



Preparation of Native Oxide and Carbon-Minimized Ge Surface by NH₄OH-Based Cleaning for High-*k*/Ge MOS Gate Stacks

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The native oxide and carbon-contaminant-minimized Ge surface with ammonium hydroxide (NH₄OH)-based cleaning for high-*k*/Ge metal-oxide-semiconductor (MOS) gate stack application is reported. Furthermore, the carbon-free interfacial Ge-oxide layer preparation on the cleaned Ge surfaces was also studied. The thickness of GeO₂ on Ge surface before, during, and after different cleaning processes was evaluated by the spectroscopic ellipsometry measurements. The HF rinsing step in the cyclic HF/deionized water cleaning was not effective for a removal of native GeO₂ because it cannot form the soluble species by a chemical reaction in the low pH HF solution. A cyclic NH₄OH-based cleaning results in a minimum residual GeO₂ at 3 and 8 Å on Ge(111) and (100), respectively. The fast regrowth of GeO₂ on cleaned Ge surfaces under air exposure was observed, regardless of the cleaning methods. However, Auger electron spectroscopy spectra showed less amount of carbon on Ge surfaces with NH₄OH-based cleaning than HF-based cleaning. The small amount of residual carbon after NH₄OH-based wet cleaning was completely removed by O₂ plasma for a very thin (~10 Å) surface oxidation in the remote plasma-enhanced chemical vapor deposition chamber.

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The necessary step for successful integration of Ge/high-*k* gate stacks for future metal-oxide field-effect transistor (MOSFET) is Ge surface preparation free of native GeO₂ and other possible contaminants (e.g., carbon).¹⁻³ To achieve a good Ge surface for MOSFET application, the removal of native oxides and the formation of a high quality interfacial oxide layer are greatly important, because the native oxide has a considerable amount of carbon species as well as high interfacial roughness.⁴ More importantly, the relatively thick native GeO₂ (>2.5 nm in ambient) on bare Ge surfaces, if not removed efficiently, makes equivalent oxide thickness control more difficult.

Initial major efforts on the task of Ge surface preparation have been made by HF-based cleaning.⁵⁻⁸ Although HF solution is very effective for Si surface preparation by providing an oxide-free and H-terminated Si surface with good resistance for ambient oxidation, it has been reported that HF is not consistently effective for Ge as much as Si, but rather has shown more complexities in previous results.⁷⁻¹² Above all, the ability of GeO₂ removal with HF showed significant dependence on cleaning process conditions such as HF concentration and cleaning time.^{7,8} There have been many inconsistent results on the capability of HF for GeO₂ removal, especially in the results for wet cleaning conducted in ambient condition.^{6,9} Although a majority of studies reported that HF solution removed GeO₂,^{6,8-10} several reports claimed the presence of residual Ge sub-oxides with HF cleaning.^{9,11} Furthermore, H passivation on Ge surface is desired with HF cleaning, but it turned out that H passivation of Ge has much lower stability compared to H passivation of Si.^{9,11,12} Even for the ultrahigh vacuum condition, Ge-H passivation is incomplete and unstable.^{13,14} The instability of incomplete H passivation for Ge becomes severe in the ambient.^{9,12}

Another challenge for Ge surface cleaning is the removal of carbon contaminants. Because the complete removal of GeO₂ with HF is difficult, carbon species incorporated in the oxide layer are also hard to eliminate. More importantly, hydrocarbon (CH_x) on Ge surfaces was reported as a chemically strong bond,¹⁵ and it is surprising that the previous result reported the increase in CH_x-Ge bonds even after HF cleaning compared to the as-received GeO₂-terminated Ge

surfaces.⁷ Therefore, it is regarded that the formation of hydrocarbon bonds might increase the instability of H passivation of Ge surfaces through H removal during the reaction.¹⁵

Consequently, it is certain, from numerous studies on HF-based Ge cleaning, that there are many more complexities in designing the cleaning process for Ge surfaces compared to Si surfaces. One of the critical issues for the selection of wet chemistry for Ge surface cleaning is a dilution of wet chemicals. Because GeO₂ is soluble in water,^{3,16} it is highly possible that the water in the diluted solutions assisted GeO₂ removal significantly. For example, many of the studies on HF cleaning on Ge surfaces used HF solution diluted by water between 10 and 50%. Therefore, it cannot be excluded that the water in solution significantly enhanced GeO₂ removal efficiency. This makes it difficult to determine the efficiency of GeO₂ removal in views of chemical reactions.

