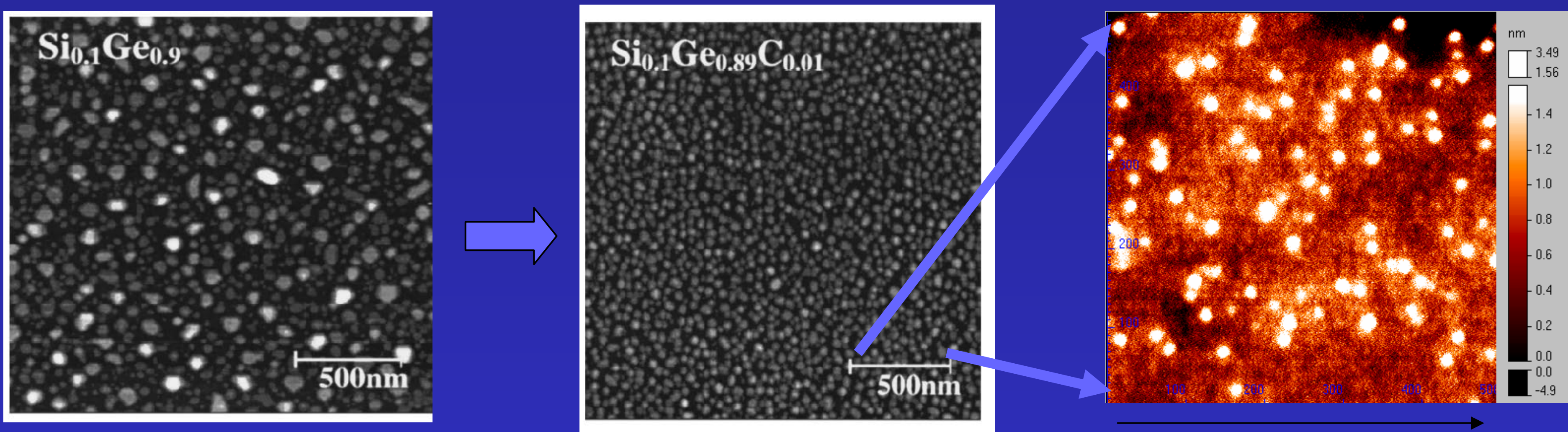
Photoluminescence of Silicon-Germanium Quantum Dots



500 nm

SiGe quantum dots grown by MBE on Si substrate with self-organization;
(left): conventional dots;
(mid): uniform dots by adding carbon
(right): SiGe dots ~20 nm in diameter grown at UD

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Arizona Nanotechnology Cluster Symposium
10 April, 2008

Delaware Location

Newark, Delaware is near Philadelphia –

Newark is about 50 Km from Philadelphia International Airport

not to be confused with Newark, New Jersey, located near New York City!

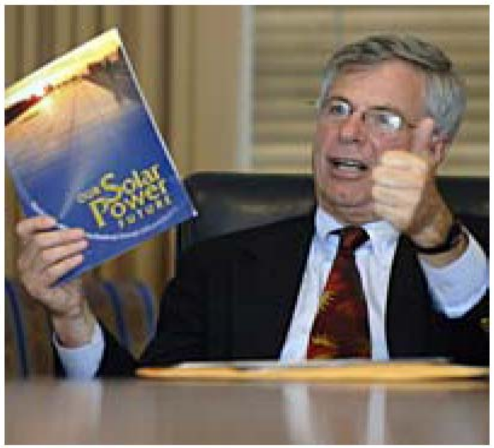
AILY

OF DELAWARE

ni | UDaily-Parents

UD to lead $53 million solar cell initiative

4:28 p.m., Nov. 2, 2005--A broad consortium led by the University of Delaware could receive nearly $53 million in funding--with the bulk of the money coming from the Defense Advanced Research Projects Agency (DARPA)--to more than double the efficiency of terrestrial solar cells within the next 50 months.

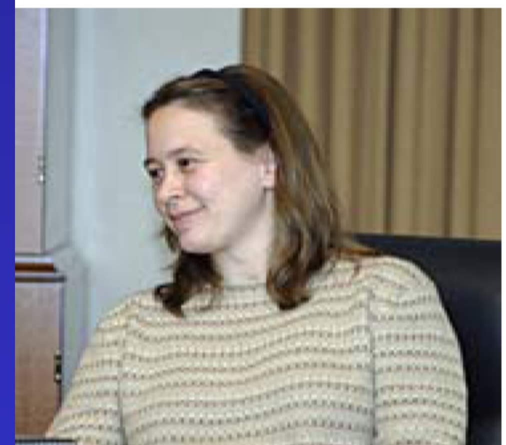


Allen Barnett, principal investigator and research professor in UD's Department of Electrical and Computer Engineering: "This project requires the consortium to invent, develop and transfer to production this breakthrough solar cell. One rarely gets an opportunity such as that."

The University's Consortium for Very High Efficiency Solar Cells, which consists of 15 universities, corporations and laboratories, could receive up to $33.6 million from DARPA, if all options are awarded, and another $19.3 million from UD and corporate team members. Those corporate members may include DuPont, BP Solar, Corning Inc., LightSpin Technologies and Blue Square Energy.

The consortium is being led by Allen Barnett, principal investigator and research professor in UD's Department of Electrical and Computer Engineering, and Christiana Honsberg, co-principal investigator and UD associate professor of electrical and computer engineering.

Univ. of Delaware DARPA funded solar energy center



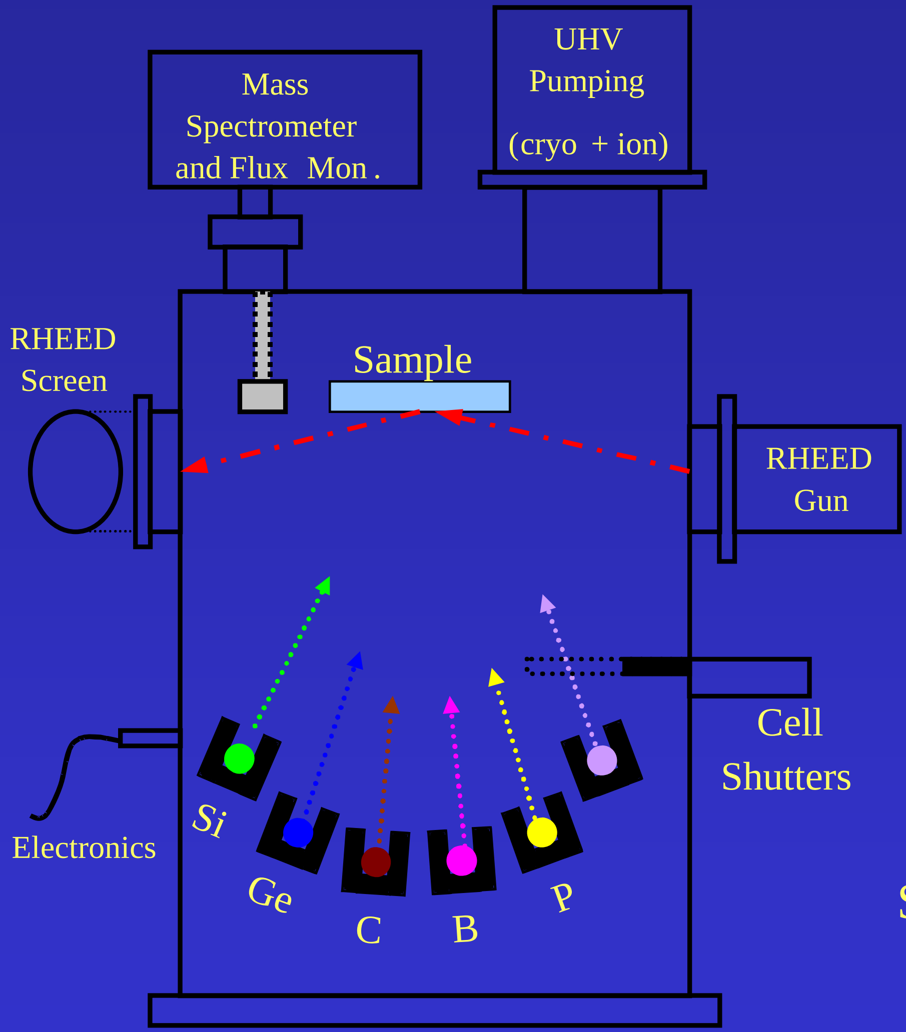
To achieve high efficiency in less than five years at low cost, Barnett and Honsberg have proposed using a new very high performance crystalline silicon solar cell platform and then adding multiple innovations. They had been working on very high efficiency solar cells long before learning of the DARPA program.

