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Surface roughening and erosion rate change at low energy SIMS depth profiling of silicon during oblique O_2^+ bombardment

B. Fares [a], B. Gautier [a,*], Ph. Holliger [b], N. Baboux [a], G. Prudon [a], J.-Cl. Dupuy [a]

[a] *Laboratoire de Physique de la Matière, Institut National des Sciences Appliquées de Lyon, UMR CNRS 5511, Bâtiment Blaise Pascal, 7 Avenue Capelle, F-69621 Villeurbanne Cedex, France*

[b] *CEA-DRT, LETI/DST, CEA/GRE, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*

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Abstract

Surface roughening of boron δ-doped Si samples under low energy (0.5 keV/ O_2^+, 44° and 54°, and 1.0 keV/ O_2^+, 48°) O_2^+ bombardment at oblique incidence with and without oxygen flooding was studied with atomic force microscopy (AFM) and secondary ion mass spectrometry (SIMS). The erosion rate, the surface topography and the depth resolution as a function of depth have been measured. Changes in secondary ion yields have been correlated with changes in surface topography.

It is found that the surface roughness depends on impact energy and incidence angle without flooding. The roughness decreases with decreasing impact energy. For the same energy (0.5 keV/ O_2^+), the wavelength increases slightly with increasing angle of incidence and the roughness increases with increasing angle of incidence.

With flooding, the roughness can be efficiently avoided. The best conditions to avoid roughness when analysing ultra shallow profiles with our magnetic sector instrument is 0.5 keV/ O_2^+, 44° with flooding.

A procedure for the depth calibration of the profiles revealed that surface roughness causes an erosion rate change as measured using the shift of the position of the measured B peaks with and without flooding. The consequences of the roughness in terms of depth resolution of the profiles are analysed with and without flooding. Moreover, we show that the value of the Gaussian broadening parameter of the depth resolution function is closely related to the final dispersion of the heights in the crater bottom.

Keywords: SIMS; AFM; δ-Doped; RMS roughness; Depth resolution

1. Introduction

The use of low energy ion bombardment in secondary ion mass spectrometry (SIMS) depth profiling is a mandatory step for the characterisation of ultra shallow junctions [1]. During the past years, the depth resolution has been enhanced, mainly by means of reduced primary ion energy and of deconvolution algorithms [2,3]. At present, the development of a severe roughness at the crater bottom remains one of the main obstacle toward the ultimate resolution [4], which makes mandatory the understanding and the experimental control of its appearance. Several past studies have aimed at this understanding: Ng et al. [5], for example, suggest a direct relation between surface composition of the crater bottom and the development of surface roughness at low energy 0.5–2 keV/O_2^+ without flooding. For the same energies and incidence angles between 45° and 80°, Jiang and Alkemade [6] show that surface roughening occurs at an eroded depth of only a few tens of nanometres. According to these authors, the inhomogeneous incorporation of oxygen, and the sputtering rate dependence on both surface topography and oxygen content, determines the occurrence of roughening [6]. Liu et al. [7] show that the highest depth resolution is achievable at 0.5 keV/O_2^+, 69° and that the onset of roughening occurs earlier for smaller incidence angles (in the 46–69° range). This angular dependence is explained using the heterogeneous layer model [8,9]. Another way to minimise roughness is the sample's rotation [10,11].

Under flooding conditions, surface roughness at low energies occurs quickly and heavily at intermediate flooding pressures [6,8,12]. However, several authors did not observe

* Corresponding author.
E-mail address: brice.gautier@insa-lyon.fr (B. Gautier).

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roughness at a saturation flooding pressure compared to UHV [5,13–15]. A number of studies [13,14] have shown that the depth resolution for B in Si bombarded by 3–8 keV/O_2^+ is better with oxygen flooding, and that no roughness is observed at O_2^+ saturation pressure. To explain this phenomenon, Ng et al. [5] suggest that the oxygen flooding leads to the formation of a homogeneous stoichiometric silicon dioxide on the crater bottom using 1 keV/O_2^+ primary energy and 56° incidence angle. However, Wittmaack and Corcoran [12] suggest that with oxygen flooding, the erosion rate in Si for oblique 2 keV/O_2^+ beam changes significantly after removal of a layer of $\simeq$20–40 nm depth, which shows that flooding may not solve all the problems.

When the roughness appears, the depth resolution degrades rapidly [16] as demonstrated, e.g. by Jiang and Alkemade [6], who worked in silicon with a boron multi-δ layer structure and a 1 keV/O_2^+, 60° O_2^+ beam. Eventually, when the roughness appears, the quantification of the SIMS analysis cannot be precise because of the variation of important parameters like the erosion rate, the ionisation yield and the sputter yield.

The present paper explores in more detail the formation of surface roughness during sputter depth profiling of Si using 1 keV/O_2^+, 48°, and 0.5 keV/O_2^+, 44° and 54° with and without oxygen flooding. The erosion rate change, the variations in secondary ion intensities, the surface roughness, and the depth resolution for B deltas are measured. Multiple δ layers are used to establish an intrinsic depth scale for ion beam sputter profiling and to measure the depth resolution. The aim of this paper is to explore the consequences of the roughness on very low primary beam energy analysis, needed for a very high depth resolution, using a direct measurement of the topography by atomic force microscopy (AFM). We also aim at establishing the optimal experimental conditions which leads to the best depth resolution with no roughness.

