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Spectral Ellipsometry of Cobalt-ions Implanted Silicon Surface

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Abstract. Monocrystalline silicon wafers implanted by cobalt ions with energy of 40 keV at a fluence range from 6.6×10^{12} to 2.5×10^{17} Co^+-ion/cm^2 were investigated by optical spectroscopic ellipsometry. By comparison of experimental data with modeling it is shown that the ellipsometric measurements are accurate and reliable method for monitoring of a low-dose ion implantation process.

Introduction

Implantation of elementary magnets ions (e.g., Co^+) into silicon creates magnetic nanoclusters and silicide layers for use as metal contacts, the gate electrodes, the magnetic field sensors, switching elements, and other multilayer structures for electronics and spintronics [1,2]. In practice interest arouses not only to high-fluence implantation of silicon, but also to an irradiation with small fluencies of ions in order to study the processes occurring in a material in the early mesotaxy stages of implantation [3].

Nanometer size structures synthesized by ion implantation dictate the need to use special control methods to study their parameters such as composition, thickness, and morphology. One of the most promising methods for studying of the implanted surface structure is optical spectroscopic ellipsometry [4].

Experimental Methods

Samples of the present experiments were monocrystalline silicon wafers with crystallographic orientation (111) and *p*-type conductivity. Ion implantation was provided with ILU-3 ion accelerator by cobalt ions with energy of 40 keV at a fluence range of $6.6\times10^{12} – 2.5\times10^{17}$ Co^+-ion/cm^2 at room substrate temperature. Ion current density does not exceed 5 μA/cm^2.

Measurements of the ellipsometric angles ψ and Δ were carried out in the optical wavelength range of 380-1050 nm by spectral ellipsometer “ES-2” with a binary modulation of the polarization state (designed and manufactured in IRE of RAS, [5]). After spectral measurements of ψ_{exp} and Δ_{exp} , spectral values of ψ_{th} and Δ_{th} parameters of heterogeneous multilayer structures were calculated in accordance with the selected model. According to the convergence between the modeled and experimental spectra it could be concluded about the correct choice of the model of implanted layer and definition of suited parameters. In the presence of the two different substances in the applied layer a selected model allows calculating the optical constants of mixtures of these substances in accordance with the effective medium approximation of Bruggeman [6].

Results and Discussion

Modeling with the SRIM code [7] for 40 keV Co^+ ion implantation into the silicon substrate gives a mean projected range of ions 38.2 nm with a straggling of 14.9 nm (Fig. 1).

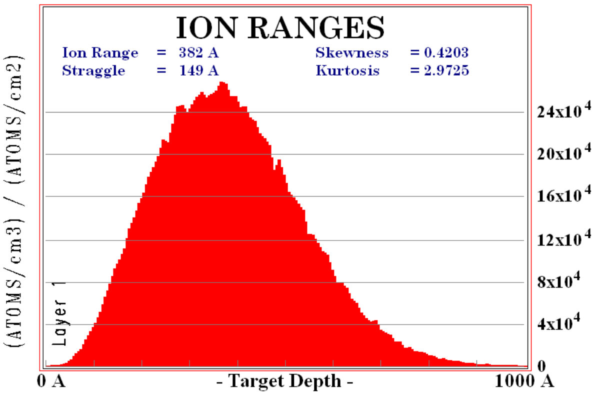


Fig.1. Distribution of Co^{+}-ions implanted into crystalline silicon at an energy of 40 keV (simulation in "SRIM-2011" program).

Fig. 2 shows characteristic example of the experimental and calculated tan(ψ) and cos(Δ) spectral dependencies in the sample implanted with fluence of 6.24×10^{13} Co^{+} ion/cm^2.

