Estimation of Temperature Distribution in Silicon during Micro Laser Assisted Machining

Presented by
Kamlesh Suthar

John Patten*
Western Michigan University
Manufacturing Engineering Department
Kalamazoo, MI-49008, USA

Lei Dong
Condor USA, Inc.
8318 Pineville-Matthews Road, Suite 276
Charlotte, NC-28226

Hisham Abdel-Aal
Department of General Engineering
University of Wisconsin at Platteville
Platteville, WI- 53818, USA
Outline

Objective

Experimental work
- Tool Modification
- Measurement of laser power
- Characterization
  - AFM
  - Thermal imaging

Analytical Modeling
- Point heat source
- Plane Heat source
- Gaussian Beam Laser Heat Source

Finite Element Analysis
- Gaussian Profile heat source

Summary
Motivation

• Semiconductor and ceramic materials are highly brittle and plastic deformation at room temperature is difficult and they prone to fracture during machining.
• Brittleness has detrimental effect on tool.
• Therefore, the challenge is to develop a cost effective machining process which can produce ultra fine surface finish.
Objective

- Silicon is highly brittle at room temperature and the hardness is the function of temperature.
- **High Pressure Phase Transformation (HPPT)** is one of the process mechanisms involved in ductile machining of semiconductors and ceramics.
- Preferentially **heat** the HPPT material to increase ductility through thermal softening:
  - Reduce tool wear
  - Minimize surface and subsurface damage.
- Thermal Softening temperature for silicon is 600-800 °C.
Effect of Temperature on Hardness of Silicon

(Trefilov, 1963)
Schematic of μ-LAM of Silicon
Diamond Tip Attachment

Attachment was done at Digital Optical Company (Charlotte, NC) by Jay Matthews
Deliverable Power After Attachment of Diamond & Laser Parameter

**IR Laser**
- **Wavelength**: 1480nm
- **Laser Power (max)**: 400mW
- **Power at Diamond Tip**: 140mW
- **Photon energy**: ~0.9 eV
- **Transitivity of Si-II**: 80-90 %
- **Absorbance in Si-II**: 10.0 %

**Diamond tool**
- **Diameter of tip**: 5-6 μm
- **Thermal conductivity**: 900-1200 W/m/K

**Silicon**
- **Specific heat**: 0.7J/g/K
- **Density**: 2.33 g/cm³
IR Softens Metallic Silicon Indent depths at different laser power

Scratching Speed Test (Load 25mN)
Speed1: 0.305 mm/sec; Speed 2: 0.002 mm/sec; Speed 3: .0002mm/sec
AFM Groove Depth Measurement
Thermal Imaging: Different Stages of Heating
Stage: 1
Thermal Imaging: Different Stages of Heating
Stage: 2

MSEC-2008 ASME Conference, Evanston, IL
Thermal Imaging: Different Stages of Heating

Stage: 3
Thermal Imaging: Different Stages of Heating
Stage: 4
Thermal Imaging: Different Stages of Heating

Stage: 5
Thermal Imaging: Different Stages of Heating
Stage: 6
Estimation of Physical properties of Si-II and their use in modeling

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Thermal Conductivity of metallic Si-II W/cm/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.0025</td>
</tr>
<tr>
<td>400</td>
<td>0.0004</td>
</tr>
<tr>
<td>500</td>
<td>0.0055</td>
</tr>
<tr>
<td>600</td>
<td>0.0075</td>
</tr>
<tr>
<td>700</td>
<td>0.0125</td>
</tr>
<tr>
<td>800</td>
<td>0.0165</td>
</tr>
<tr>
<td>900</td>
<td>0.025</td>
</tr>
</tbody>
</table>

1. Analytical modeling
   The thermo-physical properties are taken at intermediate temperature.

2. FEM formulation
   Thermo physical properties of Si-I and Si-II are taken as a function of temperature

• MatLab is used for programming analytical model
• COMSOL 3.4 is used for FEA
Analytical Modeling

