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Laser Material Interaction Modeling Using the COMSOL Multiphysics Software

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Annotation: This project focuses on the modeling and simulation of LASER material interactions using the COMSOL Multiphysics software. LASER material interactions play a crucial role in various fields, including manufacturing, electronics, and medicine. The objective of this study is to develop a comprehensive understanding of the fundamental principles underlying LASER material interactions and to utilize computational modeling techniques to analyze and predict the thermal and optical responses of different materials to LASER irradiation.

The project involves the development of a computational model using COMSOL Multiphysics to simulate the LASER material interactions on a silicon wafer. The model takes into account factors such as absorption, scattering, and thermal diffusion to accurately predict the temperature distribution.

1.1. Introduction

LASER material interaction modeling is important field of study the simulation of the interaction between LASER radiation and materials. With increasing demand for more efficient LASER-based processes, accurate modeling of LASER- material interactions has become an essential tool for optimizing the performance of LASER-based systems.

The field of LASER materials interaction modeling has grown in recent years, by computational tools and simulation software like COMSOL Multiphysics. This software allows researchers to simulate the behavior of materials under different LASER radiation conditions like high-power and short-pulse LASERs.

Solid materials can be either partially transparent or completely to light at the laser wavelength. Depending upon the degree of transparency, different approaches for modeling the laser heat source are appropriate. If the material interacting with the beam has geometric features that are comparable to the wavelength, we must additionally consider exactly how the beam will interact with these small structures.

Before starting to model any laser-material interactions, we should first determine the optical properties of the material that you are modeling, both at the laser power and in the infrared regime. we should also know the relative sizes of the objects we want to heat, This information will be useful in guiding toward the appropriate approach for modeling needs.(1)

1.1.1. Objective

In this project, we aim to use COMSOL Multiphysics software to model the laser heating of a silicon wafer. We will explore the effects of different LASER parameters on the resulting material response. Our goal is to gain a better understanding of how LASER-material interactions work and use COMSOL Multiphysics software to model it.

1.2. The Importance of Computer Modeling in LASER Material Interactions

Computer modeling plays an important role in the study of laser-material interactions by providing a virtual platform for simulating and analyzing complex physical phenomena. It has several advantages over experimental methods.

Computer models provide detailed into the processes, allowing a deeper understanding of the mechanisms involved. These allow exploration of a wide range of parameters and materials that can be difficult experimentally. Computer modeling also allows researchers to access virtual experiments, saving time and resources. (1)

1.3. Overview of COMSOL Multiphysics Software

1.3.1. Introduction to COMSOL Multiphysics:

COMSOL Multiphysics is a powerful software platform widely used for the simulation and modeling of various physical phenomena, including LASER material interactions. It provides a tools and features that enable researchers and engineers to analyze and solve complex multiphysics problems. The software employs a finite element method-based approach, allowing for the simulation of coupled physics phenomena, such as heat transfer, fluid flow, electromagnetic fields, and structural mechanics.(2)

Figure (1.1) COMSOL Multiphysics Software

1.3.2. Features and Capabilities of COMSOL Multiphysics:

a. **Multiphysics Modeling:** COMSOL Multiphysics allows for the simultaneous modeling of multiple physical phenomena, enabling the comprehensive analysis of LASER-material interactions. For example, it can capture the thermal effects, stress development, and phase transitions that occur due to LASER irradiation, providing a understanding of the process.(2)

b. **Customizable Physics Interfaces:** The software provides a wide range of predefined physics interfaces and equation sets that can be customized to model specific LASER-material interaction scenarios. These interfaces include heat transfer, electromagnetic waves, fluid dynamics, and chemical reactions, among others. Users can select and combine the relevant interfaces to create a tailored model for their specific application.(2)

c. **Optimization and Design:** The software includes optimization tools that enable researchers to perform parameter studies and design optimization. These parameters and material configurations, helping in the optimization and improvement of LASER-based processes.

2.1. The fundamental principles of LASER material interactions

Laser-material interaction is process that involves several principles, for example, laser absorption, transmission and reflection of materials.

