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Ferroelectric phase stabilization of HfO2 by nitrogen doping

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| We report that nitrogen (N) doping can drive the ferroelectricity of HfO2. It was found that N doping can cause the transition from a monoclinic |

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| phase to a highly symmetric phase. The role of N doping is discussed from the viewpoints of charge balance and bond-constraining effects. The |

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| former is responsible for the structural transformation from a paraelectric phase to a ferroelectric phase by forming an oxygen vacancy. In addition, |

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| Hf–N and N–O bonds with covalent characteristics have strong effects on HfO2 structural and electrical properties, and thus contribute to a marked HfO2 para-/ferroelectric transition. © 2016 The Japan Society of Applied Physics |

T transistors (FeFETs),2)and negative-capacitance FETs.3) attention owing to its promising applications, such as in nonvolatile memories,1)ferroelectric field-effect he ferroelectricity of HfO2 has attracted considerable

Most results reported so far on HfO2 ferroelectricity have been demonstrated by cation doping (Si,4–6)Y,7–9)Al,10) Zr,11)Sr,12)and Gd13)). Although the role of dopants is still not well understood, the ferroelectric phase is considered to originate from the structural stabilization of the non-centrosymmetric phase of HfO2, owing to cation doping. It is like dopant-induced martensitic phase transition of ZrO2 studied extensively by fine ceramics community, in which two possible reasons have been conjectured.14)One is charge balance and the other one is ionic radius.

The ferroelectricity enhancement reported in HfO2 is always accompanied by the structural phase transition. According to first-principles calculations, the free energies of two orthorhombic (O) polar phases (Pca21 and Pmn21) are relatively low and very close to those of nonpolar equilibrium phases [e.g., P21=c monoclinic (M) phase at a low temper-ature].15)The orthorhombic phase has a higher symmetry than the monoclinic one, but it has a lower coordination number of Hf (7) than that in a tetragonal (T, P42=nmc) or cubic (C, Fm�3m) case (8). From the viewpoint of the HfO2 phase transition, the metastable orthorhombic polar phase might exist at the boundary between the monoclinic and tetragonal phases.16)Therefore, the ferroelectric phase forma-tion and related ferroelectric properties should be signifi-cantly affected by phase transition processes.

In the conventional HfO2 high-k case, Y2O3 and SiO2 are the two typical dopants that induce the HfO2 phase transition to a higher symmetric one, but possibly by different mech-anisms. Y2O3 triggers the oxygen vacancy (Vo) formation for maintaining the charge neutrality, and SiO2 may distort HfO2 owing to its smaller cation radius.17)The oxygen vacancy origin may apply in sub-tetravalent ionic cation doping cases (e.g., Y, Gd, and Sr), and their ferroelectric properties, such as a large coercive field (Ec) (1.5–2 MV=cm), are quite similar.7–9,12,13)In contrast, the Si-doped HfO2 has a much smaller Ec (< 1 MV=cm) and exhibits strongly anti-ferro-electric performance.4–6)The HfO2 phase transition mechan-ism might be understandable from the charge balance and small dopant radius, but the physical origin of the ferro-electric HfO2 phase is still not well understood. Furthermore, there is no report on the effects of anion doping on the HfO2 para-=ferroelectric transition, although it was reported that

anion dopants could also induce the HfO2 phase transition to higher symmetric phases.18)   
 In this Letter, we report that N doping can cause the HfO2 para-=ferroelectric transition in addition to the fact that it can stabilize highly symmetric phases. Moreover, we have found that the phase transition in the N-doped case is different from that in the cation-doped one in several aspects. We discuss the N-doped HfO2 ferroelectricity from the viewpoint that both Hf–N and N–O bonds have more covalent bonding characters than the Hf–O counterpart in addition to the oxygen vacancy formation in HfO2.