Because of the incomplete surface passivation and cleaning on GeO₂-passivated Ge with HF in contrast to Si, there have been some researches on the passivation of Ge surfaces with other elements such as sulfur and chlorine, both in vacuum and wet solution.^{9,17-20} Among those results for different chemical treatments other than HF, some interesting results with NH₄OH-based cleaning on Ge surfaces showed the effective removal of GeO₂ and carbon on Ge surfaces.^{1,3} Especially in Ref. 1, the atomically smooth surface of Ge was achieved by NH₄OH cleaning.

In this study, the removal efficiency of HF and NH₄OH-based cleaning and the oxide regrowth after each cleaning were evaluated by the real-time visible-UV spectroscopic ellipsometry (SE) measurements. There are several effective surface-sensitive characterization techniques for the research on Ge surfaces, such as X-ray photoelectron spectroscopy (XPS) and Fourier transform IR spectroscopy. However, these techniques are incompatible with the real-time measurements on changes of surfaces during the wet cleaning process. In this regard, the optical measurement can be a great technique for the real-time analysis on the surfaces during the wet cleaning process. Similar studies on various semiconductor surfaces have been done using the specially designed SE system.^{1,21} The focus of this study is the real-time measurement on the NH₄OH-based cleaning, giving direct evidence for the GeO₂ removal efficiency by showing the instant residual oxide thickness during each wet chemical treatment. The results on GeO₂ thickness with SE measurement are compared for HF- and NH₄OH-based cleaning. In addition, residual chemical elements after (i) each cleaning process and (ii) the subsequent O₂ plasma exposure for the

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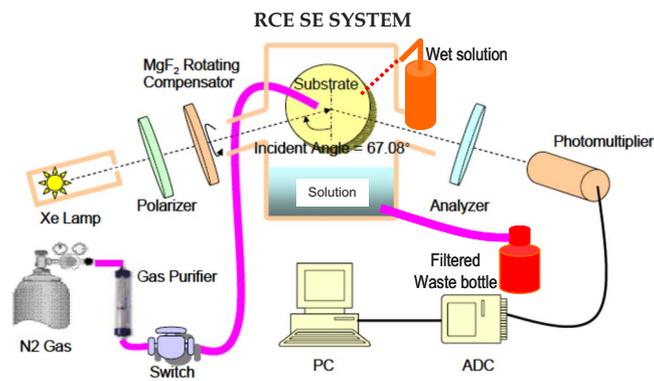


Figure 1. (Color online) An illustration of RCE SE system for the real-time measurements during the wet cleaning.²³

ultrathin Ge oxide formation were also analyzed by in situ Auger electron spectroscopy (AES). The aim of O₂ plasma exposure is to achieve the carbon-minimized ultrathin Ge-oxide deposition, which can be used for a good interlayer for the gate oxide stacks before high-*k* dielectric deposition for Ge MOSFETs.

Experimental

The bare n-type Ge(100) or (111) wafers (Semiconductor Wafer, Inc., Ga-doped p-type, 1–35 Ω cm) were treated by either HF-based or NH₄OH-based cleaning. For an HF-based treatment, wafers were dipped into diluted (10%) HF [microelectronic use complementary metal-oxide-semiconductor (CMOS), J. T. Baker] for 10 s followed by deionized water (DIW, 18.2 MΩ) dip for 20 s. This unit process which consisted of 10 s HF dip and 20 s DIW dip was repeated in six cycles. Another experiment set of HF-based treatment was a sequential process consisting of DIW dip for 2 min, 6% H₂O₂ [microelectronic use (CMOS), J. T. Baker] dip for 10 s, diluted 10% HF dip for 10 min, and final DIW rinsing. Because this cleaning recipe claimed to produce a H-terminated Ge surface in the previous report,³ it was repeated in this study for SE measurement for comparison to other cleaning methods.

