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Nano-Heterostructures Based on Solid Solution HgCdTe obtained using Silver Ion Implantation

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ABSTRACT*:* Presented in this work are the results concerning formation of nano-heterostructures Ag_2O-$Hg_{1-x}Cd_xTe$ ($x = 0.2$) on the surface of solid solution $Hg_{1-x}Cd_xTe$ ($x \sim 0.223$). Modification of this ternary chalcogenide semiconductor compound was performed using the method of doping the heterostructure samples with silver ions, which was followed by low-temperature treatment. The energy and dose of implanted ions were 100 keV and $4.8 \cdot 10^{13}$ cm^{-2}, respectively. Studied in this work are electro-physical and structural properties of the narrow-band semiconductor compound Hg(Cd)Te with the nano-heterostructure Ag_2O-$Hg_{1-x}Cd_xTe$ ($x = 0.2$) formed on its surface by using the method of ion implantation Ag+ ions in the top-down approach. These semiconductor nano-heterostructures were characterized using impedance spectroscopy, AFM-microscopy and photoelectric spectroscopy.

KEYWORDS*:* Semiconductor, ion implantation, nanostructure, electro-physical, impedance spectroscopy.

I.INTRODUCTION

Nanostructured elements consisting of Hg(Cd)Te solid solutions are effectively using in T-devices for far IR and THz ranges [1]. One unique application of semiconductor quantum dots is based on A^2B^6 compounds (CdHgTe, CdTe/CdSe, $CdTe_{1-x}Se_x$/CdS, $Hg_xCd_{1-x}Te$/CdTe/$Cd_xZn_{1-x}S$, etc. [2-4]): it is also well known as multispectral (650…900 nm) fluorescent tomography (MSFI) that is indispensable in biomedicine for early detection of severe diseases. As known, for preparation of nano-materials with unique properties, formation of hierarchical structures is required.

The Ag_2O film in the work [5] was deposited on the surface by D.C magnetron sputtering at substrate of room temperature using an Ag target (99.99% purity) in the Ar atmosphere. The oxygen was introduced during the deposition. The *n*-type Si(111) wafer was cleaned and then, *p*-Ag_2O was deposited on it. Ag_2O is a p-type semiconductor with direct band gap around 1.4eV, which is appropriate to apply to solar cells. In addition, it is expected that this configuration may be used for fabrication of the *p*-Ag_2O/other n-type materials heterojunction solar cell [5].

One of the widely spread methods for modification of structural and morphologic characteristics can be developed by ion implantation. In this paper, to form a thin film Ag_2O was used method of ion implantation Ag ions to the surface of semiconductor structure Hg(Cd)Te. Using solid solution of *n*-$Cd_xHg_{1-x}Te$ ($x = 0.22$) we can combine the functional properties of oxide Ag_2O ($Eg = 1.41$ eV) [1] and semiconductor Hg(Cd)Te ($Eg = 0.123$ eV).

Bombardment of semiconductor with ions, atomic clusters or molecules results in changing thermodynamic parameters and features inherent to surfaces of basic system components. Doping of semiconductors is used for obtaining micro-structured materials possessing multi-functionality of electric, magnetic, optical and other properties. It is enables to control material properties through choosing of appropriate irradiation regimes and conditions for thermal annealing. Several examples of formation of nano-composites and metal-oxide nano-heterostructures by using ion implantation are represented in [6-9].

That is why we require investigation of electro-physical and structural properties of the narrow-band semiconductor compound Hg(Cd)Te with the nano-heteroarchitecture Ag_2O-$Hg_{1-x}Cd_xTe$ ($x = 0.2$) formed on its surface by using the method of ion implantation by the top-down approach.

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The purpose of this work was development of new physical properties of the solid solution by nanostructurization of Hg(Cd)Te surface by ion implantation and to expand the operating range of the spectral sensitivity.

