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Thickness and composition of ultrathin SiO$_2$ layers on Si

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Ultrathin SiO$_2$ layers are of importance for the semiconductor industry. One of the techniques that can be used to determine the chemical composition and thickness of this type of layers is x-ray photoelectron spectroscopy (XPS). As shown by Seah and Spencer [Surf. Interface Anal. 33, 640 (2002)], it is not trivial to characterize this type of layer by means of XPS in a reliable way. We have investigated a series of ultrathin layers of SiO$_2$ on Si (in the range from 0.3 to 3 nm) using XPS. The samples were also analyzed by means of transmission electron microscopy (TEM), Rutherford backscattering (RBS), and ellipsometry. The thickness of the SiO$_2$ layers ($d$) was determined from the XPS results using three different approaches: the “standard” equation (Seah and Spencer) for $d$, an overlayer-substrate model calculation, and the QUASES–Tougaard [Surf. Interface Anal. 26, 249 (1998), QUASES–Tougaard: Software package for Quantitative Analysis of Surfaces by Electron Spectroscopy, version 4.4 (2000); http://www.quases.com] method. Good agreement was obtained between the results of XPS analyses using the “standard” equation, the overlayer-substrate model calculation, and RBS results. The QUASES–Tougaard results were approximately 62% above the other XPS results. The optical values for the thickness were always slightly higher than the thickness according to XPS or RBS. Using the model calculation, these (relatively small) deviations from the optical results could be explained as being a consequence of surface contaminations with hydrocarbons. For a thickness above 2.5 nm, the TEM results were in good agreement with the results obtained from the other techniques (apart from QUASES–Tougaard). Below 2.5 nm, significant deviations were found between RBS, XPS, and optical data on the one hand and TEM results on the other hand; the deviations became larger as the thickness of the SiO$_2$ decreased. This effect may be related to interface states of oxygen, which have been investigated [D. A. Muller, T. Sorsch, S. Moccio, F. H. Baumann, K. Evans-Lutterodt, and G. Timp, Nature (London) 399, 758 (1999); D. A. Muller and J. B. Neaton, Structure and Energetics of the Interface Between Si and Amorphous SiO$_2$ in Fundamental Aspects of Silicon Oxidation, edited by Y. J. Chabal (Springer, Berlin, 2001), pp. 219–246.] by means of high-resolution electron energy loss spectroscopy measurements of the O K edge in ultrathin gate oxides of SiO$_2$. © 2004 American Vacuum Society. [DOI: 10.1116/1.1701864]

I. INTRODUCTION

The layer system SiO$_2$/Si has been the subject of investigation for many years.$^{1–3}$ Photoelectron spectroscopy (XPS) is one of the techniques that have been used frequently to determine the thickness and composition of thin layers of SiO$_2$ on Si. In a recent set$^{4,5}$ of papers, the precise quantification of XPS analyses on thin layers of SiO$_2$ has been investigated in a systematic way. Much attention is paid in these papers to determine the way in which the measurements and the analysis of the results have to be carried out in order to obtain reliable results.

A comparison of various analysis techniques to determine the thickness and compositions of thin layers of SiO$_2$ on Si is given in Semak et al.$^6$ In this article, only layers with an optical thickness above 2 nm were investigated. For present innovations in the semiconductor industry, SiO$_2$ layers on Si in the range between 0.5 and 2 nm are more interesting. This motivated us to start a comparison of SiO$_2$/Si samples within this range, using four analysis techniques: ellipsometry, XPS, Rutherford backscattering (RBS), and transmission electron microscopy (TEM). The purpose of the work is to determine the optimal way to apply these techniques, both experimentally and with regard to the analysis of the results.

II. EXPERIMENT

The samples were based upon pure Si (100). After cleaning, a thin oxide film was grown using in situ steam generation oxidation. The investigated samples are given in Table I. The thickness of the SiO$_2$ layer ranges from 0.14 to 3.2 nm.
according to optical measurements. For reference purposes, measurements were also carried out on a “thick” SiO\textsubscript{2} layer on Si (120 nm, thermally grown).

