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Influence of infrared radiation on the electrical characteristics of the surface-barrier nanostructures based on MBE HgCdTe

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Abstract. Impact of illumination on the admittance of the MIS structures based on MBE $Hg_{1-x}Cd_xTe$ with graded-gap layers and single quantum wells was investigated. It is shown that for HgCdTe-based nanostructures the illumination greatly affects the capacitance and conductance dependencies. The capacitance-voltage characteristics exhibit a low-frequency behavior, which is associated with a decrease in the differential resistance of the space charge region. Especially informative illumination exposure is in the study of deep traps in *n*-HgCdTe (x=0.21-0.23) without graded-gap layer. Illumination leads to the low-frequency behavior of capacitance-voltage characteristics of MIS structures based on *p*-HgCdTe with HgTe single quantum well in the active region, and maximums in the voltage dependences do not appear.

1 Introduction

Nanostructures based on MBE $Hg_{1-x}Cd_xTe$ are promise for a new generation of devices for optoelectronics and nanophotonics [1]. Interest in MIS structures based on the HgCdTe is need to passivate the developed devices surface. The usually used method for studying of the MIS structure is a measurement of admittance in various conditions. Additional information on the physical processes in structures can give admittance measurement at illumination [2, 3].

This work presents the first results of investigation of the admittance at illumination impact for MIS structures based on HgCdTe with nanoinclusions in the active region (graded-gap layers, single quantum wells).

2 Samples and methods

MIS structures have been prepared on the basis of *n*-$Hg_{0.78}Cd_{0.22}Te$ grown by MBE on the Si (013) substrates. During growth of the heterostructures, graded-gap layers with high CdTe content were created on both sides of the working layer (figure 1). Before the formation of the insulator coatings, the conductivity and concentration and mobility of majority charge carriers were investigated by Hall measurements at 78 K. We investigated the MIS structures based on *n*-$Hg_{0.78}Cd_{0.22}Te$ / Al_2O_3 with near-surface graded-gap layer (structure No.1) and without graded-gap layer (structure No.2). The average electron concentration in the epitaxial film was 5.4×10^{14} cm^{-3} and electron mobility was 34000 $cm^2/(V\times c)$. For the structure No. 2, the near-surface graded-gap layer was removed by etching in the Br_2-HBr solution and then, a Al_2O_3 insulator was deposited used by plasma enhanced atomic layer deposition [4]. For the structure No. 1, the insulator coating was formed over the graded-gap layer. The study of these samples allows to investigate the influence of graded-gap layers on the properties of MIS structures.

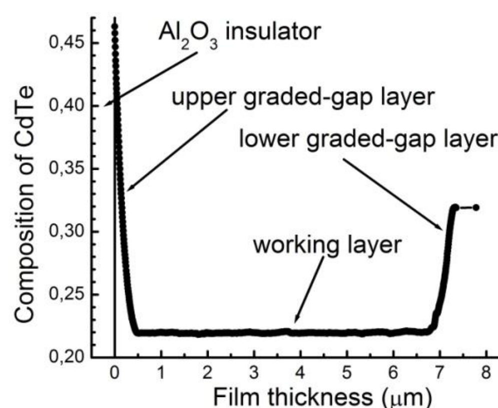

Fig. 1. Distribution of the composition over the thickness of the structure No. 1 based on MBE $Hg_{1-x}Cd_xTe$ measured with an automatic ellipsometer during the growth process.

The samples with HgTe single quantum well (SQW) were fabricated by MBE method based on *p*-HgCdTe on the GaAs (013) substrates at the Institute of Semiconductor Physics of SB RAS (Novosibirsk, Russia). The SQW thickness was 5.6 nm. $Hg_{0.35}Cd_{0.65}Te$ barrier

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layers had a thickness of 35 nm. A double-layer insulator SiO_2/Si_3N_4 was deposited over the CdTe 40 nm layer. Figure 2 shows the basic layout of the layers in the structure with SQW.

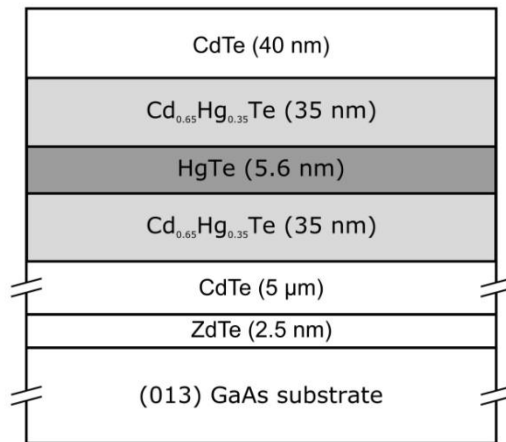


Fig. 2. Scheme of the layers position in structure with SQW.

