“A Comprehensive Study on Green Laser Annealing Technology to Activate Implanted SiC"

Research Background

A: Research Background:

- Silicon carbide (SiC) has gained considerable attention in recent years due to its unique material properties, such as high thermal conductivity, wide bandgap, and excellent chemical and mechanical stability. However, the activation of implanted dopants in SiC has been a significant challenge due to its inherent high crystalline quality and chemical inertness.

A: Research Background:

- Even though some experimental efforts have been conducted, a systematic study to laser activation is lacked. This study is to provide a comprehensive methodology to the application of laser activation technology in the SiC process, including: optical modeling and process simulation, the impact of cap materials, and analytical technologies.

Research Contents

- Modeling the process
- Simulation and optimization
- Experiment design
- Experimental validation
  1. Electrical/Optical methods
  2. Material structural analysis: XRD, TEM and Ramen.

A: Modeling the process:

- MATLAB's flexibility and extensive library of functions allow you to incorporate various physical phenomena, such as heat transfer, diffusion, and optical absorption, into your model.
- The model should consider factors like laser power, pulse duration, beam shape, heat transfer, and material properties of SiC and the annealing caps.

B:Simulation and Optimization:

- Implement the model in MATLAB and perform simulations to study the effect of different parameters on the annealing process.
- Optimize the laser parameters (power, pulse duration, etc.) to achieve the desired annealing results.
- MATLAB's optimization algorithms, such as genetic algorithms, particle swarm optimization, and nonlinear programming, efficiently explore the parameter space and find the optimal settings for laser annealing

C: Experiment Design:

- Based on the simulation results, design the system components required for laser annealing.
- This may include laser sources, beam delivery systems, control mechanisms, and safety measures.
- MATLAB can be used for system design, including optical modeling and control algorithms and also to determine the optimal experimental conditions for measuring thermal and optical profiles during laser annealing.

D: Experimental Validation:

- To analyze and visualize the measured thermal and optical profiles and compare them with the predicted profiles from your MATLAB model.
- Collect experimental data on temperature profiles, material properties, and annealing results.
- Compare the experimental data with the simulation results to validate the model and optimize the system parameters further if needed.

Advantages of modeling and simulation

- This understanding can aid in optimizing the annealing parameters for improved device performance.
- Researchers can anticipate the outcomes and make informed decisions regarding the annealing conditions and annealing caps to achieve desired results.
- Simulation and optimization techniques enable researchers to explore a wide range of annealing parameters, such as laser power, pulse duration, and annealing cap materials.
- By identifying the most critical parameters, researchers can prioritize their efforts and refine their experiments accordingly, leading to more efficient and targeted research.

- Researchers can leverage these capabilities to simulate various phenomena, including heat transfer, temperature distribution, optical absorption, and material response during laser annealing.
- These algorithms can be employed to find the parameter combinations that maximize the desired thermal and optical profiles while considering constraints such as laser system limitations and material properties.

CHALLENGES

Challenges

- **Material Properties:** Accurate characterization of SiC and the annealing caps is crucial for modeling and simulation. Obtain reliable data on thermal conductivity, specific heat, melting temperature, and other relevant properties.

- **Laser-Material Interaction:** Understanding the interaction between the laser beam and SiC, as well as the annealing caps, is challenging. Experimental characterization and modeling of laser-material interaction are necessary.

Challenges

- **Optimal Parameter Selection:** Determining the optimal laser parameters for achieving the desired annealing results while avoiding damage or contamination is a complex optimization problem.

- **System Integration:** Designing and integrating the various components of the laser annealing system require expertise in optics, control systems, and safety considerations.

Candidates:

- To study the effect of varying annealing caps on SiC substrates and compare them with carbon layered SiC substrates.

- I have the following candidates:

1. **Aluminum Nitride (AlN)**
2. **Silicon Nitride (Si_3N_4)**
3. **Titanium Nitride (TiN)**
4. **Tantalum Nitride (TaN)**
5. **Boron Nitride (BN)**
6. **Silicon Dioxide (SiO_2)**
7. **Aluminum Oxide (Al_2O_3)**

Annealing Caps group division

Annealing caps group division:

The choice of annealing caps, which absorb or transmit heat, plays a crucial role in the laser annealing process.

Group 1:

Caps absorbing the photons to generate the heat to anneal the SiC by heat radiation.

Group 2:

Transparent caps allow photons to be absorbed by the damaged SiC layer and generate the heat to anneal the SiC

Group 1: Caps that Absorb Heat:

The annealing caps are designed to absorb heat, enabling efficient energy transfer to the SiC material.

Examples: Aluminum Nitride (AlN), Silicon Nitride (Si_3N_4), Titanium Nitride (TiN), Tantalum Nitride (TaN), Boron Nitride (BN), and Carbon

1:Theoretical Understanding: It includes understanding the optical and thermal properties of the cap material and SiC layers, such as absorption coefficients, thermal conductivity, and specific heat capacity.

