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Controlled Fracture of Nonmetallic Thin Wafers Using a Laser Thermal Shock Method

We developed a theoretical model of a novel thermal laser shock method for separation of glass and glass-ceramic wafers into chips. The suggested model allowed us to determine the operating parameters of the device for wafer splitting. The investigated method involves two stages: 1) formation of a surface (blind) microcrack (or a grid of surface microcracks) using a double thermal shock method, and 2) splitting the cracked wafer into chips along the microcrack contour by applying small bending stresses. The emphasis was given to splitting of thin wafers with the thickness less than 1 mm. The latter process is more involved because of the undesirable spontaneous transition of a surface microcrack into a through crack. [DOI: 10.1115/1.1649245]

Introduction

High quality separation of nonmetallic (e.g., glass, glass-ceramic) wafers into chips is of great significance in electronic industry. Since chips often operate at large thermal loadings, high quality of wafers and, especially, the high quality of their edges is required. Indeed, most of the defects, e.g., cracks, dislocations, etc., are formed during wafer cutting. When temperature rises the defects at the edge of a wafer can propagate inside the wafer and cause mechanical failure of an electronic assembly, e.g., brittle fracture failure (see Suhir [1]). The existing methods for cutting materials used in electronic industry can be broadly divided into two categories: mechanical and nonmechanical methods. The methods of the first category comprise the widely employed diamond cutter and saw (Hnatek [2]). In spite of the simplicity of the mechanical methods and low cost, they do not allow to attain a high quality of the produced chips. At present the method of die separation using a diamond saw cutting technique is the most widely used in the integrated circuit (IC) technology due to a higher level of automation and applicability to a broader range of materials in electronic industry. Among nonmechanical methods the laser cutting methods are the most versatile and they are used in various fields of technology, e.g., processing of substrates in electronics and for solar cells production, processing of amorphous semiconductors. Up to the middle of the 1970s the laser scribing method was one of the leading methods in IC technology, and it was employed for separation of wafers into chips using industrial YAG: Nd Q-switched laser. Application of laser scribing method involves formation of a groove due to evaporation of a treated material. The laser cutting method (Lumley [3], Powell [4]) uses a single thermal effect of laser radiation for cutting a wafer by a scanning laser power beam with the intensity that is sufficient to separate the treated substrate into chips. In this method the laser radiation is absorbed in a thin subsurface region of a material, and the relaxation of the induced thermal elastic stresses under certain conditions causes initiating of a through crack (see Fig. 1(b)) from the upper to the bottom surfaces of a heated wafer which propagates along the trajectory of a laser beam scanning. This laser cutting method did not receive a wide range of applications because of the following shortcomings:

1. It does not allow to produce cracks along the intersecting directions;

2. Frequently a crack is initiated outside the line of a beam scanning at a surface of wafer. In the latter case a crack propagates in some accidental direction and "outstrips" a laser beam;
3. Relatively low rate of processing.

In recent years a novel method for a high quality separation of nonmetallic materials into chips using a surface ("blind") microcrack attracted attention in the electronic industry and in processing of optical materials. The essence of the method is that it involves the following two stages: 1) formation of a surface microcrack or a grid of surface microcracks, and 2) splitting of the cracked wafer into chips along the microcrack contour by applying small bending stresses. At the first stage a wafer is positioned on the translated X-Y table and is heated by a power laser beam up to a temperature of the order of 300°C (see Fig. 1(a)). Then the wafer is cooled by an air-water spray (double thermal shock), and due to a relaxation of thermal stresses a surface (blind) microcrack (see Fig. 1(b)) with the depth of the order of several hundred microns is formed (Karaev and Kornilov [5], Elperin et al. [6–8]). This microcrack that can be observed under the microscope propagates inside the subsurface region of a wafer faithfully following the path of the laser beam. Thus application of the latter method allows to attain a controlled fracture. In order to separate a wafer into chips it is necessary to form a grid of surface microcracks (see Fig. 1(c)) which can be viewed from the top as a system of two parallel lines intersecting at a right angle. At this stage the cracked wafer can be easily separated into chips along the microcrack contour by applying small bending stresses, and the produced chips have the mirror-like and free of macro defects edges.

