Femtosecond-laser hyperdoping: controlling sulfur concentrations in silicon for band gap engineering

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Intermediate-band photovoltaics

Metal-insulator transition

Deep level high concentration

Winkler et al., PRL 106, 178701 (2011)
Ertekin et al., PRL 108, 026401 (2012)
Outline

• fs-laser doping
• controlling sulfur concentrations
• optical properties
Fs-laser doping

- fs laser
- scanning mirror
- chamber filled with SF$_6$
- Si wafer
Fs-laser doping
Fs-laser doping

![Graph showing wavelength vs. absorptance for crystalline silicon and fs-laser hyperdoped Si](image-url)
Fs-laser doping

- Doped region
- ~1% sulfur

Cross-sectional TEM (F. Génin, LLNL)
Outline

• fs-laser doping

• controlling sulfur concentrations

• optical properties

Si
S
S
controlling sulfur concentrations

Si substrate

fs-laser: 800 nm, 80 fs, 2.5 kJ/m²
controlling sulfur concentrations

$\text{SF}_6$ pressure (Torr)

vacuum

# of laser pulses

Si substrate

600 μm

1 2 4 6
controlling sulfur concentrations

Si substrate

SIMS
$\text{SF}_6$ 100 Torr

Carlson et al., J. Physics and Chemistry of Solids 8, 81 (1959)
controlling sulfur concentrations

SIMS
4 laser pulses

Carlson et al., J. Physics and Chemistry of Solids 8, 81 (1959)
controlling sulfur concentrations

Si substrate

![Graph showing sulfur dose vs. SF\textsubscript{6} pressure](image)

- **Sulfur dose (cm\textsuperscript{-2})**
  - $10^{-6}$
  - $10^{-5}$
  - $10^{-4}$
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$
  - $10^{4}$

- **SF\textsubscript{6} pressure (torr)**
  - $10^{-6}$
  - $10^{-5}$
  - $10^{-4}$
  - $10^{-3}$
  - $10^{-2}$
  - $10^{-1}$
  - $10^{0}$
  - $10^{1}$
  - $10^{2}$
  - $10^{3}$
  - $10^{4}$
  - $10^{5}$
  - $10^{6}$
  - $10^{7}$
  - $10^{8}$
  - $10^{9}$
  - $10^{10}$
  - $10^{11}$
  - $10^{12}$
  - $10^{13}$
  - $10^{14}$

- **# of laser pulses**
  - 1
  - 2
  - 4
  - 6
controlling sulfur concentrations

Si substrate

SIMS

# of laser pulses

sulfur dose (cm$^{-2}$)

$\approx 10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$ $10^{6}$ $10^{7}$ $10^{8}$ $10^{9}$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$

SF$_6$ pressure (torr)

$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$ $10^{3}$ $10^{4}$ $10^{5}$ $10^{6}$ $10^{7}$ $10^{8}$ $10^{9}$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$
Outline

• fs-laser doping

• controlling sulfur concentrations

• optical properties
Optical properties

fs-laser: 2.5 kJ/m² 50 pulses
SF₆ 1 & 10 Torr

Si:S

45° SEM

1 μm

Si substrate
Optical properties

\[ A = 1 - T_{\text{int}} - R_{\text{int}} \]

Absorptance vs. wavelength (µm)

- Black Si
- c-Si

Si substrate
Optical properties

\[ A = 1 - T_{\text{int}} - R_{\text{int}} \]

Si:Si substrate

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Absorptance</th>
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<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

SF\(_6\) pressure (Torr)
- Black Si
- 10
- 1
- c-Si
Conclusions

• Fs-laser doping
  • light trapping surfaces
  • non-equilibrium concentrations of S in Si

• Identify parameters for controlling dopant incorporation
  • non-linear response in pressure and # of laser pulses

• IR absorption correlates with pressure of the dopant precursor
Thanks!

Questions?
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