Surface Passivation of Silicon Using HfO₂ Thin Films Deposited by Remote Plasma Atomic Layer Deposition System

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Abstract

Hafnium oxide (HfO₂) thin films have attracted much attention owing to their usefulness in equivalent oxide thickness scaling in microelectronics, which arises from their high dielectric constant and thermodynamic stability with silicon. However, the surface passivation properties of such films, particularly on crystalline silicon (c-Si), have rarely been reported upon. In this study, the HfO₂ thin films were deposited on c-Si substrates with and without oxygen plasma pretreatments, using a remote plasma atomic layer deposition system. Post-annealing was performed using a rapid thermal processing system at different temperatures in N₂ ambient for 10 min. The effects of oxygen plasma pretreatment and post-annealing on the properties of the HfO₂ thin films were investigated. They indicate that the in situ remote plasma pretreatment of Si substrate can result in the formation of better SiO₂, resulting in a better chemical passivation. The deposited HfO₂ thin films with oxygen plasma pretreatment and post-annealing at 500 °C for 10 min were effective in improving the lifetime of c-Si (original lifetime of 1 μs) to up to 67 μs.

Keywords: HfO₂ thin films, Atomic layer deposition, O₂ plasma pretreatment, Surface passivation

Background

High-quality surface passivation is very important for a range of crystalline silicon (c-Si)-based electronic devices, and especially for high-efficiency c-Si solar cells. As the need for lower-cost silicon solar cells increases, since Si material has a rather high cost, thinner Si substrates are required. Therefore, their surface/volume ratio of such substrates and the contribution of their surfaces to the overall performance are increasing. Traditional surface passivation for Si involves the formation of a thin silicon dioxide (SiO₂) layer. However, this process requires a high thermal budget process, which involves long period at high temperature. Owing to these process-related issues, considerable efforts have been made in the past to develop low-temperature surface passivation methods for both heavily doped and moderately doped c-Si surfaces. Besides SiO₂, other layers such as SiC, a-Sc:H and Si₃N₄ have been used for surface passivation [1]. Recently, Al₂O₃ films that are grown by atomic layer deposition (ALD) have been demonstrated to provide good surface passivation on c-Si [2–4]. ALD technique is a powerful method. It provides a high-level degree of precise control over the properties of the material, and especially the morphology and thickness of dielectric layers.

In the advanced semiconductor industry, hafnium dioxide (HfO₂) thin films are used to replace SiO₂ as the gate dielectric in field-effect transistors because they have better functionality and performance at lower cost [5, 6]. Additionally, the high refractive index of HfO₂ makes it a potential candidate for anti-reflection coatings [7] and interference filters [8]. However, its surface passivation properties, particularly on c-Si, have scantly been studied. For example, Jun Wang et al. [9] presented the surface passivation properties of a Si surface using a thin HfO₂ layer grown by ALD without further annealing. In another study Huijuan Geng et al. [10] reported advanced passivation using simple materials (Al₂O₃, HfO₂) and their compounds H₂(Al₃Hf)O₆ deposited by ALD. All of the previous attempts were performed to...
deposit HfO\textsubscript{2} on c-Si substrates without any pre-treatments.

In this work, the surface passivation properties of the HfO\textsubscript{2} films deposited by a remote plasma atomic layer deposition system (RP-ALD) on p-type c-Si with and without in situ oxygen plasma pretreatment were investigated. Samples were annealed at different temperatures by rapid thermal annealing (RTA) system. The structural changes and the electrical properties of the thin films induced by RTA were characterized by field-emission transmission electron microscope (FE-TEM), X-ray photoelectron spectroscopy (XPS), and capacitance-voltage (C-V) measurements. The passivation mechanism of HfO\textsubscript{2} films on Si is also investigated.

**Methods**

In this study, (100) oriented boron-doped p-type crystal-line Czochralski (Cz) Si wafers that were polished on both sides and had a resistivity of 30 Ω·cm, original lifetime of 1 μs and a thickness of 250 μm were used. Prior to the deposition of the HfO\textsubscript{2} film, all wafers were cleaned through a standard Radio Corporation of America (RCA) cleaning process followed by a dip in diluted hydrofluoric acid (HF) solution (5%) for 2 min to remove the native oxide and dried in nitrogen.

