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Second harmonic recording of low stresses change in HgCdTe layers under the influence of local heating

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The thermal effect of weak laser infrared radiation at a local point of the HgCdTe layer of the complex heterostructure (013)HgCdTe/CdTe/ZnTe/GaAs was studied with simultaneous measurement of the second harmonic signal using the null method „on reflection“. The exposure power was 0.8 mW in a laser beam 400 μm in diameter during the irradiation time of 15 minutes. The splitting of the second harmonic signal in the maxima was observed with the appearance of two additional peaks. With an increase in exposure time to 15 minutes, the magnitude of the second harmonic signal at the initial maximum decreased to the magnitude of the measurement system noise, with the simultaneous increase of the height of additional peaks from 3000 to 6000 counts unit. After the end of the laser exposure, the second harmonic form is restored to original form with a decrease in their magnitude to 1700−2200 counts unit. The temperature at the point of exposure was measured using a thermal imager and was 24.0 °C at the beginning of the measurements, and 24.6 °C at the end of exposure.

Keywords: stress, HgSdTe, second harmonic, laser, null method.

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1. Introduction

The interaction of laser radiation with solids, such as metals, semiconductors, and insulators, leads to various thermal processes during its absorption, such as heating, melting, and evaporation, due to complex electron-phonon interaction processes [1,2]. The thermal effect of laser radiation of various power with short pulses on the surface layers of semiconductors leads to various phase transitions: melting — solidification, amorphous state — crystal and crystal — amorphous state during femto — or picoseconds [3–6]. The processes of phase transitions in a solid-state semiconductor can be studied by obtaining information from analyzing their nonlinear response by measuring optical harmonics and combination frequencies [7]. As has been shown, nonlinear optical methods are extremely informative, high speed, and have high spatial resolution. For instance, the studies of the second harmonic generation (SHG) signal in case of reflection from the surface of a non-centrosymmetric GaAs crystal (class $\bar{4}3m$) and a centrosymmetric Si crystal allowed conducting dynamics studies during pulsed laser annealing (PLA) [8–10]. We conducted a series of studies of the crystal lattice state of the near-surface layers and the substrate in a multilayer (013)HgCdTe/CdTe/ZnTe/GaAs heterostructure using the second harmonic generation method by measuring the amplitude of the azimuthal dependence signal and/or the null method based on phase synchronism [11,12]. The heterostructures were grown by molecular beam epitaxy (MBE) [13]. The low power of the probing radiation allowed us to obtain information on the state of the crystal lattice deformation, the rotation of the (013) orientation plane in the growth plane and perpendicular to the growth plane, and to identify disturbances in the crystal structure in the form of misoriented microinclusions when examining layers of HgCdTe, CdTe, and GaAs substrate [14–17].

At a relatively high power of 0.3 W probing radiation, changes in the crystalline state of the near-surface HgCdTe layer were observed [11]. When exposed for 60 seconds, the magnitude of the SHG signal decreased at its maximum, with a further increase of noise after 194 seconds of observation. This was due to the local heating of the near surface layer, during which its crystalline perfection deteriorated and was not restored to its initial state. The heating of the HgCdTe layer by a laser beam of such power led to the occurrence of stresses, which resulted in the formation of disoriented micro-area occurred [11], which determine the diffuse component in the SHG signal. It has been shown that stresses value can be obtained from signal measurements using the null method „on reflection“ [12]. Therefore, this method will make it possible to conduct detailed stress measurements and estimate their magnitude while simultaneously heating the local region of the crystal and measuring the SHG signal when exposed to a low-power probing laser beam.

This paper presents the results of measuring the SHG signal to determine stresses and their changes in the local region of the HgCdTe layer in a complex structure grown by the MBE method using the null method during heating of the HgCdTe surface under the influence of weak laser infrared radiation. The results presented in the article and the results of provided in Ref. [11] suggest the possibility of using laser illumination in the HgCdTe MBE growth process to adjust the stress level.

