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [10].K1-xNaxNbO3-, | | | | | | | | | | | | | | | (Bi0.5Na0.5)TiO3-and | | | | | | | | | | | | | | | BaTiO3-based | | | | | | | | | | | | | | | systems | | | | | |
| Ferroelectric | | | | | | | | | | | | | materials | | | | | | | | are | | | | widely | | | | | | | used | | | | | in | non-volatile | | | | | | | | | | | | memo- | | | | | are | promising | | | | | | | | lead-free | | | | | | | | ferroelectric | | | | | | | | | materials | | | | | | | | [10–13],but | | | | | | | | | | | | | | their | | |
| low | depolarization/Curie | | | | | | | | | | | | | | | | | temperatures | | | | | | | | | | | and/or | | | | | | | small | | | | | | piezoelec- | | | | | | | | |
| ries | | | and | | | nanoscale | | | | | | | | | transistors | | | | | | | | | | for | | | ultralow-power | | | | | | | | | | | | | | computing | | | | | | | | | | | due | | tric | coefficients | | | | | | | | | limit | | | | | their | | | roles | | | | in | | piezoelectric | | | | | | | | | | | | | and | | | | ferroelectric | | | | | | | | | |
| to | their | | | | | switchable | | | | | | | | | | polarizations | | | | | | | | | | | by | | | an | | | applied | | | | | | | electric | | | | | | | field | | | | [1–9]. | | | | applications. | | | | | | | | Poor | | | | | compatibility | | | | | | | | | to | | | complementary | | | | | | | | | | | | | | | metal-oxide- | | | | | | | | | | |
| For | | example, | | | | | | | | | ferroelectric | | | | | | | | | | | random | | | | | | | | | access | | | | | | memory | | | | | | | | (FRAM) | | | | | | | | and | | semiconductor | | | | | | | | | (CMOS) | | | | | | | | process | | | | | | also | | | | makes | | | | | | | PZT | | | | | | and | | | | common | | | | | | |
| ferroelectric | | | | | | | | | tunnel | | | | | | | | junctions | | | | | | | | | (FTJs) | | | | | have | | | | | | been | | | | regarded | | | | | | | | | as | | | the | | lead-free | | | | | perovskites | | | | | | | | | | difficult | | | | to | | be | | | integrated | | | | | | | | | with | | | | | | the | | | | integrated | | | | | | | |
| next | | | | generation | | | | | | | | | non-volatile | | | | | | | | | | | | memories | | | | | | | | | [3,4]. | | | | | FTJs | | | | have | | | | | attracted | | | | | | | circuits. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| much | | | | | attention | | | | | | | | recently | | | | | | | due | | | | | to | | their | | | | | | giant | | | | | tunneling | | | | | | | | | | electrore- | | | | | | | In | | 2012, | | | | | the | | | | ferroelectricity | | | | | | | | | | of | | | nanoscale | | | | | | | | | | solid | | | | | | solution | | | | | | | | | thin | |
| sistance | | | | | | effect, | | | | | | | allowing | | | | | | | significant | | | | | | | | | | | modulation | | | | | | | | | | of | | | the | | | | electrical | | | | | | | films | | of | | hafnia | | | | | (HfO2) | | | | | | | and | | zirconia | | | | | | (ZrO2), | | | | | | i.e., HfxZr1-xO2 (abbre-  M ¨uller et al. [14]. Apart | | | | | | | | | | | | | | | | | | | | |
| resistance | | | | | | | | by | | ferroelectric | | | | | | | | | | | | polarization | | | | | | | | | | | switching | | | | | | | | | [4–6]. | | | | | | | The | | | | neg- | | viated | | | as | | HZO), | | | | has | | | | | been | | | demonstrated | | | | | | | | | | | by | |
| ative | | | | capacitance | | | | | | | | | | | field-effect | | | | | | | | | | transistors | | | | | | | | | | | (NCFETs), | | | | | | | | in | | | which | | | | | | | the | from | | HZO, | | | | nanoscale | | | | | | | | | thin | | | films | | | based | | | | | on | | | undoped | | | | | | | | | HfO2 and | | | | | | | | | | HfO2 | | |
| negative | | | | | | | capacitance | | | | | | | | | | | is | provided | | | | | | | | | by | | | the | | | | | ferroelectric | | | | | | | | | | oxide | | | | | | inte- | | | doped | | | with | | | | Si, | | Y, | | | Al | | or | | Gd | | have | | | been | | | | | shown | | | | | | to | | | be | | | ferroelectric | | | | | | | | | | | | as |
| grated | | | | | into | | | the | | | | gate | | | | | stack, | | | are | | | | | capable | | | | | | of | | reducing | | | | | | | | the | | | subthreshold | | | | | | | | | | | well | | [15–19].All | | | | | | | | | these | | | | | studies | | | | recognized | | | | | | | | | | that | | | | | | the | | | | high-pressure | | | | | | | | | | |
| slope | | | | below | | | | | the | | | | Boltzmann | | | | | | | | | | limit | | | | of | | | 60 | | | mV/decade | | | | | | | | | [7–9].The | | | | | | | | | | | dra- | | orthorhombic | | | | | | | | | (o) | | | | phase | | | | with | | | noncentrosymmetric | | | | | | | | | | | | | | | | | | | | | space | | | | | | group | | | |
| matic | | | | | reduction | | | | | | | | in | | power | | | | | dissipation | | | | | | | | | | | | in | | NCFETs | | | | | | | demonstrates | | | | | | | | | | | | | the | Pbc21,induced | | | | | | | | | in | | | | a | constrained | | | | | | | environment, | | | | | | | | | | | | | is | | the | | | | origin | | | | | | of | | | fer- | |
| great | | | | potential | | | | | | | | of | | ferroelectric | | | | | | | | | | | materials | | | | | | | | | for | | | ultralow-power | | | | | | | | | | | | | | nano- | | | | roelectricity. | | | | | | | | The | | | most | | | | | obvious | | | | benefit | | | | | | | of | | HfO2-based | | | | | | | | | | | | ferroelectric | | | | | | | | | |
| electronics. | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | thin | films | | | | is | their | | | | | high | | | | compatibility | | | | | | | | | | to | CMOS | | | | | technology; | | | | | | | | | | | | | however, | | | | | | |
| In | | | | terms | | | | | of | | available | | | | | | | | ferroelectric | | | | | | | | | | | | materials, | | | | | | | | | the | | | lead | | | | | zirconate | | | | | | | a  ferroelectric   post-annealing  crystallization   procedure  of (∼700–1000◦C) the films, which is  increases  needed | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | to | | | attain | | | |
| titanate | | | | | | (PZT) | | | | | system | | | | | | | is | one | | | | | of | | the | | | most | | | | | | well-known | | | | | | | | | | | and | | | | studied | | | | | the | | | com- | | | |