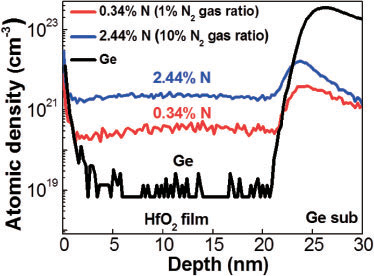
HfO2 films were fabricated by rf sputtering on highly doped p-type Ge (111) after chemical cleaning by methanol, 17% HCl, and diluted 5% HF solutions. The p+Ge substrate was reported to enhance the ferroelectric behaviors of thin HfO2 films because of the reduced interface dielectric layer at the HfO2=Ge interface.19)Less than 6 × 10−6Pa was achieved before the HfO2 film deposition, and the working pressure was 0.12 Pa during sputtering with 20 sccm Ar gas flow. For Sc-doped HfO2 (or Y-doped HfO2), the sputtering power was varied from 10 to 60 W for the Sc2O3 source (from 10 to 30 W for the Y2O3 source), while it was kept at 80 W for the HfO2 source. For N-doped HfO2, the HfO2 source power was kept at 80 W, and the N2 gas ratio [N2=(N2 + Ar)] was varied from 0.25 to 50% with 20 sccm total gas flow. In our experi-ments, the film thickness was controlled at around 28 nm, and top Au electrodes (5.7 × 10−5cm2) were thermally evapo-rated after the postdeposition annealing (PDA) at 600 °C in 1 atm N2 for 30 s. Here, thick HfO2 films and top Au elec-trode evaporation after PDA were used to limit both the surface enthalpy20)effect and top-TiN-layer21)-induced HfO2 phase transition. Polarization–voltage (P–V) and capaci-tance–voltage (C–V) characteristics were measured at 100 Hz and 10 kHz, respectively. X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS) were used for the struc-tural phase and chemical composition analyses, respectively. The atom profiles in N-doped HfO2 films were analyzed by secondary ion mass spectrometry (SIMS).

The SIMS depth profiles of annealed N-doped HfO2 stacks with 1 and 10% N2 gas ratios during the sputtering are shown in Fig. 1(a), in which the N doping concentration [the total atomic ratio in this work, N=(Hf + O + N)] was estimated to be 0.34 and 2.44%, respectively. Assuming that the N doping concentration is proportional to the N2 gas ratio, we estimated the N doping concentration of HfO2 films deposited with dif-ferent N2 gas ratios. The Ge diffusion into HfO2 can be

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(a)



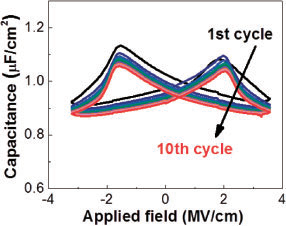
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| Fig. 1. | (b) |  |
| (a) SIMS depth profiles of N and Ge atoms in annealed N-doped | |

HfO2 films with 1 and 10% N2 gas ratios during sputtering. (b) N 1s XPS spectra of nondoped and N-doped HfO2 films (with 50% N2 gas ratio). O 1s peaks are normalized and fixed at 530.4 eV as the reference.

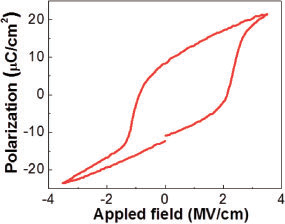
ignored because there is no Ge signal in the SIMS depth profiles of annealed HfO2 films [Fig. 1(a)]. For Sc- or Y-doped HfO2 with different sputtering powers, the doping con-centration ½Sc=ðHf þ O þ ScÞ; Y=ðHf þ O þ YÞ� was meas-ured by XPS. Figure 1(b) shows the N 1s XPS spectra of the nondoped and heavily N-doped HfO2 films (with 50% N2 gas ratio). Here, the O 1s peak was fixed at 530.4 eV as the reference. The N-doped HfO2 film exhibits a clear and strong peak at 396 eV showing the Hf–N bond formation.18)In addition, a weak peak at 403 eV indicates the existence of a small number of N–O bonds. Since both Hf–N and N–O bonds have strong covalent properties, they should affect the structural and electrical properties of HfO2.