The HfO\textsubscript{2} thin films were grown in an RP-ALD reactor (Model: Picosun, Finland) using tetraethylmethylamino hafnium (TEMAH) and remote O\textsubscript{2} plasma as the precursors for hafnium and oxygen respectively with N\textsubscript{2} as the carrier gas. In the ALD process, one deposition cycle consisted of two half cycles, one TEMAH pulse (for 1.6 s) and one O\textsubscript{2} plasma pulse (for 10 s). The nitrogen purge times for TEMAH and O\textsubscript{2} were 10.0 and 12.0 s, respectively. The samples were divided into two groups. For group one, HfO\textsubscript{2} thin films were deposited directly on the cleaned Si wafers. For group two, before deposition of HfO\textsubscript{2} thin films, Si wafers were additionally treated by remote O\textsubscript{2} plasma for 1 min. The O\textsubscript{2} plasma power for the pretreatment and for the ALD deposition process was 2500 W. The HfO\textsubscript{2} films for all of the samples were deposited at 250 °C. Different HfO\textsubscript{2} thickness (5, 15, and 25 nm) were prepared on as-cleaned Si wafers followed by annealing at 500 °C, and the corresponding minority carrier lifetimes of the passivated wafer were 9.98, 66.8, and 4.2 μs, respectively, at the injection level of 3 × 10\textsuperscript{14} cm\textsuperscript{-3}. Therefore, the thickness of 15 nm (corresponding to 168 ALD cycles) was used. The substrate pre-treatment could affect nucleation, leading to different film thickness. The thicknesses of the deposited HfO\textsubscript{2} are 15 nm ± 0.5 nm and 13 nm ± 0.7 nm for the samples with and without the oxygen plasma pretreatment, respectively. The wafer was flat on a platen. The double side coated samples processed twice, with a break in vacuum to flip the wafer in the chamber. The HfO\textsubscript{2} thin films were deposited on 2-in wafers. As the substrate holder was about 8 in, four samples were placed on the holder and processed at a time. The samples in the two groups are referred hereafter as SD (direct depositing samples) and SO (O\textsubscript{2} plasma pretreatment samples), respectively. Annealing process was performed using a RTA system at 400–650 °C in N\textsubscript{2} ambient for 10 min. Samples were identified with suffixes A400 to A650 that represent the annealing temperatures. Table 1 lists the samples.

The minority carrier lifetimes (\(\tau_{\text{eff}}\)) of the samples were assessed by photo-conductance decay method (Model: WCT-120, Sinton lifetime tester) in the quasi-steady state mode. Metal-insulator-semiconductor (MIS) structures were prepared by depositing Al electrodes with diameters of 500 μm onto the passivation layer using a sputter system and a shadow mask. The C-V characteristics were measured with a HP4284A semiconductor characterization system to extract the electrical parameters. The chemical composition and states of elements in the HfO\textsubscript{2}/Si were analyzed by XPS (Thermo Fisher K-Alpha). The ion energy used for the depth profile was 3000 eV. The physical thicknesses, microstructure and interface properties of the HfO\textsubscript{2} thin films were determined by FE-TEM (JEM-2100 F).

**Results and Discussion**

Generally, the quality of passivation is assessed in terms of \(\tau_{\text{eff}}\) or surface recombination velocity (SRV = \(S_{\text{max}}\)). The \(\tau_{\text{eff}}\) refers to the recombination at surface defects. Figure 1(a) plots \(\tau_{\text{eff}}\) and \(S_{\text{max}}\) for all samples at the injection level of 3 × 10\textsuperscript{14} cm\textsuperscript{-3}. The \(\tau_{\text{eff}}\) measurements were performed three times for each sample in the

