Estimation of Temperature Distribution in Silicon during Micro Laser Assisted Machining

Presented by

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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

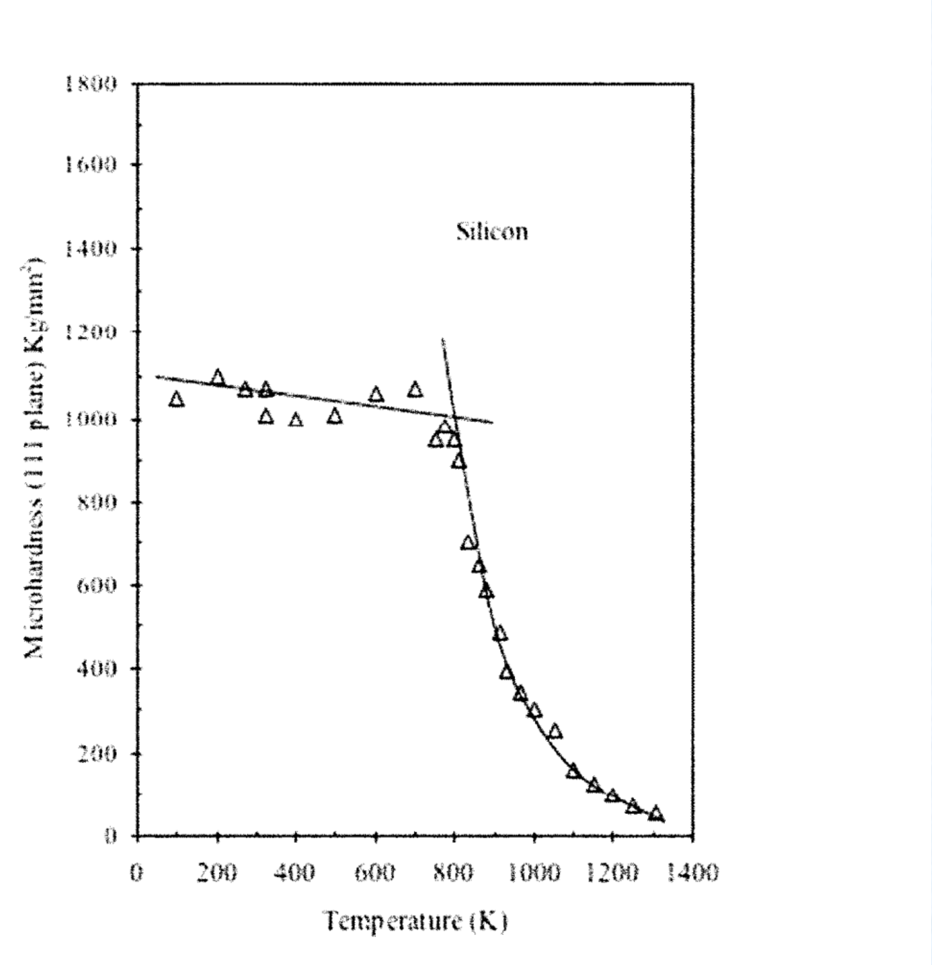
Motivation

- 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

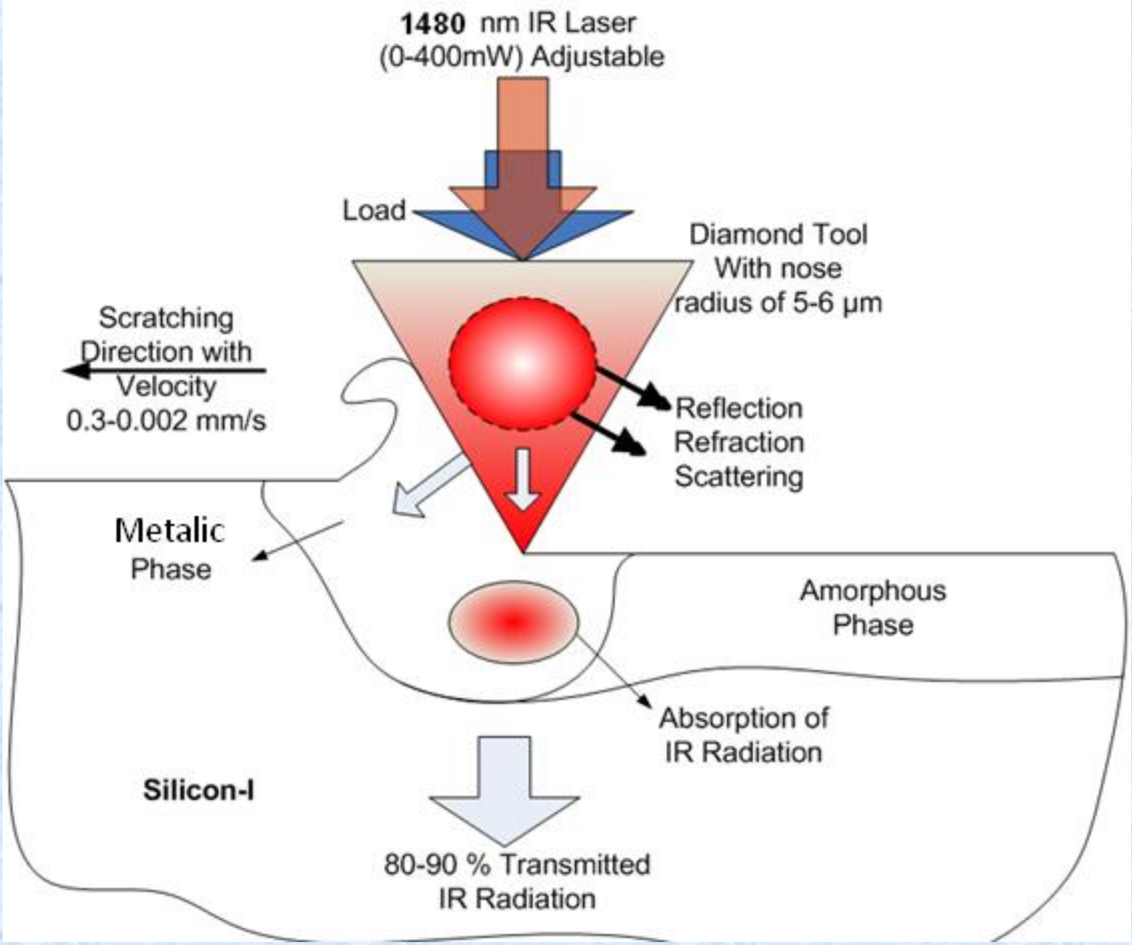
- Silicon is highly brittle at room temperature and the hardness is the function of temperature
- **H**igh **P**ressure **P**hase **T**ransformation (HPPT) is one of the process mechanisms involved in ductile machining of semiconductors and ceramics.
- Preferentially heat the HPPT material to increase ductility through thermal softening
  - Reduce tool wear
  - Minimize surface and subsurface damage.
- Thermal Softening temperature for silicon is 600-800 ^oC

