Zhang et al. Nanoscale Research Letters (2017) 12:324
DOI 10.1186/s11671-017-2098-5

Nanoscale Research Letters

NANO EXPRESS Open Access

Surface Passivation of Silicon Using HfO_2 Thin Films Deposited by Remote Plasma Atomic Layer Deposition System

Xiao-Ying Zhang[1,2], Chia-Hsun Hsu[2], Shui-Yang Lien[2*], Song-Yan Chen[3], Wei Huang[3], Chih-Hsiang Yang[4], Chung-Yuan Kung[4], Wen-Zhang Zhu[1], Fei-Bing Xiong[1] and Xian-Guo Meng[1]

Abstract

Hafnium oxide (HfO_2) 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 HfO_2 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 N_2 ambient for 10 min. The effects of oxygen plasma pretreatment and post-annealing on the properties of the HfO_2 thin films were investigated. They indicate that the in situ remote plasma pretreatment of Si substrate can result in the formation of better SiO_2, resulting in a better chemical passivation. The deposited HfO_2 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: HfO_2 thin films, Atomic layer deposition, O_2 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 (SiO_2) 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 SiO_2, other layers such as SiC, a-Si:H and Si_3N_4 have been used for surface passivation [1]. Recently, Al_2O_3 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 (HfO_2) thin films are used to replace SiO_2 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 HfO_2 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 HfO_2 layer grown by ALD without further annealing. In another study Huijuan Geng et al. [10] reported advanced passivation using simple materials (Al_2O_3, HfO_2) and their compounds $H_{(Hf)}A_{(Al)}O$ deposited by ALD. All of the previous attempts were performed to

* Correspondence: syl@mail.dyu.edu.tw
[2]Department of Electrical Engineering, Da-Yeh University, ChungHua 51591, Taiwan
Full list of author information is available at the end of the article

deposit HfO_2 on c-Si substrates without any pre-treatments.

In this work, the surface passivation properties of the HfO_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_2 films on Si is also investigated.

Methods

In this study, (100) oriented boron-doped p-type crystalline 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_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_2 thin films were grown in an RP-ALD reactor (Model: Picosun, Finland) using tetrakis (ethylmethylamino) hafnium (TEMAH) and remote O_2 plasma as the precursors for hafnium and oxygen respectively with N_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_2 plasma pulse (for 10 s). The nitrogen purge times for TEMAH and O_2 were 10.0 and 12.0 s, respectively. The samples were divided into two groups. For group one, HfO_2 thin films were deposited directly on the cleaned Si wafers. For group two, before deposition of HfO_2 thin films, Si wafers were additionally treated by remote O_2 plasma for 1 min. The O_2 plasma power for the pretreatment and for the ALD deposition process was 2500 W. The HfO_2 films for all of the samples were deposited at 250 °C. Different HfO_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^{14} cm^{-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_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_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_2 plasma pretreatment samples), respectively. Annealing process was performed using a RTA system at 400–650 °C in N_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 (τ_{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_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_2 thin films were determined by FE-TEM (JEM-2100 F).

