



**HAL**  
open science

# Impact of oxygen plasma postoxidation process on Al<sub>2</sub>O<sub>3</sub> / n -In<sub>0.53</sub>Ga<sub>0.47</sub>As metal-oxide-semiconductor capacitors

Y. Lechaux, A. Fadjie-Djomkam, S. Bollaert, Nicolas Wichmann

## ► To cite this version:

Y. Lechaux, A. Fadjie-Djomkam, S. Bollaert, Nicolas Wichmann. Impact of oxygen plasma postoxidation process on Al<sub>2</sub>O<sub>3</sub> / n -In<sub>0.53</sub>Ga<sub>0.47</sub>As metal-oxide-semiconductor capacitors. Applied Physics Letters, 2016, 109 (13), pp.131602. 10.1063/1.4963656 . hal-02115676

**HAL Id: hal-02115676**

**<https://hal.science/hal-02115676>**

Submitted on 27 May 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Impact of oxygen plasma postoxidation process on $\text{Al}_2\text{O}_3/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ metal-oxide-semiconductor capacitors

Cite as: Appl. Phys. Lett. **109**, 131602 (2016); <https://doi.org/10.1063/1.4963656>

Submitted: 08 July 2016 • Accepted: 14 September 2016 • Published Online: 27 September 2016

Y. Lechaux, A. B. Fadjie-Djomkam, S. Bollaert, et al.



View Online



Export Citation



CrossMark

## ARTICLES YOU MAY BE INTERESTED IN

Study of the oxidation at the  $\text{Al}_2\text{O}_3/\text{GaSb}$  interface after  $\text{NH}_4\text{OH}$  and  $\text{HCl}/(\text{NH}_4)_2\text{S}$  passivations and  $\text{O}_2$  plasma post atomic layer deposition process

Journal of Applied Physics **124**, 175302 (2018); <https://doi.org/10.1063/1.5049571>

Comparison of methods to quantify interface trap densities at dielectric/III-V semiconductor interfaces

Journal of Applied Physics **108**, 124101 (2010); <https://doi.org/10.1063/1.3520431>

The physics and chemistry of the Schottky barrier height

Applied Physics Reviews **1**, 011304 (2014); <https://doi.org/10.1063/1.4858400>

Lock-in Amplifiers  
up to 600 MHz



Zurich  
Instruments



## Impact of oxygen plasma postoxidation process on $\text{Al}_2\text{O}_3/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$ metal-oxide-semiconductor capacitors

Y. Lechaux, A. B. Fadjie-Djomkam, S. Bollaert, and N. Wichmann

*Institute of Electronics, Microelectronics and Nanotechnology, University of Lille 1, CNRS UMR 8520, Avenue Henri Poincaré, 59652 Villeneuve d'Ascq, France*

(Received 8 July 2016; accepted 14 September 2016; published online 27 September 2016)

Capacitance-voltage (C-V) measurements and x-ray photoelectron spectroscopy (XPS) analysis were performed in order to investigate the effect of a oxygen ( $\text{O}_2$ ) plasma after oxide deposition on the  $\text{Al}_2\text{O}_3/n\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$  metal-oxide-semiconductor structure passivated with ammonia  $\text{NH}_4\text{OH}$  solution. From C-V measurements, an improvement of charge control is observed using the  $\text{O}_2$  plasma postoxidation process on  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ , while the minimum of interface trap density remains at a good value lower than  $1 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$ . From XPS measurements, we found that  $\text{NH}_4\text{OH}$  passivation removes drastically the Ga and As native oxides on the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  surface and the  $\text{O}_2$  plasma postoxidation process enables the reduction of interface re-oxidation after post deposition annealing (PDA) of the oxide. The advanced hypothesis is the formation of interfacial barrier between  $\text{Al}_2\text{O}_3$  and  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  which prevents the diffusion of oxygen species into the semiconductor surface during PDA. *Published by AIP Publishing.*

[<http://dx.doi.org/10.1063/1.4963656>]