Effect of Temperature on Hardness of Silicon

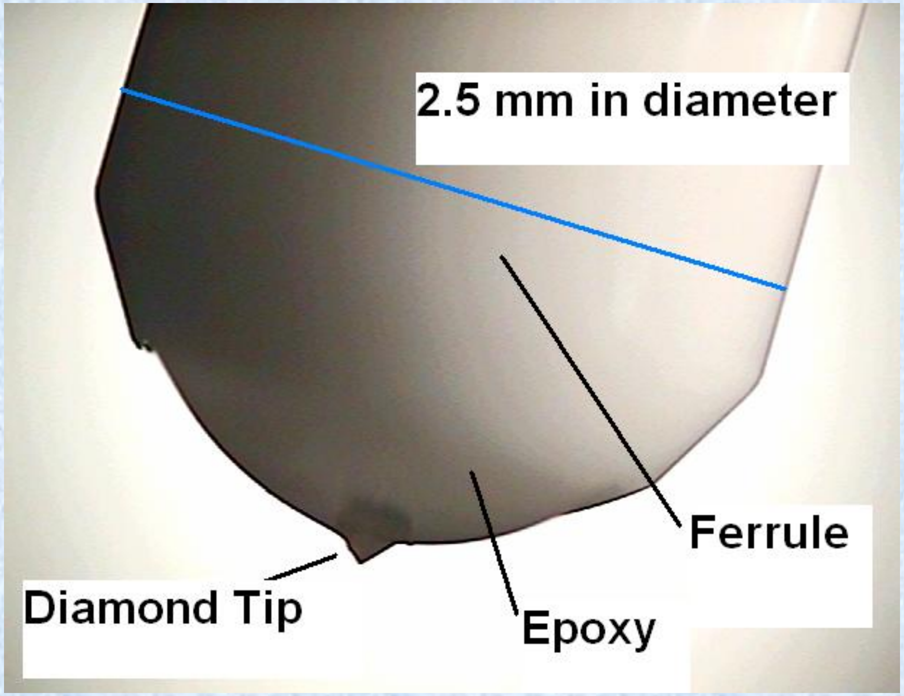


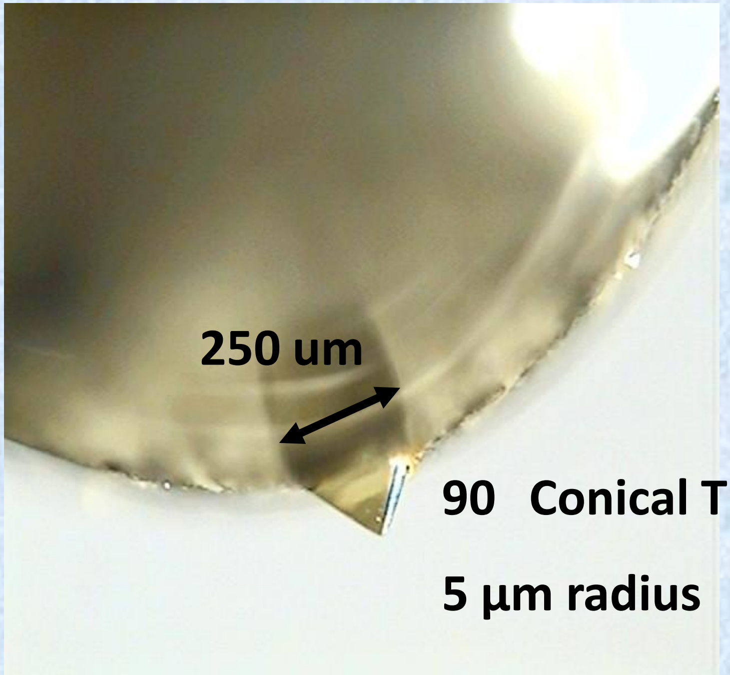
(Trefilov,1963)