Results and Discussion

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

Table 1 Details of the HfO_2 thin films

Sample	O_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

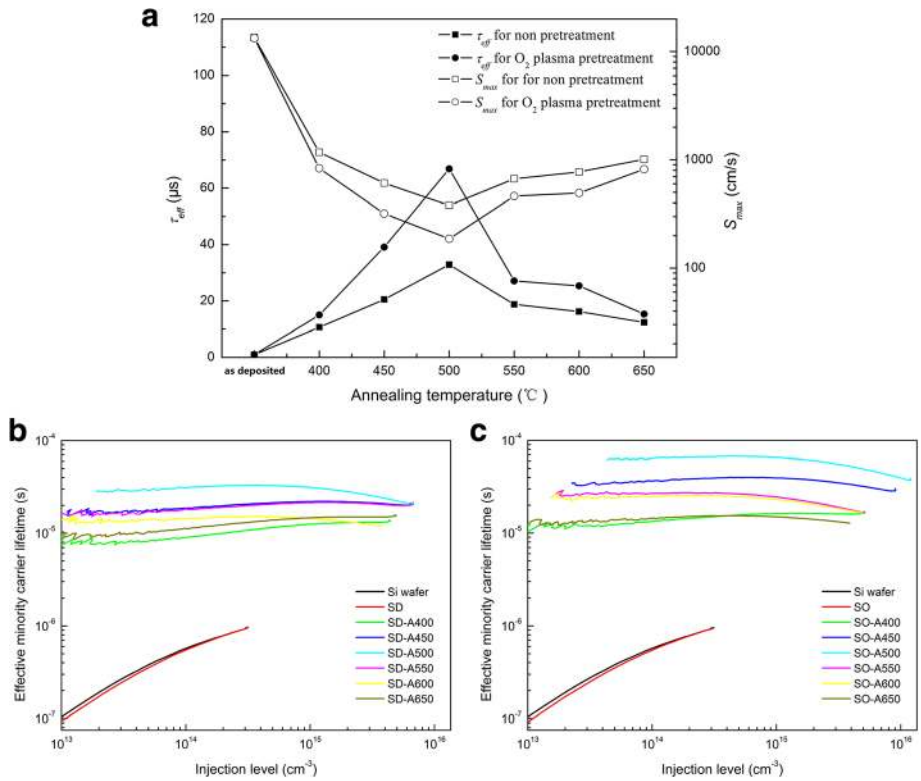

Fig. 1 **a** τ_{eff} and S_{max} of the samples at the injection level of 3×10^{14} cm^{-3}. Injection level-dependent effective minority carrier lifetime of the (**b**) SD and (**c**) SO samples

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 τ_{eff} of the annealed HfO_2 sample with O_2 plasma pretreatment at the injection level of 3×10^{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 τ_{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 τ_{eff} of 67 μs, corresponding to an S_{max} value of 187 cm/s. This calculation was based on the quasi steady-state photo conductance (QSSPC) τ_{eff} data for the injection level of 3×10^{14} cm^{-3}. S_{max} represents the upper limit of SRV, and is estimated from the measured lifetime values using the following relation [11],

$$S_{max} = \frac{W}{2\tau_{eff}}, \tag{1}$$

where W (=250 μm) is the thickness of the silicon substrate. The lower value of S_{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 τ_{eff} values were similar to that of the bare Si wafer. However, τ_{eff} of the annealed samples increased significantly and then decreased as the injection level increased from 4×10^{13} cm^{-3} to 5×10^{15} cm^{-3}. The drop in τ_{eff} with increasing injection levels is caused by Auger recombination in the bulk of the c-Si substrate. The τ_{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 3×10^{14} to 10^{13} cm^{-3}. This dependence in injection levels is much weaker for the annealed samples. The τ_{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 ($Al/HfO_2/p\text{-}Si$) 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 V < V_A < 5 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],

$$V_{FB} = \phi_{ms} - \frac{qQ_f}{C_{ox}}, \tag{2}$$

where ϕ_{ms} (=0.32 eV), q (=1.602×10^{-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_{it}) is determined using an approximation method

