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Formation of Surface Microcrack for Separation of Nonmetallic Wafers Into Chips

In recent years a technology for a high quality separation of nonmetallic materials into chips using a surface (''blind'') microcrack attracted considerable attention in the electronic industry. In this method a wafer is positioned on the translated X-Y table and is heated by a laser beam up to a temperature of the order of 300–400°C. The wafer is then cooled by an air-water spray, and a surface microcrack is formed due to relaxation of the thermal stresses. The initial microcrack with a depth of the order of several hundred microns then propagates in a subsurface region of a wafer and follows the path of the laser beam. Theoretical modeling based on the solution of the equations of thermal elasticity was performed to determine the distributions of temperature and thermal stresses that cause formation of an ''edge'' microcrack (at the edge of a wafer) followed by its transformation into a surface microcrack. The results of thermal stresses analysis are in an agreement with experimental observations. [S1043-7398(00)00804-5]

1 Introduction

High quality separation of wafers into chips is important to the electronic industry. Since chips often operate at a high power level (Bar-Cohen [1], Suhir [2]) wafers with high quality edges are required. Most of the defects, e.g., microcracks, dislocations, etc., form during cutting. During heating, the defects at the edge of a wafer (with a size larger than some critical size) propagate inside the wafer and result in mechanical failure of an electronic assembly. Thus, the presence of defects influences the thermal reliability of an assembly, and high quality separation of wafers into chips is of great importance in manufacturing electronic components. High quality cutting of various kinds of amorphous solids, e.g., glasses, is of great importance in processing of optical materials where the presence of defects with a size of the order of a wavelength of light is unacceptable.

In this study we analyze a laser method for separation of wafers manufactured from nonmetallic materials, e.g., glass, glass-ceramic and some other glass-like materials, into chips which is based on the effect of a double thermal shock. In this method the wafer is positioned on an *X-Y* table so that the direction of translation of the table is along the line of separation of wafer. The wafer is heated by a power laser beam (CO_2—laser, CW—operation), and is immediately cooled by an air-water spray similar to thermal tempering of glass (see, e.g., Ernsberger [3]). As a result of this double thermal shock a microcrack is formed at the edge of a wafer (see Fig. 1(*c*)). The microcrack with a depth of the order of several hundred microns then propagates in a subsurface region and follows the path of the laser beam (see, e.g., Karaev and Kornilov [4], Elperin et al. [5], Elperin et al. [6]). This blind microcrack can be observed under the microscope and is essentially different from a crack formed using a dicing saw (Fig. 1(*b*)) and laser scribing methods (see, e.g., Lumley [7], Powell [8] and Fig. 1(*a*)). The distinctive feature of the surface microcrack is that its formation and propagation in a subsurface region of a wafer is not accompanied by removal of the material from a microcrack. At the next stage the wafer can be easily separated into chips along the microcrack contour by applying small bending stresses. This method has a number of advantages in comparison with current laser methods, namely:

1 The edges of the chips are mirror-like, i.e., free of any defects. This property of the obtained chips is of great significance in electronic industry and in processing of optical materials;
2 The method is environmentally friendly due to the absence of the treated material dust in a zone of a separation;
3 The maximum temperature is significantly lower than the melting point of the treated material.

In this study we developed a model describing this method for thermal splitting of glass and glass-like materials. The developed model was verified experimentally, and analyzes the essential features of the method in order to employ it for separating semiconductor materials into chips.

2 Solution of the Thermal Elasticity Problem

Consider a thermal elasticity problem for a moving wafer heated by a power laser beam incident at $z=d/2$ in a normal direction to the surface and cooled by an air-water spray (see Fig. 2). In order to determine the temperature field we used a method of the unit instantaneous point heat source (Carslaw and Jaeger [9]). The temperature distribution in a wafer is governed by a nonstationary three-dimensional heat conduction equation with the appropriate initial and boundary conditions:

$$c\rho \frac{\partial T}{\partial t} = \lambda \Delta T + \delta(x)\,\delta(y-y_0)\,\delta\left(\frac{d}{2}-z\right)\delta(t) \tag{1}$$

$$T(t=0)=T_0,\quad \lambda \left.\frac{\partial T}{\partial z}\right|_{z=-d/2} = k(T-T_0),$$
$$\left.\frac{\partial T}{\partial z}\right|_{z=d/2} = \left.\frac{\partial T}{\partial y}\right|_{y=0,\infty} = \left.\frac{\partial T}{\partial x}\right|_{x=0,\pm\infty} = 0 \tag{2}$$