III-V low bandgap compound semiconductors such as InAs, GaSb, or  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  are promising materials for high-frequencies performance metal-oxide-semiconductor field effect transistors (MOSFETs) due to their high electrons mobility<sup>1-3</sup> and their bandgap engineering possibilities. However, compared to silicon with the  $\text{SiO}_2\text{-Si}$  gate stack which leads to low value of interface trap density ( $D_{it}$ ), the oxide and interface quality between oxide and III-V semiconductor with low  $D_{it}$  is still a challenge to avoid strong Fermi-level pinning<sup>4</sup> and deterioration of channel mobility. It has been reported that high  $D_{it}$  value on the  $\text{Al}_2\text{O}_3/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  interface is attributed to Ga dangling bonds, As dimers, or III-V natives oxides.<sup>5-7</sup> However, pre-treatments such as ammonium hydroxide<sup>8</sup> and ammonium sulfide passivations,<sup>9-12</sup> hydrogen<sup>13</sup> or nitrogen plasma,<sup>14</sup> and using interfacial AlN layer<sup>15</sup> or nitridation treatment<sup>16</sup> lead to a shift or a reduction of midgap  $D_{it}$ . In fact, low values of  $D_{it}$  in the range of  $1 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$  have been demonstrated on the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  MOS systems using different treatments and different gate oxides such as  $\text{Al}_2\text{O}_3$ ,<sup>17,18</sup>  $\text{HfO}_2$ ,<sup>19</sup>  $\text{ZrO}_2$ ,<sup>2</sup> and  $\text{BeO}$ .<sup>20</sup> Previous works from Takagi *et al.* on  $\text{Al}_2\text{O}_3/\text{Ge}$  gate stack using enhanced resonance cyclotron oxygen plasma report on the reduction of interface trap density by creating interfacial layer.<sup>21,22</sup> In this letter, we proposed to further improve electrical and interfacial properties of  $\text{Al}_2\text{O}_3\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$  interface using *in-situ*  $\text{O}_2$  plasma postoxidation process in atomic layer deposition (ALD) chamber.

In this work, metal-oxide-semiconductor capacitors (MOSCAPs) were fabricated and electrically characterized. Epitaxial layer was grown by solid source molecular beam epitaxy (MBE) on the InP substrate (100). It was composed as follows: an  $\text{Al}_{0.52}\text{In}_{0.48}\text{As}$  buffer layer, a highly Si-doped ( $1 \times 10^{19} \text{ cm}^{-3}$ ) *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer for ohmic contact, and a Si-doped ( $2 \times 10^{16} \text{ cm}^{-3}$ ) *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  top layer. Prior to the ALD deposition, the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$

surface was degreased in acetone, isopropanol, and rinsed in deionized water (DIW). Then, a surface treatment was used in order to eliminate native oxides and passivate the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  surface. Thus, sample was immersed in 4% diluted  $\text{NH}_4\text{OH}$  solution for 10 min followed by immersion in DIW. 2 nm of  $\text{Al}_2\text{O}_3$  was deposited by ALD at  $250^\circ\text{C}$  from trimethylaluminium (TMA) and water ( $\text{H}_2\text{O}$ ) precursors followed by *in-situ*  $\text{O}_2$  plasma postoxidation process. The  $\text{O}_2$  plasma postoxidation process consists of remote plasma with 100 W radiofrequency source using  $\text{O}_2$  (100 sccm) and Ar (200 sccm) in the ALD chamber at  $250^\circ\text{C}$ . A metal grid between the substrate and plasma source is used to prevent ion bombardment and thus only radicals reach the substrate. For higher thickness, diffusion of oxygen species should be limited and it could prevent formation of interfacial layer and then increase the interface trap density as observed by Zhang *et al.*<sup>21</sup> Then, 2 nm of ALD- $\text{Al}_2\text{O}_3$  was added to obtain a total oxide thickness of 4 nm. A post-deposition annealing (PDA) at  $600^\circ\text{C}$  under forming gas ( $\text{N}_2\text{H}_2$ ) was performed to stabilize the oxide. Circular Ni/Au top gate contacts were subsequently evaporated. After etching of low doped *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer by wet etching process, source contacts were deposited by evaporation of Ti/Pt/Au on the highly Si-doped ( $1 \times 10^{19} \text{ cm}^{-3}$ ) *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  layer to form ohmic contact. Reference sample without the  $\text{O}_2$  plasma postoxidation process was also fabricated with 4 nm  $\text{Al}_2\text{O}_3$  deposited by ALD and transmission electron microscopy confirmed equal thickness of both samples.