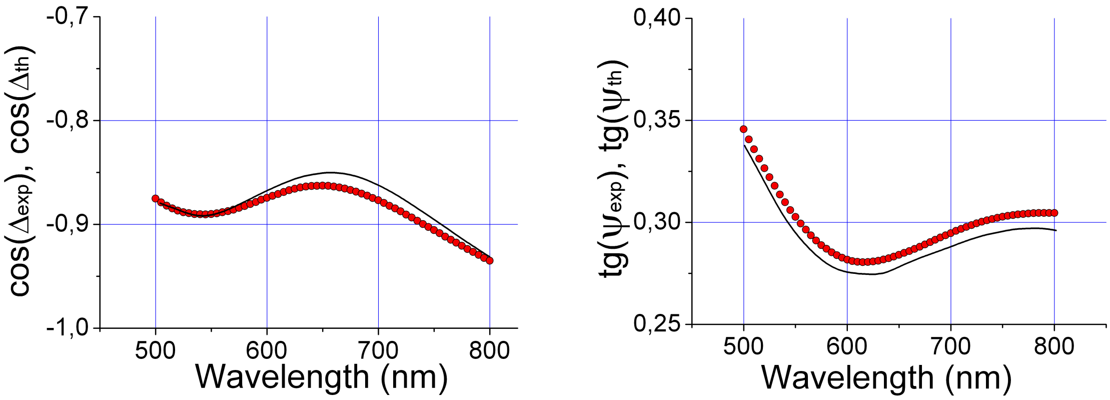


Fig. 2. Experimental (scatter) and calculated (line) spectral dependencies of ellipsometric parameters cos(Δ) and tg(ψ) of the sample implanted with fluence of 6.24×10^{13} Co^{+} ion/cm^2.

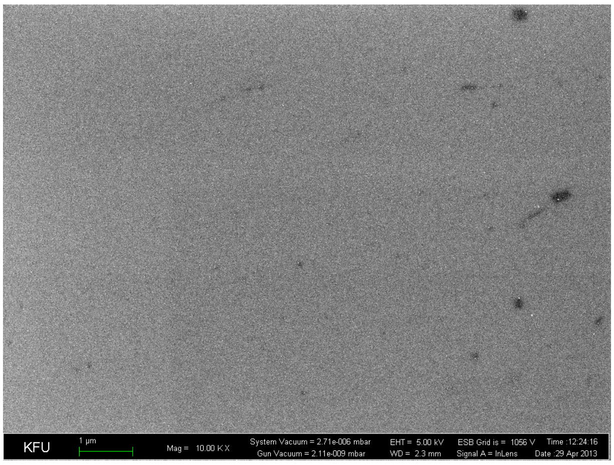
Collected ellipsometry study results are presented in Table 1.

Table 1. α-Si, crystalline Si and Co filling factors in the silicon surface layer resulting from the implantation of cobalt ions (excluding sputtering): columns 2 and 3 - the ellipsometry fitting results, 6 - calculation for a layer thickness of 60 nm, 4 and 5 - the thicknesses of the surface natural SiO_2 film and the layer subjected to the implantation by ellipsometry fitting results.

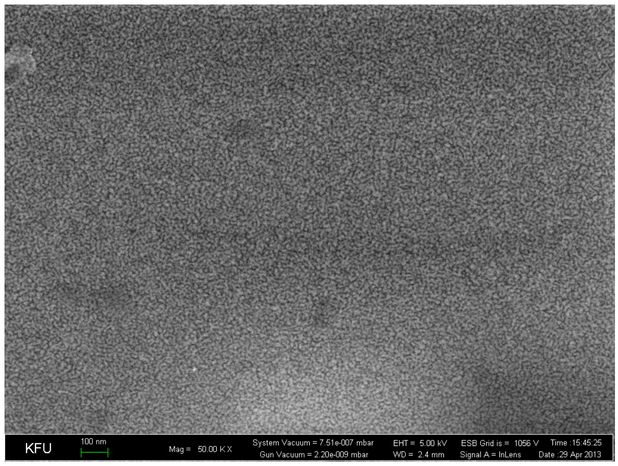
Implantation fluence [Co^{+}-ion/cm^2]	Filling factor α-Si:Co	Filling factor α-Si: crystalline- Si	SiO_2 thickness [nm]	Layer thickness [nm]	Filling factor α-Si:Co
1	**2**	**3**	**4**	**5**	**6**
initial		0 : 1	4.3	0	
6.24×10^{12}		0.01 : 0.99	5.2	40	
1.9×10^{13}		0.05 : 0.95	5.6	45	
6.24×10^{13}		0.5 : 0.5	4.3	40	
1.9×10^{14}		0.9 : 0.1	3	55	
6.24×10^{14}	1 : 0	1 : 0	6	61	
1.9×10^{15}	1 : 0		4.5	65	1.00 : 0.00
6.24×10^{15}	1 : 0		7	70	0.98 : 0.01
1.9×10^{16}	0.96 : 0.04		0	70	0.965 : 0.035
2.5×10^{16}	0.91 : 0.9		6	70	0.95 : 0.05

3.7×10^{16}	0.5 : 0.5		0	75	0.93 : 0.07
5.0×10^{16}	0.5 : 0.5		0	70	0.91 : 0.09
1.0×10^{17}	0.43 : 0.57		0	70	0.82 : 0.18
1.5×10^{17}	0.35 : 0.65		0	75	0.72 : 0.28