Absorption occurs when laser radiation interacts with matter , the matter absorbs some or all of the radiation's energy. The degree to which a material absorbs laser radiation depends on many factors ,like the optical properties of the material and the wavelength of the laser radiation ,Various physical and chemical changes such as heating, melting, and vaporization can occur when materials absorb laser radiation.(3)

Scattering occurs ,when LASER radiation interacts with a material and is redirected in a different direction. Scattering can be caused by a number of factors, including surface roughness, microstructure, and impurities in the material. The extent of scattering depends on the wavelength of the LASER radiation and the size and shape of the scattering structures in the material. Scattering can play an important role in LASER-material interactions, as it can affect the spatial distribution and intensity of the LASER radiation in the material.(3)

Thermal diffusion, occurs when a material have a temperature change as a result of LASER radiation absorption. The absorbed energy is distributed through the material by thermal conduction, which can lead to a range of thermal effects , including melting ,vaporization ,and thermal stress. The extent of thermal diffusion depends on the materials thermal properties, as well as the laser parameters such as power density and pulse duration.(3)

2.2. LASER-Material Interaction Mechanisms

LASER radiation interacts with materials through a lot of mechanisms. The primary mechanisms involved in LASER-material interactions include absorption, scattering, and thermal diffusion.

1. **Absorption**: Absorption is the process by which the energy carried by the LASER radiation is absorbed by the material. When a LASER beam interacts with a material, the photons in the beam can be absorbed by the material's electrons or molecules. This absorption leads to an increase in the internal energy of the material , resulting in temperature rise and some changes in material properties. The absorption process is effected by factors such as the wavelength of the LASER radiation, the optical properties of the material , and the energy levels of the materials.
2. **Scattering**: Scattering is a phenomenon where the direction of the LASER radiation is redirected by interaction with the material. It occurs when the LASER beam encounters particles within the material , causing the radiation to change its direction. There are different types of scattering processes , including Rayleigh scattering, Mie scattering, and Raman scattering. Scattering can affect the intensity, distribution, and polarization of the LASER beam as it propagates through the material.
3. **Thermal Diffusion**: Thermal diffusion play a important role in the redistribution of absorbed energy within the material. After absorption, the energy is transferred through the material by thermal diffusion processes. Thermal diffusion involves conduction , convection , and radiation. Conduction refers to the transfer of heat through direct contact between molecules, while convection involves the movement of heated material,. Radiation is the emission of thermal energy in the form of electromagnetic waves. Thermal diffusion leads to the propagation of temperature gradients within the material, affecting its thermal response and potentially causing changes in material structure or properties.

2.3. Factors Affecting LASER Material Interactions

- **Power Density:** the affect of power density, which represents the amount of energy delivered per unit area, on LASER material interactions. Higher power densities can induce rapid heating, melting, or vaporization of the material.
- **Wavelength:** Different materials have varying absorption characteristics at different wavelengths, affecting the energy absorption .
- **Pulse Duration:** Investigating the duration of the LASER pulse and its effect on material behavior. Shorter pulse durations can result in ultrafast heating and cooling rates, leading to unique material responses and potentially enabling precise material processing.
- **Spot Size:** Considering the size of the focused LASER beam spot and its impact on the spatial distribution of energy. The spot size determines the area over which energy is deposited and affects factors such as heating gradient , melt size, and heat-affected zone.(4)

2.4. Material Properties

- **Optical Properties**: the optical properties of materials, like absorption coefficient, reflectivity, and transmittance. These properties determine how much of the incident LASER energy is absorbed by the material and how much is reflected or transmitted.

- **Thermal Conductivity**: Materials with higher thermal conductivity can dissipate heat more efficiently, temperature gradients and heat-affected zones.
- **Melting Temperature**: When the temperature passes the melting point, materials can go phase changes, such as melting, solidification, or vaporization, affecting material response and processing outcomes.

3.1. Introduction to Modeling Laser-Material Interactions

Modeling laser-material interactions is a complex process that requires a combination of physical and mathematical models to simulate the material under laser irradiation.

