Epitaxy for Physics Research and Device Applications:

and other

Research activities in the Semiconductor Materials Research Laboratory

Ya-Hong Xie

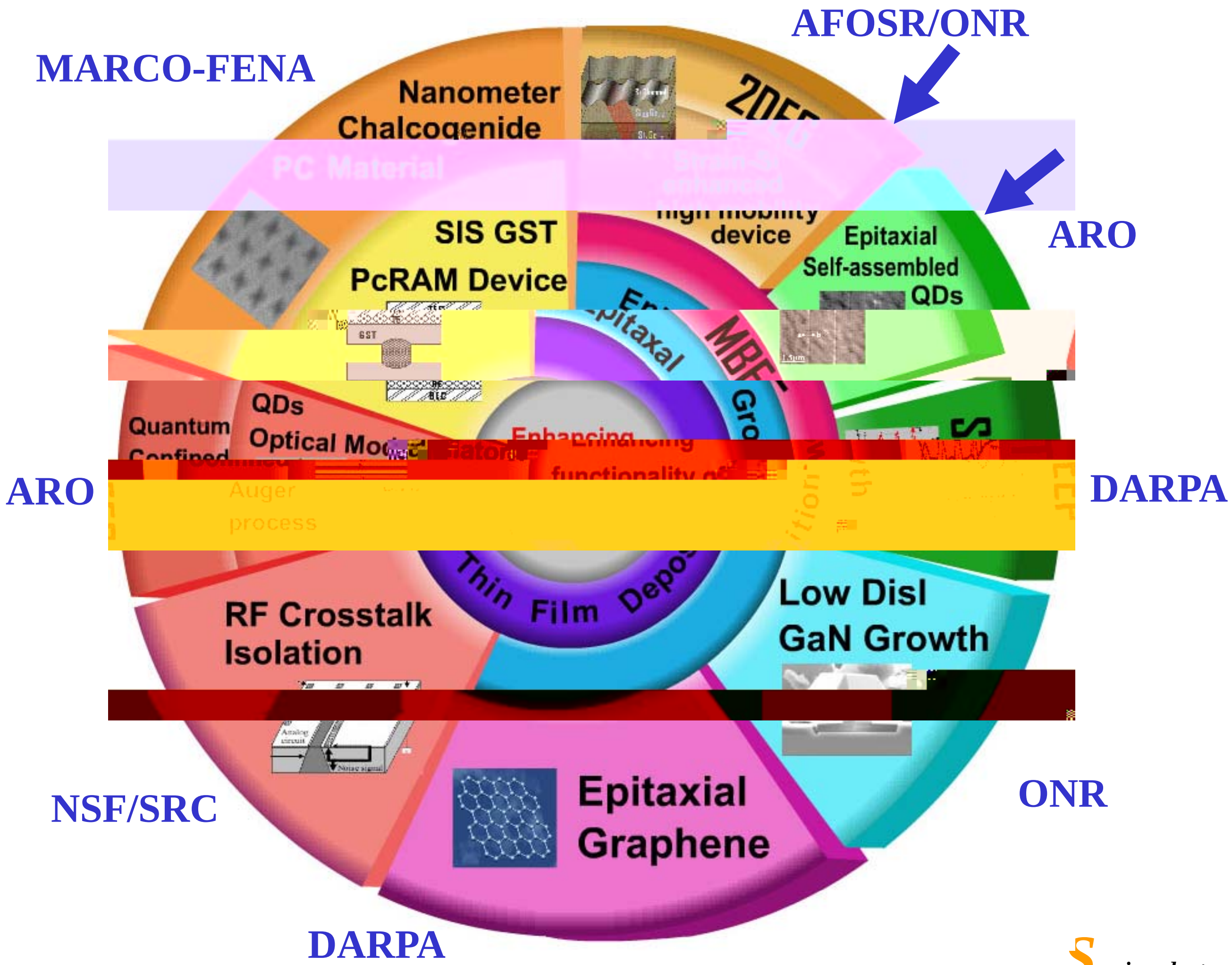
Department of Materials Science & Engineering

University of California Los Angeles

yhx@ucla.edu

Semiconductor Materials Research Lab

Outline

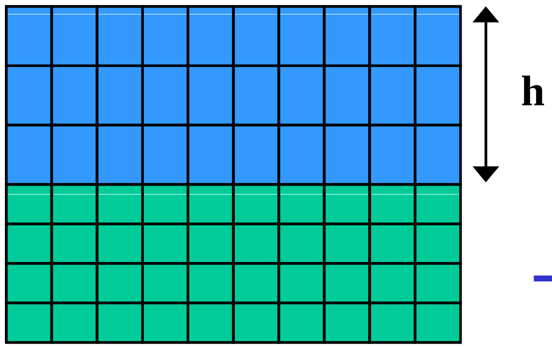


MARCO-FENA
AFOSR/ONR
ARO
ARO
DARPA
NSF/SRC
ONR
DARPA
Nanometer
Chalcogenide
SIS GST
PcRAM Device
device
Epitaxial
Self-assembled
QDs
QDs
Optical Mod
Quantum
MBE
Low Disl
GaN Growth
RF Crosstalk
Isolation
Epitaxial
Graphene
Thin Film

