



Study of compositional change in the interfacial regions between lead strontium titanate/SiO₂ and lead zirconate titanate/SiO₂ by Auger emission spectroscopy

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ABSTRACT

Auger spectroscopy was used to study the compositional change in the interfacial region between ferroelectric thin films, namely lead strontium titanate (PST) and lead zirconate titanate (PZT), and commercially available Si substrates with a 200 nm thick thermal oxide layer. Both PST and PZT thin films were prepared via a sol–gel spin coating method. The thin films from both materials were annealed under the same conditions (temperature and time). It was found that strontium stops the lead diffusion into SiO₂ by forming SrSiO₃/Sr₂SiO₄ and SrO, maintaining a well defined SiO₂ region, while PbSiO₃ is formed in the PZT/SiO₂ system. These results are important for a general understanding of interdiffusions in material interfaces in particular for the realization of future high-dielectric-constant (high-k) oxide layers and for the next generation of advanced electronic devices.

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1. Introduction

Surface diffusion not only plays an important role in atomic processes on the surface of solids but also is one major issue one meets when following the 2007th international technology roadmap for semiconductors (ITRS) [1]. It is stated that the thickness of SiO₂ gate oxides has to be less than 2 nm in the near-term technology requirements. Despite the problem that the gate leakage current will approach the ITRS-defined limit of 1 A/cm² with an applied gate voltage of 3 V when the gate oxide thickness is less than 2 nm [2], this aim also demands advanced requirements on diffusion barriers. Atomic diffusion between material interfaces is one of the main reasons for failures within electronic chip devices like memories and therefore an important subject when talking about reliability of Micro-Electro-Mechanical Systems.

When it comes to the integration of ferroelectrics the problem becomes worse because the most used ferroelectric perovskite thin film today is lead zirconate titanate (PZT) and Pb is notorious to diffuse deep into the silicon substrate [3,4], even through a TiO₂-diffusion barrier and Ti/Pt bottom electrode. SrTiO₃, a centrosymmetric paraelectric material with a perovskite structure, was used as a buffer layer and template for the integration of PZT [5–7] or as a dielectric layer itself on top of Si to replace SiO₂ as a common gate oxide [8–12]. It was shown that SrO grows first epitaxially even on H-terminated Si surfaces with a sharp interface and thus provides an ionic template for the subsequent growths of perovskite SrTiO₃

[8,10,12]. We showed earlier that a functional lead strontium titanate (PST) layer (thickness > 300 nm) grows directly on top of SiO₂ [13] and that a very thin PST film (thickness < 50 nm) can serve as a barrier layer and template for the growths of PZT on top of SiO₂ [14]. However, a direct comparison between the interfacial regions of PST/SiO₂ and PZT/SiO₂ is still outstanding. The purpose of this paper is to study these interfaces using Auger emission spectroscopy and to develop a more profound understanding of Pb diffusion and the role of Sr as a barrier layer.

2. Experimental procedure

The preparation of the starting solutions of Pb(Zr₃₀Ti₇₀)O₃ and (Pb₄₀Sr₆₀)TiO₃ was described earlier [13–16].

Both solutions were spin coated at 3000 rpm for 30 s on Si substrates with a 200 nm thick thermal SiO₂ layer. The films were dried and pyrolysed on a hotplate at 350 °C for 10 min and subsequently annealed at 650 °C for 15 min on a second hotplate. The resulting thicknesses of the films were ~50 nm. The annealing temperature of 650 °C is the crystallisation temperature of PST and is higher than for PZT, which has a crystallisation temperature at < 600 °C. According to Fick's and Arrhenius laws, diffusion is time and temperature dependent, therefore these variables should be held constant to compare the interdiffusion character in both material systems. The chosen temperature and time in this study were those for the crystallisation of PST, viz. 650 °C for 15 min.

