Thomson-Benard phenomena and Relaxed Optics

P. P. Trokhimchuck

Lesya Ukrayinka Volyn' National University, Lutsk, Ukraine,
e-mail: trope1650@gmail.com

Main peculiarities of Bernard phenomena are discussed. Corresponding models and theories, which are used for the explanation this phenomenon, are represented. Questions about possible observation these phenomena in Relaxed optics are analyzed.
Conditions for the regimes of laser irradiation and irradiated matter, which are necessary for the creation and observation the Bernard phenomena are formulated and discussed. Role and possible applications these phenomena in laser technology and modern optoelectronics are analyzed too.

Key words: Thomson-Bernard phenomena, laser irradiation, filaments, Rayleygh, liquids, Chandrasekar, hexagonal structures, Relaxed Optics, semiconductors.

Introduction

We represent question about possibility the generation laser-induced Thomson-Benard phenomena on basis of experimental data for germanium [1].

First observation the phenomena of creation polygonal forms in heated liquid was made by count Rumford in 1797 [2, 3]. In 1870, the Irish-Scottish physicist and engineer James Thomson, observed water cooling in a tub; he noted that the soapy film on the water's surface was divided as if the surface had been tiled (tesselated). In 1882, he showed that the tesselation was due to the presence of convection cells [4]. In 1900, the French physicist Henri Bénard independently arrived at the same conclusion [5]. This pattern of convection, whose effects are due solely to a temperature gradient, was first successfully analyzed in 1916 by Lord Rayleigh [6]. Rayleigh assumed boundary conditions in which the vertical velocity component and temperature disturbance vanish at the top and bottom boundaries (perfect thermal conduction). Those assumptions resulted in the analysis losing any connection with Henri Bénard's experiment. The theory of Thomson-Benard phenomena for electron gas in semiconductors was created and developed by V. Bonch-Bruevich and A. Temchin [2, 7]. A Medvid used this theory for qualitative explanation of the creation the laser-induced surface structure in germanium [1].

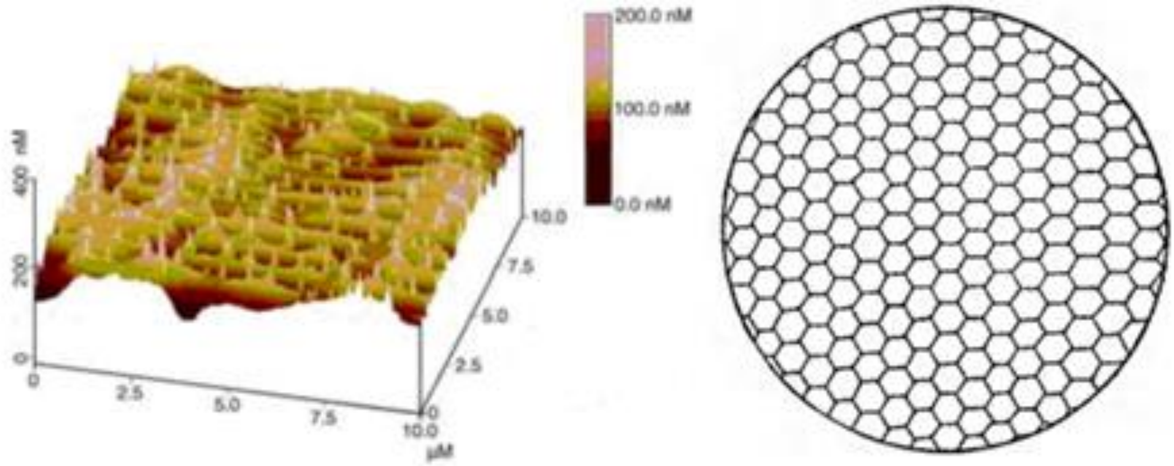
Therefore in this paper we represented basic peculiarities of Thomson-Benard phenomenon and conditions, which are necessary for its realization in Relaxed Optics [3]. Roughly speaking the Thomson-Benard phenomena is hydrodynamical effect, which is generated on the early stage of formation the hydrodynamical vortexes. It is "soft" effect. Therefore for the observation this phenomenon we must select slow regime of laser-induced melting the irradiated matter. This should be a relatively long-term process, which would include the melt of the irradiated material, its heating, and the initiation of convective fluid motion. We believe that the most suitable laser irradiation regimes can be continuous, millisecond and microsecond irradiation regimes [2, 8]. Silicon, germanium and titanium were selected as possible materials. A comparative analysis with the cascade physical-chemical model of laser-induced transformation [8] is carried out. A significant difference in obtaining the laser-induced Thomson-Benard phenomenon and physicochemical phase transformations is shown.