All XPS analyses in this article were conducted in a Quantum 2000 of PHI. The system is operating with a monochromatic Al\textsubscript{K\alpha} source. Two series of XPS measurements were done. The first series of measurements was performed with a spot size of 100 \(\mu\)m, a pass energy of 11.75 eV, and a step size of 0.025 eV; the entrance angle of the analyzer was \(\pm 20^\circ\) unless stated otherwise. A measuring angle \(\Theta\) of 34\(^\circ\) was used (\(\Theta\) denotes the angle between the surface normal and the analyzer axis) and the samples were mounted such that the analyzer azimuth angle was 22.5\(\pm 2^\circ\) with respect to the [011] direction. By doing so, the influence of the crystal structure of the substrate upon the results is minimized.\(^4\)

The second series of measurements was performed such that the results could be analyzed with QUASES–Tougaard (QT).\(^7\) Extended O 1s peaks (binding energy range of 430–700 eV) have been measured with a spot size of 1200\(\times\)500 \(\mu\)m\(^2\) (high power mode), a pass energy of 117 eV, a step size of 0.25 eV, and the analyzer entrance angle set at \(\pm 20^\circ\). Three values of the measuring angle were used: \(\Theta = 45^\circ, 34^\circ, \) and \(0^\circ\).

RBS spectra were recorded with a 2 MeV He\textsuperscript{+}-ion beam, generated in a single-ended Van de Graaff accelerator. Channeling in the (100) direction was used in order to suppress the Si signal under the oxygen peak. The scattering angle used was 86.5\(^\circ\) and the channel width was 2.165 keV. Subtraction of the silicon signal of the Si\textsubscript{O\textsubscript{2}} (assuming that it is stoichiometric 1:2) from the total silicon signal provided the contribution of the Si surface peak to the total Si peak. The Si surface peak contribution was used to normalize the integrated charge of the He\textsuperscript{+} ions, assuming that the surface peak for elementary Si (100) corresponds to 15.5 \(\times 10^{15}\) Si atoms/cm\(^2\).

For the TEM analyses, perpendicular cross sections have been made by means of mechanical (tripod) polishing down to electron transparency. In order to protect the surface of the TEM sample during the preparation, a capping layer is needed. A crystalline capping layer of aluminum was used. Low-temperature vapor deposition of Al did not alter the thickness or the composition of the Si\textsubscript{O\textsubscript{2}} layer, as was checked by means of XPS. Aluminum is preferred as a capping layer for several reasons. The interface of polycrystalline aluminum with amorphous Si\textsubscript{O\textsubscript{2}} can be imaged very sharply. Glue and other amorphous materials often have a poorly distinguishable interface with oxide layers. Furthermore, aluminum has approximately the same polishing behavior as Si\textsubscript{O\textsubscript{2}}, and is thus preferred over metals such as W or Pt that have a relatively low polishing rate. Below a W or Pt capping layer, the sample thickness at the Si\textsubscript{O\textsubscript{2}} layer will remain larger than the sample thickness at the underlying Si substrate; this makes accurate layer thickness measurements difficult.

The TEM analyses have been carried out in a FEI TECNAI F30 ST, operated at 300 kV. Energy-filtered TEM was applied and zero loss imaging was used as it improves the resolution by removing most of the chromatic aberrations.

### III. RESULTS

First, we consider the results of the XPS measurements. A typical Si 2\(p\) spectrum is shown in Fig. 1(a). To determine the peak areas corresponding to elementary Si and the (sub-)oxides of Si, the Si 2\(p\) peaks were decomposed as follows (using the software package CasaXPS\(^8\)). A Shirley background was subtracted. The best fit for elementary Si [Fig. 1(b)], as determined from the measurement on sample A (0.14 nm Si\textsubscript{O\textsubscript{2}}), was obtained with two GL(67)/T(1.45) curves (mixed Gauss–Lorentz with some tailing), a doublet distance of 0.61 eV and a ratio of 2:1. The decomposition into (sub-)oxides was based upon the findings of Lu and Graham:\(^9\) doublet of GL(20) curves with a doublet distance of 0.61 eV, equal widths and at 0.97, 1.80, 2.60, and 3.9\(\pm 0.2\) eV distance from e-Si 2\(p\)\(_3\).