A one-cycle treatment defined in NH₄OH-based cleaning included DIW dip for 5 min, and sequential rinses of the wafer surfaces with 6% H₂O₂, methanol [NH₄OH, microelectronic use (CMOS), JT Baker], 10% NH₄OH [microelectronic use (CMOS), JT Baker], and finally, DIW. This one-cycle treatment was repeated twice.

For real-time SE measurements during the wet cleaning, each wet solution rinse in a cyclic NH₄OH-based cleaning was sequentially applied to the wafers loaded on the sample stage of SE, specially designed for measurements during wet cleaning experiments, which was connected to a drain hose and filtered chemical waste bottle. The schematic description of SE used for this study is represented in Fig. 1. The photon energy of incident light generated by a xenon lamp was fixed at 1.7 eV, where the SE resolution for optically determined GeO₂ thickness can be maximized. The feedback loop of signal processing in the SE measurement enabled the single data point acquisition with the time interval of ~1 s, and therefore, it was possible to trace the instant surface changes induced by wet chemical treatments for a very short time period such as a few seconds. The details of rotating compensator enhanced (RCE) SE measurement used in this study were explained elsewhere.²² The precision of RCE SE on the determination of the oxide thickness of a semiconductor substrate such as Si and Ge was reported to be very high, with the error range of oxide thickness less than 1 Å (i.e., 0.5 Å).²³ N₂ purge on the wafer was done between each chemical rinsing step and all the time during the SE measurement to remove the residual wet chemicals on the wafers as well as to prevent the oxide regrowth caused by water absorption on Ge surfaces in the air.

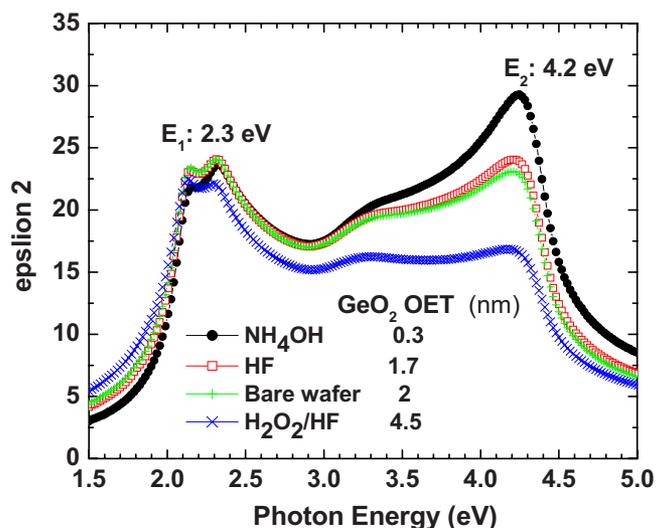


Figure 2. (Color online) Plot for imaginary parts of pseudodielectric function for Ge(111) surfaces with and without different cleaning processes: Cyclic NH₄OH-based, cyclic HF/DIW, HF/H₂O₂/DIW, and no treatment (bare wafer). E₁ and E₂ are peaks associated with Ge direct optical transition. E₂ peak height is directly related to the oxide thickness on Ge substrate. GeO₂ thickness (OET) for each treatment is indexed in the plot.

The oxide removal efficiency in all cleaning processes and oxide regrowth in the air after the cleaning were real-time monitored by SE.

The Ge wafers that were processed by each HF- and NH₄OH-based wet cleaning were introduced to a load lock chamber (base pressure at 1 × 10⁻⁸ Torr), which is in situ connected to an AES (Perkin-Elmer, Cylindrical Auger 10-155) analysis chamber (base pressure at 1 × 10⁻¹⁰ Torr) and to the remote plasma-enhanced chemical vapor deposition (RPECVD) chamber. The air exposure time of the cleaned wafer before the introduction to the load lock chamber was about 1 min. The cleaned wafers were exposed to O₂ plasma for the ultrathin GeO₂ layer deposition and residual carbon removal, and then transferred to the AES analysis chamber to investigate the relative concentration of chemical elements such as Ge, C, and O on the oxidized Ge surface. The discharge condition of O₂ plasma was 300°C substrate temperature, 30 W plasma power, 15 s exposure time, and 0.3 Torr O₂ pressure.