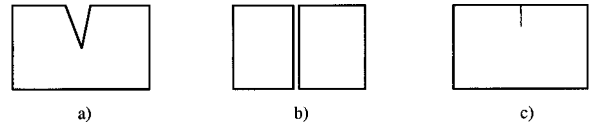

Fig. 1 Different methods for separation of wafers into chips: (*a*)-laser scribing; (*b*)-dicing saw method; (*c*)-double thermal shock method

Contributed by the Electrical and Electronic Packaging Division for publication in the JOURNAL OF ELECTRONIC PACKAGING. Manuscript received by the EEPD August 9, 1999; revised manuscript received April 13, 2000. Associated Technical Editor: B. Michel.

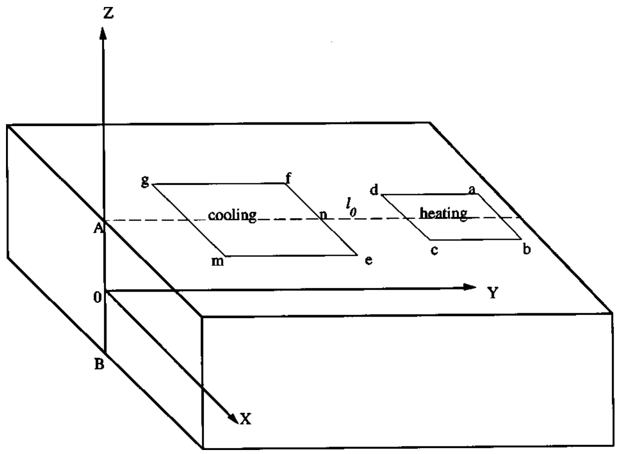

Fig. 2 Scheme of the method for separation of wafers into chips using a surface (blind) microcrack

The boundary condition of the third kind at the surface, $z = -d/2$, relates to the case when the X-Y table is heated to a constant temperature T_0 by a built-in electrical heater. Applying the Laplace-Fourier transform to Eq. (1) yields

$$\frac{d^2\Theta_{\mathrm{LFC}}}{dy^2} = \left(\frac{s}{a} + \beta^2 + p_k^2\right)\Theta_{\mathrm{LFC}} - \frac{1}{\lambda}\,\delta(y - y_0), \tag{3}$$

where

$$\Theta_{\mathrm{LFC}}(s,\beta,p_k) = \int_0^\infty \int_{-\infty}^\infty \int_{-d/2}^{d/2} (T - T_0)\exp(-st + i\beta x) \times \cos\left[p_k\left(\frac{d}{2} - z\right)\right] dt\, dx\, dz \tag{4}$$

The values p_k are determined from solution of the following transcendental characteristic equation

$$\mu_k \tan \mu_k = \mathrm{Bi}, \quad \mu_k = p_k d, \quad \mathrm{Bi} = kd/\lambda. \tag{5}$$

The solution of Eq. (3) with the boundary conditions (2) yields

$$\Theta_{\mathrm{LFC}} = \frac{1}{2\lambda\gamma_k}\left[\exp(-\gamma_k|y - y_0|) + \exp(-\gamma_k(y + y_0))\right], \quad \gamma_k \equiv \sqrt{\frac{s}{a} + \beta^2 + p_k^2}. \tag{6}$$

The inverse Laplace-Fourier transform of the expression (6) has the following form

$$\Theta = \frac{1}{4\pi\lambda t d} F(x,y,t) \sum_{k=1}^{\infty} A_k \exp\left(-\frac{\mu_k^2 a t}{d^2}\right) \cos \mu_k\left(\frac{1}{2} - \frac{z}{d}\right) \tag{7}$$

Here

$$A_k = 2(\mu_k^2 + \mathrm{Bi}^2)/(\mu_k^2 + \mathrm{Bi}^2 + \mathrm{Bi}),$$

$$F(x,y,t) = \exp\left(-\frac{x^2}{4at}\right)\left\{\exp\left[-\frac{(y - y_0)^2}{4at}\right] + \exp\left[-\frac{(y + y_0)^2}{4at}\right]\right\}.$$

