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Peculiarities of the External Photoelectric Effect in Narrow-Band Semiconductors Caused by Soft X-Ray Radiation

Victor Sredin
National Reserch
Tomsk State University
36 Lenina Ave., 634050,
Tomsk, Russia
sredinvg@rambler.ru

Ravi Ramakoti
National Research Nuclear University MEPhI
31 Kashirskoe Hwy., 115409,
Moscow, Russia
RSRamakoti@mephi.ru

Oleg Ananin
National Research Nuclear University MEPhI
31 Kashirskoe hwy, 115409,
Moscow, Russia
OBAnanini@mephi.ru

Alexandr Voitsekhovskii
National Reserch
Tomsk State University
36 Lenina Ave., 634050,
Tomsk, Russia
vav43@mail.tsu.ru

Anrey Melekhov
National Research Nuclear University MEPhI
31 Kashirskoe Hwy., 115409,
Moscow, Russia
makalu2008@yandex.ru

***Abstract*—The features of the external photoelectric effect caused by soft x-ray radiation of a laser plasma source in $Cd_xHg_{1-x}Te$ solid solutions are considered. The possibility of a contribution from the ionization of internal electron shells to the photocurrent and the generation of a pulsed electric field in the near-surface region due to the output of photoelectrons are discussed.**

***Keywords*—Laser plasma, soft x-ray, $Cd_xHg_{1-x}Te$, external photoelectric effect, defects.**

I. Introduction

Soft x-ray radiation covers the wavelength range from 10 to 300 A (1240–41.3 eV) and can interact with the substance through elastic scattering, inelastic scattering or absorption caused by photoelectric effect [1]. The scattering effects lead to a slight loss of soft x-ray energy in the substance. The main effect is related with the absorption of soft x-ray quanta, which occurs when an x-ray photon gives its energy completely to the electron of the inner atomic shell and exciting it from the atom. This leads to the appearance of external photoelectric effect and ionization of the excited atom. In the result, the atoms that absorb the photon are ionized by radiation, and most of the energy of the x-ray quantum is converted into the kinetic energy of the emitted electrons. Note that soft x-ray is completely absorbed in crystalline matter at depths of the order of 1 μm. In [2–5], during the research of effects caused by interaction of x-ray radiation with a quantum energy of the order of 60 keV (and higher) in semiconductor materials and alkali-galloid crystals, a model of defect formation during relaxation of electronic atomic excitations was proposed to explain the emerging optical and electrophysical effects. Under certain conditions, the energy of exited atom with removed electron from the inner shell level is enough to transfer it to internode with the formation of a point defect. The process of defect formation according to this model assumed the appearance of a “group of separated ions”: local formation of ions of the same charge sign, ionized by radiation [4, 5]. In the selected group, instability arises due to Coulomb repulsion. In case if the lifetime of the excited state exceeds the time of irreversible displacement of the excited ion from the equilibrium position, a point defect is born. It is assumed that the effects of electrostatic instability are more pronounced in semiconductors containing charged impurity atoms [4, 5].

This model, however, didn’t consider the possibility of the appearance of an external photoelectric effect upon irradiation of a substance by x-ray radiation and the removal of an electric charge from the substance. Apparently, the first report on the external photoelectric effect in semiconductors upon excitation of soft x-ray is [6], in which it was shown that this effect in Si single crystals has non-thermal mechanism. It was shown that, during laser plasma soft x-ray irradiation of epitaxial layers and single crystals of a $Cd_xHg_{1-x}Te$ solid solution, a modification of the surface structure of the material occurs [7, 8], as well as generation of defects in the near-surface region [9], which change the electrophysical properties of the near-surface semiconductor layer and the boundary section "dielectric-semiconductor". The formed defects are stable: repeated measurements of the density of surface states and surface concentration of charge carriers in the epitaxial layers of n-$Cd_{0.24}Hg_{0.76}Te$, performed 3 years after their irradiation with soft x-ray, showed complete reproducibility of the results with measurements carried out immediately after irradiation [9]. In the same paper, it was first time shown the fact that, as a result of the emission of electrons from the surface layer of a substance during the interaction with soft x-ray, a variable electric field arises that acts on ions. As a result for ions that has acquired additional charge during ionization, the probability of exit from the position of the crystal lattice assembly increases.

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The rest of the paper is structured as follows. In the Section II the experimental setup is given, Section III describes the experimental results, and the final Section IV discusses the results obtained.

II. EXPERIMENTAL SETUP

In this work we discuss the features of the external photoelectric effect in $Cd_xHg_{1-x}Te$ solid solutions under the influence of soft x-ray. For these purposes, we used a laser-plasma source with x-ray concentrator, the circuit of which is shown in Fig. 1.

