Germanium: Low Cost, High Performance Solar Cells and Novel Photonics Devices

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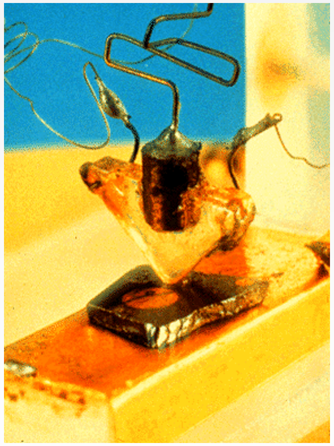
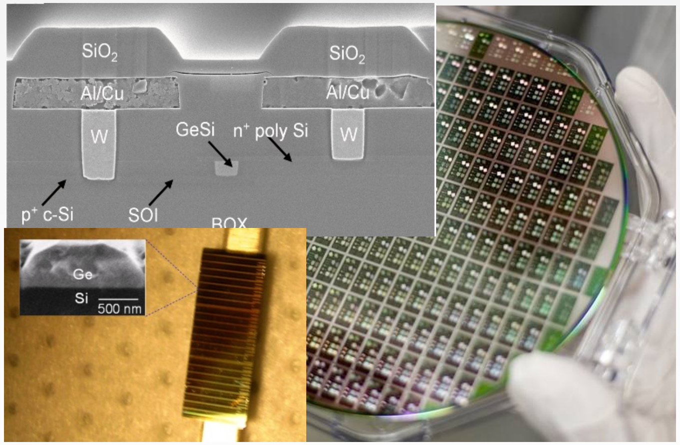
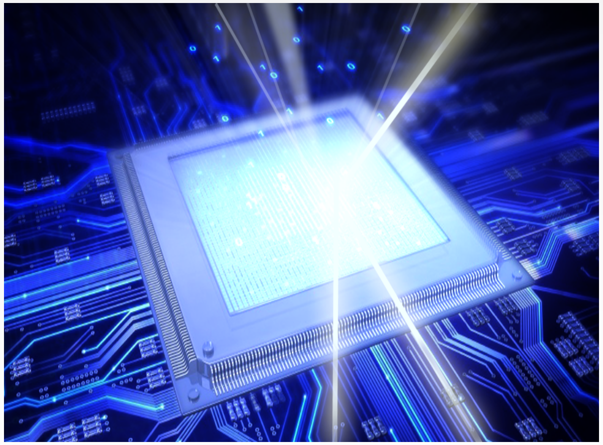
Microphotonics Center



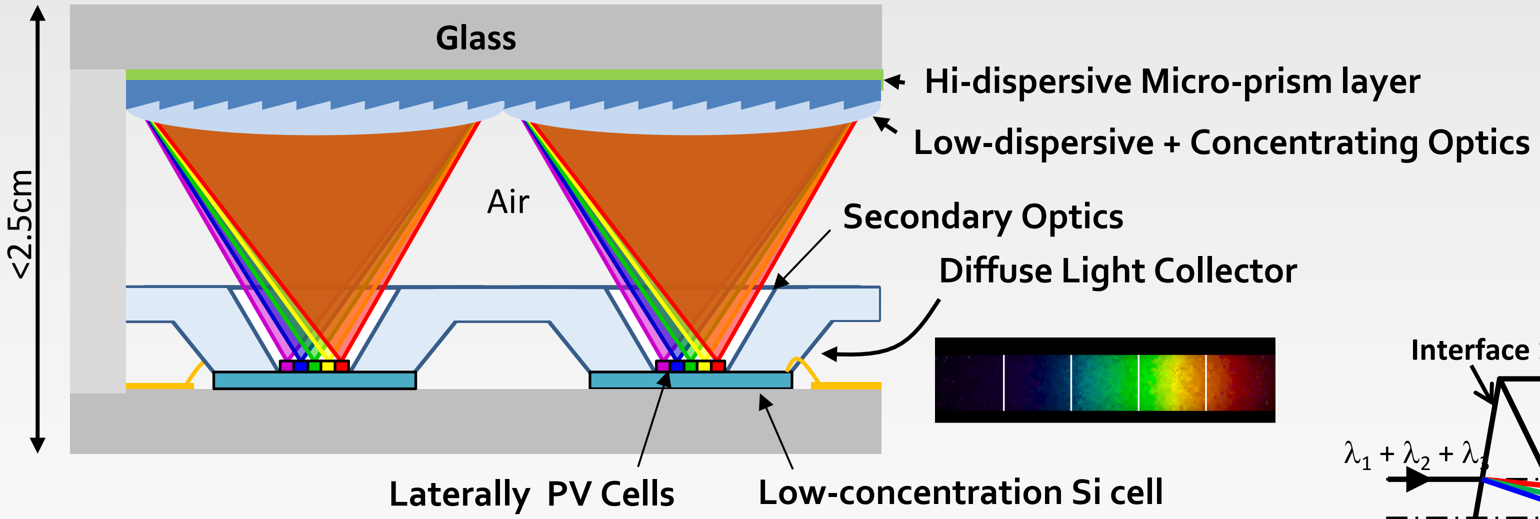


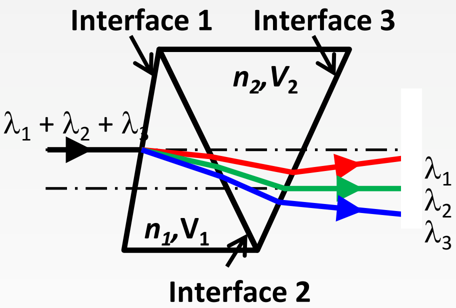


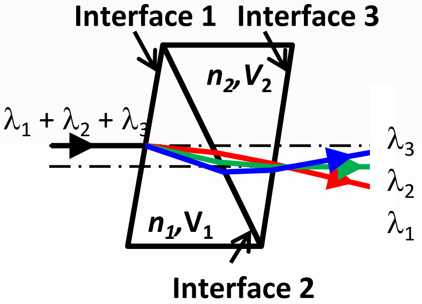
Outline

- ☐ Motivation
- ☐ Ge-on-Si Integration
- ☐ Threading Dislocation Reduction in Ge
- ☐ Ge Lateral Overgrowth
- ☐ Ge Photodetectors for BEOL Integration
- ☐ Conclusions

Dispersive Micro-concentrator Solar Cell Concept



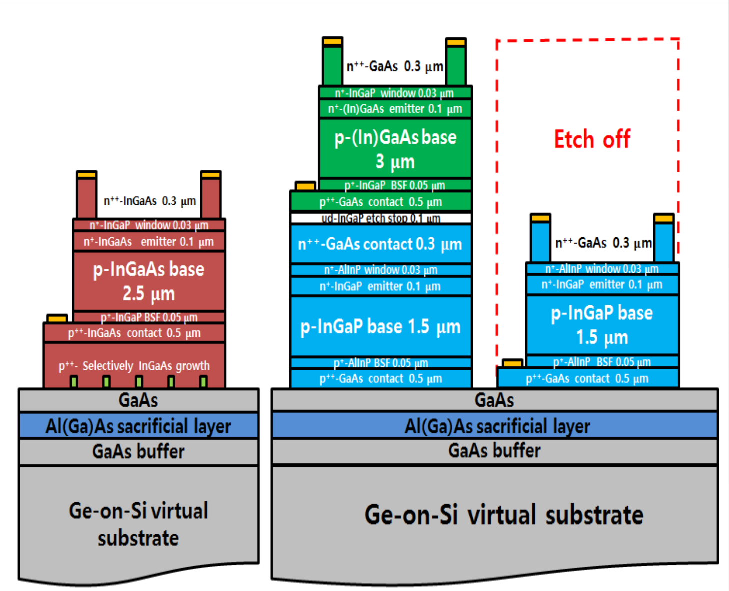


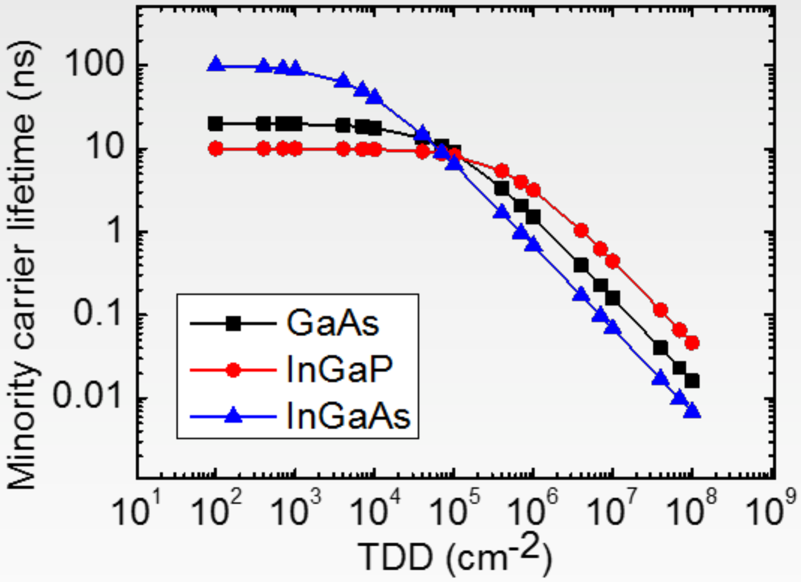


- *Hi-dispersion micro-prism array spectrally disperses DNI sunlight*
- *Low-dispersive micro-prism array cancels beam deviation but maintains dispersion*
- *Concentrating optics focuses light onto lateral multi-junction cells*
- *Secondary optic consists of a hollow reflective DNI concentrator and a solid diffuse concentrator*
- *Molded primary and secondary optical element arrays*
- *Compact micro-CPV: module thickness < 2.5cm*

