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Accurate on-line depth calibration with a laser interferometer during SIMS profiling on the Cameca IMS WF instrument

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Abstract

The presence of shallow interfaces in the crater bottom surface can lead to the appearance of several reflected beams from different depths that can distort the calibration close to these interfaces. A multi-beam scattering model has been developed. The results of this simulation are compared with experimental data and allow interpretation of the laser interferometer data for multi-layer structures. Statistical analysis of data from different types of structures show that even with the presence of measurement artifacts, the laser interferometer can be used for improving the depth scale calibration accuracy.

Keywords: Depth profile; Laser interferometer; SIMS; Depth scale calibration

1. Introduction

For many years SIMS has been used successfully for scientific research and for control of technology processes. The factors affecting SIMS accuracy have been widely discussed. One of the most important factors is the accuracy of depth scale calibration. In general, calibration is achieved by establishing a correspondence between sputtering time and sputtered depth for each point of the measurement. Despite the recent efforts to develop in situ depth calibration methods [1], the first commercially produced SIMS instrument with real-time depth calibration system (Cameca IMS WF) has been introduced only recently [2]. This system is based on laser interferometer measuring the phase shift between two laser beams, reflected from the crater bottom and from the sample surface. This technique has demonstrated its ability to provide high accuracy depth calibration under a wide range of experimental conditions [2]. However, experimental data collected from multi-layer structures and shallow implants into oxide have demonstrated the limitations of the technique. In these cases, a point-to-point depth calibration lowers the accuracy of quantification.

Recent investigation has identified multiple reflection of the laser beam from layers with different refractive indices as the main source of error. The presence of interfaces directly under the crater bottom can result in several reflected beams, originating from different layers and distorting depth calibration in the vicinity of these interfaces.

A multi-beam scattering model has been developed. The results of the simulation are compared to experimental data and allow interpretation of the laser interferometry results for multi-layer structures. Statistical analysis of the data obtained from different

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types of structures show that the laser interferometer can be used to improve depth calibration accuracy even in the presence of the artifacts outlined above.

2. Results and discussion

A laser optical setup, described in more detail in [2], is attached to IMS WF sample chamber. It measures both the phase difference φ between the two orthogonal polarized laser beams placed on the sputtered and non-sputtered areas, and the intensity of the laser beam reflected from the sputtered area ($I = E^2$). The phase difference is related to the sputtered depth. A linear relationship exists for opaque films [3]. The phase-shift measurement technique is described in [4]. The main source of the limitation of this technique when applied to shallow structures is multiple reflection of the laser beams from different layers with correspondingly different indices of refraction. The presence of shallow interfaces beneath the crater bottom surface can lead to the appearance of several reflected beams from different depths, which distorts the calibration close to these interfaces. The model developed takes into account the optical properties of the sputtered film, characterized by the complex refractive index n and the extinction coefficient η defined by the imaginary part of n and is schematically shown in Fig. 1.

Let us consider a model for phase measurement δ taking into account all reflections from the interfaces under the surface as well as refractions and absorption χ in the layers below:

$$\delta(p) = \frac{\lambda}{4\pi}(\varphi(p) - \varphi(0)) \tag{1}$$

The electromagnetic field E is given by:

$$E(p) = r_1\,\mathrm{e}^{\mathrm{i}\phi_0(p)} + \eta_1(p)\,\mathrm{e}^{\mathrm{i}\phi_1(p)} + \sum_{k=2}^{j}\eta_k(p)\,\mathrm{e}^{\mathrm{i}\phi_j(p)} = A\mathrm{e}^{\mathrm{i}\varphi(p)} \tag{2}$$

where p is the depth, and phase shift in every layer ϕ is given by:

$$\phi_j(p) = \frac{4\pi p}{\lambda} + \frac{4\pi(d_1 - p)n_1}{\lambda} + \sum_{k=2}^{j}\frac{4\pi n_k d_k}{\lambda} + \beta_j \tag{3}$$