Results and Discussion

The imaginary pseudodielectric function spectra of bare and cleaned Ge(100) wafers with SE measurements are shown in Fig. 2. The best rule to determine a clean Ge surface free of GeO₂ layer is to observe the ε₂ peak height of direct band-to-band transition states in Ge at 2.3 and 4.2 eV. These peak heights should be maxima when the thickness of the GeO₂ layer is minimized based on the heterogeneous medium optical model.²⁴ The dielectric function of the cleanest Ge surface free of GeO₂ layer was measured in the previous study on Ge surface.¹ Following the same methodology in Ref. 1, we extracted the optically equivalent GeO₂ thickness using the three-phase model calculation.

The native oxide thickness on pre-cleaned bare Ge wafer was 20 Å. The first cyclic HF/DIW treatment on Ge wafers resulted in 17 Å of GeO₂, while the second combination of DIW/H₂O₂/HF showed 45 Å of GeO₂, thicker than the native oxide layer on bare Ge wafer. Considering the rapid oxide regrowth of cleaned Ge surfaces as discussed later, the cyclic HF/DIW cleaning indeed removed the native GeO₂ layer. However, it is thought that the robust H passivation of the Ge surface was not achieved because the SE measurement for cleaned wafers was done within 10 min after the Ge cleaning process. For the cleaning consisting of DIW/H₂O₂/HF,

an H_2O_2 dip of Ge rapidly forms a chemical oxide like it does with Si;^{13,25} however, a 10 min HF dip does not remove GeO_2 effectively so that the resultant GeO_2 thickness is mostly due to the chemical oxide formed by H_2O_2 . From these results, it is concluded that diluted HF is not effective in the complete removal of GeO_2 as well as the complete H passivation of the Ge surface, although the native oxide was partially removed by the cyclic HF/DIW cleaning. Therefore, these results support some of the previous claims on the unsuccessful Ge surface cleaning with diluted HF.^{9,11}

If HF does not result in the robust H passivation on Ge surfaces, the determination of how effectively HF can remove the GeO_2 layer during the cleaning process is not straightforward because DIW also has the ability to remove the GeO_2 layer, because GeO_2 is water-soluble. It is possible, based on the results on two different HF-based cleaning processes together with previous results,^{5,3} that the partial GeO_2 removal with water is misinterpreted as the ability of HF to remove GeO_2 . Based on the reported electrochemistry of reactions of Ge surfaces in wet solutions, acid solutions having lower pH are essentially not effective in solubilizing products on Ge surfaces formed by liquid reactions because the solubility of products on Ge surfaces dramatically drops as pH is lowered.²⁶ Higher pH base solutions actively form soluble reaction products on Ge surfaces.²⁷

The enhanced GeO_2 solubility in the base solution was confirmed from the minimum 3 Å GeO_2 on Ge(111) surfaces treated by NH_4OH -based cleaning. Because this GeO_2 thickness value is not a physical thickness but an optical equivalent thickness (OET), the actual overlayer may not be a uniform layer covering the whole surface but, rather, it could be an island-type phase of GeO_2 or less than a monolayer on average. NH_4OH is a strong base chemical solution (pH 11.63), and therefore, it very effectively etches the chemically grown GeO_2 by H_2O_2 down to Ge surfaces.²⁷ This very thin GeO_2 layer was observed only when the N_2 purge was maintained on the Ge surfaces, thereby blocking oxidizing agents in the air such as water vapor. Although the regrowth of GeO_2 occurs even for NH_4OH -treated Ge surface because it does not passivate the surface, it is very crucial to observe the complete GeO_2 removal during the wet cleaning because this complete etching of native oxide is essential to achieve the removal of carbon species in GeO_2 layer.

Although the continuous N_2 purge prevents the regrowth of oxide in the air, the real condition in device manufacturing inherently requires evaluation on the time-dependent stability of Ge surfaces under air exposure. To evaluate the time-dependent stability of cleaned Ge surfaces, as well as to determine the role of specific wet chemical solution on Ge surface cleaning, real-time SE measurements for NH_4OH -based treatment were carried out.