MIT PIs: J. Michel, J.J. Hu, E.A. Fitzgerald, D. Perrault

Epitaxial Laterally Arrayed III-V Solar Cells



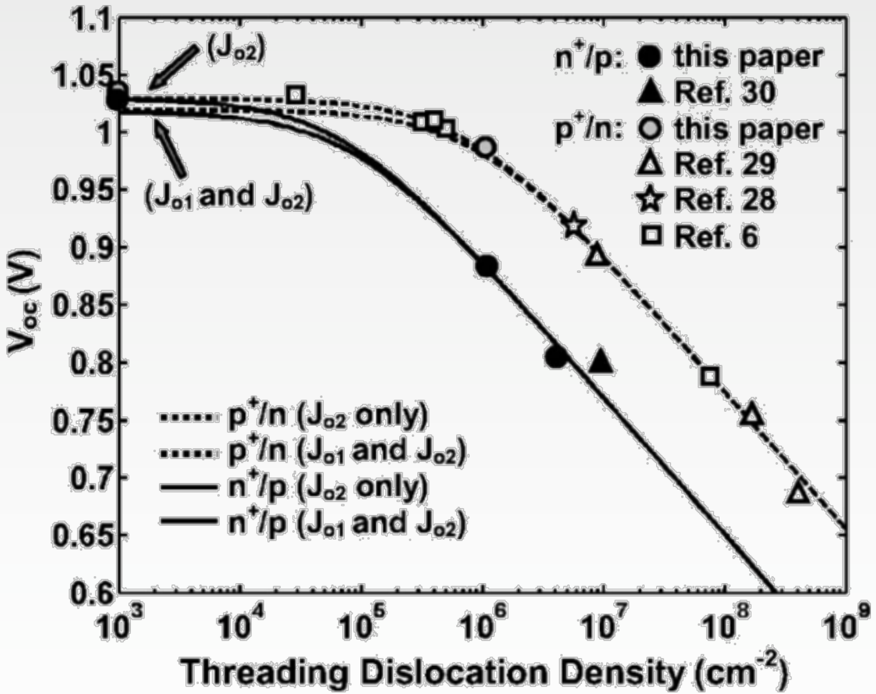


- Low-cost, high quality heteroepitaxy Ge-on-Si film
- Selective growth and lateral overgrowth to achieve below 10^6 cm^{-2} threading dislocation density
- High efficiency InGaP cells on Ge demonstrated

Threading Dislocation Reduction and Solar Cell V_{oc}

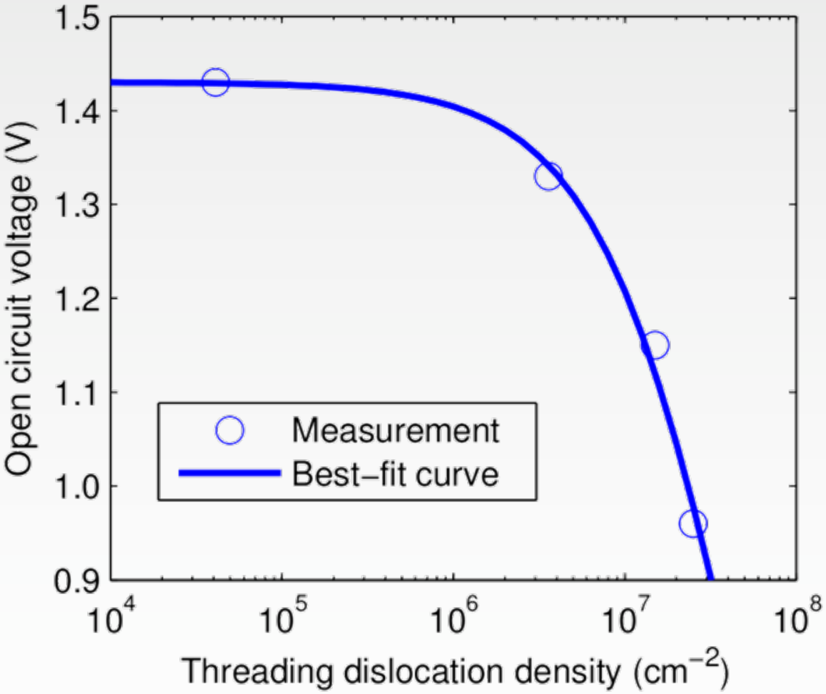
- Defect trap states from dislocations in GaAs and InGaP solar cells

GaAs



Andre, *et al*. J. Appl. Phys. **98** (2005)