Expression (7) represents Green's function for the considered boundary value problem. The temperature distribution in a wafer is given by the following expression

$$\vartheta(x,y,z,t) = \frac{1}{4\pi\lambda d}\int_0^t \int_0^\infty \int_{-\infty}^\infty \frac{Q(x_0,y_0,t_0)}{t - t_0} \times F(x - x_0, y - y_0, t - t_0)\sum_{k=1}^{\infty} A_k \times \exp\left[-\frac{\mu_k^2 a(t - t_0)}{d^2}\right]\cos \mu_k\left(\frac{1}{2} - \frac{z}{d}\right) dt_0 dy_0 dx_0 + T_0 \tag{8}$$

where $Q = q_h - q_c$ is the heat source at the surface, $z = d/2$, due to laser heating and spray cooling of a wafer. In the case where the cross-sections of a laser beam and a cooling spray have a rectangular shape with the half-width $h_x = 0.5ab$, $h_y = 0.5ad$ in the x and y-directions, respectively, for a laser beam and $c_x = 0.5ef$, $c_y = 0.5gf$ for a cooling spray (see Fig. 2), the nonstationary spatial distributions of q_h and q_c are

$$q_c = I_c H(c_x - |x_0|)[H(\overline{y_0} - 2h_y - l_0) - H(\overline{y_0} - 2h_y - 2c_y - l_0)],$$
$$q_h = I_h H(h_x - |x_0|)[H(\overline{y_0}) - H(\overline{y_0} - 2h_y)], \quad \overline{y_0} = vt_0 - y_0 \tag{9}$$

The rate of cooling I_c is determined experimentally. After substituting expressions (9) into Eq. (8) and calculating the integral one can obtain the three-dimensional distribution of temperature in a wafer.

The stress distribution at the edge of a wafer (the region of the origination of a surface microcrack) can be determined using the plane stress approach (Boley and Weiner [10]). The stress components are represented as a superposition of the stresses $\overline{\sigma}_{ij}$ arising due to compression or tension on the middle plane of a wafer and the stresses $\bar{\bar{\sigma}}_{ij}$ caused by buckling of a wafer

$$\sigma_{ij} = \overline{\sigma}_{ij}(x,y) + \frac{2z}{d}\bar{\bar{\sigma}}_{ij}(x,y) \tag{10}$$

In order to determine the stresses $\overline{\sigma}_{ij}$ and $\bar{\bar{\sigma}}_{ij}$ we represent the Laplace-Fourier transform of a temperature field in a similar form

$$\Theta_{\mathrm{LF}} = \overline{\Theta}_{\mathrm{LF}} + \frac{2z}{d}\bar{\bar{\Theta}}_{\mathrm{LF}} \tag{11}$$

The inverse cos-transform of the temperature distribution (6) reads

$$\Theta_{\mathrm{LF}}(s,\beta,z) = \frac{1}{d}\sum_{k=1}^{\infty} A_k \Theta_{\mathrm{LFC}}(s,\beta,p_k)\cos \mu_k\left(\frac{1}{2} - \frac{z}{d}\right) \tag{12}$$

The expressions for $\overline{\Theta}_{\mathrm{LF}}$ and $\bar{\bar{\Theta}}_{\mathrm{LF}}$ are obtained by integrating Eq. (12) over coordinate z

$$\overline{\Theta}_{\mathrm{LF}} = \frac{1}{d}\int_{-d/2}^{d/2} \Theta_{\mathrm{LF}} dz = \frac{1}{d}\sum_{k=1}^{\infty} A_k \Theta_{\mathrm{LFC}} \frac{\sin \mu_k}{\mu_k} \tag{13}$$

$$\bar{\bar{\Theta}}_{\mathrm{LF}} = \frac{6}{d^2}\int_{-d/2}^{d/2} \Theta_{\mathrm{LF}} z\, dz = \frac{6}{d}\sum_{k=1}^{\infty} A_k \Theta_{\mathrm{LFC}}\left(\frac{1 - \cos \mu_k}{\mu_k^2} - \frac{\sin \mu_k}{2\mu_k}\right) \tag{14}$$