II.RESULTS

Ion implantation is widely used for the manufacturing of the infrared photodiodes based on Hg(Cd)Te (MCT) solid solution [10]. The purpose of this work was to study the effect of the B^+ and Ag^+ ions irradiation on the properties of heteroepitaxial structures Hg(Cd)Te / CdZnTe. In this paper, the surface morphology as well as optical, electrical and photoelectrical properties of Hg(Cd)Te - based heterostructures were investigated. We implanted Hg(Cd)Te /CdZnTe (x=0.223) structures by the method of nonoriented irradiation with Ag^+ ions. This process was realized on a Vizuviy-5 implanter with an implantation energy of 100 keV and a dose of $3*10^{13}$ cm^{-2} with subsequent low-temperature annealing at a temperature of 75ºC in Ar atmosphere under a pressure of 0.4 MPa for 5 h. All processed surfaces were examined using atomic force microscopy (AFM - NanoScope IIIa Digital Instruments) microscopy (Fig 1 a, b). To provide electro-physical investigations, a mesa-structure was prepared using the chemical etching of the sample in the standard etchant Br-HBr. Indium electrodes were deposited on faces of the sample. Impedance characteristics of the samples were studied using the precision impedance meter Z-3000X within the frequency range 1 Hz…3 10^{6} Hz with the amplitude of a sinusoidal signal 120 mV (Fig 2, Fig 3, Fig 4 a, b) [11-12]. Photosensitivity spectrum was obtained by spectrometer SPM2 (Fig 5).

III.DISCUSSION

In the previous work [7] AFM images for the samples irradiated B^+ ions was studied. Nanostructure was formed by the metod of ion implantation MCT, Ag^+ ions (Fig. 1a, 1b). The results of topometry based on AFM measurements (Fig. 1a) show the network of quasi-pores with the depth 3.5 to 10 nm and diameter 50 to 160 nm as well as grains with sizes 40 to 80 nm densely packed in the surface plane. After implantation with silver ions (Fig. 1b), on the background of insignificant smearing of grain boundaries, with maintenance of initial surface porosity, there formed is a uniform array of cone-like spikes with the height *h* from 5 to 25 nm and base diameter *d* between 13 to 35 nm.

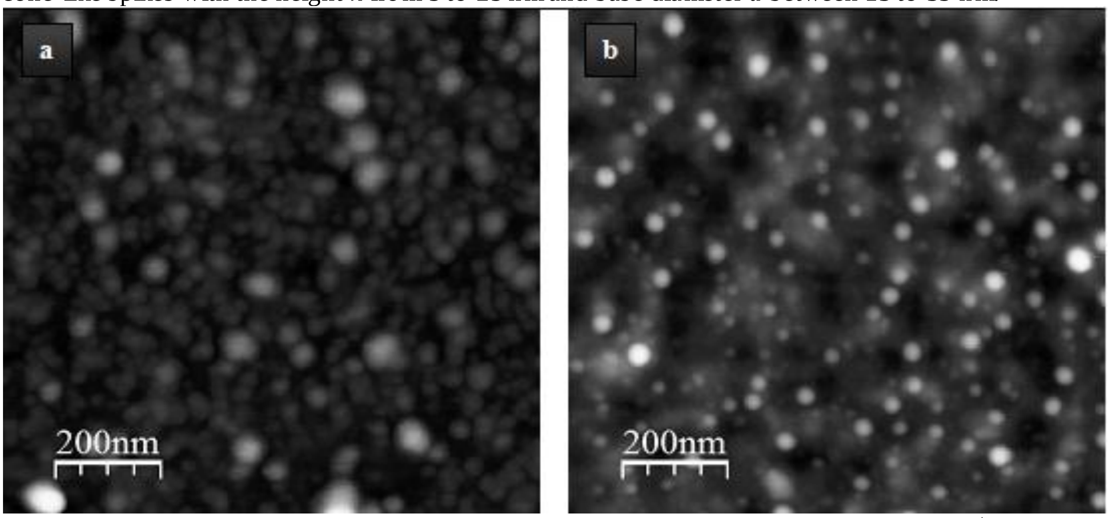

Fig. 1 AFM image of the film $Cd_xHg_{1-x}Te$ (x ~ 0.223): a) initial surface of the sample; b) after Ag^+ implantation and annealing

In the previous work in [7], as a result of ion implantation and subsequent annealing, it was found the data of modeling in the medium TRIM_2008 enabled us to determine profile for distribution and depth of localization for the embedded impurity in the sub-surface region of MCT as close to 100 nm [7]. The results of ellipsometry and GI XRD obtained for irradiated samples [13] confirmed the presence of a disturbed layer with the thickness close to 100 nm as well as formation of metal-oxide nano-heterostructures Ag_2O-$Hg_{1-x}Cd_xTe$ (x ~ 0.20) on the surface of Hg(Cd)Te solid solution. The vacancy material obtained using the liquid phase epitaxial technology demonstrates of deformation

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distortion with compression strains $\varepsilon_1 = (a_{CdHgTe} - a_0)/a_{CdHgTe} = -4.485\times10^{-4}$, $a_0 = 6.4660$ Å [13]. XRD results in the coherent-scattering region point out to the tension of the silver implanted Hg(Cd)Te layers [13]. It is found that the mechanical stresses that arise in the near-surface layer of an epitaxial MCT layer attain the maximal value of $\sigma_{max} = 2\cdot10^5$ Pa [7]. Deformations arising after embedding silver ions prevent the process of mercury diffusion in the implanted target.

