Theoretical Research of Laser-Controlled Thermocleavage of Sapphire Wafers

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Abstract

Objectives: We present the theoretical research of laser-managed thermocleavage of sapphire wafers using numerical modeling techniques, such as finite element method. **Methods/Statistical Analysis**: The model of laser treatment of sapphire wafers allows analyzing the distribution of temperature and thermal stresses in a heated sample. Simulation of sapphire wafers laser treatment was performed with the help of heat equation solution in ANSYS finite element analysis software. **Findings**: Temperature distribution and thermal stresses in sapphire wafers by irradiating Nd: YAG laser with a wavelength of 1.064 µm were obtained. It was found that the laser power density and the speed of the laser beam significantly affect sapphire cutting quality. The simulation revealed that the maximum temperature on the surface of the sapphire wafer is about 500-830°C at the average laser power of 80-100 W and a speed of movement of the laser beam 1-5 mm/s. **Application/Improvements:** The laser thermocleavage method for sapphire wafers can be used in construction of new devices in micro- and optoelectronics as well as in electronics industry.

Keywords: Laser Treatment, Numerical Modeling, Sapphire Wafer, Thermocleavage

1. Introduction

Currently, laser thermocleavage is the most effective separation method for fragile nonmetallic materials such as ceramics, quartz, and various semiconductor materials including sapphire¹. Sapphire single crystals obtained by the horizontal directional crystallization method, have high melting temperature, chemical and radiation resistance, high hardness and transparency. Therefore they find wide application in microelectronics, quantum electronics, optics and high resolution nanotechnology²⁻⁴.

Importance of the research of laser-controlled thermal splitting of sapphire plates is associated with an increase in the efficiency of their cutting. In particular, it leads to more economical use of materials and waste reduce, as well as avoiding mechanical contact (except for grinding and polishing the edges), increasing the accuracy and repeatability of cutting, increase cutting speed, and implement more complex cutting trajectory.

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In this work the numerical simulation of sapphire plate's laser processing by the radiation with a wavelength of 1.064 μ m was made. It allows analyzing the distribution of temperature and thermal stresses on a sample. The simulation algorithm of sapphire plates laser processing was implemented by the finite element analysis universal software package ANSYS^{5.6}.

2. Methods and Materials

In the process of theoretical research of sapphire plateslaser treatment it is necessary to solve the following problems:

- The setting of physical and geometrical parameters of the sapphire sample, the generation of finite element mesh, the definition of the temperature field and thermal stress in sapphire wafer;
- Determining the intensity of the heat source power (laser radiation).

For development of the model of sapphire waferslaser treatment in the ANSYS system we can make the following assumptions: the profile of the laser radiation has the form of the Gaussian distribution; the sapphire plate is isotropic, heat transfer process is described by the heat conduction and convection; sapphire elastic characteristics change during temperature increase was not considered.

We use the sapphire wafer with dimensions of 20 mm \times 10 mm \times 1 mm with the basic physical parameters given in Table 1 for sapphire laser treatment simulation.

For the numerical solution of the sapphire plate laser processing the type of transient thermal analysis (Transient Thermal) was applied. It allows taking into account the behavior of the investigated temperature characteristics during time². The sample computational grid was 24201 nodes and 5000 elements Figure 1.



Figure 1. Scheme of the sapphire wafer with a finite element mesh.

3. Results and Discussion

Initially, we calculate the heat source power density acting on the sapphire wafer. In this case, the use of laser radiation with a Gaussian distribution is the most preferred, because it allows focusing the laser radiation into a small diameter spot with a high power density of the laser radiation. Thus, the intensity of laser light was determined as follows⁸:

$$I(x, y) = I_0 \exp\left[-\frac{x^2 + y^2}{r^2}\right],$$
 (1)

Where I_0 is radiation intensity at the center of the Gaussian beam, *r*isinitial radius of the Gaussian beam, *x*andyarecurrent position.

