Influence of plasma volume discharge in atmospheric-pressure air on the admittance of MIS structures based on MBE *p*-HgCdTe

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Abstract. This article investigates the effect of a nanosecond plasma volume discharge, which is formed in an inhomogeneous electrical field at atmospheric pressure, on the electrical properties of MIS structures based on HgCdTe (MCT) epitaxial films. The MIS structure based on films exposed to the discharge significantly changed its main parameters. The most notable feature of the structure exposed to discharge is the significant increase in the positive fixed charge in the insulator. A possible reason for changes in the characteristics of MIS structure after exposure to discharge is the significant change in the impurity-defect system of the semiconductor near the interface. This is accompanied with a formation of an insulator film of nanometer thickness on the surface, which gives rise to positive fixed charge.

1. Introduction

One of the basic materials for the manufacture of IR photodetectors is the HgCdTe solid solution. This material has a low carrier concentration at the operating temperatures and a high quantum efficiency. The current task is to achieve controlled changing of material parameters for obtaining the desired semiconductor structures.

At the present moment, various types of discharge and electron beams are widely used for modifying the near-surface layers of materials [1]. Earlier studies investigated the influence of volume nanosecond pulse discharge in the air at atmospheric pressure in the epitaxial p-HgCdTe. The results showed that this effect leads to the formation of a surface layer with high electronic conductivity [2]. Further analysis [3] allowed us to suggest the formation of a layer of chemical MCT compounds with oxygen and/or nitrogen in the surface region. The formed layer has a built-in positive charge, which leads to the formation of an inversion layer of n-type conductivity at the interface of oxide / MCT. Additional studies of the surface properties of the irradiated material are required in order to confirm this hypothesis.

An MIS structure based on irradiated material was used to study the properties of the surface of semiconductor films. This paper presents the results of the studies of the effect of volume pulses nanosecond discharge in the air at atmospheric pressure on the electrical properties of MIS structures based on heteroepitaxial HgCdTe material.

2. Samples and experimental techniques

The samples of p-type conductivity ($p = 1.1 \div 2.5\times10^{16}$ cm^{-3}, $\mu_p = 300 \div 500$ cm^{2}V^{-1}s^{-1}) grown by molecular beam epitaxy in the Institute of Semiconductor Physics SB RAS (Novosibirsk) were prepared for experiment. The samples grown in this manner were put in a gas diode on a copper anode. The Radan-220 generator was used as a pulse-voltage source forming voltage pulses with the amplitude of ~ 230 kV (open-circuit voltage), the high-amplitude pulse duration of ~ 2 ns (at a matched load), and the rise time of ~ 0.5 ns. The samples were irradiated by 1,200 pulses in the periodic mode at the repetition rate of 1 Hz.

The MIS structures were formed on the basis of the initial and irradiated samples. The Al_2O_3 layer approximately 77 nm thick deposited using plasma atomic layer deposition was used as an insulator [4]. The metal electrodes are made of indium. Structures No.3 and No.4 were formed on the basis of the epitaxial film after the impact of the electromagnetic discharge. Structures No.1 and No.2 were used as control samples. The chemical mechanical surface treatment with HgCdTe was not conducted before the deposition of the insulator.

The measurements were performed using an automated setup of the nanoheterostructures admittance spectroscopy on the basis of a non-optical cryostat Janis and an immittance meter Agilent E4980A. When measuring the field dependences of the capacitance and conductance, 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.

3. Experimental results and discussion

Figure 1 shows the normalized capacitance-voltage (CV) characteristics of structures No.1 and No.3. For structures No.1 and No.2, the capacitive characteristics at 77 K were similar. The CV characteristics of structure No.4 are qualitatively similar to the CV characteristics of structure No.3. The CV characteristics of structures No.3 and No.4 are shifted into the region of higher negative voltages. At the same frequency, the CV characteristics of structures No.3 and No.4 demonstrate a lower-frequency behavior than the CV characteristics of structures No.1 and No.2. For structures No.3 and No.4, the frequency dispersion of capacitance in the minimum of CV characteristics was observed, and the slope of the CV characteristics in the depletion at the forward voltage sweep is flatter than that at the reverse sweep. Also, for these structures, the capacitance modulation at the forward voltage sweep is higher (the value of the capacitance in the minimum of the low-frequency CV characteristic is lower), and there appears a much larger hysteresis of the CV characteristics.

