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Electro-physical characteristics of a HgCdTe epitaxial films upon exposure by a volume discharge in air at atmospheric pressure

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Abstract. In this paper the influence of the volume discharge of nanosecond duration formed in a non-uniform electric field at atmospheric pressure on samples of epitaxial films HgCdTe (MCT) of p-type conductivity. It is suggested that after exposure on film surface oxide layer was formed. This layer has a built positive charge that leads to the formation of an inversion layer 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.

1. Introduction

Electric discharges of different types as well as electron beams are now widely used for the modification of near-surface layers of various materials. It was shown in [1, 2] that the metal surface can be modified and cleaned by a volume discharge induced by a runaway electrons preionized diffuse discharge (REP DD). 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. A special feature of a REP DD is a possibility of realizing high specific power of energy contribution (up to 800 MW/cm3) [3]. In so doing, beams of runaway electrons with the current amplitude of tens-to-hundreds amperes are generated from the discharge plasma, and the half-amplitude pulse duration of the beam current is in no excess of 100 ps [4]. 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 as well as UV- and VUV radiation from the discharge plasma.

The solid solution $Hg_{1-x}Cd_xTe$ (HgCdTe, MCT) is a widely used material for preparation of intrinsic detectors of infrared (IR) radiation [5]. 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

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changing of the electro-physical parameters of the material in order to obtain the desired semiconductor structures.

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 the method of molecular beam epitaxy.

2. Samples and measurement procedure

For experiments the samples of epitaxial MCT films of the n-type conductivity grown by MBE on GaAs (013) substrates with ZnTe and CdTe buffer layers were prepared at the Institute for Semiconductor Physics of the Siberian Branch of the Russian Academy of Sciences (Novosibirsk). The content of CdTe in the working 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.

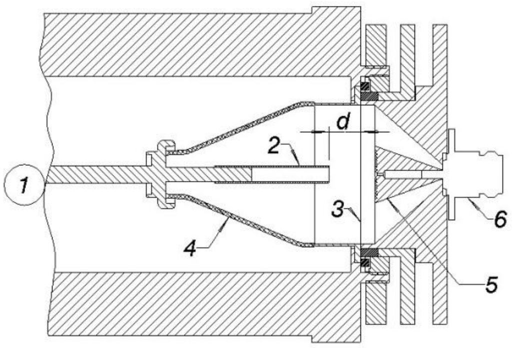

Figure 1. Schematic diagram of the gas-filled diode and collector assembly: (1) connection to a high-voltage pulse generator; (2) cathode; (3) foil anode; (4) insulator; (5) cone-shaped collector; (6) connecting socket.

Figure 2. The image of the diffuse discharge in atmospheric pressure air.

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, which is schematically depicted in figure 1. 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/cm3 under atmospheric pressure in air at electrodes spacing of 8 mm. Figure 2 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.

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.

3. Results and discussion

The results of measurements of electro-physical 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 (Figure 3, curve 2). Further increasing of the number of pulses reduces the Hall coefficient values (Figure 3, 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.

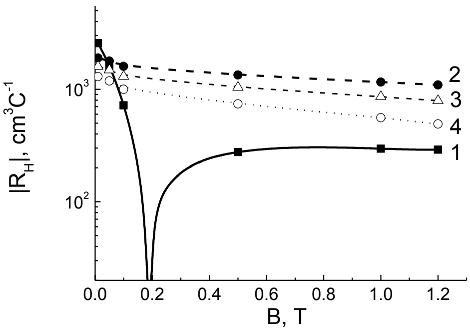

Figure 3. The field dependence of the Hall coefficient for samples of HgCdTe epitaxial films before (1) and after exposure to a volume discharge. The number of exposure pulses: (2) - 600, (3) – 800, (4) – 1000.

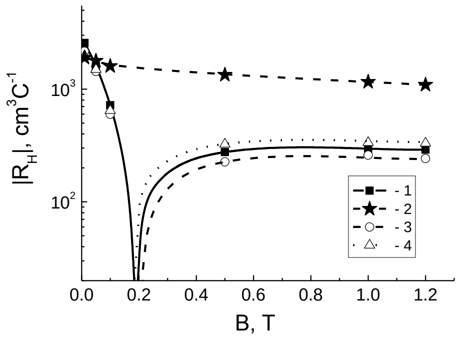

Figure 4. The field dependence of the Hall coefficient for samples of HgCdTe epitaxial films. (1) – before exposure; (2) – 600 volume discharge pulses; after etching of the irradiated sample in a solution of bromine dimethylformamide (3) and hydrochloric acid (4).

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.

After etching of the surface of the irradiated material by 0.1 mm electro-physical parameters of the irradiated samples return to baseline values (Figure 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 electro-physical parameters of the material takes place (Figure 4, curve 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 [6].

Modeling for this assumption was conducted by growing oxide on the surface of the MCT epitaxial layer by the method of anodic oxidation. After growth of anodic oxide electro-physical parameters of obtained multilayer structure were measured. The measurement results have shown that the observed changes in the field dependence of the Hall coefficient before and after the deposition of anodic oxide are similar to the results observed after irradiating the samples of MCT by volume discharge (Figure 5).

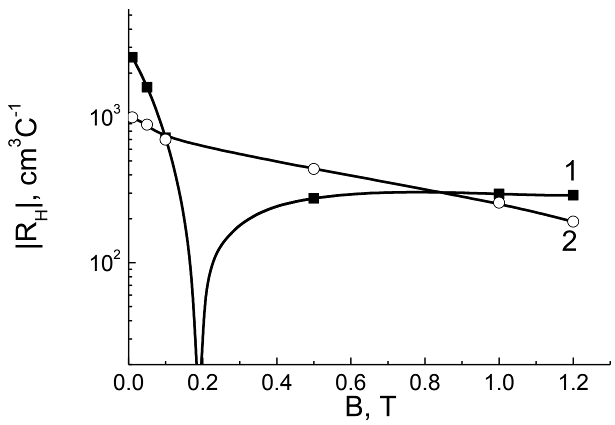

Figure 5. The field dependence of the Hall coefficient for samples of HgCdTe epitaxial films before (1) and after (2) growing of anodic oxide on the surface.

In the paper [7] the volume discharge impact on the electrical parameters HgCdTe MIS structures are investigated. It 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 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. 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 [5, 6]. It is usually associated with the presence of oxygen vacancies in the anodic oxide [8]. 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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