Measurements were performed with an automated setup for spectroscopy of the nanoheterostructure admittance based on a cryostat Janis and an immittance meter Agilent E4980A. In measurements, the voltage change from negative values to positive ones. Electrophysical characteristics were measured in the dark mode and at illumination through the substrate at light wavelength of 0.94 microns.

3 Results and discussion

3.1 MIS structures based on MBE *n*-HgCdTe with graded-gap layers

Figure 3 shows the capacitance and conductance versus voltage for MIS structures based on *n*-$Hg_{0.78}Cd_{0.22}Te$ with (structure No.1) and without (structure No. 2) a graded-gap layer at temperature 15 K for dark mode and at illumination.

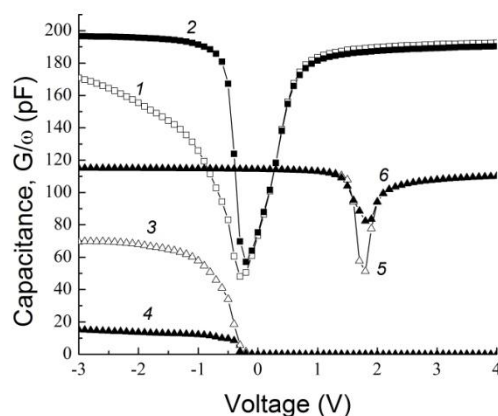
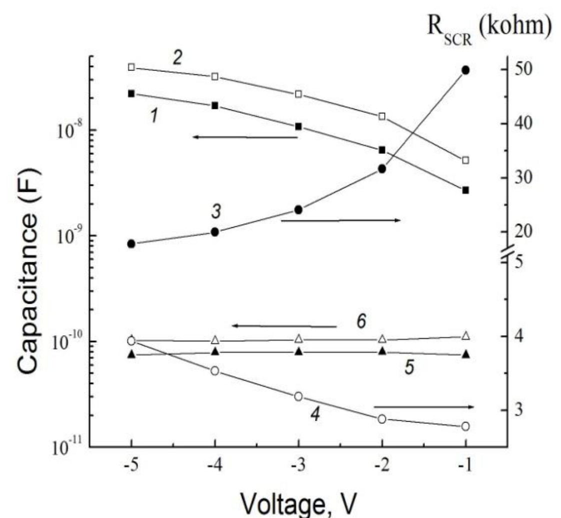


Fig. 3. Voltage dependencies of capacitance (curves 1, 2, 5, 6) and conductance at frequency 20 kHz (curves 3, 4) for MIS structures No. 1 (curves 1-4) and No.2 (curves 5, 6) measured at 15 K in dark mode (curves 1, 3, 5) and at illumination (curves 2, 4, 6). (где ось проводимости?)

Figure 4 shows the values of the equivalent circuit elements of the MIS structure in strong inversion determined from experimental data by the method described in [5]. From Figure 4 can be seen that the capacitance of the inversion layer under illumination increases, due to the increase in the concentration of minority carriers of charge. The illumination reduces the differential resistance of the space charge region (SCR) due to the appearance of an additional mechanism of generation of minority carriers (photogeneration). This reduces the time constant recharging of the inversion layer. The capacitance of the SCR under illumination is somewhat increased, due to the decrease in the maximum thickness of the SCR due to the increase in the concentration of minority carriers in the inversion layer.

From the analysis of Fig. 4, it can be concluded that a illumination strongly changes the capacitance-voltage (CV) characteristics of MIS structures based on $Hg_{0.78}Cd_{0.22}Te$ with a near-surface graded-gap layer. CV curves at illumination demonstrates a more low-frequency behavior than in the dark mode, and when illuminated capacitance increases in the minimum CV curves. At low frequencies, the illumination decreases the conductance of MIS structures based on HgCdTe with graded gap layer, and at high frequencies - to increase conductance. For structure No.2 without the graded-gap layer the impact of illumination is less pronounced, as the CV curves exhibits



low-frequency behavior of in the dark mode.

Fig. 4. Voltage dependencies of inversion layer capacitance (curves 1, 2), resistance of SCR R_{SCR} (curves 3, 4) and capacitance of SCR (curves 5, 6) for MIS structure No. 1 measured at temperature of 15 K at frequency range of 20-50 kHz in dark mode (curves 1, 3, 5) and at illumination (curves 2, 4, 6).

In order to calculate the ideal CV-characteristics at illumination, the Poisson equation for a given distribution of CdTe in the near-surface graded-gap layer was solved numerically [6]. In the calculations, we assumed local electroneutrality; the equation was solved taking into

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account the changes in the near-surface graded-gap layer permittivity, band gap, and intrinsic carrier concentration. Account of illumination conducted by adding to the equilibrium concentration of mobile carriers in the expression for the density of the charge carrier concentration encountered during photogeneration.