The surface microcrack is essentially different from a regular through crack (Fig. 1(b)) which is formed using a traditional laser scribing method. Formation and propagation of the surface microcrack inside a subsurface region of a wafer is not accompanied by the removal of the material from a microcrack and, therefore, the edges of the chips are mirror-like, i.e., free of any macro defects (see [5] for more details). Controlled fracture of thin wafers (with a thickness less than 1 mm) is a more complicated technological problem because of the undesirable competitive one-step process whereby a surface microcrack is spontaneously transformed into a through crack. Such transformation is very undesirable because after separation of wafer into two segments it is not feasible to form surface microcracks in the direction normal to a through crack and to form a grid of surface microcracks (see Fig. 1(c)). The cause of initiation of a through crack rather than a surface microcrack is a large compressive thermal stress at the upper ir-

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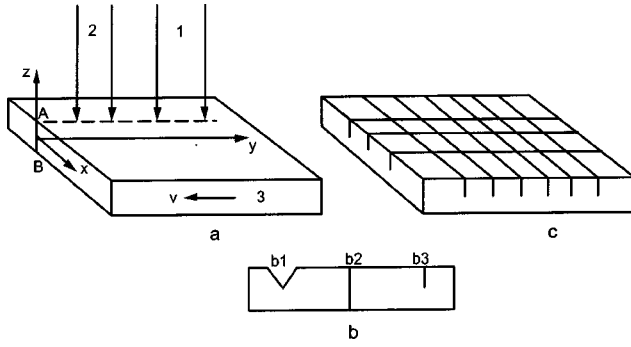


Fig. 1 (a) Scheme of the method for formation of a surface microcrack: 1—laser beam, 2—air-water spray, 3—wafer (b) cracks in a wafer obtained by different laser methods: b1-open crack, b2-through crack, b3-surface microcrack (c) grid of surface microcracks in a wafer

radiated surface of a wafer during the stage of heating of the irradiated surface of a wafer (see Fig. 1, location A), and tensile stress at the bottom surface (location B) caused by buckling of a wafer. Such stress pattern results in formation of a through crack (from A to B). In order to prevent from through crack formation it is necessary to determine the operating parameters of the device for wafer splitting (laser beam power, power distribution and configuration of a laser focal spot, rate of cooling, etc.) that allow to reduce thermal stresses at the locations A and B.

Thermal Stress Analysis

In order to determine the operating parameters of the device for wafer splitting using a double thermal shock we solved a thermal elasticity problem for a translated wafer heated by a power laser beam incident at $z = d/2$ (d is the thickness of wafer) in a normal direction to the surface and cooled by an air-water spray (see Fig. 1). The temperature distribution $T(x, y, z, t)$ in a wafer is governed by a nonstationary heat conduction equation with the appropriate initial and boundary conditions:

$$c \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q(x, y, t) \delta \left(\frac{d}{2} - z \right)$$

$$T(t=0) = T_0, \quad \lambda \frac{\partial T}{\partial z} = h(T - T_0) \quad \text{at} \quad z = -d/2. \quad (1)$$

It is assumed that the surfaces $x = \pm\infty$, $y = 0, \infty$ are thermally insulated. A wafer is heated to a constant temperature T_0 by an electrical heater built in into the translated X-Y table. Application of the heater allows to decrease temperature difference between the surfaces $z = d/2$ and $z = -d/2$ and thermal stresses in a wafer.

In this study we considered three different kinds of the laser power distribution in a laser focal spot:

1. Elliptic symmetric shape with the Gaussian dependence vs. spatial coordinates x, y (see Fig. 2(a)). The distribution of the intensity is described by the superposition of the two Gaussian functions,

$$q_h = I_h [f(\mu = \mu_1) - \chi f(\mu = \mu_2)],$$

$$f = \exp\{-\mu[x^2 + (1 - \varepsilon^2)(y - y_h)^2]\}, \quad y_h = \Delta_h + vt, \quad (2)$$

where parameter χ is equal to 0 and 1 for the TEM₀₀ (Gaussian) and TEM₀₁ laser modes, respectively;

2. Cross-section of a laser beam has a rectangular shape with a uniform power distribution $q_h = I_h$ inside ABCD (see Fig. 2(b))

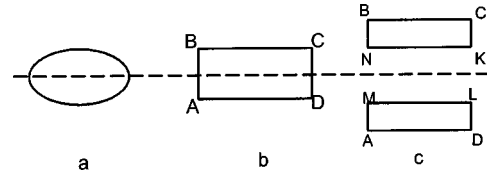


Fig. 2 Different shapes of the laser beam cross-section: a-elliptic, b-rectangular, c-“splitted” beam

3. Cross-section of a laser beam in a plane comprises two identical rectangles BCKN, AMLD (the “splitted” laser beam) with a uniform power distribution $q_h = I_h$ inside BCKN, AMLD (see Fig. 2(c)).