2. Experimental technique

Studies of the thermal effect of laser probing radiation on the crystal structure were carried out by the SHG null method in the HgCdTe sample near surface layer of the (013)HgCdTe/CdTe/ZnTe/GaAs heterostructure grown by the MBE method with control of the layer composition and thickness using highly sensitive single-wave ellipsometry *in situ* [18]. The thicknesses of the ZnTe and CdTe layers were ~ 30 nm and $\sim 5.5\,\mu$m, respectively. Figure 1 shows the composition throughout the thickness in the studied HgCdTe layer of the 1MCT191107 heterostructure. The HgCdTe layer with a homogeneous composition $X_{\mathrm{CdTe}} \sim 0.23$ $6.4\,\mu$m in thickness included wide-band plates with a change in composition from $X_{\mathrm{CdTe}} \sim 0.45$ to $X_{\mathrm{CdTe}} \sim 0.23$ with a thickness of $\sim 1\,\mu$m on a heterogeneous boundary with a CdTe buffer layer and with a change in composition from $X_{\mathrm{CdTe}} \sim 0.23$ to $X_{\mathrm{CdTe}} \sim 0.42$ with a thickness of $\sim 0.3\,\mu$m on the surface.

The state of the crystal structure of the near-surface layer of HgCdTe was measured in an ambient atmosphere at room temperature using the null method „on reflection“ by measuring the SHG signal based on phase synchronism on a high sensitivity laboratory bench for nonlinear optical diagnostics [11,12]. As an emitter, a DUETTO-OEM V3.4 pulsed-periodic diode pumped YAG:Nd-laser is used, with a wavelength of $1.064\,\mu$m, a pulse repetition rate of 50 kHz of ~ 10 pulses with a duration of one pulse in the train ~ 10 ps. The power of the probing radiation was 0.8 mW. The diameter of the probing laser beam in the studied area of the surface (center of the sample rotation) is $\sim 400\,\mu$m. The time range of the SHG signal measurement was 51 s, which was determined by the characteristics of the software, which was not synchronized with the start of the stepper motor rotating the sample. The start of rotation of the sample and the rotation speed were set manually using a separate controller, so the position of the first peak of the SHG on the scans has a different position on the graphs. The HgCdTe layers are not transparent to exciting radiation at $\lambda = 1.064\,\mu$m. According to our data and literary sources [19] the absorption depth of laser radiation in HgCdTe does not exceed $0.2\,\mu$m, in which the absorbed power is converted into heat. To measure the temperature in the laser beam area on the surface at an angle of 45°, a UTi260B thermal imager was installed with a spatial resolution of 256×192 pixels with a pixel size of $12 \times 12\,\mu$m and a temperature resolution of 0.1 °s.

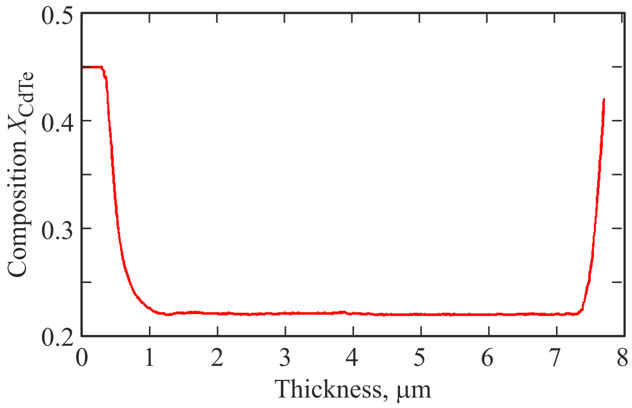

Figure 1. Distribution of the composition X_{CdTe} in the 1MCT191107 heterostructure layer. The surface of the CdTe layer in the heterostructure, located on the left, defines the zero coordinate of the horizontal axis.

3. Results and discussion

Figure 2 shows the change in the magnitude and shape of the SHG signal and the temperature in the probe beam irradiation area versus the exposure time. Narrow peaks of the SHG signals are observed at the initial stage of measurements (Figure 2, *a* left). The angle between the maxima 1 and 2 is ~ 180 degrees when the sample is rotated and makes ~ 2 rotations during measurements. Almost constant SHG signal of $\sim 3000-3500$ counts is observed during the measurement process. Such values of the SHG signal exceed the previously measured values of the SHG signals from the surface of the HgCdTe layer in a structure with a nearest distribution of composition throughout the thickness [12,17]. The increased values of the SHG signals at the maximum can be attributed to a decrease in the thickness of the sample under study and a wide-band graded layer on the surface, which is associated with increased stresses. Previously, it was shown that the observed shape, position, and angular distance in the SHG signals are determined by the stresses in the HgCdTe layers. The temperature in the local measurement area coinciding with the axis of rotation, shown by the cross (thermal imager's sight) on the thermogram (Figure 2, *a* right), was 24 °C. The white arrow on the thermograms also shows the linear size of the section of the measured structure, equal to 10 cm. SHG signals were measured after irradiation of the local area with a laser beam for 5 minutes (Figure 2, *b* left). A sharp decrease of the SHG signal from 3500 counts unit to 1100 counts unit is observed at the maximum during initial measurements, which become minima with the appearance of two new maxima, the value of which increases from 4250 to 4750 counts unit (to the left of the minimum) and 3700 to 4000 counts unit (to the right of the minimum).