The components of thermal stresses $\overline{\sigma}_{ij}$ are expressed through the Airy function U and the thermal elastic displacement potential Ψ as follows

$$\overline{\sigma}_{xx} = \frac{\partial^2\Phi}{\partial y^2}, \quad \overline{\sigma}_{yy} = \frac{\partial^2\Phi}{\partial x^2}, \quad \overline{\sigma}_{xy} = \frac{\partial^2\Phi}{\partial x \partial y}, \quad \Phi = U - 2G\Psi \tag{15}$$

The functions U and Ψ are determined by solving the following thermal elasticity boundary value problem

$$\Delta_{x,y}\Psi=\alpha(1+\nu)\overline{\Theta} \tag{16}$$

$$\Delta_{x,y}(\Delta_{x,y}U)=0 \tag{17}$$

$$\left.\frac{\partial^2\Phi}{\partial x^2}\right|_{y=0,\infty}=\left.\frac{\partial^2\Phi}{\partial x\partial y}\right|_{y=0,\infty}=0 \tag{18}$$

where $\Delta_{x,y}=\partial^2/\partial x^2+\partial^2/\partial y^2$ is the two-dimensional Laplace operator, $\overline{\Theta}$ is a temperature at the middle plane $z=0$ of a wafer.

Equation (16) for the thermal elastic displacement potential Ψ can be written as follows

$$\left(\frac{\partial^2}{\partial y^2}-\beta^2\right)\Psi_{\mathrm{LF}}=\alpha(1+\nu)\overline{\Theta}_{\mathrm{LF}} = \sum_{k=1}^{\infty}\frac{B_k}{\gamma_k}[\exp(-\gamma_k|y-y_0|)+\exp(-\gamma_k(y+y_0))] \tag{19}$$

where $B_k=(A_k/2\lambda d)(\sin\mu_k/\mu_k)\alpha(1+\nu)$. The solution of Eq. (19) yields

$$\Psi_{\mathrm{LF}}=a_1[\exp(\gamma_k y)+\exp(-\gamma_k y)]+b_1\exp[-|\beta|(y_0-y)],\quad y<y_0$$

$$\Psi_{\mathrm{LF}}=a_1[1+\exp(2\gamma_k y_0)]\exp(-\gamma_k y)+b_2\exp[-|\beta|(y-y_0)],\quad y>y_0 \tag{20}$$

Here a_1,b_1,b_2 are the arbitrary constants which are determined from the continuity conditions for functions Ψ_{LF} and $\partial\Psi_{\mathrm{LF}}/\partial y$ at $y=y_0$. The final expression for the thermal elastic displacement potential has the following form

$$\Psi_{\mathrm{LF}}=a\sum_{k=1}^{\infty}\frac{B_k}{s+a\mu_k^2/d^2}\left[\frac{1}{\gamma_k}(\exp(-\gamma_k|y-y_0|)+\exp[-\gamma_k(y+y_0)])-\frac{1}{|\beta|}\exp(-|\beta(y-y_0)|)\right] \tag{21}$$

The solution of the transformed equation (17) is

$$\left(\frac{\partial^2}{\partial y^2}-\beta^2\right)^2U_{\mathrm{LF}}=0$$

and can be written as follows

$$U_{\mathrm{LF}}=(C_k+D_k y)\exp(-|\beta|y) \tag{22}$$

The integration constants C_k and D_k are determined by substituting expression (22) into Eqs. (15) and (18). The expression for the function Φ has the following form

$$\Phi_{\mathrm{LF}}=2aG\sum_{k=1}^{\infty}\frac{B_k}{s+a\mu_k^2/d^2}\left\{2\left[\frac{1}{\gamma_k}\exp(-\gamma_k y_0)-\frac{1}{|\beta|}\exp(-|\beta|y_0)\right](1+|\beta|y)\exp(-|\beta|y)-\frac{1}{\gamma_k}[\exp(-\gamma_k|y-y_0|)+\exp(-\gamma_k(y+y_0))]+\frac{1}{|\beta|}[\exp(-|\beta||y-y_0|)+\exp(-|\beta|(y+y_0))]\right\} \tag{23}$$

Substituting Eq. (23) into Eq. (15) one can obtain the expressions for the stress components $\overline{\sigma}_{xx},\overline{\sigma}_{xy},\overline{\sigma}_{yy}$ at the middle plane $z=0$ of a wafer. The stress component σ_{xx} at the edge of a wafer $x=y=0$ is of particular interest since this component significantly affects the initiation of a microcrack.