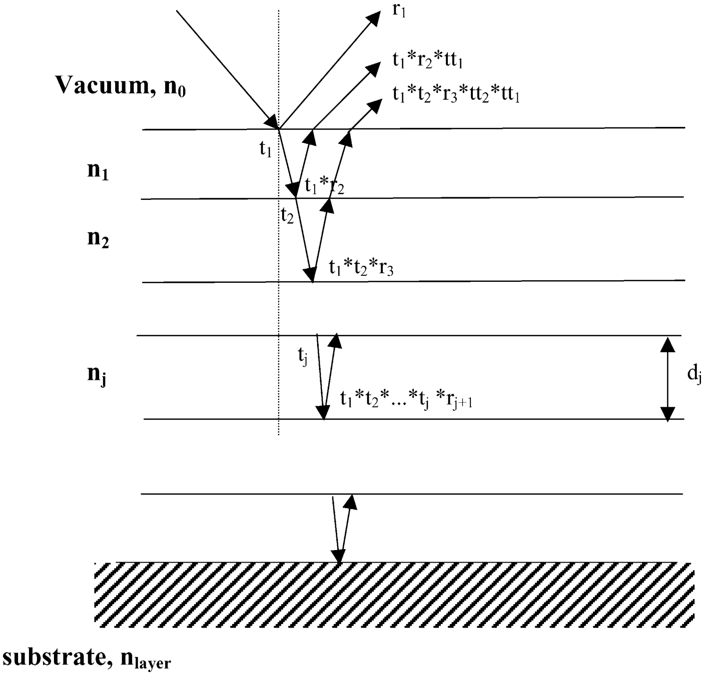

Fig. 1. Layers layout for the interferometer response function computer simulation.

where β is the sum of all phase shifts below the layer n_1 accumulated on all interfaces:

$$\beta_j(p) = \vartheta r_{j+1} + \sum_{k=1}^{j} \vartheta t_k + \vartheta tt_k$$

The extinction coefficient is determined by

$$\eta_j(p) = \chi_1(p) r_{j+1} \prod_{k=2}^{j} t_k tt_k \chi_k(p) \tag{4}$$

where the Fresnel coefficients at the boundary of two media with refractive indices n_j and n_{j-1} are for t-refracted beam, for tt-returned t, and for r-reflected beam:

$$t_j = \frac{2n_j - 1}{n_{j-1} + n_j}, \qquad tt_j = \frac{2n_j}{n_{j-1} + n_j}, \qquad r_j = \frac{n_{j-1} - n_j}{n_{j-1} + n_j} \tag{5}$$

Light absorption χ is defined as:

$$\chi_j(p) = \mathrm{e}^{-4\pi \mathrm{Im}(n_j) d_j / \lambda} \tag{6}$$

Note, that the layer n_1 has a variable thickness during the sputtering simulation. However, in some instances we consider the permanent presence of the silicon oxide layer due to oxidation under the O_2 primary beam. In this case, the thickness of the layer n_2 is variable. Below is the list of the indices n used for the calculations ($\lambda = 633$ nm): Si $= 3.87 + i0.016$; $SiO_2 = 1.46 + i0.0$; $Si_{0.68}Ge_{0.32} = 4.11 + i0.18$; α-Si $= 4.51 + i0.23$; poly-Si $= 3.51 + i0.05$.

A computer program, simulating the interferometer response based on the aforementioned formulas (1)–(5) has been developed. A first attempt was performed on the simple case of a Si substrate terminated by a native oxide layer 1 nm thick and a grown thermal oxide layer of 4 nm thickness. The result for the interferometer response simulation is shown in Fig. 2. The best fit with the experimental depth measurement data was obtained when a thin poly-silicon layer of 0.5 nm below the oxide layer was added to the model. Both simulations show good correlation with experimental data. Although the depth scale deviates from the calibration given by crater depth measurements using a stylus profilometer, it was found that the sputter rate given by laser interferometer is correct for silicon. Incorrect measurement in the oxide results in a shift of the depth