It is known that mercury migration in MCT is accompanied by the effect of "healing" of vacancy defects - V_{Hg}. In the deformed "vacancy" semiconductor film, the healing effect is absent, which is confirmed by preservation of initial porosity in MCT samples after implantation and the following thermal treatment. Apparently, transformation of the defect structure in semiconductor film reflects elastic relaxation "compression – extension – compression" in the region of MCT loosened by ion implantation [7]. Conditions for appearance and regularities in development of surface pores and cones on solid surface irradiated with ions, in accord with [13], can be explained by the processes related with ion-induced strains that arise due to saturation of the surface by embedded silver atoms. The deformation accumulation is found to lead to the topological instability of the irradiated surface. The silver atoms fill microscopic voids in crystal lattice as a result of ion-stimulated diffusion and recombination processes in sub-surface layers. Compression of more deep layers in the loosened epitaxial film (> 0.04 µm) at the moment following after extension promotes "deformation squeezing" the silver ions to surface. Silver, as usual, demonstrates high penetration ability and has an aptitude for creation of solid solutions with high liability.

Structure modification leads to change electrophysical parameters, such as CV- characteristics. Impedance spectroscopy is a very sensitive method for detection of non-stationary charge transport governed by charge-carrier relaxation in disordered semiconductors structure. Therefore heterostructure $Cd_xHg_{1-x}Te$/CdZnTe after Ag^+ implantation was characterized by impedance spectroscopy. The value and interpretation of impedance spectra are processed in analogy to equivalent circuits involving simple components such as resistors and capacitors [11]. The impedance measurements were performed at the G-Cp (parallel conductance and capacitance) configuration using Au plates as blocking electrodes. Using the impedance technique, data equivalent to the real and imaginary parts of complex electrical values are measured as a function of the frequency of the applied electric field [11].

Hodographs of impedance for samples obtained by irradiation with ions B^+ and Ag^+ were analyzed (Fig. 2, 3). Using the EIS spectrum analyzer [11] according to the Vought approach, we obtained an equivalent circuits presented on Figs. 2, 3. For a sample implanted by B^+ ions obtained dependence was with characteristic diffusion impedance (Fig. 2). Here R1 is the contact resistance, CPE1 – Warburg impedance, series R2-CPE2 – circuit corresponding to the charge transfer and capacitance of the space charge region. For a sample implanted by Ag^+ ions, corresponding dependence was obtained (Fig. 3). Here R2-CPE1 is the parallel capacitance of the disordered layer. At the same time instead of expected combination R3-CPE2, this circuit corresponds to the charge transfer and the capacitance of the space charge region. CPE3 is changed to a reactive element inductance L. Thus, we detected the presence of "treated material" a series R3-L1 for this circuit. The important peculiarity of the equivalent circuit was appearance of the inductivity L, which is not typical of semiconductor compounds. Analysis of real part impedance of the initial samples $Cd_xHg_{1-x}Te$ did not show any presence of capacitance *C*. A typical Bode plot obtained for sample Ag_2O-$Cd_xHg_{1-x}Te$ is shown in Fig. 3. Impedance locus one can see two clearly observed parts, namely: a high-frequency ray (1) and gradually decreased dependence (2).

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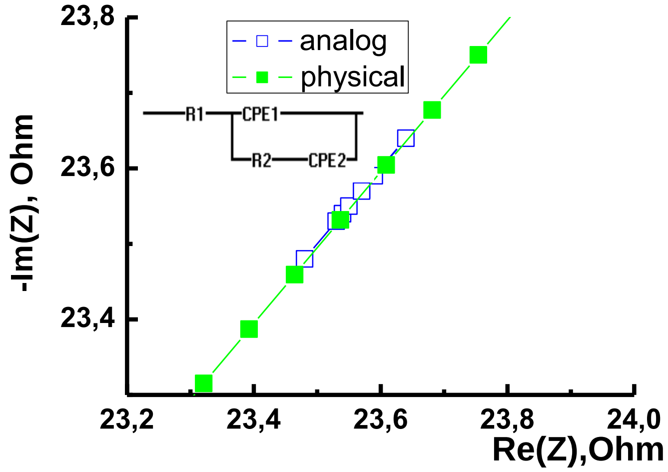

