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Some properties of near-surface layer of graded-gap MBE HgCdTe after boron ion implantation

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Abstract. The effect of ion implantation of boron ions with an energy of 100 keV and a dose of $(1\text{-}6)\times10^{15}$ cm^{-2} in the MBE HgCdTe films on the characteristics of the MIS structures based on these films was investigated. The changes of the conductivity type in the near-surface layer of HgCdTe after ion implantation of boron and etching by ions of argon were detected. The concentrations of the major charge carriers in the near-surface layer of the epitaxial films after ion implantation and after ion etching were close to 5.88×10^{16} cm^{-3} and 2.47×10^{17} cm^{-3}, respectively.

1. Objects of research

The narrow-gap HgCdTe semiconductor is widely used to create highly-sensitive infrared detectors [1]. Ion implantation method is often used when creating HgCdTe photodiodes. The admittance measurements for MIS structures allow to study the changes in the properties of the near-surface semiconductor layer after ion irradiation.

The structures based on n-$Hg_{0.775}Cd_{0.225}Te$ were grown by MBE on the GaAs (013) substrates in Rzhanov Institute of Semiconductor Physics SB RAS. Graded-gap layers with high content of CdTe were grown on both sides of the working layer. The CdTe composition distribution at thickness of the epitaxial film $Hg_{1-x}Cd_xTe$ measured by an automatic ellipsometer in the process of growing an epitaxial film is shown in figure 1. The hole concentration at 78 K was 8.6×10^{15} cm^{-3}. The hetero-epitaxial film was divided into three parts. The first part was used to make a control sample. The second part was subjected to ion etching during 5 minutes with ion energy of 0.5 keV at current density of 0.1 mA/cm^2. Implantation of boron was carried out in the third part with ion energy of 100 keV and dose of $(1\text{-}6)\times10^{15}$ cm^{-3}. MIS structure based on all films parts were created by deposition of SiO_2/Si_3N_4 insulator and indium electrodes. The inset of figure 1 schematically shows the sequence of the layers in the fabricated MIS structures.

The measurements were performed with an automated setup for spectroscopy of the nanoheterostructure admittance on the basis of non-optical cryostat Janis and immittance meter Agilent E4980A (temperature range of 8-475 K, the range of the measured impedance of 0 - 1 GOhm with the resolution on the capacitance and normalized on frequency conductance to 1 fF , the range of voltage bias of -40-+ 40 V, the frequency range of 20 Hz - 2 MHz). In measurements, the voltage change from negative values to positive ones was taken as the forward direction of sweep, and the voltage change from positive values to negative ones was taken as the reverse direction of sweep.

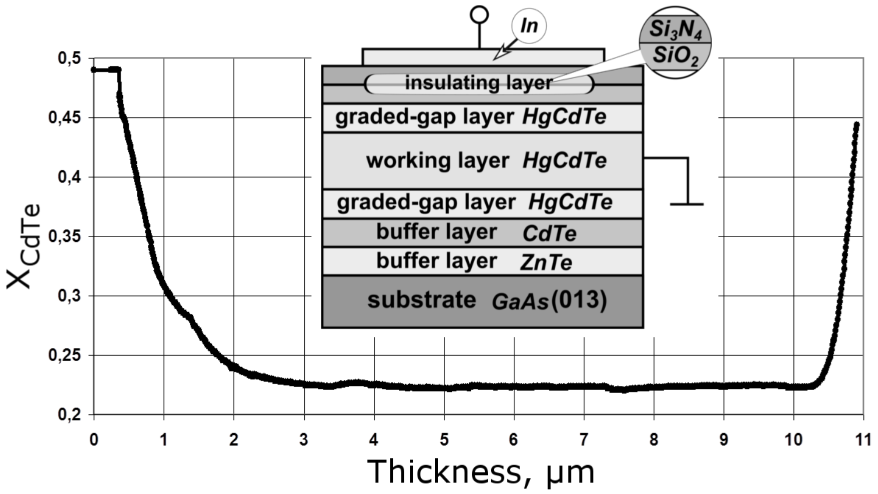

Figure 1. The CdTe composition distribution on thickness of the epitaxial film $Hg_{1-x}Cd_xTe$, measured by an automatic ellipsometer in the process of growing an epitaxial film. The inset in the figure shows the sequence of the layers in the fabricated MIS structures.

2. Results of the study

Figure 2 shows the capacitance-voltage (CV) characteristics of the MIS structure based on the initial film measured at a temperature of 77 K. Figure 2 shows that the CV characteristics correspond to the *p*-type semiconductor. The CV characteristics at a frequency of 1 MHz are almost a high-frequency behavior. For all measurements of the capacitance and conductance, the effect of the series resistance of the epitaxial film bulk was excluded [2]. For MIS structures based on *p*-HgCdTe series resistance of epitaxial film bulk is usually significant due to the low mobility of the majority charge carriers (holes). At a frequency of 10 kHz CV characteristics show the low-frequency behavior, the dip of the low-frequency CV characteristic has a large depth due to the presence of the graded-gap near-surface with a high composition of CdTe [3]. Figure 3 shows the CV characteristics of MIS structure based on the HgCdTe film after ion implantation of boron measured at 77 K at a forward voltage sweep.