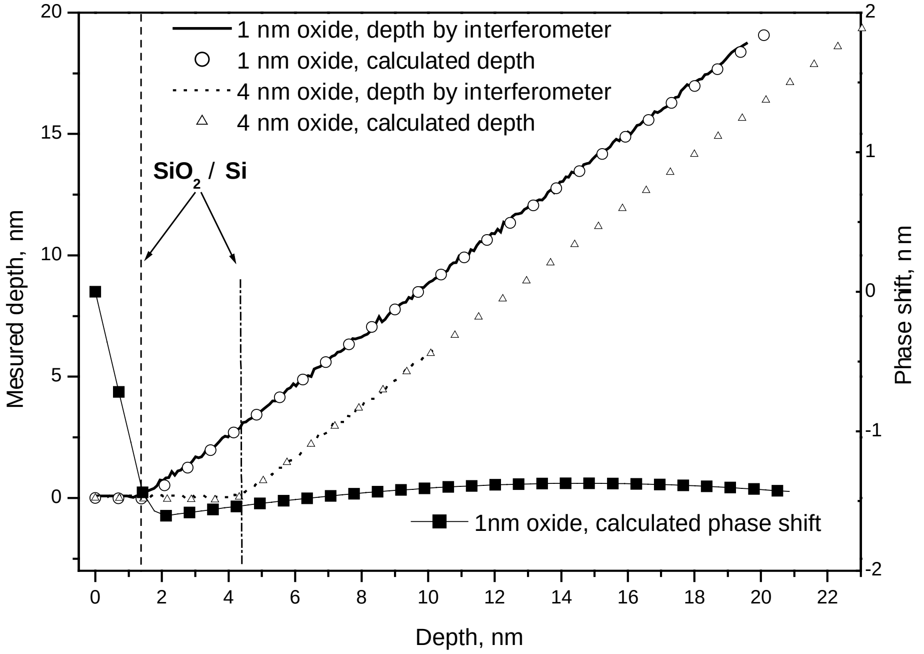

Fig. 2. Overlays of laser interferometer data with computer simulation data for SiO_2/Si 1 and 4 nm samples, measured with 500 eV Cs^+ primary beam, 0.5 nm poly-Si transitional layers are added to all interfaces.

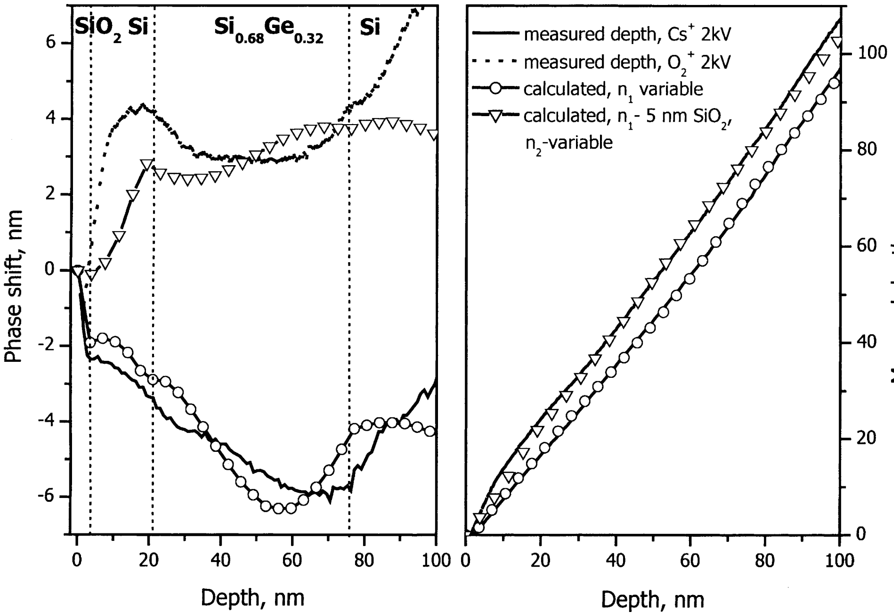

Fig. 3. Overlays of laser interferometer data with computer simulation data for Si/Si$_{0.68}$Ge$_{0.32}$/Si structure, measured with 2 keV Cs$^+$ and 2 keV O$_2^+$ primary beams, 2 nm poly-Si transitional layers are added to Si/SiGe/Si interfaces.