VHESC Program:

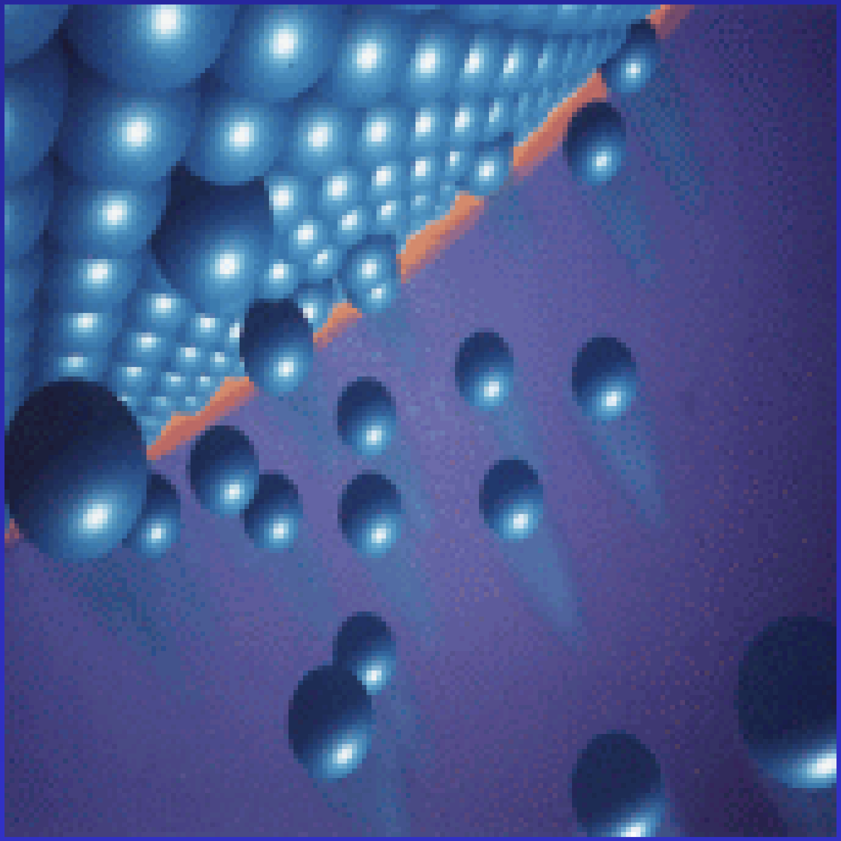
Very High Efficiency Solar Cells

Goal: 50 % conversion efficiency

Molecular beam epitaxy (MBE)



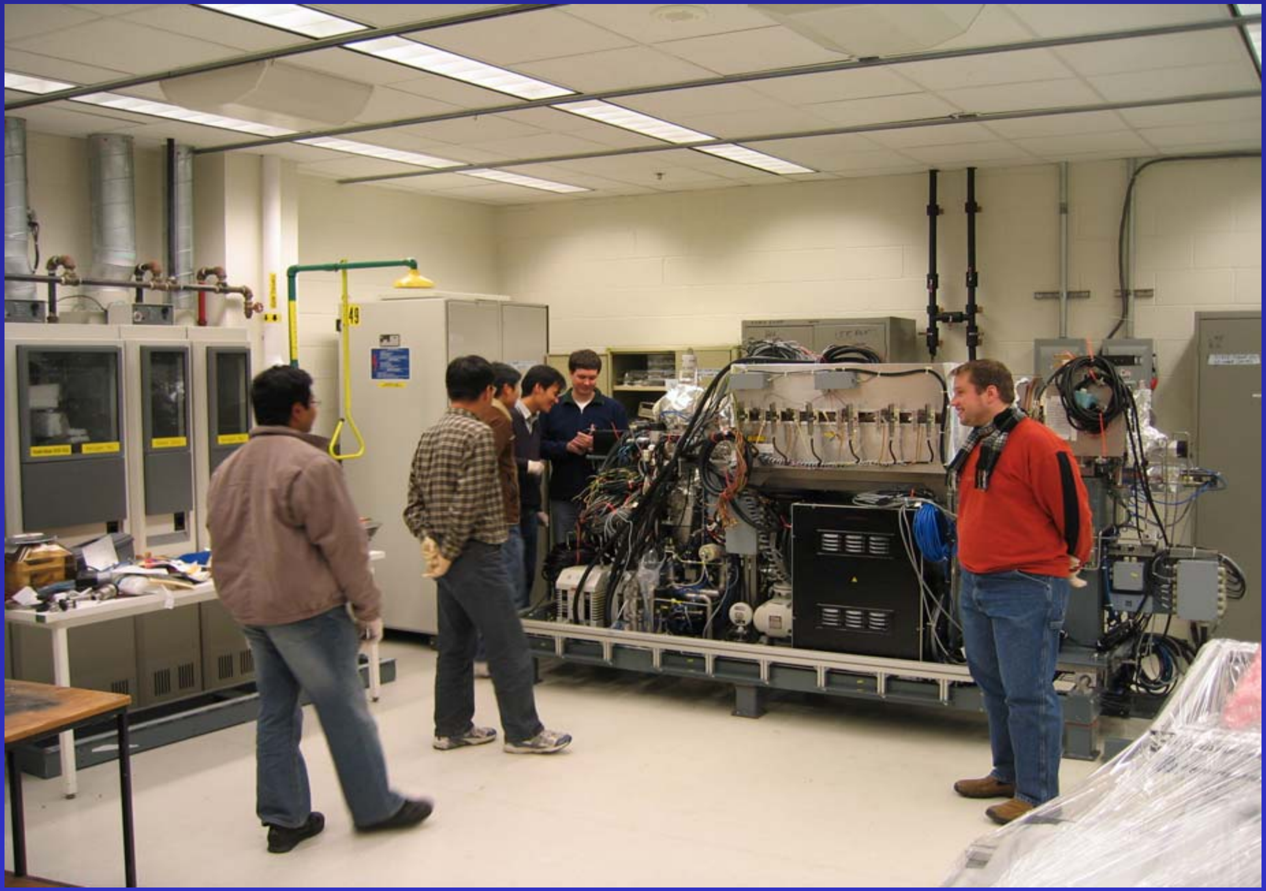
Simplified Schematic of
Si-Ge MBE



Solid source MBE in Ultra-High-Vacuum

figure from M. Dashiell, K. Eberl

U Del CVD System (Unaxis CVD 300) for SiGe Fabrication



- Sources:
  - Si, Ge, C sources
  - B (p-doping)
  - P (n-doping)
- Substrates:
  - 3 to 8 inch diameter
- Operation: June 1

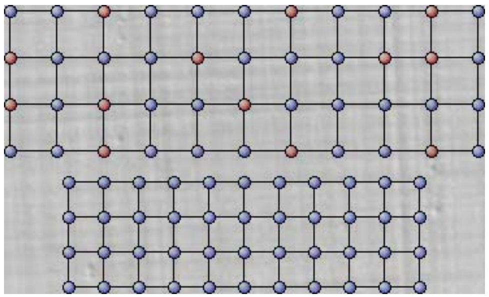
Strain in Si/Ge heterostructures

a_{si}=5.43 Å a_{Ge}=5.65 Å

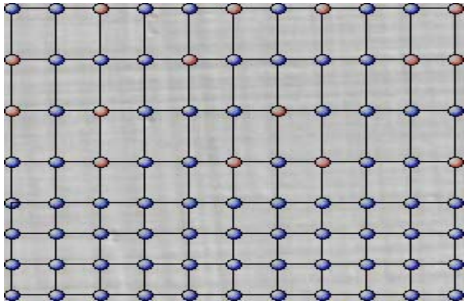
Pseudomorphic growth

Ge_xSi_{1-x}

Si



$\varepsilon^{\parallel}_{GeSi}$= x·0.042



Ge_xSi_{1-x}

on

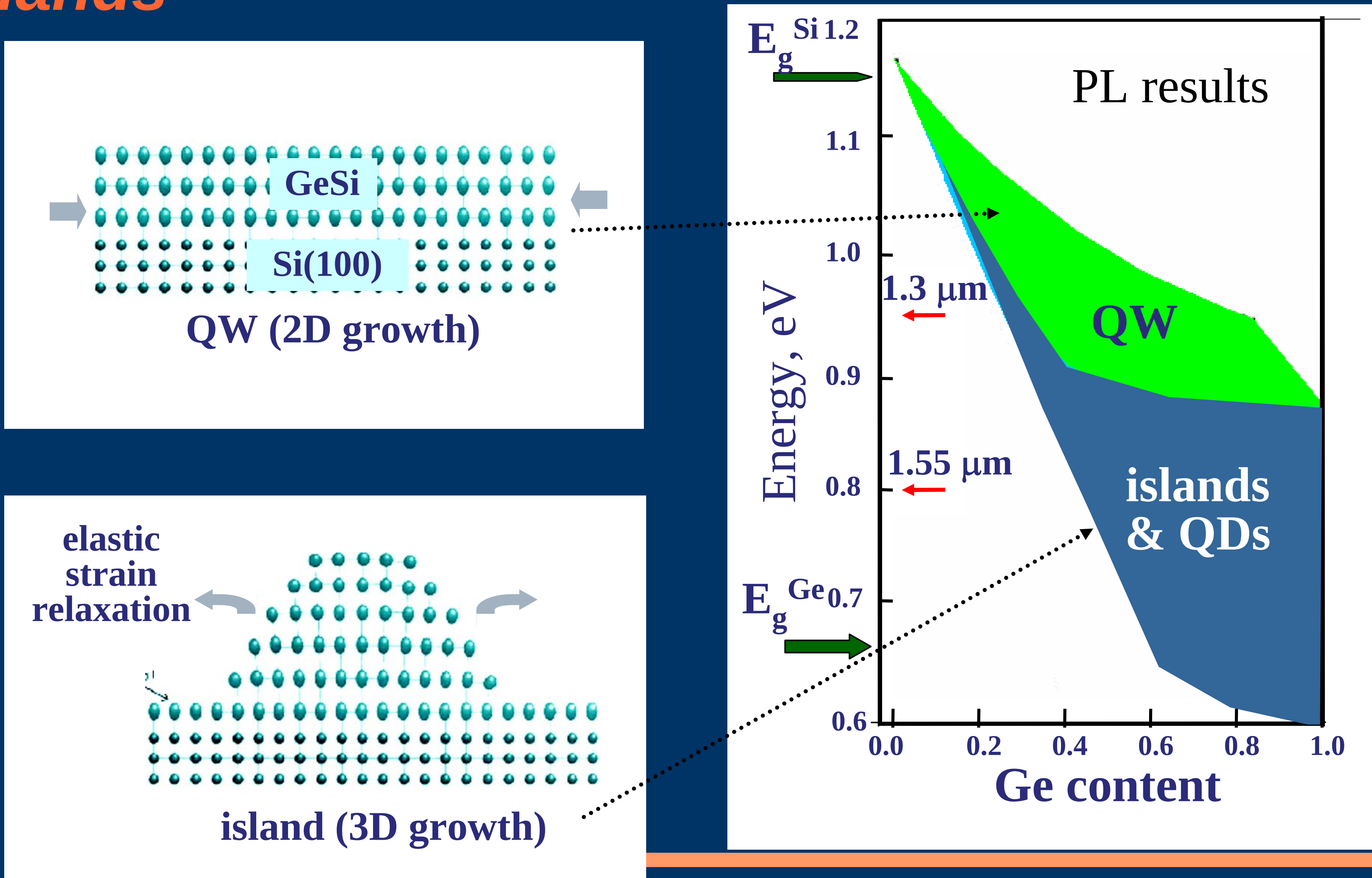
Si(001)