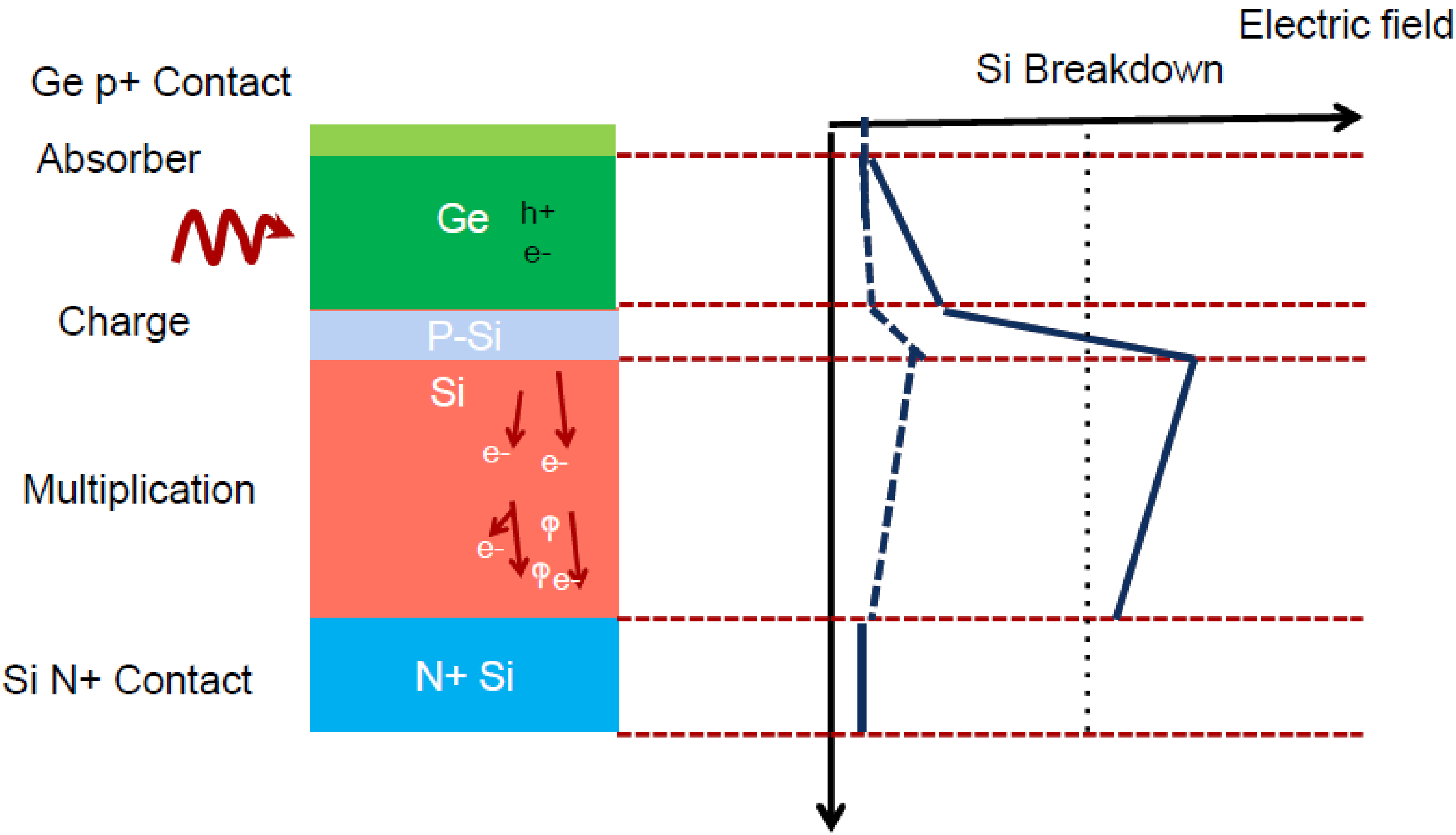
InGaP



Kim *et al*. submitted

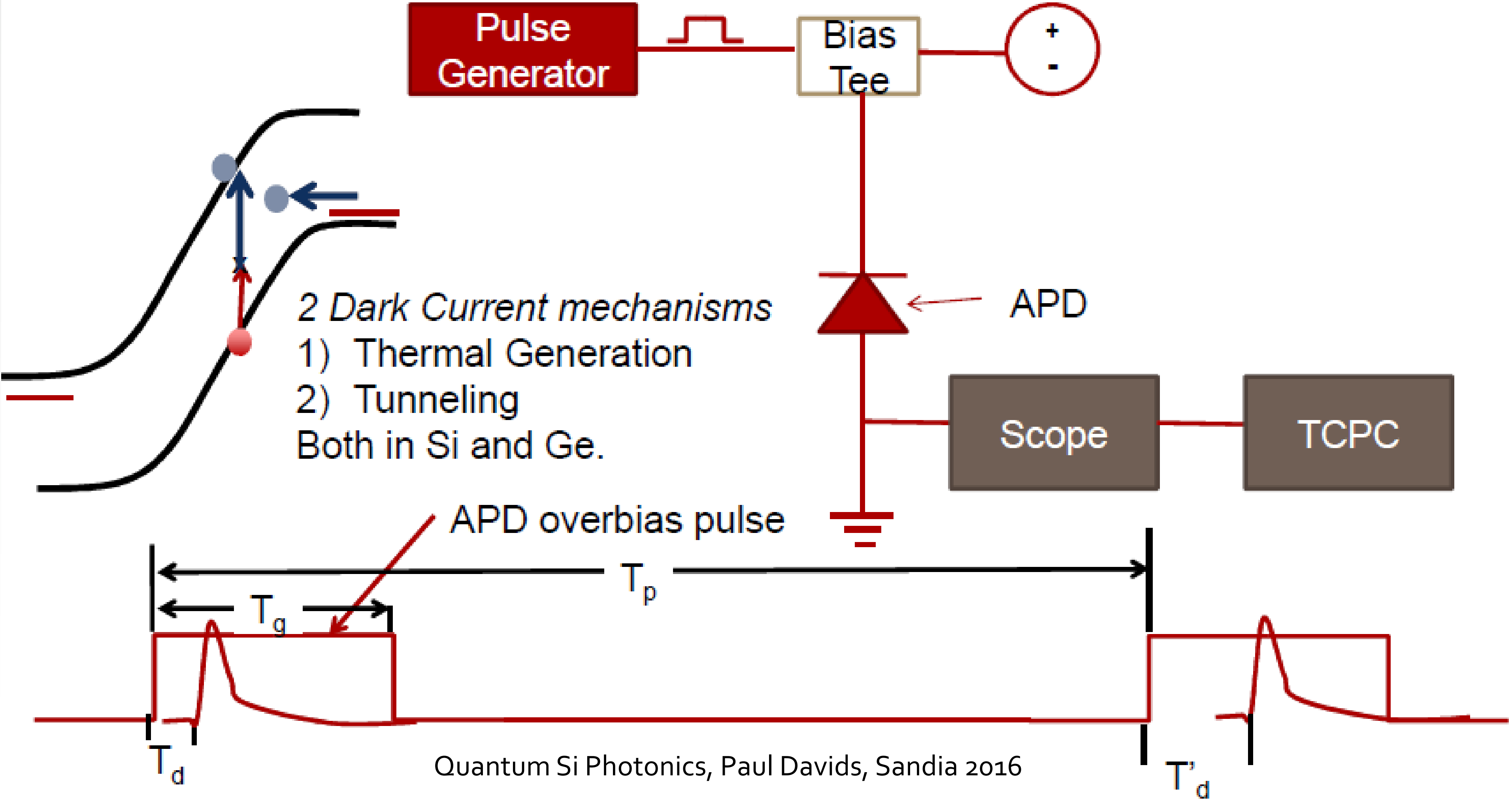
Target TDD < 10^6 cm^{-2}

Separate absorption and charge multiplication APD.



Quantum Si Photonics, Paul Davids, Sandia 2016

Dark Count Measurement

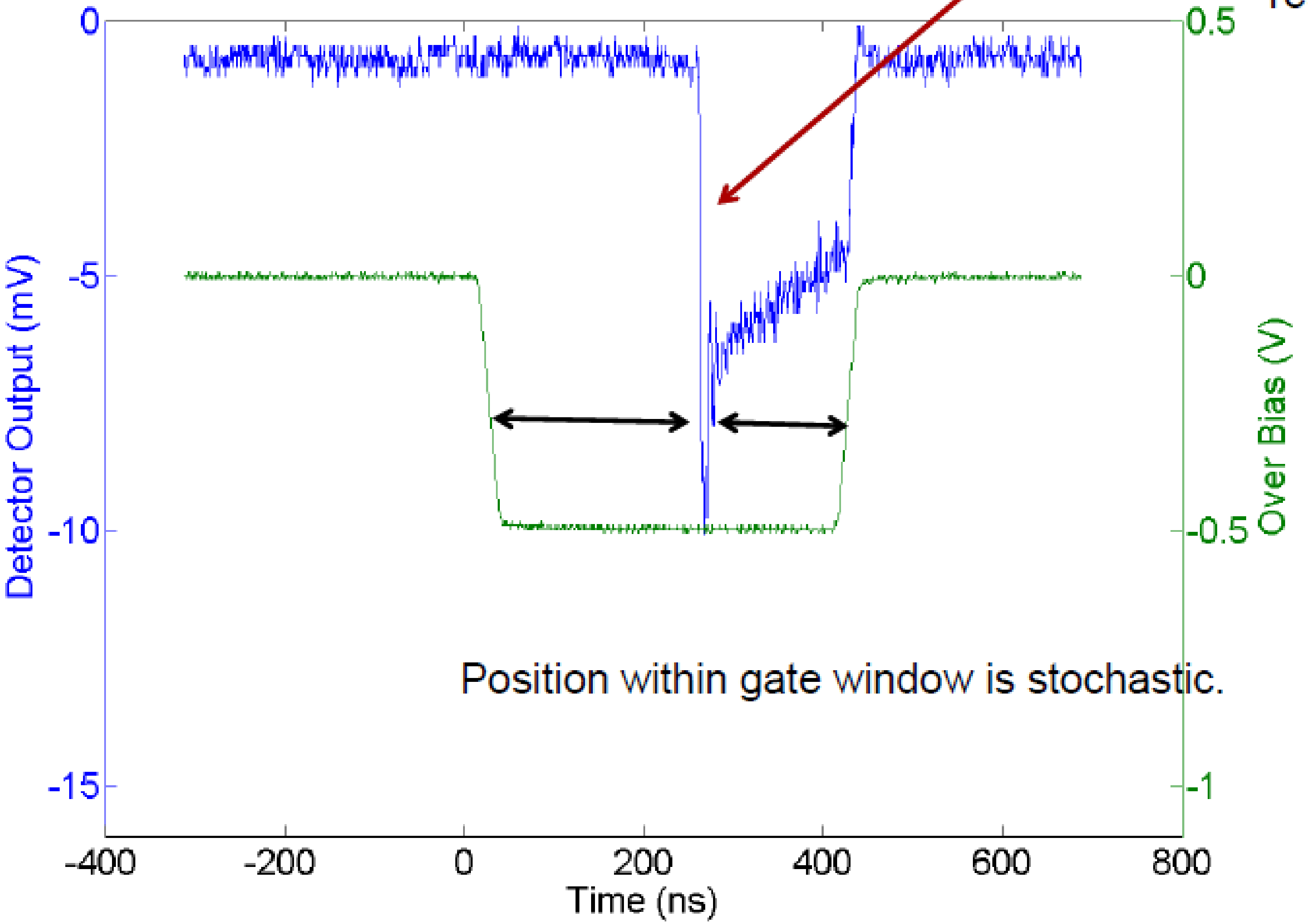


2 Dark Current mechanisms

1) Thermal Generation
2) Tunneling

Both in Si and Ge.

Measured Dark Counts



Dark count triggers Geiger response.

Position within gate window is stochastic.

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Ge Epitaxy on Si

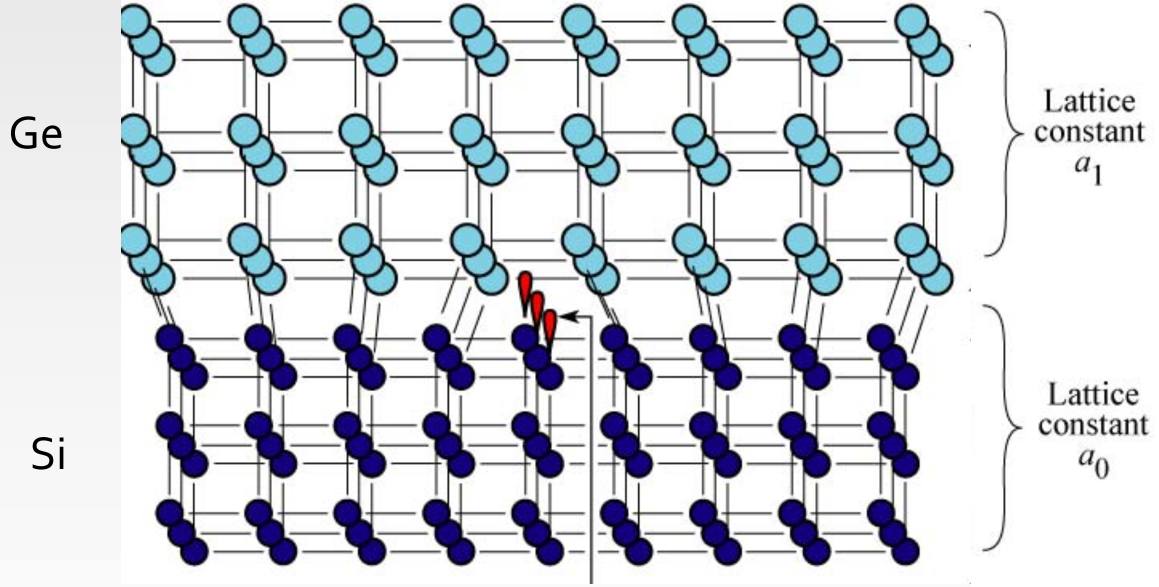
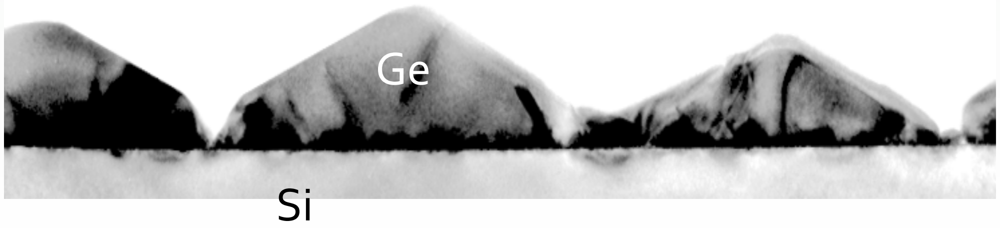


Fig. 7.12. Illustration of two crystals with mismatched lattice constant resulting in dislocations at or near the interface between the two semiconductors.