Figure 3 represents the OET evolution of GeO_2 under N_2 purge for each wet chemical agent during NH_4OH -based cleaning on Ge(111) and (100) surfaces, respectively. The initial pre-cleaning step is a Ge wafer dip in DIW for 5 min. This DIW dip step significantly removes GeO_2 for both Ge(111) and (100), as reported in other studies,^{27,15} but the GeO_2 thickness after the DIW dip is different depending on the wafer orientation: 6 Å for (111) and 12 Å for (100). After the DIW dip, as a cleaning process for SE measurement, each chemical solution is applied in the way of a downstream rinsing from a bottle between 5 and 10 s, then a N_2 blowing purge was done for the removal of the residual solution on Ge surfaces. This combined step consisting of (i) a solution rinse and (ii) a subsequent N_2 blow is defined as a unit chemical treatment step, which is indicated with dotted lines in Fig. 3.

From Fig. 3a, it is evident that the effective chemical etchants for GeO_2 are NH_4OH and water. As expected, a H_2O_2 rinsing step oxidizes the surface very quickly (only in 5 s) by forming 38 Å of GeO_2 , as reported in other results.^{25,4} Methanol is involved in neither oxidation nor oxide etching, but is supposed to remove organic residues such as hydrocarbon.²⁸ An important observation on the GeO_2 evolution plot is the GeO_2 regrowth rate right after the rinses

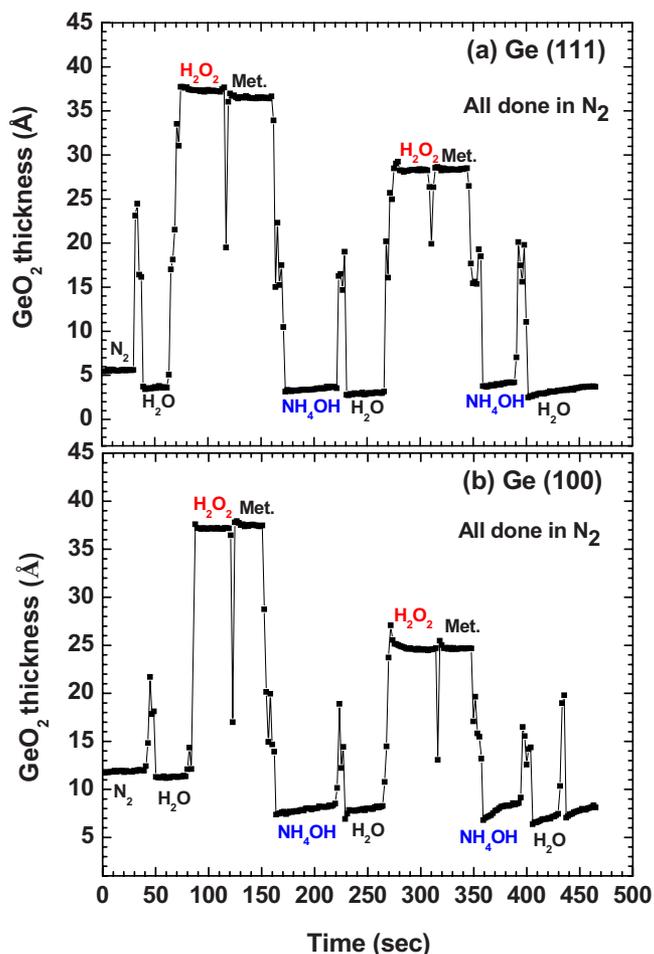


Figure 3. (Color online) Plot for GeO_2 thickness evolution during NH_4OH -based cleaning for (a) Ge(111) and (b) (100) surfaces. The GeO_2 thickness was extracted from the real-time SE measurements during the cleaning process.

with etching agents, NH_4OH and water. The thinner the GeO_2 after GeO_2 etching, the faster the GeO_2 regrowth rate observed. For example, the GeO_2 regrowth rate for the Ge surface with 2.5 Å GeO_2 after a final H_2O rinse is 1.5 Å/min even under the N_2 purge.