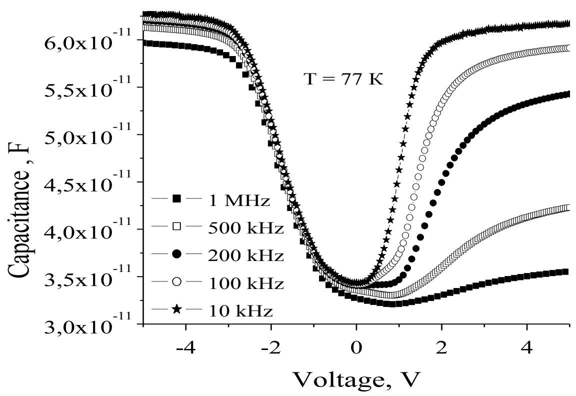

Figure 2. CV characteristics of MIS structure based on the initial HgCdTe film measured at a temperature of 77 K at different frequencies of the test signal.

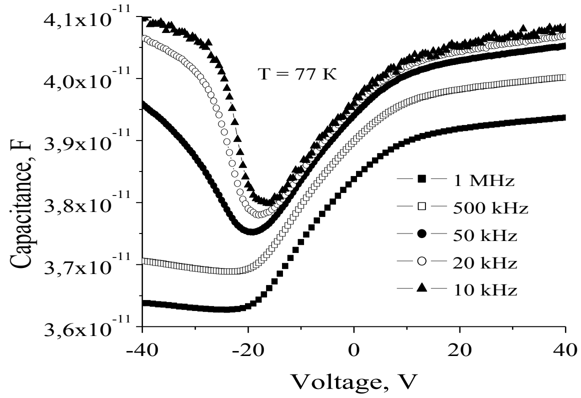

Figure 3. CV characteristics of MIS structure based on the HgCdTe film after ion implantation measured at a temperature of 10 K and 77 K at different frequencies of the test signal.

Figure 3 shows the change in the type of conductivity of the semiconductor film due to ion implantation of boron. It may be noted that the majority charge carrier concentration after ion implantation of boron has increased sharply leading to a low modulation of capacitance in the CV characteristic. Figure 4 shows the CV characteristics of MIS structure based on $Hg_{1-x}Cd_xTe$ films after etching by ions of argon measured at 77 K at different frequencies at the forward sweep of voltage. Figure 4 shows that the change of the conductivity type of epitaxial film also occurred in the case of ion etching.

Modulation of capacitance on the CV characteristics for the MIS structure based on the film after ion etching is more than for the structure based on the film after ion implantation. It indicates that the concentration of the majority charge carriers after ion etching has also increased, but not so significantly how after ion implantation of boron. The value of a slope angle for $1/C^2(V)$ dependency where C is MIS structure capacitance in the depletion mode at a frequency of 1 MHz (figure 5) was used to estimate the concentration of major charge carriers for the test samples at 77 K [4]. Defined by this method the concentration of majority carriers of charge in the near-surface layer was 2.57×10^{15} cm^{-3} for the structure based on the initial film. For the structure based on the film after ion etching the concentration of the majority charge carriers amounted to 5.88×10^{16} cm^{-3}, and for the structure after ion implantation of boron the concentration has reached the value 2.47×10^{17} cm^{-3}.

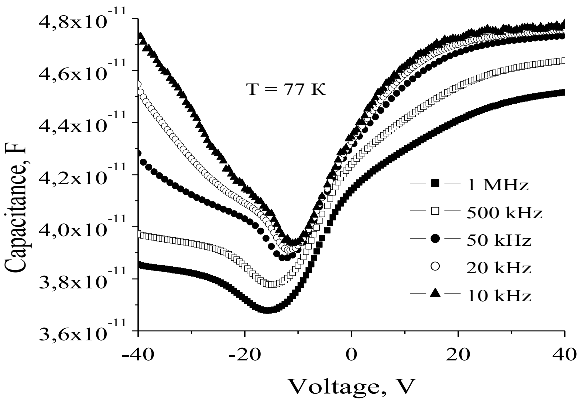

Figure 4. CV characteristics of MIS structure based on HgCdTe film after ion etching measured at a temperature of 77 K at different frequencies of the test signal.