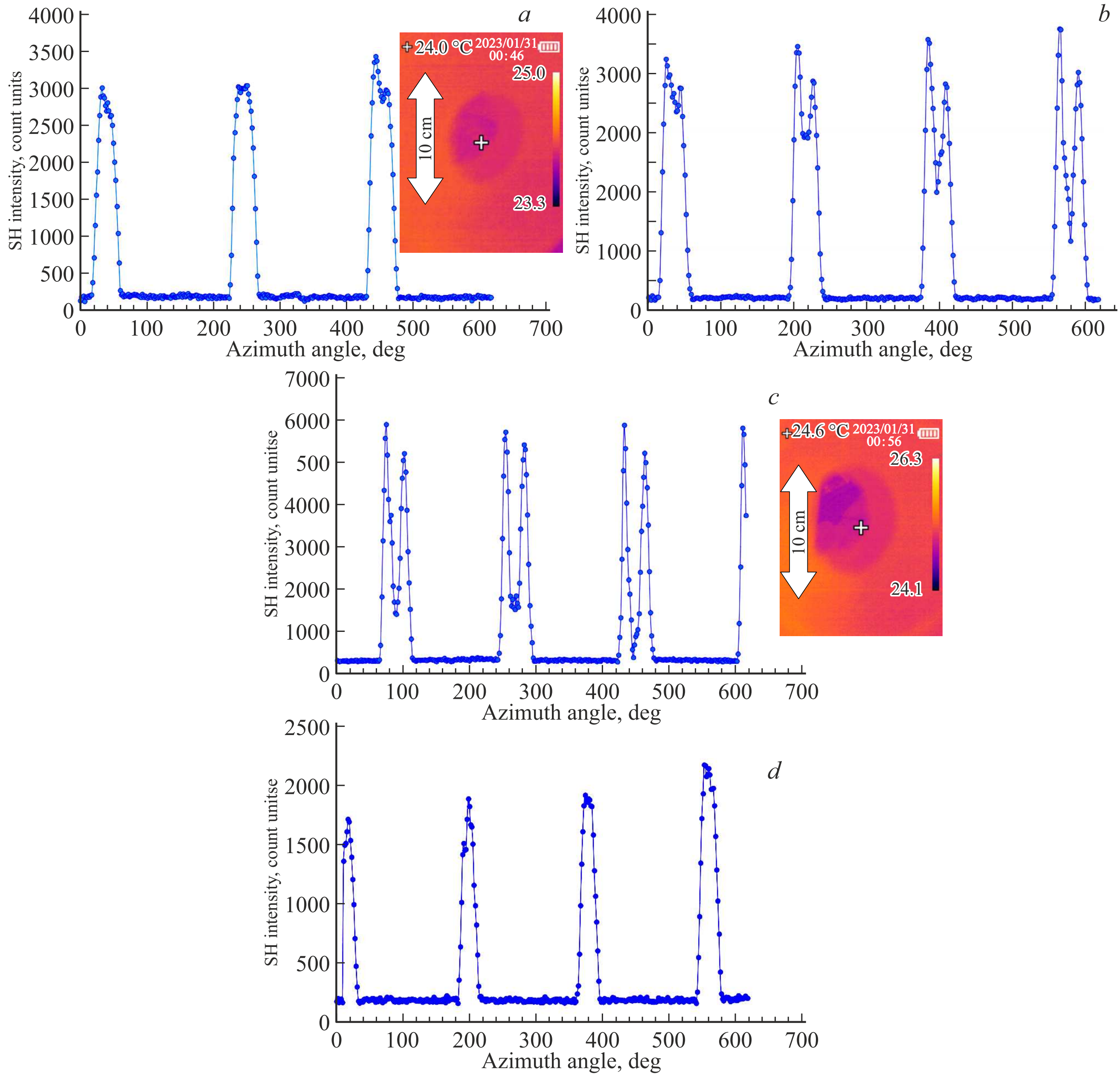

Figure 2. Graphs of the sweep of the experimental values of the SHG signal from the surface of the HgCdTe heterostructure 1MCT191107 and thermograms from a thermal imager under continuous laser exposure with a power of 0.8 mW and when the laser is turned off: *a* — 0 minutes (the beginning of measurements). The graph of the SHG signal sweep is shown at the left, the thermogram from the thermal imager (the temperature value at the sighting point is shown in the top left corner of the thermogram) is shown at the right, the linear size of the thermal object section, equal to 10 cm, is shown by a white arrow, *b* — SHG signal sweep graph after 5 minutes, *c* — after 15 minutes. The SHG signal sweep graph is shown at the left, the thermogram from the thermal imager is shown at the right (the temperature value at the sighting point is shown in the top left corner of the thermogram), the linear size of the thermal object section equal to 10 cm, is shown by a white arrow, *d* — SHG signal sweep graph after 15 minutes with the laser turned off.

The angle between maxima 1 and 2, 3 and 4 is also ~ 180 degrees when the sample is rotated. This behavior of the SHG signals may be associated with a change in the spatial distribution of stresses and an increase in their magnitude. It should be noted that the thermal effect of the laser beam during measurements occurs in a short period of time in the local region $\sim 400\,\mu$m. A further change of the SHG signals is observed after 15 minutes of irradiation (Figure 2, *c* left). Thus, the SHG signals in the newly appeared maxima increase to ~ 6000 counts unit (to the left of the minimum) and ~ 5200 counts unit (to the right of the minimum) with a decrease in the minimum between them from ~ 1500 counts unit up to the noise level of ~ 400 counts unit. It should be noted that the magnitude of the SHG signal in the maxima remains constant during the measurement process. The minimum value of the SHG signal indicates that the available stresses in their direction of initial orientation (011) are close to zero or completely absent. The temperature at the measuring point at that moment was 24.6 °C (Figure 2, *c* right). The angular dependence of the SHG signals returns to its previous form after 15 minutes of exposure of the sample without exposure of the near-surface area of the HgCdTe by laser beam, but with a decrease in the magnitude of the maxima by almost half (Figure 2, *d*). During the measurement process, there is a change in the magnitude of the SHG