Influence of pulsed nanosecond volume discharge in atmospheric-pressure air on the electrical characteristics of MCT epitaxial films

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ABSTRACT

The purpose of this paper was investigating the effect of volume nanosecond discharge in air at atmospheric pressure on the electro-physical properties of the HgCdTe (MCT) epitaxial films grown by molecular beam epitaxy. Hall measurements of electro-physical parameters of MCT samples after irradiation have shown that there is a layer of epitaxial films exhibiting n-type conductivity that is formed in the near-surface area. After more than 600 pulses of influence parameters and thickness of the resulting n-layer is such that the measured field dependence of Hall coefficient corresponds to the material of n-type conductivity. Also it is shown that the impact of the discharge leads to significant changes in electro-physical characteristics of MIS structures. This fact is demonstrated by increase in density of positive fixed charge, change in the hysteresis type of the capacitance-voltage characteristic, an increase in density of surface states. The preliminary results show that it is possible to use such actions in the development of technologies of the controlled change in the properties of MCT.

Keywords: HgCdTe, epitaxial films, electro-physical parameters, MIS-structures, diffuse volume discharge

1. INTRODUCTION

The solid solution $Hg_{1-x}Cd_xTe$ (HgCdTe, MCT) is a widely used material for preparation of intrinsic detectors of infrared (IR) radiation [1]. HgCdTe has proved to be a versatile semiconductor material for IR detection, as its tunable band gap offers the flexibility in the choice of wavelength band as well as the temperature of operation. For temperature imaging the most commonly used region of wavelengths is 8-14 μm, which corresponds to the $Hg_{1-x}Cd_xTe$ composition with $x = 0.22$. A wide variety of modern industrial, strategic, defense, and space applications require IR focal plane array detectors in large pixel formats. Therefore of particular interest is the characterization and study of properties of an epitaxial MCT material grown by molecular-beam epitaxy (MBE). Along with the study of the initial properties of epitaxial films of MCT grown by MBE a very urgent task is controlled changing of the parameters of the material in order to obtain the desired semiconductor structures. Therefore, the search for new methods of changing the initial parameters of the material is an actual problem.

At present, pulse volume (diffuse) discharges are widely used in science and engineering [2-4]. Preionization sources of different design and discharge gaps with a uniform electric field are used to form a volume discharge. It has been known that it is possible to form a diffuse discharge at atmospheric pressure of various gases even without any additional source of preionization [5]. It is shown that conditions of obtaining such diffuse discharge without a source of additional ionization are extended at the voltage pulse duration reduction and at a short interelectrode gap. At higher pressures of different gases, including air at atmospheric pressure, a volume (diffusion) discharge is formed in the inhomogeneous electrical field due to runaway electrons and X-ray radiation. This discharge was named a runaway electron preionized diffuse discharge (REP DD). A special feature of a REP DD is a possibility of realizing high specific power of energy contribution (up to 800 MW/cm^3) [6]. At the same time beams of runaway electrons with the current amplitude of tens-to-hundreds amperes are generated from the discharge plasma, and the half-amplitude duration of pulse of the beam current does not excess 100 ps [7]. Thus, during formation of a nanosecond volume discharge in the air, the anode is acted upon by a combination of a dense nanosecond-discharge plasma with the specific power of energy contribution of hundreds of megawatts per cubic centimeter and a supershort electron beam with a wide energy spectrum. In addition, the anode is affected by a shock wave of UV- and VUV radiation from the discharge plasma.

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It was shown [8, 9] that the metal surface can be modified and cleaned by a REP DD. The aim of this work was to study the effect of volume nanosecond discharge in air at atmospheric pressure on the electro-physical properties of epitaxial HgCdTe grown by MBE.

2. EXPERIMENTAL APPARATUS AND METHODS

For research a series of samples of epitaxial films of p-type HgCdTe ($p = 1 \div 2{\cdot}10^{16}$ cm^{-3}, $\mu_p = 300 \div 500$ cm^{2}V^{-1}s^{-1}) grown by molecular beam epitaxy in the Institute of Semiconductor Physics of Siberian Branch of Russian Academy of Sciences in Novosibirsk were used. The content of CdTe in the operating layer of epitaxial films was x = 0.22. The width of the upper variband layer was close to 0.4 micrometers while the content of CdTe on the surface was 0.44. The value of the content x and the width of the epitaxial film were controlled by in situ ellipsometric measurements. The controlling of the content x was conducted with the help of the optical transmittance spectra at room temperature.