The rate of cooling of a heated surface is described by a superposition of the Gaussian functions:

$$q_c = I_c [g(\mu = \mu_3) - \eta g(\mu = \mu_4)],$$

$$g = \exp\{-\mu[x^2 + (y - y_c)^2]\}, \quad y_c = \Delta_c + vt \quad (3)$$

The parameters μ_3, μ_4 and η are chosen to fit experimental data on the rate of cooling of a heated wafer by an air-water spray (see, e.g., Liu et al. [9]). Analysis of this data shows that the rate of cooling q_c weakly depends on T in the range of temperatures $100 < T < 300^\circ\text{C}$. Hereafter we assumed that q_c does not change with a temperature. The total heat source Q at the wafer surface is

$$Q = q_h - q_c. \quad (4)$$

Applying the Laplace-Fourier integral transform to the heat conduction equation and the boundary condition (1) we determined temperature distribution in a translated wafer:

$$T - T_0 = \frac{1}{4\pi\lambda d} \int_0^t dt_0 \int_{-\infty}^{\infty} dx_0 \int_0^{\infty} \frac{Q(x_0, y_0, t_0)}{t - t_0} \times \exp\left[-\frac{(x - x_0)^2}{4a(t - t_0)}\right] \left\{ \exp\left[-\frac{(y - y_0)^2}{4a(t - t_0)}\right] + \exp\left[\frac{(y + y_0)^2}{4a(t - t_0)}\right] \right\} \sum_{n=1}^{\infty} \frac{2(p_n^2 + Bi^2)}{p_n^2 + Bi^2 + Bi} \times \exp\left[-\frac{p_n^2 a(t - t_0)}{d^2}\right] \cos\left[p_n \left(\frac{1}{2} - \frac{z}{d}\right)\right] dy_0. \quad (5)$$

Here p_n are the roots of the transcendental equation $p_n \tan(p_n) = (hd/\lambda) = Bi$, and expression for the total heat flux Q is given by formulas (2)–(4). Integrating Eq. (5) over the spatial coordinates x_0, y_0 and time t_0 we arrive at the following expressions for temperature distribution in a wafer for two different profiles of the power distribution q_h

1. Power distribution is described by the formula (2)

$$T - T_0 = \frac{1}{8\lambda d \mu_1} (I_h \vartheta_h - I_c \vartheta_c), \quad (6)$$

where

$$\vartheta_h = \int_0^{\tau} [V_h(1) - V_h(\delta_1(\varepsilon))] S(\omega, z) d\tau_0,$$

$$\vartheta_c = \int_0^{\tau} [V_c(\delta_2(0)) - \gamma V_c(\delta_3(0))] S(\omega, z) d\tau_0,$$

$$S(\omega, z) = \sum_{n=1}^{\infty} A_n \exp(-\omega p_n^2) \cos\left[p_n \left(\frac{1}{2} - \frac{z}{d}\right)\right],$$

$$\omega = \frac{\tau - \tau_0}{4\mu_1 d^2}, \quad \tau = 4a\mu_1 t, \quad A_n = \frac{2(p_n^2 + Bi^2)}{p_n^2 + Bi^2 + Bi},$$

$$\bar{x} = x\sqrt{\mu_1}, \bar{y} = y\sqrt{\mu_1},$$

$$V_j[\delta_i(\varepsilon)] = F[\delta_i(\varepsilon), \bar{x}, \bar{y}, \bar{y}_j] - F[\delta_i(\varepsilon), \bar{x}, -\bar{y}, \bar{y}_j],$$

$$\delta_i(\varepsilon) = \frac{\mu_i}{\mu_1}(1 - \varepsilon^2),$$

$$F = \frac{1}{\sqrt{1 + \delta_i(0)(\tau - \tau_0)}} \times \frac{1}{\sqrt{1 + \delta_i(\varepsilon)(\tau - \tau_0)}} \\ \times \exp\left[-\frac{\bar{x}^2}{\delta_i^{-1}(0) + \tau - \tau_0}\right] \exp\left[-\frac{(\bar{y} - \bar{y}_j)^2}{\delta_i^{-1}(\varepsilon) + \tau - \tau_0}\right] \\ \times \left[1 + \operatorname{erf}\frac{\bar{y} + \bar{y}_j \delta_i(\varepsilon)(\tau - \tau_0)}{\sqrt{\tau - \tau_0} \sqrt{1 + \delta_i(\varepsilon)(\tau - \tau_0)}}\right].$$