A VG ESCALab Mk 2 Auger Emission Spectrometer (AES) was used to analyse the compositional change in the interfacial region. The Ar etching conditions depend on the material and are therefore mentioned separately.

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3. The interface between PST and SiO₂/Si

Fig. 1 shows the Auger spectra that reflects compositional changes in the interfacial region between PST and SiO₂/Si. After each measurement, the sample was etched for 100 s using the ion-sputtering unit with an ion beam output of 2 kV and 0.75 μ A (1.5 mW).

The dark blue trace, which is best seen at the top of the titanium peak at 462 eV, indicates the first measurement without an etching step. At this point only the lead peaks at 137 and 144 eV, the strontium peaks at 135 and 272 eV and the oxygen peak at 535 eV are traceable furthermore. The intensities of these peaks decrease with increasing etching time. After the fifth etching step (the brownish red trace) the Si—O peaks at 105 eV and 536 eV begin to appear. That marks the beginning of the interfacial layer. The positions of these two peaks shift to higher energies and the intensities increase with increasing etching time while the titanium, lead, strontium and oxygen peaks of the PST layer decrease. Finally, after the 14th etching step (the orange trace) the PST peaks vanish and the spectra only show the Si—O peaks, indicating the end of the interfacial layer.

The SiO₂ layer is comparably thick. Nearly forty etching steps are needed to reach the main Si substrate as depicted in Fig. 2. After that only the main Si—Si bond at \sim 100 eV is traceable.

Fig. 3 shows the corresponding depth profile. It should be noted that the unit of the abscissa is etch cycle number. Different elements and/or compounds, normally have different etch rates; therefore it is impossible to make a clear statement of the real thickness without knowing the specific etch rates. However, we know that the SiO₂ layer is 200 nm and the PST layer is \sim 50 nm thick, leading to an etch rate of approximately 0.029 nm/(mW s) and 0.033 nm/(mW s) for SiO₂ and PST respectively.

The diffusion area of the PST/SiO₂ interface is relatively small. After ten etching steps the diffusion of titanium and lead stops. Only strontium diffuses further on until it is not traceable anymore after the 14th etching step (inset in Fig. 3). The silicon diffuses stronger into the PST layer due to the large Si-source. The broad SiO₂ area is the dominant feature in this profile and the SiO₂/Si interface is clearly distinguishable.

4. The interface between PZT and SiO₂/Si

As a comparison a single layer of PZT was deposited directly onto SiO₂/Si. It is well known that Pb in PZT strongly diffuses into the substrate [3], therefore 10% Pb excess is normally given to the solution

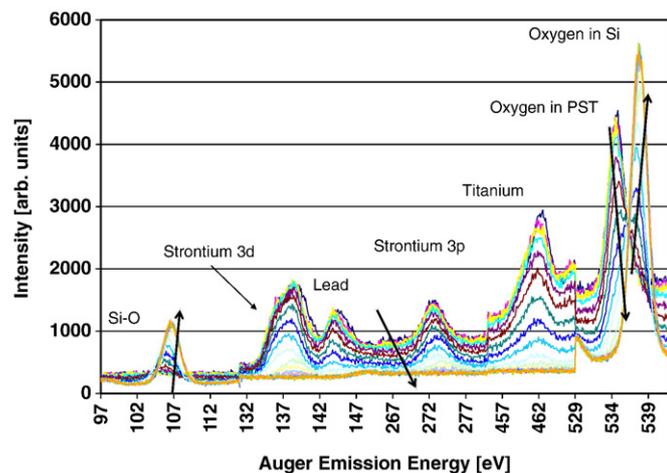


Fig. 1. Auger spectra of one layer PST and its interface to the SiO₂. Between each measurement the sample was etched for 100 s using the ion-sputtering unit with an ion current of 2 kV and 0.75 μ A. The arrows are indicating the decrease and increase of the peaks with increasing etching time.