ferroelectric materials. Soft PZT typically exhibits a high remanent

polarization (Pr) and large piezoelectric coefficients; however, its

high lead content (∼60 wt.%) raises grave environmental concerns

plexity of CMOS process integration. Nanoscale HfO2-based thin

films are typically deposited on the titanium nitride (TiN) electrode

(or capped between TiN) to achieve stable ferroelectricity since the

TiN electrode can provide the mechanical confinement needed for

the transition from the high-temperature tetragonal (t) phase to

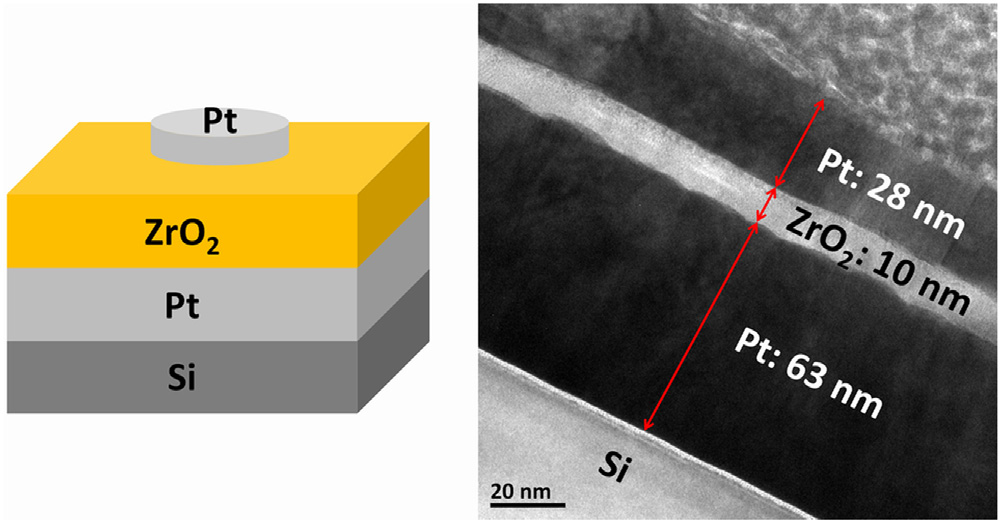
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| ∗ Corresponding authors.  E-mail addresses: [jayshieh@ntu.edu.tw](mailto:jayshieh@ntu.edu.tw) | | (J. | Shieh), | [mjchen@ntu.edu.tw](mailto:mjchen@ntu.edu.tw) | the | high-pressure | | | | | ferroelectric | | | | | o-phase | | | [14–16].Nevertheless, | | | | | | | | the |
| oxidation | | of | the | TiN | | | electrode | | | during | | | the | | film | | deposition | | and | post- | | |
| annealing | | stages | | | gives | | | rise | to | the | | increase | | | | in | the | resistivity | | of | the | |
| (M.-J. | Chen). |

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|  | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | post-annealing, | J | Eur | Ceram | Soc | (2016), | http://dx.doi.org/10.1016/j.jeurceramsoc.2016.10.028 | |  |

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| Lin | et | al. | /Journal | of | the | European | Ceramic | Society | xxx | (2016) | xxx–xxx |



**Fig. 1.** Schematic and cross-sectional TEM image of the MIM-type ZrO2 thin film

sample.

electrode and the amount of oxygen vacancies in the HfO2-based

thin films [20,21],resulting in the performance degradation of the

films.

Like HfO2,ZrO2 is also a suitable material for high-K gate

dielectrics for CMOS technology. ZrO2 and HfO2 are similar in both

physical and chemical senses [22];the similarity is related to the

electron configurations of Zr ([Kr]4d25s2) and Hf ([Xe]4f145d26s2),

which are both group IV elements. Although the ferroelectricity of

HfO2-based thin films has been extensively studied, only scattered

studies have endeavored to examine the (anti-)ferroelectricity of

ZrO2 [14,23,24].For nanoscale thin films, ZrO2 tends to crystallize

at a much lower temperature than HfO2 [25,26];this could be highly

beneficial to the induction of ferroelectricity in nanoscale ZrO2 with

a low processing temperature.

The induction of ferroelectricity in nanoscale undoped ZrO2

thin films deposited on the Pt electrode without post-annealing

is reported in this study. The as-deposited ZrO2 thin films exhib-

ited a high degree of ferroelectric crystallinity with a large stable

polarization-electric field (P-E) hysteresis. The ferroelectricity has

been confirmed to be originated from the ferroelectric o-phase

with space group Pbc21.The ZrO2 thin films were prepared on

the Pt electrode. As compared to TiN, Pt would be a preferred

electrode material in terms of preventing electrode oxidation and

film degradation, which are important for practical nanoelectronics

applications.

formity of the ZrO2 thin film (10.3 nm thick) and the clear interfaces

between the electrode and ZrO2 layers.

The crystalline phases of the ZrO2 thin films at room temper-

ature were identified using grazing incidence X-ray diffraction

(GIXRD; TTRAX III, Rigaku). Structural analyses of the thin

films were achieved by high-resolution transmission electron

microscopy (HRTEM; 2010F, JEOL) operating at 200 kV. The cross-

sectional TEM specimens of the thin films were prepared using

focused ion beam micromachining (FIB; Helios NanoLab 600i, FEI).

The contrast of HRTEM images was enhanced by fast Fourier trans-

form (FFT) using software DigitalMicrograph (Gatan, USA). The P-E

hysteresis curves of the thin films were measured at room temper-

ature using a ferroelectric analyzer (TF2000, aixACCT) operating at

alternating

if the films were   
 electric

leaky,   
 fields

the   
 of

P-E±2–4 hysteresis MVcm−1and

curves   
 2000

obtained   
 Hz. Note

would   
 that

be

distorted by leakage currents, resulting in an overestimation of Pr.