2. Laser focal spot has a rectangular cross-section, the power distribution does not depend on spatial coordinates (uniform power distribution, (Fig. 2(b), (c)). Then the temperature distribution is described by the following formula:

$$T - T_0 = \frac{I_h b_y^2}{16\lambda d} \int_0^\tau \left[\operatorname{erf}\frac{\bar{x} - \bar{a}_x}{\sqrt{\tau - \tau_0}} - \operatorname{erf}\frac{\bar{x} - \bar{b}_x}{\sqrt{\tau - \tau_0}} - \operatorname{erf}\frac{\bar{x} + \bar{a}_x}{\sqrt{\tau - \tau_0}} \right. \\ \left. + \operatorname{erf}\frac{\bar{x} + \bar{b}_x}{\sqrt{\tau - \tau_0}} \right] \left[\operatorname{erf}\frac{\bar{y} - \bar{v}\tau_0 + 1}{\sqrt{\tau - \tau_0}} - \operatorname{erf}\frac{\bar{y} - \bar{v}\tau_0}{\sqrt{\tau - \tau_0}} \right. \\ \left. + \operatorname{erf}\frac{\bar{y} + \bar{v}\tau_0}{\sqrt{\tau - \tau_0}} - \operatorname{erf}\frac{\bar{y} + \bar{v}\tau_0 - 1}{\sqrt{\tau - \tau_0}} \right] S(\bar{\omega}, z) d\tau_0 \\ - \frac{I_c}{8\lambda d \mu_1} \partial_c, \quad (7)$$

where

$$\bar{\omega} = \frac{(\tau - \tau_0)b_y^2}{4d^2}, \quad b_y = AD = BC, \quad \bar{x} = \frac{x}{b_y}, \quad \bar{y} = \frac{y}{b_y}, \\ \bar{a}_x = \frac{MN}{2b_y}, \quad \bar{b}_x = \frac{AB}{2b_y}, \quad \bar{v} = v \frac{b_y}{4a}, \quad \tau = \frac{4at}{b_y^2}.$$

In the case of the cross-section ABCD (see Fig. 2(b)) the distance $\bar{a}_x = 0$. Formulas (6), (7) are used for determining thermal stresses in a wafer.

In order to determine thermal stresses in a wafer we used the plane stress approach (Noda et al. [10]). In this model the temperature distribution θ and the stress component $\sigma = \sigma_{xx}$ (the components $\sigma_{xy} = \sigma_{yy} = 0$ because the edge of a wafer is free from the external load) are represented in the following approximate form:

$$T - T_0 = M_0 + 12 \frac{z}{d} M_1, \quad \sigma_{xx} = \sigma_1 + 2 \frac{z}{d} \sigma_2, \quad (8)$$

where

$$M_0 = \frac{1}{d} \int_{-d/2}^{d/2} (T - T_0) dz, \quad M_1 = \frac{1}{d^2} \int_{-d/2}^{d/2} (T - T_0) z dz. \quad (9)$$

Expressions for T are given by Eqs. (6) and (7), σ_1 is a stress at the middle plane $z=0$, σ_2 is a stress caused by buckling of a wafer. We determined the stress component σ_{xx} at the edge of a wafer $x=y=0$ (segment AB, Fig. 1) because this stress component is of paramount significance for initiation of a surface microcrack. All the rest components of a thermal stress tensor at this segment $\sigma_{xy} = \sigma_{yy} = 0$ because the edge of a wafer is free from the external load. The thermal stress σ_1 is expressed by the Airy function U and the thermal elastic displacement potential Ψ as follows (for details see Noda et al. [10]):

$$\sigma_1 = \frac{\partial^2 \Phi}{\partial y^2}, \quad \Phi = U - 2G\Psi, \quad (10)$$

where

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = \alpha(1 + \nu)M_0, \quad \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) = 0. \quad (11)$$

The boundary conditions at $y=0$ read:

$$\sigma_{xy} = \frac{\partial^2 \Phi}{\partial x \partial y} = 0, \quad \sigma_{yy} = \frac{\partial^2 \Phi}{\partial x^2} = 0. \quad (12)$$

Applying the Laplace-Fourier transform to Eqs. (11) and the boundary conditions (12) yields:

$$(\sigma_1)_{LF} = \frac{\partial^2 \Phi_{LF}}{\partial y^2}, \quad \Phi_{LF} = U_{LF} - 2G\Psi_{LF}, \quad (13)$$

$$\frac{\partial^2 \Psi_{LF}}{\partial y^2} - \beta^2 \Psi_{LF} = \alpha(1 + \nu)(M_0)_{LF}, \\ \left(\frac{\partial^2}{\partial y^2} - \beta^2 \right) \left(\frac{\partial^2 U_{LF}}{\partial y^2} - \beta^2 U_{LF} \right) = 0, \quad (14)$$

$$(\sigma_{xy})_{LF} = i\beta \frac{\partial \Phi_{LF}}{\partial y} = 0, \quad (\sigma_{yy})_{LF} = -\beta^2 \Phi_{LF} = 0 \quad \text{at } y=0, \\ i = \sqrt{-1}. \quad (15)$$