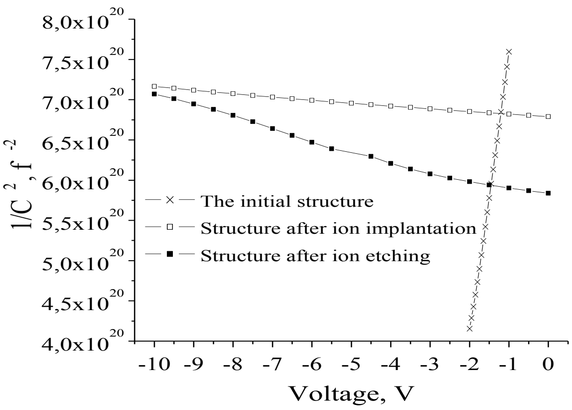

Figure 5. The slope of the $1/C^2$ in the depletion mode at a frequency of 1 MHz at temperature 77 K for all three structures.

Figure 6 shows the dependencies of the series resistance of epitaxial film bulk on reciprocal temperature at a frequency of 50 kHz for structures based on the initial film and also films after ion implantation and ion etching. Figure 6 indicates that the initial structure has the greatest value of series resistance of epitaxial film over the whole temperature range. A large value of epitaxial film resistance is typical for structures based on films with p-type conductivity. This occurs because of the low mobility of holes in the HgCdTe layer. The structure based on the film after ion implantation has the smallest value of series resistance of the epitaxial film. This is due to the fact that as a result of implantation and annealing there appears a high concentration of electrons in a sufficiently thick layer of the semiconductor film. Unlike the implantation - ion etching also is changing the conductivity of the film, but in this case, the electron concentration was not so high. It is also likely that the penetration of boron ions in the epitaxial film during ion etching $Hg_{1-x}Cd_xTe$ occurs to a lesser depth as compared with implantation.

Figure 7 shows the dependencies of the differential resistance of the space charge region (SCR) in strong inversion mode on the reciprocal temperature at a frequency of 50 kHz for structures based on the initial film and also films after ion implantation and ion etching. Figure 7 indicates that up to a temperature of about 25 K the structure based on the film after ion etching has a maximum value of the differential resistance of the SCR. However, the pace of the fall of the differential resistance at higher temperatures for a given structure results in the fact that after 30 K values of its value becomes smaller than for the other structures. The rate of the decline of the differential resistance with increasing temperature for the original structure and structure created on the film after ion implantation are similar up to a temperature of 70 K. In a whole temperature range the values of differential resistance of SCR for original structure do not exceed the values for the structure after ion implantation.

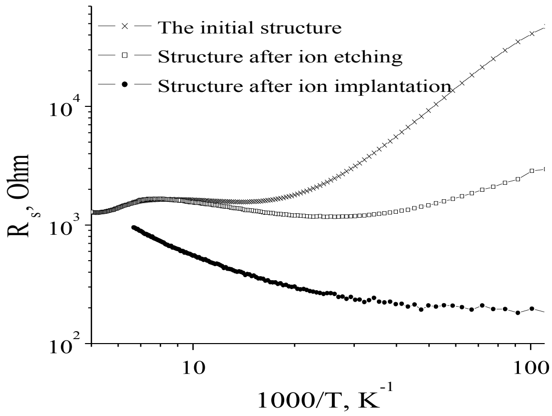

Figure 6. The dependencies of the series resistance of epitaxial film bulk on reciprocal temperature at a frequency of 50 kHz.

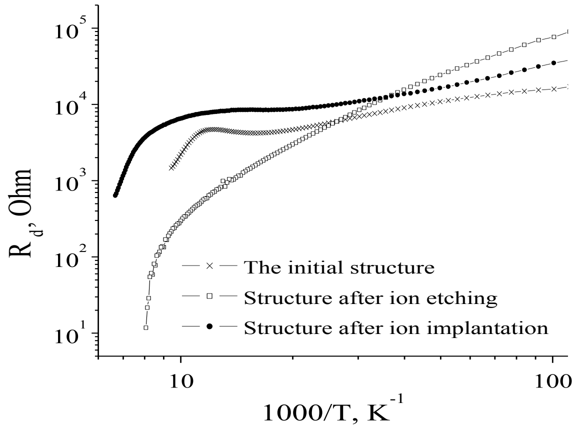

Figure 7. The dependencies of the differential resistance of the SCR in strong inversion mode on reciprocal temperature at a frequency of 50 kHz.

3. Conclusions

The conductivity type in the near-surface layer of HgCdTe changes after both radiation impacts. The electron concentration after implantation was much higher than after etching. The electron concentration determined from the CV characteristics was equal to 5.88×10^{16} cm^{-3} and 2.47×10^{17} cm^{-3} for the ion etching and ion implantation, respectively.

Ion implantation leads to a significant reduction in the resistance of epitaxial film bulk compared to ion etching under the same distance from the rear electrode to the indium field electrode. The question of the dependence of the differential resistance of the SCR on the temperature for different types of impact requires an additional study.

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