Therefore, in order to accurately determine the Pr values of the ZrO2

thin films, positive-up negative-down (PUND) measurements were

performed on the films using the ferroelectric analyzer. The PUND

method employed four successive electrical pulses (two positive

pluses followed by two negative pulses) to evaluate the leakage of

the films. Polarizations (charges) measured from the non-switching

pulses were attributed to the resistive and capacitive components

of the ZrO2 thin films.

**3. Results and discussion**

The GIXRD pattern of the sputtered Pt bottom electrode on the

Si substrate is shown in Fig. 2(a). The Pt bottom electrode was sput-

tered at room temperature and received no thermal treatment prior

to the deposition of the ZrO2 thin film. It was polycrystalline as indi-

cated

47◦,respectively.   
 in Fig. 2(a), with

Note   
 the

that   
 (111)

an   
 and

intermediate   
 (200) peaks

buffer   
 of Pt at

material 2�≈40◦and

layer

and high processing temperatures are typically needed to grow

a textured (or epitaxial) Pt electrode on the Si substrate [27,28].

The GIXRD patterns of the as-deposited and PMA-treated ZrO2 thin

films of different thicknesses for 2�= 20–80◦are shown in Fig. 2(b)

and (c), respectively. The Pt bottom electrode remained polycrys-

talline after the film preparation. As the thickness of the ZrO2 thin

film increased, the intensities of the (111) and (200) peaks of Pt

decreased under the grazing incidence condition.

Fig. 2(b) and (c) shows that both the as-deposited and PMA-

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| **2.** | **Material** | | **and** | **methods** | (MIM) | configuration | was | adopted | to | treated | ZrO2 thin | | films | | exhibited | | a | broad | diffraction | | | | | peak | | at |
| 2�(111)≈30.2◦,which and t-phase | | is | associated | | | with | the | combination | | | | of | the | | o-phase | |
| A | metal-insulator-metal | | | (011) | | peaks | | (o(111)/t(011)). | | | | As | the | film | | thickness | | |

characterize the ferroelectric properties of the ZrO2 thin films.

First,

on a p-type   
 a Pt bottom

(100)-oriented   
 electrode

Si   
 layer

substrate (∼63 by nm

sputtering   
 thick) was

at room   
 deposited

tem-

perature. A ZrO2 thin film was then deposited on the Pt layer by

remote plasma atomic layer deposition (RP-ALD; Fiji G2, Ultratech-

CNT). Tetrakis(dimethylamino)zirconium (TDMAZ, Zr[N(CH3)2]4)

and oxygen plasma were the precursors for Zr and O, respectively.

The precursors were delivered into the ALD reaction chamber with

Ar carrier gas at a deposition (substrate) temperature of 300◦C

under

had three   
 a working

different   
 pressure

thicknesses of 3×10−1Torr.

depending   
 The

on   
 ZrO2 thin

the number   
 film

of   
 layer

ALD

cycles–6.1, 10.3 and 19.6 nm. These thicknesses were confirmed by

spectroscopic ellipsometry (Elli-SE, Ellipso Technology). Finally, a

Pt

by   
 top

sputtering   
 electrode

through (∼28 nm

a shadow   
 thick) was

mask   
 deposited

to complete   
 on the

the   
ZrO2 thin

MIM con-  
film

figuration. After depositing the top electrode, some ZrO2 thin film

samples were treated with post-metallization annealing (PMA) at

600◦C in an N2 atmosphere for 30 s by rapid thermal annealing.

Fig. 1 shows the schematic and cross-sectional TEM image of the

MIM-type ZrO2 thin film sample. The TEM image reveals the uni-

increased from 6.1 to 19.6 nm, the intensity of the o(111)/t(011)

peak increased, together with the appearance of weak diffraction

peaks

(¯111) and   
 at 2�

(111)≈28.5◦and

peaks, respectively.   
 31.4◦,which

Based   
correspond

on the GIXRD   
 to the monoclinic

analyses, it

is evident that the o-/t-phase(s) was the primary phase in the ZrO2

thin films and the crystallinity of the films increased with increas-

ing film thickness. Furthermore, the post-annealing treatment did

not significantly improve the crystallinity of the ZrO2 thin films

prepared by RP-ALD at 300◦C substrate temperature.

Fig. 3(a) shows the cross-sectional HRTEM image of the

as-deposited ZrO2 thin film of thickness 10.3 nm. The FFT diffrac-

togram of the enclosed ZrO2 area of the HRTEM image is shown

as the upper inset in Fig. 3(a). The FFT diffraction pattern derived

from the enclosed area corresponds to the [0¯11]zone axis of

orthorhombic ZrO2 with space group Pbc21.The Pbc21 space group

was confirmed based on the match between the FFT diffraction

spots and simulated diffraction spots generated from the theoret-

ical structural data of ZrO2 with space group Pbc21 [29].Fig. 3(b)

shows the simulated diffraction spots of ZrO2 with space groups

Pbca (orthorhombic), Pbc21 (orthorhombic), P21/c (monoclinic) and

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|  | |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | | post-annealing, | JEur | Ceram | Soc | (2016), | http://dx.doi.org/10.1016/j.jeurceramsoc.2016.10.028 | |  |