The first approach to determine the thickness \(d\) of the Si\textsubscript{O\textsubscript{2}} layer was the use of the standard equation\(^3\)

\[
d = L_{\text{SiO}_2}(E_{\text{Si}})\cos(\Theta)\ln(1 + R_{\text{expt}}/R_0),
\]

with \(L_{\text{SiO}_2}(E_{\text{Si}})\) the attenuation length for Si 2\(p\) electrons in Si\textsubscript{O\textsubscript{2}}, \(R_{\text{expt}}\) the experimental ratio \(I_{\text{SiO}_2}/I_{e-Si}\) and \(R_0 = I_{\text{SiO}_2}^{\text{sub}}/I_{e-Si}\). The parameter \(I_{\text{SiO}_2}^{\text{sub}}\) denotes the intensity of the Si 2\(p\) line of “infinitely” thick Si\textsubscript{O\textsubscript{2}}, while \(I_{e-Si}\) corresponds to the intensity of the Si 2\(p\) line of pure elementary silicon. We adopted \(L_{\text{SiO}_2}(E_{\text{Si}}) = 3.448\) nm (see Seah and Spencer\(^d\)); the measurements have been carried out for \(\Theta = 34^\circ\).

The value of \(R_0\) is expected to depend upon the entrance angle of the analyzer. The reason is that both \(I_{\text{SiO}_2}^{\text{sub}}\) and \(I_{e-Si}\) depends upon the entrance angle; due to the crystal effects in e-Si, the dependence of these quantities upon the entrance angle is not identical [see Fig. 5(b) in Ref. 4]. The experimental value of \(R_0\) in our equipment has been determined by measuring a sample of pure silicon and a sample of infinitely thick Si\textsubscript{O\textsubscript{2}}. In the spectrum of the Si 2\(p\) peak of sample A, no contribution of Si\textsubscript{O\textsubscript{2}} was detectable [see Fig. 1(b)]. Therefore, this sample was considered to be pure silicon. The experimental value of \(I_{\text{SiO}_2}^{\text{sub}}\) was determined using sample L.

### TABLE I. Investigated samples and thickness according to optical measurements (nine-point Woollam). The variation in the thickness across the nine measurement positions is also given.

<table>
<thead>
<tr>
<th>Wafer label</th>
<th>Optical thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.137 (\pm) 0.010</td>
</tr>
<tr>
<td>B</td>
<td>0.498 (\pm) 0.010</td>
</tr>
<tr>
<td>C</td>
<td>1.001 (\pm) 0.015</td>
</tr>
<tr>
<td>D</td>
<td>1.007 (\pm) 0.010</td>
</tr>
<tr>
<td>E</td>
<td>1.065 (\pm) 0.010</td>
</tr>
<tr>
<td>F</td>
<td>1.408 (\pm) 0.035</td>
</tr>
<tr>
<td>G</td>
<td>1.421 (\pm) 0.029</td>
</tr>
<tr>
<td>H</td>
<td>1.998 (\pm) 0.030</td>
</tr>
<tr>
<td>I</td>
<td>2.203 (\pm) 0.073</td>
</tr>
<tr>
<td>J</td>
<td>2.510 (\pm) 0.030</td>
</tr>
<tr>
<td>K</td>
<td>3.200 (\pm) 0.020</td>
</tr>
<tr>
<td>L</td>
<td>120</td>
</tr>
</tbody>
</table>
The experimental values for \( I_{\text{SiO}_2}^s \) and \( I_{\text{e-Si}}^s \) were corrected for the attenuation of the signals due to a small amount of contamination with hydrocarbons. Combining the experimental values provides for \( R_0 \) in the Quantum 2000 at standard conditions (an entrance angle of \( \pm 20^\circ \)), as follows:

\[
R_0 = 0.81 \pm 0.02.
\]

The uncertainty in the value is due to the background subtraction. Our present value nicely fits into the range of values for \( R_0 \) that is found in the literature: values between 0.6 and 0.9 have been reported. We notice that the experimental value for \( R_0 \) obtained in our equipment when a small entrance angle is used (entrance angle \( \pm 4^\circ \)) is 0.91 \( \pm 0.02 \). Clearly, \( R_0 \) is not a material quantity, but rather depends upon the details of the equipment. This is probably one of the reasons for the large variety of values for \( R_0 \) found in the literature.

