Finite Element Prediction of Heat-Affected Zone in Laser-micromachining of Silicon

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Abstract

Silicon has been a major material used for fabricating MEMS devices that are now potentially a far more pervasive technology. In processing of silicon material, laser-micromachining has been increasingly employed. However, laser debris and thermal crack are problematic with laser machining and also sensitive issues with MEMS devices. This paper highlights finite element simulation of laser-micromachining of silicon as a start point of research in investigating material response to thermal effect. Simulation uses standard commercial software. Finite element model was developed with the plate and thermal rod elements using 2D mesh generator. Currently, the isotropic properties of silicon were assumed and material properties were taken from published reports. The database translation utility was modified to specify a time-dependent nodal heat flux for laser source. Thermal transient heat transfer analysis was chosen for simulation of laser-micromachining. The temperature distributions in silicon material during laser-micromachining of different geometries as well as with different pulse energies are presented and discussed. Heat-affected zone is well-identified.

I. Introduction

The role of silicon has been a major part in the development of MEMS. It is important to the extent that 'No silicon, No MEMS'. Despite such importance, understanding the characteristics of silicon during processing is still lacking, which creates processing method expensive and also leaves the life-span of MEMS unimproved [1, 2, 3, 4, 5, 6].

Conventionally, silicon processing relies on a number of tools and methodologies inherited from integrated circuit technology. Typical processes include deposition of thin film on the substrate, photolithography and selective etching. Recently, laser-micromachining has been sought for machining of silicon as conventional ones are time consuming, and have limitations and drawbacks. Direct making of required pattern with laser, so-called laser-direct write has a number of advantages such as no mask pattern, ease of programming and flexible making of complex geometries. However, again thermal effects such as potential melting or cracking which in turns, downgrades the machined components are problematic with laser-micromachining [7, 8, 9, 10].

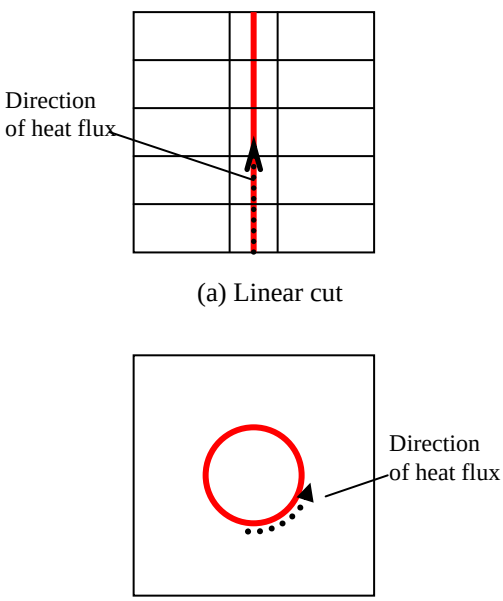
Some but limited work on laser-micromachining of silicon has been found in the literature. Significant study was focused on parametric investigation of the dynamic interaction among the machining parameters. The parameters considered were types of laser, energy of laser beam, laser repetition rate, machining velocity and beam diameter. Details can be found in [8, 9, 10]. Although the past study was trying to identify the optimal ranges of parameters, extending MEMS fabrication methodologies is still the subject of research. A lot of work needs to be done to improve the processing methods. Among them, developing a predictive computational model could help to facilitate generation of viable designs and smooth transition from conceptual design stage to fabrication [6].

Finite element method is now considered matured to develop a computational model to predict solution domain accurately without the need of expensive experimental work [11, 12, 13]. This paper aims to present numerical experiments on laser-micromachining of silicon using finite element tool. Since a predictive model for laser-micromachining is so far not available and thermal effect is a crucial factor in this technique, this work will facilitate to economically identify heat-effected zone and suitable

machining parameters to minimize it in laser-micromachining.

I. Finite Element Model

Finite element (FE) model consists of a plate and a rod representing a silicon wafer and laser heat source respectively. The wafer was discretized with 4-node plate elements while the laser source with 2-node thermal rod elements using 2D mesh generator [14]. As lots of linear cuts (channels) and holes are involved in MEMS devices [3, 5, 15, 16], two FE models were developed: (1) for linear cut and (2) for circular cut. Wafer size is 5x5 mm in both models and a centered circle of 2mm diameter was created in the latter. The models are schematically described in Figure 1.