Schematic of μ-LAM of Silicon



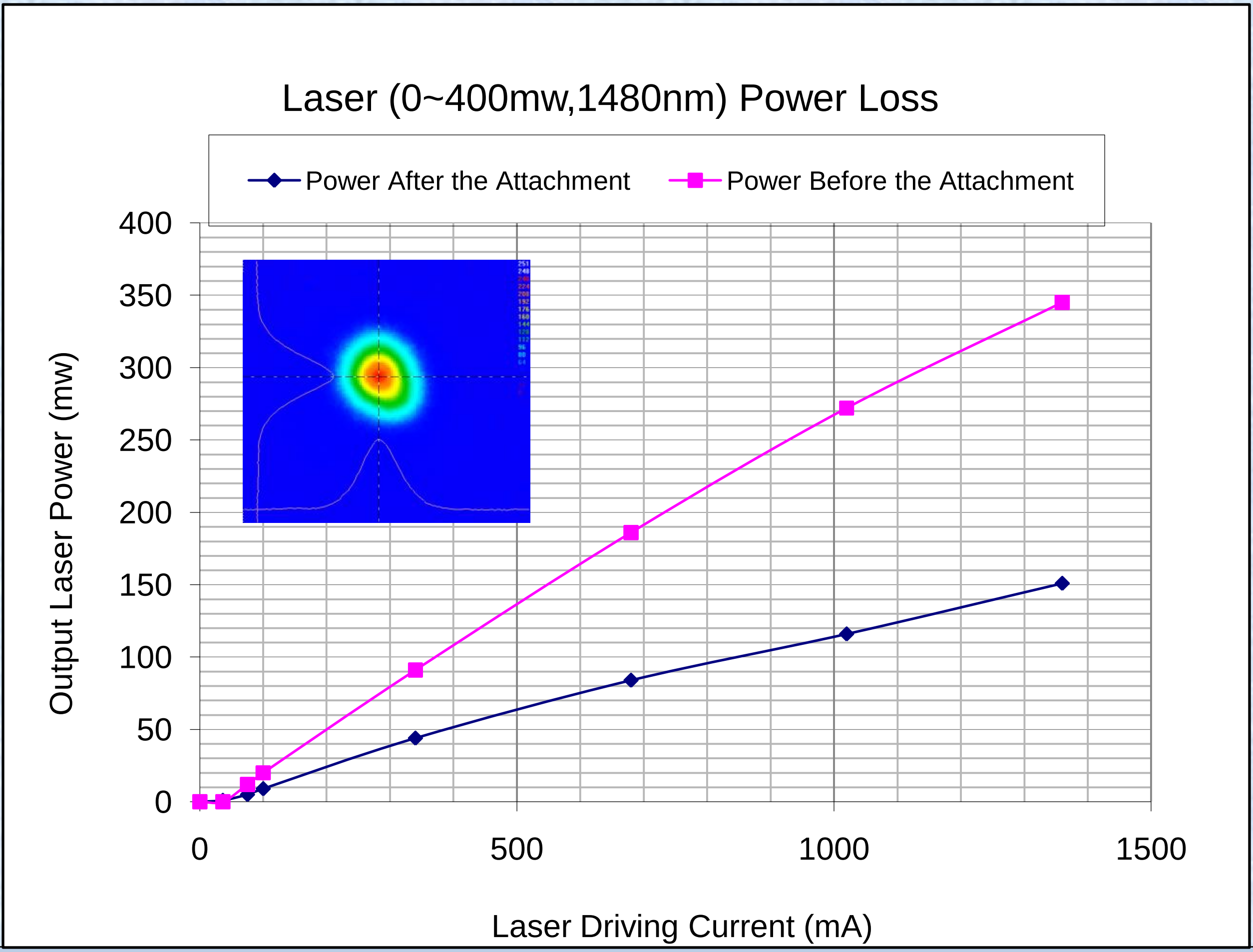
Diamond Tip Attachment





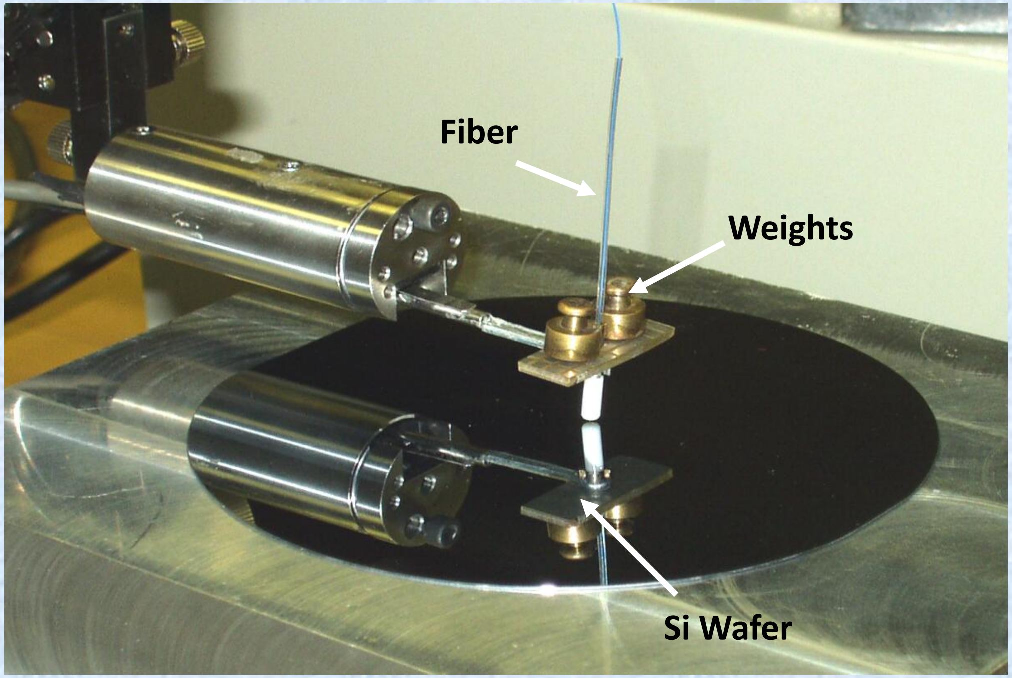
Attachment was done at Digital Optical Company (Charlotte, NC) by Jay Matthews

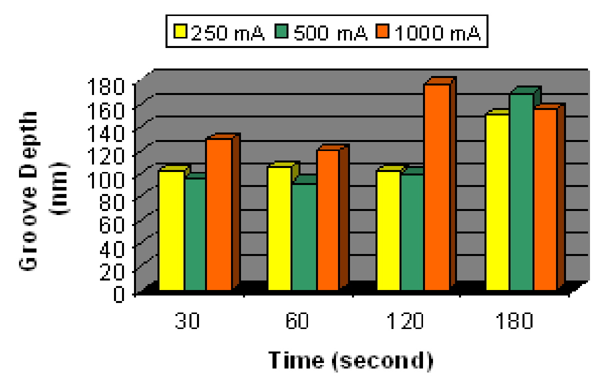
Deliverable Power After Attachment of Diamond & Laser Parameter