| Sample | O\textsubscript{2} plasma pretreatment | Annealing temperature(°C) |
|--------|-------------------------------------|--------------------------|
| SD     | N/A                                 | N/A                      |
| SD-A400| N/A                                 | 400                      |
| SD-A450| N/A                                 | 450                      |
| SD-A500| N/A                                 | 500                      |
| SD-A550| N/A                                 | 550                      |
| SD-A600| N/A                                 | 600                      |
| SD-A650| N/A                                 | 650                      |
| SO     | Yes                                 | N/A                      |
| SO-A400| Yes                                 | 400                      |
| SO-A450| Yes                                 | 450                      |
| SO-A500| Yes                                 | 500                      |
| SO-A550| Yes                                 | 550                      |
| SO-A600| Yes                                 | 600                      |
| SO-A650| Yes                                 | 650                      |
different locations, and the errors of the minority carrier lifetime were within ±5%. As the annealing temperature was increased from 400 to 500 °C, the $\tau_{\text{eff}}$ of the annealed HfO$_2$ sample with O$_2$ plasma pretreatment at the injection level of $3 \times 10^{14}$ cm$^{-3}$ increased significantly. The increase of the annealed HfO$_2$ samples without O$_2$ plasma pretreatment at the same injection level was much less than that of the annealed HfO$_2$ samples with O$_2$ plasma pretreatment. At lower temperatures ($T < 500$ °C), the annealed HfO$_2$ samples without O$_2$ plasma pretreatment had lower $\tau_{\text{eff}}$ than those with O$_2$ plasma pretreatment. The annealing process provides energy to the HfO$_2$ layer to active the passivation. When the annealing temperature higher than 500 °C, the minority carrier lifetime decreases, which might be due to the defects generated by the increased microcrystalline fraction and grain boundaries in the HfO$_2$ layer. The O$_2$ plasma pretreatment sample that had been annealed at the temperature of 500 °C had the highest $\tau_{\text{eff}}$ of 67 μs, corresponding to an $S_{\text{max}}$ value of 187 cm/s. This calculation was based on the quasi steady-state photoconductance (QSSPC) $\tau_{\text{eff}}$ data for the injection level of $3 \times 10^{14}$ cm$^{-3}$. $S_{\text{max}}$ represents the upper limit of SRV, and is estimated from the measured lifetime values using the following relation [11],

$$S_{\text{max}} = \frac{W}{2\tau_{\text{eff}}}$$  \hspace{1cm} (1)

where $W$ (=250 μm) is the thickness of the silicon substrate. The lower value of $S_{\text{max}}$ can be attributed to a lower density of interface traps. It also can be seen from Fig. 1a that the O$_2$ plasma pretreatment samples exhibited better passivation than the directly deposited samples, so they had a lower interface recombination velocity. This difference is attributable to the diffusion of O from the O$_2$ plasma to the interfacial region to form a SiO$_2$ thin film, which provides better chemical passivation of the dangling bonds.

Figure 1b, c shows the injection level-dependent effective minority carrier lifetime of the samples without and with O$_2$ plasma pretreatment. For the SO samples, the minority carrier lifetime increases with the annealing temperature between 400 and 500 °C. All of the SO samples without annealing exhibited almost no passivation, and their $\tau_{\text{eff}}$ values were similar to that of the bare Si wafer. However, $\tau_{\text{eff}}$ of the annealed samples increased significantly and then decreased as the injection level increased from $4 \times 10^{13}$ cm$^{-3}$ to $5 \times 10^{15}$ cm$^{-3}$. The drop in $\tau_{\text{eff}}$ with increasing injection levels is caused by Auger recombination in the bulk of the c-Si substrate. The $\tau_{\text{eff}}$
of the as-deposited samples depends very strongly on injection level, decreasing by approximately one order of magnitude as the injection level is decreased from $3 \times 10^{14}$ to $10^{13}$ cm$^{-3}$. This dependence in injection levels is much weaker for the annealed samples. The $\tau_{\text{eff}}$ values of the annealed samples decrease only slightly as the injection level is reduced [12].

C-V measurements are commonly used to characterize the quality of dielectric layers and their interface with the substrates. C-V measurements were performed herein at room temperature in the dark conditions at 1 MHz on a standard MIS (Al/HfO$_2$/p-Si) structure. Figure 2a, b shows the C-V curves of the HfO$_2$ thin films without and with O$_2$ plasma pretreatment, respectively. The voltage ($V_A$) that was applied across the MIS device was varied ($-5 \text{ V} < V_A < 5 \text{ V}$) with a sweep step length of 100 mV and signal amplitude of 50 mA, shifting from accumulation to inversion. The shift of C-V curves toward negative voltages demonstrates the presence of effective oxide charges of positive polarity in the as-deposited HfO$_2$ thin films. The effective oxide charge represents the sum of mobile ionic charges ($Q_m$), oxide trapped charges ($Q_{OT}$) and oxide fixed charges ($Q_f$). $Q_f$ significantly affects the flat band voltage ($V_{FB}$), as it is located at the oxide-semiconductor interface. In Fig. 2a, the C-V curves are shifted in the positive direction by the $V_{FB}$ shift because $Q_f$ decreases as the annealing temperature increases. The slope of the C-V curve increases with the annealing temperature increases, indicating that the interface trap density decreases as the annealing temperature increases. The HfO$_2$ thin films with O$_2$ plasma pretreatment exhibited a similar relationship, as shown in Fig. 2b. The presence of fixed charges arose from the charged oxygen vacancies in the films [13]. The fixed charge density is estimated using Eq. (2), assuming a negligible effect of the interface traps [14],