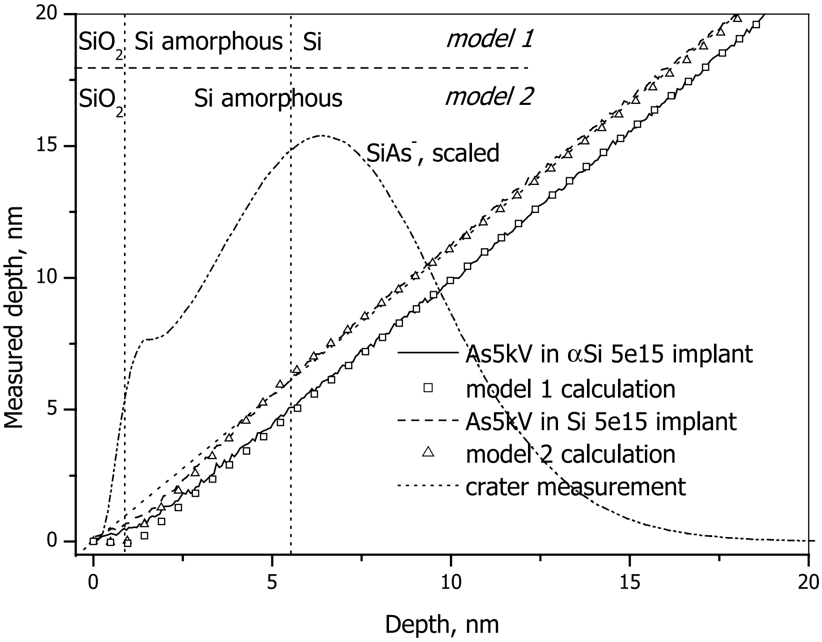

Fig. 4. Overlays of laser interferometer data with computer simulation data for As 5 × 10^{15} cm^{-2} 5 kV implants, measured with 500 eV Cs$^+$ primary beam.

profile and has to be corrected afterwards. At the same time, the depth scale calibration error can be used for precisely locating the interfaces, and is very useful for some applications. A 55 nm $Si_{0.68}Ge_{0.32}$ box profile in Si capped with a 18 nm Si cap presents a more complex system. This sample was measured with both Cs^+ and O_2^+ primary beams with impact energies of 2 keV. Experimental results and calculated depths for this sample are shown in Fig. 3. Since experimental results for Cs^+ and O_2^+ are quite different, two different models were developed. The data given by the measurement with an oxygen primary beam requires modification of the standard model. For this condition the first layer is apparently SiO_2, and its thickness depends on the impact energy. This layer moves with the sputtering surface and stays on top of it, giving a positive phase shift, which is observed in the experimental data. Simulations using this approximation show a good correlation with experimental data (see Fig. 3). The phase-shift units used in Fig. 3 are measured as the deviation from the theoretical linear response δ proportional to the depth. Another application for computer simulation program is 500 eV impact energy Cs^+ sputtering, used for depth profiling of a 5 kV 5×10^{15} cm^{-2} As implant. Implantation was done both into Si and pre-amorphized Si substrates. Calibration by crater depth measurement does not show any difference between the two profiles: the same sputter rate is recorded and As distributions differ only in the low concentration region. However, depth calibration curves, measured using the interferometer for those two implants are slightly different. Therefore, two models were employed for these samples. One is for bulk α-Si, which contains a layer of SiO_2 (native oxide) on top of α-Si layer. The second model accounts for amorphization of Si due to the high dose As implantation. It contains a 2 nm native oxide layer and a 3 nm amorphous layer on top of the bulk Si substrate. Results of the comparison of computer simulation with the experimentally observed depth scale calibration are shown in Fig. 4. An overlay of the laser interferometry data with the corresponding model calculation shows good agreement. The presence of amorphous layer in the case of high dose implants must be considered during depth scale calibration of such structures using the laser interferometer.

3. Summary and conclusion

A multi-beam scattering model has been developed for correction of laser interferometer depth measurements on the Cameca IMS WF. The results of the simulation are compared with experimental data and allow interpretation of the laser interferometer data for multi-layer structures. The presence of a SiO_2 layer on the original surface gives an error equivalent to the oxide layer thickness. This effect can be used when precise determination of the interface is most important. Depth calibration profiles, performed with Cs^+ and O_2^+ beams show some deviation from the linear proportionality between measuring phase δ and depths. The model accounts for the deviation and allows correction of the measurement. Calculations made for low Cs^+ impact energy sputtering shows some sensitivity to the amorphization of Si in the high dose As implants.

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