Symmetry-Breaking in Light-Trapping Nanostructures on Silicon

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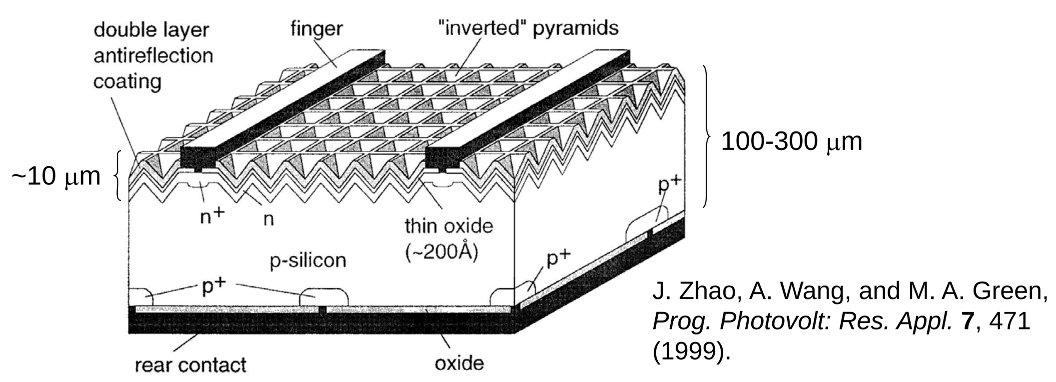
Introduction and Objectives

Light Trapping in Thick Silicon Solar Cells

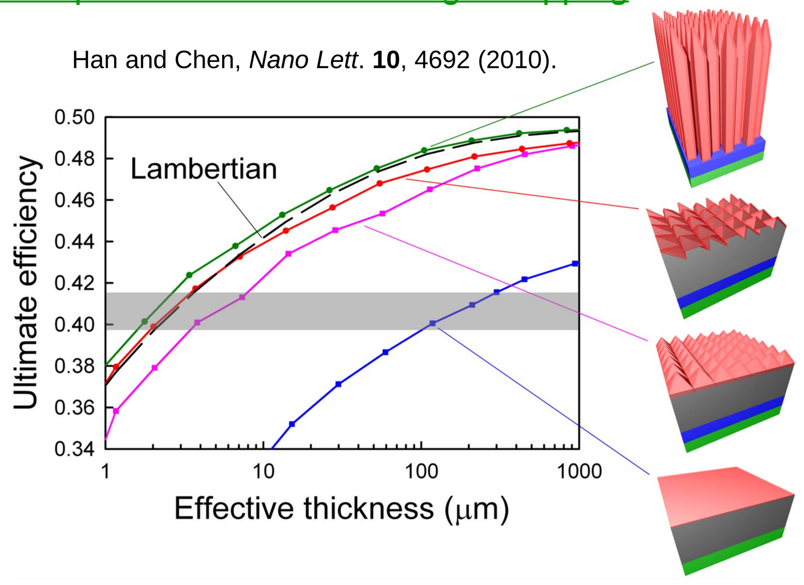


J. Zhao, A. Wang, and M. A. Green, *Prog. Photovolt: Res. Appl.* **7**, 471 (1999).

- Thick crystalline Si wafer accounts for about a half of the total module cost.
- Cost reduction can be achieved by thinning the Si wafer.
- As Si thickness decreases, absorption of sunlight becomes poor.
- Efficient light trapping of sunlight is required.

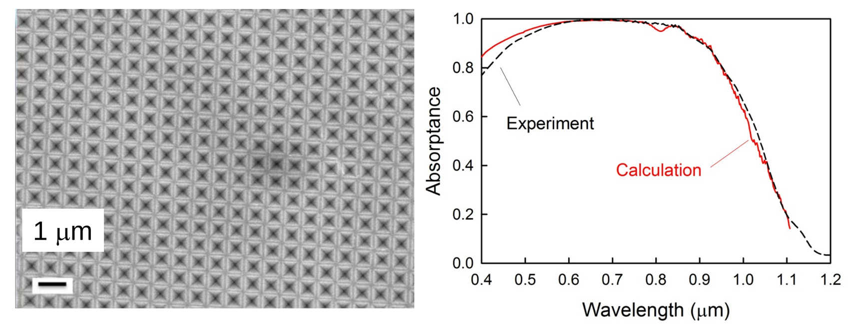
Submicron periodic structures for light trapping

Han and Chen, *Nano Lett.* **10**, 4692 (2010).



