Conclusion

Thermally stimulated current (TSC) measurements were carried out on as - grown $TlInS_2$ layered crystals doped with 0.1 % Tb and Er rate earth metal impurities in the temperature range ~80–300 K. The experimental data were analysed by using different heating rates, initial rise, curve fitting and isothermal decay methods. The results of the analysis showed good agreement with each other. The measurements revealed the presence of trapping level with activation energy of ~0.26 eV related to dopants. The corresponding capture cross - section and concentration of traps were found. TSC experiments showed the presence of a few native deep trapping defects in both investigated crystals with activation energies lying between of ~0.15 and ~0.3 eV.

References:

[1] MirHasan Yu.Seyidov [et al.] Physica B Condensed Matter. 497 (2016) 86-92.
[2] R. H. Bube, Photoelectronic Properties of Semiconductors, Cambridge University Press 1992.
[3] MirHasan Yu. Seyidov [et al.] Jpn. J. Appl. Phys. 50 (2011) 05FC08.

Features of the formation of thin films of functional coatings deposited on silicon by ion-beam sputtering of Mo, Cr, W

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Abstract

In this work, using RBS, scanning electron and scanning probe microscopy, the composition and structure of metal (Cr, Mo, W) coatings deposited on (111) Si under ion-assisted conditions are established. It was found that the deposited coatings on the (111) Si substrate have a layer of silicides and a layer containing carbides and oxides. The modification of silicon by the deposition of metal coatings under ion-assisted conditions also leads to the amorphization of the surface layer of the silicon substrate. The thickness of the coating increases with decreasing accelerating voltage for assisting ions from 15 kV to 5 kV.

Keywords: atomic force microscopy, thin films of metals, composition, surface structure.

Introduction

Traditionally, considerable attention in microelectronic engineering is paid to the study of the processes of obtaining thin films of metal oxides and their properties (including the introduction of dopants). Recently, interest in the study of these films has been growing due to the need to obtain optically transparent conducting layers for high-performance solar cells [1, 2], semiconductor lasers and light-emitting diodes, and sensor elements. The formation of the boundary between coating and silicon is an important step in the manufacture of semiconductor devices. Most of the published works are devoted to the analysis of the mixing of atoms at the metal / silicon interface caused by the action of ions of inert gases Ar, Kr, and Xe during the deposition of coatings (IBAD

method) [3]. Irradiation of a growing film with energetic particles is used to change a number of characteristics and properties that are critical to the performance of thin films and coatings, such as improved adhesion to the substrate, texture control, and changes in grain size and structure of the deposited layer. , change in electrical and optical properties. It is known that among the disadvantages of the IBAD method, one can note the introduction of inert gases into the surface layer, which can adversely affect the properties and quality of coatings. In our study, the deposition of a metal coating is accompanied by irradiation with ions of the same metal [4]. Ion bombardment during ion-assisted plating provides mutual mixing at the metal / silicon interface. This process and a number of others, such as the formation of silicide, are the subject of numerous studies in connection with their widespread use in new electronic devices [5]. Therefore, in experiments on atomic mixing of silicon with metals, it is necessary to carry out layer-by-layer elemental analysis, to study the structural-phase rearrangements and surface morphology of modified silicon samples. Thin films obtained by the proposed technology can find application in the creation of sensor micro-nanosystems for monitoring optical radiation.

Experimental

A metallic (Mo, Cr, W) coating was deposited on single-crystal silicon (111) Si wafers with the assistance of the deposited metal (Mo^+, Cr^+, W^+) ions at accelerating voltages of 5 kV – 15 kV. For this, a resonant ion source of a vacuum electric arc plasma was used, which simultaneously generates both a neutral flux of atoms and a flux of ions of the deposited metal [6]. The used type of ion source with electrodes made of the material of the applied coating (molybdenum, chromium, tungsten) allows one to simultaneously obtain controlled fluxes of metal ions J_i and neutral atoms J_A of the deposited metal. The ratio of the density of the ion flux to the density of the neutral flux, J_i/J_A, was in the experiments from 0.01 to 0.1, which corresponded to the conditions for the growth of the coating on the substrate [5, 6]. The pressure in the vacuum chamber during the deposition of coatings was ~ 10^{-2} Pa, and the rate of deposition of coatings in different experiments was ~0.12 ÷ 0.54 nm/min. The ion source was also used to create metal/Si substrate structures by passive deposition of a neutral flux of metal atoms generated by the ion source without turning on the accelerating voltage on the target holder for 60 minutes.