As observed in Fig. 3b, Ge(100) has a lower GeO_2 removal efficiency with the same NH_4OH -based cleaning compared to Ge(111). The initial thickness of GeO_2 (100) is already twice that of Ge(111), and the thinnest GeO_2 of Ge (100) during the cyclic cleaning is 6.4 Å. Therefore, the plots in Fig. 3 reinforce the assumption that GeO_2 removal efficiency has a strong dependence on Ge orientation.²¹

Figure 4 compares the GeO_2 regrowth rate for different Ge orientations in the air without N_2 purge. Before turning off N_2 purge, the same NH_4OH -based treatment as in Fig. 3 was performed for both Ge(111) and (100) wafers. The analysis of oxide regrowth kinetics gives three different growth domains. For Ge(111), right after stopping N_2 purge, GeO_2 starts to grow rapidly up to 7 Å for 9 s (0.3 Å/s); it then keeps growing to 9.4 Å for the next 46 s at the fast rate (3.8 Å/min). Then, the regrowth rate rapidly becomes lower and, finally, saturated at 12 Å after 460 s (0.2 Å/min). As a result, although NH_4OH removed GeO_2 on Ge(111) almost completely, the aggressive oxide regrowth results in 10 Å GeO_2 with only 1 min air exposure. In fact, the real GeO_2 thickness should be 1 or 2 Å less than this OET value because we confirm from SE measurements that the water vapor physisorbed on the top surface contributes some thickness to the total OET without N_2 purge. Therefore, the real

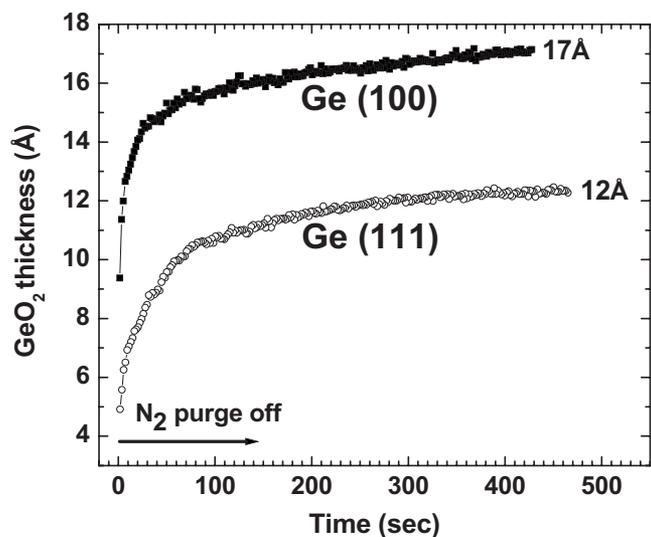


Figure 4. Plot for GeO_2 regrowth evolution during the air exposure of the cleaned Ge(111) and (100) surface as a function of air exposure time. Both surface orientations show similar regrowth features in the ambient.

physical GeO_2 thickness on a Ge(111) wafer, which is introduced into the vacuum chamber with about 1 min air exposure after the NH_4OH -based cleaning, is supposed to be about 7–8 Å.

A similar analysis can be made on the Ge(100) surface. The initial GeO_2 thickness was already 8 Å right after the NH_4OH -based cleaning and reached 14 Å in 1 min after the N_2 purge was turned off and, finally, saturated at 17 Å with air exposure for 410 s. Similarly, if the water vapor on the Ge surface is considered, the resultant physical GeO_2 thickness on the Ge(100) surface is about 12–13 Å if introduced to the vacuum chamber within 1 min. This GeO_2 (100) thickness in the vacuum chamber is equivalent to the pre- O_2 plasma Ge surface condition in this study.

From the real-time SE measurements on cleaned Ge surfaces, the rapid oxide regrowth of Ge, regardless of the wafer orientation, is common even after the complete GeO_2 removal during wet cleaning. Nevertheless, this surface cleaning based on NH_4OH is very promising for the effective Ge surface preparation for device fabrication, because it selectively and effectively removes not only the native oxide but also the chemical oxide formed by H_2O_2 dip. Furthermore, other studies on NH_4OH -based cleaning on Ge showed very good surface roughness.^{3,21,27} The regrown GeO_2 thickness on a cleaned Ge surface is higher than that on H-passivated Si (3 or 4 Å OET right after HF cleaning as measured by SE), but still placed at a reasonable level at half of the native oxide thickness on a bare Ge(100) wafer (~20 Å).