C-V measurements were carried out in order to characterize the electrical properties of the  $\text{Al}_2\text{O}_3\text{-In}_{0.53}\text{Ga}_{0.47}\text{As}$  interface on MOSCAPs. Measured capacitance and conductance were extracted using Agilent 4294A precision impedance analyzer in the frequency range from 100 Hz to 1 MHz at room temperature. Figure 1 shows the C-V characteristics as a function of gate-source voltage ( $V_{gs}$ ) for samples without

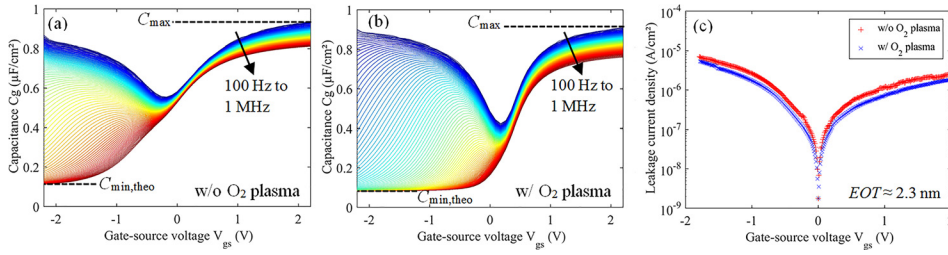


FIG. 1. C-V characteristics at room temperature of  $\text{Al}_2\text{O}_3/\text{n-InGaAs}$  MOSCAPs (a) without and (b) with the  $\text{O}_2$  plasma postoxidation process and (c) leakage current density as a function of gate-source voltage for both samples.

(Fig. 1(a)) and with (Fig. 1(b))  $\text{O}_2$  plasma postoxidation process. First, in depletion region (between  $V_{\text{gs}} = -0.5$  V and  $V_{\text{gs}} = 0.5$  V), the C-V stretch-out is considerably reduced and minimum capacitance at low frequency is lower for the sample with  $\text{O}_2$  plasma treatment. Moreover, the minimum inversion capacitance ( $C_{\text{min}}$ ) observed at high frequency is also lower for this sample ( $C_{\text{min}} = 0.08 \mu\text{F}/\text{cm}^2$ ) and is close to the theoretical value for a  $2 \times 10^{16} \text{ cm}^{-3}$  n-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  MOSCAPs ( $C_{\text{min,theo}} = 0.06 \mu\text{F}/\text{cm}^2$ ). The humps observed in the inversion region that start at higher frequency for the sample with  $\text{O}_2$  plasma process suggested a reduction of interface traps density. Such humps were also observed by Krylov *et al.* comparing  $\text{Si}_3\text{N}_4$  and  $\text{Al}_2\text{O}_3$  gate oxides<sup>8,23</sup> and were attributed to false inversion due to the midgap interface states.<sup>24,25</sup> The previous observations suggest an improvement of Fermi level movement (Fermi level unpinning) at the interface and lower  $D_{\text{it}}$  for the sample treated with  $\text{O}_2$  plasma postoxidation process. However, the maximum accumulation capacitance ( $C_{\text{max}} \approx 0.9 \mu\text{F}/\text{cm}^2$ ) for both samples is lower than oxide capacitance ( $C_{\text{ox}}$ ) estimated at  $1.44 \mu\text{F}/\text{cm}^2$ . This effect can be related to the low density of state of the  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  conduction band which considerably reduces the accumulation capacitance. Besides, as maximum accumulation capacitances at 1 kHz are equal for both samples, the effective oxide thickness ( $EOT \approx 2.3$  nm) is not modified using the  $\text{O}_2$  plasma treatment. Furthermore, we observed for both samples a large frequency dispersion in accumulation region, between  $V_{\text{gs}} = 1$  V and  $V_{\text{gs}} = 2$  V. This dispersion in accumulation is not clear and is likely attributed to border traps in oxide close to interface.<sup>26,27</sup> In order to estimate the current leakage, current-voltage (I-V) measurements were performed (Fig. 1(c)). A value of  $1 \times 10^{-5} \text{ A cm}^{-2}$  was obtained for both samples indicating a good oxide quality. Moreover, a slight reduction of leakage current is observed using the  $\text{O}_2$  plasma treatment.