Elastic energy

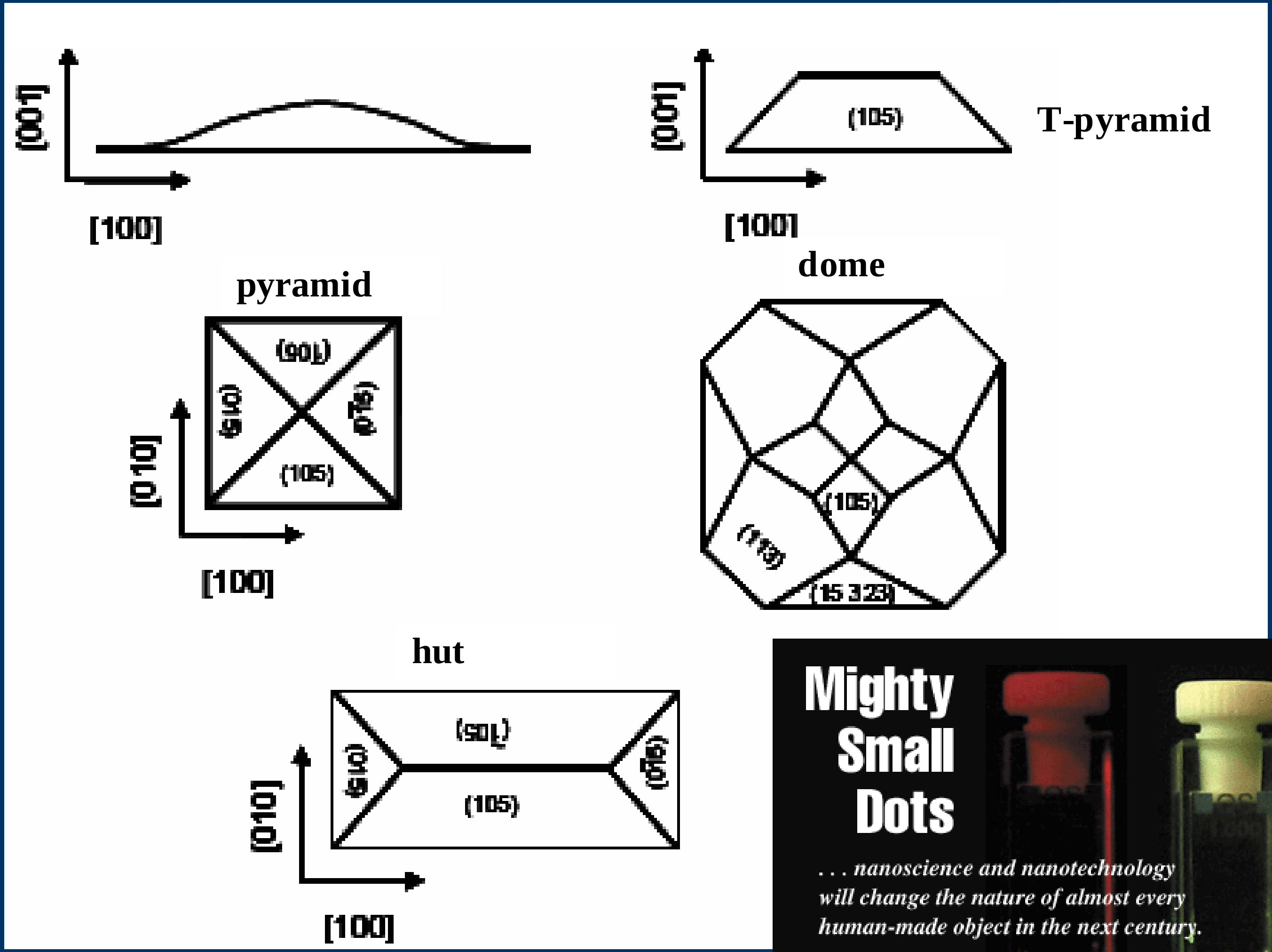
$$E_{GeSi}=2\cdot G\cdot((1+\nu)/(1-\nu))\cdot\varepsilon^2{}_{GeSi}\cdot d_{GeSi}$$

G – shear modulus, ν - Poisson's ratio, $\varepsilon_{GeSi}=0.042\cdot X_{Ge}$ – in plane strain, X_{Ge} – part of Ge in GeSi layer, d_{GeSi} – thickness of GeSi layer

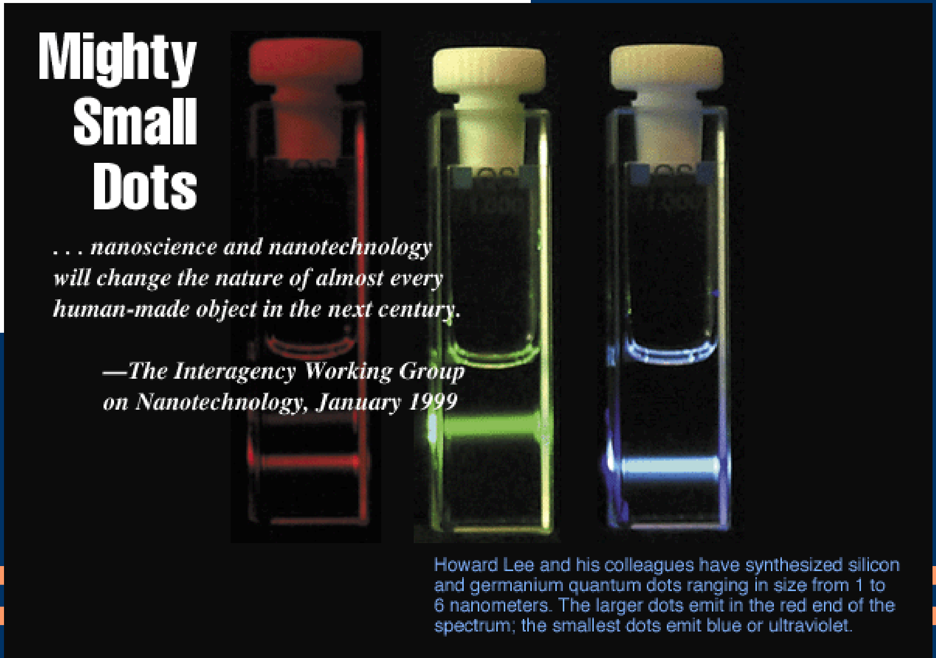
Motivation
Optical properties of Ge(Si) self-assembled islands