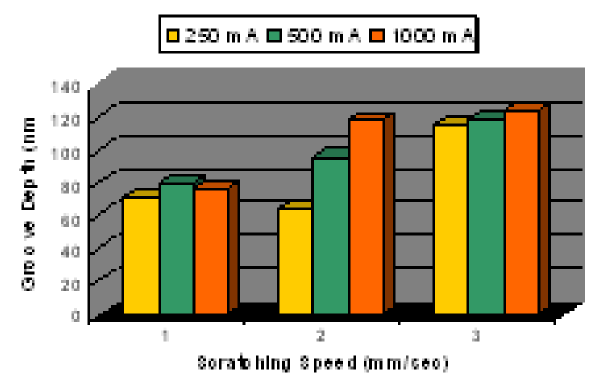
IR Laser	
Wavelength	1480nm
Laser Power (max)	400mW
Power at Diamond Tip	140mW
Photon energy	~0.9 eV
Transitivity of Si-II	80-90 %
Absorbance in Si-II	10.0 %
Diamond tool	
Diameter of tip	5-6 μm
Thermal conductivity	900-1200 W/m/K
Silicon	
Specific heat	0.7J/g/K
Density	2.33 g/cm^3

IR Softens Metallic Silicon
Indent depths at different laser power





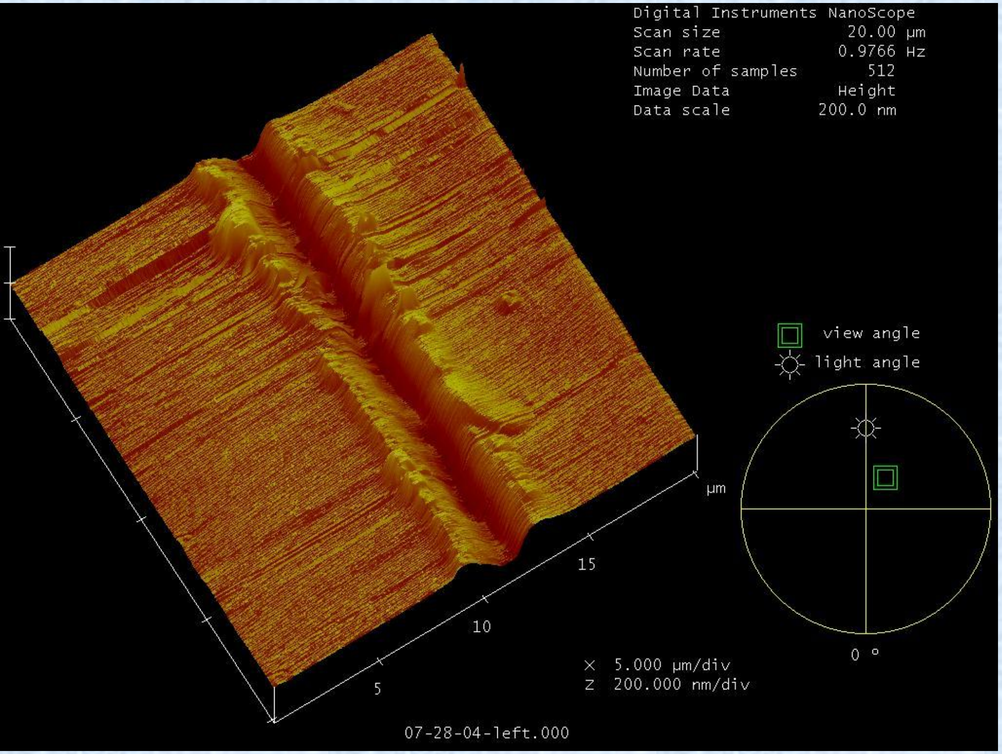
Scratch and stay test (load 25mN)



Scratching Speed Test (Load 25mN)