Modeling laser-material interactions has many applications in various fields, such as manufacturing, biomedicine, energy, and environmental science. By predicting the response of materials to laser irradiation, models can be used to optimize laser processing techniques, avoid material damage, and design new laser-based applications.(1)

3.2. Experimental Methods for Studying LASER Material Interactions.

1. *High-Speed Imaging Techniques*

High-speed imaging techniques involve capturing rapid changes in the material's response to LASER irradiation. These techniques utilize high-speed cameras capable of capturing thousands to millions of frames per second, allowing researchers to observe dynamic phenomena, such as material ablation, melting, and vaporization. High-speed imaging provides valuable visual information about the evolution of the material's surface, plume formation, and shockwave propagation during LASER irradiation.(5)

2. *Time-Resolved Spectroscopy*

Time-resolved spectroscopy involves studying the temporal evolution of optical properties and emissions from the material during LASER irradiation. It utilizes spectroscopic techniques, such as time-resolved photoluminescence spectroscopy or transient absorption spectroscopy, to measure the changes in optical signals over time. This method provides information about energy transfer, relaxation processes, and material response on a picosecond to nanosecond timescale.(6)

3. *Raman Spectroscopy*

Raman spectroscopy is a technique used to study the molecular composition and structural changes in materials under LASER irradiation. It involves illuminating the material with a LASER beam and analyzing the scattered light. Raman spectroscopy can provide information about molecular vibrations, chemical composition, and phase changes induced by LASER energy.(7)

4. *Thermal Analysis Techniques*

Thermal analysis techniques, such as thermography and infrared imaging, are used to study the temperature distribution and thermal behavior of materials during LASER irradiation. These techniques rely on the measurement of infrared radiation emitted by the material, which is correlated to its temperature. Thermal analysis provides insights into heat conduction, thermal gradients, and material response to LASER energy.(8)

3.3. Computational Methods for Modeling LASER Material Interactions

Computational methods play a important role in modeling LASER material interactions , These methods involve the development of mathematical models and numerical techniques to simulate the complex interactions between LASER energy and materials.

1. *Finite Element METHOD (FEM)*

Finite Element Analysis (FEM) is a widely used computational method for modeling LASER material interactions. FEM divides the material into a finite number of small elements and solves the equations of physics (such as heat transfer, electromagnetic radiation, and stress-strain) within each element. By considering the material properties, boundary conditions, and LASER parameters, FEM predicts the temperature distribution, stress development, and other relevant phenomena within the material.(9)

FEM is applied to character geometries and multiphysical behavior, both of material properties and of problems where it is generally not possible to obtain any analytical solution directly with the use of mathematical expressions. Some of the areas that use the finite element method to solve problems are heat transfer, fluid flow, mass transport, distribution of electromagnetic fields, and structural analysis .

The FEM is widely used due to the ease of introducing complex calculation domains (in two or three dimensions). In addition, the method is easily adaptable to problems of heat transmission, (9)

FEM offers several advantages, including the ability to handle complex geometries, account for material nonlinearity, and analyze dynamic or transient behavior. It provides a flexible and powerful tool for engineers and scientists to simulate and understand the behavior of systems under various conditions.

the Finite Element Method is a widely used numerical technique for solving complex engineering problems by dividing them into smaller, elements and solving the equations numerically.

FEM reduces computational effort by discretizing the domain into smaller elements and can leverage parallel processing and efficient solvers.

3.4. Use of COMSOL Multiphysics to model Laser Heating of a Silicon Wafer

The temperature response of a silicon wafer subjected to a laser heating process is simulated. The laser moves in a radial fashion over time, while the wafer rotates on its stage. The laser's heat is considered as a distributed source on the wafer's surface, and the transient thermal behavior of the wafer is analyzed. The average, maximum, and minimum temperatures, as well as the peak temperature difference across the wafer.