The polarization–field (P–E) and capacitance–field (C–E) characteristics of 0.34% N-doped HfO2 films are shown in Figs. 2(a) and 2(b), respectively. Figure 2(c) shows the di-electric and ferroelectric properties of HfO2 films as a function of N doping concentration. Interestingly, 0.34% N doping is sufficient to maximize the remanent polarization Pr, while it is markedly suppressed when the doping concen-tration is more than 1%. For the nondoped HfO2 film, the monoclinic phase is dominant, and thus the dielectric con-stant of HfO2 is approximately 18. Nevertheless, 10 µC=cm2 of the switchable polarization PSW (Pr+− Pr−) is observed for the nondoped HfO2. This was also previously reported for sputtered nondoped HfO2 films.7)An approximately 20% highly symmetric phase was found in the nondoped HfO2 (Fig. 3), which supports the observed ferroelectric behavior. The ferroelectricity in the nondoped HfO2 might be caused by the formation of highly symmetric phases in sputtering or

(a)



(b)



(c)

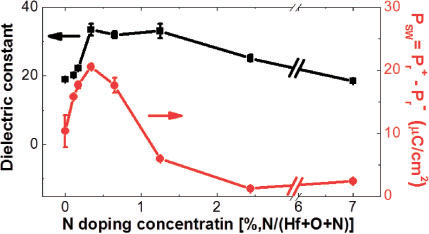
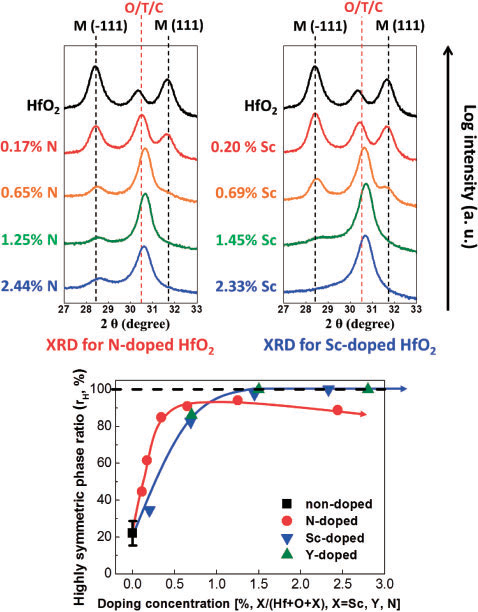


Fig. 2. (a) P–E (100 Hz) and (b) C–E (10 kHz) characteristics of the 28-nm-thick 0.34% N-doped HfO2 film. (c) Switchable polarization PSW (Pr+− Pr−) and relative dielectric constant of 28-nm-thick HfO2 films with different N doping concentrations. Pr+and Pr−are positive and negative remanent polarizations under zero bias condition, respectively. The dielectric constant is estimated from the central crossing point of C–E curves.

PDA processes. For example, it is known that Ar atoms, doped into HfO2 during sputtering, can stabilize highly symmetric phases.22)Moreover, rapid PDA processes were used to obtain HfO2 highly symmetric phases in conventional high-k research.23)A small amount of N doping (<0.7%) can enhance both the Pr and dielectric constant of HfO2 owing to the formation of ferroelectric orthorhombic phases. However, the ferroelectricity will be markedly suppressed when the N doping concentration is over 1%, while the dielectric con-stant will still be kept above 30. This suggests the transition from the ferroelectric orthorhombic phase to the paraelectric orthorhombic, tetragonal or cubic phase. The ferroelectricity was lost by further increasing the N doping concentration to over 2%, although the highly symmetric phase is still dominant in the XRD patterns.

Intuitively, the role of N doping can be considered from two aspects: the introduction of oxygen vacancy as required for keeping the charge neutrality when N3−replaces O2−and the formation of Hf–N and N–O covalent bonds. The latter seems to bring some properties different from those in the case of ionic cation doping. To further distinguish N bond

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| (a) | (b) | (a) | |  |
| (c) | | (b) | |  |
| Fig. 4. | (a) Switchable polarization of 28-nm-thick HfO2 films with | |
| different N, Sc, or Y doping concentrations. (b) Schematic descriptions of N- | | |

and Sc- (or Y-) doping-induced para-=ferroelectric transition. Vo can stabilize   
higher symmetric phases, and thus lead to the para-=ferroelectric transition.   
This is the case for Sc or Y doping. However, in the N-doped HfO2 case, a   
marked para-=ferroelectric transition is observed as a strong effect from the   
direction N bonds.