Fig. 2 Hodograph of the impedance for the heterostructure $Cd_xHg_{1-x}Te$ (x = 0.223) after B^+ implantation

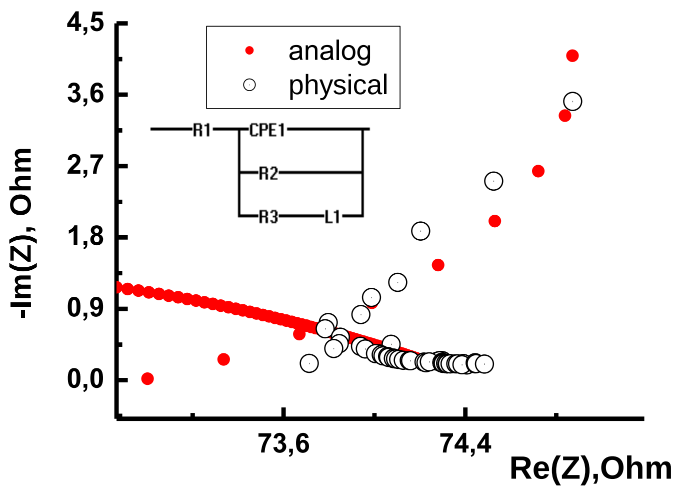

Fig. 3 Hodograph of the impedance for the heterostructure $Cd_xHg_{1-x}Te$ (x = 0.223) after Ag^+ implantation

Frequency dependence of real and imaging part of admittance of the system Ag_2O-$Cd_xHg_{1-x}Te$ was analyzed (Fig. 4a, 4b). Analysis of the real part of admittance *Y'* (Fig. 4a), the frequency dispersion is not observed within the range (1 Hz…1 MHz). This behavior of the measured electric circuit indicates presence of some capacitance *C*. In the low-frequency range (10^2…10^4) Hz, the implanted samples show specific features that are indicative on resonance levels of charge transfer processes in structured material (first circle Fig. 4a). The observed sharp drop within the high-frequency range (1…3) MHz (second circle Fig. 4a) can be caused by geometrical and electrical related of the studied samples. The imaginary part of admittance *Y''* has practically very low value, but within the total range of measurements increases by almost 3^th^ orders (Fig. 4 b). In our assumption, this dependence is a part of semi-circle (in the versus Nyquist diagram) with the maximum located at higher frequencies.

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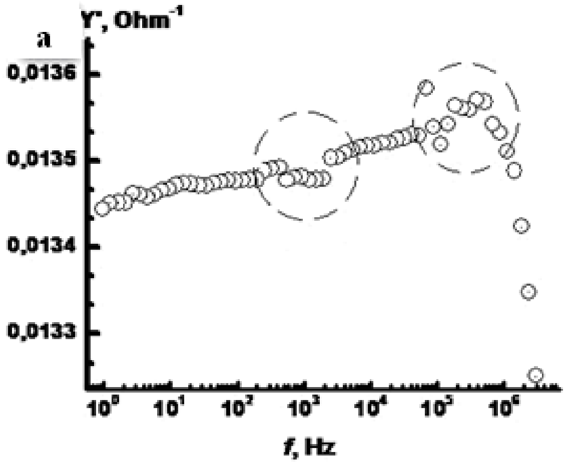

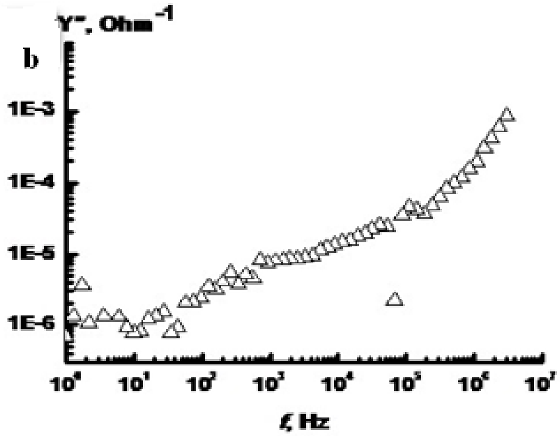

Fig. 4 a) Frequency dependence of real part of admittance of the heterostructure; b) frequency dependence of imaging part of admittance of the heterostructure, for the system Ag_2O-$Cd_xHg_{1-x}Te$ (x = 0.223)