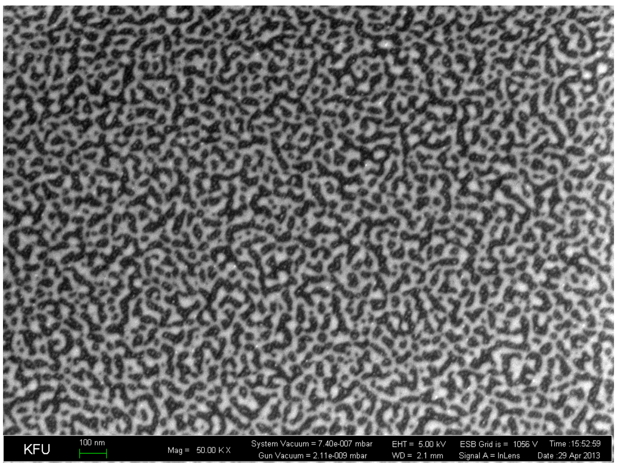
It is found that a fluence of complete amorphization of silicon surface layer is in a range of (2-6)$\times10^{14}$ Co^+-ion/cm^2. At fluencies in range of (1-10)$\times10^{16}$ Co^+- ion/cm^2 it needs to use a more complicated model of three films in implanted layer for convergence of experimental and calculated spectral dependencies of ellipsometric angles. At fluencies exceeded 10^{17} Co^+- ion/cm^2 a matching of the experimental and calculated values of the ψ and Δ angles throughout the used wavelength range cannot be reached. This may be due to the fact that at the indicated implantation fluencies silicon surface gets morphology relief or porous structure as it is evident from the scanning electron microscopy (SEM) images (Fig.3). Additional cause of the discrepancy between the experimental and calculated spectra could be started the process of phase formation of cobalt silicide (Co_2Si, CoSi, $CoSi_2$) with optical constants, which are different from the optical constants of a statistical mixture of cobalt and silicon substances.



(a)



(b)



(c)

Fig. 3. SEM images of the surface of the silicon samples implanted with various fluences: 5.0×10^{16} (a), 1×10^{17} (b), 1.5 $\times10^{17}$ (c) Co^+-ion/cm^2.

The magnetic properties of the surface layers were also analysed by surface-scanning magnetooptical Kerr polarimeter in the longitudinal mode (Fig.4). It was shown that both the coercive field and the residual magnetization of silicon surface layer were increased with fluence growth.

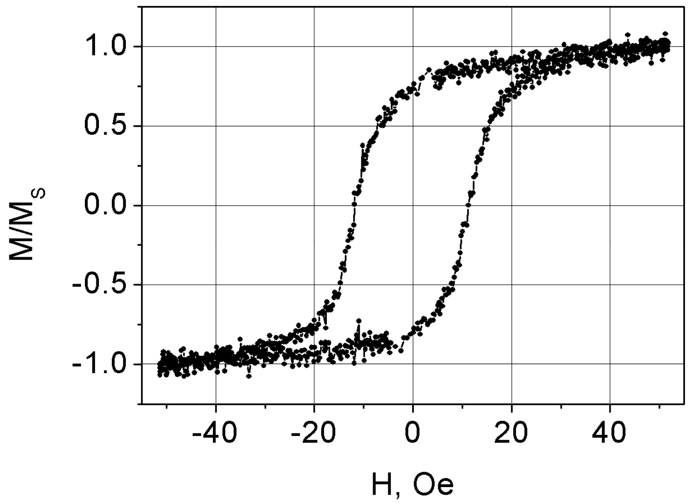


Fig. 4. Normalized magnetization (M/Ms) curves for silicon implanted with 2.5×10^{17} Co^{+}-ion/cm^2.

Conclusions

Thus, monocrystalline silicon wafers implanted with 40 keV cobalt ions in the fluence range $6.6\times10^{12} – 1.5\times10^{17}$ Co^{+}-ion/cm^2 were investigated by optical spectroscopic ellipsometry.

The analysis and modeling of the observed ellipsometric spectra using multivariate models has been carried out. As a result of such analysis it could be concluded that the good agreement between the experimental and calculated spectra achieved by taking into account the changing depth of the implanted layer for fluence not exceeding 1×10^{17} Co^{+}-ion/cm^2.

Presented data demonstrated efficiency of optical spectroscopic ellipsometry for characterization of materials with complex inhomogeneous surface morphology such as, for example, for porous silicon fabricated by implantation with Ag- [8] or Co-ions (Fig. 3).

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