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The impact of the plasma volume discharge in the atmospheric-pressure air on the distribution of the surface potential in a V-defect region of epitaxial HgCdTe films

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Abstract. In the present report we demonstrate the experimental data obtained as a result of studying the impact of nanosecond plasma volume discharge in the atmospheric-pressure air on the distribution of the surface potential in the V-defect regions of epitaxial HgCdTe films. The experimental data obtained for the variation of the contact potential difference (ΔCPD) between the V-defect and the main matrix of the epitaxial film show that the mean value of ΔCPD for the original surface differs from the one for the irradiated surface for 55 eV. At the same time the mean value of ΔCPD changes its sign indicating that the original surface of the epitaxial HgCdTe film predominantly contains the grains with increased cadmium content while after the irradiation the grains possess an increased content of mercury. Therefore, during the irradiation process a decrease of the mercury content in the near-surface region of the semiconductor takes place resulting in the alteration of the electrophysical properties in the film's near-surface region.

1. Introduction

The ternary semiconductor compounds $Hg_{1-x}Cd_xTe$ (HgCdTe, MCT) are one of the major materials used for manufacturing the inherent infrared (IR) photodetectors for the wavelength ranges of 3-5 and 8-14 micrometres [1]. The heteroepitaxial HgCdTe films grown by molecular beam epitaxy (MBE) are one of the most promising materials for manufacturing multi-element photodetecting devices capable of the signal processing directly in the focal region (FPA – focal plane array). The investigations of the epitaxial growth process of HgCdTe have shown that without reference to the substrate type there occurs the formation of macroscopic V-defects that represent the inclusions of polycrystalline phase of HgCdTe with material composition different from that of the bulk of the epitaxial film [2, 3]. These defects are mostly impacted on the performance capabilities of photosensitive element arrays in the focal plane. Because of the fact that the spectral range and sensitivity of the final photoelectric cell greatly depends on the material composition one of the important problems is not only to study but also to control the composition of both the individual crystal grains and the overall V-defect.

At the present time the plasma generated by nanosecond pulses have gained wide adoption for using in order to modify the near-surface properties of materials [4]. It was demonstrated that one can form a volume discharge in a non-uniform electric field at atmospheric pressure. In atmospheric pressure air and a non-uniform electric field the volume discharge forms at both voltage pulse directions on the electrode with a small radius of curvature. The characteristics of such discharges represent the complex influence of a dense nanosecond discharge plasma with the specific power of heat input of the order of hundreds of megawatts per cubic centimetre, of an ultrashort electron beam with a wide energy spectrum and of the optical radiation of different spectral ranges from the discharge plasma.

The aim of this work is to study the effect of a nanosecond volume discharge plasma forming in an inhomogeneous electrical field at atmospheric pressure on the distribution of the surface potential in the V-defect regions of epitaxial HgCdTe films.

2. Experimental apparatus and methods

For experiments the samples of epitaxial HgCdTe 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. The content x was controlled based on the optical transmittance spectra at room temperature.

The as-grown samples were placed in a gas diode on a copper anode. The samples were irradiated by 1200 pulses in the pulse-periodic mode at the pulse repetition rate of 1 Hz. The distance between flat anode and tubular cathode was 8-16 mm. The interelectrode voltage was supplied from a pulser of the RADAN-220 type, which generated 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 showed that the current pulse amplitude for both polarities of the applied voltage pulse 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 provided specific power input in gas discharge plasma above 0.8 GW/cm3 under atmospheric pressure of air. The electrodes spacing was 8 mm. The volumetric character of the discharge also remained at a pulse repetition rate of 3 kHz.

For the original surface and the one exposed to discharge the surface potential distribution was studied by the Kelvin Force Probe Microscopy (KFPM). This method is widely used for studying the distribution of the inherent and surface potentials of instrumental micro-and nanostructures [5-7]. The measurements were performed on a commercial atomic-force microscope (AFM) "Solver HV" (produced by NT-MDT). We used polysilicon B-doped probes covered with platinum (probe type NSG11/Pt, manufactured by NT-MDT). To obtain the surface potential profile we measured the contact potential difference (CPD) distribution between the AFM probe and the surface of the epitaxial film. The CPD distribution was measured together with the surface morphology. In order to minimize the influence of the morphology on the CPD distribution we carried out our measurements at distance of sample-probe dz = 50-100 nm.

3. Experimental results and discussion

For the original surface and the one exposed to discharge using the Kelvin force probe microscopy we studied the distribution of the surface potential for at least 10 randomly chosen V-defects. A typical image of the distribution of the CPD is presented on figure 1. One can see that the distribution is significantly inhomogeneous, exhibiting regions where the CPD is either lower or higher than that of the epitaxial film. On the periphery of each individual crystal grain there is a dramatic variation of the CPD, which can indicate the presence of a modified potential.

Using the distribution of the surface potential we derived the difference (ΔCPD) between the CPD value for individual crystal grains of a V-defect and the mean value of the CPD of epitaxial film.