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| **Fig.** | | | | | **3.** | | (a) | | Cross-sectional | | | | | | | | | | | | | | l HRTEM | | | | | | | | image | | | | of | | as-deposited | | | | | | | | | ZrO2 thin | | | | | | | film | | | | of | | thickness | | | | |
| 10.3 | | | | | nm | | | – | upper | | | | | | and | | | | lower | | | | | insets | | | | | | are | | the | | | FFT | | | and | | | lattice | | | | fringes | | | | of | | the | | | | enclosed | | | | | | ZrO2 | | |
| area, | | | | | | respectively, | | | | | | | | | | revealing | | | | | | | | | | diffraction | | | | | | | | spots | | | | corresponding | | | | | | | | | | to | [0¯11] | | | | | | zone | | | | axis | | of | | o- |
| phase | | | | | | | (Pbc21)and | | | | | | | | | (111) | | | | | | plane | | | | | of | | | o-phase. | | | | | | (b) | | Simulated | | | | | | | diffraction | | | | | | | | patterns | | | | | | | of | ZrO2 | | |
| with | | | | | | space | | | | groups | | | | | | | Pbca | | | | | (orthorhombic), | | | | | | | | | | | | | Pbc21 (orthorhombic),  to [0¯11] zone axis. | | | | | | | | | | | | | | | P21/c | | | | | | (monoclinic) | | | | | | | |
| and | | | | | P42/nmc | | | | | | | (tetragonal) | | | | | | | | | | | corresponding | | | | | | | | | | | |
| The | | | | | | HRTEM | | | | | | | | analysis | | | | | | | | | confirmed | | | | | | | | | | | that | | | | the | | | as-deposited | | | | | | | | | | ZrO2 thin | | | | | | | | | | film | | |
| prepared | | | | | | | | | | by | | | | RP-ALD | | | | | | | | | was | | | | | crystalline | | | | | | | | | | and | | | | predominant | | | | | | | | | | | with | | | | | | the | | fer- | | |
| roelectric | | | | | | | | | | | o-phase. | | | | | | | | | | As | | | indicated | | | | | | | | | | by | | | the | | GIXRD | | | | | | results | | | | | | (see | | | | | | Fig. | | | 2), | | the | |
| Pt | | | | bottom | | | | | | | | | electrode | | | | | | | | | | was | | | | | | polycrystalline | | | | | | | | | | | | | | before | | | | | and | | | | after | | | | | | the | | | film | | |
| deposition. | | | | | | | | | | | | | The | | | | | effect | | | | | | | of | | polycrystallinity | | | | | | | | | | | | | | | | of | the | | | Pt | | electrode | | | | | | | | | | | on | | the | |
| crystalline | | | | | | | | | | | | | growth | | | | | | | | of | | | ZrO2 by | | | | | | | | | RP-ALD | | | | | | | is | | | still | | | unclear | | | | | | | and | | | | | requires | | | | | |
| **Fig.** | **2.** | GIXRD | patterns | | | of | (a) | | Pt | bottom | electrode | and | (b) | | as-deposited | | | | and | | (c) | PMA- | further | | | | | | | studies. | | | | | | | | | It | | is | | | believed | | | | | | | | | that | | | | | the | | | polycrystalline | | | | | | | | | | | | | | Pt | | | electrode | | | | | | |

treated ZrO2 thin films of different thicknesses (6.1, 10.3 and 19.6 nm).

P42/nmc (tetragonal), corresponding to the [0¯11]zone axis and

generated from the theoretical structural data of ZrO2 [29]. Upon

comparing Fig. 3(a) and (b), it is evident that our experimental

FFT diffraction pattern matches the simulated diffraction pattern

of orthorhombic Pbc21.

The lattice fringes of the ZrO2 layer, shown as the lower inset in

Fig. 3(a), reveal the o(111) plane with an interplanar distance (d) of

3.03 Å, which is slightly larger than the theoretical value (2.96 Å).

acted as a bonding layer to join the ZrO2 thin film and Si substrate,

which have very different thermal expansion coefficients (i.e., 10.3

and 2.5 10−6/K for ZrO2 and Si, respectively). This large difference

in the thermal expansion coefficients was needed to successively

induce sufficient thermal stresses at the material interface under

the pulsating plasma flow of RP-ALD to stabilize the high-pressure

ferroelectric o-phase in the ZrO2 thin film.

Fig. 4(a)–(c) shows the P-E hysteresis curves of the as-deposited

and PMA-treated ZrO2 thin films of three different thicknesses–6.1,

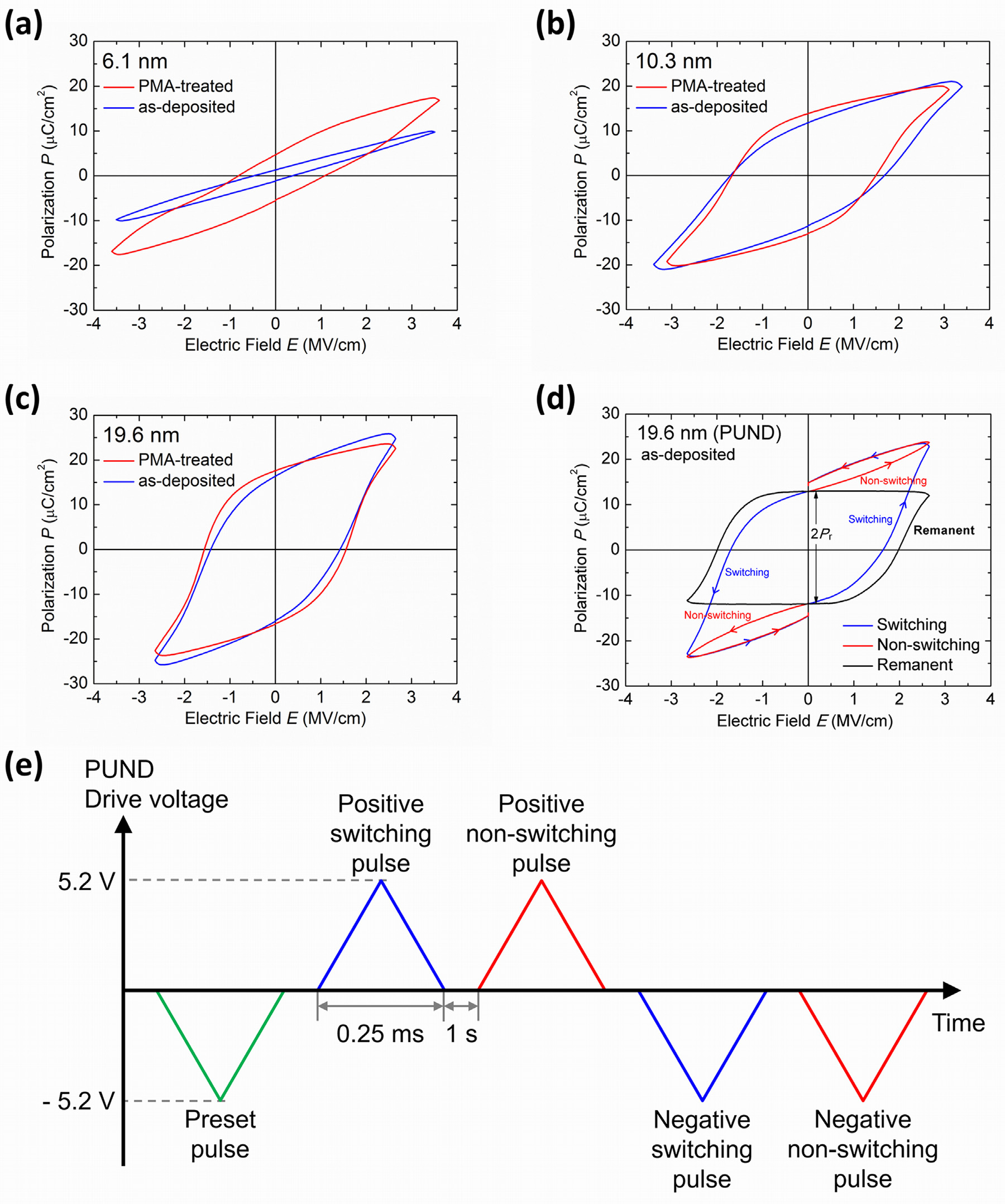
10.3 and 19.6 nm, respectively. For the 6.1-nm-thick ZrO2 films, the

