Laser-Induced Incandescence of Microparticles Deposited on Surfaces of Transparent 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:
Kateryna Zelenska, Ph.D., Engineer (Taras Shevchenko National University of Kyiv, Ukraine)
Maksym Kokhan, MSc student (Taras Shevchenko National University of Kyiv, Ukraine).

[2] Progress of Scientific Activity

According to the research plan of the project, the following scientific activities were performed at Taras Shevchenko National University of Kyiv and at Research Institute of Electronics, Shizuoka University:

i. computer simulations,
ii. development of a suitable method of deposition of carbon microparticles on a flat surface, and
iii. measurements of laser-induced incandescence (LII) of the particles deposited according to the method (ii).

The mentioned activities were performed at Taras Shevchenko National University of Kyiv, Faculty of Physics, Department of Optics (i–iii) and Research Institute of Electronics, Shizuoka University (ii–iii).

The computer simulations were intended to estimate the effect of the surface material parameters on the characteristics of LII of a microparticle located on the surface of a transparent material.

For the particles deposition and LII measurements, two YAG:Nd pulsed lasers with different characteristics were used at TSNUK and at RIE. For characterization of the surfaces with deposited particles, an atomic force microscope and a scanning electron microscope were used at TSNUK and at RIE.

Besides the above-mentioned, 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, August and September 2017, when Prof. *Toru Aoki* visited Ukraine.

The participants of the project actively collaborated in organizing the 18th Intern. Young Scientists Conference "Optics & High Technology Material Science" SPO 2017 held at the Faculty of Physics of Taras Shevchenko National University of Kyiv 26-29 Oct. 2017. Prof. S. Zelensky was the member of the Program Committee, Prof. *T. Aoki* was the member of the International Committee, and Dr. *K. Zelenska* and Prof. *T. Aoki* were the members of the Organizing Committee of SPO-2017. Prof. S. Zelensky presented the project-related results at SPO-2017 and XXIII ISSSMC conferences.

[3] Research Results

The project was aimed to investigate the properties of LII of microparticles located on a flat surface of a transparent material. As a primary task, the project scheduled the investigation of the effect of the surface thermal conductivity on LII kinetics. The main idea is that the surface's thermal conductivity can significantly affect the decay of LII, hence LII can be a promising method for visualization of local thermal properties of surface layers (at least for transparent materials).

For the mentioned purpose of the project, carbon microparticles are the best candidate for measurements. Carbon particles are easy to be deposited on a surface by laser ablation; carbon has high absorption coefficient at the wavelength of YAG:Nd laser and high temperature of vaporization (approximately 4000K at atmospheric pressure).

Prior to the measurements of LII of surface-deposited microparticles, computer simulations were performed. In the calculations, a single light-absorbing particle located on a flat surface of transparent material was irradiated by a single laser pulse. Due to the absorption of laser radiation, the particle can be heated to incandescent temperatures. Transient temperature field $T(\boldsymbol{r},t)$ can be calculated with the use of classical equation of thermal diffusion

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

where κ is the thermal conductivity, c_p is the heat capacity, ρ is the density, α is the absorption coefficient, F. is the laser power density (the Gaussian-shaped laser pulse with the length of 20 ns was used). The absorption of laser radiation was accounted with the following equation

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

where the coordinate z presents the direction of the laser beam propagation.

For simplification of the calculations, the particle shape was chosen as shown in Fig.1. In the figure, irradiated is the top surface with the area of $\pi\left(D/2\right)^2$, and the size of the particle-to-surface contact spot (diameter d) is a variable parameter.

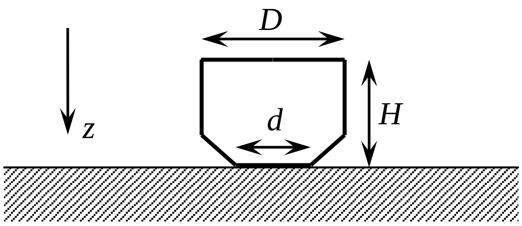

Fig.1. Carbon particle dimensions (D – diameter, H – height, d – particle-to-surface contact spot diameter).