For comparison, the regrown oxide thickness for the cleaned Ge(100) surface with HF/DIW cyclic cleaning was 15 Å OET after 8 min air exposure without N_2 purge, which is almost the same as that of the NH_4OH -treated Ge surface. Therefore, the resultant oxide thickness in the air is not largely different, regardless of the cleaning methods. Rather, there is an apparent difference in the residual carbon amount in the oxide and Ge top surface between two different cleaning methods. In this regard, NH_4OH -based cleaning is proved to be superior to a cyclic HF/DIW cleaning based on SE and AES analyses, as discussed in the following.

Figure 5 represents the AES wide- and narrow-scan spectra for different Ge surfaces. In Fig. 5a, there are energy peak states associated with germanium (45–50 eV), carbon (268 eV), and oxygen (509 eV) species.^{29,30} Particularly, Ge peaks are related to two different bonding states, Ge–O (44 eV) and Ge–Ge (48 eV),²⁹ and the narrow-scan AES spectra between 40 and 60 eV is shown in Fig. 5b.

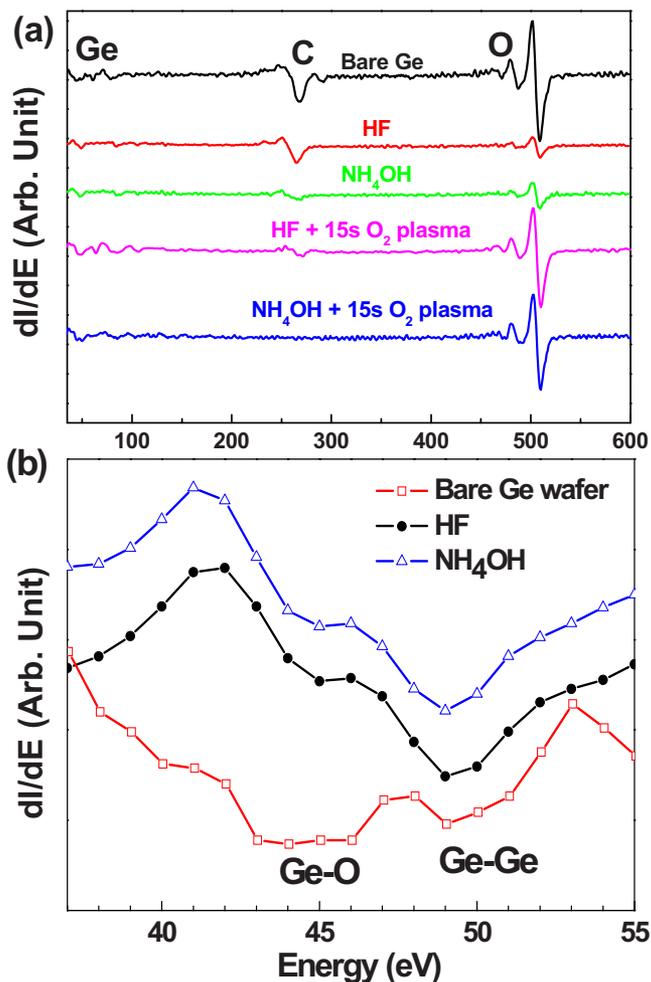


Figure 5. (Color online) AES (a) wide- and (b) narrow-scan spectra for Ge(100) surface with and without surface treatments: Bare, cyclic HF-, and NH_4OH -based cleaning. For wide energy scan, there are energy peak states associated with germanium (45–50 eV), carbon (268 eV), and oxygen (509 eV) species. For narrow energy scan, there are Ge peaks related to two different bonding states, Ge–O (44 eV) and Ge–Ge (48 eV).

For the relative comparison of each chemical element amount, every spectrum has been normalized to the Ge–Ge peak intensity in the spectra of bare Ge wafers.