apparent weak ferroelectricity could be attributed to its poor crys-

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| This | would | suggest | the | presence | of | stresses | within | the | ZrO2 layer. | tallinity | as | indicated | by | the | GIXRD | results | (see | Fig. | 2). | In | contrast, |

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**Fig. 4.** P-E hysteresis curves of as-deposited and PMA-treated ZrO2 thin films of three different thicknesses: (a) 6.1, (b) 10.3 and (c) 19.6 nm. (d) Switching, non-switching

and remanent hysteresis curves of as-deposited ZrO2 thin film (19.6 nm thick) obtained from PUND test. (e) Sequence of applied electrical pulses of PUND test.

Fig. 4(b) and (c) shows that for the ZrO2 thin films of thickness 10.3 induced from the resistive and capacitive behaviors of the ZrO2 thin

and 19.6 nm, both the as-deposited and PMA-treated films exhib- film were subtracted from the apparent hysteresis, leaving only the

ited stable P-E hystereses with large Pr,which could be attributed

to their prominent ferroelectric crystallinity (i.e., Pbc21 o-phase) as

indicated by GIXRD and HRTEM. The remanent hysteresis curve of

the as-deposited, 19.6-nm-thick ZrO2 film derived from the PUND

test is shown in Fig. 4(d) (black line). The sequence of the applied

contribution of the intrinsic hysteretic component. Fig. 4(d) indi-

cates that the 2Pr value of the as-deposited, 19.6-nm-thick ZrO2

film, which possessed a strong ferroelectricity and prepared with-

out post-annealing, was 24�C cm−2(i.e., average Pr = 12�Ccm−2).

This value is comparable to those of HZO thin films [14,30].

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| electrical | pulses | of | the | PUND | test | is | shown | in | Fig. | 4(e). | The | PUND | It | is | evident | from | Fig. | 4 | that | for | the | thickness | of | 10.3 | or |

method allowed a more accurate determination of Pr of the thin

film which exhibited leakage characteristics based on the measured

P-E hysteresis. By subtracting the polarization values of the non-

19.6 nm, there is no obvious difference in ferroelectricity between

the as-deposited and PMA-treated ZrO2 thin films. This is con-

sistent with the GIXRD results which revealed that the intensity

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| switching | pulses | from | those | of | the | switching | pulses, | polarizations | of | the | o(111)/t(011) | peak | was | not | improved | by | the | PMA | treat- |