$$V_{FB} = \phi_{mg} - \frac{qQ_f}{C_{ox}},$$

where $\phi_{mg}$ (=0.32 eV), q (=1.602 $\times$ 10$^{-19}$ C), $C_{ox}$, and $V_{FB}$ are the difference between the work functions of metal and the semiconductor, the electronic charge, the capacitance of the dielectric per unit area and the flat band voltage, respectively.

The values of $Q_f$ for the as-deposited and annealed HfO$_2$ thin films are shown in Fig. 2c. $Q_f$ decreases as the annealing temperature increases. The annealing process appears to reduce the density of oxygen vacancies that are responsible for the presence of positive fixed charges, which may be related to the reconstruction of the oxide film near the interface [15]. Furthermore, the $Q_f$ of SO samples are lower than that of SD samples at the same annealing temperature. The interfacial defect density ($D_{\text{it}}$) is determined using an approximation method.

![C-V characteristics measured at 1 MHz for (a) directly deposited samples without O$_2$ plasma pretreatment, and (b) samples with O$_2$ plasma pretreatment; (c) estimated $Q_f$ of the annealed HfO$_2$ thin films](image-url)
given by W. A. Hill and C. C. Coleman [16]. The \( Q_f \) and \( D_{it} \) values are listed in Table 2.

Cross-sections of the annealed thin films were evaluated by a FE-TEM for assessing the film microstructure and \( \text{HfO}_2/\text{Si} \) interface. The FE-TEM cross-section analysis of the \( \text{HfO}_2 \) thin film annealed at 500 °C (a) without and (b) with \( \text{O}_2 \) plasma pretreatment is shown in Fig. 3. From the FE-TEM images, the annealed \( \text{HfO}_2 \) thin films consist of three regions, which are the \( \text{HfO}_2 \) layer, an interfacial oxide and the Si substrate. The atoms in the \( \text{HfO}_2 \) layer are orderly arranged in some areas, indicating that the \( \text{HfO}_2 \) layer is microcrystalline structure. A very thin interfacial oxide layer is formed between the high \( k \) film and the substrate in the as deposited and annealed samples [17]. The \( \text{HfO}_2 \) layer and the interfacial layer of the sample with oxygen plasma treatment are 15.3 and 2.7 nm, respectively. Whereas, the \( \text{HfO}_2 \) layer and the interfacial layer of the sample without the pretreatment are 13.9 and 2.2 nm, respectively. This thickness difference should not cause the significant lifetime variation (35 and 67 μs for the samples without and with the pretreatment). Therefore, the significant lifetime improvement could be attributed to the different interface layers with the oxygen plasma pretreatment.

Figure 4 shows the elemental depth profiles of the \( \text{HfO}_2 \) films annealed at 500°C without and with \( \text{O}_2 \) plasma pretreatment obtained by XPS. Three regions are observed. In Region A, when the etching time was below 100 s, the relatively uniform atomic percentages of Hf and O corresponded to the RP-ALD \( \mu \text{-HfO}_2 \) layer. In Region B, the O and Hf atomic percentages decreased as the etching time increased from 130 to 175 s, indicating that the O elements diffused into the c-Si substrate, forming an interfacial layer [18, 19]. In Region C, when the etching time increased above 175 s, the Si signal drastically increased up to more than 60%, corresponding to the surface of the c-Si substrate. The oxygen atomic percentage and Hf atomic percentage in the c-Si substrates are due to the Ar ion sputtering effect. During the sputter process of the XPS measurement, some of the Hf or O atoms may reside on the silicon substrate surface and then be detected. Notice that in Region B, in addition to lower Hf and O with a corresponding increase in Si signal in the interface region, the sample with the oxygen pretreatment has also a larger Si signal in the bulk of the \( \text{HfO}_2 \) film that may account for the percentage differences. The similar results can be obtained at the other investigated annealing temperatures. A possible reason might be that the \( \text{O}_2 \) pretreatment leads to the growth of a very thin SiO\(_2\) layer reducing the Hf and O diffusion coming from the subsequently deposited \( \text{HfO}_2 \). Fewer atomic vacancies are formed by diffusion in the \( \text{HfO}_2 \) on the sample with the \( \text{O}_2 \) pretreatment. Thus, the \( \text{O}_2 \) pretreatment can be expected to yield fewer interface traps and exhibited higher chemical passivation quality.