2:Method Selection: This model should consider factors such as laser intensity, pulse duration, cap material properties, and the temperature dependence of the SiC's material parameters.

Group 1: Caps that Absorb Heat:

3:Process Realization: This involves coding the equations that govern the heat transfer process and integrating them into a simulation framework

4:Challenges: Address potential challenges during the simulation, such as accurately modeling the laser beam profile, accounting for non-linear material properties at high temperatures, and accurately simulating the thermal behavior of the cap material.

Group 1: Expected Outcomes:

Expected Outcomes: Through simulations, you can expect to obtain temperature profiles within the SiC material and the heat-absorbing cap. This information can help optimize the annealing process by determining the laser parameters required to achieve the desired temperature distribution for effective defect annealing.

Group 2: Caps Transparent to Heat:

The annealing caps are designed to be transparent so that photons are absorbed by the SiC.

Examples: Silicon Dioxide (SiO_2) and Aluminum Oxide (Al_2O_3)

1:Theoretical Understanding: Analyze the heat transfer principles and optical properties of transparent cap materials and the different SiC layers with various damages. Consider factors such as transmittance, reflectance, and refractive index, such as absorption coefficients, thermal conductivity, and specific heat capacity.

2:Method Selection: Select a suitable mathematical model that accounts for the transmission of laser energy through the transparent cap. This model should consider the laser intensity, pulse duration, cap material properties, and the effect of heat transfer on the SiC material.

Group 2: Caps Transparent to Heat:

3:Process Realization: Implement the selected mathematical model in MATLAB. Develop appropriate algorithms to describe the laser transmission through the cap, including factors such as absorption, scattering, and reflection. Combine this with heat transfer equations to simulate the temperature distribution within the SiC material.

4:Challenges: Address challenges related to accurately modeling the transmission properties of the cap material, accounting for multiple reflections within the cap, and considering the variation in optical properties with temperature.

Group 2: Expected outcomes:

Expected Outcomes: Simulations will provide insights into the temperature distribution within the SiC material when using transparent annealing caps. This information can help optimize the laser parameters and cap design to achieve the desired temperature profile for efficient defect annealing .

Advantages of using different annealing caps:

- Enhanced laser absorption
- Better surface protection
- Improved process control

Advantages of using different annealing caps:

- AlN has high thermal conductivity and stability.
- Si_3N_4 has good thermal and mechanical properties.
- TiN has good adhesion and oxidation resistance.
- TaN has good chemical stability and low resistivity.
- BN has high thermal conductivity and low dielectric constant.
- SiO_2 has high stability and low thermal expansion.
- Al_2O_3 has good mechanical and thermal properties.

Potential applications and impact of the research::

- Improvement of the device performance.
- Reduction of the production costs.
- Reproducibility in the outcome.
- Development of new materials for advanced electronic and optoelectronic devices

CANDIDATES

Candidates

Name	Melting point (C)	Band Gap (eV)	Thickness (nm)
AlN	2200	6	100-200
Si_3N_4	1900	5.5	50-150
TiN	2950	1.8	50-100
TaN	3090	1.2	50-100
Al_2O_3	2072	8.7	50-150
BN	3000	5.9	50-150
SiO_2	1710	8.9	50-150
C	3550	5.4	50-150

Aluminum Nitride (AlN)

- High thermal conductivity and thermal stability.
- High electrical insulation, prevents electrical leakage.
- Chemical stability, prevents oxidation and contamination barrier.
- Non-toxic in nature.
- Similar crystal structure, good lattice match.
- Can be removed via wet chemical (HF or H_3PO_4) or dry plasma etching.
- Incase of cross contamination,

1. It can lead to chemical reactions forming Al or Si oxides on cap surface.
2. Health safety risks (respiratory or skin issues).

Aluminum Nitride (AlN) vs Carbon (C)

- C has high solubility in SiC which leads to carbide phases and resulting poor surface quality. AlN has lower solubility in SiC thus cleaner interfaces and improved performance achieved.

- C is prone to oxidation at high temp which leads to formation of CO_2 and CO. AlN is chemically stable, provides resistance to oxidation at higher temps.

- C has low thermal conductivity, leading to thermal gradients and non-uniform heating. Contrary to it, AlN has higher thermal conductivity, leading to uniform heating.

Silicon Nitride (Si_3N_4)

- High thermal and chemical stability.
- Good thermal and electrical insulation.
- Helps to maintain a uniform temperature across the wafer.
- Low diffusion coefficient.
- Can be removed via wet chemical or dry plasma etching and thermal stripping in inert gas environment.
- Incase of cross contamination,

1. Decrease in the layers potential to act as a barrier.
2. Formation of new phases or compounds via reactions.

Silicon Nitride (Si_3N_4) vs Carbon (C)

- Carbon has a high absorption coefficient for laser radiation result in a significant amount of laser energy being absorbed by the annealing cap rather than the SiC. In contrast, Si3N4 has a lower absorption coefficient for laser radiation, which results in more efficient energy transfer to the SiC.