(a) Linear cut

(b) Circular cut

Figure 1. Finite element model

The governing equations for heat transfer are given as:

$$kt\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)=\rho C_P\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=0$$

with the boundary conditions:

$$T=T_a$$

$$-k\left(\frac{\partial T}{\partial n}\right)=2h(T-T_a)$$

where k is thermal conductivity, t the wafer thickness, ρ the density, C_P specific heat, T_a ambient temperature and h convection heat coefficient. It was assumed that both sides of the plate convected to an ambient temperature of 25°C with a coefficient of $5\text{x}10^{-5}$ W/mm^2·°C. The temperature field was discretized by:

$$T(x,y)=\sum_{i=1}^{M}N_i(x,y)T_i$$

Currently, temperature-dependent properties of silicon were taken from the published reports [10, 17].

II. Simulation

Transient heat transfer analysis was chosen to simulate laser-micromachining. Laser source was represented by time-dependent nodal heat flux that would travel in a designated path and also define moving speed, cutting velocity in other words. Heat load was applied in such a way that the flux due to laser ramped up from 0 to full amount in 0.1 second, stayed constant for 0.3 seconds, then ramped down to 0 in 0.1 seconds and remained zero until the computation at the first node was complete. Then the same amount of flux would go to second node and repeat the computational procedure. It was programmed that the laser flux started to hit at the bottom node and moves up with a specified speed along a designated path. The moving speed was set to be a constant of 1 mm/s in all simulations. The laser spot size was controlled by thermal rod element definition. Pulse energy was given by nodal heat flux and activation time. The machining parameters set in the simulation were based on the literature [9, 10, 18, 19]. Table 1 summarizes the parameters considered in the simulations.

TABLE 1: SIMULATED PARAMETERS

Case study	**Cutting geometry**	**Pulse energy (mJ)**	**Spot size (μm)**	**Cutting velocity (mm/s)**
1 2	Linear	1 5	10	1
3	Circular	1	10	1

III. Results and Discussions

As mentioned earlier, the laser starts to move from the bottom node in all simulations. In linear cut, the laser moves up straight till the top node while in the case of circular cut, laser moves counterclockwise from the bottom node to complete the circle. Figures 2 to 5 illustrate the temperature distribution in silicon when shooting with laser pulse energy of 1 mJ in linear movements. Figure 2 shows temperature distribution in silicon when laser flux reaches second node from the bottom. Maximum temperature concentrating at the node is about 94°C. When the laser goes to the third node, the temperature at the previous node becomes decreased as depicted in Figure 3. This indicates that some heat is swiftly dissipated to the ambient temperature as the heat convection is considered in the finite element formulation and it happens in a very short duration. Such heat dissipation is desirable to eliminate thermal effect on the silicon.