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| ment. | | | | | The | | | | | | | post-annealing | | | | | | | | | | | | | | | | | | step | | | | | | is | | | therefore | | | | | | | | | | | | not | | | | | | essential | | | | | | | | | | | | | for | | | | | the | | | [7] | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | [Salahuddin,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | [Datta,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | [Use](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | [negative](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | | [capacitance](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | | | | | | | | | [t](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | [o provide](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | | | [voltage](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0035) | | | | | | | | | | | | | |
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| [V.V.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | [Zhirnov,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | [R.K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | [Cavin,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | [Nanoelectronics:](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | | | | | | | | | | [negative](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | | | | | [capacitance](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | | | | | [to](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | [the](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | [rescue?](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | |
| ness | | | | 10–20 | | | | | | | | | nm, | | | | prepared | | | | | | | | | | | | by | | | RP-ALD | | | | | | | | | | at | | | a | substrate | | | | | | | | | | | | | temperature | | | | | | | | | | | | | | | | | of | |
| [Nat.Nanotechnol.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | | | | | | | [3](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | [(2008)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | [77–78.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0040) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 300◦C. | | | | | | | In | | | | contrast, | | | | | | | | | , our | | | | | | preliminary | | | | | | | | | | | | | | experiments | | | | | | | | | | | | | | | | indicated | | | | | | | | | | | | that | | | | | | | the | | | [9] | | [D.J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [Appleby,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | [N.K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | [Ponon,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | [K.S](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [. Kwa,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [B.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [Zou,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | [P.K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [Petrov,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | [, T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [Wang,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | [N.M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [Alford,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) |
| post-annealing | | | | | | | | | | | | | | | | | procedure | | | | | | | | | | | | was | | | | | indeed | | | | | | | | | needed | | | | | | | | | to | | | | crystallize | | | | | | | | | | | | | | the | | | | | fer- | | | [10] | | [O’Neill,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [Experimental](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | [observation](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [negative](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | [capacitance](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [ferroelectrics](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | | [at](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | |
| [room](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | [temperature,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | [Nano](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | [14](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | [(2014)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | [3864–3868.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0045) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| roelectric | | | | | | | | | | | o-phase | | | | | | | | | when | | | | | | | | the | | | | | ZrO2 thin | | | | | | | | | | | | films | | | | | | | were | | | | | | | | deposited | | | | | | | | | | | | | | | at | | a |
| [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | [Rödel,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | [W.Jo,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | [K.T.P.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | [Seifert,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | [E.M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | [Anton,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | [Granzow,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | | [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | [Damjanovic,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | | | | | | | | | |
| substrate | | | | | | | | | | | temperature | | | | | | | | | | | | | | | below | | | | | | | 300◦C. | | | | | | | | | It | | | s | therefore | | | | | | | | | | | | | concluded t | | | | | | | | | | | | | | | | that | | | [Perspective](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | [on](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | [the](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | [development](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | | | | | [f](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | [lead-free](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | [piezoceramics, J](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | | | | | | | [.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | [Am.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | [Ceram.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | [Soc.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | |
| RP-ALD | | | | | | | | | growth | | | | | | | | at | | | 300◦C | | | | | | | | | can | | | | provide | | | | | | | | | | | sufficient | | | | | | | | | | | | heat | | | | | | and | | | | | | thermal | | | | | | | | | | [11] | | [92(2009)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | [1153–1177.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0050) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| stresses | | | | | | | | | during | | | | | | | | the | | | | | deposition | | | | | | | | | | | | | | stage | | | | | | | to | | | induce | | | | | | | | | | the | | | | | | t-to-o | | | | | | | | | phase | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | [Shieh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | [K.C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | [Wu,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | [C.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | [Chen,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | [Switching](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | | | | | | [haracteristics](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | [MPB](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | [compositions](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | |
| |  |  | | --- | --- | | [(Bi0.5Na0.5)TiO3–BaTiO3–(Bi0.5K0.5)TiO3](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) [lead-free](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055)  [Mater. 55 (2007) 3081–3087.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | f | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [erroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | | | | | | | [ceramics,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | | | | | | [, Acta](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0055) | | | | |
| transformation | | | | | | | | | | | | | | | | | in | | | nanoscale | | | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | | films. | | | | | | | | The | | | | | | nanoscale | | | | | | | | | | | | | | ZrO2 | | | | |
| thin | | | film | | | | | | | | confined | | | | | | | | | by | | | | | the | | | | Pt/Si | | | | | | substrate | | | | | | | | | | | under | | | | | | | | | | plasma | | | | | | | | | bombard- | | | | | | | | | | | | | [12] | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | [Shieh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | [Y.C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | [Lin,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | [C.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | [Chen,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | [Intricate](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | | | | | [straining](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | [f manganese-doped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ment | | | | | could | | | | | | | | be | | | regarded | | | | | | | | | | | as | | | a | | highly | | | | | | | | constrained | | | | | | | | | | | | | | | | environment | | | | | | | | | | | | | | | | | [31], | | | | | [13] | | |  |  | | --- | --- | | [(Bi0.5Na0.5)TiO3–BaTiO3–(Bi0.5K0.5)TiO3](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) [lead-free](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060)  [Phys. D Appl. Phys. 43 (2010) 025404.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | f | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [erroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | | | | | | | [ceramics,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | | | | | | [, J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0060) | | | | |
| in | | which | | | | | | | | | the | | | | t-to-o | | | | | | | phase | | | | | | | transformation | | | | | | | | | | | | | | | | | | | circumvents | | | | | | | | | | | | | | | | the | | | | | | t-to-m | | | | | | | |
| [G.H.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | [. Kwei,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | [A.C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | [Lawson,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | [S.J.L.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | [Billinge,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | [S.W.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | [. Cheong,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | | | [Structures](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | [the](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | | |
| phase | | | | | transformation | | | | | | | | | | | | | | | | | | | | typically | | | | | | | | | | observed | | | | | | | | | | | in | | | bulk | | | | | | | ZrO2. | | | | | | | | | | | | | | | | | | | | | | [14] | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | [phases](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | [barium-titanate,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | | | | | | | | [J.Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | [Chem.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | [97](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | [(1993)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | [2368–2377.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0065) | | | | | | | | | | | |
| [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | [M](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) [¨uller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | [T.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | B[¨oscke,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | Schr[¨oder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | [Mueller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | [Br¨auhaus,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | [B¨ottger, L](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | [.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | [Frey,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | |
| **4.** | **Conclusions** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | | | | | | | | | | | | | | | [Mikolajick,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | [simple](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | [binary](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | [ZrO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | [HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070),[Nano](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | [12](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | |
| [(2012)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [4318–4323.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0070) | | | | | | | | | | | | | | | | | | | | | |
| [15] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [P.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | [Polakowski,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | [Müller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | [undoped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | | | | | [hafnium](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | | [oxide,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | [Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | |
| In | | | | | this | | | | | | | study, | | | | | | | large | | | | | | | | stable | | | | | | | | ferroelectricity | | | | | | | | | | | | | | | | | | | | has | | | | | been | | | | | | | demon- | | | | | | | | | | | [16] | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | [106](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | [(2015)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | [232905.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0075) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [T.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | [Böscke,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | [J](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | [. Müller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | [Bräuhaus,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | [Schröder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | [Böttger,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | | [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | |
| strated | | | | | | | in | | | | nanoscale | | | | | | | | | | | | undoped | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | | films | | | | | | | on | | | | the | | | | | Pt | | | electrode. | | | | | | | | | | | | |
| [17] | | [hafnium](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | [oxide](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080), | | | | | | [Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | [99](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | [(2011)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | [102903.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0080) | | | | | | | | | | | | | | | | | | | | | | | |
| The | | | crystalline, | | | | | | | | | | | | | | ferroelectric | | | | | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | | films | | | | | | were | | | | | | | | prepared | | | | | | | | | | | | | by | | | | RP- | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | [Müller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Schröder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [T.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | [. Böscke,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [I.Müller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | [Böttger,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | [L.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | [Wilde,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Sundqvist,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | |
| ALD | | | at | | | | a | | | substrate | | | | | | | | | | temperature | | | | | | | | | | | | | | | | of | | | 300◦C | | | | | | | | | without | | | | | | | | | | | post-annealing. | | | | | | | | | | | | | | | | | | | [18] | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Lemberger,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [, P.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Kücher,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Mikolajick,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | | [, L.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | [Frey,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | | | |
| [yttrium-doped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | | | [hafnium](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | [oxide,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | [J.Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | [110 (](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | [(2011)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | [114113.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0085) | | | | | | | | | | | | | | | | | | | |
| The | | | existence | | | | | | | | | | | | | of | | the | | | | | ferroelectric | | | | | | | | | | | | | | | o-phase | | | | | | | | | | with | | | | | | | space | | | | | | | group | | | | | | | | | | Pbc21 | | | | | |
| [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | [Mueller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | [Mueller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | [Singh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | [Riedel,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | [Sundqvist,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | [Schroeder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | |
| in the ZrO2 thin  HfO2-based thin | | | | | | | | | | | | | | | | | | | film | | | | | | | has | | | | been | | | | | | | confirmed. | | | | | | | | | | | | | | As | | | | | compared | | | | | | | | | | | | | | to | | | | | the | | |
| [Mikolajick,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | [Incipient](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | [ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | [Al-doped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | | | | | | [HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090), | | | | | | [Adv.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | [Funct.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | |
| flms | | | | | | | reported | | | | | | | | | | | in | | | | the | | | | | literature, | | | | | | | | | | | | | | for | | | | which | | | | | | | | | | | the | | | [19] | | [Mater.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | [22](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | [(2012)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | [2412–2417.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0090) | | | | | | | | | | | | | | | | | | | |
| [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | [Mueller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | [C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | [Adelmann,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | [A](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | [Singh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | [Van](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | [Elshocht,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | [Schroeder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | [Mikolajick,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | |
| post-annealing | | | | | | | | | | | | | | | | | treatment | | | | | | | | | | | | | at | | | 700–1000◦C | | | | | | | | | | | | | | | | and | | | | | | | TiN | | | | | electrode | | | | | | | | | | | | | | are | | |
| [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | [Gd-doped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | [HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095), | | | | | | | | [ECS](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | [Solid](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | [State](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | [Sci.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | [Technol.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | [1](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) |
| needed | | | | | | | to | | | | | achieve | | | | | | | | | crystallization | | | | | | | | | | | | | | | | | | and | | | | | | stable | | | | | | | | ferroelectricity, | | | | | | | | | | | | | | | | | | | | | | the | | |
| [(2012)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | [N123–N126.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0095) | | | | | | | | | | | | | | | | | | | | |
| low-temperature-prepared | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ferroelectric | | | | | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | | | films | | | | | | developed | | | | | | | | | | | | | [20] | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | [Shimizu,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [Yokouchi,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [Oikawa,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [Shiraishi,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [Kiguchi,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | [Akama,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | [T.J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | |
| in | | this | | | | | study | | | | | | | | offer | | | | | superior | | | | | | | | | | | | flexibility | | | | | | | | | | | | in | | | terms | | | | | | | | | of | | | device | | | | | | | | | integra- | | | | | | | | | | [Konno,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | [Gruverman,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | | [H.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | [Funakubo,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | | [Contribution](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [oxygen](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | [vacancies](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | [to](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | [the](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | |
| [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | [behavior](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | [Hf0.5Zr0.5O2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | | | | | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100), | | | | | | | | [Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | [106](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | [(2015)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | |
| tion. | | | | This | | | | | | | huge | | | | | | advantage | | | | | | | | | | | | makes | | | | | | | | | the | | | | | ferroelectric | | | | | | | | | | | | | | | | ZrO2 thin | | | | | | | | | | | | | | films | | | | |
| [112904.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0100) | | | | | | | | | |
| relevant | | | | | | | | | for | | | | | technological | | | | | | | | | | | | | | | | applications | | | | | | | | | | | | | | | in | | | the | | | | field | | | | | | | | of | | non-volatile | | | | | | | | | | | | | | | | [21] | | [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Zhou,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | [, J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Xu,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | [Q.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Li,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | [Y.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Guan,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | [F.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | [Cao,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | [X.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Dong,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | [, J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | [Müller,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Schenk,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | [Schröder,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | |
| memories | | | | | | | | | | | | and | | | | ultralow-power | | | | | | | | | | | | | | | | | | | nanoelectronics. | | | | | | | | | | | | | | | | | | | | | | | | | [Wake-up](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | [effects](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | [Si-doped](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | | | | [hafnium](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | [oxide](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | | | | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105), | | | | | | [Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | |
| [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | [103](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | [(2013)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | [192904.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0105) | | | | | | | | | | | | | | |
| [22] | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [X.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | [Zhao,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | [Vanderbilt,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | [First-principles](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | | | | | | | [study](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | [structural,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | | [vibrational,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | | | [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | |
| **Acknowledgements** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [23] | | | | | | | | | | | | | | | | | | | | | | | | [lattice](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | [dielectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | [properties](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | [hafnium](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | [oxide,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | [Rev.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | [B](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | [65](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | [(2002)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | | | [233106.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0110) | | | | | | |
| [S.E.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | [Reyes-Lillo,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | | [K.F.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | [Garrity,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | | [K.M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | [Rabe](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | [, Antiferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | [thin-fil](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115)m | | | | | | | | | | [ZrO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | |
| This | | | | | | | work | | | | | | | | was | | | | supported | | | | | | | | | | | | | | by | | | the | | | | | Ministry | | | | | | | | | | of | | | | | Science | | | | | | | | | and | | | | | | | Tech- | | | | | | [24] | | [from](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | [firs](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115)t | | | | [principles,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | [Rev.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | [B](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | [90](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | [(2014)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | [140103.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0115) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [Z.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | [Fan,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | [Deng,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | [, J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | [Wang,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | [Z.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | [Liu,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | [P.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | [Yang,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | [Xiao,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | [X.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [Yan,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [Z.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | [Dong,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | [Wang,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | [J.Chen,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | |
| nology | | | | | | | (MOST) | | | | | | | | | | of | | | Taiwan | | | | | | | | | | [grant | | | | | | | | | numbers | | | | | | | | | | | 105-2622-8-002-001, | | | | | | | | | | | | | | | | | | | | | | | | | | | | [25] | | [Ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | | | | | [emerging](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [strained](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | [(111)-textured](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | | | | | | | | | | | [ZrO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120), | | | | | | [Appl.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | |
| 104-2622-8-002-003, | | | | | | | | | | | | | | | | | | | | | | | | | 103-2221-E-002-078-MY2]; | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | and | | | | | the | | | | | Taiwan | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [108](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | [(2016)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | [012906.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0120) | | | | | | | | | | | | | | | |
| [C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | [Zhao,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | [G.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | [. Roebben,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | [Heyns,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | [O.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | [Van](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | [der](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | [Biest,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | [Crystallisation](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | | | | [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | |
| Semiconductor | | | | | | | | | | | | | | | | | Manufacturing | | | | | | | | | | | | | | | | | | Company | | | | | | | | | | | (TSMC). | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [tetragonal-monoclinic](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | | | | | | | | [transformation](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | [ZrO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | | [HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) [dielectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | [films](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125), | | | | |
| [Key](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | [Eng.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | [Mater](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | [. 206](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | [(2002)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | [1285–1288.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0125) | | | | | | | | | | | | |
| **References** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [26] | | | | | | | | | | | | | | | | | | | | | | | | [Y.W.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | [Lu,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | [Shieh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | [F.Y.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | [Tsai,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | [, Induction](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | [ferroelectricity](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | [nanoscale](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | | | [ZrO2/HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | |
| [bilayer](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | [film](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130)s | | | | | [on](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | [Pt/Ti/SiO2/Si](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | | | | | | [substrates,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | | | | | [Acta](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | [Mater.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | [115](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | [(2016)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | | | [68–75.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0130) | | | | | | |
| [1] | | | [P.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | [Muralt](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | [, Ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | [film](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005)s | | | | | [for](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | [micro-sensors](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | | | | | | [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | [actuators:](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | | [a](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | [review,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | [27] | | [R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | [. Ramesh,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | [Lee,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | [Sands,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | [V.G.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | [Keramidas,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | | | | [O.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | [Auciello,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | | [Oriented](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | | | |
| [La-Sr-Co-O/Pb-La-Zr-Ti-O/La-Sr-Co-O heterostructures on [001] Pt/SiO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) [Si](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135)  [substrates using a bismuth titanate template layer, Appl. Phys. Lett. 64 (1994)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [2] | | | [Micromech.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | | | [. Microeng.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | [10](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | [(2000)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | [136–146.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0005) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [28] | |
| [J.F.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | [Scott,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | [C.A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | [Paz](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | [de](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | [Araujo,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | [Ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | | | | | [memories,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | | | | [Science](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | [246](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | [(1989)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | | | | | |
| [2511–2513.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0135) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [1400–1405.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0010) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | [Akai,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | [K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | [Hirabayashi,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | [Yokawa,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | [K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | [Sawada,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | [Ishida,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | [Epitaxial](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | [growth](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | |
| [3] | | | [H.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Kohlstedt,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | [Y.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Mustafa,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Gerber,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Petraru,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Fitsilis,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | [R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | [Meyer,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | [U.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | [Böttger,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | |
| [Pt(001)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | [thin](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | [film](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140)s | | | | [on](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | [Si](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | [substrates](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | | [using](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | [an](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | [epitaxial](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | [�-Al2O3(001)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | | | | | | [buffer](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | |
| [4] | | | [R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [Waser,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | [Current](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | [status](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | [challenges](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | | | [memory](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | [devices,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | | | | [29] | |
| [layer,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | [Cryst.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | [Growth](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | [264](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | [(2004)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | [463–467.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0140) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [Microelectron.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | | | | [Eng.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | [80](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | [(2005)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | [296–304.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0015) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [J.E.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | [Lowther,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | [J.K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | [Dewhurst,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | | | | [J.M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | [Leger,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | [Haines,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | | | | [Relative](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | [stability](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | [ZrO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) [and](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | |
| [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Chanthbouala,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Crassous,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | [V.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [. Garcia,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | [K.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Bouzehouane,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | [Fusil,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | [X.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Moya,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | |
| [HfO2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) [structural phases,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145)  [M.H. Park, H.J. Kim, Y.J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | | | | | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | [Rev.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | [B](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | [60](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | [(1999)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | | | [14485–14488.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0145) | | | | | | | | | | | | | | | | | | | | | |
| [Allibe,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | [B.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Dlubak,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Grollier,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | [S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Xavier,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | [C.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Deranlot,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Moshar,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | [R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [Proksch,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | [N.D.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | |
| [5] | | | [30] | | [Kim,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | [W.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | [Lee,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | [T.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | [Moon,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | [C.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | [Hwang,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | | [Evolution](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | [phases](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | |
| [Mathur,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | [M.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Bibes,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | [A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | [Barthélémy,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | [Solid-state](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | [memories](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | [based](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | [on](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | | | |
| [andferroelectric properties of thin Hf0.5Zr0.5O2](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) [film](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150)s [according to](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150)  [thickness and annealing temperature, Appl. Phys. Lett. 102 (2013)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | [the](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150)  [242905.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0150) | | | | | | | | | |
| [tunnel](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | [junctions,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | [Nat.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | [Nanotechnol.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | | [7](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | [(2012)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | [101–104.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0020) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [M.Y.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | [Zhuravlev,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | [R.F.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | [Sabirianov,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | | [S.S.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | [Jaswal,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | [E.Y.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | [Tsymbal,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | [Giant](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | | | | | | | | | | | |
| [31] | | [E.H.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | [Kisi,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | [C.J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | [Howard,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | [R.J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | [Hill,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | [Crystal-structure](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | [orthorhombic](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | | | | | | | [zirconia](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | |
| [electroresistance](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | | | | | | | [in](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | | | [tunnel](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | [junctions,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | [Rev.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | [Lett.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | [94](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | [(2005)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | |
| [partially](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | [stablished](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | | | [zirconia,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | | | [J.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | [Am.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | [Ceram.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | [Soc.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | [72](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | [(1989)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | [1757–1760.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0155) | | | | | | | | | | | | | | | | | | |
| [246802.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0025) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [6] | | | [H.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | [Kohlstedt,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | [N.A.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | [Pertsev,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | [J.R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | [Contreras,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | [R.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | [Waser,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | [Theoretical](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [current-voltage](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | | | | | [characteristics](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | | [of](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | [ferroelectric](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | [tunnel](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | [junctions,](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | [Phys.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | [Rev.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | [B](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| [72(2005)](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | [125341.](http://refhub.elsevier.com/S0955-2219(16)30580-5/sbref0030) | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

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|  | |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | | post-annealing, | J | Eur | Ceram | Soc | (2016), | http://dx.doi.org/10.1016/j.jeurceramsoc.2016.10.028 | |  |