Interface trap density was evaluated by means of conductance method developed by Nicollian and Brews.<sup>28</sup> From the measured conductance, normalized parallel conductance  $[(Gp/\omega)/Aq]$  was calculated<sup>28</sup> where  $Gp$  is the equivalent parallel conductance,  $\omega$  is the angular frequency,  $A$  is the surface area of top gate contact, and  $q$  is the elementary charge. Figure 2 shows the normalized parallel conductance map without (Fig. 2(a)) and with  $\text{O}_2$  plasma postoxidation process (Fig. 2(b)). This map shows the magnitude of the normalized parallel conductance  $[(Gp/\omega)/Aq]$  as a function of frequency and  $V_{\text{gs}}$  at RT. The frequency shift with gate voltage of  $[(Gp/\omega)/Aq]_{\text{max}}$  is an indicator of Fermi level movement at  $\text{Al}_2\text{O}_3/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  interface. If  $[(Gp/\omega)/Aq]_{\text{max}}$  is moving vertically with gate bias, the band bending is efficient.<sup>24,29</sup> Therefore, as indicated in Fig. 2(b), Fermi

level movement is improved with the  $\text{O}_2$  plasma postoxidation process. Moreover,  $[(Gp/\omega)/Aq]_{\text{max}}$  does not move for frequencies less than 20 kHz (Fig. 2(a)) and 600 Hz (Fig. 2(b)) suggesting that Fermi level can be moved for lower energies into bandgap with the  $\text{O}_2$  plasma process.<sup>29</sup> Both samples show  $D_{\text{it}}$  lower than  $1 \times 10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$ . Astonishingly, we noticed a lower value for sample without  $\text{O}_2$  plasma process ( $D_{\text{it}} = 6 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ ) compared to the sample with  $\text{O}_2$  plasma ( $D_{\text{it}} = 8 \times 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$ ) which is probably due to large frequency dispersion observed in accumulation region.

XPS measurements were performed in order to characterize the  $\text{Al}_2\text{O}_3/\text{n-type In}_{0.53}\text{Ga}_{0.47}\text{As}$  interface. An Al  $K\alpha$  radiation ( $h\nu = 1486.6 \text{ eV}$ ) was used as an excitation source and the measurements were obtained at a pressure of  $5 \times 10^{-9}$  mbar at  $75^\circ$  angle. First, we analyzed the effect of  $\text{NH}_4\text{OH}$  passivation. Figure 3 shows the XPS spectra of In  $3d_{5/2}$ , Ga  $2p_{3/2}$  and As  $2p_{3/2}$  (top) without passivation and (bottom) with  $\text{NH}_4\text{OH}$  passivation. For each component, we noticed the presence of native oxides at higher binding energy with respect to the bulk core-levels ( $\Delta\text{BE}$ ) which is reduced using  $\text{NH}_4\text{OH}$  passivation. For In  $3d$  core-levels (Figs. 3(a) and 3(d)), native In-O ( $\Delta\text{BE} = +1 \text{ eV}$ ) is decreased of about 10% of total area with a shift to lower binding energy ( $\Delta\text{BE} = +0.6 \text{ eV}$ ) after the  $\text{NH}_4\text{OH}$  passivation. Same effects were observed on Ga  $2p$  core-levels (Figs. 3(b) and 3(e)) where native Ga-O ( $\Delta\text{BE} = +1.2 \text{ eV}$ ) is decreased of about 34% of total area with a shift to lower binding energy ( $\Delta\text{BE} = +0.8 \text{ eV}$ ) after  $\text{NH}_4\text{OH}$  passivation suggesting a modification of both In-O and Ga-O stoichiometry. For As  $2p$  core-levels (Figs. 3(c) and 3(f)), we noticed two native oxides before passivation,  $\text{As}_2\text{O}_3$  and  $\text{As}_2\text{O}_5$  ( $\Delta\text{BE} = +3.3 \text{ eV}$  and  $\Delta\text{BE} = +4.4 \text{ eV}$ , respectively). However after passivation,  $\text{As}_2\text{O}_5$  oxide is found to be below the detection threshold whereas area of  $\text{As}_2\text{O}_3$  component slightly decreases without a significant shift of its binding energy.