The expression for σ_{xx} according to the Eq. (10) comprises two terms. The first term in the expression for σ_{xx} at $z=0$ is determined from Eqs. (15) and (23)

$$(\overline{\sigma}_{xx})_{\mathrm{LF}}=8aG\sum_{k=1}^{\infty}\frac{B_k}{s+a\mu_k^2/d^2}\left[|\beta|\exp(-|\beta|y_0)-\frac{\beta^2}{\gamma_k}\exp(-\gamma_k y_0)\right]-4G\sum_{k=1}^{\infty}\frac{B_k}{\gamma_k}\exp(-\gamma_k y_0) \tag{24}$$

The latter expression is the Laplace-Fourier transform of the Green's function that represents a stress caused by the unit instantaneous point heat source located at $y=y_0$, $z=d/2$. Using the tables of Laplace-Fourier integral transforms, the convolution theorem and integrating the obtained expression with the heat source function $Q(x_0,y_0,t_0)$ over the spatial variables x_0,y_0 and time t_0 we find

$$\overline{\sigma}_{xx}=8aG\sum_{k=1}^{\infty}B_k(I_hL_h-I_cL_c)-2\alpha(1+\nu)G\overline{\vartheta}(y=0) \tag{25}$$

where the temperature rise at a middle plane of a wafer $\overline{\vartheta}$ is

$$\overline{\vartheta}=\frac{1}{d}\int_{-d/2}^{d/2}(\vartheta-T_0)dz$$

The expression for L_h has the following form

$$L_h=\frac{1}{\pi}\int_0^{\infty}\int_{-h_x}^{h_x}\int_{y_{h1}}^{y_{h2}}\int_0^{t}\beta\cos\beta x_0\times\left\{\exp(-\beta y_0)\exp[-a\mu_k^2(t-t_0)/d^2]-\frac{\sqrt{a}}{\sqrt{\pi}}\beta\exp(-a\mu_k^2t/d^2)\int_0^{t-t_0}\frac{1}{\sqrt{t'}}\times\exp[-(a\beta^2t'+y_0^2/4at')]dt'\right\}d\beta\,dx_0\,dy_0\,dt_0 \tag{26}$$

Here $y_{h1}=r_1H(r_1)$, $y_{h2}=vt_0$. Integrating Eq. (26) over β, x_0,y_0 yields

$$L_h=\int_0^{t}\exp[-a\mu_k^2(t-t_0)/d^2]\left\{\frac{2}{\pi}[\arcsin(y_{h2}/\sqrt{h_x^2+y_{h2}^2})-\arcsin(y_{h1}/\sqrt{h_x^2+y_{h1}^2})]-\frac{1}{2\sqrt{\pi}}\frac{h_x}{\sqrt{a}}\int_0^{t-t_0}\frac{1}{(t')^{3/2}}\times\exp(-h_x^2/4at')[\mathrm{erf}(y_{h2}/2\sqrt{at'})-\mathrm{erf}(y_{h1}/2\sqrt{at'})]dt'\right\}dt_0 \tag{27}$$

The expression for L_c has a form similar to expression (27) where h_x, y_{h1} and y_{h2} are replaced by c_x, $y_{c1}=r_3H(r_3)$ and $y_{c2}=r_2H(r_2)$, respectively.

In order to determine the thermal stress caused by buckling of a wafer, i.e., the second term in Eq. (10), we used the formulas of Duhamel-Neumann (see, Boley and Weiner [10]) that provide relationships between elastic stresses, strains and temperature

$$\sigma_{xx}=\frac{E}{1-\nu^2}[\varepsilon_{xx}+\nu\varepsilon_{yy}-\alpha(1+\nu)T],$$
$$\sigma_{yy}=\frac{E}{1-\nu^2}[\varepsilon_{yy}+\nu\varepsilon_{xx}-\alpha(1+\nu)T] \tag{28}$$