The oscillograms of thermal emission at a fixed wavelength were calculated with Planck's blackbody emission law with the use of transient temperature field $T(\boldsymbol{r},t)$ calculated with equations (1) and (2).

Typical calculated oscillograms of LII of a carbon particle located on a glass surface are given in Fig.2 and 3, where the particle dimensions are the following: $D = H = 1$ μm, $d = D/10$. In the calculations, LII signal is collected from the top and side surfaces of the particle, at a fixed wavelength of 450 nm.

Computer modeling was performed for surface materials with different thermal transport characteristics. The calculations show that thermal conductivity of the surface material affects (i) the intensity of LII, and (ii) the time of LII decay. With the increase of the surface thermal conductivity, the intensity of LII decreases, and the LII decay time shortens. In the current project, the efforts were concentrated on the characteristics of LII decay, because the decay time measurements do not require strict stabilization of laser parameters, whereas the LII intensity is extremely sensitive to the fluctuations of laser power density.

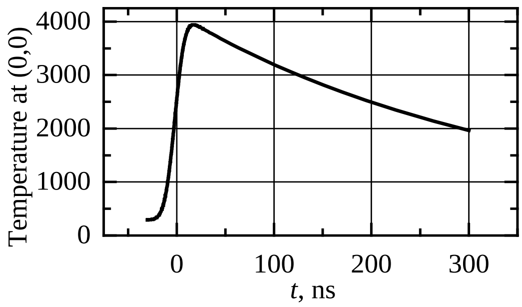

Fig.2. Calculated particle temperature history. Coordinates (0,0) correspond to the center of the particle's top surface.

As an example, Fig.3 presents the calculated LII oscillograms for carbon particles on two surfaces with different thermal diffusion characteristics. As is seen from the figure, LII decay time for sapphire surface is twice as small as for glass surface, and this difference is caused by the differences in thermal conductivity and heat capacity of sapphire and glass.

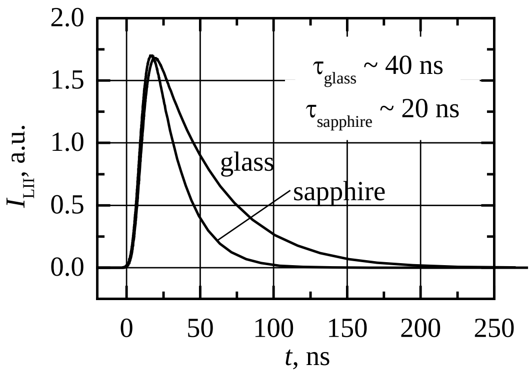

Fig.3. Calculated LII oscillograms for a carbon particle on a glass surface and on a sapphire surface.

Thus the above-given results of computer simulations show that LII decay time of surface-located carbon particles can be used for sensing the thermal characteristics of the surface's material.

For experimental verification of the mentioned conclusion, measurements were performed with carbon miroparticles deposited on different surfaces by laser ablation technique. Laser deposition was made in the air with the use of different carbon sources: china ink (dried on a glass surface), bulk carbon electrode rod, carbon-containing light-tight paper, carbon black powder. Size of the deposited particles was measured by scanning electron microscopy and by atom force microscopy methods. The size of the laser-deposited particles was approximately (0.2–0.5) μm.

Typical oscillograms of LII of surface-deposited carbon microparticles are given in Fig.4. Numbers near the curves represent the numbers of laser shots in the sequence.

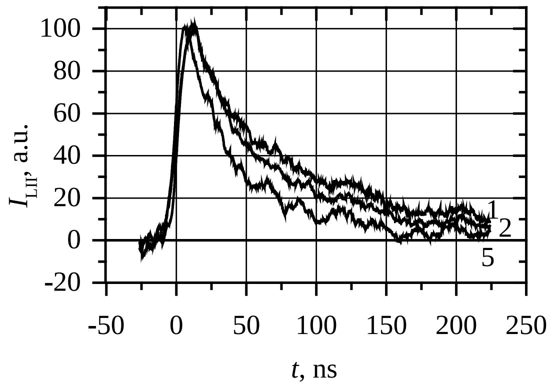

Fig.4. Typical LII oscillograms of carbon microparticles deposited on a glass surface by laser ablation technique.

