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Laser-induced incandescence imaging of hidden inhomogeneities in surface layers of light-absorbing materials

[1] Organization

Project Leader: *Serge Zelensky*, D.Sc., Prof. (Taras Shevchenko National University of Kyiv, Ukraine).

Representative at RIE: *Toru Aoki*, Ph.D., Prof. (Research Institute of Electronics, Shizuoka University, Japan).

Participants:

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[2] Progress of Scientific Activity

According to the research plan of the project, scientific activities were stipulated to be performed at Taras Shevchenko National University of Kyiv and Research Institute of Electronics, Shizuoka University. These activities include computer simulations (performed at Taras Shevchenko National University of Kyiv) and testing (performed at Taras Shevchenko National University of Kyiv and Research Institute of Electronics, Shizuoka University). The computer simulations were intended to predict general features of laser-induced incandescence of surface layers with local variations of thermal and optical parameters regardless of the particular composition of the irradiated object. For the above-mentioned testing, two pulsed lasers were employed: YAG:Nd laser working at the basic frequency (testing performed at Taras Shevchenko National University of Kyiv) and YAG:Nd laser working at the third harmonic (testing performed at Research Institute of Electronics, Shizuoka University).

Besides, the activities included discussions of the project course and of the obtained results. During the period of the project, the participants discuss its progress via e-mail and on meetings in Kyiv, June and October 2016, when Prof. *Toru Aoki* visited Ukraine, and in Strasbourg, France, 29 October – 6 November 2016, when Prof. *Toru Aoki* and Ms. *K. Zelenska* attended the 23rd International Symposium on Room-Temperature Semiconductor Detectors (RTSD 2016), 2016 IEEE Nuclear Science Symposium & Medical Imaging Conference (2016 NSS/MIC).

The participants of the project actively collaborated in organizing the 17^{th} Intern. Young Scientists Conf. “Optics & High Technology Material Science” SPO 2016 held at the Faculty of Physics of Taras Shevchenko National University of Kyiv 27-30 Oct. 2016. Prof. S. Zelensky was the member of the Program Committee, and Ms. *K. Zelenska* and Prof. *T. Aoki* were the members of the Organizing Committee of SPO-2016. Prof. S. Zelensky and Ms. *K. Zelenska* presented the project-related results at SPO-2016. The project-related results were also presented at the annual conference of the Faculty of Physics of Taras Shevchenko National University of Kyiv “Science in XXI Century: Modern Problems of Physics”, May 17-19, 2016, where Prof. S. Zelensky was the member of the Program Committee.

[3] Research Results

The project was aimed to develop a new method for imaging of hidden inhomogeneities in surface layers of light-absorbing materials under pulsed laser irradiation. Under the laser irradiation, overheated areas of surface layers emit thermal emission named LII (laser-induced incandescence). For excitation of LII, nanosecond-scale laser pulses are usually used. Laser intensity necessary for observation of LII is of the order of dozens of MW/cm^2. Under such excitation, LII is observed as short pulses of white light with the pulse duration of the order of dozens of nanoseconds.

An important feature of LII of surface layers is the dependence of its intensity on the local value of thermal conductivity. This conclusion was made on the basis of the results of calculations performed within the margins of the project.

According to the research plan of the project, computer simulations were performed prior to the experimental testing. The calculations were based on the classical heat conduction equation

$$\mathrm{div}\left(\kappa\ \mathrm{grad}T\right)+\alpha I=c_p\frac{\partial T}{\partial t} \qquad (1)$$

(where $T(\mathbf{r},t)$ represents the transient temperature field in the surface layer) together with the equation of transport of laser power density I

$$\mathrm{d}I=-\alpha I\ \mathrm{d}z \qquad (2)$$

for a Gaussian-shaped laser pulse

$$I=I_0\exp\left[-\left(t/\tau_\mathrm{i}\right)^2 4\ln 2\right] \qquad (3)$$

To a first approximation, the macroscopic parameters of the surface layer (thermal conductivity κ, heat capacity c_p, absorption coefficient α) were assumed to be independent of temperature and of the laser power.