Main types of GeSi self-assembled

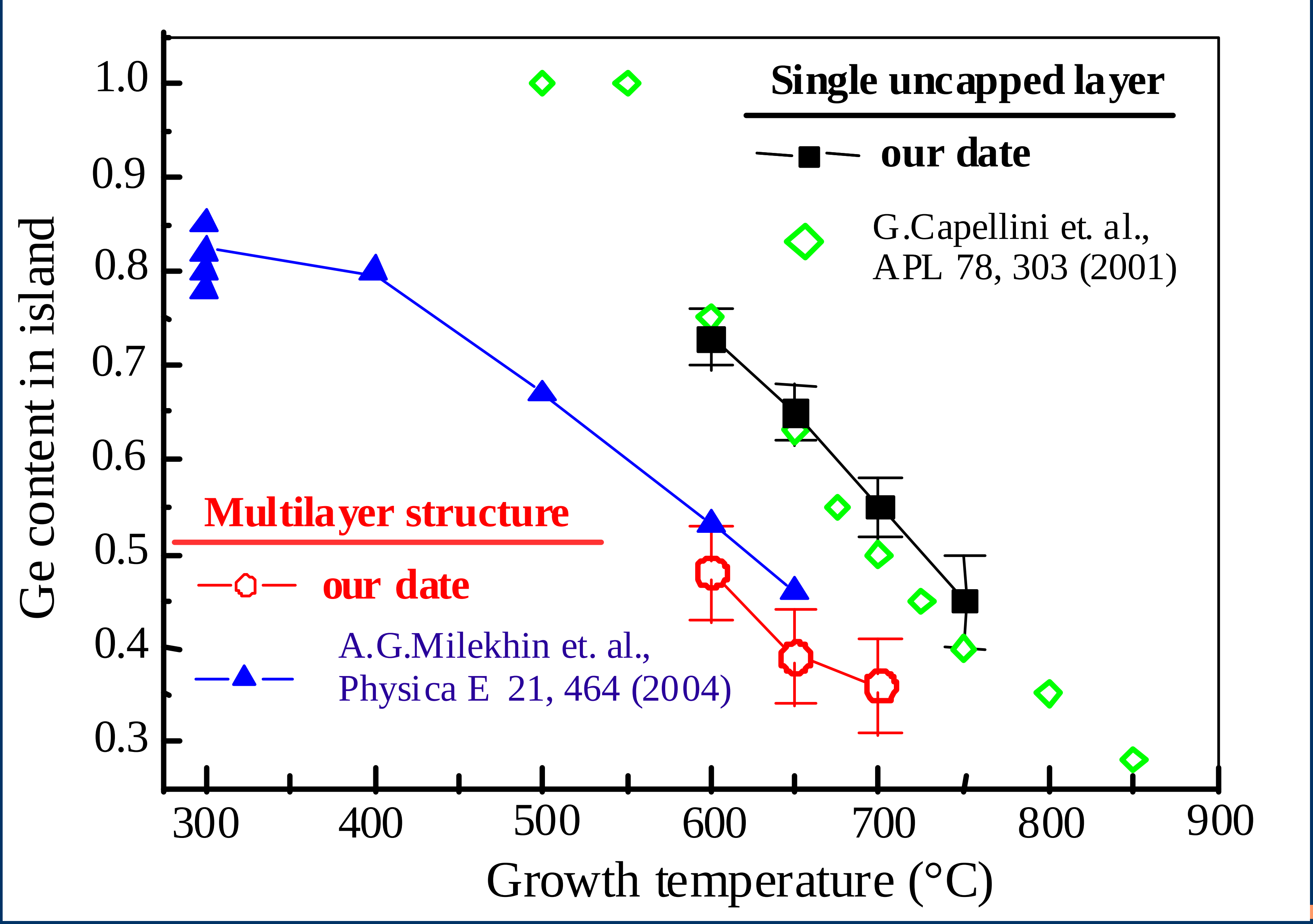


size matters!

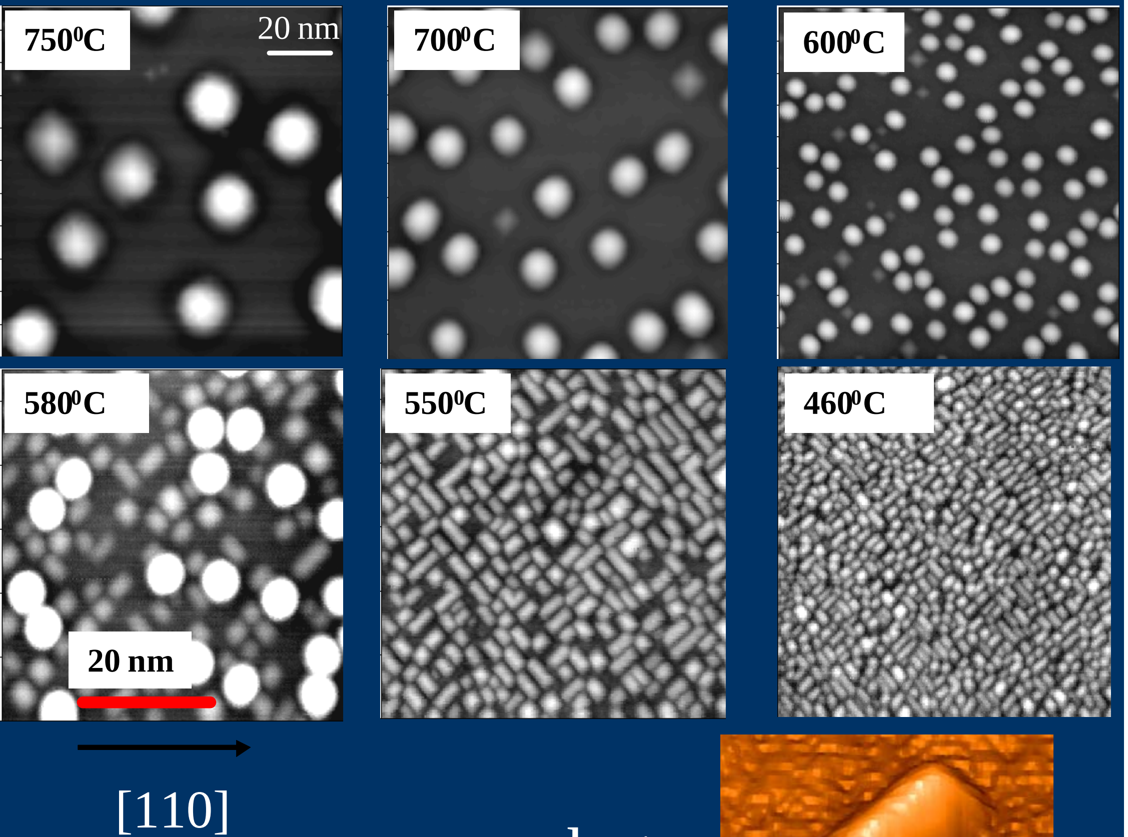


Lawrence Livermore Labs

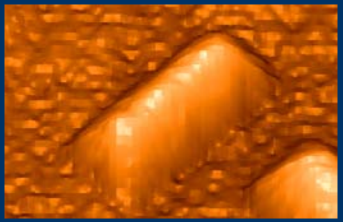
Composition of islands in dots & multilayers