Consider the thermal stress distribution in a wafer heated by the instantaneous point heat source $q_p(x_0, y_0, z=d/2)$. The expressions for the temperature distribution T and the integral M_0 are obtained from Eq. (1) using the Laplace-Fourier transform:

$$T_{LF} = \frac{q_p}{2\lambda d} \sum_{n=1}^{\infty} \frac{A_n}{\gamma_n} [\exp(-\gamma_n|y-y_0|) + \exp(-\gamma_n(y+y_0))] \\ \times \cos\left[p_n\left(\frac{1}{2} - \frac{z}{d}\right)\right], \\ (M_0)_{LF} = \frac{q_p}{2\lambda d} \sum_{n=1}^{\infty} \frac{A_n}{\gamma_n} [\exp(-\gamma_n|y-y_0|) + \exp(-\gamma_n(y+y_0))] \\ \times \frac{\sin p_n}{p_n}, \quad \gamma_n = \sqrt{\frac{s}{a} + \beta^2 + \frac{p_n^2}{d^2}}. \quad (16)$$

Substituting Eq. (16) into Eq. (14) we arrive at the solution for the functions Ψ_{LF} and U_{LF} :

$$\Psi_{LF} = \frac{q_p \alpha(1 + \nu)}{2\lambda d} \sum_{n=1}^{\infty} \frac{A_n}{\gamma_n^2 - \beta^2} \frac{\sin(p_n)}{p_n} \left\{ \frac{1}{\gamma_n} [\exp(-\gamma_n|y-y_0|) \right. \\ \left. + \exp(-\gamma_n(y+y_0))] - \frac{1}{|\beta|} \exp[-|\beta|(y-y_0)] \right\}, \\ U_{LF} = \sum_{n=1}^{\infty} (B_n + C_n y) \exp(-|\beta|y). \quad (17)$$

The integration constants B_n , C_n are determined from the boundary conditions (15). Substituting expressions (17) into Eq. (13) we determine the thermal stress $(\sigma_1)_{LF}$ at $x=y=0$:

$$(\sigma_1)_{LF} = \frac{4q_p \alpha(1 + \nu)G}{\lambda d} \sum_{n=1}^{\infty} \frac{A_n}{\gamma_n^2 - \beta^2} \frac{\sin p_n}{p_n} \left[|\beta| \exp(-|\beta|y_0) \right. \\ \left. - \frac{\beta^2}{\gamma_n} \exp(-\gamma_n y_0) \right] - 2\alpha(1 + \nu)G(M_0)_{LF}. \quad (18)$$

Table 1 Operating parameters for splitting of glass wafers using TEM₀₀ and TEM₀₁ laser modes

I_c (W/m ²)	v (m/s)	μ_1 (m ⁻²)	μ_2 (m ⁻²)	μ_3 (m ⁻²)	μ_4 (m ⁻²)	ε	η
10^6	0.05	$2.50 \cdot 10^5$	$3.75 \cdot 10^5$	$2.70 \cdot 10^5$	$4.50 \cdot 10^5$	0.8	0.3

The latter expression is the Laplace–Fourier transform of the stress σ_1 caused by the instantaneous point heat source q_p . Using the tables of Laplace–Fourier integral transforms and the convolution theorem allows us to determine the inverse transform of the expression (18):

$$\begin{aligned} \sigma_1(x_0, y_0, t_0) = & \frac{8q_p \alpha (1 + \nu) G a}{\pi \lambda d} \sum_{n=1}^{\infty} A_n \frac{\sin p_n}{p_n} \exp\left(\frac{a p_n^2 t_0}{d^2}\right) \\ & \times \int_0^{\infty} \left\{ \beta \cos(\beta x_0) \left[\exp(-\beta y_0) \right. \right. \\ & \left. \left. - \sqrt{\frac{a}{\pi}} \beta \int_0^{t_0} \frac{1}{\sqrt{t_1}} \exp\left(-\frac{y_0^2}{4at_1} - a\beta^2 t_1\right) dt_1 \right] \right\} d\beta \\ & - 2\alpha(1 + \nu) G M_0. \end{aligned} \quad (19)$$

Substituting the total heat source $Q(x_0, y_0, t_0)$ instead of q_p into Eq. (19) and integrating $\sigma_1(x_0, y_0, t - t_0)$ over the spatial variables x_0, y_0 and time t_0 we determine the stress at $x=y=z=0$.