The formulas for strain tensor components are

$$\varepsilon_{xx} = \overline{\varepsilon_{xx}} - z\frac{\partial^2 w}{\partial x^2},$$
$$\varepsilon_{yy} = \overline{\varepsilon_{yy}} - z\frac{\partial^2 w}{\partial y^2} \tag{29}$$

where $\overline{\varepsilon_{xx}}$, $\overline{\varepsilon_{yy}}$ are the strain tensor components at the middle plane, $z=0$, of a wafer. Substituting Eq. (29) into Eq. (28) and using the linear approximation of the temperature field Θ provided by Eq. (11), one can obtain the following formulas for the components of the stress tensor

$$\sigma_{xx} = \overline{\sigma_{xx}} - \frac{E}{1-\nu^2} z\left[\frac{\partial^2 w}{\partial x^2} + \nu\frac{\partial^2 w}{\partial y^2} + \frac{2\alpha(1+\nu)}{d}\bar{\bar{\Theta}}\right],$$
$$\sigma_{yy} = \overline{\sigma_{yy}} - \frac{E}{1-\nu^2} z\left[\frac{\partial^2 w}{\partial y^2} + \nu\frac{\partial^2 w}{\partial x^2} + \frac{2\alpha(1+\nu)}{d}\bar{\bar{\Theta}}\right] \tag{30}$$

At the edge of a wafer the stresses $\sigma_{yy} = \overline{\sigma_{yy}} = 0$. Therefore,

$$\frac{\partial^2 w}{\partial x^2} = -\frac{1}{\nu}\left(\frac{\partial^2 w}{\partial y^2} + \frac{2\alpha(1+\nu)}{d}\bar{\bar{\Theta}}\right) \tag{31}$$

Now we use the boundary condition for a free supported wafer at $y=0$

$$\frac{\partial^2 w}{\partial y^2} = -\frac{12\alpha(1+\nu)}{d^3}\int_{-d/2}^{d/2}\Theta z\, dz \tag{32}$$

Substituting Eqs. (31), (32) into Eq. (30) and integrating with the heat source function $Q(x_0, y_0, t_0)$ over the spatial variables x_0, y_0 and time t_0 we arrive at the expression for the stress tensor component σ_{xx} at the edge of a wafer

$$\sigma_{xx} = \overline{\sigma_{xx}} - 4\alpha(1+\nu)G\frac{z}{d}\bar{\bar{\vartheta}} \tag{33}$$

where the temperature distribution $\bar{\bar{\vartheta}}$ is similar to that given by Eq. (14)

$$\bar{\bar{\vartheta}} = \frac{6}{d^2}\int_{-d/2}^{d/2}\vartheta z\, dz$$

Using Eq. (25) the expression for σ_{xx} can be rewritten as follows

$$\sigma_{xx}(x=y=0) = 8aG\sum_{k=1}^{\infty} B_k(I_h L_h - I_c L_c) - 2\alpha(1+\nu)G\left(\overline{\vartheta} + 2\frac{z}{d}\bar{\bar{\vartheta}}\right) \tag{34}$$

3 Results and Discussion

Using Eq. (8) we determined the three-dimensional temperature distribution in a translated wafer heated by a power laser beam and cooled by an air-water spray. Figure 3 shows the dependence of the temperature $\vartheta(x=0,\ z=d/2)$ on the line of scanning of a laser beam versus coordinate *y* for different values of time, *t*. The results are obtained for a glass wafer with a thickness $d = 0.001$ m, $\mathrm{Bi}=0.1$, $T_0 = 150°$C and operating parameters of the laser splitting method given in Table 1. Calculations show that the maximum temperature is attained at the location a (Fig. 2). As the laser beam is translated away from the edge $y=0$, the value of the maximum temperature decreases slightly until it reaches the quasi-stationary value.

Using the above expressions, we investigated the effect of the operating parameters, i.e., velocity of translation of a wafer, dimensions of a laser focal spot, rate of a spray cooling, etc., on the temperature and stress distributions in a wafer. One of the most important parameters that affects the thermal elastic stresses and the initiation of a surface (blind) microcrack is the temperature

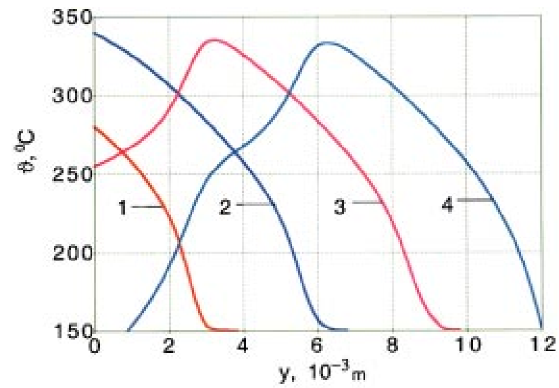

Fig. 3 Temperature ϑ at $x=0$, $z=d/2$ versus coordinate y for different values of time t (curve 1−t=0.03 s, 2−0.06 s, 3 −0.09 s, 4−0.12 s)