The layer-by-layer elemental analysis of the initial (111)Si samples modified by ion-assisted deposition of a metal coating was studied using the Rutherford backscattering (RBS) method of helium ions with E_0 = 1.5 MeV at scattering, inlet and outlet angles of 110°, 0°, 70°, respectively, and computer simulation of the experimental ROP spectra with the RUMP program. The energy resolution of the analyzing system was 15 keV, which provided a depth resolution of ~ 15 nm.

The topography of the coating surface was studied by scanning electron probe microscopy (EDX Oxford Instruments AZtecEnergy-Advanced) and atomic force microscopy (NT 206 (Microtestmachines Co., Belarus) in the contact mode with the use Micromach CSC38 probes.

Results and discussion

In fig. 1 shows the profiles of the depth distribution of elements in W/Si samples obtained at an accelerating voltage of 15 kV. Analysis of the concentration dependences of the distribution of elements in the formed metal coatings reveals a significant difference depending on the metal of the deposited coating, as well as the technological conditions of deposition. The concentration of W atoms is 30 at.% when creating metal coatings on Si and about 40 at. % on the W/Si structure, which gradually decreases to 2-5 at.% to the coating/silicon interface. The concentration of metal on the surface, the resulting simulation of the RBL was confirmed by examining the surface on a scanning electron microscope in the analysis of secondary scattered electrons.

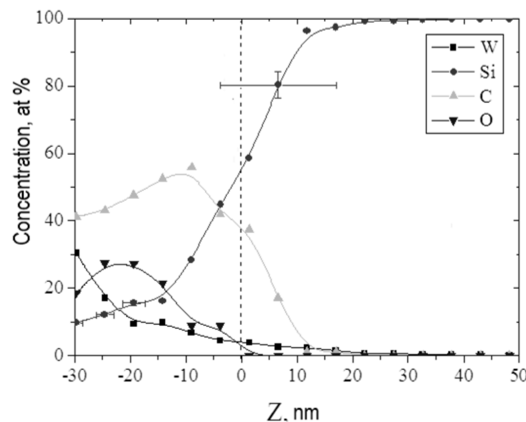

Figure 1. Depth distribution of elements in samples after W coating with ion-assisted (accelerating voltage 15 kV)

Plating the prepared metal/Si structures allows for thicker coatings. The presented concentration profiles of the depth distribution of the components (fig. 2) indicate the position of the interface in the coating/silicon systems, which is established according to the well-known method of introducing a xenon marker [7]. A similar picture as for tungsten is observed in the distribution of molybdenum and chromium in the coating, but the maximum concentration at the coating surface is only 7 at.%, gradually decreasing to 1.5-3 at.% to the coating/substrate interface. A decrease in the accelerating voltage for assisting ions to 5 kV makes it possible to increase the thickness of the deposited coating due to a decrease in the intensity of the sputtering of the deposited coating.