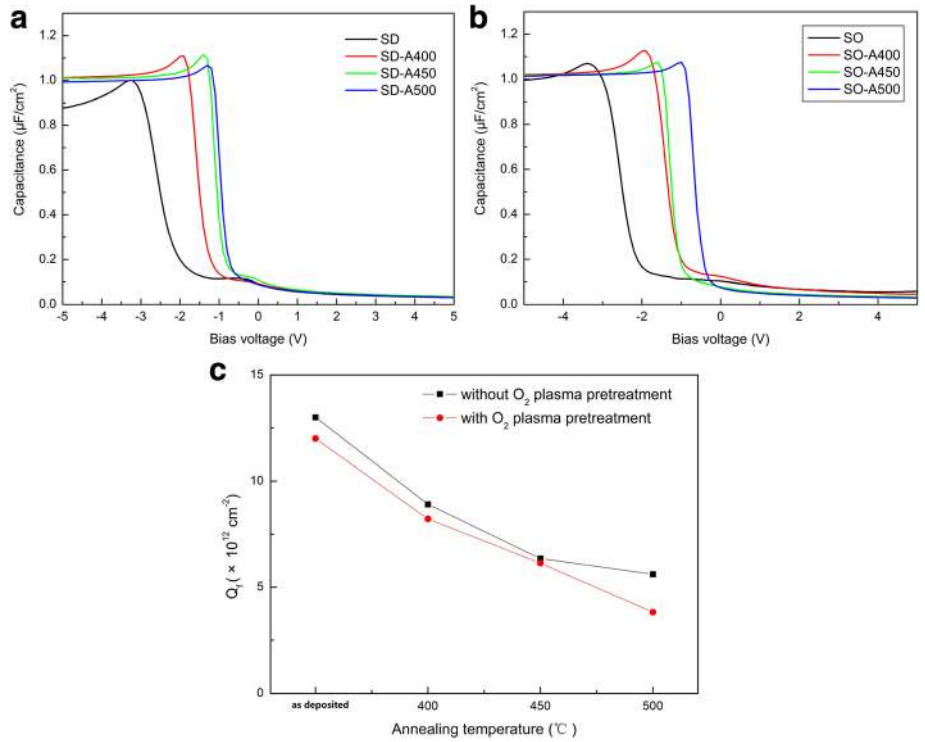

Fig. 2 C-V characteristics measured at 1 MHz for (**a**) directly deposited samples without O_2 plasma pretreatment, and (**b**) samples with O_2 plasma pretreatment; (**c**) estimated Q_f of the annealed HfO_2 thin films

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 HfO_2/Si interface. The FE-TEM cross-section analysis of the HfO_2 thin film annealed at 500 °C (a) without and (b) with O_2 plasma pretreatment is shown in Fig. 3. From the FE-TEM images, the annealed HfO_2 thin films consist of three regions, which are the HfO_2 layer, an interfacial oxide and the Si substrate. The atoms in the HfO_2 layer are orderly arranged in some areas, indicating that the 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 HfO_2 layer and the interfacial layer of the sample with oxygen plasma treatment are 15.3 and 2.7 nm, respectively. Whereas, the 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 HfO_2 films annealed at 500°C without and with 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 μc-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 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 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 HfO_2. Fewer atomic vacancies are formed by diffusion in the HfO_2 on the sample with the O_2 pretreatment. Thus, the O_2 pretreatment can be expected to yield fewer interface traps and exhibited higher chemical passivation quality.

Table 2 Calculated fixed charge density (Q_f) and interface defect density (D_{it}) from C-V measurement of the HfO_2 thin films

Sample	Fixed charge density, Q_f ($\times 10^{12}$ cm^{-2})	Interface defect density, D_{it} ($\times 10^{13}$ eV^{-1} cm^{-2})
SO	12.0	5.21
SO-A400	8.22	4.73
SO-A450	6.13	4.42
SO-A500	3.82	3.82