1. Moving point heat source (scratch test)

\[
T = \frac{2q(1-r)}{C_p \rho \, 4\pi \alpha} \int_{\tau=0}^{\tau=t} \frac{d\tau}{\tau^{3/2}} e^{-\frac{x^2+y^2+z^2}{4\alpha \tau}}
\]

\(\alpha\) : Thermal Diffusivity (cm\(^2\)/s)

\(r\) : Reflectivity

\(\rho\) : Density (g/cm\(^3\))

\(k\) : Thermal Conductivity (W/cm/K)
Analytical Modeling....

2. Moving Plane Heat Source

\[ T = \frac{2q(1-r)v}{16k\alpha \pi^{3/2}} e^{\left(-\frac{Xv}{2a}\right)^2 \frac{t}{4a}} \int_{0}^{\infty} \frac{d\sigma}{\sigma^{3/2}} e^{\left(-\sigma - \left(\frac{u^2}{2a}\right)\right)} \]

\( \alpha \) : Thermal Diffusivity (cm\(^2\)/s)
\( r \) : Reflectivity
\( P \) : Density (g/cm\(^3\))
\( k \) : Thermal Conductivity
   \( W/cm/K \)
Analytical Modeling....

3. Gaussian Beam profile Moving Plane with Laser as heating source (scratch test)

\[ I(x, y) = I_o \exp \left[ -\left( \frac{x}{r_x} \right)^2 + \left( \frac{y}{r_y} \right)^2 \right] \]

\[ T(x, y, z) = \frac{Q}{\pi^{\frac{3}{2}} k} \int_0^\infty f(u) du \]

\[ f(u) = \frac{\exp \left( -\left[ \frac{X + V \sigma u^2}{u^2 + 1/\beta} + \frac{Y^2}{u^2 + \beta} + \frac{Z^2}{u^2} \right] \right)}{\left[ u^2 + 1/\beta \right]^{\frac{3}{2}}} \]

\[ X = \frac{x}{r}, \quad Y = \frac{y}{r}, \quad Z = \frac{z}{r}, \quad V = \frac{v}{r}, \quad \sigma = \frac{r^2}{4\alpha}, \quad Q = \frac{q}{r}, \quad u = \left( \frac{2\alpha t}{r^2} \right)^{\frac{3}{2}} \]
3. Gaussian Beam profile Moving Plane......

Temperature Profile

Maximum Temp 468 Deg C at V = 0.002 mm/s

2D Surface plot
Maximum Temp Rise 468 C
Finite Element Analysis
Summary

• Thermal images: the absorptivity of the Si-II is different than the Si-I and therefore the temperature rise occurs is due to HPPT
• The temperature rise for the stationary point heat source is 778°C.
• For the moving plane heat source $\Delta T$ at 0.0002 mm/sec, is 468°C,
• The COMSOL result, for a stationary heat source temperature rise of 631°C. The COMSOL results are in good agreement with the previous estimated temperature
Future Work

• Numerical Analysis of the Moving laser with varying laser power with varying absorption with the depth.
• Investigate the possibility of other wavelength.
• Machining using chemical etching
• Investigation of acoustic emission of the machining process
References


Thank you
<table>
<thead>
<tr>
<th>Designation</th>
<th>Structure</th>
<th>Pressure region (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-I</td>
<td>Cubic diamond</td>
<td>0–11</td>
</tr>
<tr>
<td>Si-II</td>
<td>Body-centered Tetragonal (β-Sn)</td>
<td>~11–15</td>
</tr>
<tr>
<td>Si-III</td>
<td>Body-centered cubic</td>
<td>~10–0</td>
</tr>
<tr>
<td>Si-V</td>
<td>Primitive hexagonal</td>
<td>~14–40</td>
</tr>
<tr>
<td>Si-VII</td>
<td>Hexagonal close-packed</td>
<td>~40</td>
</tr>
</tbody>
</table>