Epitaxy of Semiconductors for Physics Research and Device Applications

Fundamentals of Epitaxy

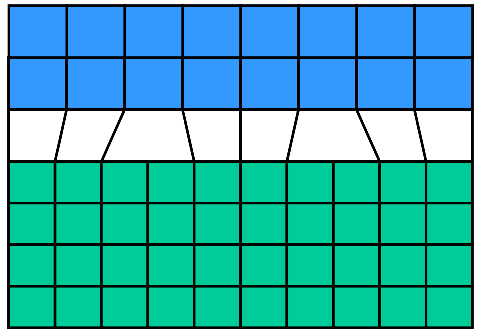
Hetero-epitaxy



$$E_\varepsilon = B\varepsilon^2 h$$

$$where \quad B = 2Y_s \frac{1+\nu}{1-\nu}$$

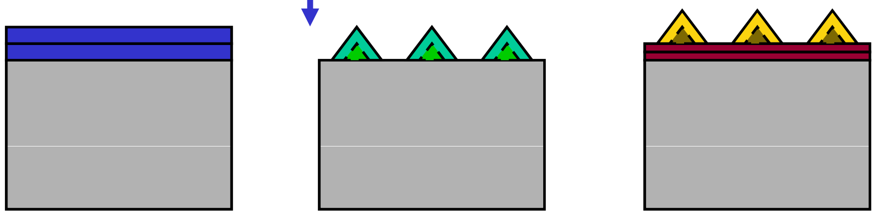
"Electronic thin film science for electrical engineers and materials scientists", Tu, et al, MacMillan, NY, 1992