Speed1: 0.305 mm/sec; Speed 2: 0.002 mm/sec; Speed 3:.0002mm/sec

AFM Groove Depth Measurement



```
Digital Instruments NanoScope
Scan size                20.00 µm
Scan rate               0.9766 Hz
Number of samples          512
Image Data              Height
Data scale             200.0 nm
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X  5.000 µm/div
Z  200.000 nm/div
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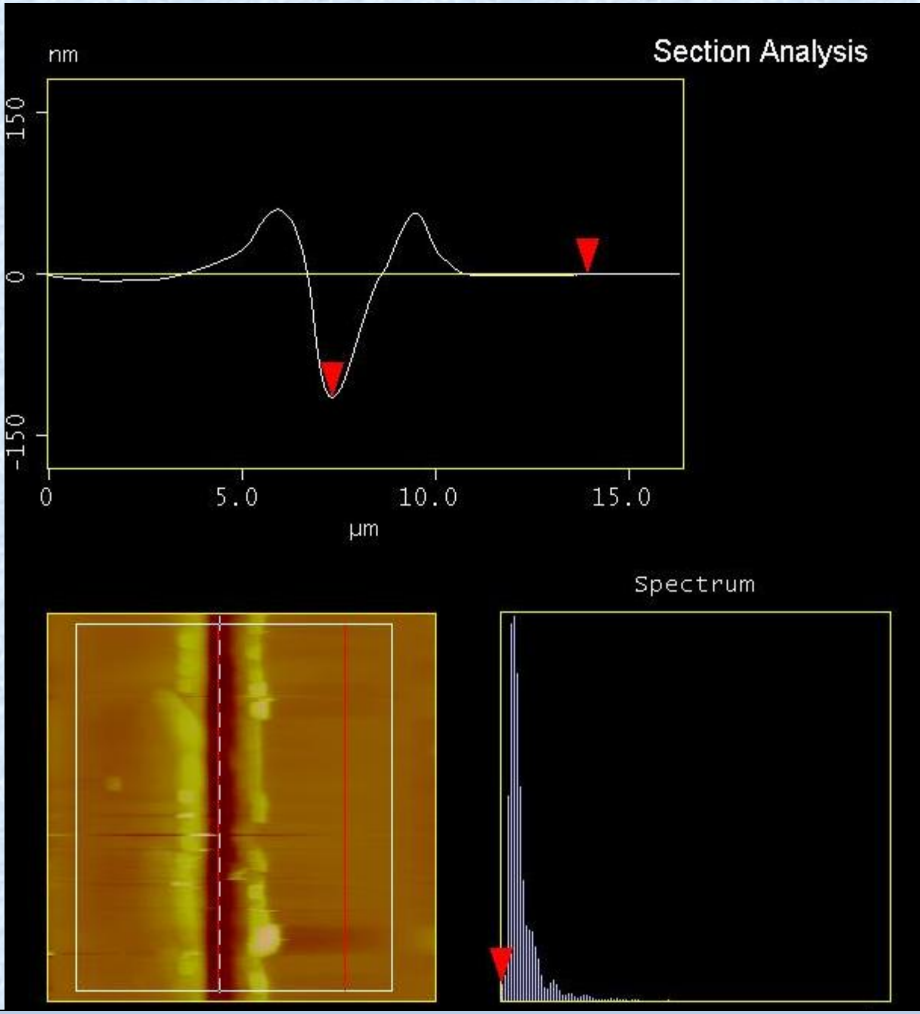
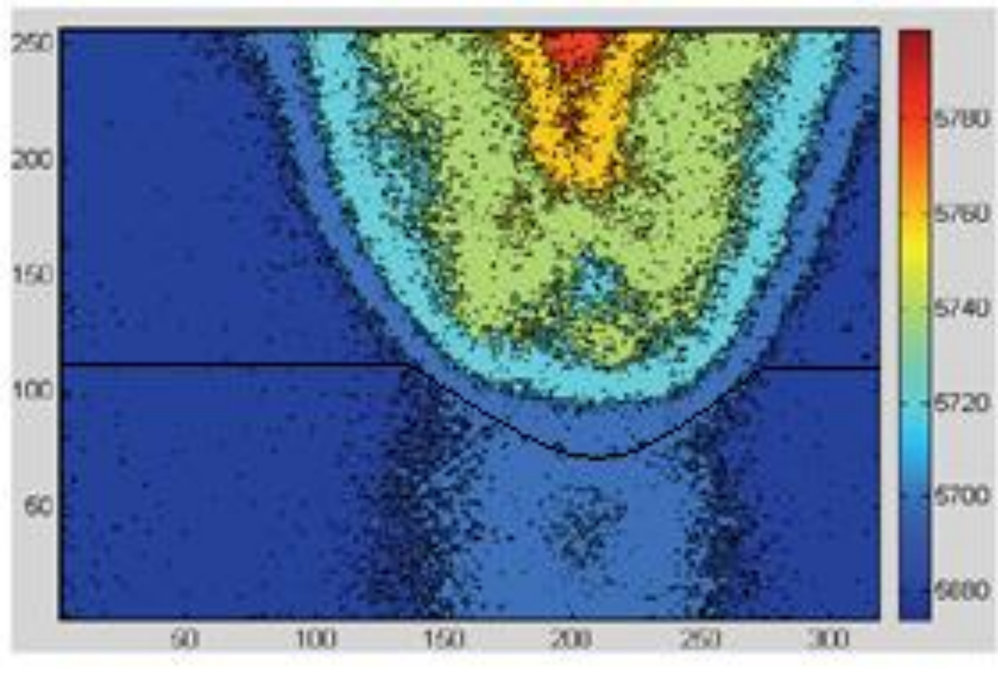


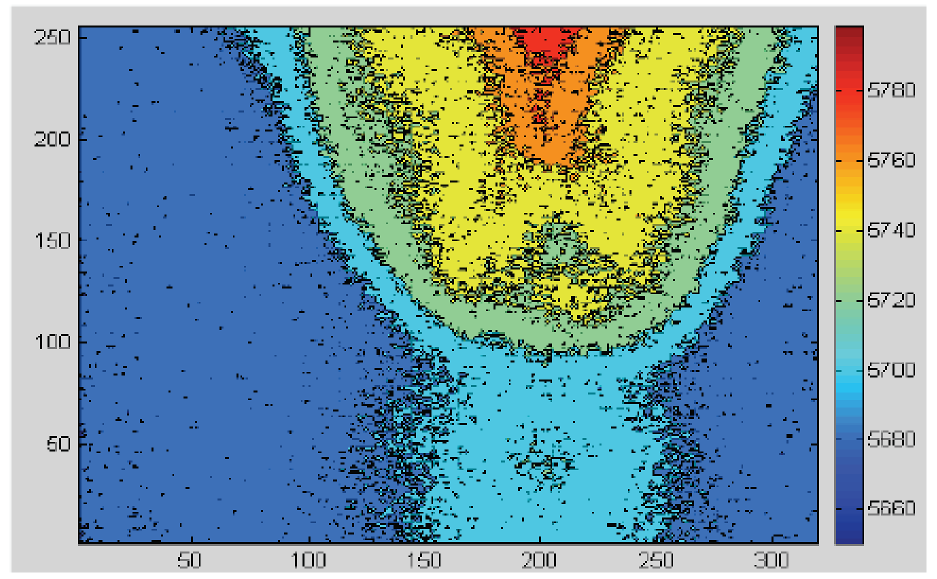
Thermal Imaging : Different Stages of Heating

Stage :1



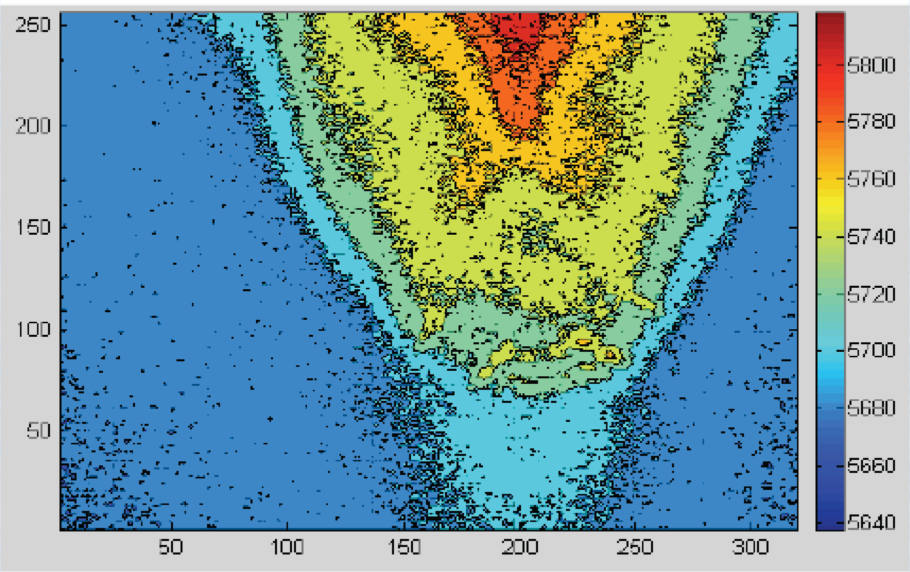
Thermal Imaging : Different Stages of Heating

Stage :2



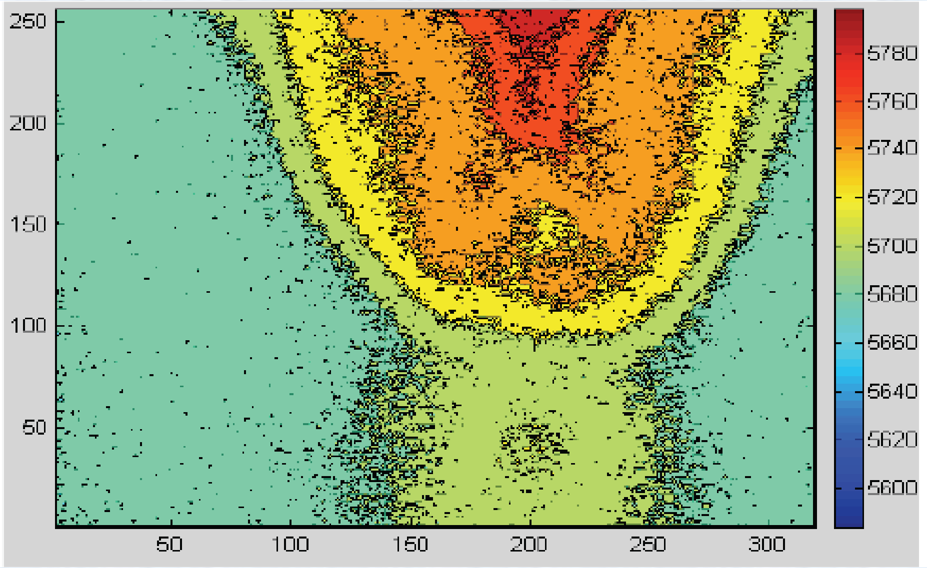