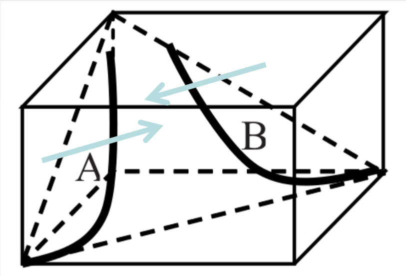
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

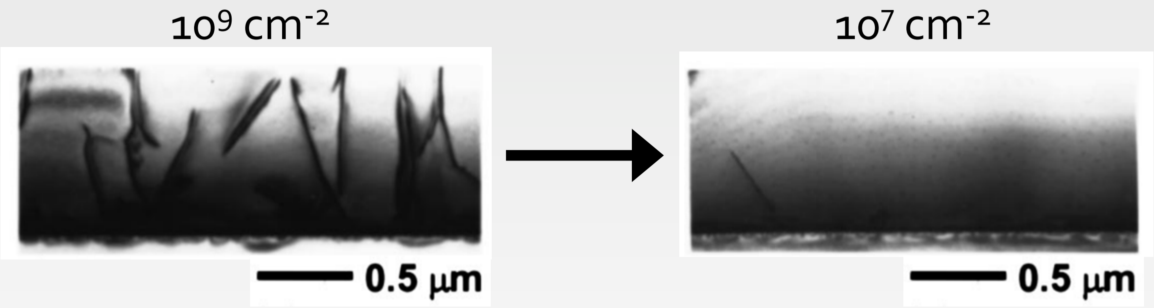


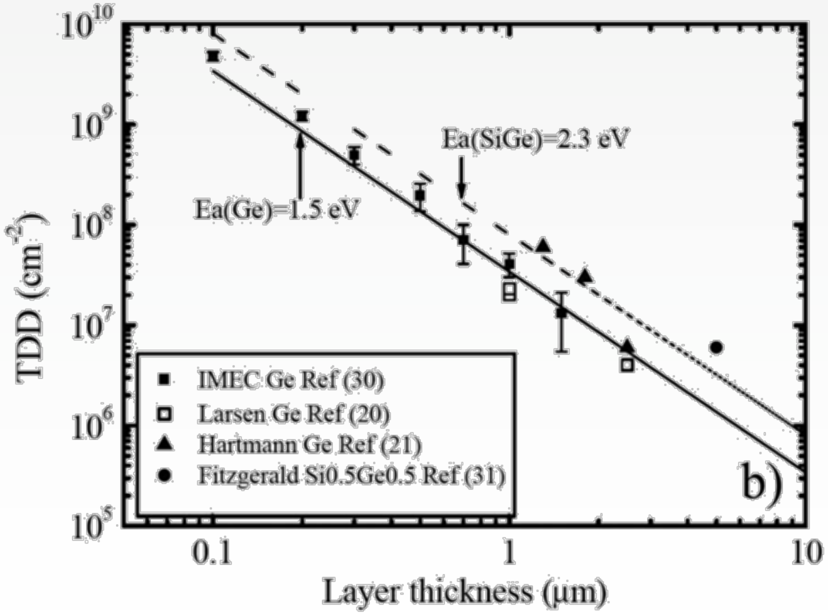
Ge epitaxial growth on Si at 550C

Limited TDD Reduction by Dislocation Reactions

Create thermal stress between Si/Ge to induce dislocation glide







Limitation to TDD reduction in blanket, thin Ge films

Loo, J. Electrochem. Soc. **157**, H13 (2010)
H.-C. Luan, *Appl. Phys. Lett.* **75**, 2909 (1999)
G. Wang, APL **94**, 102115 (2009)

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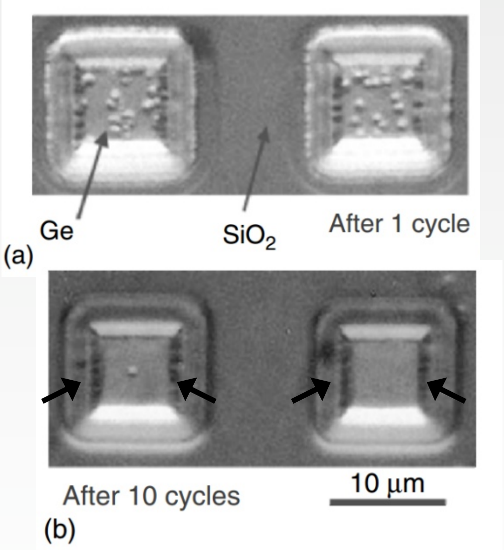
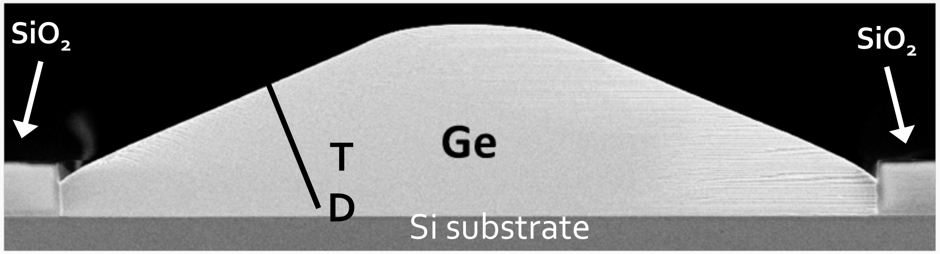
Limited TDD reduction in selectively-grown Ge

- Further dislocation reduction by introducing dislocation sinks
  - Selective chemical vapor deposition of Ge on Si between SiO_2 sidewalls
  - Threading dislocations leave film at edges
  - TDD in mesa center reduced to 2 x 10^6 cm^{-2} for 10 µm x 10 µm mesas

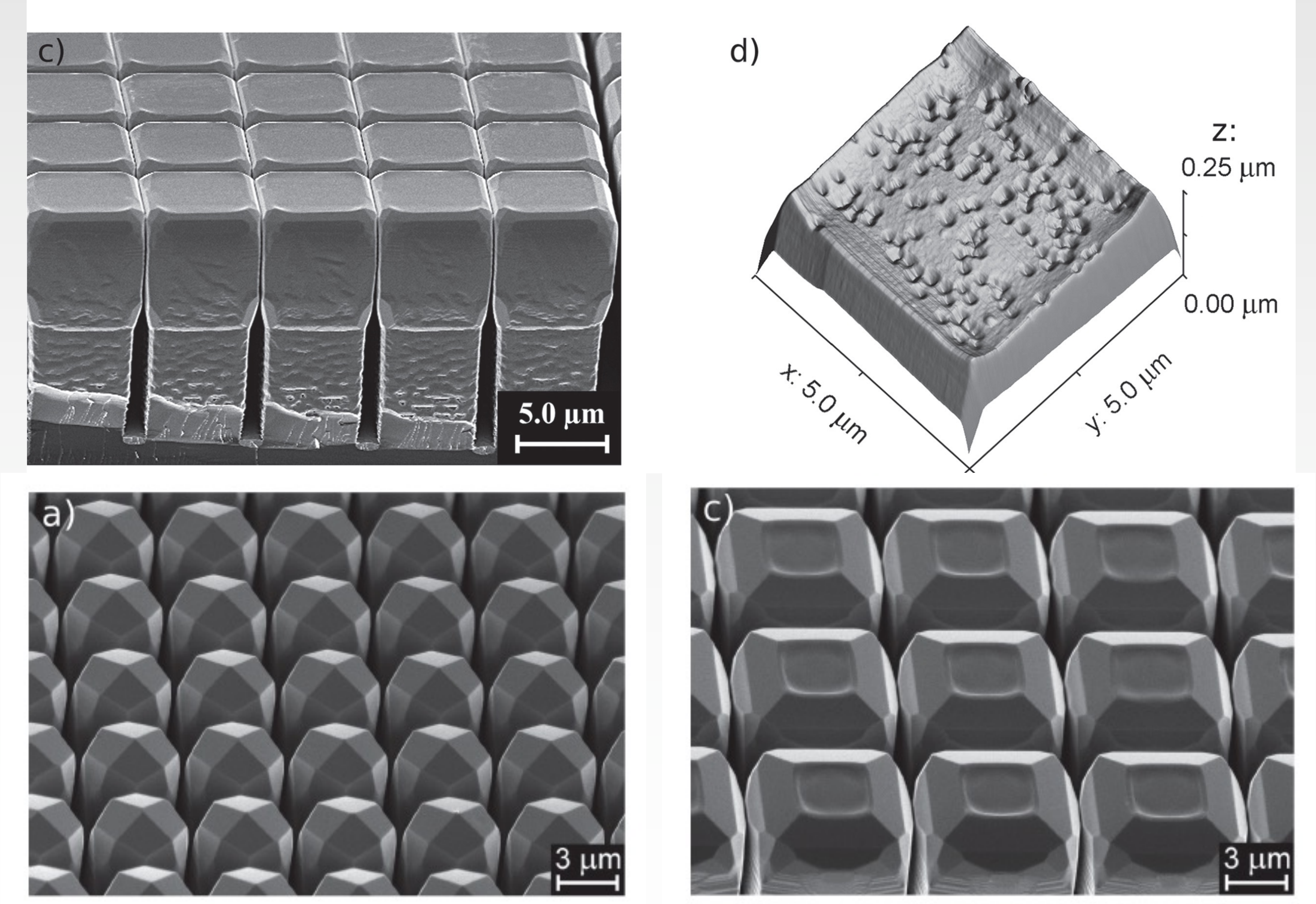




- Limitation to TDD removal by dislocation sinks
- Can Ge lateral overgrowth lead to low TDD Ge films?

