Investigation of the effect of soft X-ray radiation on the electrophysical characteristics of \( n \)-Cd\(_{x}\)Hg\(_{1-x}\)Te epitaxial layers

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Abstract. The impact of soft X-ray radiation on the electrophysical characteristics of MIS structures formed on irradiated graded-gap MBE \( n \)-Cd\(_{0.24}\)Hg\(_{0.76}\)Te was investigated. It is established that the electron concentration, the differential resistance of the space-charge region in the strong inversion mode, and the spectra of fast surface states change nonmonotonically with increasing radiation dose. The results can be explained by the mechanism of the decay of electronic excitations.

1. Introduction

The main mechanism for the interaction of X-rays with matter is photoionization. Subsequent to the absorption of the X-ray quanta, the decay of the electronic excitation can lead to the generation of defects in crystals or the rearrangement of the structure of the defects existing in them, as a result of an electrostatic interaction or a number of other mechanisms [1, 2]. Earlier it was shown that irradiation with soft X-ray radiation ( SX R) of monocrystals and epitaxial layers of a solid solution of Cd\(_x\)Hg\(_{1-x}\)Te leads to the modification of the morphology of their surface [3, 4]. SX R is absorbed in a thin near-surface layer of thickness up to several microns, so no significant changes in the concentration or mobility of charge carriers in the bulk of the material were detected. At the same time, in the study of the capacitance-voltage (C-V) characteristics of MIS structures created on the surface of irradiated epitaxial layers \( p \)-Cd\(_{0.23}\)Hg\(_{0.77}\)Te, changes in the carrier concentration and built-in charge density were observed, which may be associated with the generation of radiation defects in near-surface region during irradiation [5]. The nature of these defects for the studied material has been little studied. In this paper, the effect of SX R on the electrophysical properties of epitaxial layers of \( n \)-Cd\(_{0.24}\)Hg\(_{0.76}\)Te is investigated.

2. Samples and Methods

The investigated layers were heteroepitaxial structures of \( n \)-Cd\(_x\)Hg\(_{1-x}\)Te (\( x = 0.24 \)) and were grown by molecular beam epitaxy (MBE) on GaAs (013) substrates at the A.V. Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk. The working layer 15 \( \mu \)m thick was surrounded on both
sides by the graded-gap layers with the thickness of about 0.3 μm with a composition of x = 0.45 on the surface.

The plasma of a laser-induced vacuum spark containing quanta with energy in the range 0.5÷10 keV was used as a source of SXR [6]. The spark was initiated by a pulse of a YAG: Nd laser operating in the Q-switched mode (the wavelength is λ = 1.06 μm, pulse duration τ ≤ 15 ns, power density of laser radiation at the target P = 10^{10} W/cm^2). The radiation was focused on the material of the cathode of the electric spark gap. The electrodes were placed in a vacuum chamber and were connected to a battery of capacitors with a stored energy of ≤ 1 J via a low-inductance vacuum current lead. The SXR spectrum contains two components: plasma bremsstrahlung and characteristic radiation arising from the recombination of excited cathode ions. It was extended to 10 keV. To cut off visible radiation and fluxes of corpuscular particles, a filter (aluminized mylar with a thickness of 3 μm) was transparent in the region above 0.75 keV. The calculated irradiation doses of the test samples were up to 1.5 J/cm^2. The duration of the X-ray pulse was Δτ ≤ 200 ns.

MIS structures were created after irradiation by deposition of Al_2O_3 layers onto the epitaxial layers. On the MIS structures obtained in this way, admittance studies were carried out in the temperature range of 9-77 K. The measurements were carried out on an automated setup of admittance spectroscopy based on a Janis cryostat and an Agilent E4980A immittance meter. In measurements, the voltage changed from negative values to positive ones was taken as the forward direction of sweep, and the voltage changed from positive values to negative ones was taken as the reverse direction of sweep. Equivalent circuits of MIS structures in different modes and experimental data processing techniques are given in [7-9].

3. Experimental Results

The depth at which SXR penetrates the crystal is comparable to the width of the space-charge region (SCR), which depends on the permittivity of the semiconductor, the temperature and concentration of the majority charge carriers. For n-Cd_{0.24}Hg_{0.76}Te at 77 K, the maximum width of SCR penetration is about 0.26 μm with an electron concentration of 3×10^{15} cm^3 and 0.78 μm at a concentration of 2×10^{14} cm^3.

The capacity of the MIS structure depends on the distribution of the composition and concentration of the majority charge carriers in the near-surface semiconductor layer, the density of surface states and their ability for charge exchange with a change in the test voltage, the densities of the fixed and mobile charge in the insulator. Some of these parameters can be determined from the research of the C-V curves.

Figure 1 shows the C-V characteristics of the MIS structure based on the initial n-Cd_{0.24}Hg_{0.76}Te, measured at 77 K at forward and reverse voltage sweeps at frequencies of 10 and 100 kHz. For C-V curves, a significant hysteresis of the injection type is observed [10]. At a frequency of 10 kHz, the C-V curve exhibits a low-frequency behavior relative to the inversion layer formation time. The absence of a dependence of the capacitance values in the minimum on the frequency indicates that the C-V characteristics of the MIS structure based on HgCdTe with graded-gap layer shows a high-frequency behavior relative to the recharge time of fast surface states. In this case, it is possible to determine the concentration of the majority charge carriers in the SCR by the capacitance value at the minimum of the C-V curve [8, 9, 11].