Plastic relaxation of misfit strain

The importance of dislocation dynamics

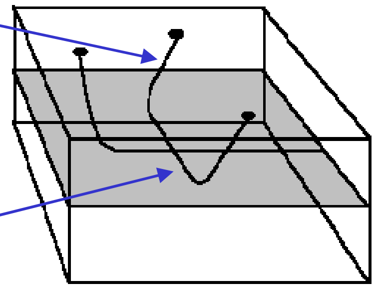
Elastic relaxation of misfit strain



FM mode **VW mode** **SK mode**

Self-assembled quantum dots

Threading segment



misfit segment

2DES

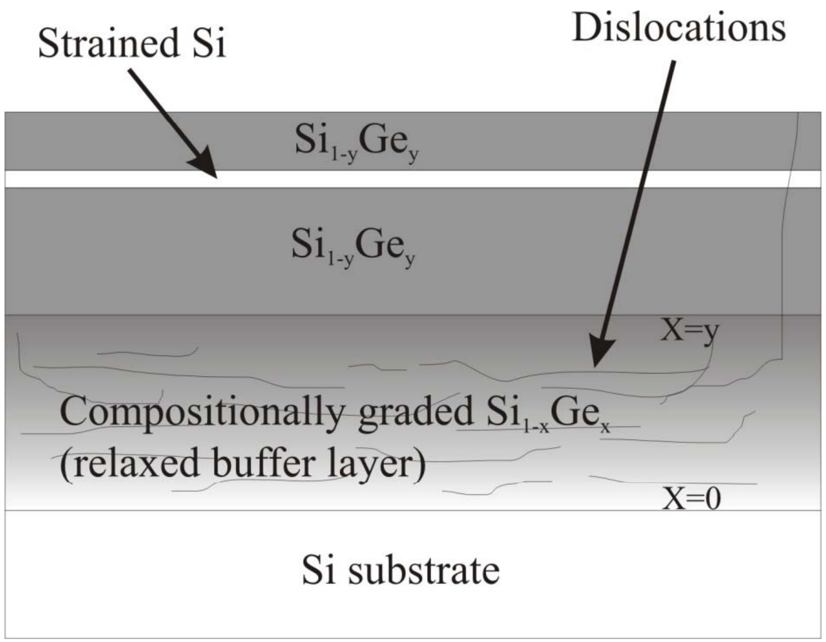
Semiconductor Materials Research Lab

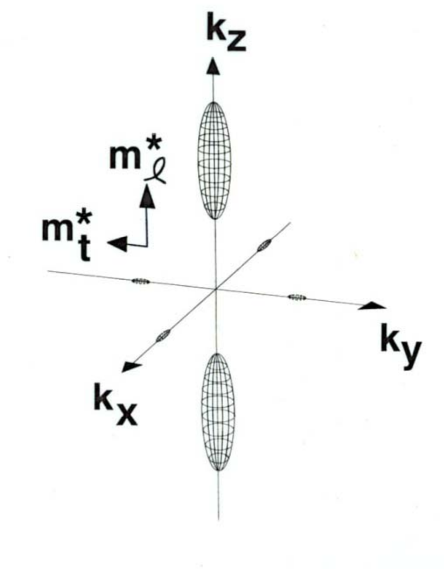
2D Electron System in Strained Si

in collaboration with D.C. Tsui & group, Princeton Univeristy

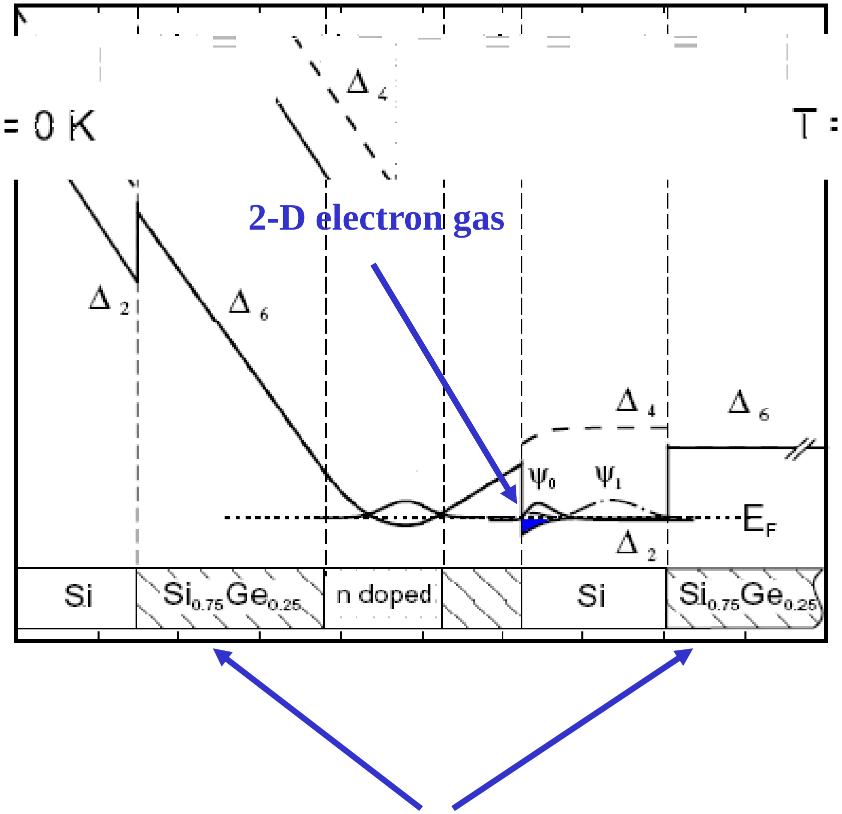
Other collaborations: Marc Kastner (MIT); Jagadeesh Moodera (MIT magnet lab)

- The compositionally graded, relaxed SiGe buffer layers: the controlled plastic relaxation of misfit strain that forms the foundation for the fabrication of strained Si;
- The magnitude of strain required for effective separation between the 2- & 4-fold conduction band valleys: ~1%;