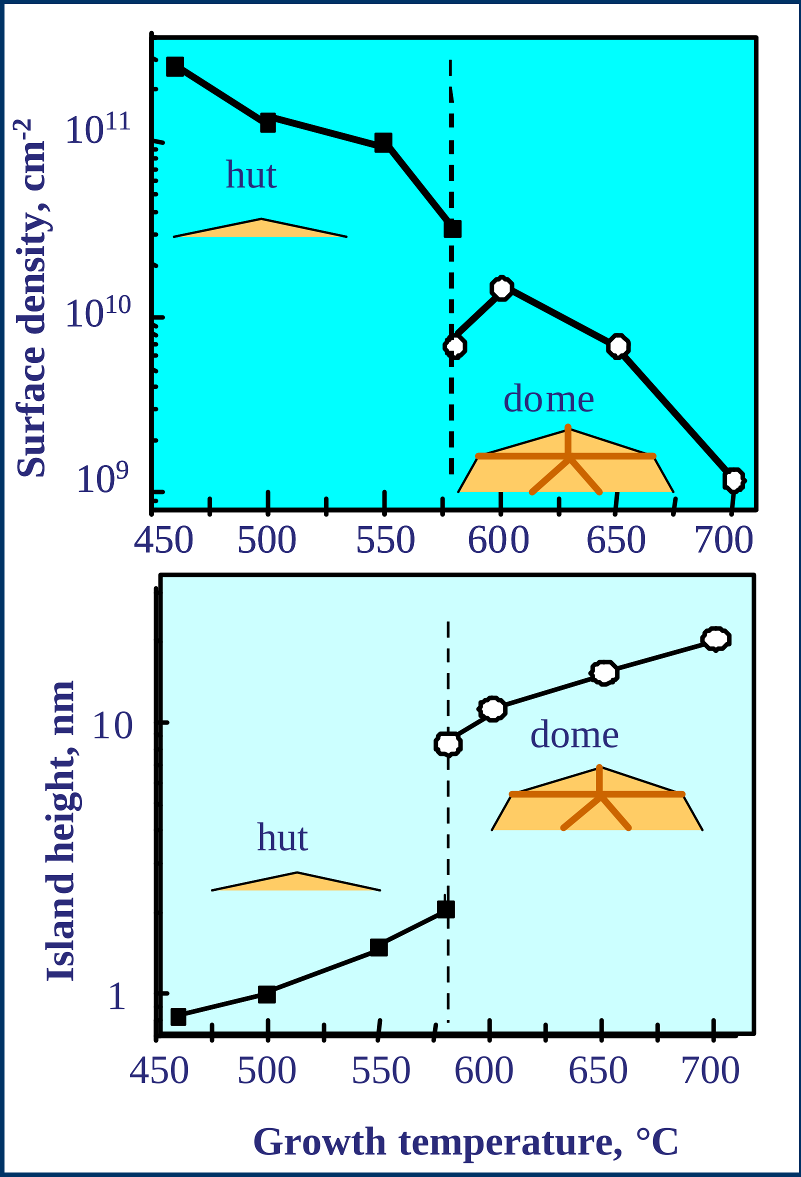


Main types of GeSi self-assembled islands



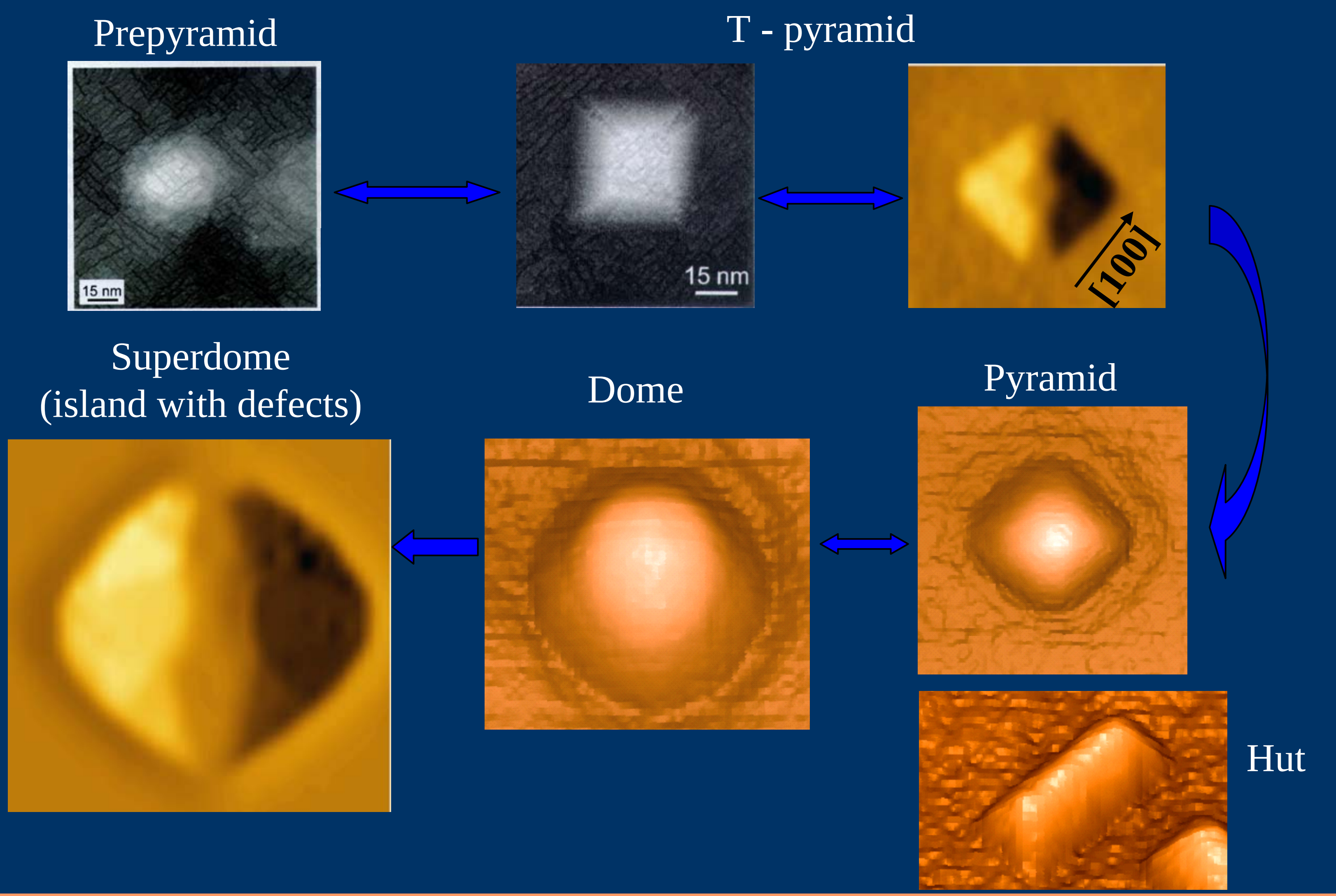
hut



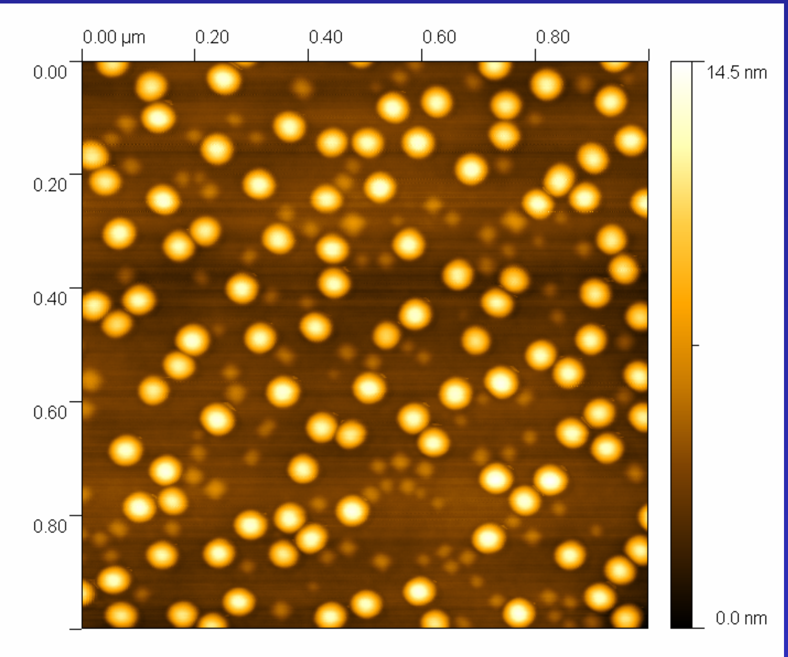


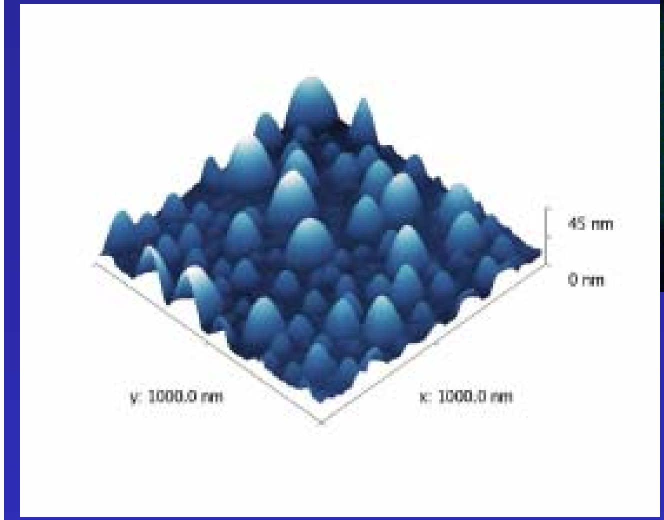
Main types of GeSi self-assembled islands

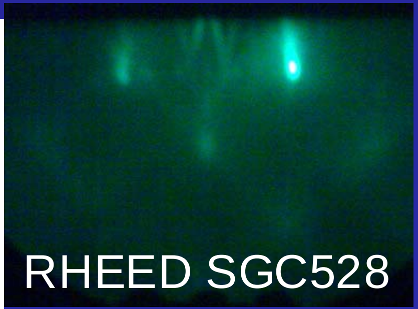
A.Rastelli, et. al., PRB **68**, 115301 (2003),
J.Tersoff et. al., PRL **89**, 196104 (2002)



AFM Data of SGC-528 Ge Quantum dots on Si







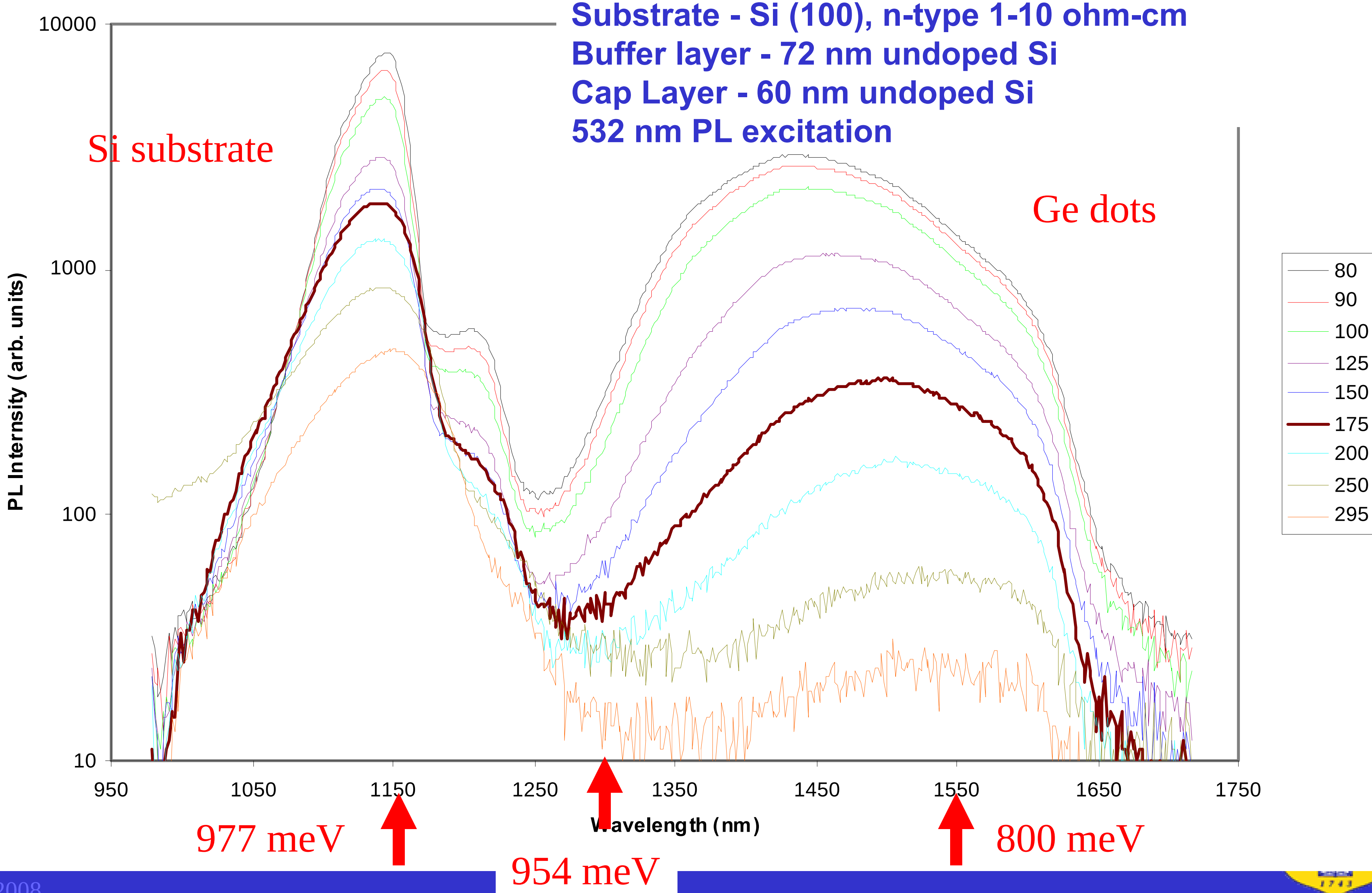
Ge islands at 605°C on Si buffer (d_{Ge} ~ 7.5 ML, v_{Ge} ~ 0.15 Å/sec)