Main results and discussions

Experimental data by A. Medvid, which he wanted to explain as Benard phenomenon, are represented in Fig. 1a [1]. Samples of Ge {111} and Ge {001} *i*-type single crystals are used in experiment. Nd:YAG laser (wavelength 1,064 μm, duration of pulse 15 ns, pulse rate 12,5 Hz, power P = 1 MW) was used for the irradiation.

Real Thomson-Benard phenomenon (Benard cells) is represented in Fig. 1, *b* [2, 5]. Hexagonal forms of cells are characterized thinner layers, for thicker layers other polygonal structures may appear, this fact was also noted by Thomson [3, 4].

But the pictures of Fig. 1, *a* and Fig. 1, *b* are various. Therefore we must be search another ways of explanation the data of Fig. 1, *a* and must be formulated basic conditions for the receiving Thomson-Benard phenomena by methods of Relaxed Optics.



a ***b***

Fig. 1. – **(***a*) Three-dimensional AFM image of nanostructures after Nd:YAG laser irradiation with density of power 28 MW/cm^2 on Ge surface [1]; **(***b*) Benard cells in spermaceti. Cells visualization transmission: temperature 61.36 °C, thickness – 0.64 mm [4]**.**

Since there is a density gradient between the top and the bottom plate, gravity acts trying to pull the cooler, denser liquid from the top to the bottom. This gravitational force is opposed by the viscous damping force in the fluid. The balance of these two forces is expressed by a non-dimensional parameter called the Rayleigh number. The Rayleigh number is defined as [2, 3, 6]:

$$Ra = \frac{g\alpha\beta}{\kappa\nu} d^4 , \qquad (1)$$

where g denotes the acceleration due to gravity, d the depth of the layer, $\beta = \left|\frac{dT}{dz}\right|$ the uniform adverse temperature gradient which is maintained, and α, κ and ν are the coefficients of volume expansion, thermometric conductivity and kinematic viscosity, respectively [2, 6].

The theory of Thomson-Benard phenomena for electron gas in semiconductors was created and developed by V. Bonch-Bruevich and A. Temchin [3, 7]. This theory makes it possible to determine the possibility of the appearance of prevortexes states in the electron gas of nondegenerate semiconductors (gas concentration up to 10^{19} cm^{-1}).

Roughly speaking the Thomson-Benard phenomena is hydrodynamical effect, which is generated on the early stage of formation the hydrodynamical vortexes. It is “soft” effect. Therefore for the observation this phenomenon we must select slow regime of laser-induced melting the irradiated matter. This should be a relatively long-term process, which would include the melt of the irradiated material, its heating, and the initiation of convective fluid motion. We believe that the most suitable laser irradiation regimes can be continuous, millisecond and microsecond irradiation regimes [3]. Silicon, germanium and titanium were selected as possible materials [8]. A comparative analysis with the cascade physical-chemical model of laser-induced transformation [8] is carried out. A significant difference in obtaining the laser-induced Thomson-Benard phenomenon and physicochemical phase transformations is shown in [3].

We must see on the Thomson-Benard phenomena with physical-chemical point of view. In the case of liquid and electronic gas these phenomena has nonequilibrium nature in Relaxed Optics – irreversible nature. Therefore, we must represent the possible realization of these processes with help first kinetic concept of Relaxed Optics.