H.-C. Luan, *Appl. Phys. Lett.* **75**, 2909 (1999)

Ge Lateral Overgrowth: Can it work?



A. Marzegalli et al. “Unexpected Dominance of Vertical Dislocations in High- Misfit Ge/Si(001) Films and Their Elimination by Deep Substrate Patterning”, *Adv. Mater.* **25**, 4408 (2013)

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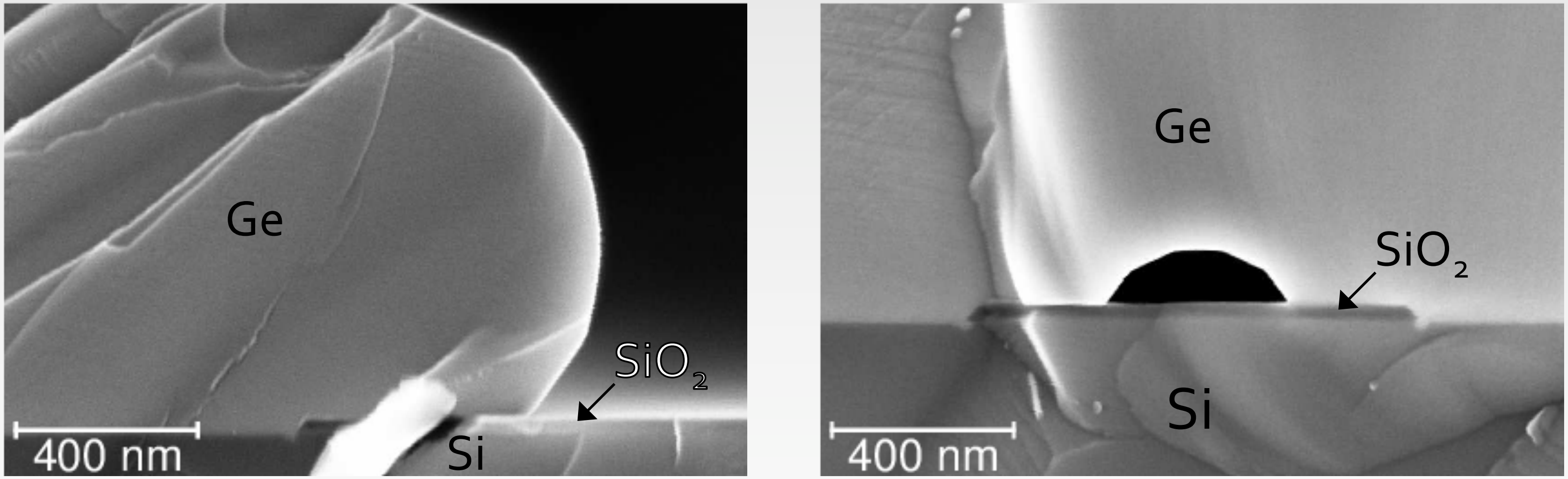
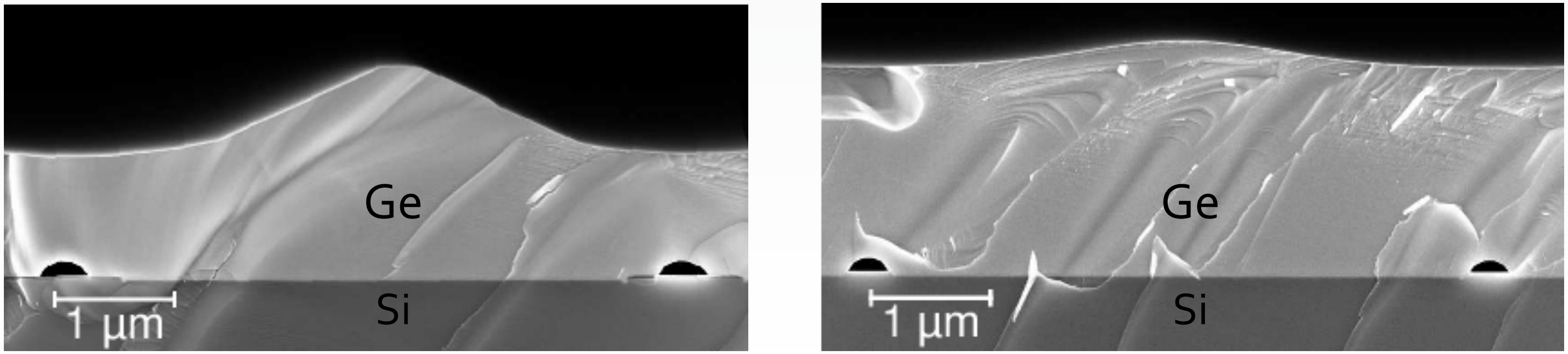
Lateral Overgrowth between Ge Strips

High Ge/SiO_2 surface energy: Reduced growth rates, voids



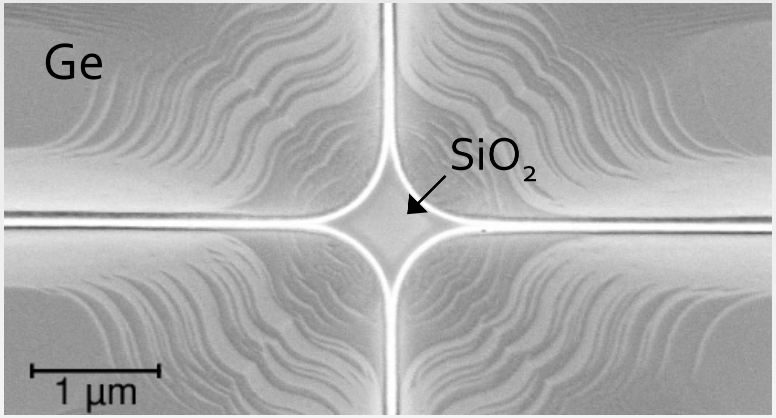
Once coalescence is complete, further growth self-planarizes