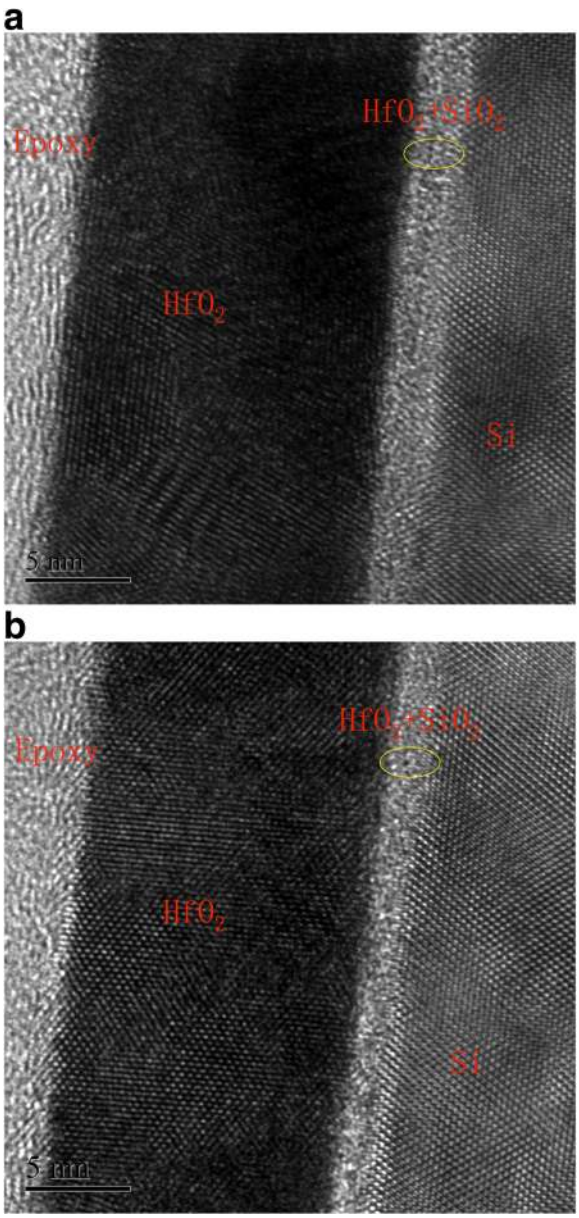

Fig. 3 FE-TEM cross-section analysis of the HfO_2 film annealed at 500 °C (**a**) without and (**b**) with O_2 plasma pretreatment

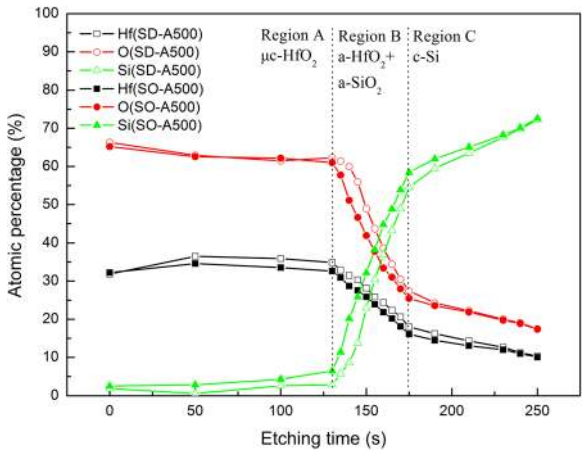

Fig. 4 Elemental depth profiles of HfO_2 annealed at 500 °C without and with O_2 plasma pretreatment versus etching time

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 when preparing Al_2O_3 thin films by plasma ALD, they found a very thin (~1.5 nm) SiO_x interfacial oxide layer was formed, which provides good passivation to c-Si surface. They attributed this to the exposure of the substrate to the oxygen plasma in the very first ALD cycles. Although in this study the HfO_2 thin films are prepared, the oxygen plasma pretreatment is found to result in a similar interfacial oxide layer (a-HfO_2 + a-SiO_2). The oxygen plasma pretreatment could improve the surface passivation of Si wafers.

Conclusions

In this work, HfO_2 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 O_2 plasma pretreatment of the Si substrate before the deposition of HfO_2 thin films and post-annealing at 500 °C for 10 min effectively reduced the trap density at the HfO_2/Si interface, yielding a highest lifetime of 67 μs. The HfO_2 thin films deposited by RP-ALD with O_2 plasma pretreatment have potential as passivation layers in high-quality Si solar cells.