- Pyramidal submicron nanostructures are efficient in light trapping.
- Symmetry-breaking in the nanostructures can decrease the thickness by an order of magnitude at the same efficiency by achieving absorption close to the theoretical limit (Lambertian limit).

Previous Results for Inverted Nanopyramids



Mavrokefalos, Han, Yerci, Branham, and Chen, *Nano Lett.* **12**, 2792 (2012).

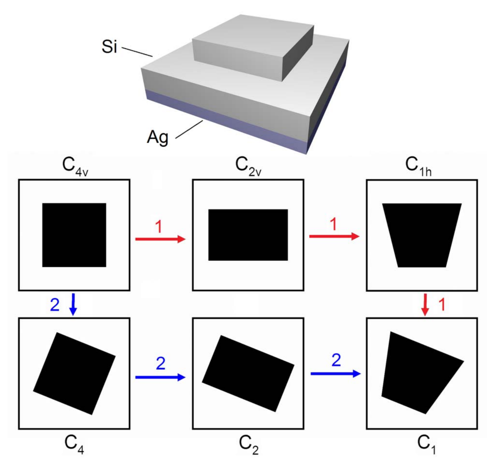
- Inverted nanopyramids are efficient in light trapping and can be fabricated on Silicon using simple wet etching.
- Absorption in experiment matched well with theory.
- Further absorption enhancement would require symmetry-breaking.

Objectives

- Elucidate the reason why low symmetry increases absorption by comparing numerical calculations with group theory.
- Realize low symmetry inverted nanopyramids on (001) Silicon surface in experiment.