The irradiation of the MCT epifilms samples by REP DD was carried out with specially designed setups. The irradiations were performed using a discharge chamber (Fig. 1a). The as-grown samples were placed in a gas diode on a copper anode. A distance from a flat copper to a tubular electrode could be varied within 8–16 mm. The interelectrode voltage was supplied from a pulser of the RADAN-220 type, which generates voltage pulses with an amplitude of ~230 kV (in the open-circuit regime), a FWHM of ~ 2 ns (on a matched load), and a leading front width of ~ 0.5 ns. The discharge current was measured using a shunt composed of chip resistors connected between the foil anode and the discharge chamber housing. The results of measurements have shown that the current pulse amplitude for both polarities of the applied voltage was ~3 kA and the total duration of the discharge current pulse was ~30 ns (the first half-period of the discharge current pulse had a duration of ~8 ns). The generator RADAN-220 provides specific power input in gas discharge plasma above 0.8 GW/cm^3 under atmospheric pressure in air at electrodes spacing of 8 mm. Figure 1b shows a photograph of the discharge. The samples were irradiated in the repetitively pulsed mode with a pulse repetition rate of 1 Hz. Exposure was carried out in the range of 100 ÷ 1200 pulses. The surface of the irradiated samples was studied using atomic force microscope (AFM) "Ntegra Prima" (by NT-MDT) and optical profilometer MicroXAM-100 at ambient conditions.

a) b)

Figure 1. The image of the discharge chamber in setup (a) and of REP DD in atmospheric pressure air (b).

Two series of samples were prepared. The first samples series was made for conducting Hall measurements. Electro-physical parameters of the MCT samples before and after exposure were determined from measurements of the Hall effect by van der Pauw method. The measurements were performed at a constant current flowing through the sample (I = 1 mA) for the two directions of the current and two directions of a constant magnetic field. Removal of thin layers from irradiated material’s surface was carried out in a 0.2% solution of bromine in dimethylformamide.

The second series of samples was used to create the MIS structures. In this series the two samples were used. The first was control sample. The second sample was irradiated with 1200 pulses of REP DD. The measurements of MIS structures parameters were performed with an automated setup for spectroscopy of the nanoheterostructure admittance based on a non-optical cryostat Janis and an immittance meter Agilent E4980A (the temperature range of 8–475 K, the range of the measured total resistance of 0-1 GΩ with the capacitance resolution and frequency normalized conductivity up to 1 fF, the set up voltage range of –40 – +40 V, and the frequency range of 20 Hz – 2 MHz). In these 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.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Analysis of the results of measurements of electrophysical parameters of the irradiated samples of epitaxial MCT have shown that after irradiation in the range of 100 ÷ 1200 pulses an increase in conductivity is visible for all the samples. Moreover, for samples exposed to pulses in the range from 100 to 400, a decrease in the value of the Hall coefficient is observed. In this case, a shift of the inversion point for the sign of the Hall coefficient in the region of higher magnetic fields (from 0.17 T to 0.28 T) at the field dependence of the Hall coefficient is observed. Increasing the number of pulses of impacts of volume discharge to 600 pulses results in a reversal of the sign of the Hall coefficient (Fig. 2, curve 2).

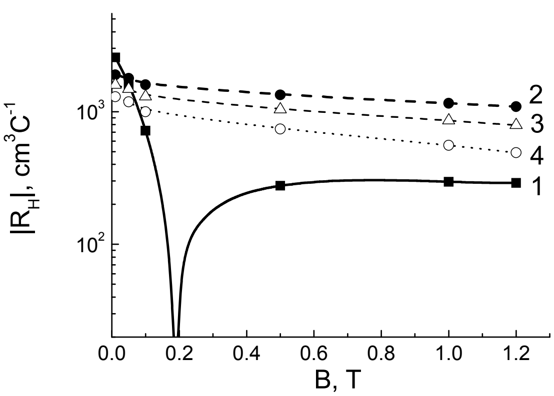

Figure 2. The field dependence of the Hall coefficient for samples of CdHgTe epitaxial films before (1) and after exposure to a volume discharge. The number of exposure pulses: (2) - 600, (3) – 800, (4) – 1000.

Further increasing of the number of pulses reduces the Hall coefficient values (Fig. 2, curves 2, 3, 4), wherein the epitaxial HgCdTe samples are characterized by low electron mobility values ~ $(2÷3)·10^3$ $cm^2V^{-1}s^{-1}$, which is two orders of magnitude lower than the corresponding values for the epitaxial n-type material of high quality. The results obtained made it possible to suggest that in the process of impact of volume discharge on the samples of epitaxial films a layer with high electron concentration is formed at the surface or in the surface region of the material. The conductivity of this layer is such that it bypasses the bulk of the epitaxial film in the measurements of the Hall effect.