Table 1 shows the main parameters of MIS structures No.1 - 4, which were obtained from the measurements of the CV characteristics at 77 K. The densities of fixed and mobility charges were determined from the shifts of the flat-band voltage in real and ideal structures. MIS structures based on HgCdTe exposed to the impact of discharge have a greater density of positive fixed charge. The mobile charge density in these samples is also higher.

An important characteristic of an MIS structure is the value of the differential resistance of the space-charge region (SCR) in the strong inversion mode (R_{SCR}) [5]. The research of the differential resistance of the SCR for MIS structures based on MBE *n* (*p*)-HgCdTe (x = 0.21-0.23) in a wide temperature range was carried out in other articles [6, 7]. The studies of the differential resistance at 200 kHz showed that, at 77 K, it was about 1,800 Ohm for structures No.1 and No.2. For structures No.3 and No.4, the values of the differential resistance of the SCR were so small that they did not exceed the error in determining R_{SCR} in a wide temperature range. The results of the measurements of the differential resistance of the SCR explain the low-frequency type of CV characteristics at sufficiently high frequencies for structures No.3 and No.4. The small values of the differential resistance of the SCR for structures No.3 and No.4 indicate a high rate of minority carriers (electrons) flow to the inversion layers. The most likely mechanism for the appearance of additional minority carriers in the inversion layer is the exchange of electrons with the inversion layer in the after-electrode region. This layer is induced by a significant positive fixed charge [5, 8].

One possible reason for the presence of a positive fixed charge can be the appearance of a thin insulator film on the surface of HgCdTe. This is due to the formation of oxides when exposed to the discharge. It is known that a positive fixed charge is typical for the anodic oxide film on HgCdTe [9, 10]. It is usually associated with the presence of oxygen vacancies in the anodic oxide [11]. In the system of MCT – anodic oxide at a distance of 10 nm from the interface – the slow surface states can exchange their charge with the semiconductor by means of tunneling. The fixed charge is located at the distance of more than 10 nm from the interface [10].