1. *Model Definition*

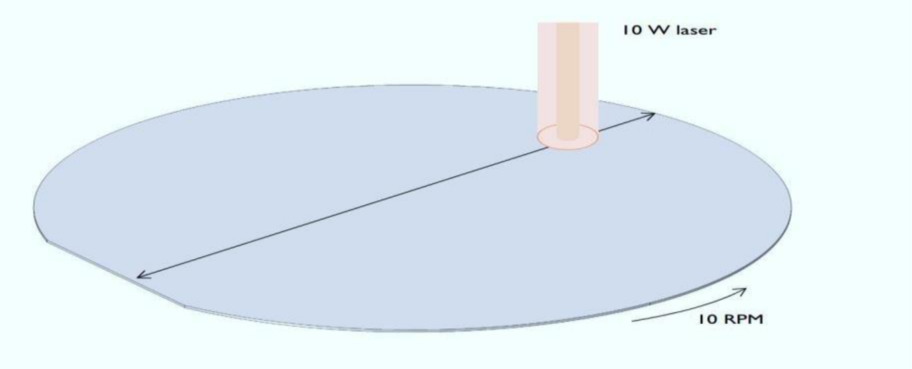


Figure (3.1) : A silicon wafer is heated with a laser that moves back and forth.

In Figure 1, a silicon wafer with a diameter of 5 cm is subjected to heating for a duration of one minute. The heat is applied by a 10 W laser that moves in a back- and-forth motion, while the wafer simultaneously rotates on its stage. It is assumed that the wafer is well insulated from the surroundings, and the only heat loss occurs from the top surface through radiation to the walls of the processing chamber. The temperature of these chamber walls remains constant at 20°C.

2. *Definition of Parameters*

The laser beam heat source is modeled as a heat source moving across the surface of the spinning wafer. Gaussian distribution of the laser heat load around the focal point, as it moves back and forth across the spinning structure

In the results visualization of the temperature profile across the wafer, the results can be visualized in either the spatial frame or the material frame,

The emissivity of the surface of the wafer is approximately 0.8. At the operating wavelength of the laser, it is assumed that absorptivity equals emissivity

Table (3.1) Definition of Parameters

Name	***Expression***	***Value***	***Description***
r_wafer	2.5[cm]	0.025 m	Wafer radius
thickness	0.4[mm]	4E-4 m	Wafer thickness
v_rotation	10[rpm]	0.16667 1/s	Rotational speed
period	15[s]	15 s	Time for laser to move back and forth
r_spot	2[mm]	0.002 m	Laser beam radius
emissivity	0.8	0.8	Surface emissivity of wafer
p_laser	10[W]	10 W	Laser power

Assuming that the laser is operating at a wavelength at which no light is passing through the wafer. Therefore, all of the laser heat is deposited at the surface

4.1. Introduction

The simulation results provide insights into the thermal behavior of the silicon wafer during laser heating. These results are important to optimizing the laser heating process and ensuring controlled temperature distribution across the wafer. Further research in alternative heating profiles could lead to improved process efficiency and enhanced semiconductor device fabrication.

4.2. Results

Figure (4.1) shows the plots of the maximum, minimum, and average temperatures of the wafer, The temperature distribution across the wafer is plotted in Figure(4.2). The heating profile does introduce some significant temperature variations, because the laser deposits the same amount of heat over a larger total swept area when it is focused at the outside of the wafer.