A typical calculated oscillogram of LII of surface layer of a carbon sample is given in fig.1. Note should be made, the calculated oscillogram is in good agreement with the oscilloram detected for a carbon test sample (carbon spectral electrode) under excitation by a Q-switched YAG:Nd^{3+} laser (pulse length $\tau_\mathrm{i}=20$ ns, wavelength 1064 nm). Besides, the calculation-predicted nonlinear response of LII on the variations of laser intensity is also in good agreement with the experiments. The mentioned calculations and measurements were performed at Taras Shevchenko National University of Kyiv.

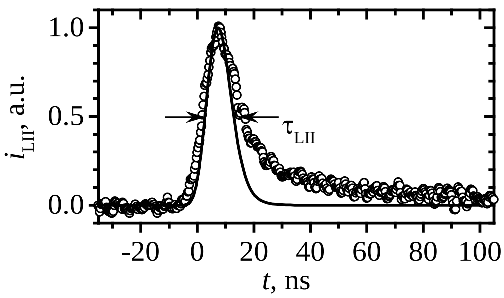

Fig.1. Oscillogram of LII of the surface of carbon electrode rod. Points – experiment; solid line – calculation with the use of (1) – (3) and $\tau_\mathrm{i}=20$ ns.

The computer simulations performed within the project show that local variations of the above-mentioned parameters of surface layers can cause significant changes of local LII signals. For example, local variations of thermal conductivity by 10% result in the appropriate change of local LII intensity by 30% (see fig.2). Similar response is also predicted for local variations of heat capacity and absorption coefficient. The mentioned simulations were performed at Taras Shevchenko National University of Kyiv.

For testing of the above-mentioned predictions of computer simulations, the experiments were performed with the use of powerful YAG:Nd^{3+} laser (Spectra-Physics Quanta-Ray Pro-230 at Research Institute of Electronics, Shizuoka University) operating at the third harmonic (τ_i = 8 ns, wavelength 355 nm). For the experiments, a set of samples was used, including carbon and semiconductor crystals of Si, porous Si, Ge, GaAs, and GaSb/InGaSb heterojunction.

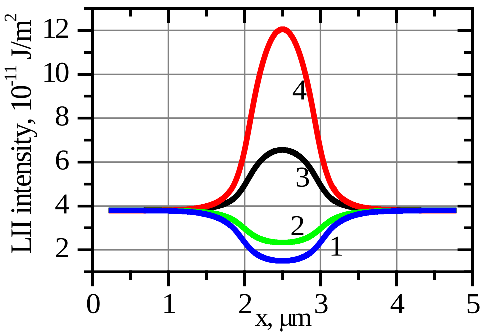

Fig.2. Calculated LII intensity as a function of coordinate along the surface with a micron-sized local variation of thermal conductivity $\Delta\kappa/\kappa$ = +20% (1), +10% (2), –10% (3), –20% (4).

In the experiments, LII of surface layers was detected with the use of a CCD camera in the visible spectral range. Example images of LII of surface layers are given in fig.3, where the laser beam simultaneously irradiate two different surfaces (GaAs and Si, and two surfaces of Si with different level of doping).

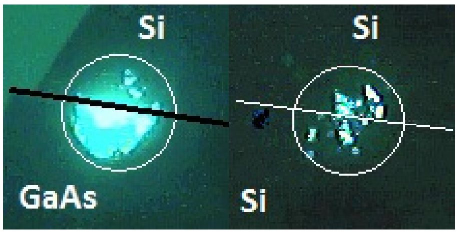

Fig.3. LII of GaAs and Si surface. Laser excitation 355 nm, 8 ns.

Typical detected variation of LII intensity along the surface coordinate of GaSb crystal is presented in fig.4. The observed variations of

LII are caused by at least two factors (except the noise): by variations of the laser intensity, and by variations of the surface parameters.