2. Experimental setup

All SIMS depth profiles were performed on a Cameca IMS 5f instrument. The experiments reported here were carried out using an oxygen (O_2^+) primary beam with a primary current in the 18.4–19 nA range at impact energy of 1 keV/O_2^+ and incidence angle of 48°, and 0.5 keV/O_2^+ at two different incidence angles (44° and 54°). When oxygen flooding was used, the pressure was set at the saturation pressure of 2.0×10^{-6} Torr (we have checked that the saturation was effectively reached by varying the flow of the oxygen leak). The final crater depths were measured with a Tencor P10 surface profilometer and the depth scale was established assuming a constant erosion rate.

The B δ-doped Si sample [17] (abbreviated Si:B in the rest of the text) used in this work consists of one (mono) δ layer at a depth of 17.9 nm under the surface, followed by five double δ layers separated by approximately 1, 2, 3, 6 and 10 nm, respectively, and eventually another (mono) δ. The position of the different layers, and the distance between them can be estimated from Fig. 1b. Surface topography measurements of the crater bottoms were performed using a Digital Instrument

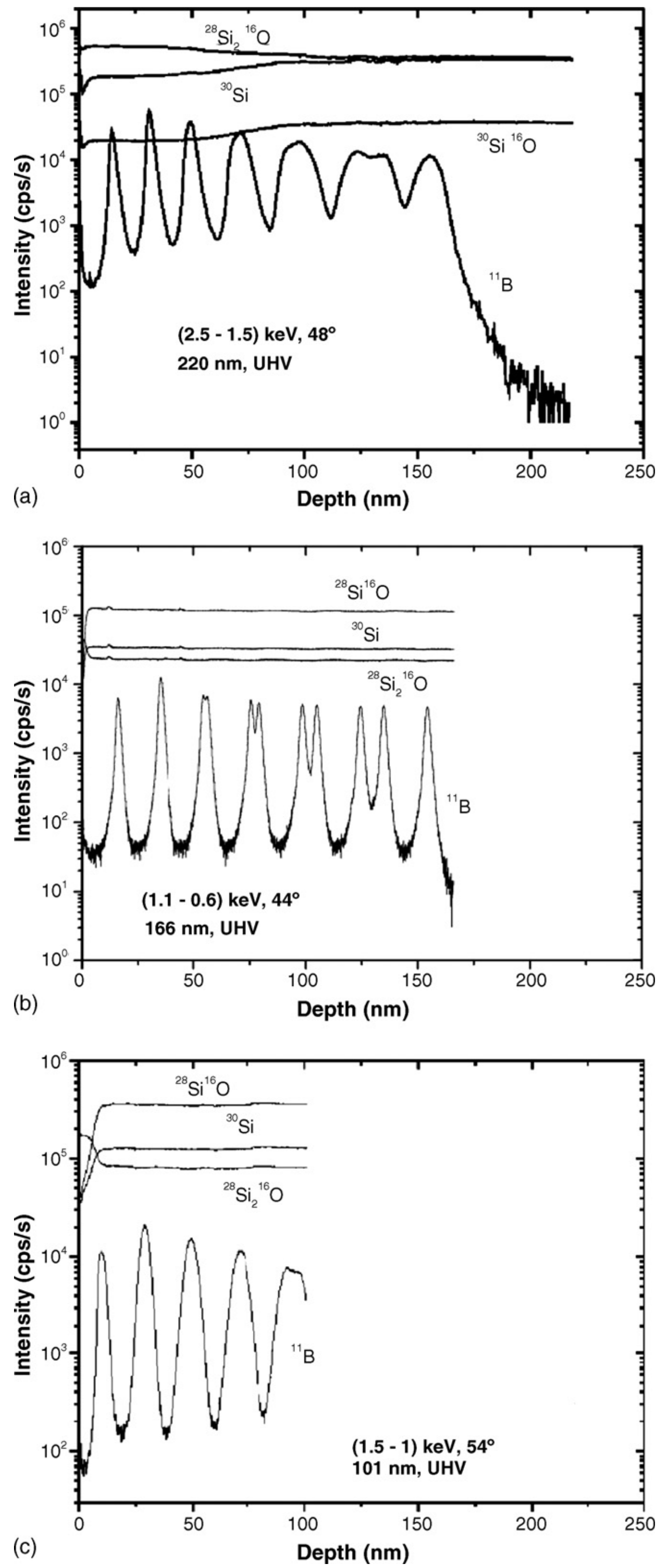

Fig. 1. SIMS profiles of secondary ions from the B deltas analysed with: (a) $E_p = 1$ keV/ O_2^+, 48°; (b) 0.5 keV/ O_2^+, 44°; (c) 0.5k eV/ O_2^+, 54° under UHV.

Dimension 3100 atomic force microscopy, operated in tapping mode. All AFM images were collected using the same silicon tips ($\simeq$300 kHz resonance frequency, 40 N/m stiffness, radius $<$ 10 nm), with scan sizes of 1 μm × 1 μm.