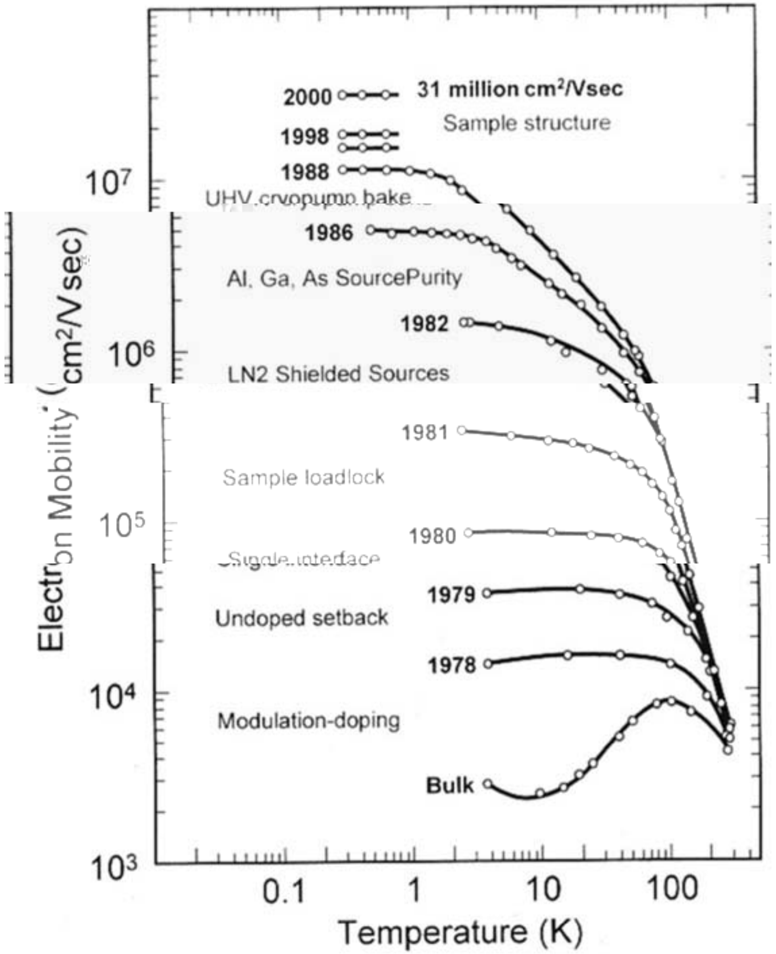




Modulation Doped 2DES

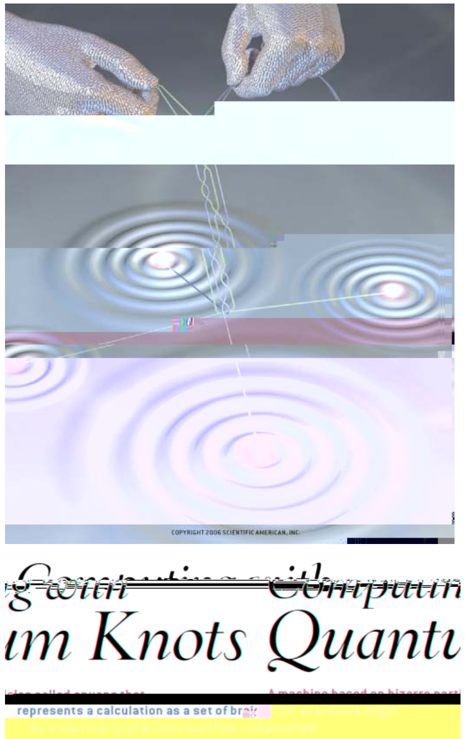


Relaxed SiGe buffer layer on Si (001)



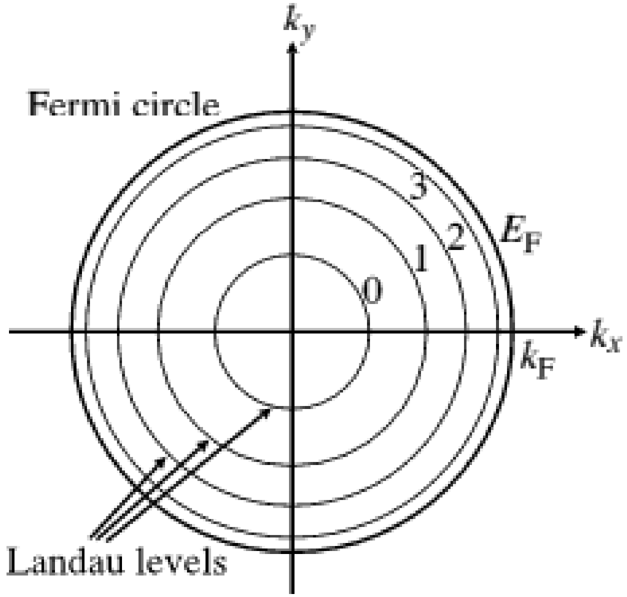
The “Usefulness” of 2-dimensional Electron Systems in Strained Si

- Room T applications:
  - Mobility being limited by phonon scattering;
  - High carrier density: the need for large current drive;
  - The importance of the out of plane effective mass;
- Low T transport research:
  - High mobility: fine features in the transport characteristics;
  - Low carrier density: the importance for correlated behaviors;
  - Application: topological quantum computing?
  - Understanding correlated electron behaviors is at the forefront of condensed matter physics;