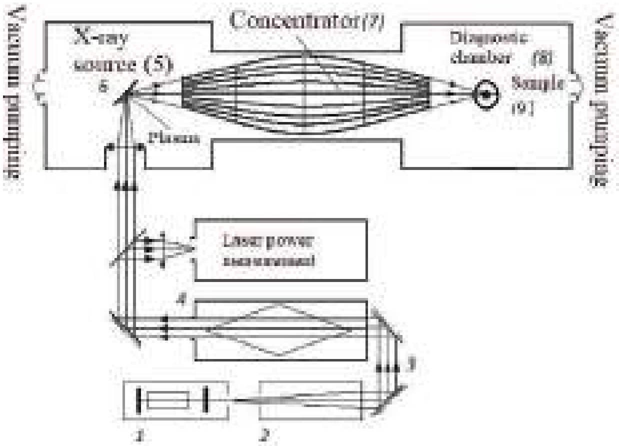

Fig. 1. Experimental setup. 1 – laser radiation generator, 2 – single-pass amplifier, 3 – rotary mirror system, 4 – multi-pass amplifier, 5 – soft x-ray source chamber, 6 – laser-plasma target, 7 – soft x-ray concentrator, 8 – diagnostic chamber, 9 – sample inside integrating the sphere

Laser radiation from a glass with Nd^{3+} and wavelength of 1.054 μm with an pulse energy in the range from 5 to 10 J was focused on a copper target located in a chamber with a vacuum of $P \approx 10^{-5}$ Torr. The power density of the laser radiation on the target was $10^{13} - 10^{14}$ W/cm^2. To focus soft x-ray on a CdHgTe sample and to protect the sample from the flow of charged particles produced by laser plasma, x-ray concentrator was used. X-ray concentrator is assembly of quartz capillaries. The pulsed power of the x-ray radiation was 5×10^4 W with a pulse duration of 20 ns (energy in the soft x-ray pulse <= 1 mJ). The x-ray source is characterized by a continuous emission spectrum in the range of 80–600 eV (Fig. 2). In this range, *N* edges of Hg and *M* edges of Cd and Te ions are located [10].

The diameter of the soft x-ray focusing spot after the x-ray concentrator was $d = 2$ mm. To collect electrons emitted by soft x-ray integrating aluminum sphere was used with an inner diameter $d = 6$ cm. In the center of sphere there was an electrode isolated from the sphere body. The studied sample was attached to the electrode, to which a negative potential was applied to push out electrons. Electrons through a 50-ohm resistance flow from the housing to the ground. The value of the emitted charge is determined by numerically integrating the signals recorded on the load over a time equal to the duration of the x-ray pulse. Fig. 3 shows graphs of the dependence of the registered emitted charge on the applied voltage for for monocrystal $Cd_{0.2}Hg_{0.8}Te$. Immediately before measurements, the crystals went through standard chemical etching in a bromine etchant.

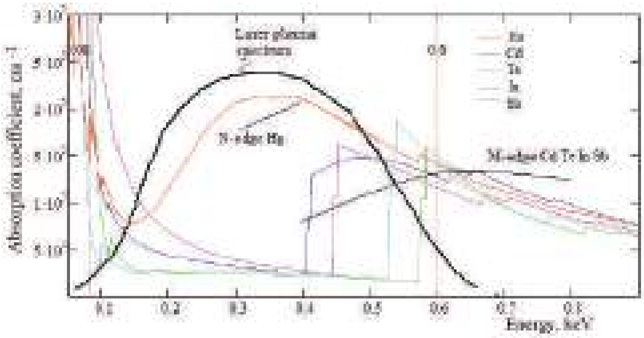

Fig. 2. The emission spectrum of a laser-plasma source.

III. RESULTS

The basic idea of defect formation as a result of relaxation of electronic excitation caused by absorption of soft x-ray on the inner shells of atoms forming an idealized semiconductor can be represented using the modified Einstein equation for the external photoelectric effect:

$$h\nu_{\text{soft x-ray}} = mv^2/2 + A_{\text{exit}} + A_{\text{nuclear}}\,, \qquad (1)$$

where the first term on the right-hand side is the kinetic energy of a free photoelectron in a vacuum, A_{exit} includes the ionization energy of atom with formation of electron in the conduction band plus electron affinity, A_{nuclear} is the atomic excitation energy. A_{nuclear} is energy of an ion with an additionally ionized by soft x-ray inner shell.

If the quantity $A_{\text{nuclear}} > \Delta E_d$ (ΔE_d is the energy of point defect formation), then in addition to the generation of a free electron, the birth of a point defect is also possible. However, this model doesn't consider the effect of electric field generation in the near-surface region due to the departure of photoelectrons from this area. The time during which this field exists is apparently limited by the lifetime of the hole at the internal energy level of the atom.