$\vartheta^*(ef)$ at the points of the interval (ef) (see Fig. 2). The maximum value of $\vartheta^*(ef)$ at the location *n* will satisfy the condition $\vartheta_m^*(ef) > 250°$C (for glass) to provide an effective cooling of the heated surface of a wafer and to initiate a surface (blind) microcrack. The temperature $\vartheta^*(ef)$ should be as high as possible, provided that the maximum temperature ϑ_m in a zone of heating is less than the temperature of softening of the treated material. Calculations performed using Eq. (8) showed that for materials with low thermal conductivity the temperature ϑ_m scales with the velocity of translation v as $\vartheta_m \propto v^{-1/2}$ in the range of velocities $0.01\ \mathrm{m/s} < v < 0.1\ \mathrm{m/s}$ that are used during treatment of glass and glass-like materials. However, in the case of materials with a high thermal conductivity, e.g., silicon and some semiconductor materials, this dependence is weaker than that presented above. Therefore, for semiconductor materials the feasibility of increasing the value of ϑ_m by decreasing the velocity of translation v is rather limited. An alternative method to control the temperature field for a given laser power q_h is to change the dimensions of a laser focal spot h_x and h_y. Calculations show that in the case of materials with a low thermal conductivity the temperature ϑ_m increases with decreasing h_y. Thus, at $v=0.1$ m/s the temperature ϑ_m increases only by 9 percent with the decrease of h_y from 0.003 to 0.001 m. However, the value of h_x strongly affects the temperature ϑ_m, especially in the case of materials with a low thermal conductivity. For example, in the case of a glass wafer moving with a velocity $v=0.1$ m/s we obtained an approximate dependence $\vartheta_m \propto h_x^{-1}$. In a case of materials with a high thermal conductivity the value of the maximum temperature attained within a laser spot strongly depends on h_x while the temperature $\vartheta^*(ef)$ at the location *n* only weakly depends on h_x and h_y because of a high rate of temperature relaxation from the laser spot at the surface of a wafer. Therefore, for treatment of materials with a low thermal conductivity it is preferable to use the laser beam spot that is extended in the *y*-direction, i.e., $5 < h_y/h_x < 10$. For materials with a high thermal conductivity, the cross-section shape of a laser beam with a given power q_h only slightly affects a temperature distribution at a zone of cooling. Therefore, the control of temperature and stress distribution is much more complicated than in a case of materials with low thermal conductivity.

Table 1 Operating parameters for laser splitting of glass

E_0 (W)	I_c (W/m²)	v (m/s)	l_0 (m)	h_x (m)	h_y (m)	c_x (m)	c_y (m)
15	10^6	0.1	0.003	0.001	0.003	0.002	0.002

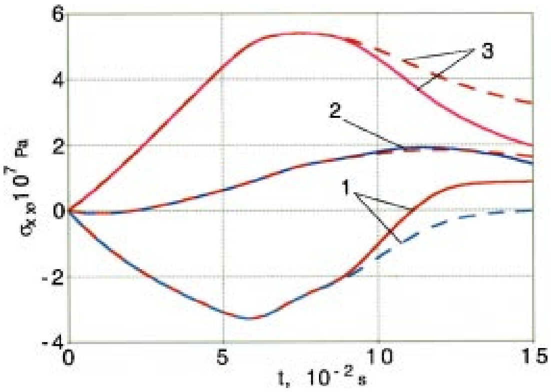

Fig. 4 Thermal stress σ_{xx} at the edge $x=y=0$ of a wafer versus time t (curve 1—the upper plane $z=d/2$, 2—the middle plane $z=0$, 3—the lower plane $z=-d/2$ of a wafer. Solid lines—cooling rate $I_c=10^6$ W/m^2, dashed lines—cooling rate $I_c=0.5\times10^6$ W/m^2).