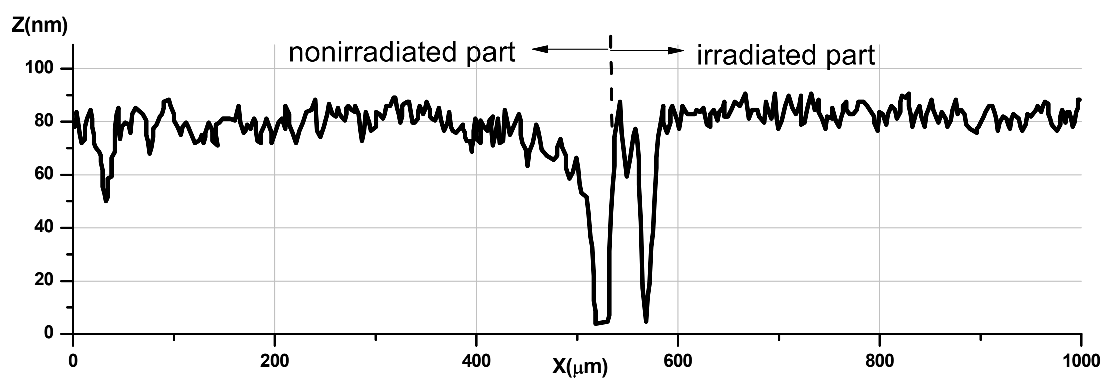

Figure 3. The surface profile of the MCT sample for which part of the surface was closed with dielectric plate during irradiation.

The study of the surface structure of initial and irradiated epitaxial films with atomic force microscope has revealed that the surface quality of the samples after exposure to a volume discharge does not change. Surface roughness slightly increases from 1.6 to 2.2 nm. Additionally, the surface distribution profile of the sample for which part of the surface was closed with the dielectric plate during irradiation was investigated. Surface profile measurements were carried out with an optical profilometer MicroXAM-100. Analysis of measurement results have shown that the interface irradiated / unirradiated sample has no characteristic step that leads to the conclusion about the absence of an alien film on the surface of the exposed part of the test sample (Fig. 3).

After etching of the surface of the irradiated material by 0.1 mm electrophysical parameters of the irradiated samples return to baseline values (Fig. 4, curve 3). The obtained results allow concluding that during the impact of volume discharge on the samples of epitaxial films high conductivity layer forms in the surface region of the material. Furthermore, it was found that after treatment of the irradiated samples in a solution of concentrated hydrochloric acid the restoration of the original values of electrophysical parameters of the material takes place (Fig. 4, curve 4).

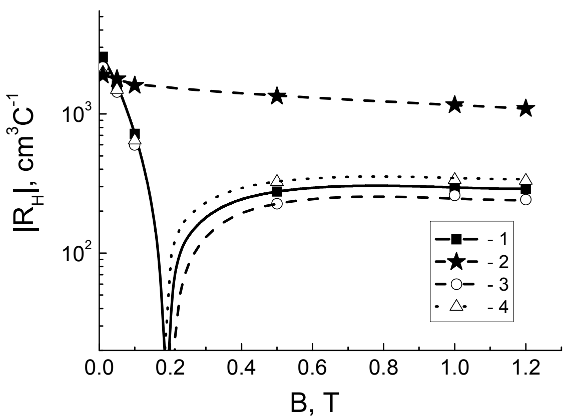

Figure 4. The field dependence of the Hall coefficient for samples of CdHgTe epitaxial films. (1) – before exposure; (2) – 600 volume discharge pulses; after etching of the irradiated sample in a solution of bromine dimethylformamide (3) and hydrochloric acid (4).

However, hydrochloric acid does not chemically react with initial MCT or with a material subjected to a radiation treatment. In the gas diode during a volume nanosecond discharge in air after a short voltage pulse in the discharge gap plasma consisting of an electron beam of positively and negatively charged ions is formed and the current flows through the diode. In this case, the sample of epitaxial MCT film located at the anode is exposed to complex effect consisting of a beam of electrons and negative ions, which cause the formation of different chemical MCT compounds after the influence on the sample surface.

The obtained data allow concluding that in the surface region of irradiated material the formation of chemical compounds of MCT with oxygen and nitrogen atoms occurs (such as anodic oxide which dissolve in hydrochloric acid). Analysis of published data shows that such chemical compounds contain significant concentration of positively charged centers that lead to the formation of an inversion layer at the interface with the epitaxial MCT film of p–type of conductivity. The formation of such an inversion layer is shown during the study of the properties of the interface between the oxide film and MCT [10]. For investigation of the properties of interface materials MIS structures are widely used. Therefore, for initial and irradiated samples MIS structures were created and their electrical parameters were measured.