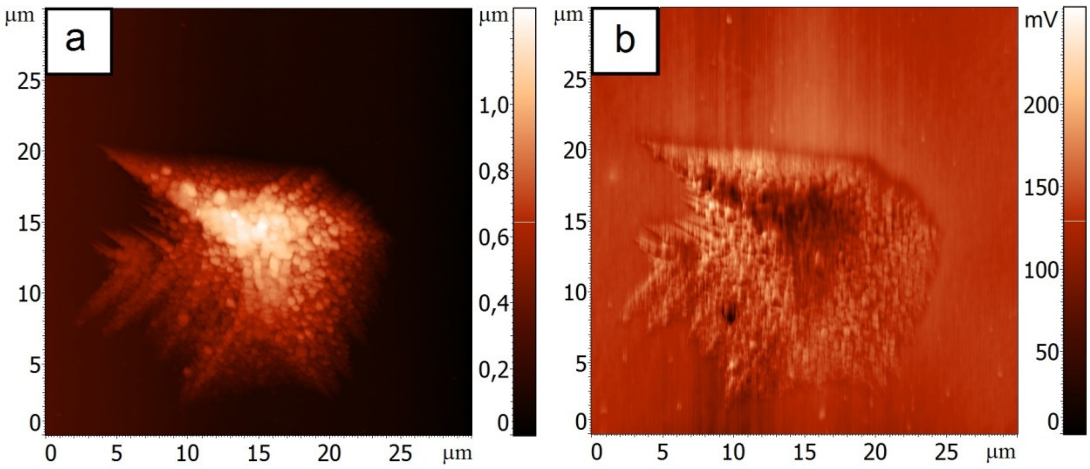

Figure 1. AFM image of a V-defect surface morphology (a) and the distribution of the surface potential or CPD (b).

The distributions of the ΔCPD for a film before and after exposure to radiation are presented on figure 2. The ΔCPD distribution possesses a complex character and can be described by an assemblage of normal distributions. Since the work function of the cantilever needle-point does not change during the measurement process it becomes clear that the observed changes are related to the local changes of the HgCdTe work function, i.e. the changes of the work functions of individual crystal grains of the V-defect are observed. Using the expression for the dependency of the HgCdTe solid solution electron affinity on the component composition [8] one can write the expression for the ΔCPD in the following form:

$$\Delta CPD = \left[1.29 - 7.13\cdot 10^{-4} T\right](x_1 - x_2) - 0.54\left(x_1^2 - x_2^2\right) + 0.56\left(x_1^3 - x_2^3\right), \quad (1)$$

where x_1 is the cadmium content in the epitaxial film and x_2 is the cadmium content in a selected V-defect crystal grain. It is fair to assume that the value of x_1 does not change, in that case one can use the value of the ΔCPD to derive the value of Δx that characterizes the variation of the cadmium content in a selected crystal grain relative to the epitaxial film.

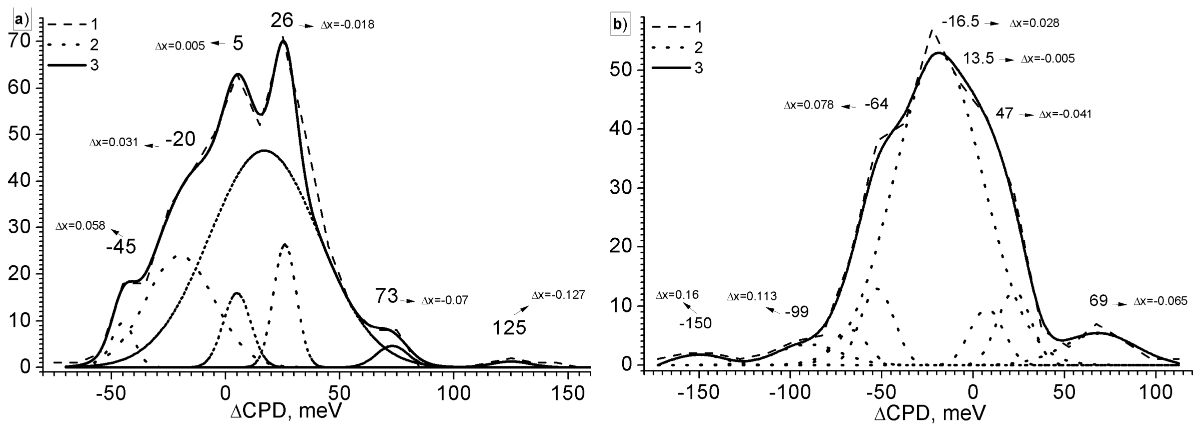

Figure 2. Distribution of the deviation of the CPD value of individual crystal grains of a V-defect versus the CPD of the epitaxial film: a) original film; b) after irradiation, 1 – distribution of ΔCPD, 2 – assemblage of normal distributions, 3 – combined distribution; the arrows indicate the variation Δx of the CdTe content for the given value of ΔCPD.

Taking into account the expression (1) and the data presented on the figure 2 one can show that before and after the exposure to radiation individual crystal grains of a V-defect may possess a higher mercury content ($\Delta x < 0$) as well as a higher cadmium content ($\Delta x > 0$). In the original unirradiated sample the crystal grains with a higher mercury content prevail while in the irradiated sample dominate the grains with a higher cadmium content.

Given the complex character of the ΔCPD distribution consider the mean values of this parameter for the original (27 mV) and the irradiated (-28 mV) surface of HgCdTe. These mean values differ for 55 eV. Note also that the mean value of the ΔCPD changes its sign. Using the expression (1) it can be shown that the original surface of the HgCdTe epitaxial film mainly contained the crystal grains with an increased mercury content while the irradiated surface mainly contains the crystal grains with an increased cadmium content. It follows that during the irradiation process the decrease of the mercury content in the semiconductor near-surface region takes place and, hence, occur the changes of the electrophysical properties in the near-surface region of the film.

4. Conclusion

Using the Kelvin force probe microscopy we showed that the exposure to the radiation of nanosecond volume discharge leads to changes of the material composition of the solid solution of individual V-defect crystal grains. As the decrease of the mercury content is expected to be observed not only in the crystal grains but also in the overall epitaxial film, one can infer that the mercury desorption rate is higher for the crystal grains than for the film itself.

It should also be noted that such a situation is expected to hold true for other triple and quadruple semiconductor compounds with second-phase inclusions.

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