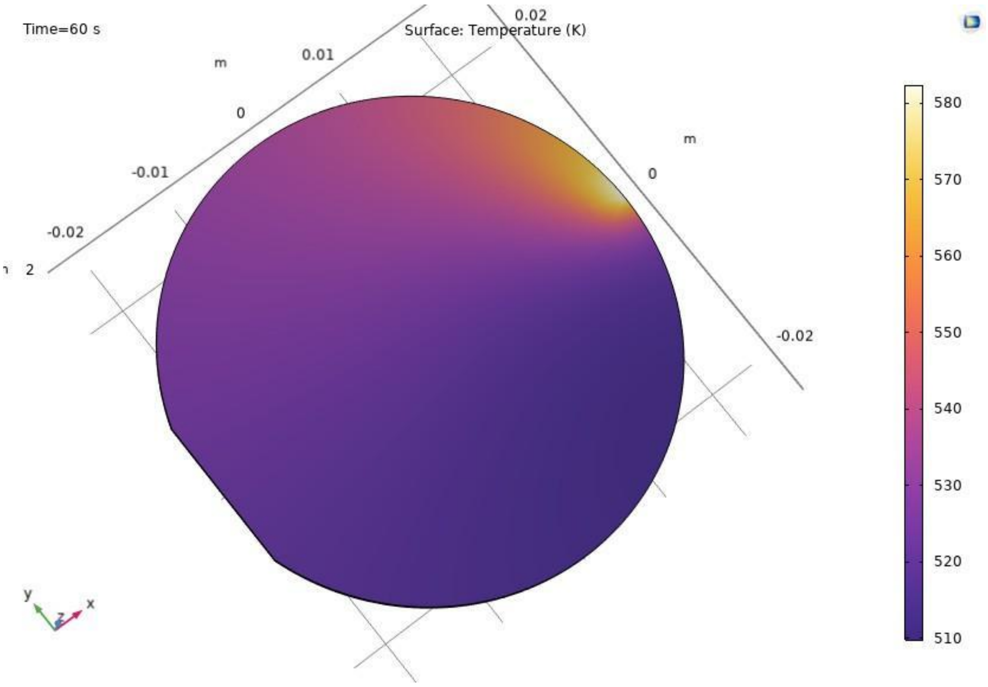


Figure (4.1) : Temperature variation across the wafer.

Figure (4.2) show the Maximum , minimum, and average temperatures of the wafer as functions of time when it heated by laser.

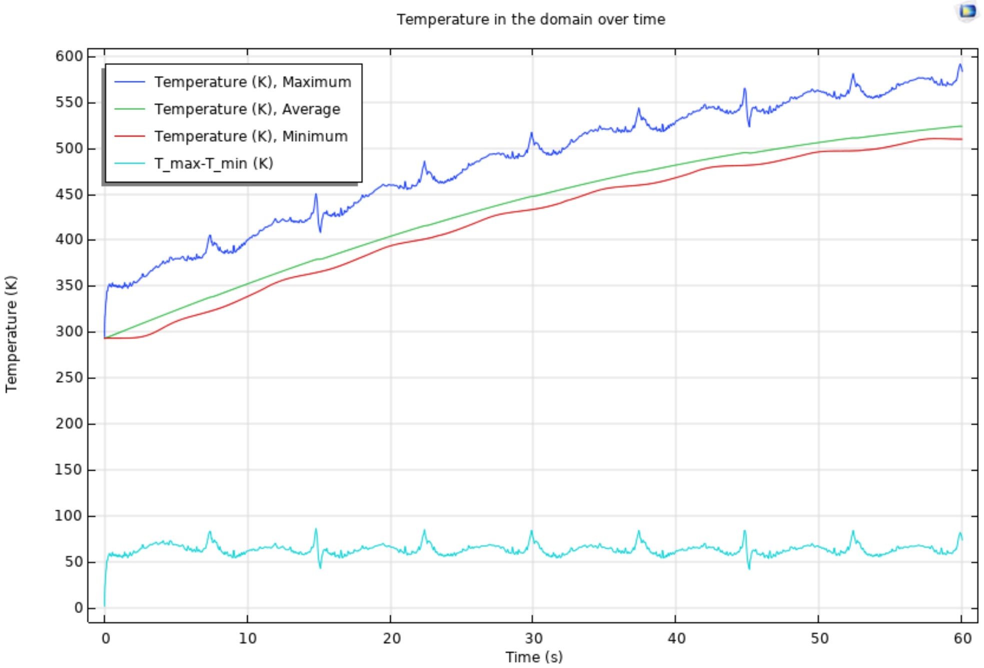
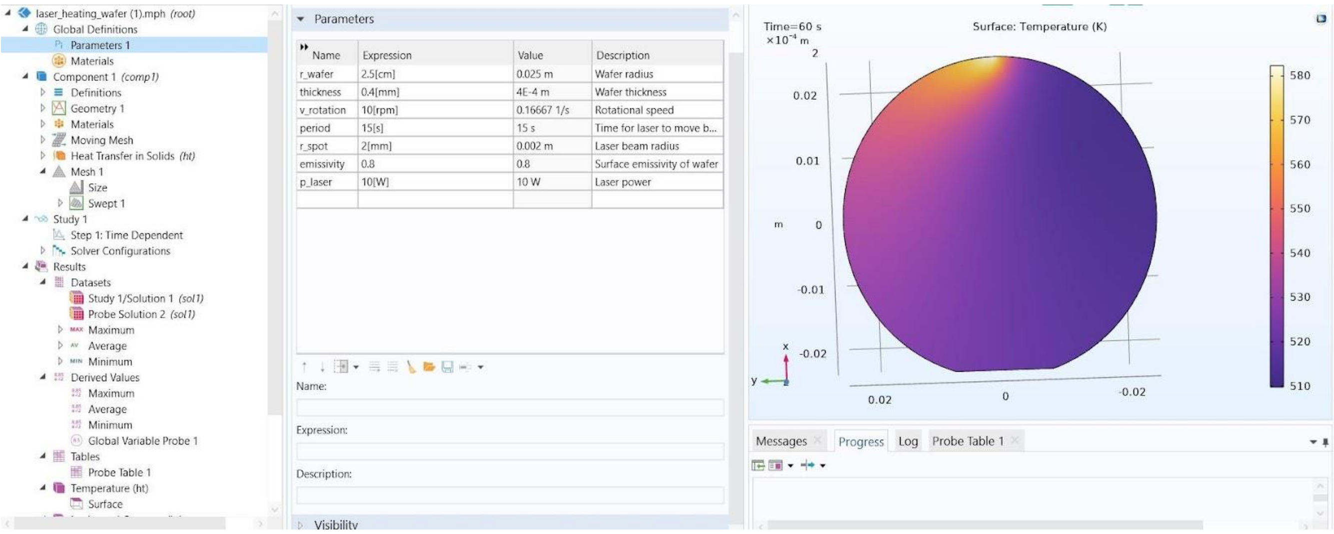