Island surface density:
$N_s^{pyramid} = 8.8\times10^{9}\ cm^{-2}$
$N_s^{dome} = 9.2\times10^{9}\ cm^{-2}$
$N_s^{total} = 1.8\times10^{10}\ cm^{-2}$

Islands sizes: domes: <h> = 10.35 nm, <D> = 66.5 nm
max height of pyramids: 3.6 nm

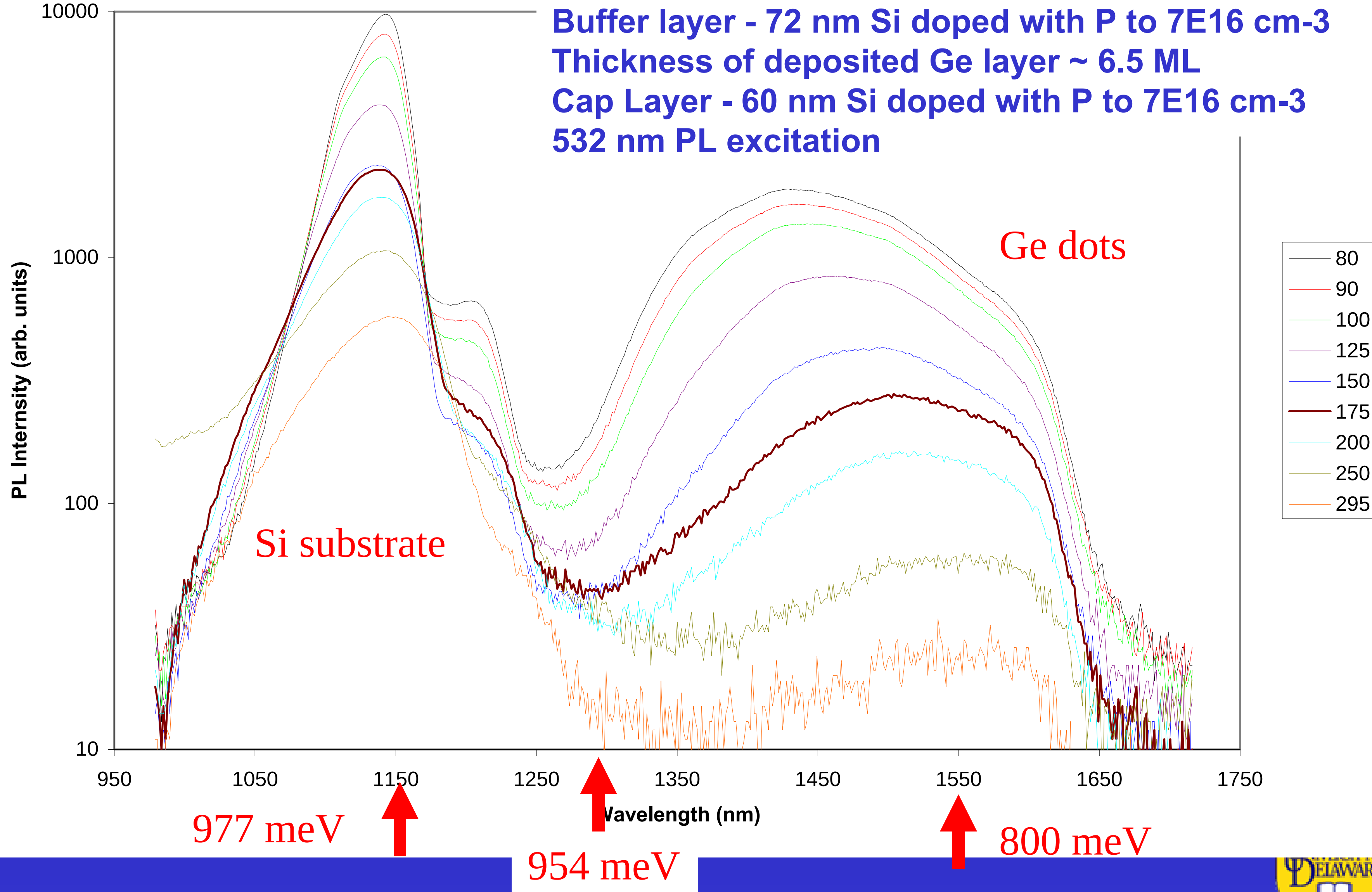
Photoluminescence of Ge Quantum dots on Si

SGC 520: Ge quantum dots on undoped Si buffer
Growth temp: 600 °C - Ge dot layer ~ 6.5 ML
Substrate - Si (100), n-type 1-10 ohm-cm
Buffer layer - 72 nm undoped Si
Cap Layer - 60 nm undoped Si
532 nm PL excitation



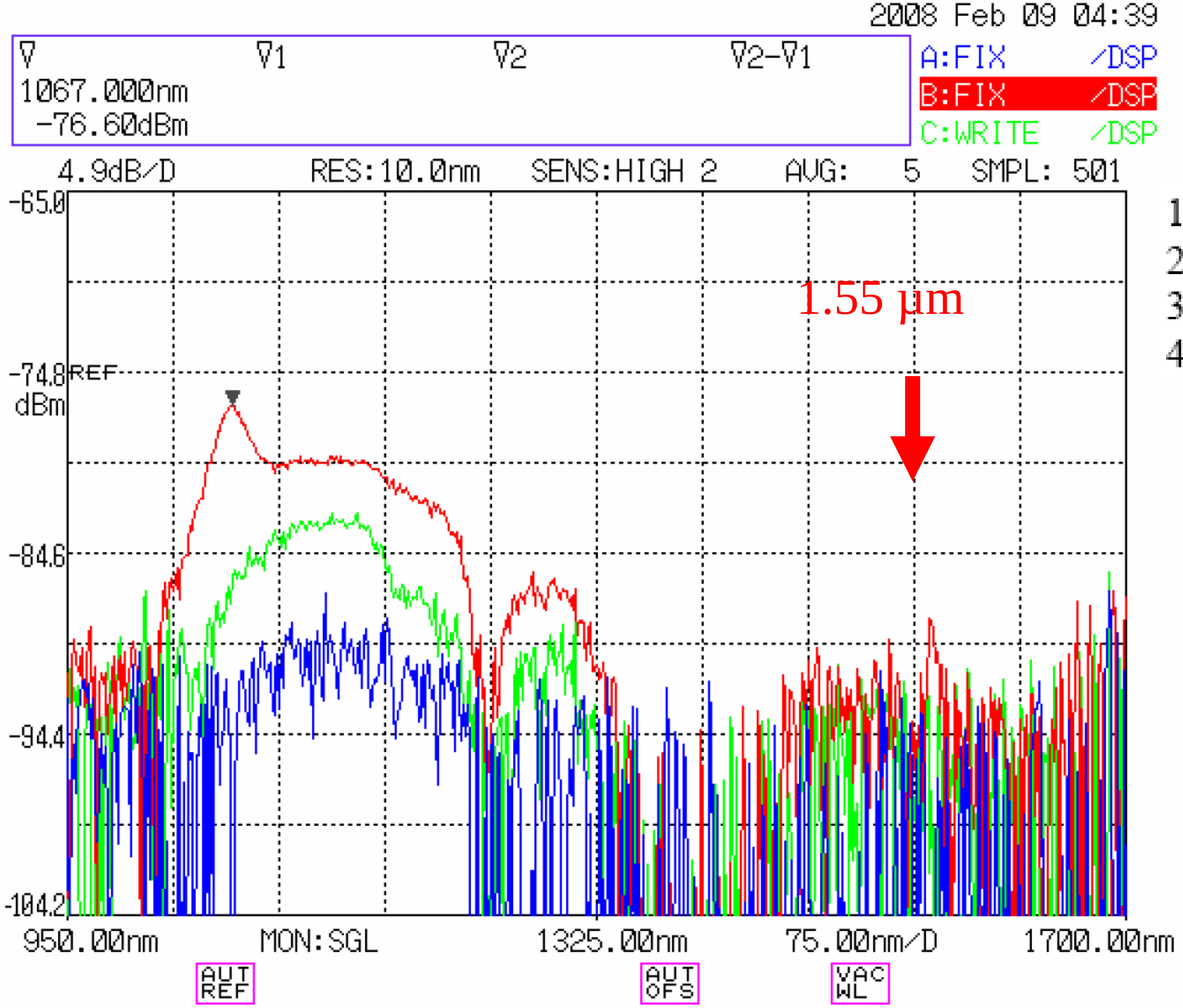
Photoluminescence of Ge Quantum dots on Si

SGC 521: Ge dots on a Si:P buffer
Substrate - Si (100), n-type 1-10 ohm-cm
Buffer layer - 72 nm Si doped with P to 7E16 cm-3
Thickness of deposited Ge layer ~ 6.5 ML
Cap Layer - 60 nm Si doped with P to 7E16 cm-3
532 nm PL excitation



Photoluminescence of Ge Quantum dots on Si at room temperature

Sample 541



1) 532 nm, 50 mW
2) 639 nm, 30 mW (Blue data)
3) 780 nm, 60 mW (Red data)
4) 850 nm, 40 mW (Green data0