Fig. 3. XRD patterns of annealed 28-nm-thick (a) N- and (b) Sc-doped HfO2 films with different doping concentrations. The black dotted lines represent monoclinic ð�111Þ and (111) peaks, and the red dotted lines represent orthorhombic (111), tetragonal (111) and cubic (111) peaks. (c) Highly symmetric phase (O=T=C) of HfO2 (rH) with different N, Sc, or Y doping concentrations.

effects from Vo effects, Sc- and Y-doped HfO2 films were studied considering that two Sc (or Y) atoms (replace Hf)20) or two N atoms (replace O)24)can make one oxygen vacancy, respectively. Figure 4(a) shows the switchable polariza-tion PSW for N-, Sc-, and Y-doped HfO2 as a function of doping concentration. As expected, the Sc- and Y-doped HfO2 exhibit quite similar behaviors. With the coordination number 8, ionic Sr3+has an 87 pm radius, which is very close to that of Hf4+(83 pm), while the radius of ionic Y3+is 102 pm.25)This suggests that the Sc- or Y-doping-induced HfO2 para-=ferroelectric transition is dominated by the Vo mechanism, whereas the ionic radius effect is not dominated. For the N-doped HfO2, slight doping can enhance the ferro-electricity, but overdoping can eliminate the ferroelectricity. This tendency is similar to Sc and Y doping cases. How-ever, note that 0.34% N is sufficient to maximize the ferroelectricity, and 2.44% N can totally suppress PSW below 2 µC=cm2, whereas 0.7 and over 4% are needed for Sc doping and Y doping cases, respectively.

In addition, the XRD patterns of N-doped HfO2 are different from those of Sc-doped HfO2 [shown in Figs. 3(a) and 3(b)]. The highly symmetric phase ratio rH shown in Fig. 3(c) is calculated from the XRD results according to where I is the XRD peak area intensity. We noted that N the equation rH ¼ IO=T=Cð111Þ=½IMð�111Þ þ IO=T=Cð111Þ þ IMð111Þ�, doping is more effective in driving the HfO2 phase transition to a highly symmetric phase than Sc or Y doping in a slightly doped region; however, we also observed opposite behaviors

in a heavily doped region, in which the monoclinic phase can survive in over 2% N-doped HfO2 but disappears in over 2% Sc- or Y-doped HfO2. From the Vo viewpoint, rH can be increased and finally becomes 100% as the stabilized tetragonal or cubic phases by introducing enough oxygen vacancies. This can explain the Sc- or Y-doping-induced HfO2 phase transition behaviors very well, but it is not suitable in the N doping case. We attribute the unique N-doping behaviors to N bond effects.

Here, since Vo is the key ingredient for structural phase transition and the present doping systems can be regarded as diluted doping, we assume that the key parameter in the N-doped case is still the oxygen vacancy motion. Therefore, we discuss the results in Figs. 3(c) and 4(a) thermodynami-cally from the viewpoint of the activity of Vo (aVo) as follows:

aVo / �VoCVo; ð1Þ in which CVo and γVo are the concentration and activity coefficient of Vo, respectively. In the N doping case, aVo increases with CVo more sharply than that in the cation doping case at a small doping stage. On the other hand, γVo in N-doped HfO2 sharply decreases when CVo is over 1% owing to stronger N bond effects, while it is not the case in Sc- or Y-doped HfO2, in which the Vo activity is simply equal to the Vo density. For the ferroelectricity enhancement region, Vo can cause the phase transition from the monoclinic phase to higher symmetric phases, and then generates metastable polar phases at the boundary of M and T phases. Therefore, slight Sc, Y, and N dopings are all effective in enhancing the HfO2 ferroelectricity. Here, N-doped HfO2 exhibits a marked phase transition in a small doping region, which should be related to N bond effects. In the ferroelectricity suppression region, it is understandable that the overdoping of Sc and Y can eliminate the ferroelectricity as the stabilization of the T or C