| Sample   | Fixed charge density, \( Q_f \) \((\times10^{12}\text{ cm}^{-2})\) | Interface defect density, \( D_{it} \) \((\times10^{13}\text{ eV}^{-1}\text{ cm}^{-2})\) |
|----------|-------------------------------------------------|----------------------------------|
| SO       | 12.0                                            | 6.21                             |
| SO-A400  | 8.22                                            | 4.73                             |
| SO-A450  | 6.13                                            | 4.42                             |
| SO-A500  | 3.82                                            | 3.82                             |

Fig. 3 FE-TEM cross-section analysis of the \( \text{HfO}_2 \) film annealed at 500 °C (a) without and (b) with \( \text{O}_2 \) plasma pretreatment.
Growth of a thin oxide film on a clean but unpassivated Si surface leads to the formation of new covalent bonds (chemical passivation) and termination of the dangling bonds [9]. Si/oxide interfaces often carry some fixed charges. These charges can induce an electric field at the surface of Si and can potentially reduce the recombination rate at the Si/oxide interface (field effect passivation). It has been reported by Hoex et al [20] that remote O₂ plasma pretreatment could improve the surface passivation of Si wafers.

**Conclusions**

In this work, HfO₂ thin films with a thickness of 15 nm were deposited on p-type crystalline silicon wafers using a remote plasma atomic layer deposition system. In situ remote O₂ plasma pretreatment of the Si substrate before the deposition of HfO₂ thin films and post-annealing at 500 °C for 10 min effectively reduced the trap density at the HfO₂/Si interface, yielding a highest lifetime of 67 μs. The HfO₂ thin films deposited by RP-ALD with O₂ plasma pretreatment have potential as passivation layers in high-quality Si solar cells.

**Abbreviation**

ALD: Atomic layer deposition; \( C_{D_s} \): The capacitance of the dielectric per unit area; c-Si: Crystalline silicon; C-V: Capacitance-voltage; CZ: Czochralski; \( D_{ic} \): Interfacial defect density; FE-TEM: Field-emission transmission electron microscope; HF: Hydrofluoric acid; HfO₂: Hafnium oxide; MIS: Metal-insulator-semiconductor; \( q \): The electronic charge; \( Q_o \): Oxide fixed charges; \( Q_{ox} \): Mobile ionic charges; QSSPC: Quasi steady-state photoconductance; RCA: Radio Corporation of America; RP-ALD: Remote plasma atomic layer deposition; RTA: Rapid thermal annealing; SD: Direct depositing samples; SiO₂: Silicon dioxide; SO: O₂ plasma pretreatment samples; SRV: Surface recombination velocity; TEMAH: Tetraethylammonium fluoride; \( V_c \): Voltage; \( V_{fb} \): Flat band voltage; XPS: X-ray photoelectron spectroscopy; \( \tau \): Lifetime; \( \phi_{inj} \): The difference between the work functions of metal and the semiconductor.

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**Authors’ contributions**

XYZ carried out the characterization of the HfO₂ thin films deposited by ALD and drafted the manuscript. OHH and SYL led the experimental and analytical effort on the passivation of the HfO₂ on Silicon. SYC and WH contributed to the deposition of the HfO₂ thin films. CHY and CYK assisted in design and analysis of the experiments for the HfO₂ thin films. WZZ, FBX, and XGM contributed to the valuable discussion on experimental and theoretical results, respectively. All authors read and approved the final manuscript.

**Competing interests**

The authors declare that they have no competing interests.