Thermal Imaging : Different Stages of Heating

Stage :3



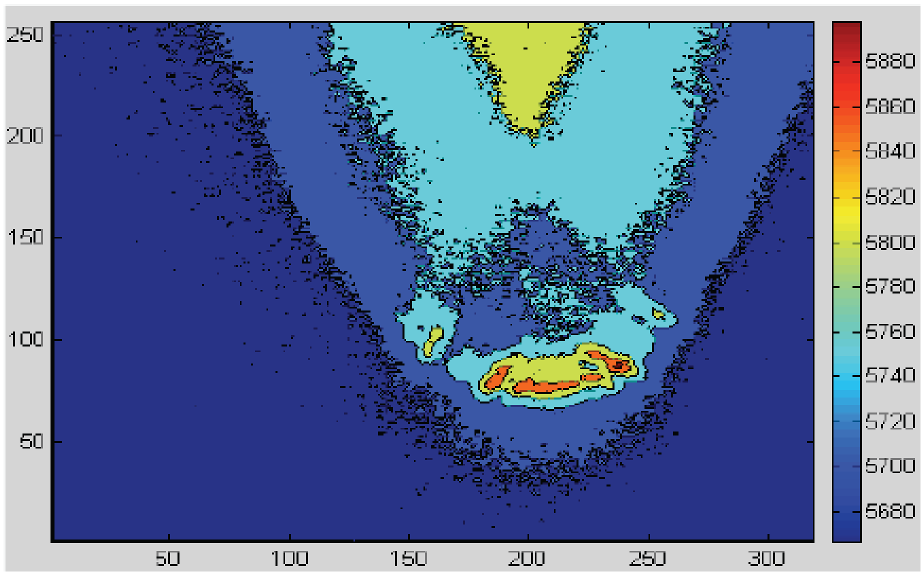
Thermal Imaging : Different Stages of Heating

Stage :4



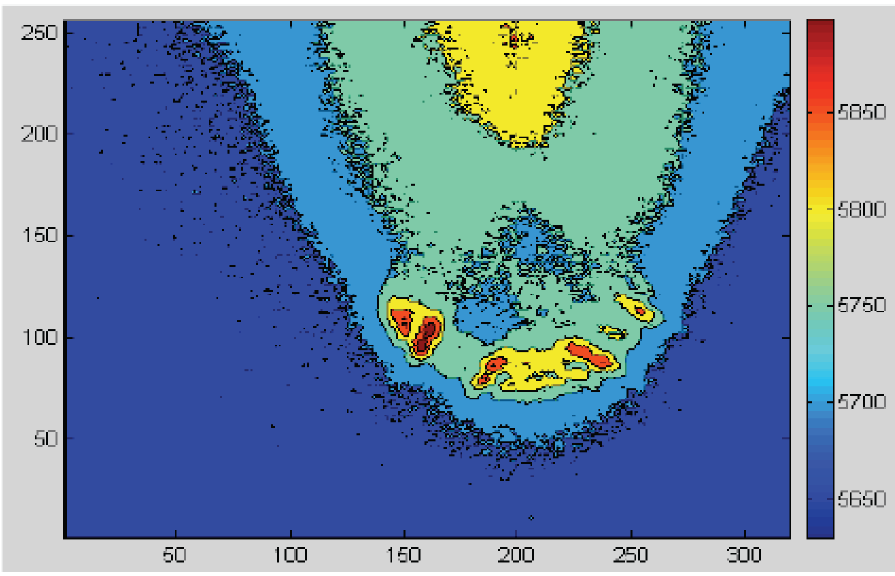
Thermal Imaging : Different Stages of Heating

Stage :5



Thermal Imaging : Different Stages of Heating

Stage :6



Estimation of Physical properties of Si-II and their use in modeling

Temperature (K)	Thermal Conductivity of metallic Si-II W/cm/K
300	0.0025
400	0004
500	0.0055
600	0.0075
700	0.0125
800	0.0165
900	0.025

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 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)

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

α :Thermal Diffusivity (cm^2/s)