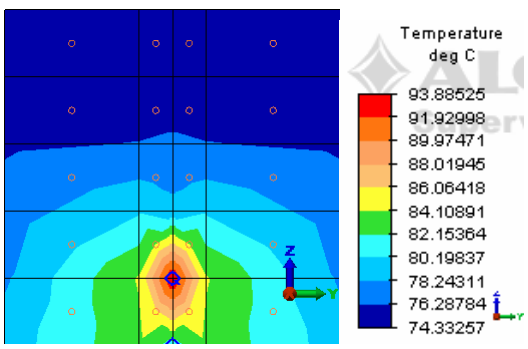


Figure 2. Temperature distribution in silicon after the laser traveled 1 mm

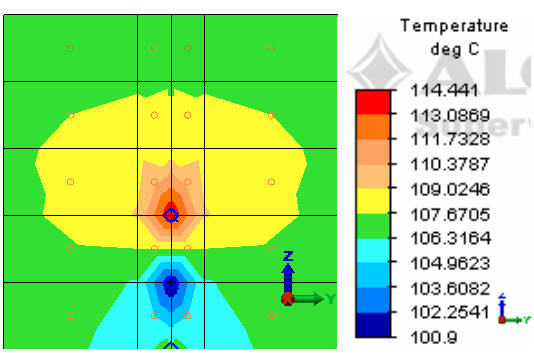


Figure 3. Temperature distribution in silicon when the laser goes further

Some heat may also be added to the following node as the temperature goes up slightly as the laser moves further. It seems that the further the laser goes, the higher the temperature induced in the cutting material. Figure 3 to 5 reveals this phenomenon. The maximum induced temperature after the laser moves about 4.5 mm is found to be 207°C. However, the overall temperature contour demonstrates the laser path logically. In addition, as will be shown later, the overall temperature distribution is generally uniform.

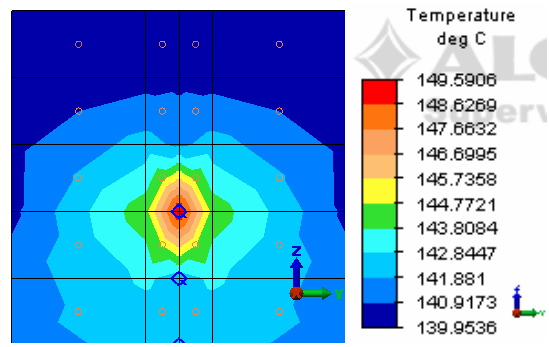


Figure 4. Temperature distribution in silicon after the laser traveled 2 mm

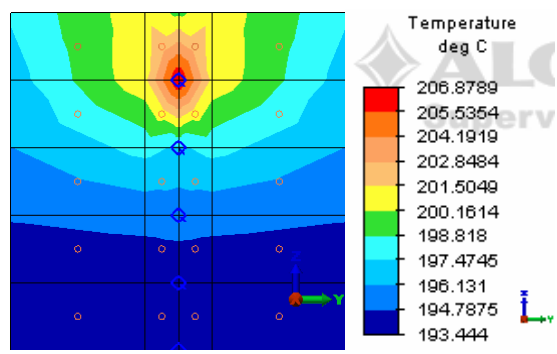


Figure 5. Temperature distribution in silicon after the laser traveled 4 mm

Similar trend is followed when the laser makes a circular geometry except the fact that the maximum temperature goes higher than that in linear movement for the same laser energy. Maximum temperature can be as high as 350°C, meaning that the heat-affected zone in silicon is attributed to the geometry shaped by the laser. Figure 6 to 8 illustrates the temperature distribution as the laser goes along the circular pattern.

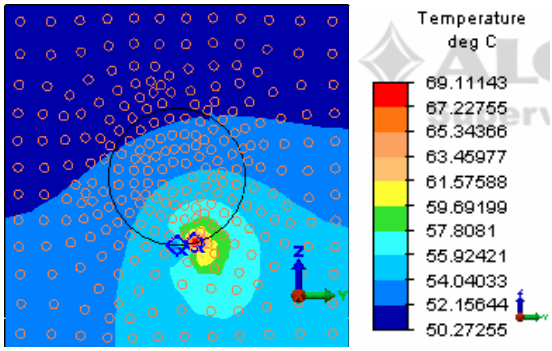


Figure 6. Temperature distribution in silicon when the laser started to move circular geometry

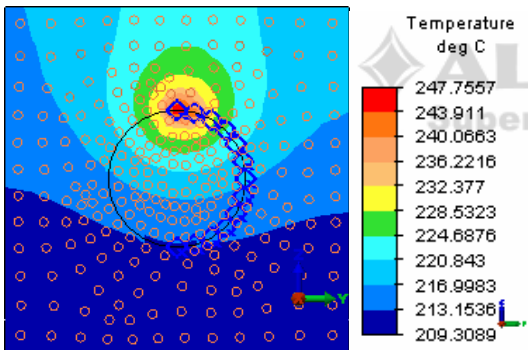


Figure 7. Temperature distribution in silicon after the laser traveled a half of the circle