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**References**

1. Mohammad Ziaur R (2014) Advances in surface passivation and emitter optimization techniques of c-Si solar cells. Renew Sustain Energy Rev 30:734–742
2. Shu-Yang L, Chih-Hsiang Y, Kuei-Ching W, Chung-Yuan K et al (2015) Investigation on the passivated Si/Al₂O₃ interface fabricated by non-vacuum spatial atomic layer deposition system. Nanoscale Res Lett 10:993-99
3. Abdulrahman M (2014) Albadri. Characterization of Al₂O₃ surface passivation of silicon solar cells. Thin Solid Films 562:451–455
4. Simon DK, Jordan PM, Dirstorfer I, Benner F, Richter C, Mikolajick T et al (2014) Symmetrical Al₂O₃-based passivation layers for p- and n-type silicon. Sol Energy Mater Sol Cells 131:72–76
5. Xiaowei C, Xiaoling L, Chao L, Han-Hong C, Cheng L, Songyan C, Hongkai L, Wei H, Jianfang X et al (2016) An improvement of HfO₂/Ge interface by in situ remote N₂ plasma pretreatment for Ge MOS devices. Materials Research Express 3:035012–035012-5
6. Vikram Singh, Satinder K. Sharma, Dinesh Kumar, R.K. Nahar, et al. Study of rapid thermal annealing on ultra thin high-κ HfO₂ films properties for nano scaled MOSFET technology. Microelectronic Engineering. 2012;91:137-143
7. Wang Y, Lin Z, Cheng X, Xiao H, Zhang F, Zou S et al (2004) Study of HfO₂ thin films properties for nano scaled MOSFET technology. Microelectronic Engineering. 2012;91:137-143
8. Toleodano-Lupeu M, San Andres E, del Prado A, Marti I, Luca ML, Gonzalez-Diaz C, Martinez F, Bohme W, Rohrich J, Stubb E et al (2007) High-pressure reactively sputtered HfO₂ composition, morphology, and optical properties. J Appl Phys 104:044106-044106-8
9. Wang J, Mottaghiyan SS, Baroughi MF et al (2012) Passivation properties of atomic-layer-deposited hafnium and aluminum oxides on Si surfaces. Transactions on Electron Devices 59(2):342–348
10. Huijuan G, Tingjui L, Ayra Jagadhamma L, Huey-Liang H, Kyznetsov FA, Smirnova TP, Saralev AA, Kaichev VV et al (2014) Advanced passivation techniques for Si solar cells with high-k dielectric materials. Appl Phys Lett 105:123905

11. Jhuma Gope V, Neha B, Jagannath P, Rajbir S, Maurya KK, Ritu S, Singh PK et al (2015) Silicon surface passivation using thin HfO2 films by atomic layer deposition. Appl Surf Sci 357:635–642

12. Lin F, Hoex B, Koh YH, Lin JJ, Aberle AG et al (2012) Low-temperature surface passivation of moderately doped crystalline silicon by atomic-layer-deposited Hafnium oxide films. Energy Procedia 15:84–90

13. Xiong K, Robertson J, Gibson MC, Clark SJ et al (2005) Defect energy levels in HfO2 high-dielectric-constant gate oxide. Appl Phys Lett 87:183505–183505-3

14. Dieter K. Schroder. Semiconductor material and device characterization, 3rd edition. Wiley:2006.

15. Cheng X, Song Z, Jiang J, Yu Y, Yang W, Shen D et al (2006) Study of HfOxSi film prepared by electron beam evaporation for high-k gate dielectric applications. Appl Surf Sci 252:8073–8076

16. Hill WA, Coleman CC (1980) A single-frequency approximation for interface-state density determination. Solid State Electron 23:987–993

17. Choi K, Temkin H, Harris H, Gangopadhyay S, Xie L, White M (2004) Initial growth of interfacial oxide during deposition of HfO2 on silicon. Appl Phys Lett 85(2):215–217

18. Wei-En F, Chang C-W, Chang Y-Q, Yao C-K, Liao J-D et al (2012) Reliability assessment of ultra-thin HfO2 films deposited on silicon wafer. Appl Surf Sci 258:8974–8979

19. Ran J, Erqing X, Zhenfang W (2006) Interfacial chemical structure of HfO2/Si film fabricated by sputtering. Appl Phys Lett 89:142907–142907-3

20. Hoex B, Heil SBS, Langeriez E, van de Sanden MCM, Kessels WMM et al (2006) Ultralow surface recombination of c-Si substrates passivated by plasma-assisted atomic layer deposited Al2O3. Appl Phys Lett 89:142112–142112-3

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