Figure 4 shows the dependence of thermal stresses at locations A (curve 1), O (curve 2) and B (curve 3) versus time t using Eq. (34). Calculations show that during the time interval $t<0.09$ s, i.e., before cooling of a heated surface, the thermal stresses at the opposite surface of a wafer $z=-d/2$ are tensile (Fig. 4, curve 3). This is the reason that a crack initiates across the whole width AB of a wafer (''edge'' crack). This theoretical result is also observed experimentally. When an air-water spray is applied at the surface heated by a laser beam at time $t=0.09$ s, the stress distribution in a wafer changes abruptly. The tensile stress at $z=-d/2$ significantly decreases while the compressive stress at $z=d/2$ becomes tensile (Fig. 4, curve 3) that favors the transformation of an edge crack into a surface (''blind'') microcrack. Calculations of a stresses distribution showed that the rate of cooling significantly affects this transformation. The tensile stress at $z=-d/2$ and compressive stress at $z=d/2$ tend to increase, and both these factors prevent the transformation of the edge crack into a blind microcrack. This tendency is shown in Fig. 4 by the dashed lines obtained for the rate of cooling $I_c=0.5\times10^6$ W/m^2 while the solid lines demonstrate the stress dependence versus time for $I_c=10^6$ W/m^2. Therefore, to initiate a surface microcrack it is necessary to provide the highest possible cooling rate of a heated surface.

4 Conclusions

We developed a physical model for wafer separation into chips that uses the initiation of a surface microcrack in nonmetallic materials by double thermal shock technique. The analyzed separation technique comprises the following two stages: heating of a wafer by a focused laser beam and high rate cooling by an air-water spray. This combined heating and cooling results in the initiation of the surface microcrack that propagates in the subsurface region of a wafer and follows the laser beam path without removal of material from the microcrack. We obtained a solution of a nonstationary three-dimensional thermal elasticity boundary value problem for determining the parameters, e.g., dimensions of a laser focal spot, velocity of translation of a wafer, rate of cooling of a wafer, a distance between a zone of heating and a zone of cooling, that are favorable for formation of a surface microcrack. The results show that for materials with a low thermal conductivity, i.e., glass and glass-like materials, the following methods should be used to control the temperature field in a zone of cooling:

1 A laser spot with a rectangular cross-section extended in a direction of the translation of a wafer;

2 The velocity of the translation of a wafer can be varied in the range 0.01–0.1 m/s.

The dependence of the thermal elastic stress at the edge of a wafer versus time is not monotonic as a laser beam moves away from the edge. Initially when a laser beam is located at a distance $y<3h_y$, the stress is compressive in a zone of heating and is tensile at the opposite surface of a wafer. Therefore, the crack is initiated at the location B (see Fig. 2), and propagates along the line AB to the upper surface (edge crack). In order to transform the edge crack into a surface (blind) microcrack (the main purpose of this investigation), it is necessary to provide a high cooling rate of wafer. This provides a decrease in compressive stress at the subsurface layer that inhibits the transformation of an edge crack into a surface microcrack.

Nomenclature

a = thermal diffusivity of a wafer
Bi = Biot number
c = specific heat
c_x, c_y = half-width of a zone of cooling in x and y-directions, respectively
d = wafer thickness
E_0 = laser power
E = elastic modulus
G = shear modulus
$H(x)$ = Heaviside step function
h_x, h_y = half-width of a laser beam in x and y-directions, respectively
I_h, I_c = laser beam intensity absorbed by wafer and rate of cooling, respectively
i = $\sqrt{-1}$
k = coefficient of heat transfer
l_0 = distance between a laser beam and a cooling spray at the surface of a wafer
Q = total heat source at the surface of a wafer
p, s = parameters of cosine and Laplace transforms with respect to coordinate z and time t
T_0 = initial temperature of a wafer
t = time
U = Airy function
v = velocity of translation of a wafer
w = displacement of the middle plane of a wafer in z-direction
x, y, z = Cartesian coordinates
α = coefficient of linear thermal expansion
β = Fourier transform variable conjugate to coordinate x
$\delta(t)$ = Dirac's delta function
Δ = three-dimensional Laplace operator
σ_{ij} = stress tensor component
λ = thermal conductivity
ν = Poisson's ratio
ρ = density
Ψ = thermal elastic displacement potential
Θ = Green's function
ϑ = temperature distribution in a wafer

Subscripts

C = cosine transform
L = Laplace transform
F = Fourier transform

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