Figure 5 shows the dependence of semiconductor capacity in the minimum low-frequency CV characteristics calculated at different temperatures for a structure with graded gap layer and without the graded-gap layer, and the dependence of semiconductor capacity at high frequency in the strong inversion mode calculated for structures with graded-gap layer at a temperature of 77 K.

Convenient to use for the characterization of illumination intensity ratio p1/p0, where p1 - concentration of minority carriers under illumination, p0 - concentration of minority carriers in the dark mode in the semiconductor bulk [3]. It can be seen that for a structure without a graded-gap layer capacity increase in the minimum CV characteristics begins with small values p1/p0 (curve 5), for structures with graded gap layer at low values of p1/p0 capacity at the minimum low-frequency CV curves does not change, and the increase in capacity at the minimum CV characteristics occurs, starting with a certain value p1/p0, which increases with decreasing temperature. The reason for this is that the value of p0, calculated near the interface at the maximum content of CdTe is less than the mean effective concentrations of minority carriers in the SCR as the equilibrium dark concentration of minority carriers in the graded-gap layer increases with distance from semiconductor boundary.

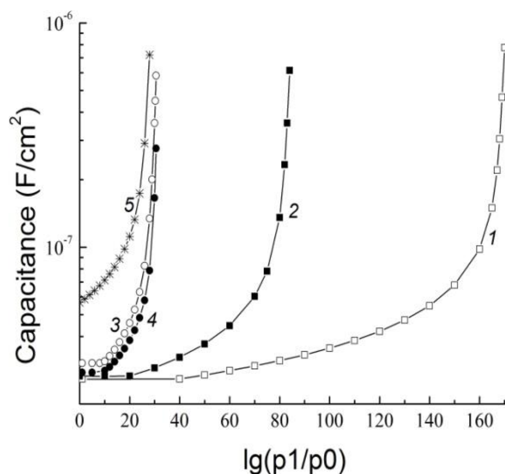


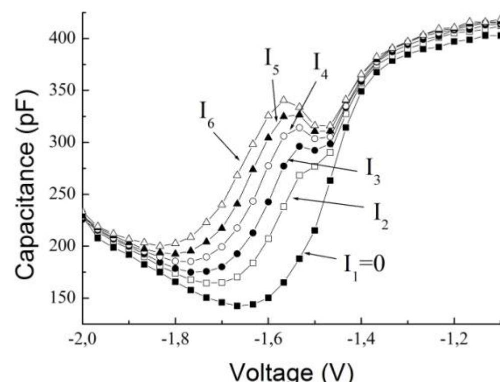
Fig. 5. Calculated dependencies of capacitance in minimum of low-frequency CV curves versus relation of minority carrier concentration at illumination (p1) to minority carrier concentration in dark mode for graded-gap n-$Hg_{0.78}Cd_{0.22}Te$ at electron concentration of $1.7*10^{15}$ cm^{-3} for various temperatures 15 (curve 1), 30 (curve 2), 77 K (curve 3), for n-$Hg_{0.78}Cd_{0.22}Te$ without graded-gap layer at 15 K (curve 5) and high-frequency capacitance in strong inversion mode for graded-gap n-$Hg_{0.78}Cd_{0.22}Te$ at 77 K (curve 4).

Investigation admittance under illumination for MIS structures based on *n*-HgCdTe in the strong inversion mode allows you to determine the value of the insulator capacitance, which is impossible for MIS structures based on *n*-HgCdTe in the accumulation mode due to the effects of degeneracy and non-parabolicity of conduction band.

3.2 MIS structures based on MBE *n*-HgCdTe with deep traps

Especially informative illumination exposure in the study of deep traps in *n*-HgCdTe without graded-gap layer. The appearance of deep traps in the CV characteristics under illumination only was observed (in dark mode, the traps levels are filled, and traps are not manifested in the measurements). If the deep traps appear in dark characteristics, the illumination typically reduces recharge time for deep traps which exhibit a low-frequency behavior at higher frequencies.

It is of interest that the special features associated with the capacity due to a deep level appear in the capacitance-voltage and volt-siemens characteristics of the MIS structures, for which the maximal photo-emf drop is observed under illumination in the strong inversion mode [7]. Without illumination, no special features were observed in the capacitance-voltage characteristics of some samples. Figure 6 shows the CV curves for the MIS HgCdTe/AOF structures without a graded-band-gap layer in the dark and on illumination. The capacitance-voltage characteristics for the illuminated MIS *n*-HgCdTe structures with different insulator coatings are found to differ from each other indicating that this deep level is rather due to the epitaxial-film properties than to the insulator-semiconductor interface. The special features in the voltage dependences of capacitance due to the deep level testify to the fact that the states located in the vicinity of the insulator-semiconductor interface (possible, at the interface between the natural oxide layer and epitaxial film) take part in the formation of capacitance properties of the structures. No special features were observed in the capacitance-voltage characteristics under illumination of



samples produced from other wafers.