Table II. Thickness in nanometers of the SiO\(_2\) layers \( d \) according to the analysis of the XPS spectra with the standard Eq. (1), with QT, and with the model calculation. The thickness of the organic contamination and the total thickness (organic + SiO\(_2\)) is also given. In the right most column, the concentration ratio \([c_O/c_{Si}]\) in the SiO\(_2\) layers, as determined in the model calculation, is shown.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Optical thickness ( d ) (nm)</th>
<th>Standard Eq. (1) ( d ) (nm)</th>
<th>QT</th>
<th>Model calculation ( d ) (nm)</th>
<th>( d_{\text{org}} ) (nm)</th>
<th>( d_{\text{total}} ) (nm)</th>
<th>([c_O/c_{Si}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.14</td>
<td>0.0</td>
<td>0.11</td>
<td>0.04</td>
<td>0.28</td>
<td>0.32</td>
<td>⋯</td>
</tr>
<tr>
<td>B</td>
<td>0.50</td>
<td>0.29</td>
<td>0.73</td>
<td>0.36</td>
<td>0.16</td>
<td>0.53</td>
<td>⋯</td>
</tr>
<tr>
<td>C</td>
<td>1.07</td>
<td>0.56</td>
<td>1.20</td>
<td>0.66</td>
<td>0.19</td>
<td>0.85</td>
<td>2.8</td>
</tr>
<tr>
<td>E</td>
<td>1.00</td>
<td>0.72</td>
<td>1.14</td>
<td>0.78</td>
<td>0.15</td>
<td>0.93</td>
<td>2.6</td>
</tr>
<tr>
<td>D</td>
<td>1.01</td>
<td>0.77</td>
<td>1.35</td>
<td>0.83</td>
<td>0.18</td>
<td>1.01</td>
<td>2.5</td>
</tr>
<tr>
<td>G</td>
<td>1.42</td>
<td>1.19</td>
<td>1.82</td>
<td>1.21</td>
<td>0.18</td>
<td>1.39</td>
<td>2.3</td>
</tr>
<tr>
<td>F</td>
<td>1.41</td>
<td>1.21</td>
<td>1.92</td>
<td>1.24</td>
<td>0.14</td>
<td>1.38</td>
<td>2.4</td>
</tr>
<tr>
<td>H</td>
<td>2.00</td>
<td>1.86</td>
<td>2.76</td>
<td>1.85</td>
<td>0.14</td>
<td>1.99</td>
<td>2.2</td>
</tr>
<tr>
<td>I</td>
<td>2.20</td>
<td>1.94</td>
<td>3.10</td>
<td>1.92</td>
<td>0.09</td>
<td>2.02</td>
<td>2.2</td>
</tr>
<tr>
<td>J</td>
<td>2.51</td>
<td>2.38</td>
<td>3.39</td>
<td>2.35</td>
<td>0.14</td>
<td>2.49</td>
<td>2.2</td>
</tr>
<tr>
<td>K</td>
<td>3.20</td>
<td>3.09</td>
<td>4.71</td>
<td>3.03</td>
<td>0.11</td>
<td>3.14</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Using the standard Eq. (1), we have calculated values for \( d \) of the series of samples. The contribution of sub-oxides was taken into account by adding a weighed average, given by

\[
R_{\text{exp}} = \frac{I_{\text{SiO}_2} + 0.75I_{\text{Si}_2\text{O}_3} + 0.5I_{\text{SiO}} + 0.25I_{\text{Si}_2\text{O}}} {I_{\text{e-Si}}}. \quad (3)
\]

The results are given in Table II.

The XPS results were also analyzed using a model calculation, in which the samples are assumed to consist of a substrate of pure Si, a SiO\(_2\) layer with thickness \( d \), and an organic contamination containing only the elements C and H, with thickness \( d_{\text{org}} \). The principle of this method is presented only briefly; for details and other examples of applications, we refer to Ref. 10. Within the model, simple exponential attenuation of the XPS signals is assumed. The intensity of the C 1s signal is expressed in terms of the thickness \( d_{\text{org}} \), the atomic density of the organic contamination, the XPS cross section or the sensitivity factor of the C 1s line, the attenuation length \( L_{\text{C}}(\text{C 1s}) \) for C 1s electrons in the organic layer, and a number of instrumental parameters, such as the x-ray flux, the transmission function, the detector efficiency for a given kinetic energy \( E_\text{kin} \), and the correction factor for the asymmetry effect. Similar expressions can be derived for the intensity of the O 1s signal, the intensity of the Si 2p signal originating in the SiO\(_2\) layer, and the Si 2p signal coming from the e-Si substrate. For the attenuation in the organic contamination, we adopted values for the IMFP given by Cumpson. Elastic scattering in the SiO\(_2\) layer and in the substrate was taken into account by using values for the attenuation length, taken from Ref. 4. This provides, all together, four equations with four unknown parameters: the thickness of the organic contamination \( d_{\text{org}} \), the thickness of the SiO\(_2\) layer \( d \), the concentration ratio \([c_O/c_{Si}]\) in the SiO\(_2\) layer, and the x-ray flux. Reversal of these equations provides expressions for \( d \), \( d_{\text{org}} \), and \([c_O/c_{Si}]\) in terms of the