In order to determine the thermal stress σ_2 caused by buckling of a middle plane $z=0$ of a wafer we used the Duhamel–Neumann relationships between the elastic stresses, strains and temperature (see Noda et al. [10]). Using the boundary condition at $y=0$ for a free supported wafer we arrive at the following expression for the thermal stress σ_2 (for details see Elperin et al. [6]):

$$\sigma_2 = -12\alpha(1 + \nu) G M_1, \quad (20)$$

where M_1 is given by Eq. (9). The final expression for the stress σ_{xx} is obtained from Eq. (8) using Eqs. (19) and (20).

Results and Discussion

We solved thermal elasticity problem for a glass or glass-ceramic wafer subjected to a scanning laser radiation beam. We determined temperature and stress distributions in a wafer for two different kinds of the power distribution q_h in a laser focal spot, elliptic and rectangular distributions, respectively (see Fig. 2). Thermal and mechanical characteristics of glass used in the calculations are as follows: $\lambda = 1.2$ (W/m²K), $a = 2 \cdot 10^{-7}$ (m²/s), $G = 26$ (GPa), $\nu = 0.3$, $\alpha = 8.8 \cdot 10^{-6}$ (°K⁻¹). Consider some results obtained for a glass wafer with a thickness $d = 1$ (mm) and the initial temperature $T_0 = 150$ (°C). The operating parameters of the laser splitting method with an elliptic power distribution of laser radiation in a focal spot (2) are as follows: $I_h = 4.3$ (MW/m²), Biot number $Bi = 1$, radius of a zone cooled by a water-air spray $R = 2.5$ mm, all the rest operating parameters are presented in Table 1. Figure 3 shows the dependence of the temperature T (Eq. (6)) on the line of scanning ($z = d/2$) of a laser beam vs. coordinate y (the initial distance between the axis of a laser beam and the edge of a wafer $\Delta_h = 2$ mm) for different values of time, t . The curves 1–3 have two maxima because the power of a laser beam decreases towards the beam center ($\chi = 1$, Eq. (2)), curve 4 (dashed line) is obtained for the Gaussian power distribution ($\chi = 0$). The maximum temperature in the case of the Gaussian power distribution is lower than in the case of the power distribution (2) with $\chi = 1$.

Figure 4 shows the dependence of thermal stress $\sigma_{xx} = \sigma$ at locations A (a microcrack is originated in this location) and B (see Fig. 1) vs. time t determined for the case of power distribution (2)

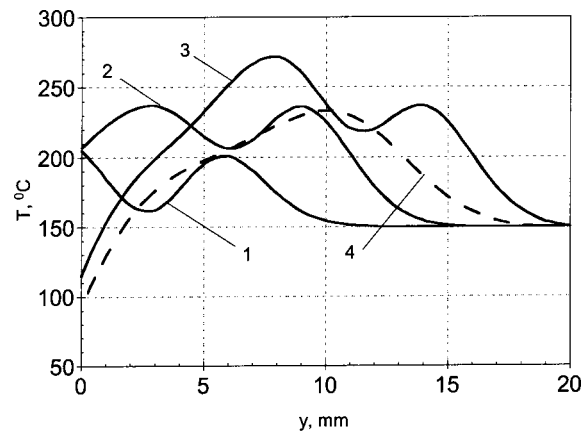


Fig. 3 Temperature T on the line of scanning of a laser beam (Gaussian power distribution) vs. longitudinal coordinate y for different values of time t (curve 1— $t=0.02$ s, curve 2— $t=0.1$ s, curves 3, 4— $t=0.2$ s)

with $\chi = 1$. These stresses are responsible for formation of a surface microcrack and, also, for the undesirable initiation of a “through” crack caused by a high magnitude of a tensile stress at the location B. Calculations show that during the initial time interval ($t < 0.15$ s), i.e., before cooling of a heated surface, the thermal stresses at locations A and B are compressive and tensile, respectively. In the case when the initial distance between a laser beam and the edge of a wafer $\Delta_h = 0$, the tensile stress at the location B attains large values (up to 30 MPa) and can cause formation of an undesirable through crack. When the distance Δ_h is in the range $2 \text{ mm} < \Delta_h < 3 \text{ mm}$, thermal stresses decrease at the beginning of a stage of cooling. The tensile stress at location B becomes compressive while the compressive stress at location A becomes tensile that favors the propagation of a surface microcrack. In a case of the Gaussian distribution (2) with $\chi = 0$ the tensile stress at location B is high and can cause the initiation of a through crack. Therefore, application of a laser beam with the Gaussian power distribution for formation of a surface microcrack in a thin wafer ($d < 1$ mm) is questionable.