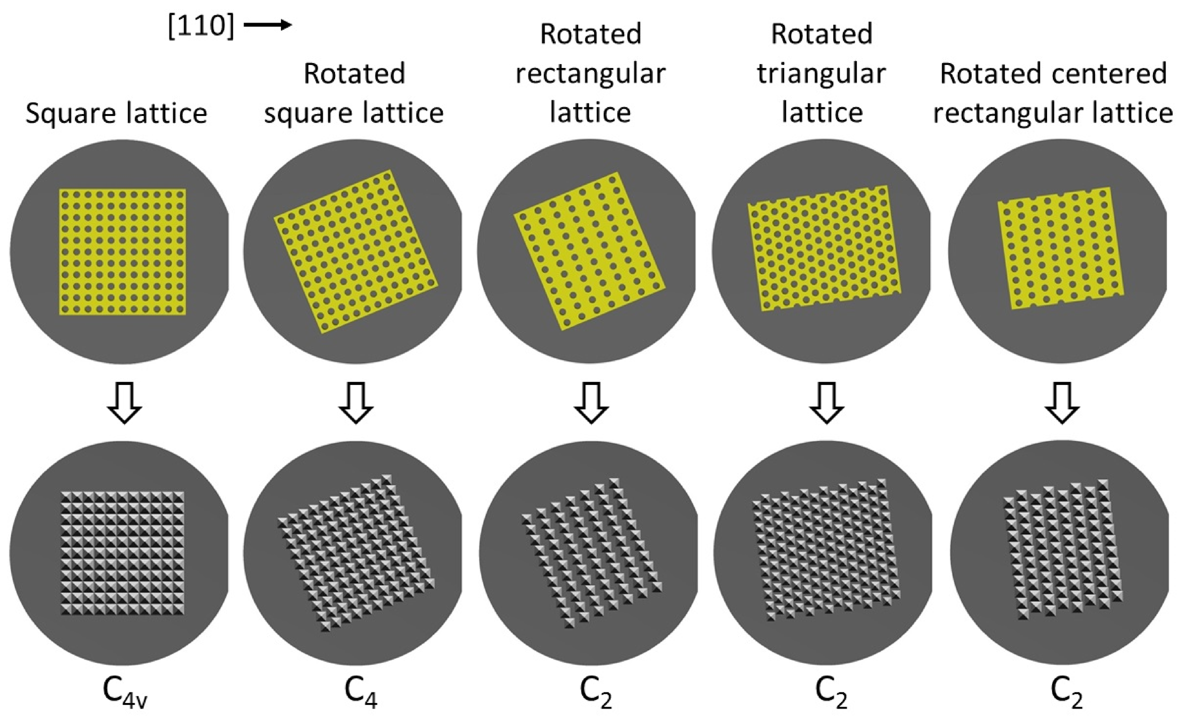
Methods

Symmetry Breaking Paths



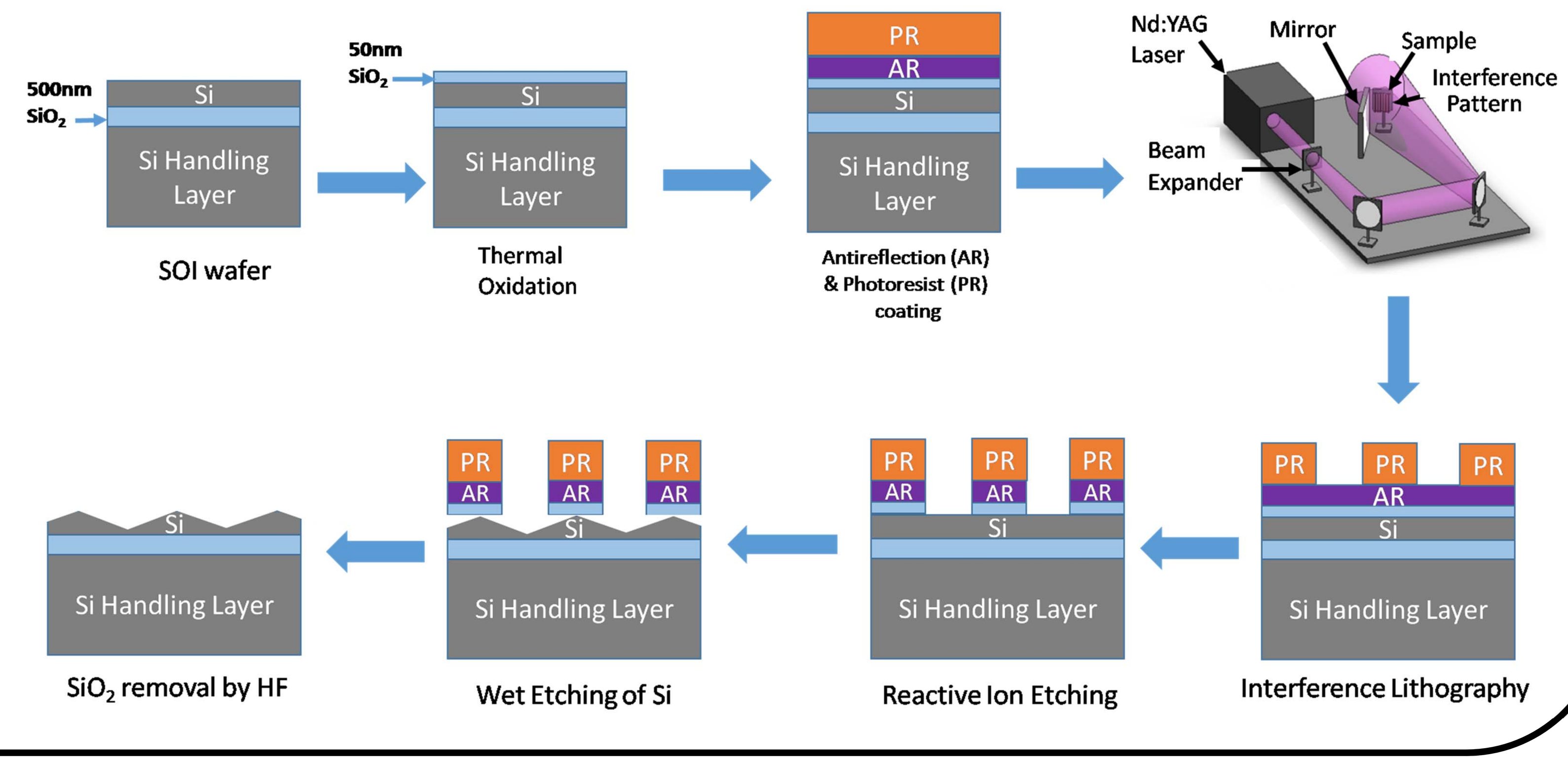
- Consider two symmetry-breaking paths in a square lattice.
- Count the number of peaks in λ=0.7-1.0 μm (unit cell 0.7 μm x 0.7 μm)
- Compare spectral average absorptance with the number of peaks

Symmetry Breaking in Inverted Pyramids



- Rotate the photoresist pattern with respect to [110] direction and perform wet etching.
- Lower symmetry photoresist pattern would lower the symmetry of the inverted pyramids.
- Low symmetry inverted pyramids that possess only 180º rotation symmetry (C_2) could be fabricated by this approach.