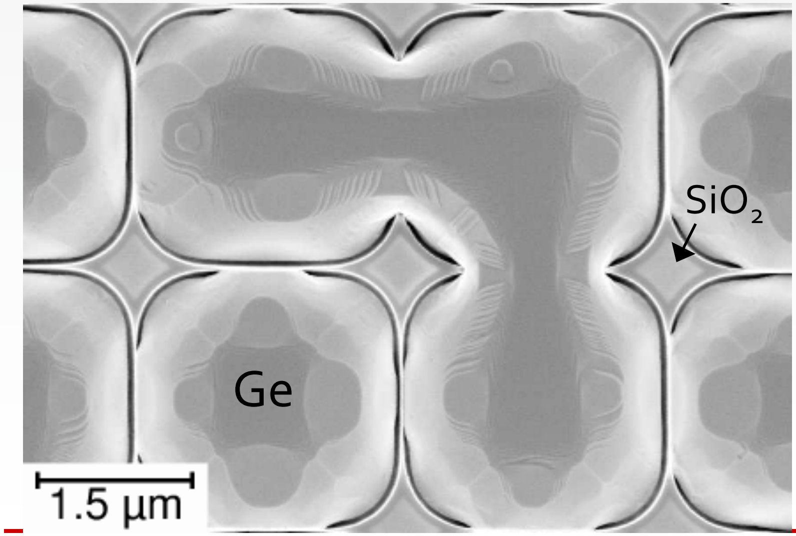


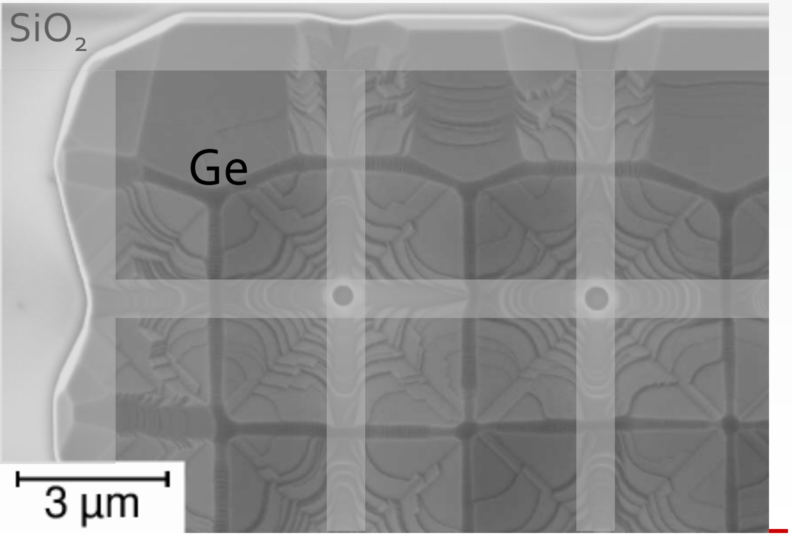
Delayed ELO from Ge Mesa Corners

- Film growth at mesa convex corners becomes bounded by slow growing facets

Complete film coalescence over mesa corners is severely delayed



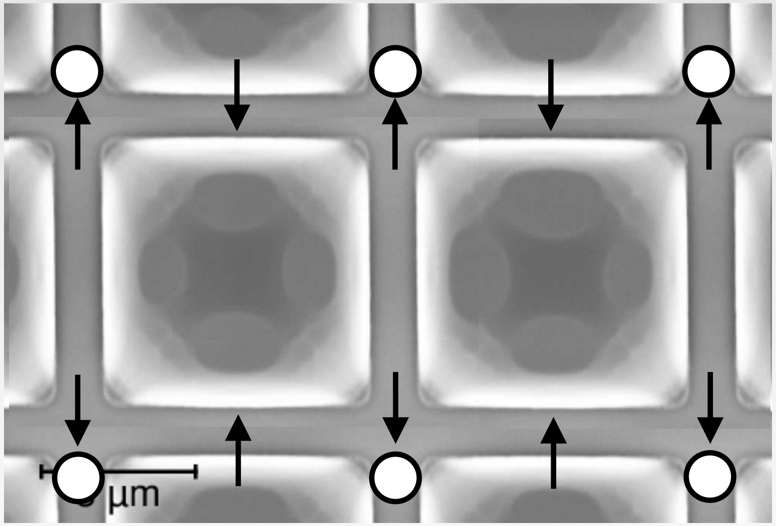


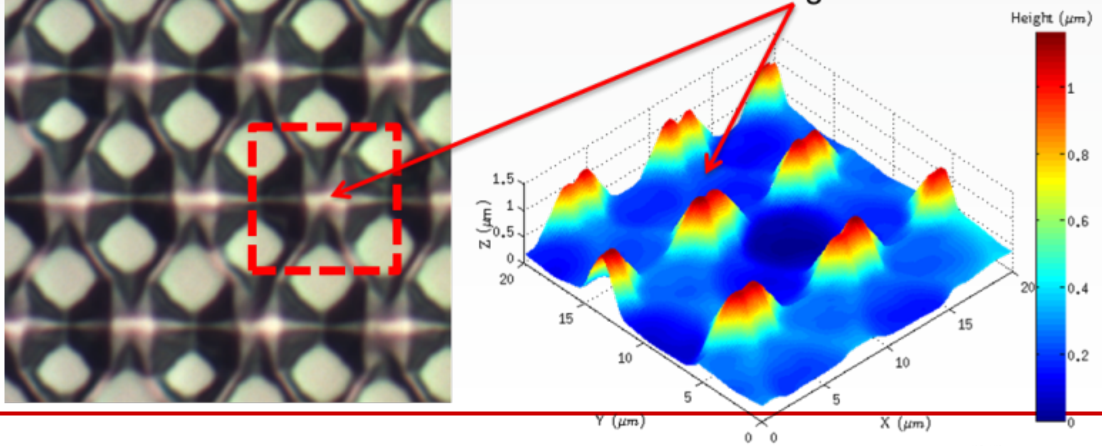


Increased Coalescence Rates in Staggered Grids

- Eliminate coalescence points entirely dependent on growth from convex mesa corners

Time required before complete coalescence reduced by > 50%

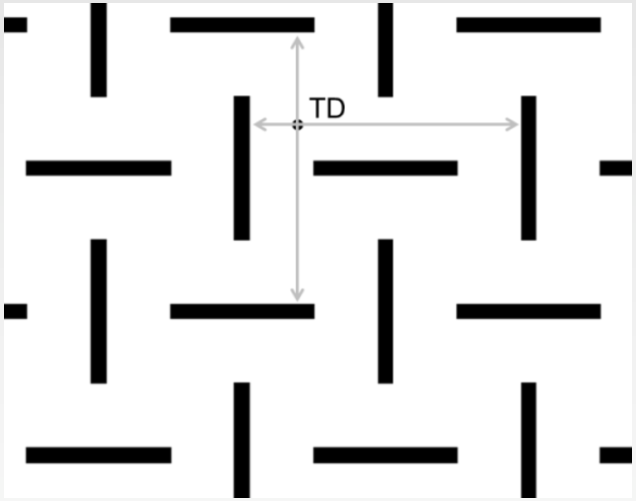


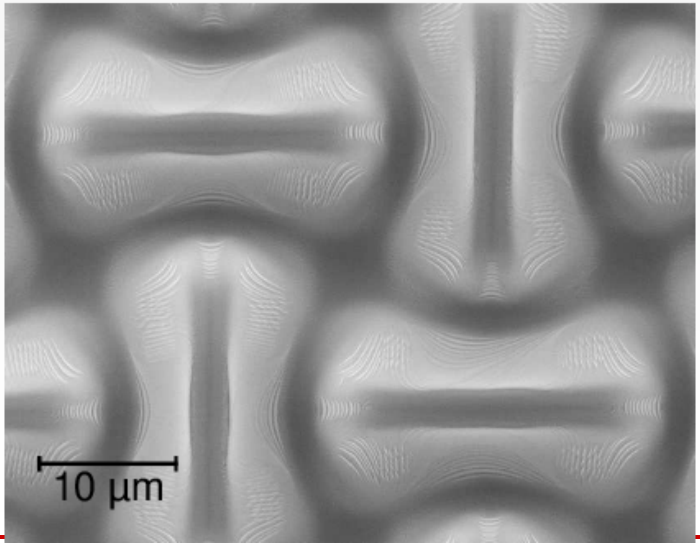

Center of original mesa

Accelerated ELO above Isolated Sidewall Lines

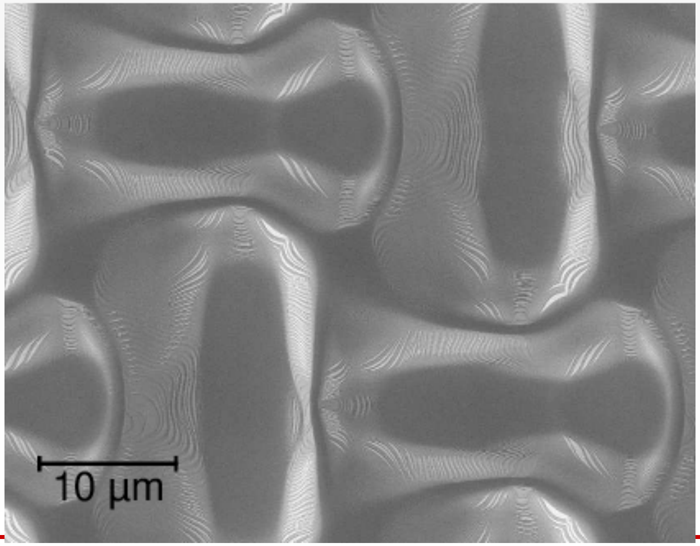
- Remove all convex corners
- Guarantee film edges for all threading dislocation to reach

Complete film coalescence occurs more readily due to concave Ge film perimeter





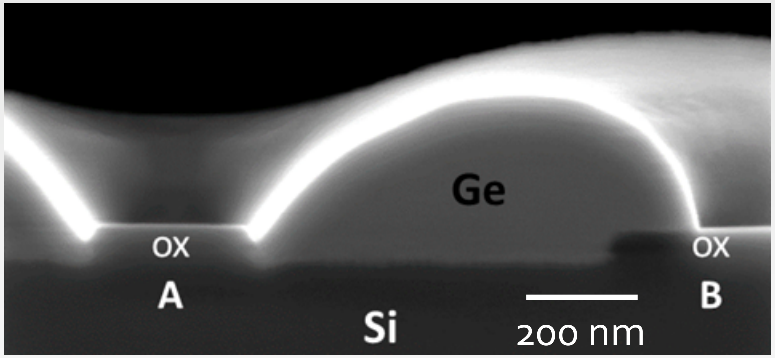
On-axis coalesced film

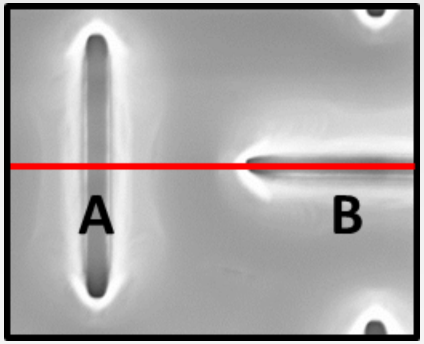


Off-axis coalesced film

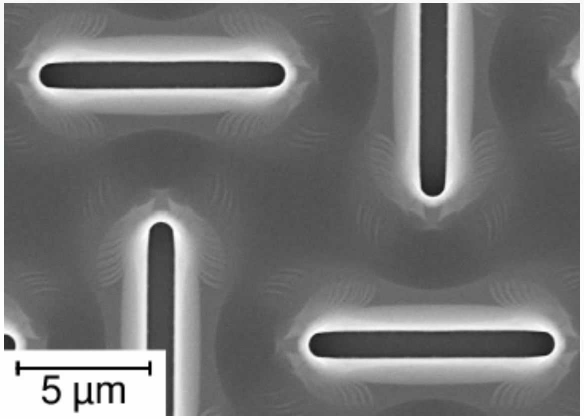
Increased Coalescence Rate for Narrow Isolated Lines