Fig. 6. CV curves for MIS structure based on n-$Hg_{0.77}Cd_{0.23}Te$ without graded-gap layer at 77 K at various intensity of illumination ($I_6 > I_5 > I_4 > I_3 > I_2 > I_1 = 0$).

Estimations of the deep-level energy position made by the method of high-frequency capacitance-voltage characteristics using the dark capacitance-voltage

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characteristic show that the observed deep level is 0.04–0.05 eV above the valence-band top. The level of a doubly ionized mercury vacancy, being an acceptor center, can have a similar energy position.

Thus, a levels can be present in the near-surface layer of the *n*-HgCdTe film. These levels determine the shape of the capacitance-voltage characteristics of the MIS structures under illumination.

3.3. MIS structures based on MBE *p*-HgCdTe with HgTe SQW

Figures 7 and 8 show dependencies of capacitance on voltage for MIS structure with SQW measured at a temperature of 8 K for various frequencies of test signal in dark mode and under illumination, respectively. It may be seen that HgCdTe has a *p*-type conductivity, and in the strong inversion mode at frequencies from (1-20) kHz non-monotonic change in capacitance is observed due to the recharging quantization levels [8]. At low frequencies CV characteristic have a low-frequency behavior and maxima become less pronounced than at frequencies of 1–20 kHz.

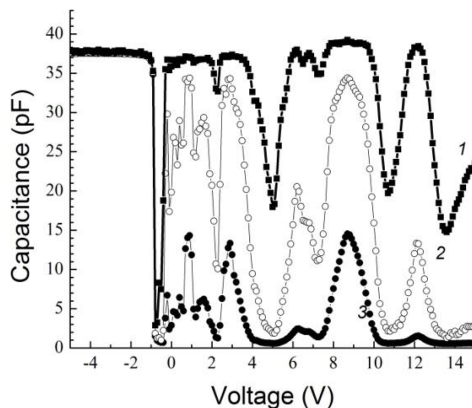

Fig.7. CV curves for MIS structures based on *p*-$Hg_{0.35}Cd_{0.65}Te$ with HgTe SQW measured at 8 K in dark mode at various frequencies, kHz: 1 – curve 1, 5 – curve 2, 20 – curve 3.

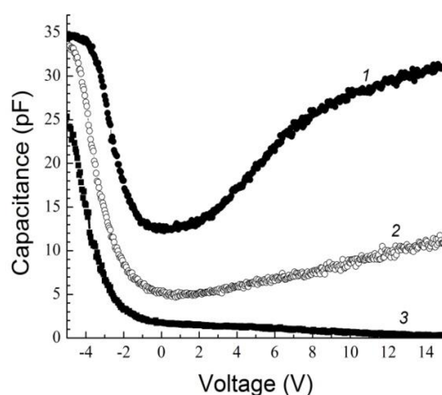

Fig.8. C-V curves for MIS structures based on *p*-$Hg_{0.35}Cd_{0.65}Te$ with HgTe SQW measured at 8 K at illumination at various frequencies, kHz: 1 – curve 1, 5 – curve 2, 20 – curve 3.

Under illumination maxima in the voltage dependences do not appear (Fig. 8). A possible cause is the photoexcitation of charge carriers from the quantum-well levels.

4 Conclusions

Thus, to study the effect of illumination on the electrical characteristics of MIS structures based on HgCdTe, including for cases presence of graded-gap layers and quantum wells in the active region.

CV measurements have shown that for structure with graded-gap layer under illumination reduces the time of formation of the inversion layer and an increase in capacitance value at the minimum low-frequency CV curves. Parallel differential conductance of MIS structure under illumination decreases at low frequencies, but increases at high frequencies. The changes under illumination element values equivalent circuit in strong inversion mode at different bias voltages were investigated. Low-frequency and high-frequency CV characteristics of MIS structures based on MBE *n*-$Hg_{0.78}Cd_{0.22}Te$ in the dark and under different illumination intensities were numerically simulated. For structures with graded gap layer at low illumination intensities, there is a reduction of the surface potential, but there are no changes in the capacitive characteristics.

It is noted that the deep levels manifest themselves in the capacitance-voltage characteristics upon illumination of the MIS structures based on *n*-$Hg_{0.78}Cd_{0.22}Te$ without graded-gap layer under study. The deep-level energy according to the admittance measurements is 0.04–0.05 eV of the valence-band top.

It is experimentally shown that for MIS structures based on MBE *p*-HgCdTe the presence of a SQW thickness of 5.6 nm can lead to the appearance of capacitance-voltage characteristics peaks in the strong-inversion mode. Under illumination maxima in the voltage dependences do not appear due to photoexcitation of charge carriers from the SQW levels.

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