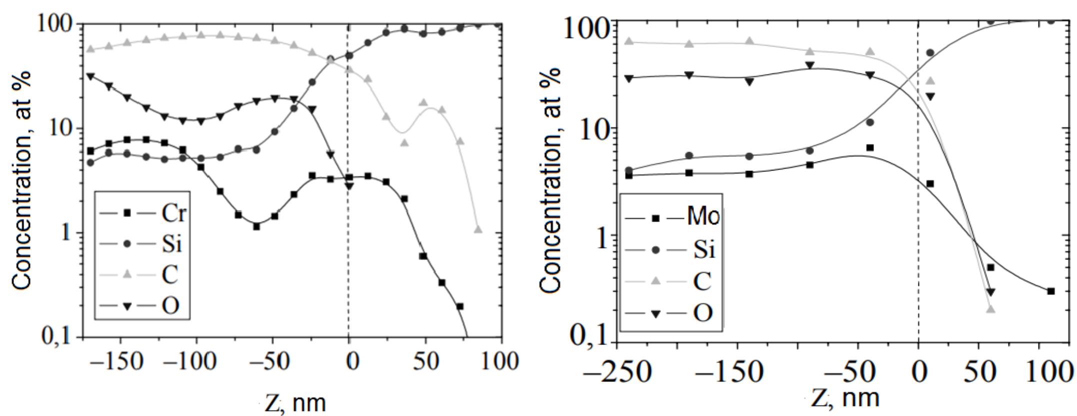

Figure 2. Depth distribution of elements in samples after applying chromium and molybdenum coatings with ion-assisted chromium and molybdenum ions, respectively

Oxygen and carbon are unevenly distributed in the coatings. Thus, the oxygen concentration increases to 30 at% in the coating and decreases to 2-5 at.% to the coating/substrate interface, and in silicon it becomes lower than the metal concentration, fig. 2. The distribution of carbon is qualitatively similar to the spatial distribution of oxygen. However, the concentration of C is approximately 2 times higher in the coating and decreases to 40 at. % to the coating/substrate interface. In silicon, the carbon content is several orders of magnitude higher than the металловconcentration. In addition, silicon with a concentration of 10-40 at.% Is contained throughout the entire thickness of the deposited coating. The appearance of silicon in the coating is associated with counter-diffusion from the substrate.

The distribution of chromium and molybdenum in the coating is 3-5 at.% over the entire thickness of the coating with an increase up to 5-7 at.% to the coating - substrate interface for Mo and a decrease from 7 to 3 at.% for chrome-containing coatings. As expected, the thickness of the coating increases with the modification time. At an irradiation time of 1 h, the thickness of the coating is ~ 20 nm, 3 h –50 nm, and 6 h - 240 nm. The average growth rate of the deposited metal-containing coating on silicon is about 0.5 nm/min.

Using atomic force microscopy, images of the surface of raw silicon and coatings were obtained (Fig. 3). It was found that the roughness of the original cream is insignificant and amounts to 0.2 nm, increasing upon application of coatings up to 1.7 nm (Table 1), which still suggests a high quality of the surface and its suitability for use as a substrate for sensor elements.

Table 1 - Contact angle of wetting with water of the surface of the original and modified by the application of various metal coatings of silicon

Parameter	Silicon	Metal coatings on silicon		
		Cr	W	Mo
CAW, °	68.1	70.7	79.6	77.0
Ra, nm	0.2	0.7	1.7	1.3