Firstly, we must estimate temporal and energetic characteristics of regimes the laser irradiation, which can be search of these processes according to first (kinetic) concept of Relaxed Optics [3, 8].

The chain of hierarchy of corresponding times may be represented in next form. Let τ_i is the time of laser irradiation of matter; τ_h is the time of heat the irradiated matter to point of its melting; τ_m is the time of existing the melting phase, including heatind in liquid phase; τ_{TB} is the time of generation Thomson-Benard structures and its life, τ_c is cooling time of irradiated.
The time hierarchy for laser-induced Thomson-Benard phenomena is next

$$\tau_i << \tau_h < \tau_m << \tau_{TB} \sim \tau_c. \quad (2)$$

Energy characteristic of irradiation is next: laser radiation must have self-absorption nature with absorption index ~ 10 – 100 cm^{-1} melting layer must be having sufficiently large value. This condition is necessary for the homogeneous power transmission of laser radiation to irradiated matter. So, irradiation of indium antimonide and indium arsenide by millisecond pulses of Ruby and Neodymium lasers (index absorption ~ 10^5 cm^{-1}) is connected with heterogeneous processes of phase transformations in irradiated matter, which is caused by the processes of second-order reradiation of first-order absorption radiation [3]. For the observation of pure laser-induced Thomson-Benard phenomena, we must create the conditions of homogeneous absorption of light in subsurface region of irradiated matter. For the regimes of absorption the laser irradiation with absorption indexes ~ 10 – 100 cm^{-1} processes of second-order reirradiation have analogous absorption indexes. It is allow receiving homogeneous conditions of radiation in corresponding subsurface layer of irradiated matter. This regime of irradiation allows increasing the value of homogeneous depth (distribution) of irradiated matte [3].

Basic difference between data of Fig. 1 and Fig. 2 is nature of proper phenomena. Data of Fig. 1 has irreversible nature, Fig. 2 – nonequilibrium nature.

In addition, the image shown in Fig. 1 rather resembles a picture of growing crystal twins from a solution rather than a Benard cell [3, 8]. Therefore, the conclusion suggests itself about the creation of a theory of laser-induced phase transformations, in which the parameters of the irradiation and the structure of the irradiated material play the main role. Based on this, the theory of cascade excitation of chemical bonds in the excitation saturation mode was developed. Roughly speaking, this theory includes the processes of multiphoton absorption, as well as other nonlinear optical effects with irreversible (nonradiative) relaxation, and whether the trace of these phenomena in the irradiated medium [3].

It is known that silicon and germanium have four crystalline and eight quasicrystalline phases. Therefore, sequential irradiation (preferably with a series of relatively low-power pulses) leads to step-by-step phase transformations with a decrease in the symmetry of the irradiated material. In addition, these crystals are covalent and initially the energies of all bonds for the main crystallographic modification (diamond lattice) are the same [3, 8, 9]. This greatly simplifies the modeling procedure.

The classic Benard cells have two-dimensional surface symmetry (Fig. 2), laser-induced structures of Fig. 1 have three-dimensional crystallographic symmetry. If we represent creation of structures Fig. 1 as prevortexes and vortexes structural phase transformations, then we can talk about crystallographic phase transformations similar to the Thomson-Benard phenomenon. In this case we must synthesize in one system elements of nonlinear dynamics and theories of phase transformations, including elements the theory of creation new phases (Vitaly Stafeev electrostatic phason theory [10]). In this case microscopic mechanism of creation the phase transformations is connected with short range electromagnetic (crystallography) laser-induced interactions.

Conclusions

1. The experimental data of creation the laser-induced hexagonal structures in germanium are represented.
2. Basic peculiarities of Thomson-Benard phenomena in hydrodynamics and for electron gas are discussed.
3. Conditions for the generation of Thomson-Benard processes in phenomena in the laser-irradiated matter are formulated.
4. Comparative analysis of conditions the irradiation for laser-induced physical-chemical processes and Thomson-Benard phenomena is represented.
5. Questions about role of direct laser-induced physical-chemical phase transformations on the formation represented structures are discussed too.

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