We considered temperature and stress distributions in a wafer with a rectangular cross-section of a laser beam (Fig. 2(b),(c)). The operating parameters of a laser beam are as follows:

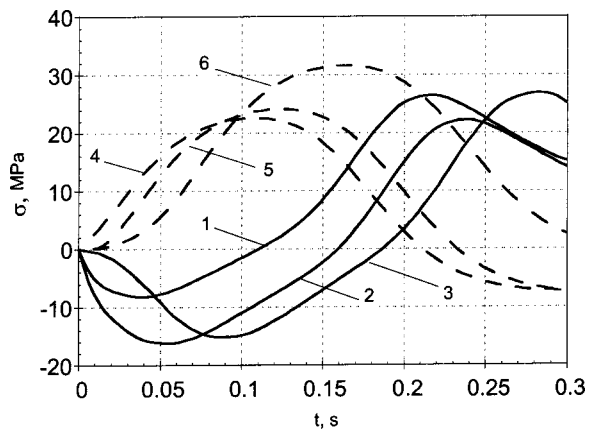


Fig. 4 Thermal stress σ at the edge of a wafer (location A—solid lines and location B—dashed lines) vs. time t for different values of the initial distance Δ_h between a laser beam and the edge of a wafer: $\Delta_h = 3$ mm (curves 1, 4), $\Delta_h = 2$ mm (curves 2, 5) and $\Delta_h = 0$ (curves 3, 6)

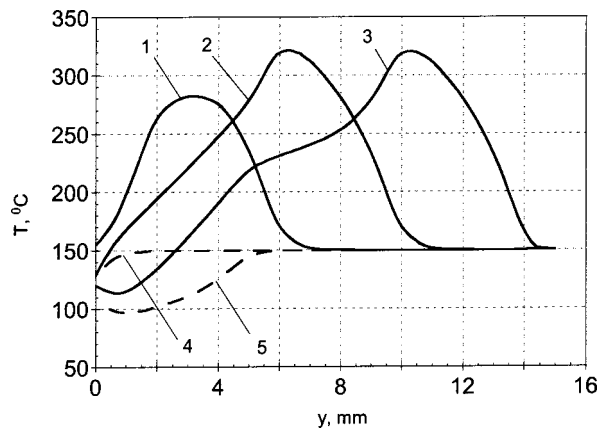


Fig. 5 Temperature T on the line of scanning of a laser beam (uniform power distribution-solid lines, “splitted” laser beam-dashed lines) vs. longitudinal coordinate y for different values of time t (curve 1— $t=0.02$ s, curves 2, 4— $t=0.1$ s, curves 3, 5— $t=0.2$ s)

$I_h = 1 \text{ MW/m}^2$, $v = 0.05 \text{ m/s}$, $\Delta_h = 5 \text{ mm}$, and we considered the following dimensions of a laser spot:

1. $AB/2 = b_x = 2.5 \text{ mm}$, $AD = b_y = 4.0 \text{ mm}$ for a rectangular cross-section ABCD;
2. $MN/2 = a_x = 1.5 \text{ mm}$, $AB/2 = b_x = 4.0 \text{ mm}$, $AD = b_y = 4.0 \text{ mm}$ for a “splitted” beam (AMLD and BCKN).

In both cases the cross-sections areas of a laser beam are the same. Figure 5 shows the temperature distribution as a function of coordinate y (Eq. (7)) obtained for the cross-section ABCD (solid line) and the “splitted” beam (dashed line). Calculations show that in the case of the “splitted” beam the maximum values of temperature $T_0 \approx 300^\circ\text{C}$ are attained at a distance $x = 2.5\text{--}3.0 \text{ mm}$ from the line of scanning of a laser beam. Temperature in a zone adjacent to a line of scanning $x=0$ does not exceed the initial temperature $T_0 = 150^\circ\text{C}$, and it decreases due to cooling of a surface $z = d/2$ (curves 4, 5). In a case of the rectangular cross-section ABCD the maximum value of temperature (Fig. 5) is attained at the line of scanning $x=0$ of a laser beam. When a laser beam with the cross-section ABCD is used, the thermal stresses at the locations A and B are tensile (Fig. 6), during the stage of cooling the stress increases up to 28 MPa and can cause propagation of a through crack. In contrast to this, in a