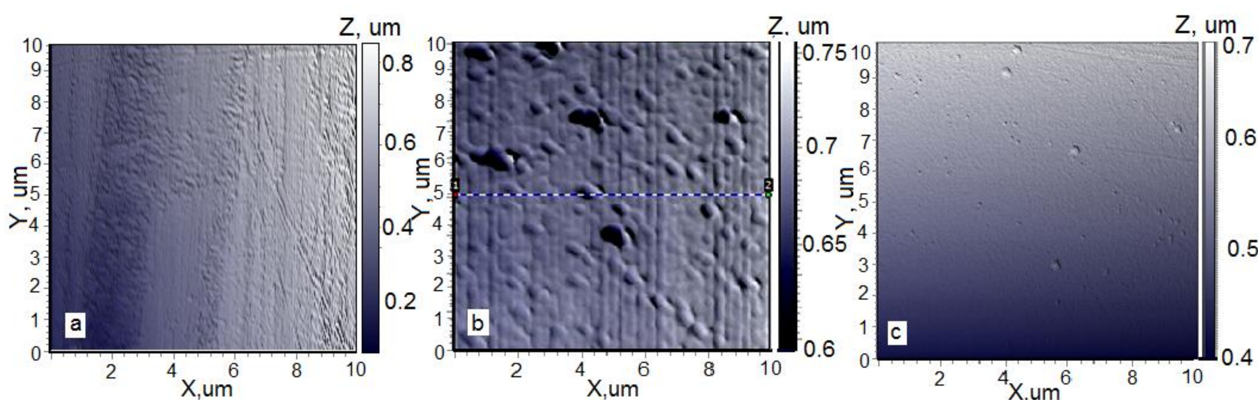

Figure 3. Silicon surface a – chrome-plated, b – pure, c – molybdenum-plated

An analysis of the CAW values of water on a silicon surface modified by the deposition of metal-based coatings shown in Table 1 leads to the conclusion that the surface composition and coating material affect the hydrophobicity properties and surface of products with a minimal effect of surface topography.

Conclusion

As a result of studies carried out by the Rutherford backscattering method, it was found that the composition of coatings obtained on silicon wafers includes atoms of the deposited metal, technological impurities of carbon and oxygen from the vacuum chamber, as well as silicon as a result of counter diffusion from the substrate into the coating. With a decrease in the accelerating voltage for assisting ions from 15 kV to 5 kV, the coating thickness increases from 30-45 nm to 90-120 nm, which is explained by the different intensity of the coating sputtering processes. are deposited at different energies of auxiliary ions, and the activation of migration processes during coating. It should be noted that the deposition of coatings with ions on the prepared metal/Si structures contributes to the production of thicker films containing metal silicide phases. Along with the formation of silicides, carbides, and oxides during ionic deposition of coatings, amorphization of the surface layer of the

silicon substrate is observed.The possibility of controlling the wettability, and hence the free surface energy of the surface, by applying metal-containing coatings on silicon is shown.

Acknowledgment

The article was prepared with the financial support of the Ministry of Education of the Republic of Belarus (No. GR 20211250 and 20211394).

References:

[1] Razykov T. K. [et al.] Appl. Sol. Energy 57(2) (2021) 113–119.
[2] Baraishuk S. M. [et al.] J. Surf. Invest. 12(6) (2018) 1077-1081.
[3] Carter G. [et al.] J. of Advanced Materials 5(1) (1999) 1-6.
[4] Tashlykov I. S. [et al.] J. Surf. Invest. 5 (2009) 92-95.
[5] Bobrovich O. G. [et al.] Inorg. Mater. Appl. Res.. 6(3) (2015) 229-233.
[6] Baraishuk S. [et al.] Physics and Chemistry of Materials Treatment. 1 (2011) 66 (In Russian).
[7] Bobrovich O. G. [et al.] Proceedings of BSTU, series VI, Physical-mathematical sciences and informatics, 2005, issue XIII, pp. 90–92 (In Russian).
[8] Stanchik A. [et al.] Mendeleev Commun. 5 (2021) 726-727.

Interconnection between structure, thermoelectric and electric properties of doped ZnO-based ceramic materials

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Abstract

ZnO–based ceramics were prepared by annealing of powder mixtures of ZnO and doping metal (Fe, Co, Al) oxides. Doped samples contained mainly wurtzite phase with some extra phases ($ZnFe_2O_4$, $ZnAl_2O_4$ and rest metal oxides). In binary Fe-doped ceramics, the $ZnFe_2O_4$ phase increased Seebeck coefficient S(300 K) from 300–400 μV/K for ZnO to ~ 800 μV/K, when the mean electron concentration reached values $\sim 1 \cdot 10^{21}$ cm^{-3}. Doping with Fe and Co leaded to an increase in resistivity, while the doping with Al and the presence of $ZnFe_2O_4$ phase in different combinations reduced resistivity leading to an increase in the power factor.

Keywords: ZnO, ceramic materials, resistivity, Hall effect, Seebeck effect, power factor.

Introduction

In the last time, we observe the growth of interest to the search of new ZnO-based ceramic materials for thermoelectric applications [1-4]. This forces to develop cost-effective production technologies correctly selecting regimes of synthesis and the doping type [2-6]. The main problem is to reduce the thermal conductivity of ZnO by suppressing the phonon contribution to it (for example, by increasing the scattering of phonons at grain boundaries, inclusions of secondary