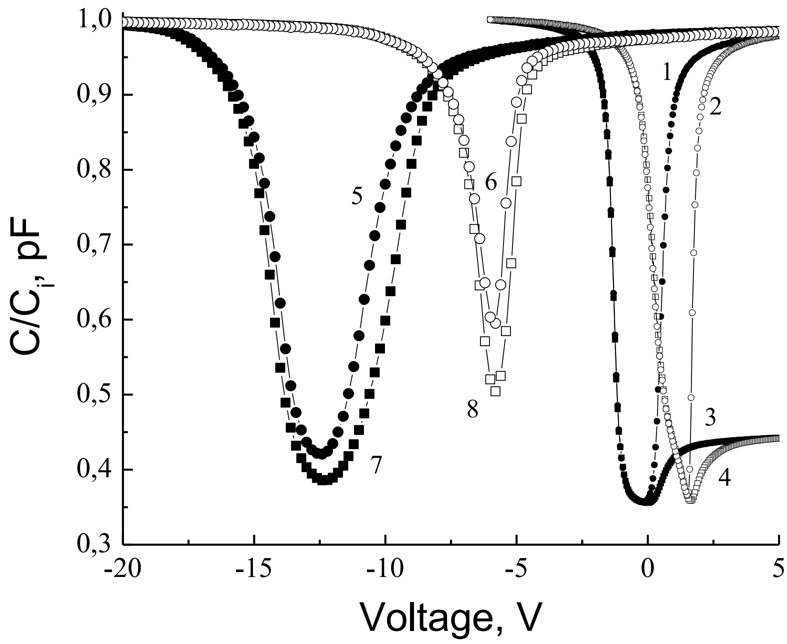

Figure 1. CV characteristics of MIS structures based on *p*-HgCdTe (control sample, structure No.1 (curves 1, 2, 3, 4) and No.3 (curves 5, 6, 7, 8)) measured at 77 K at the forward (curves 1, 3, 5, 7) and reverse (curves 2, 4, 6, 8) voltage sweeps at different frequencies. Curves 1, 2, 5, 6 - 10 kHz, the curves 3, 4, 7, 8 - 1 MHz

Table 1. Parameters of MIS-structures based on *p*-HgCdTe obtained from CV characteristics at 77 K

No.	Fixed charge density, cm^{-2}	Mobile charge density, cm^{-2}	The major carrier concentration obtained from minimum of the CV characteristic, cm^{-3}	The major carrier concentration obtained from $1/C^2(V)$ dependency in depletion mode, cm^{-3}
1	$1.15 \cdot 10^{11}$	$5.73 \cdot 10^{11}$	$4.05 \cdot 10^{15}$	$3.96 \cdot 10^{15}$
2	$9.49 \cdot 10^{10}$	$2.93 \cdot 10^{11}$	$4.60 \cdot 10^{15}$	$4.63 \cdot 10^{15}$
3	$3.28 \cdot 10^{12}$	$3.36 \cdot 10^{12}$	$6.30 \cdot 10^{15}$	$1.25 \cdot 10^{16}$
4	$6.77 \cdot 10^{12}$	$4.93 \cdot 10^{12}$	$9.22 \cdot 10^{15}$	$2.40 \cdot 10^{16}$

For the studied structures, the thickness of the insulator layer must be several nanometers. At a larger thickness, reduction in capacitance would be observed due to the insulator thickness increase. Therefore, an insulator layer with a small thickness has a higher density of the fixed positive charge than a typical anodic oxide. It is possible that, after the impact of the discharge in HgCdTe, a layer with a high density of build-in positive charges appears near the surface. These charges cannot change their state of charge due to the potential barriers.

4. Conclusions

The admittance of MIS structures based on MBE hetero-epitaxial *p*-$Hg_{0.78}Cd_{0.22}Te$ was investigated in a wide range of frequencies and temperatures. The investigated samples can be divided into two groups: MIS-structures that are based on the initial MCT films (control samples) and MIS-structures that are based on films exposed to the discharge. It is shown that the impact of the discharge substantially changes the characteristics of MIS structures.

The most notable feature of the structure exposed to discharge is a significant increase in the positive fixed charge in the insulator. This causes the appearance of an inversion layer in the after-electrode regions, which acts as the source of minority carriers and contributes to the formation of a sub-electrode inversion layer. Typical features of structures after exposure to discharge are extremely low values of the differential resistance of the SCR in the strong inversion mode and low-frequency behavior of the experimental CV characteristics at high frequencies.

The impact of the discharge increases the effective density of the mobile charge and the appearance of hysteresis of the electrical characteristics. A feature of the hysteresis is the difference of the capacitance in the minimum of the experimental low-frequency CV characteristics at the forward and reverse voltage sweeps and a change in the slope of the CV characteristics in the depletion mode. It is probable that the impact of the discharge increases the average density of the surface states in the depletion region.

MIS structure based on films exposed to the discharge significantly changed its main parameters. The heterogeneity of the changes in the properties over the structure area after the impact of the discharge points toward the heterogeneity of the discharge of its cross section. A possible reason for changes in the characteristics of MIS structures after exposure to discharge is the significant change in the impurity-defect system of the semiconductor near the interface. This is accompanied with a formation of an insulator film of nanometer thickness on the surface, which gives rise to positive fixed charge.

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