

1D to 3D Coupling of an Infinitesimal Width Moving Laser on a Silicon Substrate

T. Mulembo, B. Ikua, J. Keraita, A. Niyibizi, C. Kagiri

Abstract—Micromechanical components such as acceleration sensors in car safety systems and micro-fluidic circuits are normally made of monocrystalline silicon. The modeling of laser micromachining of complex shapes using silicon still remains a vital area of research. This paper explores the current status of research and developments of 3D modeling techniques for laser micromachining of silicon substrate. It covers a brief insight of the laser propagation and absorption as well as the resulting material heat responses. This paper further presents the model to implement the heat sources motion when coupling a 3D temperature variable, T , to a 1D equation. The subdomain extrusion coupling variable using a general transformation has also been analyzed. The method for using a separate geometry and equation to model the source term is presented. This is very useful because it provides that term directly at the test-function level.

Keywords—Laser, Mesh, Micromachining, Modeling, Silicon.

I. INTRODUCTION

LASER BEAMS are commonly used to locally heat the surface of various substrates, for example, in laser welding or thermal annealing such as on layered silicon devices [1]. The laser beam typically moves over a surface in a periodic fashion to produce the desired localized heating. In the case of layered silicon devices, each layer is very thin, making the modeling of the penetration depth caused by the moving laser a strongly time-dependent problem [2].

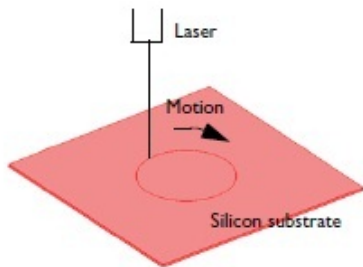


Fig. 1. A moving laser heating a thin silicon substrate. [3]

Fig. 1 shows the localized transient heating caused by a laser beam that moves in circles over a silicon substrate. The beams penetration depth, which can be described with an absorption coefficient, depends on the ambient temperature. The geometry under study represents the top layer of a silicon

device. The model examines the penetration depth and the influence of the laser motion on the transient temperature distribution. This model considers the laser beam as having an infinitesimal width and thus treats it as a line heat source. As such it is not meaningful to study the maximum temperature because it is mesh dependent. However, the overall heat flux and temperature distribution on a macroscopic level are both accurate. For photothermal processing, the material response can be explained as a result of elevated temperatures. Therefore, it is important to be able to model the flow of heat inside a material. The temporal and spatial evolution of the temperature field inside a material are governed by a heat equation. This paper introduces the governing differential equations and the related boundary conditions.

II. MODEL DEFINITIONS

Fig. 1 models the silicon substrate as a 3D object with the following dimensions:

- Thickness: 1 mm
- Width: 10 mm-by-10 mm

It handles the variation of laser intensity with penetration depth using a 1D geometry that represents the substrates thickness.

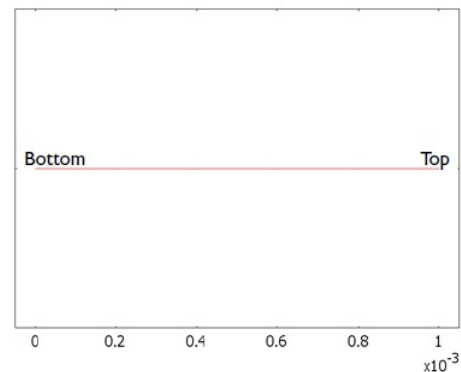


Fig. 2. The 1D model geometry.

The model makes use of the Conduction application mode to describe the transient heat transfer in the 3D geometry. The transient energy-transport equation for heat conduction is

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \quad (1)$$

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where ρ is the density, C_p is the specific heat capacity, k is the thermal conductivity tensor, and Q is the heat source term, which was set to zero (this case models the source in a different way).

The material properties are those of silicon, using an anisotropic conductivity of $(k_{xx}, k_{yy}, k_{zz}) = (163, 163, 163)$ in units of $W/(m.K)$, a density of $2330 \text{ kg}/m^3$, and a specific heat capacity of $703 \text{ J}/(kg.K)$.