As the result, the power density distribution of the laser radiation for Nd:YAG laser (wavelength of 1.064 μ m, pulse durationof 84 ns, pulse repetition rateof 10 kHz, average power of 100 W) on the sapphire sample surface is shown in Figure 2. It ranges from 10 to 40 MW/m².



Figure 2. The Gaussian distribution of power density of the laser radiation.

To determine the temperature distribution in the sapphire wafer we used the heat equation. It allows obtaining the temperature dependence of the spatial coordinates and time⁹:

$$\rho C_T \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + Q, \tag{2}$$

Where ρ is density, C_T is thermal conductivity, t is time, λ is thermal conductivity, Q is power density of the heat source.

In order to solve the thermal conductivity differential equation (2) we set boundary conditions: the initial temperature distribution in the sample (initial condition) and heat transfer boundary conditions on the sample (boundary conditions). The initial condition sets the temperature distribution on the sample surface, which has the form T (x, y, z, 0) = T_0 (a uniform temperature distribution). On the irradiated sapphire wafer surface (at z = 0) there are the boundary conditions of the third kind defining the convection heat transfer between the environment and the sample surface⁹:

$$q_{0} = \beta (T_{1} + T_{0}), \tag{3}$$

Where q_0 is the heat beam by convection, β is convection heat transfer coefficient characterizing the intensity of heat transfer between the surface and the environment, T_i is current temperature, T_0 is ambient temperature.

As the result of simulation in the system ANSYS we obtain temperature distribution in the sapphire wafer with thickness of h = 1 mm at different times by the influence of laser radiation with wavelength of 1.064 µm and beam scan velocity v = 1 mm/s Figure 3.

After determining the temperature field we calculate the thermal stresses and strains arising from uneven sapphire wafer heating by laser radiation. For a homogeneous and isotropic sapphire sample the tensor of displacement in Cartesian coordinates is determined by the following equation¹⁰:

$$\mathcal{S}_{ij} = \alpha T \sigma_{ij}, \tag{4}$$

ŧ

Where ε_{ij} is the strain, α is the thermal expansion coefficient, T is the temperature, and σ_{ij} is the thermal stress.

Thermal stresses σ_{ij} , which cause additional extensions and changes in the sapphire sample according to the formulas of the classical theory of elasticity, are subject to the following equation:

$$\varepsilon_{ij} = \frac{1}{2E} \left(\sigma_{ij} - \frac{\mu}{1+\mu} \sigma_{kk} \sigma_{ij} \right) + \alpha T \sigma_{ij}, \qquad (5)$$

Where *E* is Young modulus, μ is Poisson ratio.

Figure 4 shows the dependence of temperature and stress tensor components σ_{xx} , σ_{yy} , σ_{zz} of the time in the middle of the sapphire wafer (x = 10 mm, y = 5 mm) on the front (-) (z = 1 mm) and back edge (- - -) (z = 0 mm) at an average power of laser radiation of 100 W and laser beam scan velocity of 1 mm/s.



Figure 4. Dependence of temperature and stress tensor components σ_{xx} , σ_{yy} , σ_{zz} on the time in the middle of the sapphire wafer.

Based on the data¹¹⁻¹⁵ we simulate the strain and mechanical (thermal) stresses distribution in sapphire wafer during laser treatment with ANSYS system. The simulation results are presented in Table 2 (the scan velocity of the laser beam 1-5 mm/s and an average laser power of 80-100 W) and Figure 5.

4. Conclusions

The simulation of temperature and deformation stresses distribution in the sapphire wafer during laser processing was performed in ANSYS system. The simulation task is associated with solution of important problems such as laser-controlled thermocleavageof sapphire wafers. The simulation revealed that the maximum temperature on the surface of the sapphire wafer is about 500-830°C at the average laser power of 80-100 W and a speed of movement of the laser beam 1-5 mm/s. This fact leads to emerging and expansion of separating cracks and allows making a thermal cleavage with local heating of sapphire wafer surface.