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phase. As shown in Figs. 3(b) and 3(c), the monoclinic phase has totally transformed to highly symmetric phases when the doping concentration is over 1.5%, and accordingly, the ferroelectricity of Sc- or Y-doped HfO2 is suppressed in this doping region. However, in the N-doped HfO2 case, although we can observe the coexistence of the M and highly symmetric phases, the ferroelectricity is more markedly suppressed than that in the cation doping case. This indicates that a large number of N bonds, especially N–O bonds, might be responsible for suppressing atomic motions, and thus contribute to a marked suppression of HfO2 ferroelectricity.

In this study, the electrical and structural phase properties of N-doped HfO2 have been investigated. A small amount of N doping drives the ferroelectricity of HfO2, and the para-= ferroelectric transition in HfO2 is more sensitive to N doping than to Sc or Y doping. The oxygen vacancy formation due to the replacement of O2−by N3−may explain the para-= ferroelectric transition origin in N-doped HfO2. Moreover, note that directional N bonds (Hf–N and N–O) have strong effects on the oxygen vacancy activity, which is different from that of the trivalent cation doping case. N bonds initially help increase the Vo activity and then weaken it in HfO2. N doping has two directly opposite effects, namely, to trigger the ferroelectricity and suppress it.

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and T. Mikolajick, [Appl. Phys. Lett. 99, 112904 (2011).](http://doi.org/10.1063/1.3636434)

5) D. Martin, J. Müller, T. Schenk, T. M. Arruda, A. Kumar, E. Strelcov, E.

Yurchuk, S. Müller, D. Pohl, U. Schröder, S. V. Kalinin, and T. Mikolajick, [Adv. Mater. 26, 8198 (2014).](http://doi.org/10.1002/adma.201403115)

6) D. Zhou, J. Muller, J. Xu, S. Knebel, D. Brauhaus, and U. Schroder, [Appl.](http://doi.org/10.1063/1.3688915)  [Phys. Lett. 100, 082905 (2012).](http://doi.org/10.1063/1.3688915)

7) T. Olsen, U. Schroder, S. Muller, A. Krause, D. Martin, A. Singh, J. Muller, M. Geidel, and T. Mikolajick, [Appl. Phys. Lett. 101, 082905 (2012).](http://doi.org/10.1063/1.4747209)

8) S. Starschich, D. Griesche, T. Schneller, R. Waser, and U. Bottger, [Appl.](http://doi.org/10.1063/1.4879283)  [Phys. Lett. 104, 202903 (2014).](http://doi.org/10.1063/1.4879283)

9) S. Starschich, S. Menzel, and U. Bottger, [Appl. Phys. Lett. 108, 032903](http://doi.org/10.1063/1.4940370)  [(2016).](http://doi.org/10.1063/1.4940370)

10) S. Mueller, J. Mueller, A. Singh, S. Riedel, J. Sundqvist, U. Schroeder, and T. Mikolajick, [Adv. Funct. Mater. 22, 2412 (2012).](http://doi.org/10.1002/adfm.201103119)

11) J. Müller, T. S. Böscke, U. Schröder, S. Mueller, D. Bräuhaus, U. Böttger, L. Frey, and T. Mikolajick, [Nano Lett. 12, 4318 (2012).](http://doi.org/10.1021/nl302049k)

12) T. Schenk, S. Mueller, U. Schroeder, R. Materlik, A. Kersch, M. Popovici, C. Adelmann, S. Van Elshocht, and T. Mikolajick, [Proc. European Solid-State Device Research Conf., 2013, p. 260.](http://doi.org/10.1109/ESSDERC.2013.6818868)

13) S. Mueller, C. Adelmann, A. Singh, S. Van Elschocht, U. Schroeder, and T. Mikolajick, [ECS J. Solid State Sci. Technol. 1, N123 (2012).](http://doi.org/10.1149/2.002301jss)