Overgrowth at zero and negative concavity Ge film perimeters

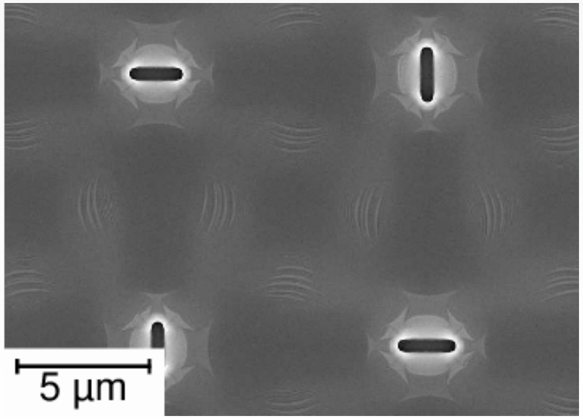




Accelerated coalescence increases for reduced line widths



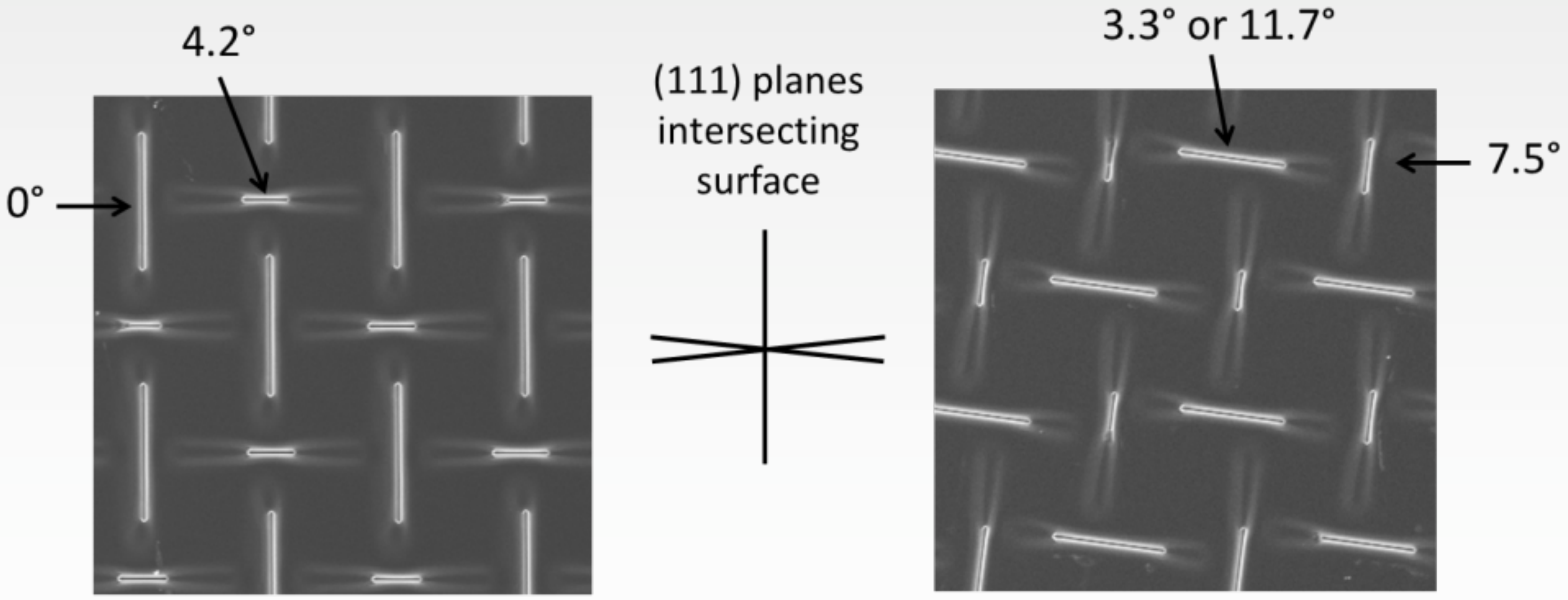
1.0 µm wide isolated SiO_2 lines



0.5 µm wide isolated SiO_2 lines

Optimal Sidewall Line Misorientation for Coalescence

ELO maximized for line orientations between 0° and 15° away from the intersection of {111} planes with the substrate surface

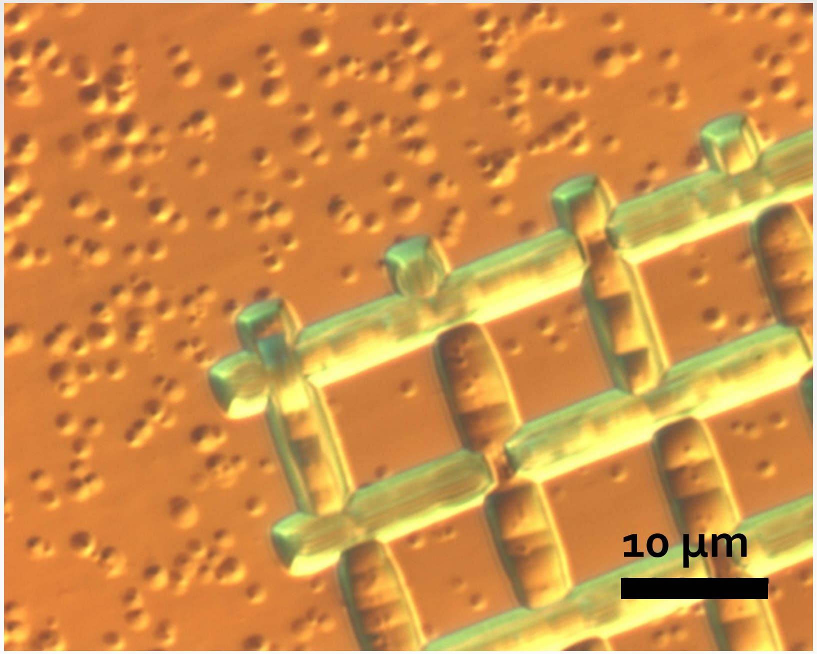


Aligned to <110>

Aligned 7.5° from <110>

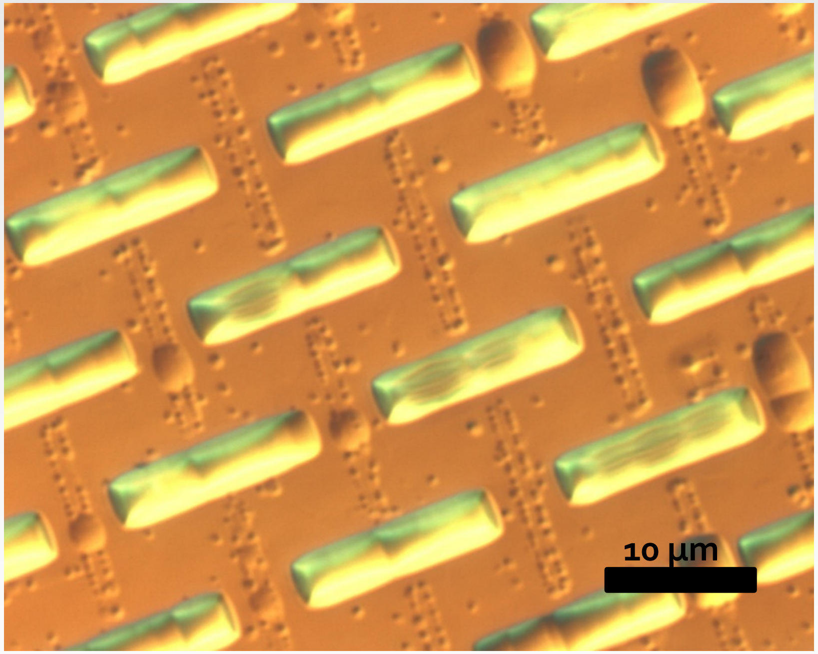
Optimal offset 5° to {111} surface intersection directions

Threading dislocation densities reduction for Ge-on-Si substrates



Optical microscope for Ge-on-Si, patterned and unpatterned Ge show significant difference in threading dislocation densities.

Patterned Ge: ~10^6 cm^{-2}



TDD can be reduced to below 10^6 cm^{-2} in small areas.
Lateral overgrowth should extend low TDD across entire wafer.

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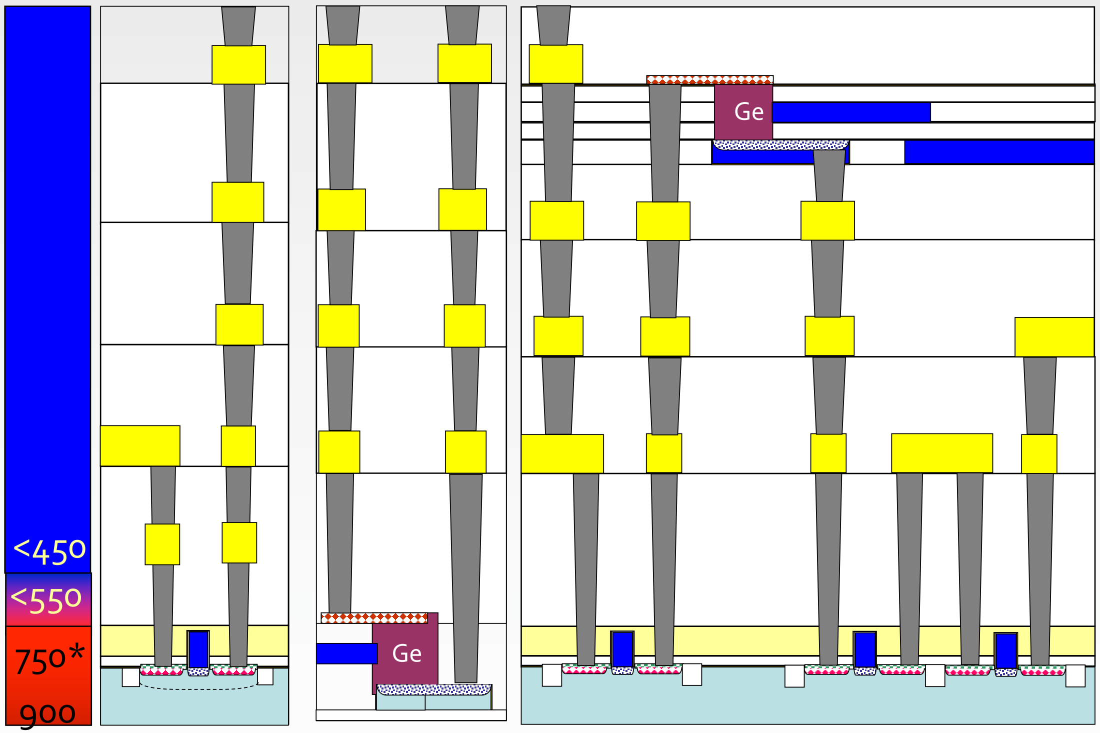
Electronic-Photonic 'CMOS'