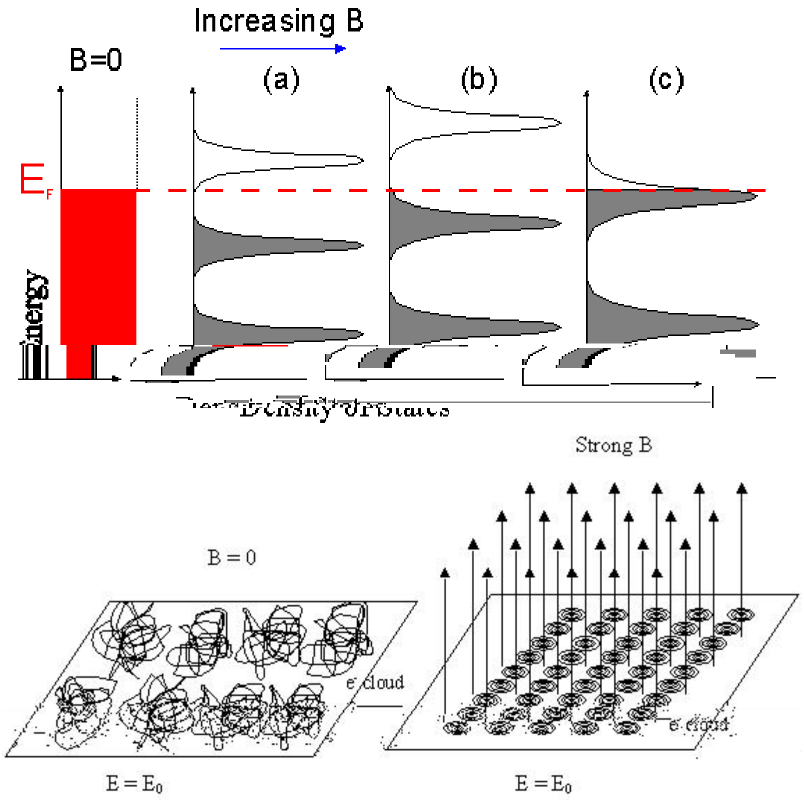
Scientific American, p.56, April 2006,

Integer Quantum Hall Effect: electron localization



2D density of states of electrons (B=0):

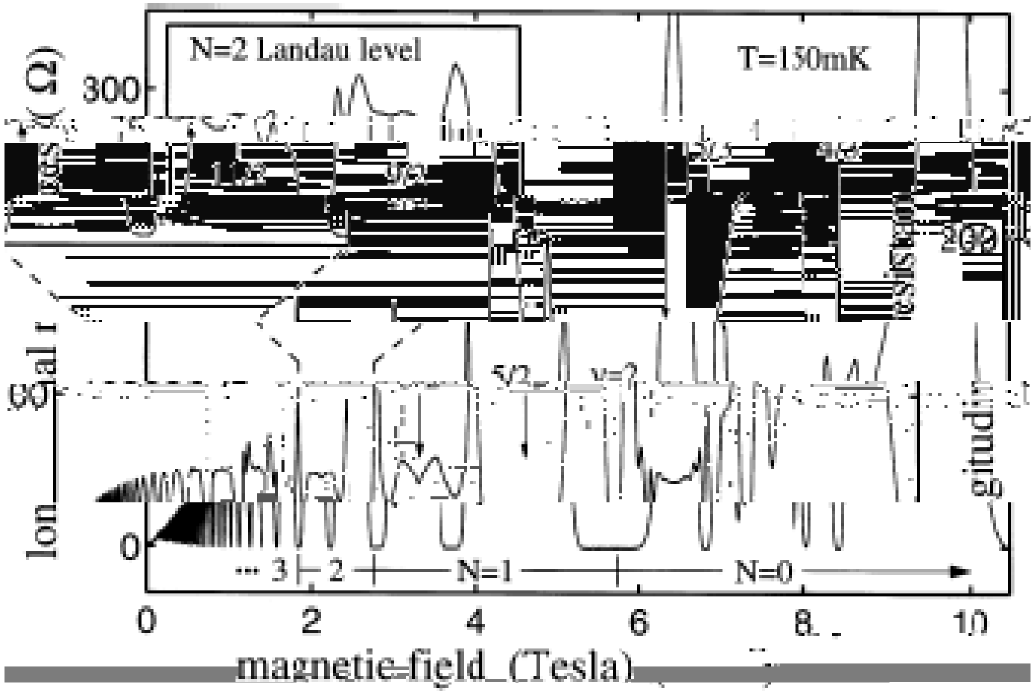
$$g(E) = \frac{m^*}{\pi\hbar^2}$$



The density of state increases and the 2D electrons pack closer together with increasing B

Fractional Quantum Hall Effect: Composite Fermions

J.P. Eisenstein, et al, Phys E, v.6, 29 (2000)