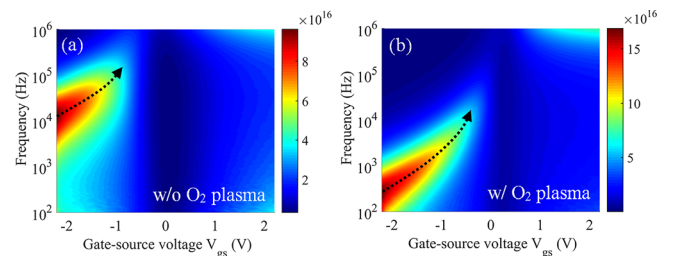


FIG. 2. Conductance map representing magnitude of the normalized parallel conductance as a function of frequency and gate voltage of  $\text{Al}_2\text{O}_3/\text{n-type In}_{0.53}\text{Ga}_{0.47}\text{As}$  MOSCAPs (a) without and (b) with the  $\text{O}_2$  plasma postoxidation process. The dotted-line arrow is a guide to the eye to trace the position of the normalized parallel conductance maximum.



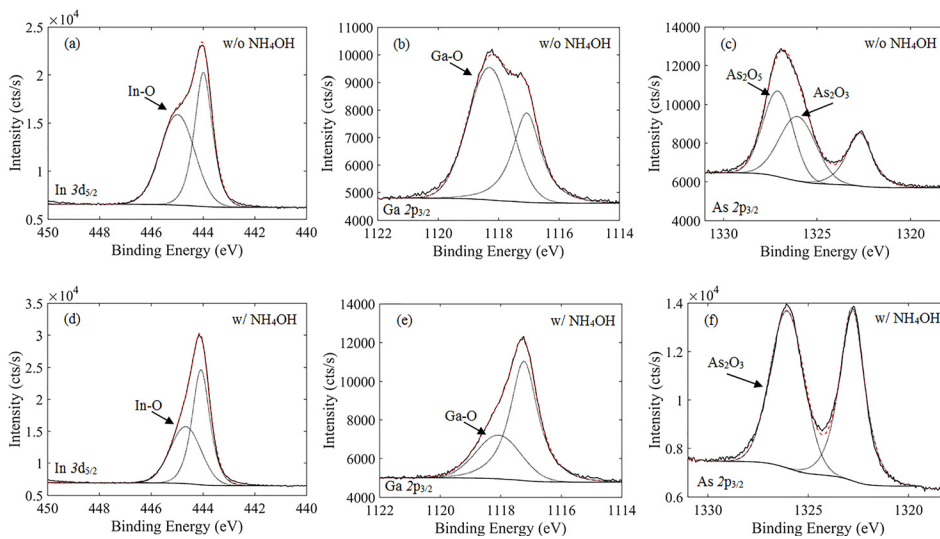


FIG. 3. XPS Spectra of *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  surface (top) without passivation and (bottom) with  $\text{NH}_4\text{OH}$  passivation (bottom). (a)–(d) For In  $3d_{5/2}$  core-levels, (b)–(e) for Ga  $2p_{3/2}$  core-level, and (c)–(f) for As  $2p_{3/2}$  core-levels.

Second, we focused on the In  $3d_{5/2}$  XPS spectra to study the effect of  $\text{O}_2$  plasma postoxidation process. Figure 4 shows the XPS spectra of In  $3d_{5/2}$  after  $\text{NH}_4\text{OH}$  passivation,  $\text{Al}_2\text{O}_3$  deposition, and post deposition annealing for the samples (Fig. 4(a)) without and (Fig. 4(b)) with the  $\text{O}_2$  plasma postoxidation process. Compared with Fig. 3(d), In-O is shifted to higher binding energy ( $\Delta\text{BE} = +1.8\text{ eV}$ ) for samples with or without the  $\text{O}_2$  plasma process, indicating a modification of In-O stoichiometry. Furthermore, for the sample without treatment an increase in the In-O peak area<sup>30</sup> of about 6% of total area is observed compared to the sample with  $\text{O}_2$  plasma. Thus, the  $\text{O}_2$  plasma postoxidation process prevents the diffusion of oxygen species into the semiconductor surface during post deposition annealing and limits the interface re-oxidation. The hypothesis we proposed is the creation of an interfacial layer between InGaAs and  $\text{Al}_2\text{O}_3$  as observed by Takagi and coworkers with  $\text{Al}_2\text{O}_3/\text{Ge}$  gate stacks.<sup>22</sup>