Based on O peak intensities at 509 eV, O amount was significantly reduced in AES spectra for both HF- and NH_4OH -based cleaning compared to the bare wafer. In addition, the relative ratio of peak intensity of Ge–O (44 eV) over Ge–Ge (48 eV) in Fig. 5b also showed a similar amount of Ge–O bond for both HF (the ratio at 0.2) and NH_4OH (the ratio at 0.3) based cleaning. These AES results agree with the similar GeO_2 OET between HF- and NH_4OH -based cleaning after air exposure.

However, there is a clear difference in the residual carbon amounts on Ge surfaces between two cleaning methods. AES data in Fig. 5a suggest that carbon was not effectively removed on the Ge surfaces with the cyclic HF/DIW cleaning, but it was considerably reduced by NH_4OH -based cleaning. The residual carbon on Ge surfaces was never removed completely (i.e., below AES detection limit) in many repeated experiments based on these cleaning methods. In fact, many reports addressed a difficulty in completely removing surface carbon on Ge surfaces (e.g., strong Ge–C bond) with wet cleaning.^{7,4} In this study, the reduced carbon amount after NH_4OH -based cleaning was completely removed by O_2 plasma for the ultrathin oxidation of Ge surfaces below the AES detection limit

because the reactive atomic O radicals form volatile CO and CO₂ gas products as a result of the reaction with the surface carbon.³⁰ The effective removal of surface Si–C bonds with O₂ plasma below the XPS detection limit was reported for the study on Si surface cleaning.³⁰ Therefore, this result with NH₄OH-based cleaning and O₂ plasma process in Fig. 5 suggests that O₂ plasma is effective for the removal of surface carbon on Ge as well as on Si. In contrast, the AES spectra of Ge surface processed with the cyclic HF cleaning and subsequent O₂ plasma oxidation revealed the presence of a residual carbon peak, although the amount of carbon has been significantly reduced compared to HF-cleaned Ge surface. It is clear that the residual carbon of HF-cleaned Ge surface even after O₂ plasma oxidation is due to the relatively high pre-existing carbon amount in GeO₂, which is not completely removed during a cyclic HF cleaning. Consequently, NH₄OH-based wet cleaning is essential for the complete removal of residual carbon on Ge surfaces (i.e., below AES detection limit) with O₂ plasma oxidation.

As a result, the combined SE and AES results suggest several crucial aspects on Ge surface preparation. The fast regrowth rate of Ge surface in the air results in the regrown GeO₂ saturated at about 1.5 nm for both cyclic HF/DIW and NH₄OH-based cleaning, but there are meaningful advantages in NH₄OH-based cleaning such as (i) the efficient carbon removal on Ge surfaces and (ii) the complete native GeO₂ lift-off, ensuring Ge surface conditioning even for a short time period during the cleaning process.

In particular, the final O₂ plasma step for the very thin GeO₂ growth (~1 nm for 15 s) completely removed the residual carbon so it provides a possible pathway for a carbon-free interfacial oxide layer preparation before a high-*k* dielectric deposition for Ge MOS-FET fabrication.

Conclusions

We reported the native oxide and carbon-contaminant-minimized Ge surface and interfacial oxide layer preparation with NH₄OH-based cleaning and remote O₂ plasma for high-*k* dielectrics/Ge MOSFET application. The GeO₂ thickness on the Ge surface before and after different cleaning processes was compared by the optically equivalent oxide thickness of GeO₂ as determined by SE measurements. The HF rinsing step in cyclic HF/DIW cleaning was not effective for the removal of native GeO₂, because it cannot form the soluble species by a chemical reaction with GeO₂ in a low pH solution; rather, it is supposed that the DIW rinsing step removed GeO₂. A cyclic cleaning in the sequence of H₂O, H₂O₂, methanol, NH₄OH, and H₂O results in a minimum residual GeO₂ at 3 and 8 Å on Ge(111) and (100) under N₂ purge, respectively. The fast regrowth of GeO₂ on cleaned Ge surfaces in the air revealed 12 Å (111) to 15 Å (100) GeO₂ by 7 min exposure to air regardless of the cleaning methods. However, AES spectra showed much less amount of carbon on the Ge surface with NH₄OH-based cleaning

than HF-based cleaning. The small amount of residual carbon after NH₄OH-based wet cleaning was completely removed by O₂ plasma for very thin (~10 Å) surface oxidation in the RPECVD chamber.

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