Femtosecond-laser microstructuring of silicon for novel photovoltaic devices

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Motivation

solar spectrum
Motivation

solar spectrum

![Graph showing the spectral irradiance of the solar spectrum. The graph displays the spectral irradiance in kW/m²/μm as a function of wavelength in μm. The peak spectral irradiance is labeled as 1353 W/m² at 0.4 μm.]
Motivation

solar spectrum

[caption]

![Graph showing solar spectrum with crystalline silicon band gap at 1.12 µm and 23% transparency of sun's energy.]

- c-Si band gap = 1.12 µm
- Crystaline silicon: transparent to 23% of sun's energy
- 1042 W/m²
current silicon-based solar cells cannot absorb all available energy

- c-Si band gap = 1.12 µm
- a-Si band gap = 0.71 µm

amorphous silicon: transparent to 53%
crystalline silicon: transparent to 23% of sun’s energy

Motivation
Outline

femtosecond-laser structuring process
material properties
solar cell results on crystalline silicon wafers
thin-film silicon results
outlook
Structuring process
Structuring process

SF$_6$ gas
100 fs
800 nm
Structuring process

SF₆ gas
100 fs
800 nm
Structuring process

- SF₆ gas
- 100 fs
- 800 nm

3 µm
Material properties
Material properties

absorptance: $A = 1 - (T + R)$
Material properties

absorptance: \[ A = 1 - (T + R) \]
Material properties

absorptance: \[ A = 1 - (T + R) \]
Material properties

absorbs nearly all incident light!
Material properties

why?

![Graph showing absorptance vs. wavelength (µm) for crystalline silicon and SF$_6$. The graph indicates that SF$_6$ has a higher absorptance across most wavelengths compared to crystalline silicon.](image-url)
Material properties

surface morphology?

![Graph showing absorptance vs. wavelength for SF$_6$ and crystalline silicon.](image)
Material properties

surface morphology?
Material properties

surface morphology?
Material properties

surface morphology?

![Graph showing absorptance vs. wavelength for different gases and crystalline silicon.](image)
Material properties

surface morphology?
Material properties

surface morphology?

![Graph showing absorptance vs. wavelength for different materials: vacuum, SF₆, Cl₂, air, H₂, N₂, crystalline silicon.](image)
Material properties

sulfur is the key

![Graph showing absorptance vs. wavelength for various gases and materials: vacuum, SF$_6$, Cl$_2$, N$_2$, H$_2$, air, crystalline silicon.](image)
Material properties
Material properties

surface layer
1.6% sulfur
polycrystalline

original substrate
Material properties

diodic junction forms across interface
diodic junction forms across interface
diodic junction forms across interface
Material properties

diodic junction forms across interface
Material properties

diodic junction forms across interface

thermal anneal
Material properties

diodic junction forms across interface

evaporate Cr/Au
diodic junction forms across interface
Material properties

diodic junction forms across interface

![Graph showing current vs. bias](image)

- Back bias: $V < 0$
- Forward bias: $V > 0$
Material properties

absorbs nearly all incident light (250 - 2500 nm)

can form p-n junction
Material properties

- Absorbs nearly all incident light (250 - 2500 nm)
- Can form p-n junction
- Great properties for solar cell!
Solar cell results
Solar cell results

illuminated $IV$ curve
Solar cell results

1.5% efficiency, a good beginning

remove V source, insert load

100 mW

1.5 mW

measure I

current (mA)

bias (V)

dark

illuminated

1.5% efficiency
Solar cell results

compare to current silicon-based solar cells

- single crystal: 25 – 28%
- polycrystalline: 14 – 15%
- thin-film: amorphous and microcrystalline: 8 – 10%
Solar cell results

thin-film: amorphous and microcrystalline 8 – 10%

-5
-10
-15
-20
0
1
2
3
4
5
-5
-10
-15
-20
0
1
2
3
4
5
bias (V)
current (mA)
dark
illuminated
1.5 mW
1.5% efficiency
advantages:

thin-film silicon is cheaper
Thin-film silicon

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has a similar structure to our microstructured layer
Thin-film silicon

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thin-film silicon is cheaper

has a similar structure to our microstructured layer

potential significant increase in efficiency of thin film silicon solar cells

our samples absorb nearly all sunlight after formation of layer < 1 µm thick
Thin-film silicon results

irradiation of amorphous silicon thin-film

![Absorptance of 2 μm thick a-Si vs wavelength (μm)]
Thin-film silicon results

Irradiation of amorphous silicon thin-film

- Absorptance vs. wavelength (µm)
- 2 µm thick a-Si
- After irradiation
- Deposited energy
Thin-film silicon results

irradiation of amorphous silicon thin-film

![Graph showing absorptance versus wavelength for 2 \( \mu \text{m} \) thick a-Si before and after irradiation, with an arrow indicating the deposited energy.](image-url)
Thin-film silicon results

irradiation of amorphous silicon thin-film

![Graph showing absorptance vs. wavelength for 2 µm thick a-Si after irradiation. There is an arrow indicating deposited energy.]
Outlook

manufacture solar cells from femtosecond-laser microstructured thin-film silicon
Summary

femtosecond-laser microstructured silicon:
absorbs nearly all incident sunlight
can be incorporated into a photovoltaic device
may increase efficiency of silicon thin film solar cells
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