In summary, we have demonstrated the improvement of Fermi level movement efficiency on  $\text{Al}_2\text{O}_3/n$ -type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  MOSCAPs using the  $\text{O}_2$  plasma postoxidation process. It is found that the  $\text{O}_2$  plasma prevents the interface re-oxidation by limiting diffusion of oxygen species from oxide into semiconductor surface. This method yields to  $\text{Al}_2\text{O}_3/n$ -type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  MOS capacitors with good electrical properties with  $D_{it}$  lower than  $1 \times 10^{12}\text{ cm}^{-2}\text{ eV}^{-1}$ . As a result, the oxygen plasma postoxidation method is a promising solution for fabricating gate stacks with good interface

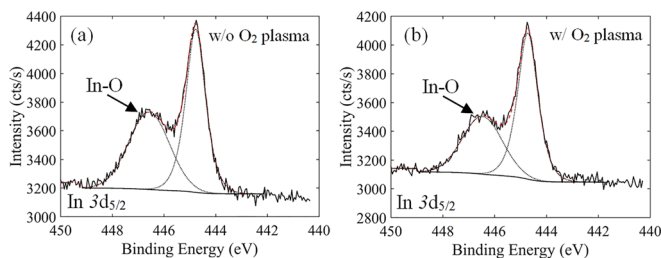


FIG. 4. In  $3d_{5/2}$  spectra of *n*-type  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  surface after  $\text{NH}_4\text{OH}$  passivation,  $\text{Al}_2\text{O}_3$  deposition, and post deposition annealing for samples (a) without and (b) with the  $\text{O}_2$  plasma postoxidation process.

quality between oxide and semiconductor for MOSFETs application. Currently,  $\text{HfO}_2$ -based gate stacks using the  $\text{O}_2$  plasma postoxidation process is being investigated.

This work has been supported by the Agence Nationale de la Recherche through the Project No. ANR-13-JS03-0001-01. This work was developed in IEMN's cleanroom, a part of the French National Fabrication Network (RENATECH).

- <sup>1</sup>Y. Xuan, Y. Q. Wu, H. C. Lin, T. Shen, and P. D. Ye, *IEEE Electron Device Lett.* **28**, 935 (2007).
- <sup>2</sup>N. Goel, D. Heh, S. Koveshnikov, I. Ok, S. Oktyabrsky, V. Tokranov, R. Kambhampati, M. Yakimov, Y. Sun, P. Pianetta, C. K. Gaspe, M. B. Santos, J. Lee, S. Datta, P. Majhi, and W. Tsai, *Tech. Dig. - IEEE Int. Electron Devices Meet.* **2008**, 1–4.
- <sup>3</sup>T. D. Lin, W. H. Chang, R. L. Chu, Y. C. Chang, Y. H. Chang, M. Y. Lee, P. F. Hong, M.-C. Chen, J. Kwo, and M. Hong, *Appl. Phys. Lett.* **103**, 253509 (2013).
- <sup>4</sup>K. Martens, W. Wang, K. De Keersmaecker, G. Borghs, G. Groeseneken, and H. Maes, *Microelectron. Eng.* **84**, 2146 (2007).
- <sup>5</sup>J. Robertson, Y. Guo, and L. Lin, *J. Appl. Phys.* **117**, 112806 (2015).
- <sup>6</sup>L. Lin and J. Robertson, *Appl. Phys. Lett.* **98**, 082903 (2011).
- <sup>7</sup>J. Robertson, *Appl. Phys. Lett.* **94**, 152104 (2009).
- <sup>8</sup>I. Krylov, A. Gavrilov, M. Eizenberg, and D. Ritter, *Appl. Phys. Lett.* **101**, 063504 (2012).
- <sup>9</sup>H. D. Trinh, E. Y. Chang, P. W. Wu, Y. Y. Wong, C. T. Chang, Y. F. Hsieh, C. C. Yu, H. Q. Nguyen, Y. C. Lin, K. L. Lin, and M. K. Hudait, *Appl. Phys. Lett.* **97**, 42903 (2010).
- <sup>10</sup>E. O'Connor, B. Brennan, V. Djara, K. Cherkaoui, S. Monaghan, S. B. Newcomb, R. Contreras, M. Mилоjevic, G. Hughes, M. E. Pemble, R. M. Wallace, and P. K. Hurley, *J. Appl. Phys.* **109**, 24101 (2011).
- <sup>11</sup>M. F. Mohd Razip Wee, A. Dehzangi, S. Bollaert, B. Yeop Majlis, and N. Wichmann, *Micro Nano Lett.* **8**, 836 (2013).
- <sup>12</sup>P. K. Hurley, E. O'Connor, V. Djara, S. Monaghan, I. M. Povey, R. D. Long, B. Sheehan, J. Lin, P. C. McIntyre, B. Brennan, R. M. Wallace, M. E. Pemble, and K. Cherkaou, *IEEE Trans. Device Mater. Rel.* **13**, 429 (2013).
- <sup>13</sup>A. D. Carter, W. J. Mitchell, B. J. Thibeault, J. J. M. Law, and M. J. W. Rodwell, *Appl. Phys. Express* **4**, 91102 (2011).
- <sup>14</sup>V. Chobpattana, J. Son, J. J. M. Law, R. Engel-Herbert, C.-Y. Huang, and S. Stemmer, *Appl. Phys. Lett.* **102**, 22907 (2013).
- <sup>15</sup>Q. H. Luc, E. Y. Chang, H. D. Trinh, Y. C. Lin, H. Q. Nguyen, Y. Y. Wong, H. B. Do, S. Salahuddin, and C. C. Hu, *IEEE Trans. Electron Devices* **61**, 2774 (2014).
- <sup>16</sup>T. Hoshii, S. Lee, R. Suzuki, N. Taoka, M. Yokoyama, H. Yamada, M. Hata, T. Yasuda, M. Takenaka, and S. Takagi, *J. Appl. Phys.* **112**, 73702 (2012).
- <sup>17</sup>J. Hu and H.-S. Philip Wong, *J. Appl. Phys.* **111**, 44105 (2012).