signal at the maximum, slightly increasing from 1700 counts unit to 2200 counts unit, but with the appearance of a barely noticeable splitting and decrease in magnitude at the 4th maximum. This behavior can be attributed to the residual elevated temperature at the measuring point compared to the ambient temperature, i. e. there is no complete cooling at the measured point on the surface of HgCdTe in 15 minutes cooling.

As follows from the above data, during measurements, weak heating occurs simultaneously in the area of irradiation of the material with a probing laser beam with a power of 0.8 mW, as previously mentioned. This statement follows from the consideration of the SHG signals (Figure 2, *b* left) when the magnitude of the peaks in the maxima changes with their increase and decrease in the minimum during the measurement process. This behavior indicates a decrease in stresses and an increase in structural quality at the irradiated point. Continuously acting weak probing radiation creates local temperature gradients, which leads to a change in the positions of atoms in the crystal lattice, and, accordingly, to a radical change in the shape and magnitude of the SHG signal. The observed change in the shape of the SHG signal indicates a stress relief at this local point during radiation treatment and indicates an azimuthal stress redistribution. The decrease in stresses in the region of the initial maximum can be attributed to the processes of laser annealing with a low-power beam, which can lead to an improvement in the structural perfection of the processed area of the crystal. Such a procedure can reduce the stresses that arise during the growth of the heteroepitaxial structure. Indeed, with the simultaneous process of growth of the heterostructure with micron-thick HgCdTe layers for infrared (IR) photodetectors (PD) exposed to laser irradiation of the growing surface, an increase in the quality of the crystal structure over the entire thickness of the layers with a decrease or complete absence of stresses should be expected. After growing the heterostructure by the MBE method, the dislocation density in HgCdTe layers on GaAs and Si substrates ranges from 10^6 cm^{-2} to more than 10^7 cm^{-2}, respectively [20]. Hard thermal cycling in the temperature range of 250–400 °C [21] or 300–500 °C [20] allows increasing the structural perfection of the material by reducing the density of dislocations by almost an order of magnitude. However, this procedure leads to a strong diffusive blurring of wide-band graded layers intended for