Figure (4.2) : Maximum, minimum, and average temperatures of the wafer as functions of time.



Name	Expression	Value	Description
r_wafer	2.5[cm]	0.025 m	Wafer radius
thickness	0.4[mm]	4E-4 m	Wafer thickness
v_rotation	10[rpm]	0.16667 1/s	Rotational speed
period	15[s]	15 s	Time for laser to move b...
r_spot	2[mm]	0.002 m	Laser beam radius
emissivity	0.8	0.8	Surface emissivity of wafer
p_laser	10[W]	10 W	Laser power

Figure (4.3) surface of sillicon with temperature variation and the parameters used in the project

4.3. Discussion

The simulation results reveal a non-uniform temperature distribution across the wafer surface. At the orange region where the the laser spot the heat load is maximum and the temperature reaches its peak. As we move away from the laser, the temperature decreases.

The temperature distribution is effected by various factors, including the laser power, spot size, and duration of exposure. Higher laser power leads to a more significant temperature increase, resulting in a wider range of temperatures across the wafer. a smaller spot size concentrates the heat, resulting in a localized region of higher temperature.

the thermal conductivity and thickness of the wafer play a crucial role in determining the temperature distribution. Wafers with higher thermal conductivity exhibit better heat dissipation, leading to a more uniform temperature distribution.

5.1. Conclusions and Future Works

This chapter explain the conclusions and future works related to this project .

5.2. Conclusions

this project focused on modeling LASER material interactions, specifically the laser heating of a silicon wafer, using the COMSOL Multiphysics software. The simulation results provided insights into the temperature distribution, energy transfer mechanisms, thermal response, material modification effects, and the influence of laser parameters.

The simulation revealed a non-uniform temperature distribution across the wafer surface, with the highest temperatures at the center of the laser spot. The analysis highlighted the importance of conduction, convection, and radiation in heat transfer. The thermal response of the wafer, including peak temperature and cooling behavior, was observed.

5.3. Future Works

Investigating alternative laser heating profiles, such as uniform or tailored intensity distributions, to study their effects on temperature distribution and material response.

Analyzing the material response of the silicon wafer during and after laser heating, including stress and strain distribution, phase transformations, and structural changes.

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