- <sup>18</sup>H.-C. Lin, W.-E. Wang, G. Brammertz, M. Meuris, and M. Heyns, *Microelectron. Eng.* **86**, 1554 (2009).
- <sup>19</sup>Y. Xuan, Y. Q. Wu, T. Shen, T. Yang, and P. D. Ye, *Tech. Dig. - IEEE Int. Electron Devices Meet.* **2007**, 637–640.
- <sup>20</sup>H. S. Shin, J. H. Yum, D. W. Johnson, H. R. Harris, T. W. Hudnall, J. Oh, P. Kirsch, W.-E. Wang, C. W. Bielański, S. K. Banerjee, J. C. Lee, and H. D. Lee, *Appl. Phys. Lett.* **103**, 223504 (2013).
- <sup>21</sup>R. Zhang, T. Iwasaki, N. Taoka, M. Takenaka, and S. Takagi, *Microelectron. Eng.* **88**, 1533 (2011).
- <sup>22</sup>R. Zhang, T. Iwasaki, N. Taoka, M. Takenaka, and S. Takagi, *Appl. Phys. Lett.* **98**, 112902 (2011).
- <sup>23</sup>I. Krylov, A. Gavrilov, D. Ritter, and M. Eizenberg, *Appl. Phys. Lett.* **99**, 203504 (2011).
- <sup>24</sup>R. Engel-Herbert, Y. Hwang, and S. Stemmer, *J. Appl. Phys.* **108**, 124101 (2010).
- <sup>25</sup>T. Kent, K. Tang, V. Chobpattana, M. A. Negara, M. Edmonds, W. Mitchell, B. Sahu, R. Galatage, R. Droopad, P. McIntyre, and A. C. Kummel, *J. Chem. Phys.* **143**, 164711 (2015).
- <sup>26</sup>E. J. Kim, L. Wang, P. M. Asbeck, K. C. Saraswat, and P. C. McIntyre, *Appl. Phys. Lett.* **96**, 12906 (2010).
- <sup>27</sup>Y. Yuan, L. Wang, B. Yu, B. Shin, J. Ahn, P. C. McIntyre, P. M. Asbeck, M. J. W. Rodwell, and Y. Taur, *IEEE Electron Device Lett.* **32**, 485 (2011).
- <sup>28</sup>E. H. Nicollian and J. R. Brews, *MOS (Metal Oxide Semiconductor) Physics and Technology* (Wiley, New York, 1982).
- <sup>29</sup>H. C. Lin, G. Brammertz, K. Martens, G. de Valicourt, L. Negre, W.-E. Wang, W. Tsai, M. Meuris, and M. Heyns, *Appl. Phys. Lett.* **94**, 153508 (2009).
- <sup>30</sup>R. V. Galatage, H. Dong, D. M. Zhernokletov, B. Brennan, C. L. Hinkle, R. M. Wallace, and E. M. Vogel, *Appl. Phys. Lett.* **99**, 172901 (2011).