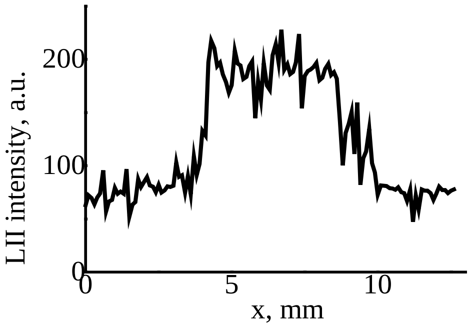

Fig.4. LII intensity as a function of coordinate along the surface of GaSb. Laser excitation 355 nm, 8 ns.

The data obtained with the above-mentioned materials under 355 nm laser excitation are under thorough processing. Preliminary conclusions drawn from the obtained results are the following.

(i) Under the equal conditions of laser excitation, local surface areas with different macroscopic thermal and optical parameters emit LII with different pulse energy (different time-integrated LII signals are observed).

(ii) Cross-beam non-uniformity of laser power density significantly distorts the observed surface distribution of LII intensity; this fact is a consequence of high non-linearity of LII response on the laser power density.

(iii) Roughness of the irradiated surface is an important factor for observation of LII of surface layers (as a rule, for rough surfaces, excitation of LII requires less laser intensity than for smooth surfaces). This circumstance is also important in case of laser-induced transformations of the surface under irradiation by a sequence of laser pulses. The experiments at 1064 and 355 nm show that the laser-induced transformations are observed at almost all of the investigated samples; this experimental fact complicates the interpretation of the LII data obtained.

[4] Publications *(published and submitted by the CRP participants during the project period 2016/6/30 – 2017/3/31)*

1. M.Kokhan, I.Koleshnia, S.Zelensky, Toru Aoki On the possibility of visualization of undersurface submicron-sized inhomogeneities via laser-induced incandescence of surface layers/ Proc. SPIE 10097, High-Power Laser Materials Processing: Applications, Diagnostics, and Systems VI, 100970G (February 22, 2017); doi:10.1117/12.2253006.
2. K. Zelenska, S. Zelensky, A. Kopyshinsky, T. Aoki, Impact of laser-induced pore expansion on thermal emission of porous carbon/ Materials Today: Proceedings, in press
3. K. Zelenska, S. Zelensky, A. Kopyshinsky, T. Aoki, Impact of laser-induced pore expansion on thermal emission of porous carbon, International Conference on Science and Technology of Emerging Materials (STEMa2016), Book of Abstracts, 2016, Abstract No PO-COB03, 87 (Pattaya, Thailand, 27-29 July 2016).
4. V.Karpovych, K.Zelenska, S.Zelensky Kinetics of laser-induced incandescence of porous carbon surface/ “Optics & High Technology Material Science” SPO 2016. Scientific works. Oct. 27-30, 2016. Kyiv, Ukraine. P.157.
5. M.Kokhan, I.Koleshnia, S.Zelensky Visualization of undersurface submicron-sized inhomogeneities via laser-induced incandescence of surface layers / “Optics & High Technology Material Science” SPO 2016. Scientific works. Oct. 27-30, 2016. Kyiv, Ukraine. P.173.

Traveling Report

Name:	Serge Zelensky
Affiliation and address:	Taras Shevchenko National University of Kyiv, 60 Volodymyrska Street, Kyiv, 01033, Ukraine
Period of time:	01 February 2017 – 20 Februaty 2017
Destination:	Research Institute of Electronics, Shizuoka University
Purpose:	Study of laser-induced incandescence of surface layers under excitation by YAG:Nd laser working at the third harmonic for testing of the predictions made on the basis of computer simulations. Participation in scientific meetings at Research Institute of Electronics, Shizuoka University during the period of stay.
Name of receiver:	Prof. Toru Aoki