Fabrication Process Flow



Results and Discussion

Irreducible Representation

C_1	←	C_{1h}	←	C_{2v}	←	C_{4v}	→	C_4	→	C_2	→	C_1
A	←	A'	←	A_1	←	A_1	→	A	→	A	→	A
A	←	A''	←	A_2	←	A_2	→	A	→	A	→	A
A	←	A'	←	A_1	←	B_1	→	B	→	A	→	A
A	←	A''	←	A_2	←	B_2	→	B	→	A	→	A
$A+A$	←	$A'+A''$	←	B_1+B_2	←	E	→	E	→	$B+B$	→	$A+A$

Bright modes

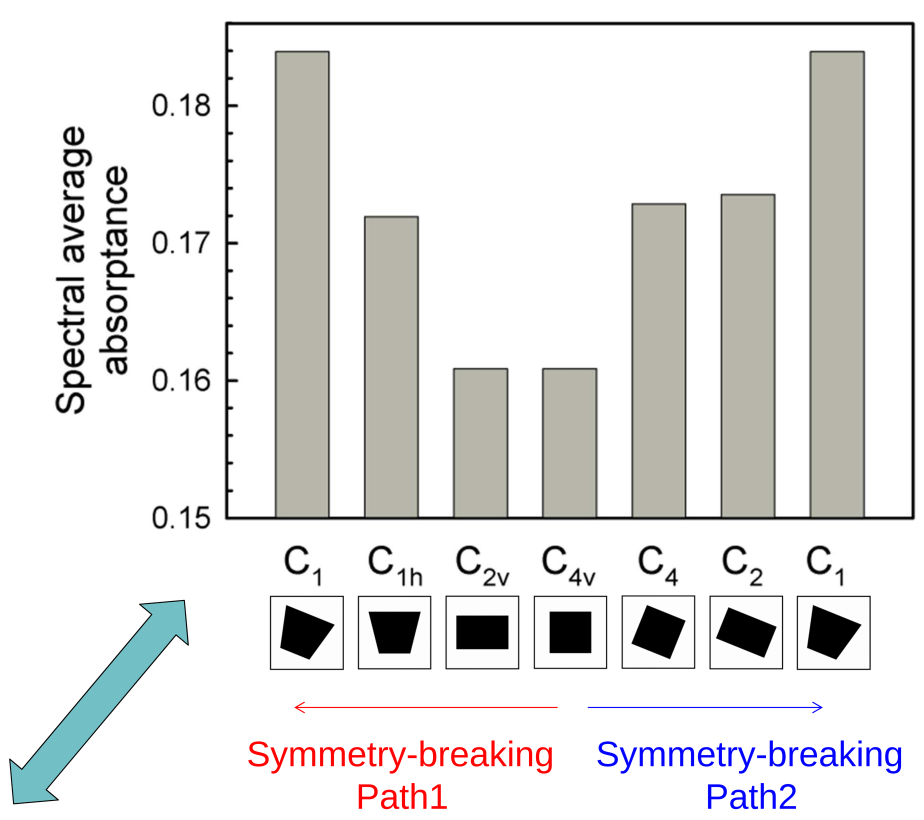
Dark modes

Number of peaks

Path1 ← → Path2

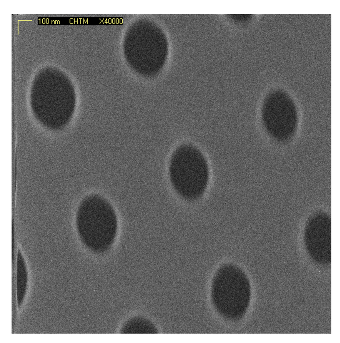
	C_1	C_{1h}	C_{2v}	C_{4v}	C_4	C_2	C_1
Vertical polarization	16	15	10	10	10	10	16
Unpolarization	20	19	14	10	10	15	20