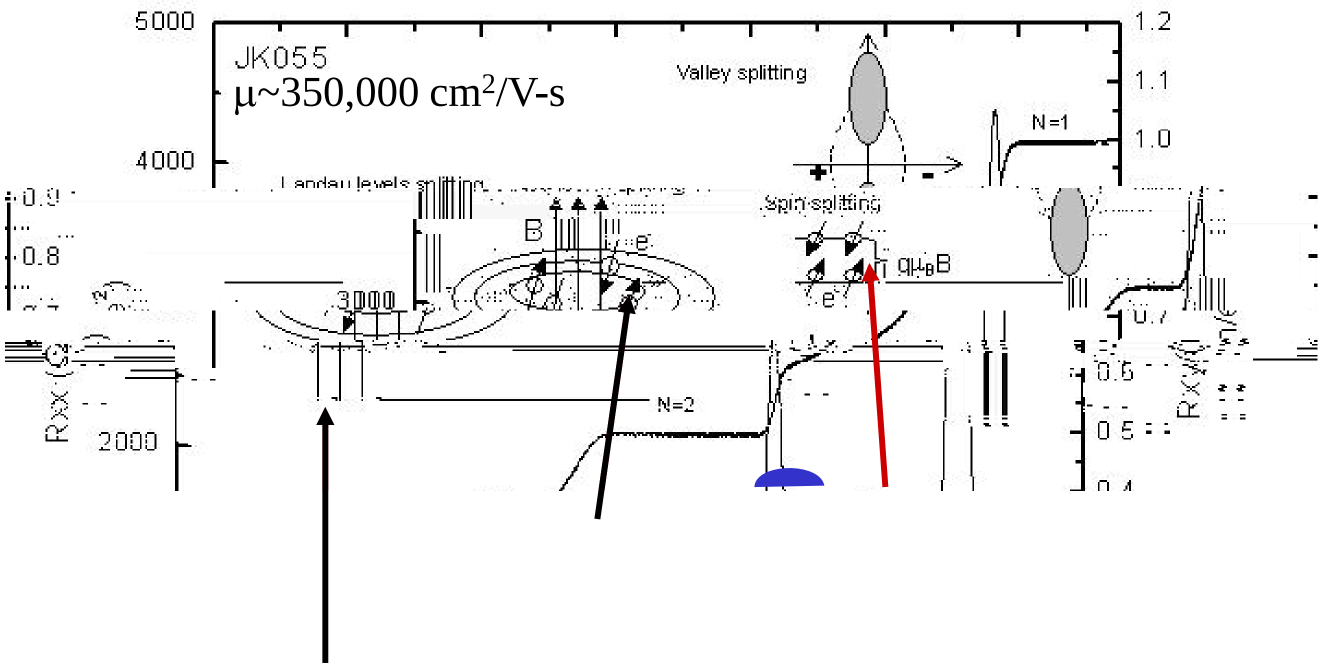
μ~11,000,000 cm^2/V-s
2DES in GaAs/AlGaAs

The details of the ρ_{xx}-B relation can be visible only if the mobility is high;

Fractional quantum Hall effect: the need to invoke correlated electron behaviors

What high mobility provides for us

The in-ability of resolving fine features in the transport (R_{xx} & R_{yy}) curves because of low μ.



The quest for lower 2DES density

- The importance of low carrier density for the study of correlated behaviors:

  The dimensionless density parameter:

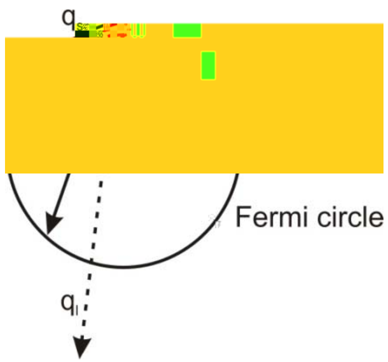
  $$r_s = E_{e\text{-}e}/E_F$$

  Given that $E_{e\text{-}e} \sim \sqrt{(n_s)}/\varepsilon$ and $E_F \sim n_s/m^*$, where n_s =carrier density, ε=dielectric constant and m*=effective mass.

  Therefore:

  $$r_s \sim m^*/\ \varepsilon\sqrt{(n_s)}$$

  To achieve large r_s, we need large m*, and small n_s.

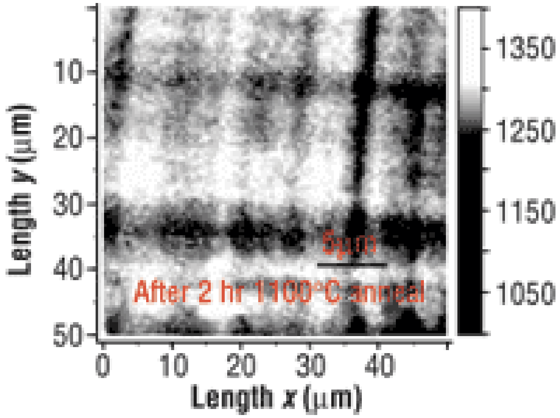


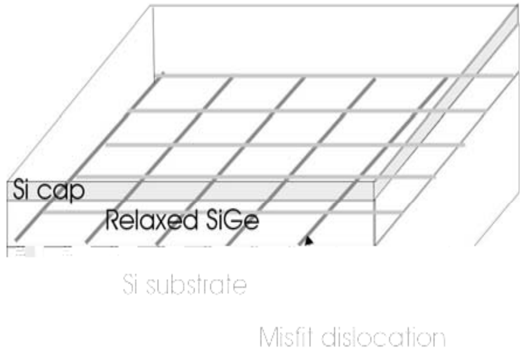
- The factors that could limit the achievable carrier density;
  - Localization induced by impurities and other inhomogeneity in the sample;
  - The uniqueness of 2DES in strained Si: another source for poor homogeneity.