Abbreviation

ALD: Atomic layer deposition; C_{ox}: The capacitance of the dielectric per unit area; c-Si: Crystalline silicon; C-V: Capacitance-voltage; Cz: Czochralski; D_{it}: Interfacial defect density; FE-TEM: Field-emission transmission electron microscope; HF: Hydrofluoric acid; HfO_2: Hafnium oxide; MIS: Metal-insulator-semiconductor; q: The electronic charge; Q_f: Oxide fixed charges; Q_m: Mobile ionic charges; Q_{OT}: Oxide trapped charges; QSSPC: Quasi steady-state photo conductance; RCA: Radio Corporation of America; RP-ALD: Remote plasma atomic layer deposition; RTA: Rapid thermal annealing; SD: Direct depositing samples; SiO_2: Silicon dioxide; SO: O_2 plasma pretreatment samples; SRV: Surface recombination velocity; TEMAH: Tetrakis (ethylmethylamino) hafnium; V_A: Voltage; V_{FB}: Flat band voltage; XPS: X-ray photoelectron spectroscopy; τ_{eff}: Lifetimes; ϕ_{ms}: The difference between the work functions of metal and the semiconductor

Acknowledgements

This work is sponsored by the Ministry of Science and Technology of the Republic of China under the grants No. 105-2632-E-212-001 and 104-2221-E-212-002-MY3. This work is also supported by the National Natural Science Foundation of China (No. 61474081, 61534005, and 61307115), the science and technology project of Xiamen (No. 3502Z20141042) and the Fundamental Research Funds for the Central Universities (No. 20720150028).

Authors' contributions

XYZ carried out the characterization of the HfO_2 thin films deposited by ALD and drafted the manuscript. CHH and SYL led the experimental and analytical effort on the passivation of the HfO_2 on Silicon. SYC and WH contributed to deposit the HfO_2 thin films. CHY and CYK assisted in design and analysis of the experiments for the HfO_2 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.

Publisher's Note

Author details

[1]School of Opto-electronic and Communication Engineering, Fujian Key Laboratory of Optoelectronic Technology and Devices, Xiamen University of Technology, Xiamen 361024, China. [2]Department of Electrical Engineering, Da-Yeh University, ChungHua 51591, Taiwan. [3]Department of Physics, OSED, Xiamen University, Xiamen 361005, China. [4]Department of Electrical Engineering, National Chung-Hsing University, Taichung 40227, Taiwan.

Received: 28 December 2016 Accepted: 20 April 2017
Published online: 04 May 2017

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. Shui-Yang L, Chih-Hsiang Y, Kuei-Ching W, Chung-Yuan K et al (2015) Investigation on the passivated Si/Al_2O_3 interface fabricated by non-vacuum spatial atomic layer deposition system. Nanoscale Res Lett 10:93-93-9
3. Abdulrahman M (2014) Albadri. Characterization of Al_2O_3 surface passivation of silicon solar cells. Thin Solid Films 562:451–455
4. Simon DK, Jordan PM, Dirnstorfer I, Benner F, Richter C, Mikolajick T et al (2014) Symmetrical Al_2O_3–based passivation layers for p- and n-type silicon. Sol Energy Mater Sol Cells 131:72–76
5. Xiaowei C, Xiaoling L, Chao L, Haiyang H, Cheng L, Songyan C, Hongkai L, Wei H, Jianfang X et al (2016) An improvement of HfO_2/Ge interface by in situ remote N_2 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-*k* HfO_2 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 HfO_2 thin films prepared by electron beam evaporation. Appl Surf Sci 228:93–99
8. Toledano-Luque M, San Andres E, del Prado A, Martil I, Lucia ML, Gonzalez-Diaz G, Martinez FL, Bohne W, Rohrich J, Strub E et al (2007) High-pressure reactively sputtered HfO_2: composition, morphology, and optical proterties. J Appl Phys 102:044106-044106-8
9. Wang J, Mottaghian 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, Saraev 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 HfO_2 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 HfO_2 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 HfOSi 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 HfO_2 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 HfO_2 films deposited on silicon wafer. Appl Surf Sci 258:8974–8979
19. Ran J, Erqing X, Zhenfang W (2006) Interfacial chemical structure of HfO_2/Si film fabricated by sputtering. Appl Phys Lett 89:142907–142907-3
20. Hoex B, Heil SBS, Langereis E, van de Sanden MCM, Kessels WMM et al (2006) Ultralow surface recombination of c-Si substrates passivated by plasma-assisted atomic layer deposited Al_2O_3. Appl Phys Lett 89:142112–142112-3