Modeling of pulsed Laser Thermal Annealing for junction formation optimization and process control

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OUTLINE

- Laser Thermal Annealing technology
- Experiments
- Model
  - Phase-Field approach
  - Dopant diffusion and segregation
- Results
- Conclusions
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Pulsed excimer Laser Thermal Annealing (LTA)

- Laser absorption
- Melting and recrystallization

Low thermal budget process

- High temperature localized in space and time
  - Shallow depth effect (<µm)
  - Ultrafast (<µs)
Laser tool characteristics

- **High Energy Gas laser**
  - XeCl excimer gas
  - UV 308nm wavelength
  - Pulsed

- **Challenge:** process variability
  - Energy and pulse variations
Laser Thermal Annealing Process Parameters

- **Long pulse laser**
  - Pulse Duration: ~150 ns

- **Uniform high Energy Density**
  - Up to 3 J/cm²
  - Up to 2x2 cm² area
Process variability and junction formation

- **Other laser annealing process parameters**
  - Melt Depth (ex-situ measurement)
  - Temperature (no direct measurement)

- **Depend on**
  - Laser **Energy Density**
  - Pulse shape

→ **LTA process simulation**
  - Linking tool parameters to process
  - Understanding process variability
LTA simulation: 2 steps

**Thermal step**
- Laser parameters
- Structure
  - Material properties
  - Geometric dimensions
- Process Window determination to avoid damage
  - Temperature profiles
  - Melt dynamics

**Diffusion step**
- Temperature profiles & Melt dynamics
- Junction formation
  - Dopant distribution
- Dopant profiles
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Typical Boron profiles after LTA

- Melt Depth estimation vs Energy Density
- Profiles not explained by simple diffusion (Fickian)

Secondary Ion Mass Spectroscopy (SIMS) error:
±5% in depth and ±10 in concentration
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Phase-Field model

- Heat (T) and Phase (\(\varphi\)) equations are connected by coupling terms
- Formalism: \(-1 \leq \varphi \leq +1\)

\[ \text{Heat equation} \]
\[ \rho \cdot c_p \cdot \frac{\partial T}{\partial t} - \nabla^2 (k \cdot T) = \rho \cdot \frac{L_{fus}}{2} \cdot \frac{15}{8} \cdot (\varphi^2 - 1)^2 \cdot \frac{\partial \varphi}{\partial t} + S(x, t) \]

- Source equation
\[ S(x, t) = ED \cdot P_n(t) \cdot (1 - R) \cdot \alpha \cdot e^{-\alpha \cdot x} \]

- Phase change equation
\[ \tau \cdot \frac{\partial \varphi}{\partial t} = W^2 \cdot \nabla^2 \varphi - \varphi \cdot (\varphi^2 - 1) - \frac{\lambda}{L_{fus}} \cdot (T - T_M) \cdot (\varphi^2 - 1)^2 \]

[Karma and Rappel, PRE 1998] [La Magna et al., JAP 2004]
Dopant distribution simulation

\[ \frac{\partial C_B}{\partial t} = \nabla \left( D_B \nabla C_B \right) - \nabla \left( D_B \frac{C_B}{C_{equ}} \nabla C_{equ} \right) \]

Fickian diffusion  
Adsorption and segregation

- With
  - \( C_B \): Boron concentration (cm\(^{-3}\))
  - \( D_B \): Boron diffusion coefficient (cm\(^2\)s\(^{-1}\), phase dependent)
  - \( C_{equ} \): Equilibrium concentration (fit parameter)

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Thermal and phase change simulation

- Model fit very well the experimental data
  - Accuracy: $R^2 > 95\%$
Dopant distribution simulation

- Good simulation of LTA junction formation
- Good agreement between simulation and experience
- Model accuracy: $R^2 > 90\%$
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CONCLUSIONS

- **Objective**
  - Linking tool parameters to process
  - Model validation

- **Conclusions**
  - Good agreement between model and experiences in case of LTA time shift
    - Melt Depth
  - Good simulation of LTA junction formation
    - Diffusion & segregation

- **Perspectives**
  - Tool for process integration
  - Extend to other dopants
THANK YOU FOR YOUR THE ATTENTION !