CHERENKOV RADIATION AND RELAXED OPTICS

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Short review of basic peculiarities of Cherenkov radiation is represented. Influences of various types of irradiation on formation the Cherenkov radiation are discussed. Conditions of receiving Cherenkov radiation as phenomenon of Nonlinear Optics (multiphoton absorption in regime of saturation of excitation) are formulated. Three types of models are used for the representation of proper experimental data. Experimental data of receiving the cascade of volume laser-induced destruction in silicon carbide are analyzed. The role of shork processes, including Cherenkov radiation, and diffraction stratification of focused light in the formation experimental picture is observed. The modified Rayleygh model is used for the estimation the sizes and form of receiving nanovoids. Good agreements of modeling and experimental data were received.

Keywords: Cherenkov radiation; Nonlinear Optics; Relaxed Optics; Rayleygh model; shork processes; nanovoids; cascade processes; Bohrs Model; saturation of excitation.

Introduction

The problem of receiving and application of Cherenkov radiation is very interesting problem of Relaxed Optics [1-3].

Now Cherenkov radiation is received after transmission high-energy particles (electrons, ions, γ-quanta) through matter. Difference Cherenkov and slowing-down radiation is next. Cherenkov radiation has two stages [4-6]: first is polarization of matter, second – the radiation of this polarized matter.

Cherenkov radiation may be represented as shock electromagnetic process too [4-6].

Three types models may be used for the explanation this phenomenon.

First, classical Tamm-Frank concept is represented Cherenkov radiation as reaction of irradiated matter on shock excitation of matter [4, 6].

Niels and Aage Bohrs theory is based on theory of slowing-down of charged particles [5]. This concept may be represented as microscopic nature of Cherenkov radiation. But for high-energy particles each particle is polarized the matter in large volume. We have cone of excitation for each particle. Perpendicular to surface of this cone is corresponded to Cherenkov angle. Number of cones is equaled the number of particles projectile. In this case we have fracturing the energy of each charge particle projectile.

But other way of receiving Cherenkov radiation may be realized. It is optical method [3]. After irradiation the matter in the range of light transmission of matter by femtosecond laser irradiation we must have multiphotonic polarization of matter in the regime of saturation the excitation. In this case for irradiation of laser mode TEM_{oo} we have only one cone. One cone may be received foe the focused radiation too. But for regime of focusing we can have diffraction stratification of radiation and cascade of Cherenkov radiators. Thus, we can create radiators in self-absorption range in volume of irradiated matter. It may be used for the local change of properties of irradiated matter in volume.

The change of physical properties of irradiated matter in conical sections for optical case is simple to high-energy particles irradiation. But in this case, we have lesser radiation damages. For modeling these processes may be used the kinetic method for the estimations of proper mechanisms of multiphotonic light scattering. Roughly speaking we have spectrum of various nonlinear optical phenomena. Therefore, spectrum of this radiation must be continuous as for other cases the receiving of Cherenkov radiation.

This radiation may be source of creation Relaxed Optical processes in volume of irradiated matter.

Basic results and discussions

Experimental data, which are validated the optical generation of Cherenkov radiation and its using the further destruction of irradiated matter were received by Okada group for 4H-SiC [7, 8].

In [7, 8] for minituarization of receiving structures of crystals 4H-SiC were irradiated by pulses of femtosecond laser (duration of pulses 130 fs, wavelength 800 nm, frequency of pulses 1 kHz, density of energy 200-300 nJ/pulse) with help microscope [7]. Femtosecond laser pulses were irradiated along the lines inside 4H-SiC single crystals at a depth of 30 μm by moving the sample at a scan speed of 10 μm/s. The laser beam was irradiated at a right angle to the (0001) surface of the crystal. The irradiated lines were almost parallel to the $\left[1\bar{1}00\right]$ direction.

Bright-field TEM image of the cross section of a line written with the pulse energy of 300 nJ/pulse is shown on Fig. 1 [7].

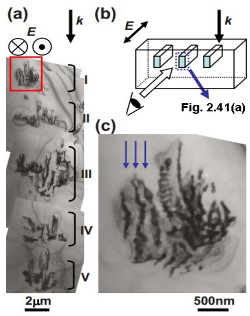

Fig. 1. (a) Bright-field TEM image of the cross section of a line written with a pulse energy of 300 nJ/pulse. (b) Schematic illustration of a geometric relationship between the irradiated line and the cross-sectional micrograph. (c) Magnified image of a rectangular area in (a). Laser-modified layers with a spacing of 150 nm are indicated by arrows [7]

Bright-field TEM image of a portion of the cross section of a line written with a pulse energy of 200 nJ/pulse is represented in Fig. 2 [8].