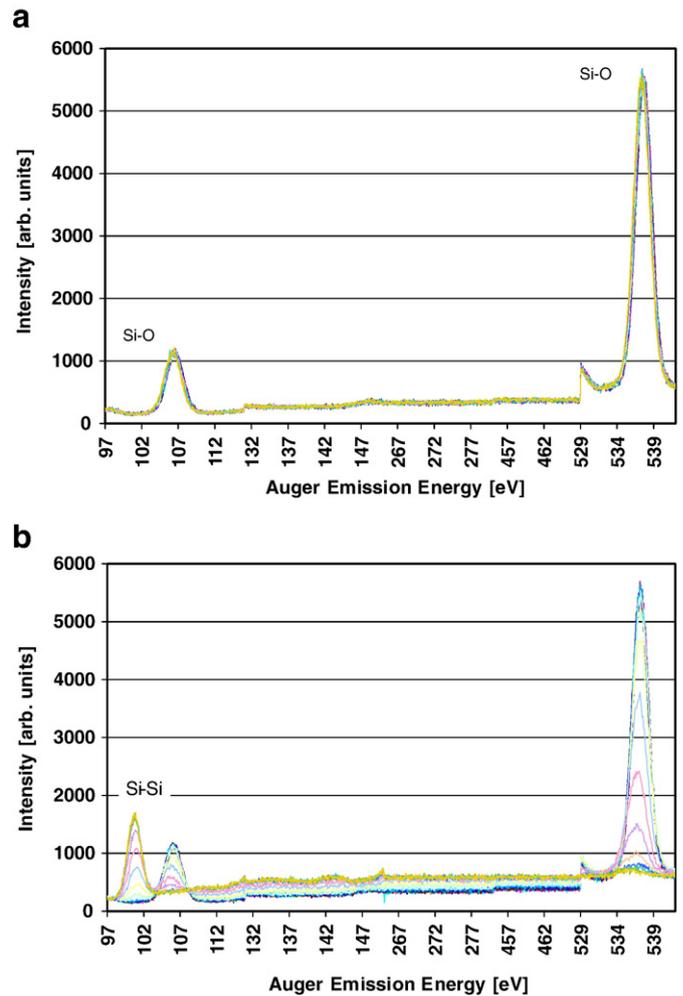


Fig. 2. Auger spectra of the SiO₂ layer (a) and its interface to the Si main substrate (b).

to compensate the Pb loss during the heat treatment of the thin film. The depth profile of this sample is shown in Fig. 4.

The etch rates in this system are considerably lower compared to the PST sample. The etching parameters were adjusted to 100 s, 2 kV and 0.9 μ A (1.8 mW) for each etch step. Although that means a higher ion beam output more etch cycles were needed to reach a comparable depth. Assuming the same layer thicknesses as PST this leads to an etch rate of 0.009 nm/(mW·s) for PZT and 0.012 nm/(mW s) for the

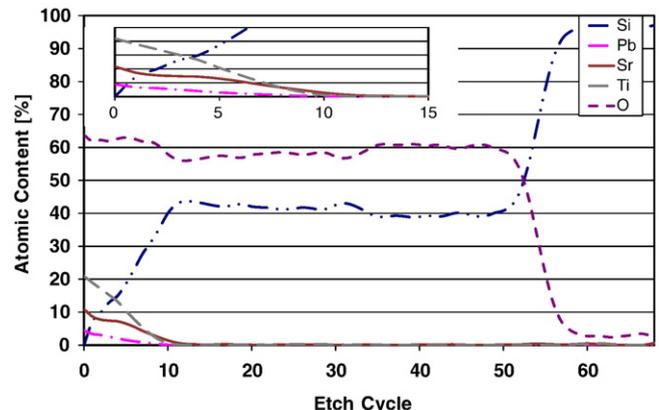


Fig. 3. Depth profile of one layer PST on SiO₂/Si – a close up towards the first 15 etch cycles is presented in the inset. The interface regions are clearly visible.