r : Reflectivity
P : Density (g/cm^3)
k : Thermal Conductivity
W/cm/K

Analytical Modeling….

2. Moving Plane Heat Source

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

α :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)

Gaussian Profile

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

Temperature Profile

$$T(x,y,z) = \frac{Q\ \ 1-r}{\pi^{3/2}k}\int_0^{\infty} f(u)\,du$$

Temperature function

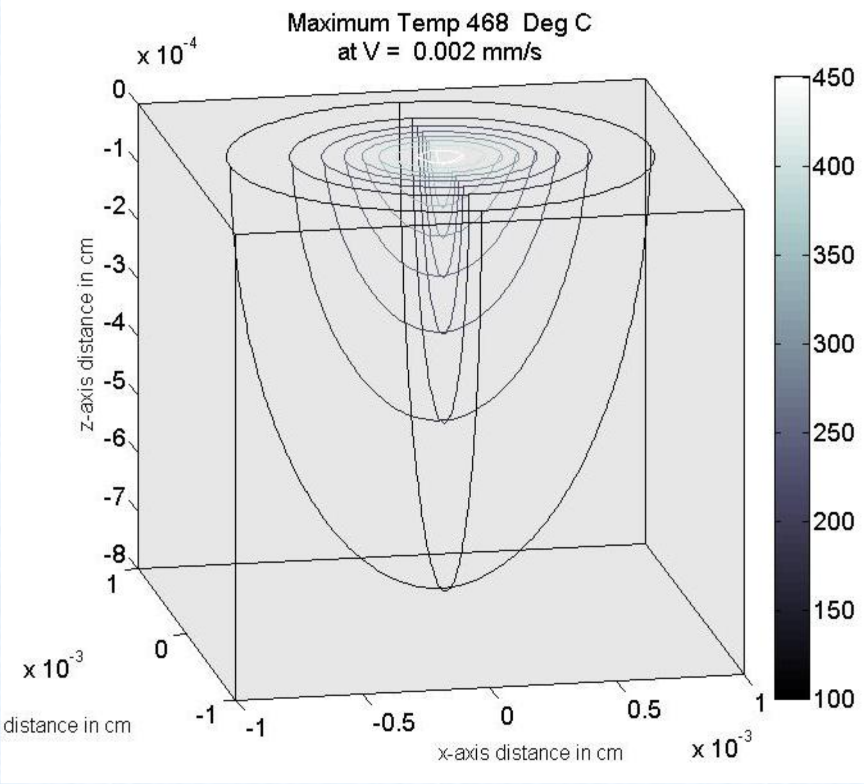
$$f(u) = \frac{\exp\left(-\left[\frac{X+V\sigma u^2\ \ ^2}{u^2+1/\beta} + \frac{Y^2}{u^2+\beta} + \frac{Z^2}{u^2}\right]\right)}{\left[u^2+1/\beta\ \ \ u^2+\beta\ \right]^{1/2}}$$

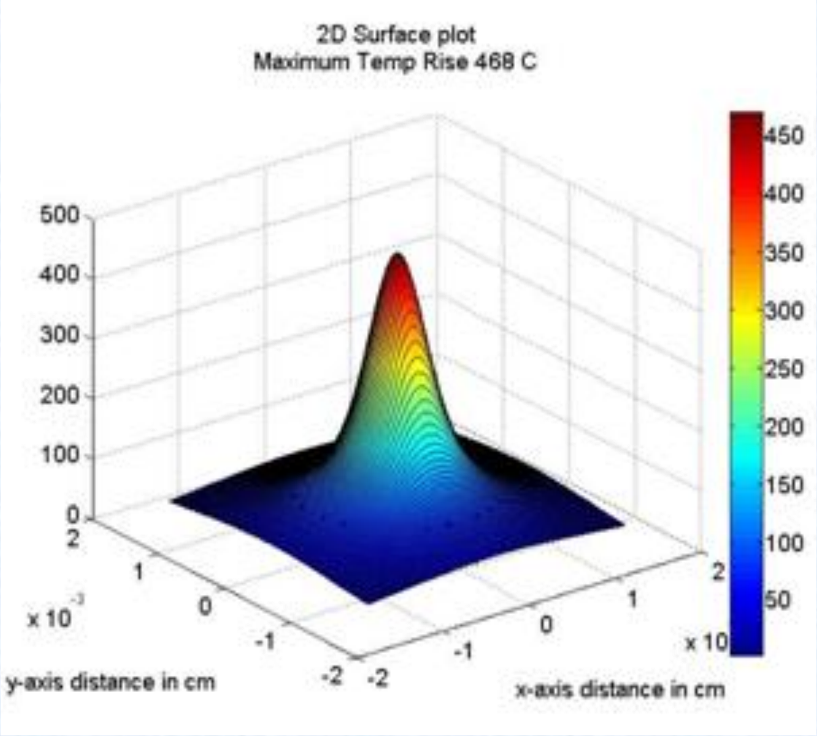
Non-dimensional parameter