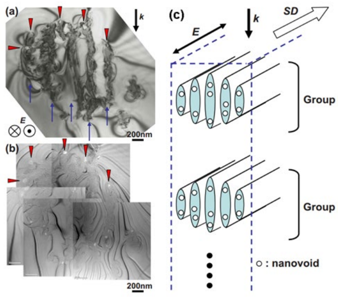

Fig. 2. (a) Bright-field TEM image of a portion of the cross section of a line written with a pulse energy of 200 nJ/pulse. (b) Zero-loss image of a same area as in (a) with nanovoids appearing as bright areas. Correspondence with (a) is found by noting the arrowheads in both micrographs. (c) Schematic illustrations of the microstructure of a laser modified line. Light-propagation direction (*k*), electric field (*E*), and scan direction (SD) are shown. Only two groups (groups I and II) of the laser-modified microstructure are drawn [8].

In contrast to the formation of surface periodical structures three-dimensional periodic structures were obtained in this case. Sectional area of these structures was ~ 22 µm, the depth of ~ 50 µm. As seen from Fig. 1(a) we have five stages disordered regions, which are located at a distance from 2 to 4 µm apart vertically [7]. Branches themselves in this case have a thickness from 150 to 300 nm. In this case there are lines in the irradiated nanocavity spherical diameter of from 10 nm to 20 nm. In this case irradiated structures have crystallographic symmetry of the initial structure.

The explanation basic peculiarities of these data according to [2, 3] may be next.

The creation of cascade the volume destruction (Fig. 1(a)) may be represented as result of diffraction stratification [3]. The estimation of sizes the cascade of volume destructions maybe explains in next way. The sizes (diameters) of proper stages d_{nir} of cascade are proportionally to corresponding diffraction diameters (diameter of proper diffraction circle) d_{ndif}:

$$d_{nir} = kd_{ndif}, \qquad (1)$$

where k is the proportionality constant.

The diffraction diameters d_{ndif} may be determined with help condition of diffraction-pattern lobes (modified Rayleygh ratio):

$$d_{ndif} = n\lambda. \qquad (2)$$

The estimations of diffraction diameters d_{ndif} for λ = 800 nm are represented in Table 1 [3].

Table 1. The estimations of diffraction diameters

n	1	2	3	4	5
d_{ndif}, nm	800	1600	2400	3200	4000

The data of Table 1 for *n* = 1, 2, 3 allow to explain of sizes the first three stages of cascade the volume destruction (Fig. 1 (a)). For this case coefficient k ~ 2. But for stages 4 and 5 of Fig. 1 (c) our estimations k_4 ~ 1.2 and k_5 = 1. Various values of coefficients k_i are explained of various conditions of optical breakdown and creation proper phase transformations.

The distance between diffraction spots and proper «moving» foci may be determined with help next formula:

$$l_{nf} = \frac{d_{ndif}}{2\tan \varphi/2}. \qquad (3)$$

These distances for φ_1 = 20° and φ_2 = 30° are represented in Table 2 [3].

Table 2. The distance between diffraction spots and proper «moving» foci

n	1	2	3	4	5
l_{nf}, nm; φ_1 = 20°	2269	4538	6807	9076	11345
l_{nf}, nm; φ_2 = 30°	1493	2985	4478	5970	7463

Qualitative explanation of development of cascade the destructions may be next. The focus of each diffraction zone (spot) is the founder proper shock optical breakdown. But foci with more high number may placed in the "zone" of influence of previous foci. Therefore, only first stage of Fig. 1 (c) is represented pure shock mechanism (Mach cone). Mach cones are characterized the second and third stages of Fig. 1 (c). But its maximums are displaced from center. It may be result if interaction second and third shock waves with previous shock waves: first – for second wave and first and second for third wave. The chock mechanism of destruction certifies a linear direction of optical breakdown. This direction is parallel to direction of shock wave and radiated spectrum is continuum as for Cherenkov radiation and as for observed laser-induced filaments in water and air [9]. Thus, basic creator of optical breakdown traces is secondary Cherenkov radiation and shock waves. This radiation is absorbed more effectively as laser radiation and therefore the creation of optical breakdown traces is more effectively as for beginning laser radiation. Cherenkov radiation is laid in self-absorption range of 4H-SiC, but 800 nm radiation – in intrinsic range. For the testing of this hypothesis we must measure the spectrum of secondary radiation.

The cone character the one knot of Fig. 1(c) may be represented as frozen pattern of Cherenkov radiation with optical pumping [3]. The angle 2θ at the pick of Fig 1(c) is corresponded to the Cherenkov angle or angle of Mach cone [3]. According to these data next conclusion may be made: the creation of cascade of destructions is connected of the shock ionization and this effect is analogous to microscopic mechanism of Cherenkov radiation [3]. But this angle is smaller or equaled of Cherenkov angle which is determined as

$$\cos\theta_{ch} = \frac{1}{n}, \qquad (4)$$

where n – refractive index. For 4H-SiC n = 2.77 [3] θ_{ch} = 69°. In Bohrs theories Cherenkov angle is determined as angle between direction of particle moving and perpendicular to hyperboloid of electromagnetic excitation of matter. In this case the next correlation is true:

$$\theta_{ch} + \alpha_{ex} = 90°, \qquad (5)$$

where α_{ex} is half angle of hyperboloid for Bohrs case or half angle of focusing light in matter.