Figure 5. Thermal stresses and strains in the sapphire wafer by the laser radiation.

Table 1. The physical parameters of the sapphire wafer

Density (kg/m ³)	4000
Melting temperature (K)	2323
Heat capacity (J/kg·K)	1430
Thermal conductivity (W/m·K)	5
Absorption coefficient (cm ⁻¹)	0.3
Poisson ratio	0.27
Young modulus (GPa)	345
Strength (MPa):	
compressive	2000
tensile	275-400

Table 2. The calculated values of the maximum tensileand compression stresses and maximum temperaturein the sapphire wafer

Maximum stress, MPa	P = 80 W		P = 100 W	
	v = 1	v =	v = 1 mm/s	v = 5mm/s
	100	511111/3	111111/3	511117,5
tensile	198	103	247	142
compressive	-233	-132	-291	-190
Maximum temperature, °C	675	505	832	629

The results have shown the perspective of the laser thermocleavage process of sapphire wafer using laser with wavelength of $1.064 \mu m$. We have found that the laser power density and the speed of the laser beam-significantly affect sapphire cutting quality. The laser thermocleavage method for sapphire wafers can find its application in construction of new devices in micro- and optoelectronics as well as in electronics industry.

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6. References

- 1. Kondratenko VS. Laser material processing. Nauka i Tekhnologii: Moscow. 2011; 56(5-6):341-88.
- Malyukov SP, Klunnikova YV, Sayenko AV. Investigation of laser processing of materials for microelectronics. Izv. Saint-Petersburg Electrotechnical University (LETI). 2014; 8(3):15-9.
- 3. Cherednichenko DI, Malyukov SP, Klunnikova YV. Heatphysical processes at the sapphire crystals growth by horizontal directed crystallization. Sapphire: Structure, Technology and Applications. In: Tartaglia I, editor. USA: Nova Science Publishers; 2013. p. 101-8.

- Malyukov SP, Sayenko AV, Klunnikova YV. Simulation of laser processing of sapphire. Proceedings of SFU. Technical Science. 2014; 9(158):39-45.
- 5. Segerlind LJ. Applied finite element analysis. New York: Wiley; 1976.
- 6. Rumyantsev AV. Finite element method in heat transfer problems. Kaliningrad: KGU; 1995.
- 7. Moaveni S. Finite element analysis: Theory and application with ANSYS. Pearson Education India; 2003.
- 8. Rykalin NN. Laser and electron-beam machining of materials. Moscow: Mashinostroyeniye; 1985.
- 9. Veyko VP, Konov VI. Interaction of laser radiation with material. Moscow: Fizmatlit; 2008.
- Boley BA, Weiner JH. Theory of thermal strees. New York: Wiley; 1960.
- 11. Malyukov SP, Klunnikova YV, Sayenko AV. Laser controlled thermocracking of sapphire wafers. Izv. Saint-Petersburg Electrotechnical University (LETI). 2015; 9(1):6-10.
- Anand MD, Maharaja NL, Kailordson KS, Prabhu N. Theoretical study and analysis on performance enhancement of a ceramic monolith heat exchanger. Indian Journal of Science and Technology. 2016; 9(13):1-11.
- Ratyan MAM, Mohammad AAM. Saudi Higher Education reality and prospects: Evaluating careers' dimensions of university teaching, scientific research and community service Northern Border University as a model. Indian Journal of Science and Technology. 2016; 9(4):1-6.
- Bedrik AV, Chernobrovkin IP, Lubskiy AV, Volkov YG, Vyalykh NA. Value Policy: Conceptual Interpretation of Research Practices. Indian Journal of Science and Technology. 2016; 9(5):1-6.
- 15. Vardhini KK, Sitamahalakshmi T. A review on naturebased swarm intelligence optimization techniques and its current research directions. Indian Journal of Science and Technology. 2016; 9(10):1-13.