Fig. 1. (a) Typical example of a Si 2p peak. The spin–orbit splitting in the right-hand peak, corresponding to elementary Si, is clearly visible; the FWHM of the components of this peak is 0.31 eV. Sub-oxides are barely present between the peaks of e-Si and SiO\(_2\). (b) Si 2p peak measured for the sample A \( (d_{\text{optical}} = 0.14 \text{ nm}) \); no SiO\(_2\) contribution is visible.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Optical thickness ( d ) (nm)</th>
<th>Standard Eq. (1) ( d ) (nm)</th>
<th>QT</th>
<th>Model calculation ( d ) (nm)</th>
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<td>3.14</td>
<td>2.1</td>
</tr>
</tbody>
</table>
measured intensities. This model analysis has been applied to the present set of XPS analyses, all for $\Phi = 34^\circ$ and azimuth $= 22.5^\circ$. The sensitivity factor for the Si 2$p$ peak was chosen such that for sample L (not-contaminated, infinitely thick SiO$_2$), the ratio $c_O / c_{Si}$ = 2.0 was obtained. The intensity of the Si 2$p$ peak of elementary signal depends—due to crystal effects—upon the measuring geometry ($\Theta$ and azimuth), and is also reduced by intrinsic plasmon losses. To take these effects into account, the measured signal of the Si substrate was divided by $R_0^{th} / R_0^{exp} = 0.65$ with $R_0^{th} = 0.529$ (see Ref. 4) and $R_0^{exp} = 0.81$ [Eq. (2)]. The results of the analysis are given in Table II and in Fig. 2(a).

The thickness of SiO$_2$ layers on Si can also be determined by means of an analysis of the e-loss phenomena of the O 1$s$ peak, using the method called QUASES—Tougaard. An interesting property of this method is that it is independent of crystal effects, because the amount of oxygen is being determined. Measurements of the extended O 1$s$ peaks have been carried out for $\Theta = 0^\circ$, $34^\circ$, and $45^\circ$. Extended SiO$_2$ peaks of sample L were used as a reference to "scale" the spectra; for the attenuation length of O 1$s$ electrons in SiO$_2$, we adopted the value $L_{SiO_2}(E_{O 1s}) = 2.551$ nm. The results of the QT analysis obtained at different angles are in very good mutual agreement, the differences being <0.2 nm [see Fig. 2(b)]. Average values of the thickness of the SiO$_2$ layers are given in Table II.

Next, we consider the results of the RBS measurements. The simulation program RUMP was used to model the spectra and to determine the amount of oxygen at the surface. During RBS analysis, some carbon deposition occurs at the surface of the samples due to cracking of hydrocarbons in the
corrected for the influence of the "buried" oxygen (1.0 × 10^{15} \text{O atoms/cm}^2) before and after the RBS analysis. The raw RBS data were confirmed by XPS analysis of a number of samples both before and after the RBS analysis. The raw RBS data were corrected for the influence of the "buried" oxygen (1.0 × 10^{15} \text{atoms/cm}^2 was subtracted). The thickness of the SiO_2 layers was obtained using a density of 2.27 g/cm^3, corresponding to an atomic density of 6.83 × 10^{22} \text{atoms/cm}^3. The results of the layer thickness measurements with RBS are shown in Table III.