Figure 5 shows the normalized capacitance-voltage characteristics (CV characteristics) for the structure 1 (for initial sample) and 2 (for irradiated sample). CV characteristics of structure 2 are shifted toward into region of negative voltages. At the same frequency, CV characteristics for the structure 2 have more low-frequency shape than for the structure 1. For structure 2 frequency dispersion of capacitance in the minimum of CV characteristics is observed. At the same time slopes in depletion mode with forward scan of voltage are more acclivous. Also for this structure CV characteristics at the forward and reverse scans of voltage in the minimum of capacitance values are different, as well as much larger hysteresis of capacitive characteristics takes place.

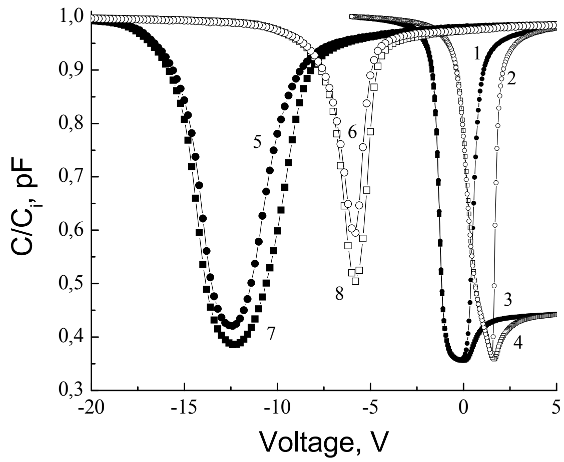

Figure 5. CV characteristics of the MIS structure on the basis of p-HgCdTe (control sample, structure number 1 (curves 1, 2, 3, 4) and number 2 (curves 5, 6, 7, 8)) measured at 77 K under the direct (curves 1, 3, 5, 7) and reverse (curves 2, 4, 6, 8) scan of voltage at different frequencies. Curves 1, 2, 5, 6 - 10 kHz, curves 3, 4, 7, 8 - 1 MHz

Table 1. Parameters of MIS-structures defined from CV characteristics at 77 K.

Structure number	**Fixed charge density, cm^{-2}**	**Mobile charge density, cm^{-2}**	**The concentration of the major carriers defined from the minimum of CV characteristics, cm^{-3}**	**The concentration of the major carriers defined from the $1/C^2(V)$ 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	$6.77 \cdot 10^{12}$	$4.93 \cdot 10^{12}$	$9.22 \cdot 10^{15}$	$2.40 \cdot 10^{16}$

Table 1 shows the main parameters of MIS structures (numbers 1, 2) which were obtained from the measurements of CV characteristics at 77 K. Density of fixed and mobility charge were determined by using shift of the flat-band voltage in real and ideal structures. The calculation of the parameters has shown that irradiated sample has a greater density of positive fixed charge. The density of the mobile charge in this sample is also great. The differential resistance of the space-charge region (RSCR) in the strong inversion for the MIS-structure was calculated. The value of RSCR at 200 kHz and 77 K for initial sample was about 1800 Ohm. For irradiated structure the value of the RSCR was so small that it does not exceed the error in determining RSCR in a wide temperature range. This result explains the low-frequency type of CV characteristics at sufficiently high frequencies for irradiated sample and indicates a high flow rate of minority carriers (electrons) in the inversion layer. The most likely mechanism for the emergence of additional minority carriers in the inversion layer is exchange of electrons with the inversion layer outside the field electrode. This layer is induced by a significant positive fixed charge [10].

One possible reason for the presence of a positive fixed charge can be the appearance of a thin dielectric film on the surface of HgCdTe. It is connected with the formation of oxides by stimulated discharge. It is known that a positive fixed charge is typical for the anodic oxide film in HgCdTe [1, 10]. It is usually associated with the presence of oxygen vacancies in the anodic oxide [11]. For the studied structures the thickness of the dielectric layer must be several nanometers. At larger thicknesses of the dielectric layer reduction in capacitance will be observed due to the increase in passivating coating thickness. Therefore, a dielectric layer with a small thickness has a higher density of fixed positive charge than the typical anodic oxide. It is possible that after exposure in discharge a layer with a high density of embedded positive charges appears near the surface of HgCdTe. These charges cannot change its state of charge due to the potential barriers surrounding the charges.

4. CONCLUSION

Thus, the experimental data have shown that the exposure of MCT epitaxial films to the pulse volume nanosecond discharge in air at atmospheric pressure leads to formation of a dielectric layer with a small thickness in the surface layer of material. The formed layer has a built-in positive charge that leads to the formation of an inversion layer at the oxide / MCT interface which "shunts" the rest of the sample so that the measured field dependence of Hall coefficient corresponds to the material of n-type of conductivity.

Our results show that it is possible to use the volume discharge induced by an avalanche electron beam for the development of technologies for the controlled change of the properties of MCT narrow-band solid solutions and production of structures which are heterogeneous with respect to conduction.

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