The electron concentration, determined in this manner, is shown in figure 2 depending on the dose of SXR. It can be seen from the figure that the electron concentration increases slightly with increasing dose. Figure 2 also shows the dose dependence of the product (R_{SCR}A) of the SCR differential resistance R_{SCR} in the strong inversion mode on the area of the field electrode A. The R_{SCR}A value decreases non-monotonically with increasing the radiation dose. It should be noted that the value of this parameter is determined primarily by the impurity-defective system of the SCR.

In addition, studies of the C-V characteristics showed that SXR leads to a change in the spectra of the fast surface states of MIS structures (figure 3). When calculating the spectra (the dependences of the density of surface states on the energy – N_s(E)), a high-frequency method was used. It can be seen
from the figure that this dependence has a non-monotonic character. The reason for the described effects is the rearrangement of the impurity-defective system of the dielectric-semiconductor interface and the near-surface layer of the semiconductor, the presence of a dose-dependent dependence of the effects indicates their radiative character.

Figure 1. The C-V curves of the MIS structure based on the initial $n$-Cd$_{0.24}$Hg$_{0.76}$Te measured for the reverse and forward voltage sweeps at different frequencies and temperature of 77 K.

Figure 2. Dependence of the electron concentration and the product $R_{SCR}$ on the irradiation dose for the epitaxial layer $n$-Cd$_{0.24}$Hg$_{0.76}$Te at temperature of 77 and 12 K, respectively.

Figure 3. Spectra of surface states for MIS structures based on $n$-Hg$_{0.76}$Cd$_{0.24}$Te with a graded-gap layer after exposure to SXR measured at a frequency of 10 kHz at 77 K for different doses of radiation.

4. Discussion
Since direct generation of defects under the action of SXR in crystals is impossible, one of the most probable mechanisms of their occurrence is defect formation in the decay of electronic excitations [1, 2]. Under the conditions of our experiment, the SXR spectrum is concentrated in the 1.5-7 keV range, with the radiation maximum being limited to the interval of 2-5 keV [5]. There is the electron energy of the M shells of the Hg ion in the latter. While the energy levels of the inner shells of Te and Cd are shifted to the region of higher energies [12]. Thus, the primary effect of SXR interaction with a solid solution of Cd$_x$Hg$_{1-x}$Te is the excitation of internal electron shells of Hg ions, which is accompanied
by an external photoelectric effect. As a result, a triply charged \( \text{Hg}^{3+} \) ion is formed, whose lifetime is limited by the Auger effect and is estimated at 10-13 s [1]. As the defect formation model assumes the decay of electronic excitations during this time, as a result of the Coulomb interaction, an ion with an additional charge can move to the interstitial space forming a vacancy or a complex vacancy + atom in the interstices.

Our previous measurements on the \( p-\text{Cd}_{0.23}\text{Hg}_{0.77}\text{Te} \) layers showed a certain increase in the hole concentration after SXR irradiation with the same spectral composition as in the present study, and this does not contradict the hypothesis of generation of Hg vacancies during irradiation [5]. The observed increase in the electron concentration in \( n-\text{Cd}_{x}\text{Hg}_{1-x}\text{Te} \) can not be caused by the same effect. Apparently, in the MBE epitaxial layers of \( \text{Cd}_{x}\text{Hg}_{1-x}\text{Te} \), there is a complex system of post-growth defects of an unknown nature, both donor and acceptor types, the degree of compensation of which can be shifted in a complex manner when exposed to an impurity-defective system of layers.

We note that due to the known anisotropy of the surface properties of \( \text{Cd}_{x}\text{Hg}_{1-x}\text{Te} \) [13, 14] inherent in all multicomponent materials with the sphalerite structure, it can be expected that the surface defect formation process will also depend on the crystallographic orientation of the irradiated surface.

5. Conclusion

Thus, the effect of SXR radiation of a plasma of a laser-induced vacuum spark with a quantum energy of 1.5-7 keV and doses of 0.03-1.5 J/cm\(^2\) on the electrophysical characteristics of MIS structures formed on irradiated semiconductor material (MBE \( n-\text{Cd}_{0.2}\text{Hg}_{0.7}\text{Te} \) with graded-gap layers) was investigated. The effect of SXR on \( n-\text{Cd}_{0.23}\text{Hg}_{0.77}\text{Te} \) leads to changes in the electrophysical characteristics of MIS structures formed on the basis of the irradiated semiconductor, which manifests itself in a non-monotonic increase in the electron concentration from \( 2.6\times10^{15} \) cm\(^{-3}\) to \( 3.9\times10^{15} \) cm\(^{-3}\). An increase in the radiation dose also results in a non-monotonic decrease in the \( R_{\text{SCR}} \) product from 41.87 to 10.81 Ohm\( \times \)cm\(^2\). The impact of SXR leads to a decrease in the density of surface states near the middle of the forbidden band by more than 10 times to values \( (4\div5)\times10^{10} \) eV\(^{-1}\)\( \cdot \)cm\(^{-2}\). It is interesting that the minimum dose of 0.03 J/cm\(^2\) does not cause the described changes in electrophysical properties. The results can be explained by a change in the impurity-defect system of the near-surface semiconductor layer. One of the most probable mechanisms is defect formation in the decay of electronic excitations.

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