Formula (5) may be used for the determination Cherenkov angle with help of α_{ex} and for the determenatiion θ_{ch} with help α_{ex}.

Smaller value of angle θ in Fig. 1 (c) maybe explains of two ways: 1) on the basis of nonlinear defocusing of initial radiation and 2) increasing of Cherenkov angle for nonlinear regime of irradiation («optical pumping» of Bohrs hyperboloid, which may be transformed to other cone for optical case) [3, 5].

Influence of geometry of irradiation on Cherenkov radiation was researched in [6]. This question was represented from polarized point of view.

The microscopic nature of Cherenkov radiation may be explained on the basis Bohrs theory and cascade theory of excitation of proper scattering centers in the regime saturation of excitation (Nonlinear and Relaxed optical processes [1-3]. In this case we can represent microscopic nature of Cherenkov irradiation with physical-chemical point of view.

Now we estimate the basic energy characteristics of experimental data, where are represented in Fig. 1 (a) [3]. Let each stage of cascade has ~200 nanotubes with sizes – d_{nt} =20 nm in diameter and with length l_{nt} = 500 nm. General number of these nanotubes is N_{1snt} ~ 1000. Its summary volume has value:

$$V_{lsnt} = N_{lsnt}\frac{\pi d_{nt}^2}{4} l_{nt} = 0.63 \mu m^3 . \quad (6)$$

The average atom density of 4H-SiC may be determined with help next formula:

$$N_a = \frac{\rho N_A}{A} \quad (7)$$

where ρ – density of semiconductor, N_A – Avogadro number, A – a weight of one gram-atom. For 4H-SiC $N_{aSiC} = 2.4 \cdot 10^{22}$ cm^{-3}.

Number of atoms in summary volumes of nanotubes is equalled:

$$N_{asnt} = N_{aSiC} V_{lsnt} = 1.51 \cdot 10^{10}. \quad (8)$$

Energy, which is necessary for the optical breakdown our nanotubes may be determined in next way. Zeitz threshold energy for 4H-SiC is equaled E_{Zth} ~ 25 eV [3]. Let this value is corresponded to energy of optical breakdown. Therefore, summary energy E_{1ob} is equaled:

$$E_{lob} = N_{asnt} \cdot E_{zth} = 30.2 \text{ nJ}. \quad (9)$$

This value is equaled of 10 % from pulse energy. In this case we have more high efficiency of transformation initial radiation to «irreversible» part of Cherenkov radiation as in classic case [3-6].

Nanovoids may be represented as results of the laser-induced laser-induce breakdown and creation of cavitation bubbles [2, 3] too. The light pressure may be determined with help of next formula [2, 3]:

$$p_0 = \frac{E_{ir}}{\tau_i c S}, \quad (10)$$

where E_{ir} – energy of irradiation, τ_i – pulse duration, S – area of irradiation zone, c – speed of light.

For the estimations of maximal radius of nanovoids we must use modified Rayleygh formula [2, 3]:

$$R_{max} = \frac{2R}{0.915 r}\sqrt{\frac{E_{ir}}{\pi \tau_i c E}} \quad (11)$$

where R – radius of nanotube, r – radius of irradiated zone.

If we substitute r = 250 nm, R = 10 nm, E = 600 GPa [2, 3], E_{ir} = 130 nJ, τ_i = 130 ps, $c = 3 \cdot 10^8$ m/s, then have R_{max} =11 nm.

The ellipticity of nanovoids may be determined with help formula [3]:

$$\alpha = \frac{\vartheta_{ts}}{\vartheta_{ls}} = \sqrt{\frac{(1-2\nu)}{2(1-\nu)}} = \frac{R_{max\,l}}{R_{max\,t}} = 0.33, \quad (12)$$

where ϑ_{ts} – transversal speed of sound; ϑ_{ls} – longitudinal speed of sound; R_{maxl} – maximal longitudinal radius of nanovoid; R_{maxt} – maximal transversal radius of nanovoid; ν – Poisson ratio.

In this case we represented 4H-SiC as isotropic plastic body. For real picture we must represent hexagonal structure. But for the qualitative explanation of experimental data of Fig. 1 this modified Rayleygh model allow explaining and estimating the sizes and forms of receiving nanovoids.

Thus, we give answer on basic peculiarities of experimental data of Fig. 1 and Fig. 3 and represented models are explained the basic volume processes and phenomena of Relaxed Optics in 4H-SiC.

These processes must be used for the creation of optical fibers lines of communication.

Conclusions

Basic peculiarities of modeling the Cherenkov radiation are analyzed. We show that ultrashort pulse laser irradiation may be source of Cherenkov radiation.

The role of Cherenkov radiation in generation of cascade volume destructions in 4H-SiC is observed.

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