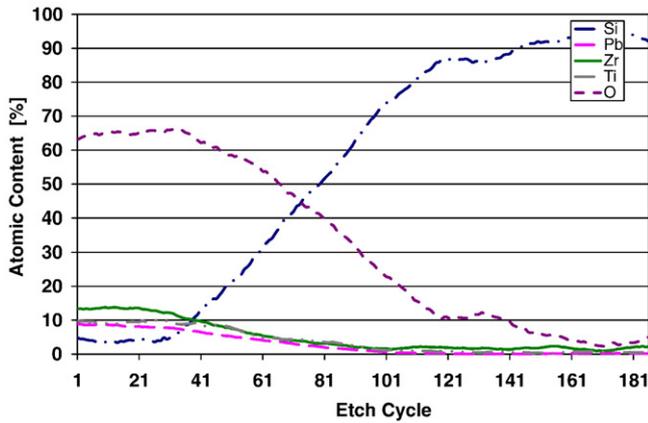


Fig. 4. Depth profile of one layer PZT on SiO_2/Si . The interface regions are blurred.

SiO_2 interdiffusion layer. The lower etch rate of the latter layer was explained by a formation of some lead silicate (PbSiO_3), which is harder to etch than SiO_2 using the ion-sputtering unit.

Fig. 5 shows the details of the Auger analysis for Pb, O and Si traces. The first two traces after etch cycles 15 and 32 (top blue and magenta in the Pb and O spectra) show that Pb and O are present in a similar way like in Fig. 1, viz. a Pb double peak at 140 and 146 eV and an O_{PZT} peak at 536 eV. The Si is not really traceable in this region. After etch cycle 54 (thick black curve) a second O peak begins to appear at 539 eV and the Si shows two weak peaks at 102 and 107 eV. At the same time the Pb double peak moves slightly to lower energies and begins to “wobble” around with increasing depth until it vanishes after the 94th etch cycle (thick blue curve). After the Pb is not traceable anymore O shows only one peak at higher energy and the Si only one at lower energy. The oxygen peak is decreasing and the Si is increasing while shifting again to higher energies with further etch cycles.

These results indicate that the region between the 54th and the 94th etch cycles can be regarded as the main diffusion area of these three elements. The appearance of the second O peak and the Si double peak, together with the shift of the Pb peak to lower energies indicates further on a bonding mechanism between Pb, O and Si. The rocking motion of the Pb double peak system and the disappearance of the Si peak at 107 eV may be explained by a variable stoichiometric composition of these three. However, the formation of some lead silicate $\text{Pb}_x\text{O}_{(1-x)}\text{SiO}_2$ in this region is the most likely process to explain this behavior.

5. Discussion

Figs. 4 and 3 show that the Pb diffusion into Si from the PZT thin film is significantly higher than from the PST thin film. Sr diffuses slightly more into the SiO_2 layer than Ti in Fig. 3, followed by Pb, which diffusion stops almost immediately, whereas in Fig. 4 Pb, Zr and Ti are diffusing at the same extent. The shift of the Sr peaks in Fig. 1 after etch steps 11, 12, and 13 to higher energies indicates that the Sr changes its bonding partner towards SiO_2 . This demonstrates that Sr grows first on top of the SiO_2 layer and makes it chemically inert to further oxidation or possible reactions with other elements, thus preventing interdiffusion in both ways.

While Si is a covalently bonded material, PST is an ionic crystal that is unable to form covalent bonds. An electronically saturated Si–PST stack must thus exhibit an interfacial layer which provides a covalent bonding environment towards the silicon substrate and in addition an ionic template compatible with that of PST or SrTiO_3 . SrO covalently saturates all Si dangling bonds by forming SrSiO_3 and/or Sr_2SiO_4 . This provides the necessary ionic template towards the perovskite SrO-terminated SrTiO_3 , on which PST can grow further on.