$$X = \frac{x}{r} \qquad Y = \frac{y}{r} \qquad Z = \frac{z}{r} \qquad V = \frac{v}{r} \qquad \sigma = \frac{r^2}{4\alpha} \qquad Q = \frac{q}{r} \qquad u = \left(\frac{2\alpha t}{r^2}\right)^{1/2}$$

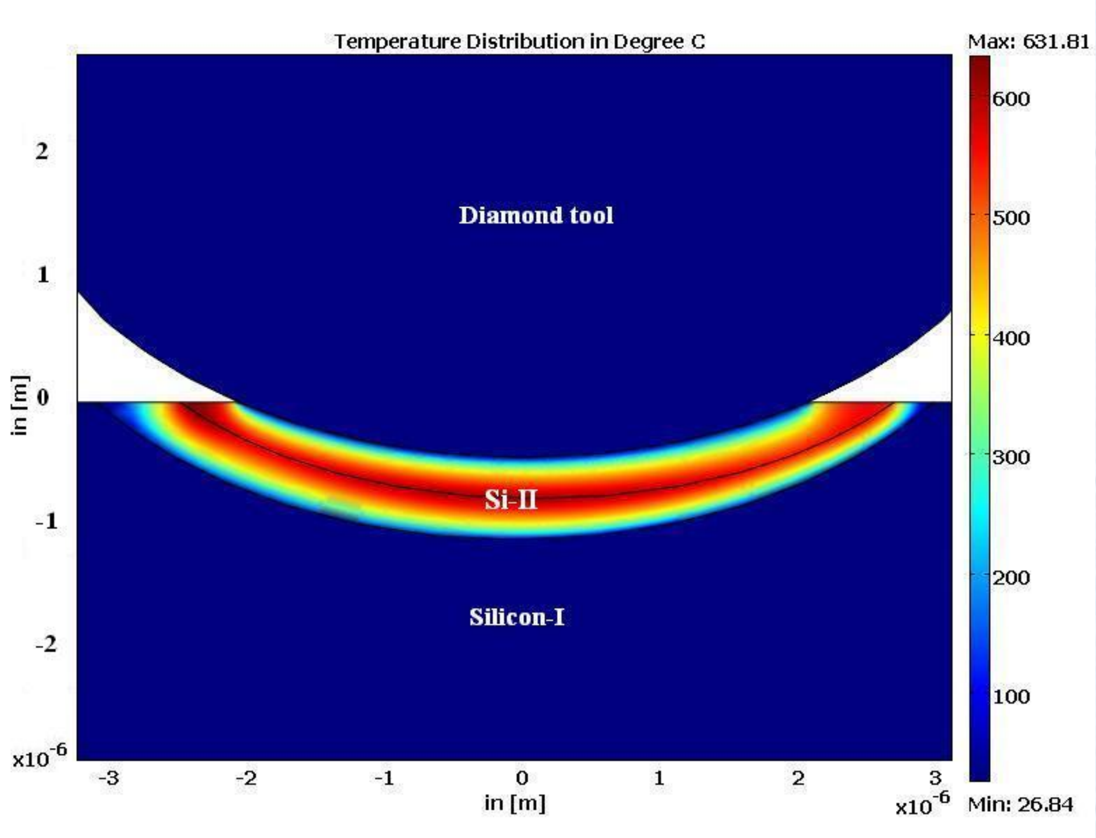
3. Gaussian Beam profile Moving Plane…….

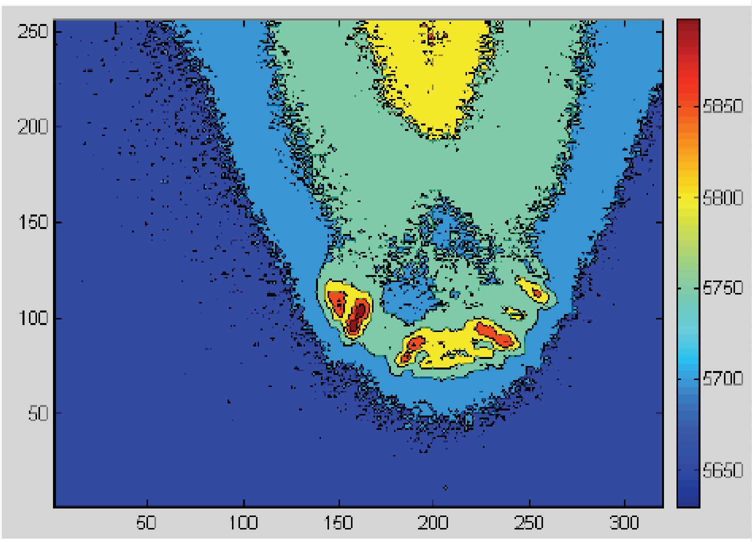
Temperature Profile





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 ΔT 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

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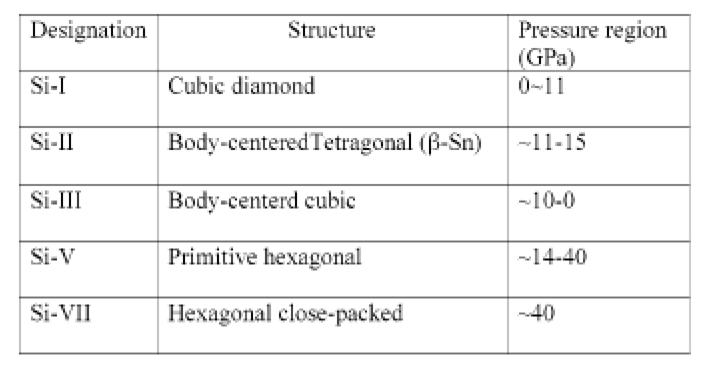
Thank you



Designation	Structure	Pressure region (GPa)
Si-I	Cubic diamond	0~11
Si-II	Body-centeredTetragonal (β-Sn)	~11-15
Si-III	Body-centerd cubic	~10-0
Si-V	Primitive hexagonal	~14-40
Si-VII	Hexagonal close-packed	~40