Spectral average absorption

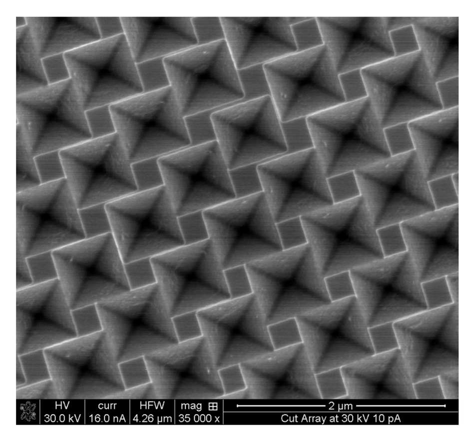


- For both paths, symmetry-breaking increases both the number of peaks and the spectral average absorptance

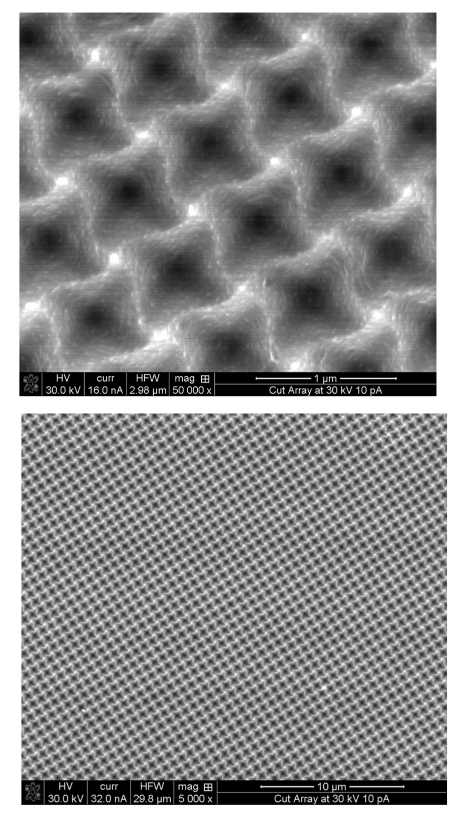
Symmetry breaking in inverted pyramids



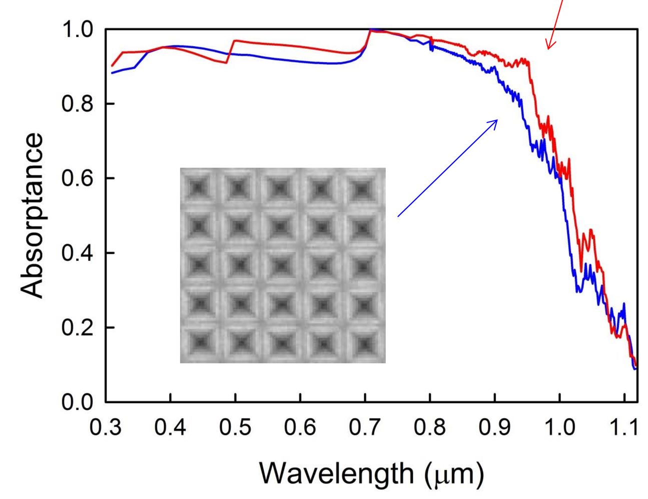
Photoresist pattern



KOH etching 1 min 45 sec
Isotropic etching 3 sec



KOH etching 1 min 45 sec
Isotropic etching 18 sec



- Rotate photoresist pattern by 22.5º.
- Wet etching created inverted pyramid with C_4 symmetry.
- Further isotropic etching removed unetched regions.
- Optical absorption was enhanced by this symmetry breaking.

Conclusion

- As the symmetry of light trapping structures is systematically lowered, the number of optical absorption peaks increases in a manner consistent with group theory.
- With symmetry-breaking, both the number of absorption peaks and the average absorptance increase.
- Symmetry breaking in general enhances the absorption integrated over a broad spectrum by increasing the number of resonant peaks.
- Symmetry breaking can be realized in inverted nanopyramids on (001) Si wafers by simple wet etching.
- Isotropic etching after anisotropic alkaline etching can remove unetched regions to enhance light trapping.
- Absorption increases by symmetry breaking in inverted nanopyramids.

Acknowledgement

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