14) J. Tang, F. Zhang, P. Zoogman, J. Fabbri, S.-W. Chan, Y. Zhu, L. E. Brus, and M. L. Steigerwald, [Adv. Funct. Mater. 15, 1595 (2005).](http://doi.org/10.1002/adfm.200500050)

15) T. D. Huan, V. Sharma, G. A. Rossetti, Jr., and R. Ramprasad, [Phys. Rev. B](http://doi.org/10.1103/PhysRevB.90.064111)  [90, 064111 (2014).](http://doi.org/10.1103/PhysRevB.90.064111)

16) M. Hoffmann, U. Schroeder, T. Schenk, T. Shimizu, H. Funakubo, O.

Sakata, D. Pohl, M. Drescher, C. Adelmann, R. Materlik, A. Kersch, and T. Mikolajick, [J. Appl. Phys. 118, 072006 (2015).](http://doi.org/10.1063/1.4927805)

17) C. Lee, E. Cho, H. Lee, C. S. Hwang, and S. Han, [Phys. Rev. B 78, 012102](http://doi.org/10.1103/PhysRevB.78.012102)  [(2008).](http://doi.org/10.1103/PhysRevB.78.012102)

18) K. Sarakinos, D. Music, S. Mráz, M. to Baben, K. Jiang, F. Nahif, A. Braun, C. Zilkens, S. Konstantinidis, F. Renaux, D. Cossement, F. Munnik, and J. M. Schneider, [J. Appl. Phys. 108, 014904 (2010).](http://doi.org/10.1063/1.3437646)

19) P. D. Lomenzo, Q. Takmeel, C. M. Fancher, C. Zhou, N. G. Rudawski, S.

Moghaddam, J. L. Jones, and T. Nishida, [IEEE Electron Device Lett. 36,](http://doi.org/10.1109/LED.2015.2445352)

[766 (2015).](http://doi.org/10.1109/LED.2015.2445352)

1) M. H. Park, Y. H. Lee, H. J. Kim, Y. J. Kim, T. Moon, K. D. Kim, J. 20) A. Navrotsky, [J. Mater. Chem. 15, 1883 (2005).](http://doi.org/10.1039/b417143h)

Muller, A. Kersch, U. Schroeder, T. Mikolajick, and C. S. Hwang, [Adv.](http://doi.org/10.1002/adma.201404531)  21) P. Polakowski and J. Muller, [Appl. Phys. Lett. 106, 232905 (2015).](http://doi.org/10.1063/1.4922272)

[Mater. 27, 1811 (2015).](http://doi.org/10.1002/adma.201404531)  22) T. Iwai, Y. Nakajima, T. Nishimura, K. Nagashio, and A. Toriumi, Int.

2) U. Schroeder, S. Mueller, J. Mueller, E. Yurchuk, D. Martin, C. Adelmann, Conf. Solid State Devices and Materials, 2012, p. 767.

T. Schloesser, R. van Bentum, and T. Mikolajick, [ECS J. Solid State Sci.](http://doi.org/10.1149/2.010304jss)  23) Y. Nakajima, K. Kita, T. Nishimura, K. Nagashio, and A. Toriumi, [ECS](http://doi.org/10.1149/1.3372576)

[Technol. 2, N69 (2013).](http://doi.org/10.1149/2.010304jss)  [Trans. 28 [2], 203 (2010).](http://doi.org/10.1149/1.3372576)

3) S. Salahuddin and S. Datta, [Nano Lett. 8, 405 (2008).](http://doi.org/10.1021/nl071804g)  24) K. Xiong, J. Robertson, and S. J. Clark, [J. Appl. Phys. 99, 044105 (2006).](http://doi.org/10.1063/1.2173688)

4) T. S. Böscke, St. Teichert, D. Bräuhaus, J. Müller, U. Schröder, U. Böttger, 25) R. D. Shannon and C. T. Prewitt, [Acta Crystallogr., Sect. B 25, 925 (1969).](http://doi.org/10.1107/S0567740869003220)

091501-4 ©2016 The Japan Society of Applied Physics