The model assumptions are:

- Material properties are assumed to be constant.
- The electromagnetics of the laser beam is not simulated.
- The effect of electromagnetic wavelength is not explicitly modeled
- The effect of complex refractive index of silicon is modeled using an absorption and reflection coefficient.
- The simulation does not involve modeling phase change.
- The boundaries are insulating

In the 1D geometry, this model uses the Weak Form, Subdomain application mode to model the laser penetration. In the equation 2 describing the penetration

$$\frac{\partial I}{\partial x'} = k_{abs} I \quad (2)$$

I represents the relative laser intensity (the variable in the Weak Form, Subdomain application mode), x' represents the 1D coordinate, and k_{abs} is the absorption coefficient. The absorption coefficient can depend on the temperature, and the expression used in this model is

$$k_{abs} = 8 * 10^3 m^{-1} - 10(m \cdot k)^{-1}(T - 300K) \quad (3)$$

The volumetric heat source term, Q , in the 3D geometry is then

$$Q = P_{in} k_{abs} I \quad (4)$$

where P_{in} is the total power of the incoming laser beam.

Both of these equations are included in the Weak Form, Subdomain application mode, where they become one equation:

$$I_{test} * (Ix - k_{abs} * I) + k_{abs} * I * P_{in} * T_{test} \quad (5)$$

The first part of this expression describes the penetration equation, and the second part comes from the heat-source term in the 3D Heat Transfer application mode.

At the left boundary, apply a homogeneous Neumann condition [4]–[7], and at the right boundary set the relative intensity, I , to unity. The total incoming laser power, P_{in} , is 50 W.

The model implements the heat source femtosecond motion when coupling the 3D temperature variable, T , to the 1D equation. It does so with a subdomain extrusion coupling variable using a general transformation. A time-dependent transformation expression results in a moving heat source. This case describes a circular repeating motion using the transformation expressions

$$x = R \sin(\omega t), y = R \cos(\omega t), z = x' \quad (6)$$

where x , y , and z correspond to the 3D coordinates, and x' represents the 1D coordinate. Furthermore, R is the radius of circular motion, ω is the angular velocity, and t is time. The

model uses the parameter values $R = 0.02 \text{ m}$ and $\omega = 10 \text{ rad/s}$, the latter value corresponding to a period of roughly 0.628s for the laser motion.

This method that employs the use of a separate geometry and equation to model the source term is very useful because it provides that term directly at the test function level. Furthermore, it models the source motion separately with the transformation expressions, making it simple to alter. It is indeed the best way to model a moving point or line source. The 3D model makes use of an extruded triangular mesh, which has a fine resolution close to the laser incident line and is coarse elsewhere. This results in a high-resolution solution with minimum computation requirements. The mesh results in around 10,000 elements and 6200 degrees of freedom.

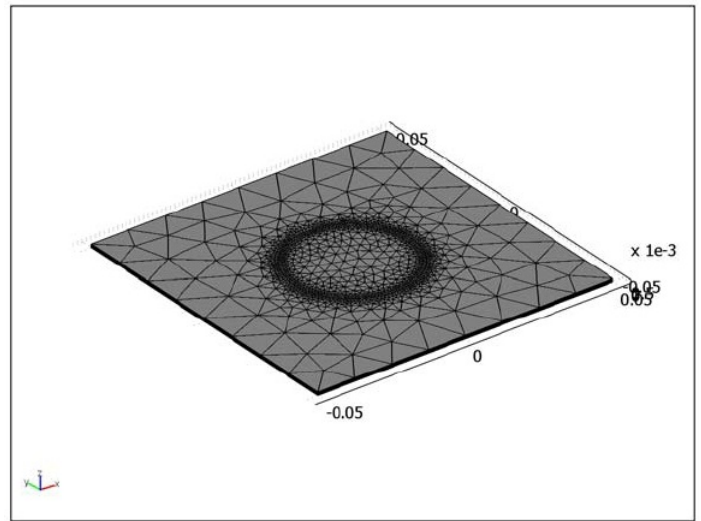


Fig. 3. The 3D mesh produced by extruding a 2D triangular mesh, refined along the circular laser incident line.

III. RESULTS AND DISCUSSION

Fig. 4 depicts the temperature distribution at the laser-beam incident surface.