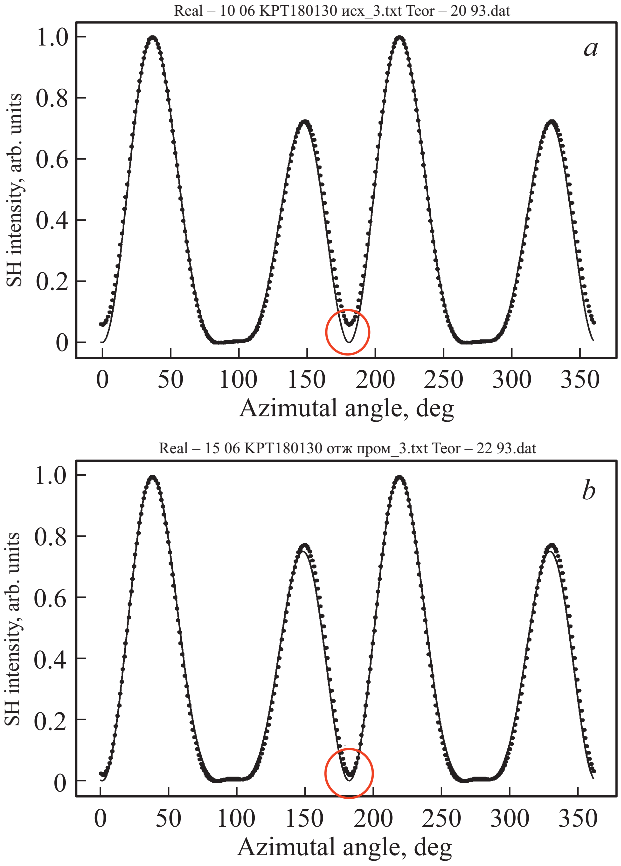

Figure 3. Azimuthal dependence of the SHG amplitude in the HgCdTe layers of the 1KRT189130 heterostructure: *a* — after growth, *b* — after thermal annealing at 200 °C during 24 hours.

passivation of the photosensitive layer at heterogeneous boundaries, which provided an increase in the characteristics of the infrared PD, and the appearance of a developed morphology. Softer thermal annealing at 200 °C also leads to an increase in the structural perfection of the HgCdTe layer, but without diffusive blurring of the profile of the HgCdTe layer. Figure 3 shows the azimuthal dependences of the amplitude of the reflected SHG signal that occurs in the near-surface layers of the (013)HgCdTe/CdTe/ZnTe/GaAs heterostructure after growth and after standard thermal annealing at 200°C for 24 hours in an inert atmosphere for conductivity type conversion.

When comparing the graphs of the amplitude dependences of the SHG's reflected signal obtained from model calculations (solid curves) and from the experiment (dots), it can be seen that there is a difference in the magnitude of the signals in the minima in which the calculation and experiment have the greatest difference (indicated by red circles). The height of such minima relative to the noise of the measuring path is in the ratio 3 : 1 for HgCdTe layers after growth (Figure 3, *a*) and 1 : 1 after thermal annealing (Figure 3, *b*). This difference indicates a lower stress value in the HgCdTe layer after soft thermal annealing, i. e. stress relaxation and an increase in structural quality occur during its process. This procedure makes it possible to provide HgCdTe layers *p*-type conductivity on GaAs substrates with the required parameters and high structural quality to ensure high sensitivity of IR photodetectors. Consequently, laser exposure during HgCdTe epitaxy in the MBE method will ensure high structural quality in the material after growth.

4. Conclusion

The null method based on the generation of the second harmonic „on reflection“ showed that weak laser infrared radiation at a local point leads to a significant change in stress and its structure in the HgCdTe layer of a complex heterostructure (013)HgCdTe/CdTe/ZnTe/GaAs. It is shown that the stresses detected in the uniaxial direction are removed by laser exposure over a period of 15 minutes, during which heating occurs at a local point. The complex pattern of the appearance of new peaks in the SHG signal is probably related to the inhomogeneous temperature distribution in the volume of the studied HgCdTe layer. The results obtained can be used in the heterostructures growth by the MBE method with simultaneous exposure to laser radiation during growth to reduce or completely removal stress. This, in turn, will allow for higher structural perfection of HgCdTe layers after growth or other heteroepitaxial structures, for example, HgTe.

Thus, the practical application of laser heat treatment is possible for post-growth processing of CdHgTe layers of various compositions, as well as quantum structures to reduce residual deformations and obtain uniformity of their distribution over a large area. Also, the obtained results, together with the results from Ref. [11], allow applying them for the possible use of laser illumination in the HgCdTe MBE process to adjust the stress level in the layers. Also, the results obtained, as well as the results from Ref. [11], allow talking about the possibility of using laser illumination in the HgCdTe MBE process to adjust the stress level.

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Conflict of interest

The authors declare no conflict of interest.

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