High-Resolution Rutherford Backscattering Analysis of SiO$_2$/Si Interface Strain

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ABSTRACT

The strain found in the SiO$_2$/Si interface was quantified with the use of a channelling technique in high-resolution Rutherford backscattering spectrometry. Measurements were taken using a 90° sector magnetic spectrometer in conjunction with the Centre for Ion Beam Applications (CIBA) Singletron accelerator. The Singletron accelerator provides a stable ion beam with favourable phase space characteristics. The magnetic spectrometer consists of a UHV scattering chamber equipped with a computer-controlled five axis goniometer for sample orientation. Channeled spectra were taken at a scattering angle of 65° with beam energy of 500 keV and energy resolution of 1 keV FWHM. The sample thickness was found to be 45 angstroms. The silicon lattice at the SiO$_2$/Si interface was found to be compressed vertically with a strain of 1.8%.

INTRODUCTION

Silicon dioxide (SiO$_2$) is widely known as a good electrical insulator and can easily be grown from silicon by thermal oxidation. With the development of metal-oxide semiconductor field-effect transistors (MOSFETs), silicon dioxide saw extensive use in the microelectronics industry. Recent efforts to scale down MOSFETs encountered several problems. One of which is the quantum mechanical effect of electron tunneling through the thin silicon dioxide layer known as gate oxide leakage. Suggestions have been made to replace silicon dioxide with high-k dielectric materials in order to maintain a high capacitance while increasing the layer thickness. Due to integration issues however, there often is an intentional or unintentional formation of an ultrathin silicon dioxide film between the high-k dielectric and the silicon substrate (de Almeida, 2003). Furthermore, although several alternative materials are under investigation and are expected to replace it (de Almeida, 2003; Wilk, 2001; Gusev; 2001), silicon dioxide remains a ubiquitous component of MOSFETs. Hence, it is imperative to understand the SiO$_2$/Si interface. It has been found in previous studies that the silicon substrate experiences vertical strain (Kim, 1997; Daum, 1993) at the SiO$_2$/Si interface, and it is useful to characterize this strain quantitatively by means of a nondestructive technique. High resolution Rutherford backscattering spectrometry offers us such a possibility.

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EXPERIMENTAL PROCEDURE

Experimental Set-up
Channelling measurements were done using a HRBS500 magnetic spectrometer system manufactured by Kobelco Steel in conjunction with the CIBA Singletron 3 MV accelerator (Mous, 1997). The Singletron provides high beam stability and large brightness that minimizes possible energy variations on the energy resolution. The HRBS endstation, installed at the 45° beamline, is composed of a UHV scattering chamber that works at a basepressure below $5 \times 10^{-9}$ bar. Backscattered particles are double focused through a 90° sector magnet and hit the multichannel plate (MCP) stacked on top of a 1-D position sensitive detector (PSD). The sample holder is attached to a computer controlled five axis goniometer that allows translations along the x, y and z axes as well as rotations about the vertical ($\theta$) and horizontal ($\phi$) axes. Details of the characteristics and calibration procedure of the HRBS spectrometer can be found in a recent paper on the CIBA high resolution RBS facility (Osi powicz, 2006). The MCP raw position to energy spectra extraction is nonlinear and follows the following equation:

$$ f(E) = F(X(E/E_0)) \frac{1}{E_0} \frac{dX}{d\varepsilon} \bigg|_{\varepsilon=E/E_0} $$

A laterally uniform sample of SiO$_2$/Si of unknown thickness and composition was placed in the sample holder and positioned with a scattering angle of 65° in IBM geometry. A 500keV beam of He$^+$ particles was calibrated and then used to probe the sample.

Channeling Axis
In order to obtain channeled spectra, the sample must first be aligned along the [111] axis. This was achieved by doing a box scan around the [111] axis in the (110) plane. It was found that the angle of incidence ($\theta$) for [111] channeling is 54.74° (Nakajima, 2003). However, it is highly improbable to always place the sample such that the (110) plane aligned with the theta rotation. However, the offset was only slight, and so the box scan could be used to look for the exact values of $\phi$ and $\theta$ by varying around the previously known [111] vicinity. The box scan was done by first tilting the sample by a $\theta$ of 54.74°. From there, the sample was tilted again by a $\theta$ of 2°, and then the backscattering yield was taken as $\phi$ was varied in increments of 0.2°. The $\phi$ was then fixed and the $\theta$ varied in increments of 0.2° to obtain the backscattering spectrum at the right axis. A similar procedure was done for the bottom and left axes. Straight lines, approximating the curved plane projections, were drawn to connect the plane positions (dips) at the box edges. The horizontal line in the box scan represents the (110) plane. The coordinates of the intersection of these lines give the $\theta$ and $\phi$ values for which the sample is aligned along the [111] axis. For this experiment, it was found that $\theta = 54.00^\circ$ and $\phi = 2.90^\circ$.

RESULTS AND DISCUSSION

Properties of the Sample
It is known that the sample consists of a thin amorphous silicon dioxide layer on a silicon crystal substrate. The exact thickness and composition of the sample can be found by fitting a
simulated spectrum to a channeled spectrum. For this experiment, the spectrum channeled through the [111] axis was taken and the underlying substrate signal was subtracted from it. A simulated spectrum was then fitted to the subtracted spectrum using RUMP. Assuming a stoichiometric oxide, the SiO$_2$ layer was found by fitting the simulated spectrum to the oxygen surface peak and was found to be $29.7 \times 10^{13}$ atoms/cm$^2$ or 45 angstroms. The silicon surface peak cannot be used to find this thickness because of the currently unquantifiable contribution of the silicon surface peak. The energy resolution was found to be 1.2 keV.

**Channelled Spectrum**

A set of channeled spectra was obtained by taking the spectrum at the aligned [111] axis and then at increments of $\Delta \theta_i = 1^\circ$ away from the aligned axis both in the positive and negative directions. A total of 20 spectra were obtained in this way. For each spectrum, a strip having a width of 8 channels or 1.5656 keV was taken starting at the interface. The total backscattering counts within this energy range was then summed up. Finally, the total number of counts in one 8-channel strip was plotted against $\theta$ across the 20 spectra. In this way, successive 8-channel strips were taken starting from the vicinity of the interface and down until just above the oxygen peak. The counts versus $\theta$ plots at different energy windows were then compared in a single graph.

In Figure 1, the $\theta$ in the x-axis is in terms of relative difference from the angle at which the sample is aligned with the [111] axis. It can be observed that channelling is most pronounced at 0°. This drop in backscattering yield is called a dip. As we move nearer towards the SiO$_2$/Si interface, the dip shifts towards larger angles. The dip shift is evidence of vertical strain. The amount of strain experienced at the interface can be calculated using equation

$$
\varepsilon = \frac{2 \Delta \theta_i}{\sin 2 \theta_i},
$$

with $\Delta \theta_i = 0.5^\circ$ and $\theta_i = 54.74^\circ$. The strain $\varepsilon$ experienced by the silicon crystal substrate near the interface was then found to be 1.8%. The part of the silicon lattice under strain has an estimated width of 20 angstroms, measured from the interface.
Figure 1. Silicon yields for different energy depth regions of 1.565 keV wide shown as a function of the angle of incidence around the [111] channelling direction. The channelling dip shifts towards larger incident angles with decreasing energy depth.

CONCLUSION

The strain near the SiO₂/Si interface was characterized by channelling technique. The sample thickness and composition were found using a simulation fit to the background subtracted spectrum of a [111] channeled spectrum and was found to be 29.7 x 10¹⁵ atoms/cm² or 45 angstroms. The amount of strain at the interface was found to be 1.8%.

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