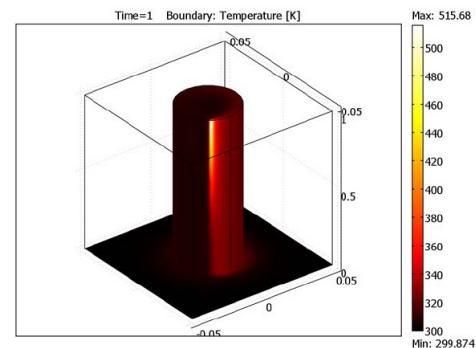


Fig. 4. Temperature distribution after 1s of laser heating.

Fig. 4 clearly shows a hot spot where the laser beam is located at a specific time. Furthermore, the results show a

cold side and a warm side next to the vertical line below the laser beam. The warm side represents the area where the beam has just swept through. A better way to study these effects is by plotting the temperature at the top surface along the circular laser-beam incident pattern as in Fig. 5.

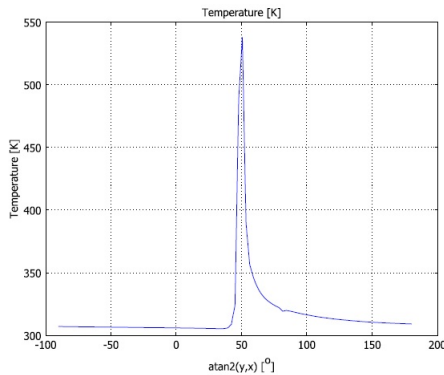


Fig. 5. Temperature distribution along the laser-beam incident trajectory on the top surface after 0.7 s.

Here the laser beam moves from right to left, and the warm side is on the right side of the peak. Locally the temperature reaches around 510K, but this value is completely mesh dependent. Nevertheless, the temperature distribution just a few mesh elements away represents the real temperature quite well.

Finally, Fig. 6 shows beam penetration into the substrate. The heating at the bottom of the substrate is practically zero.

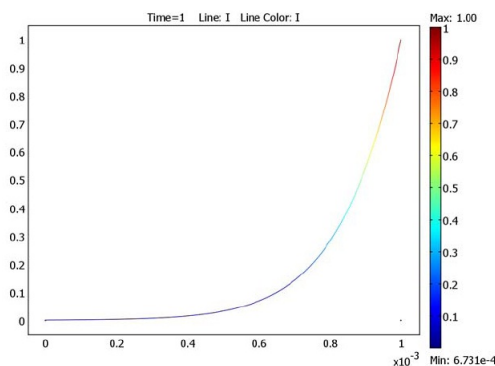


Fig. 6. Relative laser-beam intensity as a function of sample depth.

IV. CONCLUSION

In this paper, the model implements the heat sources motion when coupling the 3D temperature variable, T , to the 1D equation. The subdomain extrusion coupling variable using a general transformation has been analyzed. The method for using a separate geometry and equation to model the source term has been presented. This is very useful because it provides that term directly at the test-function level. In

a later publication, the temperature distribution at the laser-beam incident surface results from the models will be validated against values obtained from experiments.

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REFERENCES

- [1] V. Tangwarodomnukun and J. Wang, "Laser micromachining of silicon substrate," *Advance material research*, vol. 76, pp. 416–421, 2009.
- [2] Y. Jiwang, A. Tooru, and K. Tsunemoto, "Response of machining damaged single-crystalline silicon wafers to nanosecond pulsed laser irradiation," *Semiconductor Science and Technology*, vol. 22, pp. 392–395, 2007.
- [3] L. Yu, "Three dimensional finite element method of laser cutting," *journal of Materials processing Technology*, vol. 63, pp. 637–639, 1997.
- [4] Z. H. Shen, S. Y. Zhang, J. Lu, and X. Ni, "Mathematical modeling of laser induced heating and melting in solids," *Optics and Laser Technology*, vol. 33, pp. 533–537, 2001.
- [5] R. Gospavic and V. Popov, "Modeling of laser material interaction using semi analytical approach," *Mathematics and computers in simulation*, vol. 65, pp. 211–219, 2004.
- [6] B. S. Yilbas, "Electron kinetic theory approach-one and three dimensional heating with pulsed laser," *International journal of Heat and Mass Transfer*, vol. 44, pp. 1925–1936, 2001.
- [7] B. S. Yilbas, S. A. Gbadebo, and M. Sami, "Laser heating: an electrokinetic theory approach and induced thermal stresses," *Optics and Laser Engineering*, vol. 33, pp. 65–79, 2000.