The Challenges in Achieving Low 2DES Density

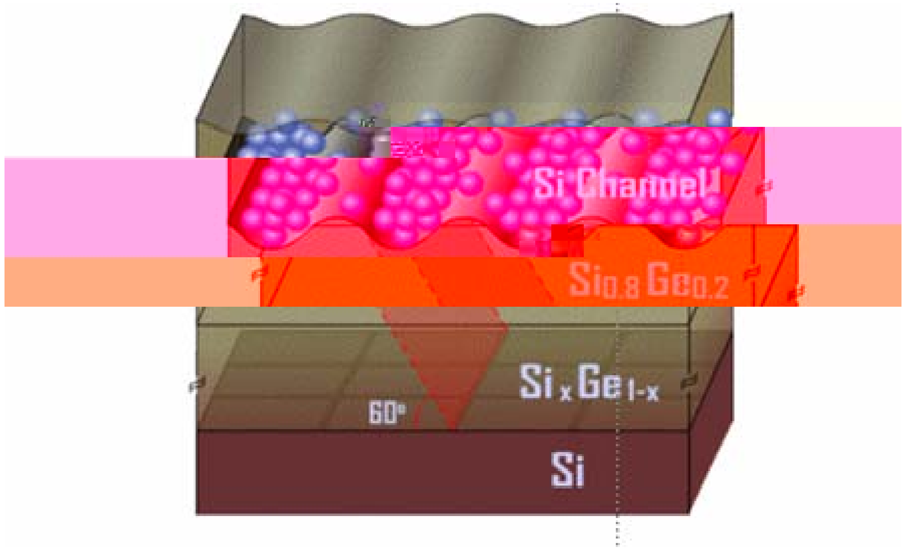
Raman Mapping of SSOI

(Mark Kennard, SOITEC)





Deformation potential calculation



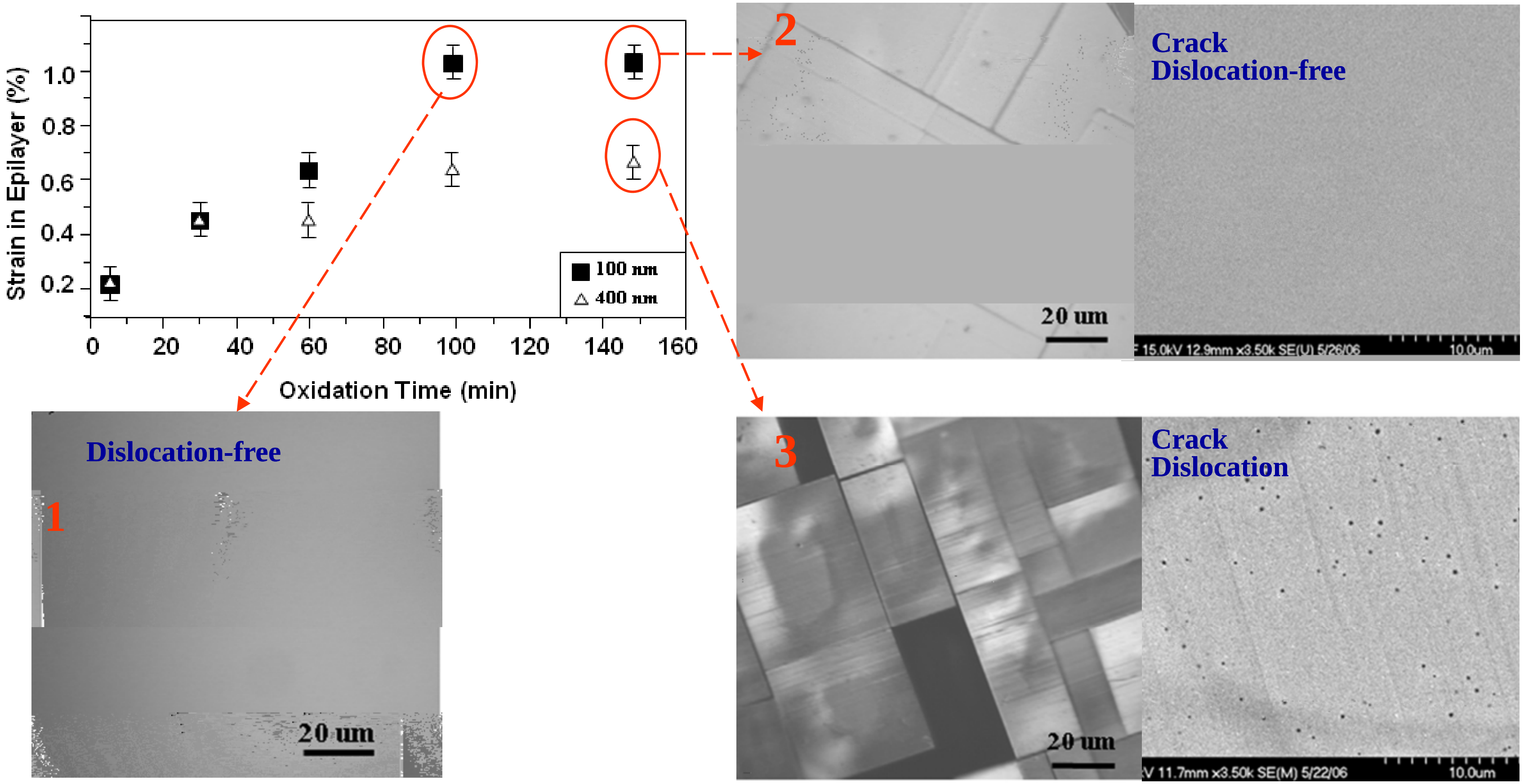
Amplitude of potential undulation: 7 meV
Spatial correlation: ~1 um;
Lower limit of carrier density : 5~6x10^{10}cm^{-2}