Finally, we consider the TEM analyses. A typical TEM photograph is shown in Fig. 3. For each sample, at least three high-resolution images were stored that were taken from areas at least a few micrometers apart. The magnification was calibrated on every image studied; the calibration factor that was determined for each image appeared to be nearly constant for all images studied, illustrating the intrinsic reproducibility of the instrument. The thickness was determined using a box, drawn with its edges parallel and perpendicular to the surface normal. Within this box, two parallel lines are drawn that are manually aligned to the SiO_2/Si and SiO_2/Al interfaces. The thickness determined for the various samples determined in this way is given in Table III. Changing the site of the interface (i.e., on a row of atoms or between two rows of atoms) results in a 0.10 to 0.15 nm shift in the resulting thickness values. This is the main source for errors. Consequently, we estimate the absolute accuracy of the TEM thickness values in Table III to be ±0.1 nm.

### IV. DISCUSSION

First, we consider the results in Table II. The thickness of the SiO_2 layers according to the model calculation is always less than the optical thickness, the difference being, on average, 0.2±0.1 nm. It is interesting to see that the "total thickness" (\(d + d_{\text{org}}\)) is in good agreement with the optical thickness. Apparently, the optical measurements determine the thickness of the combination of SiO_2 layer and the organic contamination. The thickness obtained with the standard Eq. (1) is in good agreement with the results of the model analysis: the difference is, on average, 0.02 nm, the largest difference being 0.10 nm.

The concentration ratio \([c_0/c_{\text{Si}}]\) in the layers is within the experimental accuracy close to 2.0 for \(d>2.5\) nm, but increases when the thickness decreases. For thin SiO_2 layers (\(\approx 1\) nm), the precision is typically ±0.2 as a consequence of the statistical errors in the curve fit results; the precision is better for thicker SiO_2 layers. The deviating values of \([c_0/c_{\text{Si}}]\) are not due to an oxygen component in the organic contamination, as the C 1s peak in all cases corresponded to a aliphatic hydrocarbon without a detectable fraction of C–O bonds, and because the thickness of the organic contamination was always less than 0.2 nm. This point is discussed further in Ref. 10.

The results of the QT approach were, in all cases, above the results according to the standard equation, the model calculations, and the optical thickness; the difference between the QT results and the standard equation is, on average, 62% for \(d_{\text{opt}}\geq 1\) nm.

The RBS results were, after a correction for the adhesion of oxygen during the RBS measurements, in good agreement with the results of the standard equation and the model calculation, the difference being, on average, less than 0.1 nm (see Table III). We also notice that, in previous analyses, differences have been found between the results according to QT and RBS results of, on average, 45% (see Ref. 6, Table 5). Apparently, the modeling that is being used in the software package QT is not completely accurate for SiO_2.
The SiO$_2$/Si interface is different from that of bulk SiO$_2$, indicating that the chemical environment of the oxygen at the interface is different from bulk SiO$_2$. Further, the concentration ratio $c_{O}/c_{Si}$ in these layers is larger than 2.0 and increases when the SiO$_2$ thickness decreases. The effects may be related to penetration of interfacial oxygen into the silicon, as observed using EELS in ultrathin gate oxides of SiO$_2$ and visible as protrusions of SiO$_2$ into silicon in high-resolution TEM images.

V. CONCLUSIONS

We have shown that the determination of the thickness of ultrathin SiO$_2$ layers using RBS, using the standard equation for XPS, or applying a model analysis of XPS results provides consistent results. Model analysis of XPS results demonstrated in a quantitative way that deviations from the optical results are a consequence of surface contaminations of the samples with hydrocarbons. QUASES–Tougaard analysis of extended O $1s$ peaks has also been applied. The results were found to be independent of crystal effects, as expected. Yet, the thickness of the SiO$_2$ layers was approximately 62% higher than the thickness determined with the other methods.

TEM results are in agreement for thickness exceeding 2.5 nm, but in samples with SiO$_2$ layers $<2.5$ nm, the TEM thickness is larger than the RBS or XPS thickness. Together with this effect, we have observed that the concentration ratio $c_{O}/c_{Si}$ in these layers is larger than 2.0 and increases when the SiO$_2$ thickness decreases. The effects may be related to penetration of interfacial oxygen into silicon, as observed using EELS in ultrathin gate oxides of SiO$_2$ and visible as protrusions of SiO$_2$ into silicon in high-resolution TEM images.

7. Software package for the analysis of XPS results, CasaXPS version 2.2.32, see http://www.casaxps.com
13 M. Seah, J. Vac. Sci. Technol. A, these proceedings.