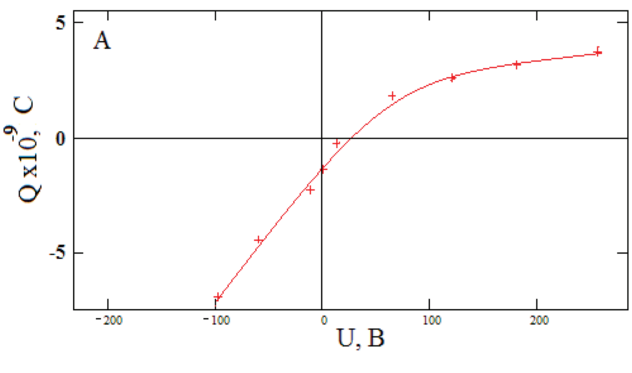

Fig. 3. Dependence of the registered emitted charge on the applied buoyant voltage. $T = 300$K

IV. Discussion

For a detailed analysis of the external photoelectric effect under the influence of soft x-ray, it is necessary to use monochromatic radiation, nevertheless we will try to analyze the results using (1). Firstly, it can be seen from Fig. 3 that the external photoelectric effect, accompanied by the release of electrons, is also observed for the blocking directions of the external field (right upper quadrant). Apparently, this component of the photocurrent is associated with the release of valence electrons, for which the second term in (1), which describes the work function of the photoelectrons, doesn't include the ionization energy of the internal levels of the atom (Fig. 2), therefore it is relatively small, and the third the term is simply missing. The second feature of the graph is a steeper increase in the magnitude of the emitted charge when the external field is pushed out (the lower left quadrant of the graph). We propose that in this case, in addition to valence electrons, the electrons of the inner shells of atoms, which are pulled out by soft x-ray quanta, also take part in the formation of the photo current. In our case (Fig. 2), these are electrons of the *N*-level of the Hg ion and electrons of the *M*-level of Cd. The energy of their ionization is hundreds of eV, to which the work of the exit from the crystal itself is added. The order of magnitude of ΔE_d can be taken from [3]: it is of the order of 10 eV for A^2B^6 materials. Thus, in addition to valence electrons, electrons released from the inner shells of atoms also fall under the action of the repulsive voltage. It was shown in [9] that, for the composition of the solid solution under consideration, it is more likely that these are electrons released from Hg ions than from Cd ions. And finally, thirdly, the model under consideration doesn't consider the effect of electric field generation in the near-surface region due to the departure of photoelectrons from this region. The time during which this field exists is apparently limited by the lifetime of the hole at the internal energy level of the atom. The magnitude of the field induced by the external photoelectric effect, estimated in the classical approximation, is magnitude in order of 10^8 V m^{-1}.

V. Conclusion

The study of the external photoelectric effect caused by soft x-ray from laser plasma source in $Cd_xHg_{1-x}Te$ solid solution, demonstrated the possibility of excitation of the inner shells of atoms with their ionization and the generation of a pulsed electric field in the under-surface region of the crystal due to release electrons from the material.

Acknowledgment

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References

[1] A. Michette, *Optical Systems for Soft X Rays*. NY: Plenym Press, 1986.

[2] J. I. Klinger, C. V. Pushchin, T. V. Mashovets, G. A. Kholodar, M. K. Sheinkman, M. A. Elango, “Creation of defects in solids during the decay of electronic excitations,” *Physics-Uspekhi*, vol. 147, No. 3, pp. 523–558, 1985.

[3] V. S. Vavilov, “The migration of atoms in semiconductors and changes in the number and structure of defects initiated by excitation of the electronic subsystem,” *Physics-Uspekhi*, vol. 167, No. 4, pp. 470–412, 1997.

[4] N. A. Vitovsky, M. I. Klinger, T. V. Mashovets, D. Mustafakulov, S. M. Ryvkin, “About the feasibility of the ionization mechanism of defect formation in impurity semiconductors under “subthreshold” irradiation,” *Fiz. Techn. Poluprov. (Sov. Phys. Semicond.)* vol. 13. no. 5. p. 925, 1979.

[5] M. I. Klinger, V. V. Emtsev, T. V. Mashovets, S. M. Ryvkin, N. A. Vitovskii, “Ionization mechanism of the defect production in semiconductors,” *Radiation Effects*, vol. 56, p. 229, 1981.

[6] O. B. Ananyin, Yu. A. Bykovsky, A. A. Zhuravlev, V. Yu. Znamensky, “Photoelectronic emission from the surface of materials under the influence of pulsed short-wave radiation,” *Letters ZhTF*, vol. 17, No. 12, pp. 5–8, 1991.

[7] V. G. Sredin, O. B. Ananyin, I. D. Burlakov, G. S. Bogdanov, E. A. Ivanitskaya, D. V. Lavrukhin, A. P. Melekhov, “Effect of soft x-ray radiation on surface properties of $Cd_xHg_{1-x}Te$ solid solutions,” *Izvestiia VUZov. Fizika,* vol. 56, no. 9/2, pp. 113–115, 2013.

[8] V. G. Sredin, O. B. Ananyin, I. D. Burlakov, A. E. Mirofyanchenko, A. P. Melekhov, I. K. Novikov, “The study of the action of soft x-ray radiation on the surface of CdxHg1-xTe solid solutions by atomic force microscopy,” *Prikladnaja fizika*, no. 6, pp.17–20, 2013.

[9] V. G.Sredin, A. V. Wojciechowski, O. B. Ananyin, A. P. Melekhov, S. N. Nesmelov, S. M. Dzyaduh, “Formation of surface defects in n - CdxHg1-xTe by soft x-ray radiation from a laser plasma,” *Prikladnaja fizika*, no. 4, pp. 54–60, 2018.

[10] http://henke.lbl.gov/optical_constants/filter2.html