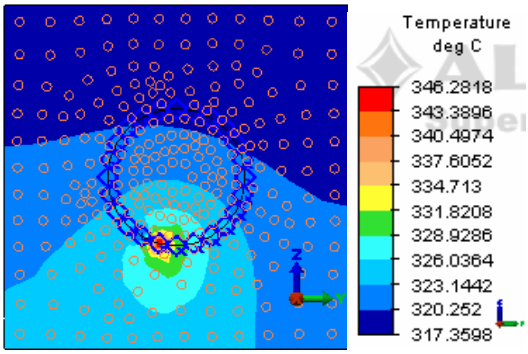


Figure 8. Temperature distribution in silicon after the laser traveled a complete round

When the energy of laser source is increased, the maximum temperature goes to above 1000°C to make the same geometry and length with the same moving speed. Figure 9 depicts the temperature distribution in silicon after the laser moves 4 mm linear. The energy of laser pulse in this case was set to be 5 mJ. Heat-affected zone is found to be considerably larger than that occurs in moving with lower-energy laser pulse. Laterally, the size of this zone is in order of 300 µm which is unacceptable for MEMS feature as far as the miniaturization is concerned. This problem could be resolved by increasing moving speed of the laser.

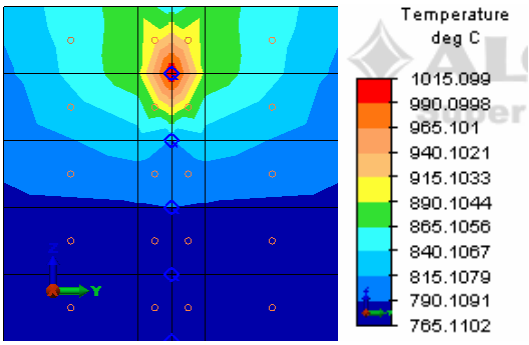


Figure 9. Temperature distribution in silicon when shooting with laser source of higher energy

Figure 10 compares temperature distribution in silicon when shooting with same speed but different energies of laser pulses. As can be seen in the figure, using pulse energy five times higher causes the temperature field unstable compared to using pulse of lower-energy. This may lead to a great amount of redeposited silicon particles spoiling the surface finish.

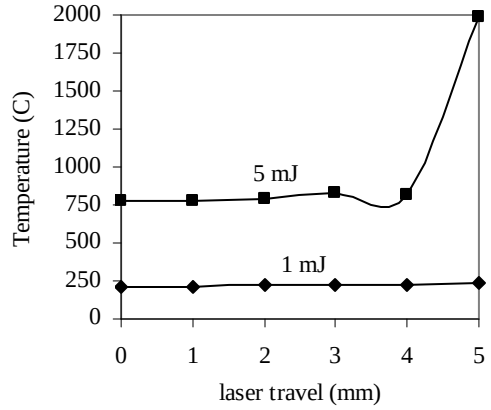


Figure 10. Comparison of nodal temperatures for the different energies of laser pulse

The overall results show that finite element predictions are in general consistent with the published

experimental work [9, 10] from the view point of physical phenomena. However the accuracy of the numerical figures much relies on that of material properties adopted in finite element modeling. In the present work, the property data of silicon readily available in the literature were used. Consequently, it is hard to identify the mechanism of laser-micromachining. In future work, the material properties need to be experimentally obtained or at least verified if taken from the literature prior to use in the simulation process. Based on finite element prediction so far, the laser moving speed needs to be compromised with pulse energy while other factors are not concerned in order to generate features on silicon with good surface finish by laser-micromachining.

IV. Conclusion

Simulation of the fabrication process prior to the real work is desirable as it is an economically-viable method. It is possible to simulate laser micromachining even of complex geometries. A lot of simulation works need to be done before going down to actual machining as not only MEMS feature but the silicon material itself is so delicate. Referring to the results predicted by finite element method, the following conclusions can be drawn:

- The crucial factors to reduce heat-affected zone in laser-micromachining of silicon are pulse energy and moving speed.
- Cutting velocity and pulse energy are strongly interrelated. A compromise between cutting velocity and laser pulse energy would help to make features with good surface finish in economical means.
- As far as the heat-affected zone is concerned, uniform temperature along the laser path would produce features with good surface finish.

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