Excitation wavelength dependence

Measurements by Matt Kim, QuantTera

JSK2008

Optical transitions in Ge(Si)/Si(001) islands

Aleshkin V.Ya., et. al., *JETP Lett.* **67**, 48-53 (1998)

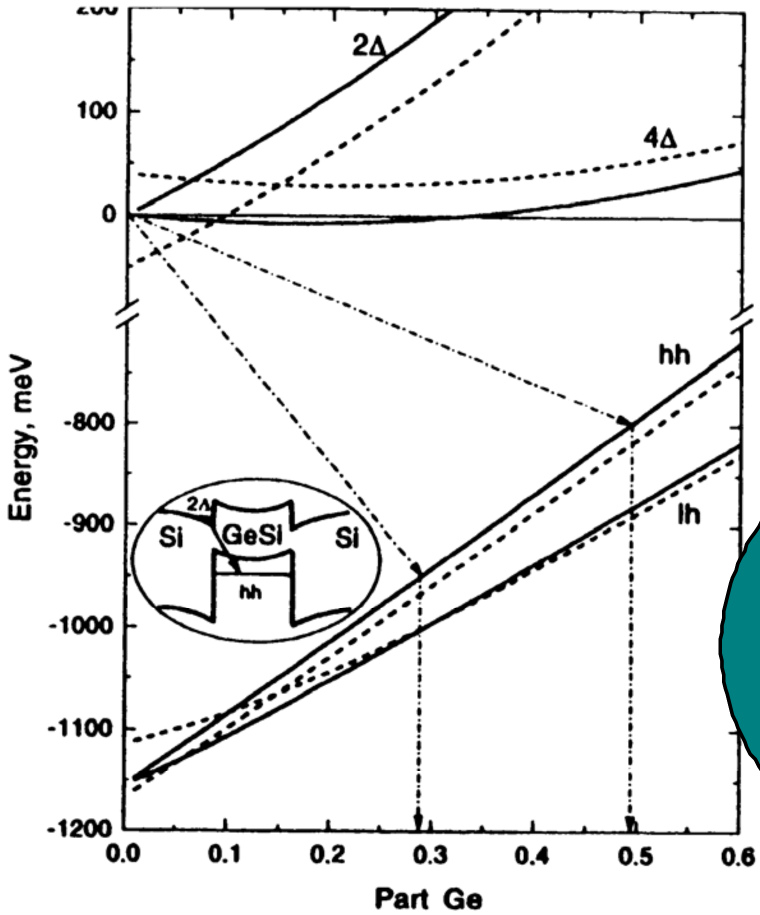
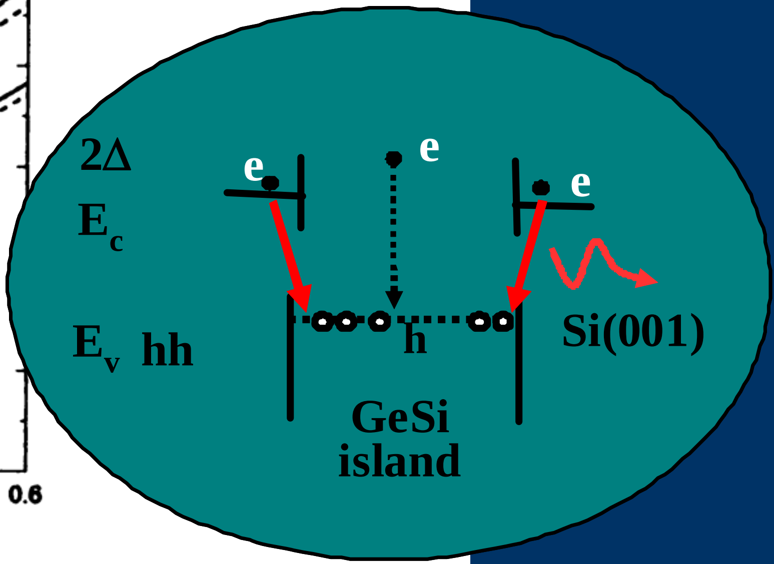
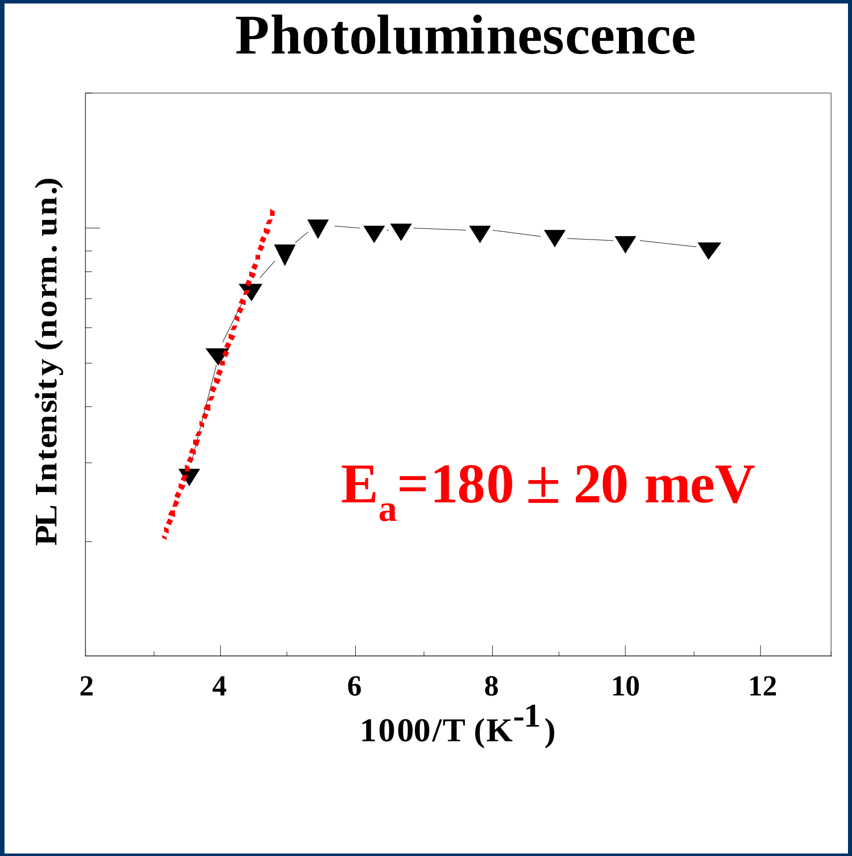
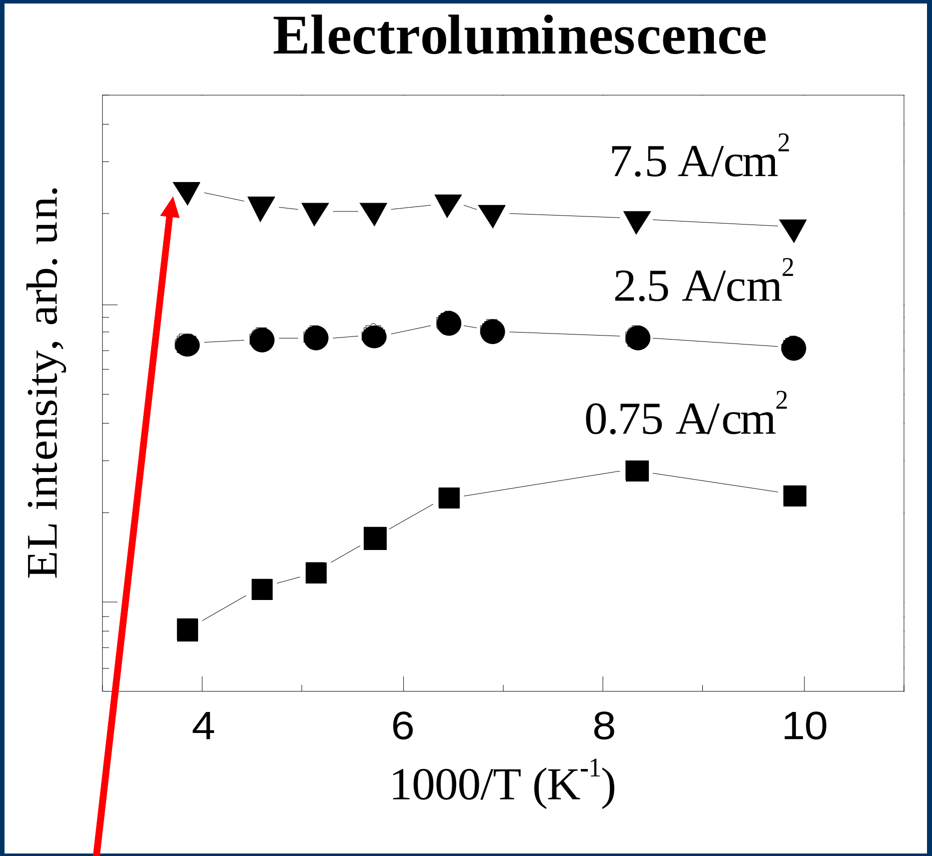


FIG. 3. Calculation of the conduction and valence bands of the solid solution $Si_{1-x}Ge_x$ grown homomorphically on a Si(100) substrate (lattice constant — 5.43 Å, solid lines). The dashed line corresponds to the elastically strained silicon (lattice constant — 5.46 Å). Inset: Band diagram for the case when $x>0.32$.