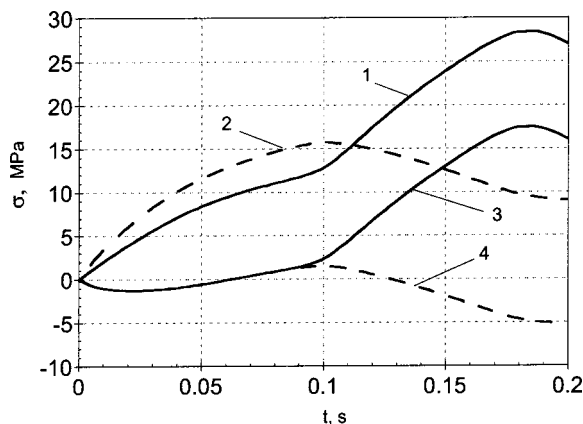


Fig. 6 Thermal stress σ at the edge of a wafer (location A-solid lines and location B-dashed lines) vs. time t for a uniform power distribution (curves 1, 2) and a “splitted” laser beam (curves 3, 4)

case of a “splitted” beam the locations A and B are practically free from the thermal stresses (curves 3, 4) before the stage of cooling ($t < 0.1$ s). When an air-water spray is applied at the surface $z = d/2$ the stress becomes compressive at the location B (curve 4) and tensile at the location A which is lower than in a case of rectangular cross-section ABCD. The moderate tensile stress at the location A favors formation of a surface microcrack at the edge of a wafer ($y=0$), and a compressive stress at the location B prevents from transformation of a surface microcrack into a through crack. Thus, using the “splitted” laser beam one can obtain the optimal thermal stress distribution at the edge of a wafer which favors formation of a surface microcrack.

Conclusions

We developed a physical model for separation of thin nonmetallic wafers into chips using double thermal shock method. The considered separation technique comprises the stage of heating of a wafer by a scanning laser beam and the stage of a high rate cooling by an air-water spray. The combined effect of high rate heating and cooling results in the initiation of a surface microcrack. This microcrack propagates in a subsurface region of a wafer and follows the beam path without removal material from the microcrack. We obtained a solution of an unsteady three-dimensional thermal elasticity problem and determined the temperature and thermal stress distributions in a wafer for the Gaussian (TEM_{00} mode), non Gaussian (similar to TEM_{01} mode) and uniform distributions of a laser beam power in a focal spot. We found that using the “splitted” laser beam with a uniform distribution of power one can obtain the optimal conditions for initiation and propagation of a surface microcrack. In this case the temperature of a wafer in a region adjacent to a surface microcrack remains close to the initial temperature T_0 , i.e., it does not change during propagation of a microcrack along the line of scanning of a laser beam $x=0$. The maximum value of temperature is attained at the distance $x = 2\text{--}3 \text{ mm}$ from the line of scanning $x=0$. This temperature distribution results in tensile thermal stress in the subsurface region of a wafer heated by a laser beam, and causes formation and propagation of a surface microcrack. Notably, the thermal stress at the opposite side of a wafer is compressive preventing from the formation of a through crack. Thus, a shape of the laser beam power distribution and a geometrical shape of a laser focal spot are of the paramount importance for formation and propagation of a surface microcrack.

The developed theoretical model can also be applied to moderately brittle semiconductor materials with a relatively low thermal conductivity. In a case of materials with a high thermal conductivity and very brittle materials (for example, GaAs) it is difficult (if possible at all) to obtain a stable surface microcrack.

Nomenclature

- a = thermal diffusivity
- Bi = Biot number
- c = specific heat
- d = wafer thickness
- G = shear modulus
- h = coefficient of heat transfer between a wafer and a X-Y table
- $H(\xi)$ = Heaviside step function
- I_h = maximum value of power of a laser beam absorbed by a wafer
- I_c = maximum value of cooling rate by a spray applied at a heated wafer
- q_c = rate of a spray cooling
- q_h = power of a laser beam
- q_p = power of the instantaneous point heat source
- Q = total heat source
- R = radius of a cooled zone
- s = Laplace transform variable conjugate to time t

t = time
 T_0 = initial temperature
 U = Airy function
 v = velocity of translation of a wafer
 x, y, z = spatial coordinates
 $\bar{x}, \bar{y}$ = dimensionless spatial coordinates
 α = coefficient of linear thermal expansion
 β = Fourier transform variable conjugate to coordinate x
 $\delta(\xi)$ = Dirac's delta function
 Δ_h = distance between the axis of a laser beam and the edge $y=0$ of a wafer at $t=0$
 Δ_c = distance between a cooling spray and the edge of a wafer
 ε = eccentricity of a laser beam spot
 λ = thermal conductivity
 μ, χ = parameters of the power distribution of a laser beam
 ν = Poisson's ratio
 σ = thermal stress
 τ = dimensionless time
 Ψ = thermal elastic displacement potential

Subscripts

LF = Laplace–Fourier transform

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