The LII oscillograms in Fig.4 were collected with the use of a photomultiplier (with time resolution of 1.3 ns) and a digital oscilloscope (with the bandwidth of 200 MHz). Spectral interval of LII was approximately (400–450) nm.

For better visual demonstration of the laser-induced changes of LII decay time, the oscillograms in Fig.4 are normalized by their maximal values.

As is seen from Fig.4, with the increase of the laser irradiation dose *N*, the oscillograms become shorter. This fact can be interpreted as a consequence of decrease of size of the particles due to the laser-induced vaporization. The effect of laser-induced vaporization can be reduced by the decrease of laser intensity in the experiments.

Fig.5 presents the LII decay time as a function of the number of laser shots in the sequence, for two surfaces of different transparent materials: glass and sapphire. Both of the surfaces were polished.

As is seen from Fig.5, at N>5, the LII decay time of carbon-on-glass sample is approximately twice as large as of carbon-on-sapphire sample. This result is in agreement with the results of calculations given in Fig.3.

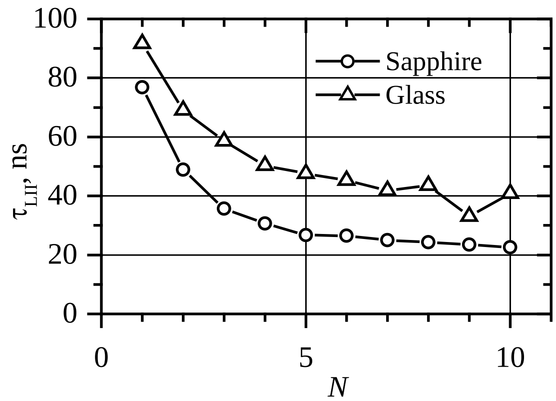

Fig.5. LII decay time as a function of the laser shot number in the sequence for carbon particles on glass and sapphire surfaces.

Thus we can conclude that the results of calculations and the experimental data confirm the main idea of the project: the LII decay time of carbon-on-surface samples depend on the surface material's thermal properties.

[4] Publications *(published and submitted by the CRP participants during the project period 2017/5/24 – 2018/3/31)*

1. K. Zelenska, S. Zelensky, A. Kopyshinsky Effect of Thermal Conductivity of Carbon Superficial Layers on the Kinetics of Laser-Induced Incandescence// Thai J. Nanosci. Nanotechnol. 2017. V.2. N.1. P.1–8.
2. V. Karpovych, K. Zelenska, S. Zelensky, S. Yabl ochkov, T. Aoki Evolution of Laser-Induced Incandescence of Porous Carbon Materials under Irradiation by a Sequence of Laser Pulses// Thai J. Nanosci. Nanotechnol. 2017. V.2. N.2.
3. M. Kokhan, I. Koleshnia, S. Zelensky, Y. Hayakawa, T. Aoki Laser-induced Incan-descence of GaSb/InGaSb Surface Layers// XXIII Galyna Puchkovska Intern. School-Seminar “Spectroscopy of Molecules and Crystals”. Kyiv, Ukraine, Sept. 20–25, 2017. P.197.
4. V. Karpovych, S. Zelensky, S. Yablochkov Laser-induced incandescence of porous carbon materials under pulsed laser irradiation/ “Optics & High Technology Material Science” SPO 2017. Scientific works. Oct. 26–29, 2017. Kyiv, Ukraine. P.121.
5. M. Kokhan, I. Koleshnia, S. Zelensky, Y. Hayakawa, T. Aoki Laser-induced Incandescence of GaSb/InGaSb Surface Layers// Article under consideration in “Optics & Laser Technology” journal.

Traveling Report

Name:	Serge Zelensky
Affiliation and address:	Taras Shevchenko National University of Kyiv, 60 Volodymyrska Street, Kyiv, 01033, Ukraine
Period of time:	10 November 2017 – 26 November 2017
Destination:	Research Institute of Electronics, Shizuoka University
Purpose:	Study of laser-induced incandescence and laser ablation of carbon with the use of YAG:Nd laser and SEM measurements of laser-ablated carbon microparticles for testing of the predictions 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