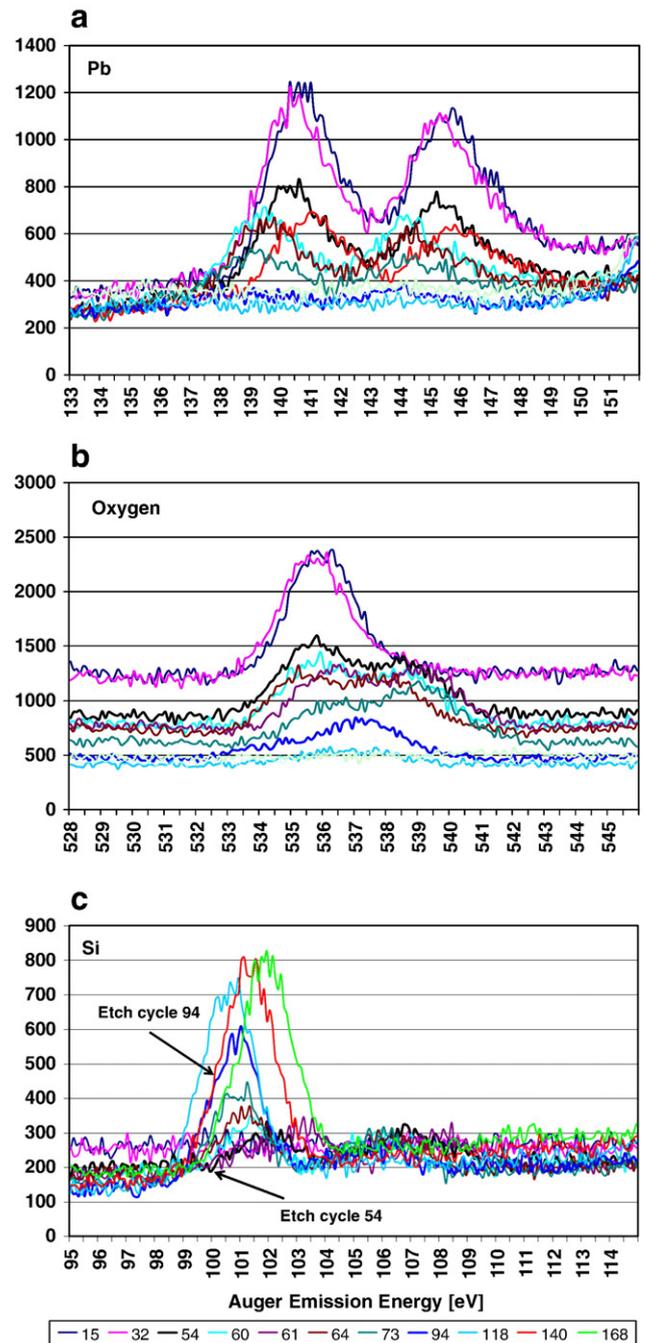


Fig. 5. Details of the Auger analysis for Pb, oxygen and Si in the interfacial region of PZT on SiO_2/Si . The main interdiffusion area is located between the etch cycles 54 and 94 (thick traces). The legend box shows the relevant etching cycles.

Remarkable is furthermore the missing of a clear distinct SiO_2 region in Fig. 4. It is assumed that the formation of some lead silicate in this region may be a possible explanation. This would also explain the lower etching rate in the PZT system.

6. Conclusions

All these results show that the SrTiO_3 is an effective diffusion barrier on top of SiO_2/Si . It inhibits the interdiffusion of all components of PST into the SiO_2/Si and vice versa. These offers the possibility to realise a thin interfacial layer for future integrations of ferroelectrics in all kinds of devices like non-destructive read out ferroelectric Random-Access Memories [5,9,11,12] or simply as a buffer layer for the realization

of ferroelectrics onto Si without the common Ti/Pt bottom electrode [5–7,13].

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