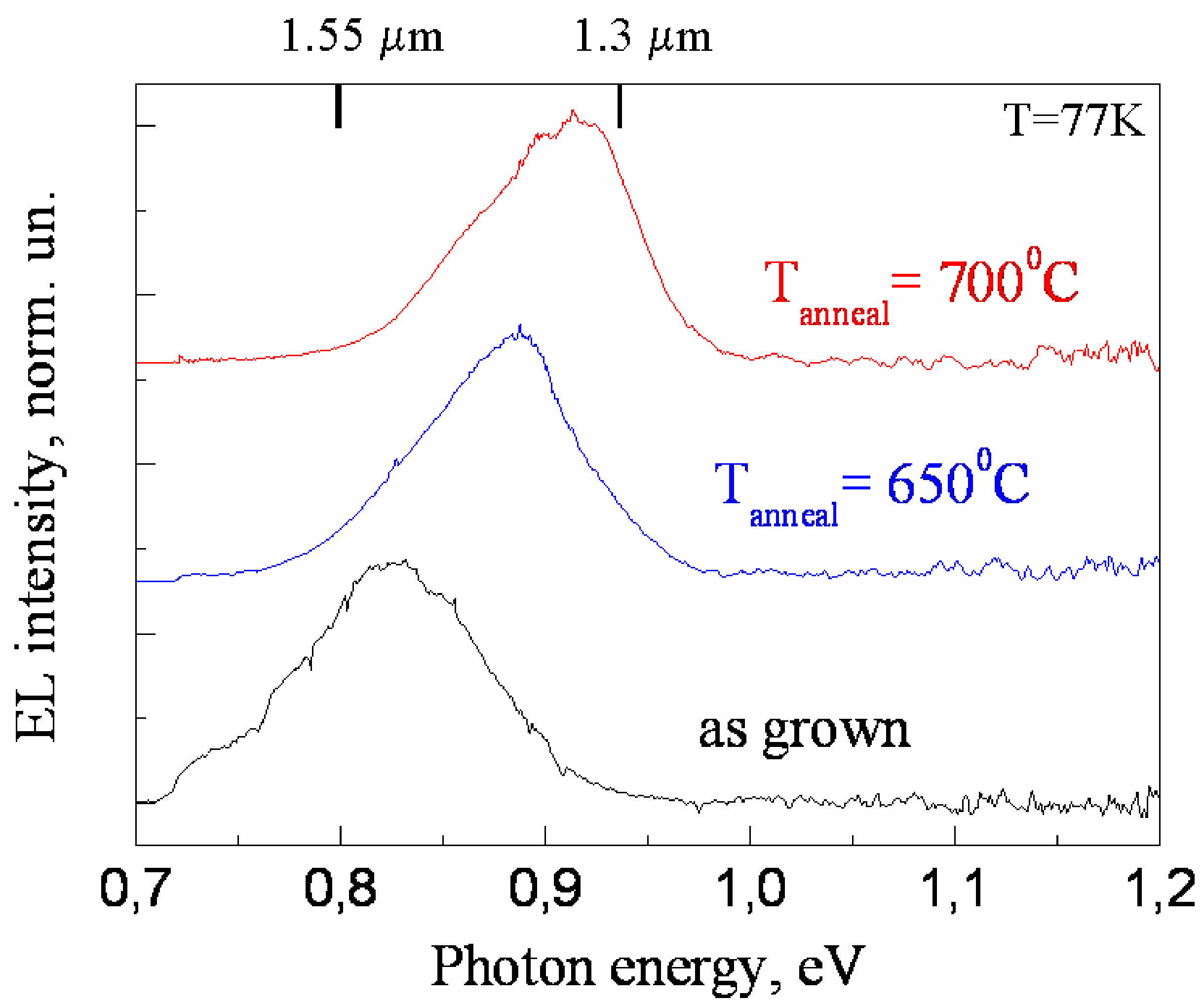
Temperature quenching of PL and EL from Ge(Si) islands



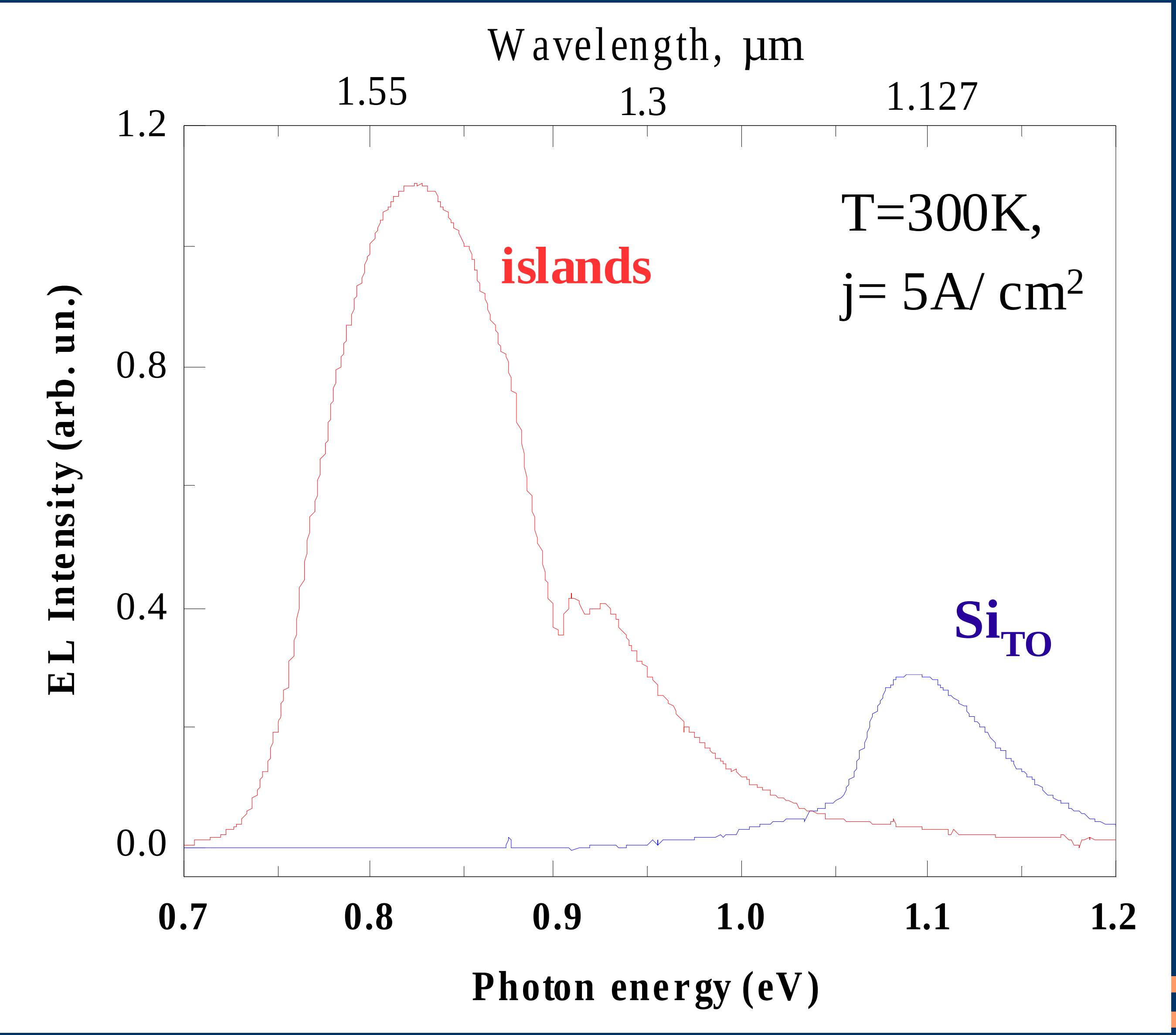


$\eta_{ext} = 2 \times 10^{-5}$

Wavelength tuning of Electroluminescence from Ge(Si) islands



Room-temperature Electroluminescence with Ge(Si) islands and Wetting Layer



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- Special Thanks to Arizona Nanotechnology Cluster for making my visit possible!

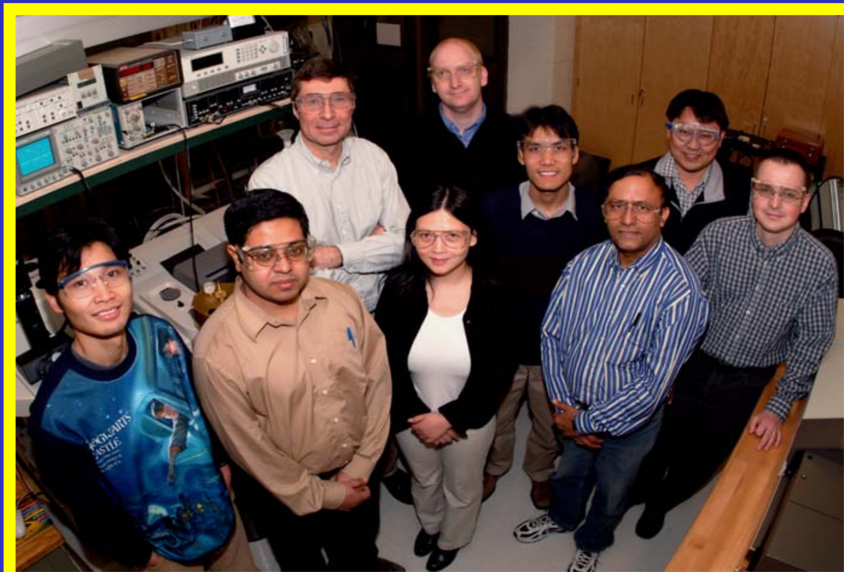
CONCLUSIONS:

SiGe Quantum Dot Light Emitters: A new circuit technology, or a disappointment?

- silicon-germanium based light emitters are useful for spectroscopy, communication, computing, sensing, imaging, materials scanning, and are compatible with integrated circuit processing

More device and system demonstrations are needed:

"In theory, there is no difference between theory and practice; but in practice, there is."



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