- Si_3N_4 as an annealing cap on SiC for laser annealing has several advantages over using carbon, including better chemical stability, higher thermal conductivity, and more efficient energy transfer.

Titanium Nitride (TiN)

- High thermal and chemical stability.
- Good thermal and electrical conductivity.
- Helps to maintain a uniform temperature across the wafer.
- Biocompatible nature.
- Low diffusion coefficient.
- Can be removed via wet chemical etching (HF or HNO_3).
- Incase of cross contamination,

1. Uneven hearting or cooling.
2. Reduced protection leading to oxidation of SiC.

Titanium Nitride (TiN) vs Carbon (C)

- TiN has a similar thermal expansion coefficient to SiC, which reduces the risk of thermal stress-induced cracks in the annealed material. Helps to maintain a uniform temperature across the wafer.
- Carbon may be more prone to oxidation than TiN.
- TiN has a lower electrical resistivity than carbon, which can improve the efficiency of the annealing process
- TiN is more chemically inert than carbon, which means that it is less likely to react with the SiC substrate during annealing.

Tantalum Nitride (TaN)

- High thermal and chemical stability.
- Good thermal and electrical conductivity.
- Non-toxic in nature and low thermal expansion coefficient.
- Help to reduce the resistance of the contacts on the SiC.
- Good diffusion barrier.
- Can be removed via wet chemical etching (HCl, HF, or H_2O_2).
- Incase of cross contamination,

1. Layers barrier capacity is reduced.
2. Undesirable phases or compounds may be generated.
3. Voids or defects may be generated.

Tantalum Nitride (TaN) vs Carbon (C)

- TaN is a good absorber of laser energy and can efficiently transfer heat to the SiC substrate, resulting in effective annealing. Carbon, on the other hand, has a low absorption coefficient for laser energy, and as a result, it is not as effective in transferring heat to the substrate.

- TaN is a refractory metal that has high melting point and good thermal stability, making it suitable for high temperature applications. Carbon, on the other hand, has a low melting point and can be easily damaged by high temperatures.

- Both TaN and carbon are compatible with SiC, and they do not react with the substrate during annealing.

Boron Nitride (BN)

- High thermal and chemical stability.
- Low thermal expansion coefficient.
- Good thermal conductor and electrical insulation.
- Good diffusion barrier.
- Compatible with SiC.
- Can be removed via wet chemical etching.
- Incase of cross contamination,

1. Formation of boron carbide (B_4C) at interface.
2. Formation of undesirable oxides.

Boron Nitride (BN) vs Carbon (C)

- BN have high thermal conductivity, allows for more efficient heat transfer from the laser to the SiC substrate. Result faster annealing times and more uniform heating across the substrate as compare to carbon.
- BN is a highly inert material that is resistant to oxidation and other chemical reactions at high temperatures helps maintaining integrity of material.
- BN offers advantages in terms of thermal conductivity, chemical stability, and high-temperature performance.

Silicon Dioxide (SiO_2)

- High thermal and chemical stability.
- Low thermal expansion coefficient.
- Good electrical insulation.
- Good diffusion barrier.
- Can be removed via wet chemical and dry plasma etching.
- Incase of cross contamination,

1. Incase of diffusion from cap to bulk, unintentional doping results.
2. Incase of diffusion from bulk to SiO_2, surface contamination and reduction of caps ability to prevent oxidation.

Silicon Dioxide (SiO_2) vs Carbon (C)

- SiO_2 has a higher thermal resistance than carbon, which can lead to better thermal insulation during laser annealing.

- SiO_2 have chemical stability, and ease of deposition compared to carbon.

Aluminum Oxide (Al_2O_3)

- High thermal and chemical stability.
- Non-toxic in nature and good electrical insulation.
- Good diffusion barrier.
- Helps to reduce the thermal stress which can prevent cracking or damage.
- Improve the surface quality by smoothing out any surface roughness or defects.
- Can be removed via wet chemical and dry plasma etching.
- Incase of cross contamination,

1. Evolution of unwanted compounds.

Aluminum Oxide (Al_2O_3) vs Carbon (C)

- Carbon has a relatively low melting point and a high coefficient of thermal expansion, which can lead to cracking and delamination of the cap during annealing while Al_2O_3 low coefficient of thermal expansion, and is highly transparent to laser radiation.

- Carbon can also introduce unwanted impurities while Al_2O_3 is highly stable and inert material, which means that it will not introduce unwanted impurities into the annealed material.

Expected Outcomes

Expected outcomes

The simulations conducted using MATLAB will provide insights into the thermal behavior of SiC during laser annealing with different cap materials. The expected outcomes include:

1:Identification of optimal cap materials:

A: Determine the cap materials that result in improved temperature control and heat distribution during annealing.

B: Identify the materials that achieve desired material modifications, such as improved dopant activation and reduced defect formation.

Expected outcomes

2:Optimization of annealing parameters:

A: Optimize laser parameters, cap thickness, and placement to achieve precise and controlled annealing effects.

B: Determine the laser power and duration required for specific material modifications.

THANK YOU