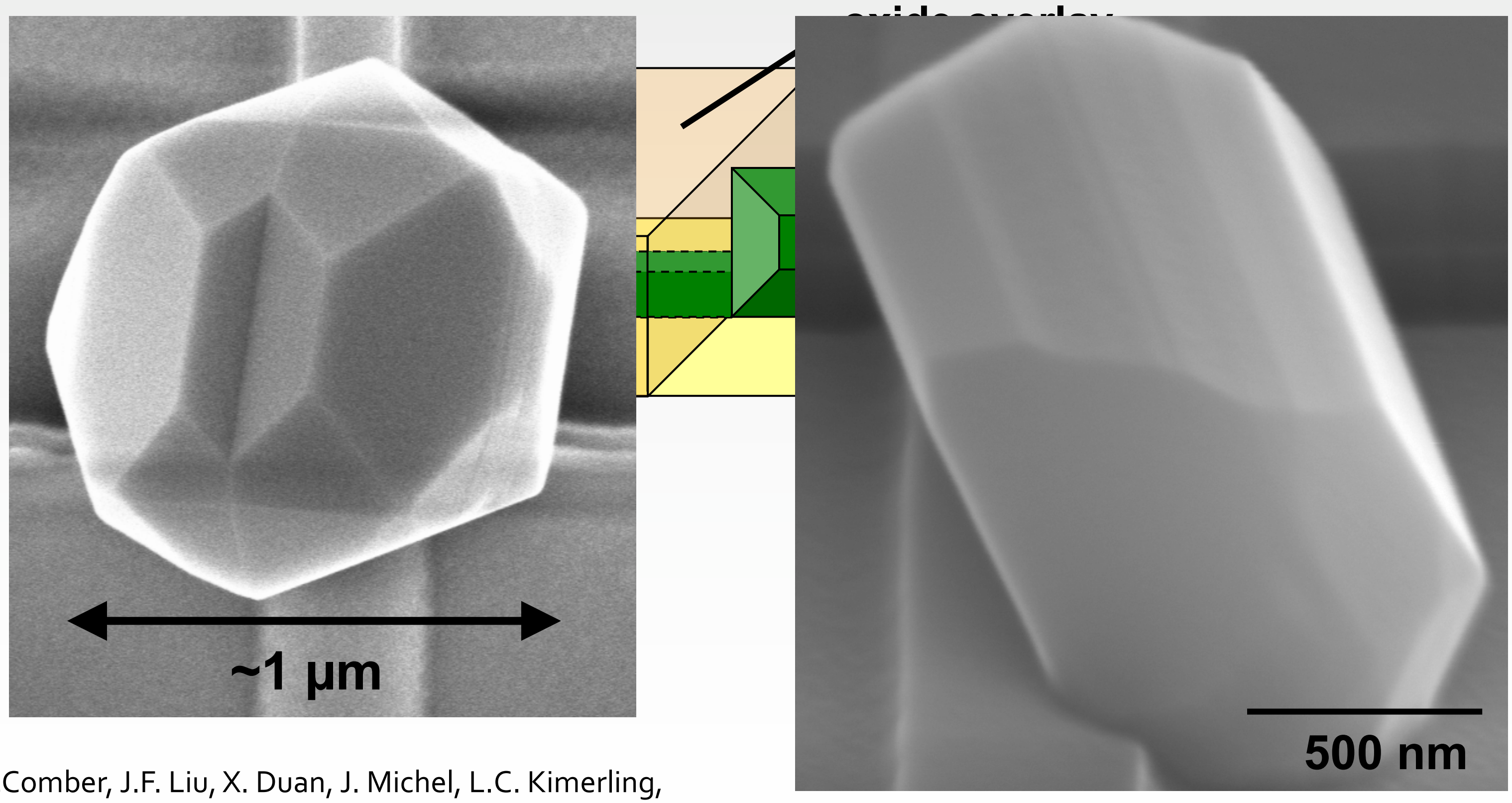
Si CMOS FEOL BEOL

Bulk Si SOI Bulk Si or SOI

Si FET **Photonic Integration Scenarios**

BEOL Single Crystal Ge Devices

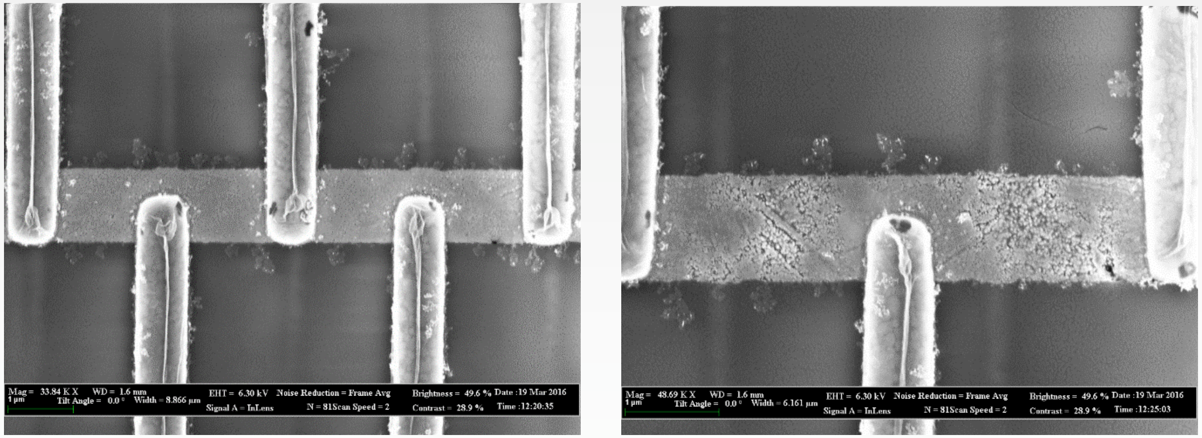
- Confine growth vertically AND laterally on amorphous Si
- Limit process temperature to 450C

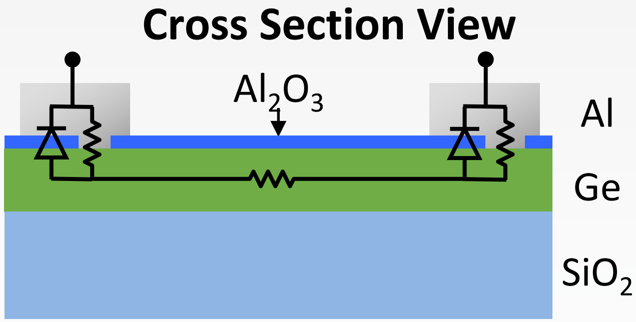


K.A. McComber, J.F. Liu, X. Duan, J. Michel, L.C. Kimerling, *Advanced Functional Materials* **7**, 1049 (2012)

Back-End MSM Photodetectors

- Structural damage from pre-metallization clean
- BEOL compatible Ge responds reacts differently to clean than epi-Ge

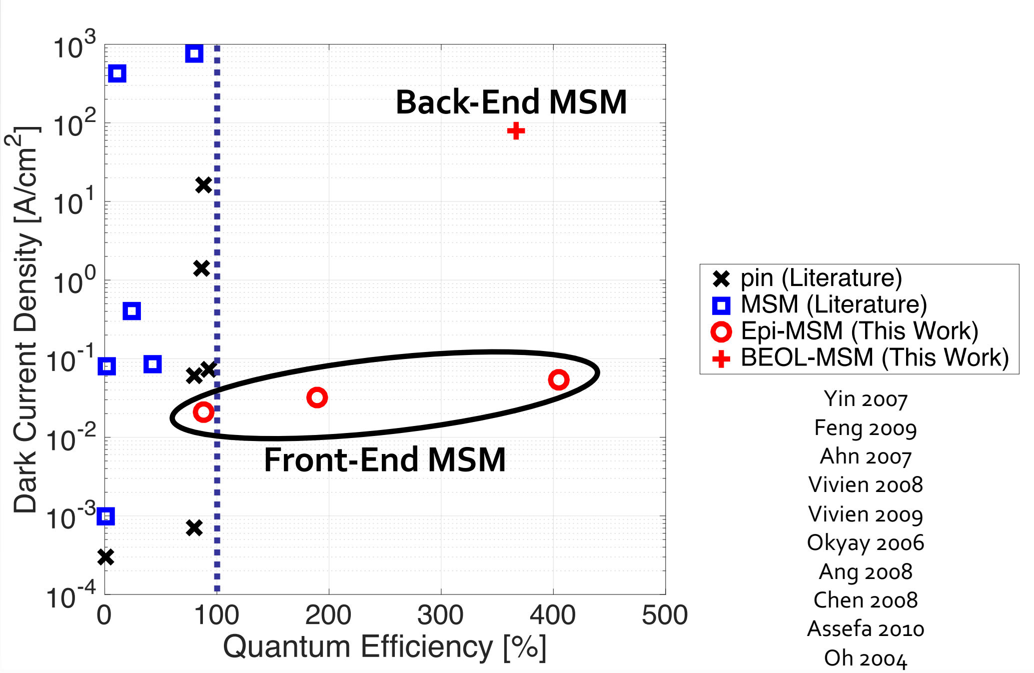




Chemical cleaning damages BEOL compatible Ge

Ge Photodetectors: Comparison with Literature

- State of the art detectors on crystalline Ge
- First device to demonstrate QE > 100%
- MSM on amorphous substrates exhibit potential, but need to decrease leakage current



Yin 2007
Feng 2009
Ahn 2007
Vivien 2008
Vivien 2009
Okyay 2006
Ang 2008
Chen 2008
Assefa 2010
Oh 2004
Bandaru 2004
Colace 2005

First device to demonstrate QE > 100%

Conclusions

- Low TDD Ge-on-Si has the potential to enable novel devices and low cost substrates for III-V materials and devices.
- Ge-on-Si based III-V solar cells will reduce cost by at least 10x.
- Ge single photon detectors for room temperature operation in the near IR are possible.
- High performance Ge BEOL photodetectors are viable for low temperature processing.

Contributors

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