Presence of the oxide on the surface of the metal particles Ag is explained by equivalent circuit of non-metallic components. Probably, this fact determines the appearance of the other equivalent circuit that describes the behavior of the samples, where additional oxide barriers inhibit the current transfer. This explains the presence of series R2-L1 in the equivalent circuit. The presence of oxygen impurity on the surface of the implanted layers is explained by adsorption of the residual atmosphere of the vacuum chamber and distributed in the depth of the target as a result of stimulating radiation and thermal diffusion processes. Relatively high concentrations of impurities introduced the process temperature and the enthalpy of formation of oxide phases contributed to their synthesis under ion irradiation. Irregularities presented on the surface of the samples $Cd_xHg_{1-x}Te$ have an important role in the processes of oxygen penetration adsorption during ion implantation. Thus, the C2 (the capacitance of the space charge region) is converted to the inductance, which is inherent, for example, to electronic gyrators [12]. In our opinion, the offered way to form the nano-dimensional relief on the surface of the film prepared from narrow-band semiconductor is promising for creation of efficient photo-converters based on Hg(Cd)Te compound [14].

The observed effect of nano-structuring can be useful from the viewpoint of developing a new class of electro-optical facility based on Hg(Cd)Te that possesses a necessary combination of optical, electro-physical and photoelectric properties. Photoelectric properties were studied in the IR and sub-mm range. Photosensitivity in IR was obtained at temperature T= 77K, as shown in Fig. 5. Sensitivity is observed in the area 1-4 μm IR-range.

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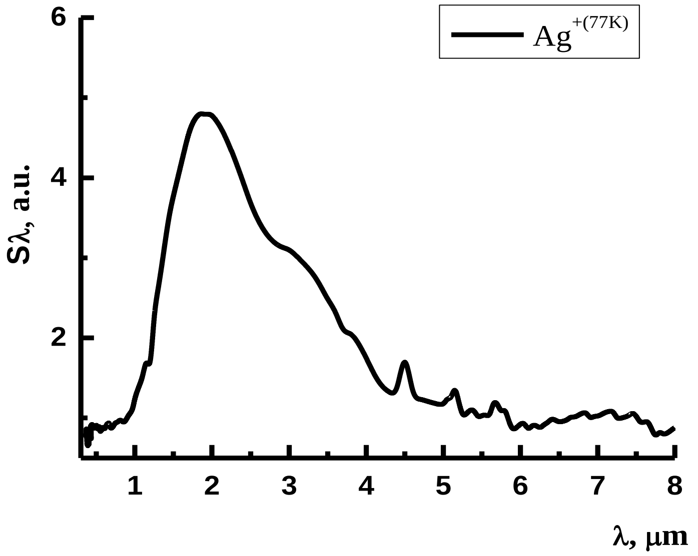

Fig. 5 Spectral sensitivity for the system Ag_2O-$Cd_xHg_{1-x}Te$ (x = 0.223).

Photosensitivity in sub-mm range was obtained at the room temperature. NEP = 2.7 * 10^{-8} (W $Hz^{-1/2}$) and D = 3 * 10^9 (sm $Hz^{1/2}W^{-1}$) were calculated for the mentioned heterostructure. The results indicate the use of this structure for manufacturing of Hg(Cd)Te photodetectors both in sub-THz and IR regions [15].

IV. CONCLUSION

1. Using the method of silver implantation of the solid solution $Hg_{1-x}Cd_xTe$ (x ~ 0.223) with the next low-temperature treatment, the authors obtained nano-heterostructure Ag_2O-$Hg_{1-x}Cd_xTe$ (x = 0.2) on surface of the samples.
2. Analog model of impedance spectroscopy was obtained using the EIS analyser. Analog model of impedance spectroscopy containing the inductance L was defined. Possible to this fact explained by the presence the current transfer inhibit additional oxide barriers.
3. A phase shift between the current and voltage φ = 86° point out the loss mechanical energy in the nano-material. So, we have approximation for a general piezoelectric transducer (actuator) operating near resonance.
4. Photosensitivity was obtained in both in sub-THz and IR regions. Therefore nano-heterostructure Ag_2O-$Hg_{1-x}Cd_xTe$ (x = 0.2) can be used for manufacturing photodetectors of multispectral range.

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2. Travel Contingency Grant 2005
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