Alternatives: avoid dislocation

An alternative method for fabricating dislocation-free strained Si

An alternative method for fabricating dislocation-free strained Si

After defect etch



Dislocation-free 100nm thick Si film under 1% tension with strain variation undetectable by Raman

Summary of 2DES in Strained Si

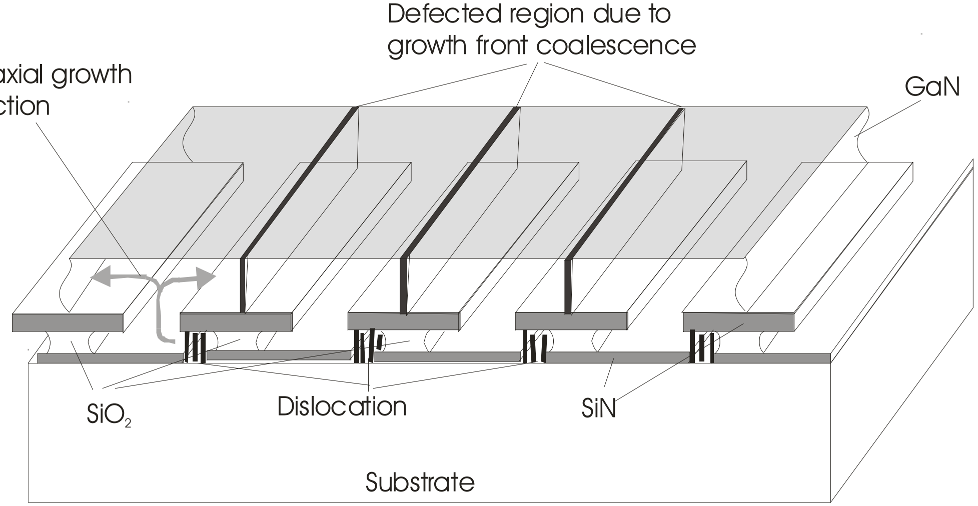
- Sample fabrication (the enabling factor): The continued quest for 2-D electron or hole systems with higher mobility and/at carrier density.
- Physics: 2-D electron and hole systems with increasingly complex energy band structures that allows the probing into the complex world of correlated behaviors.

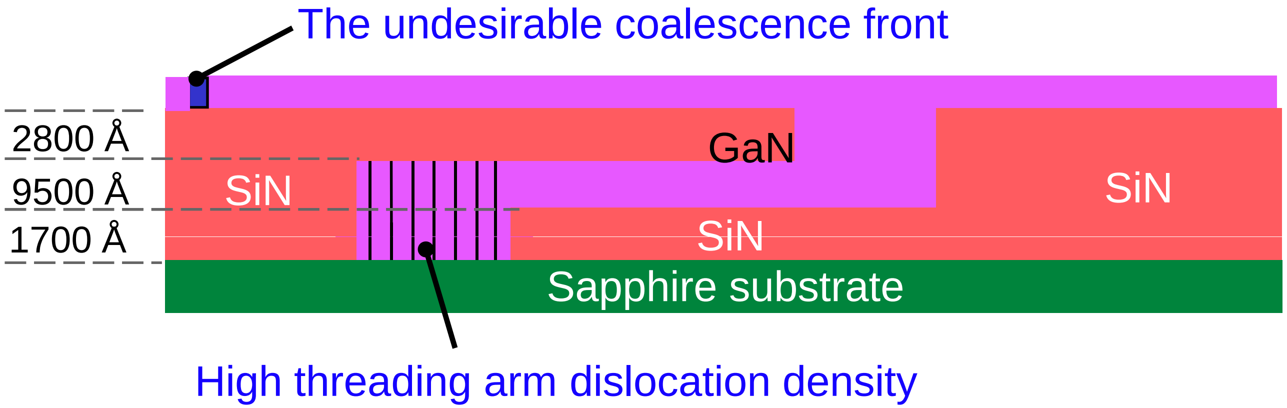
and other Epitaxy related

Research activities in the Semiconductor Materials Research Laboratory

Selective-Epi of GaN using Patterned Substrates

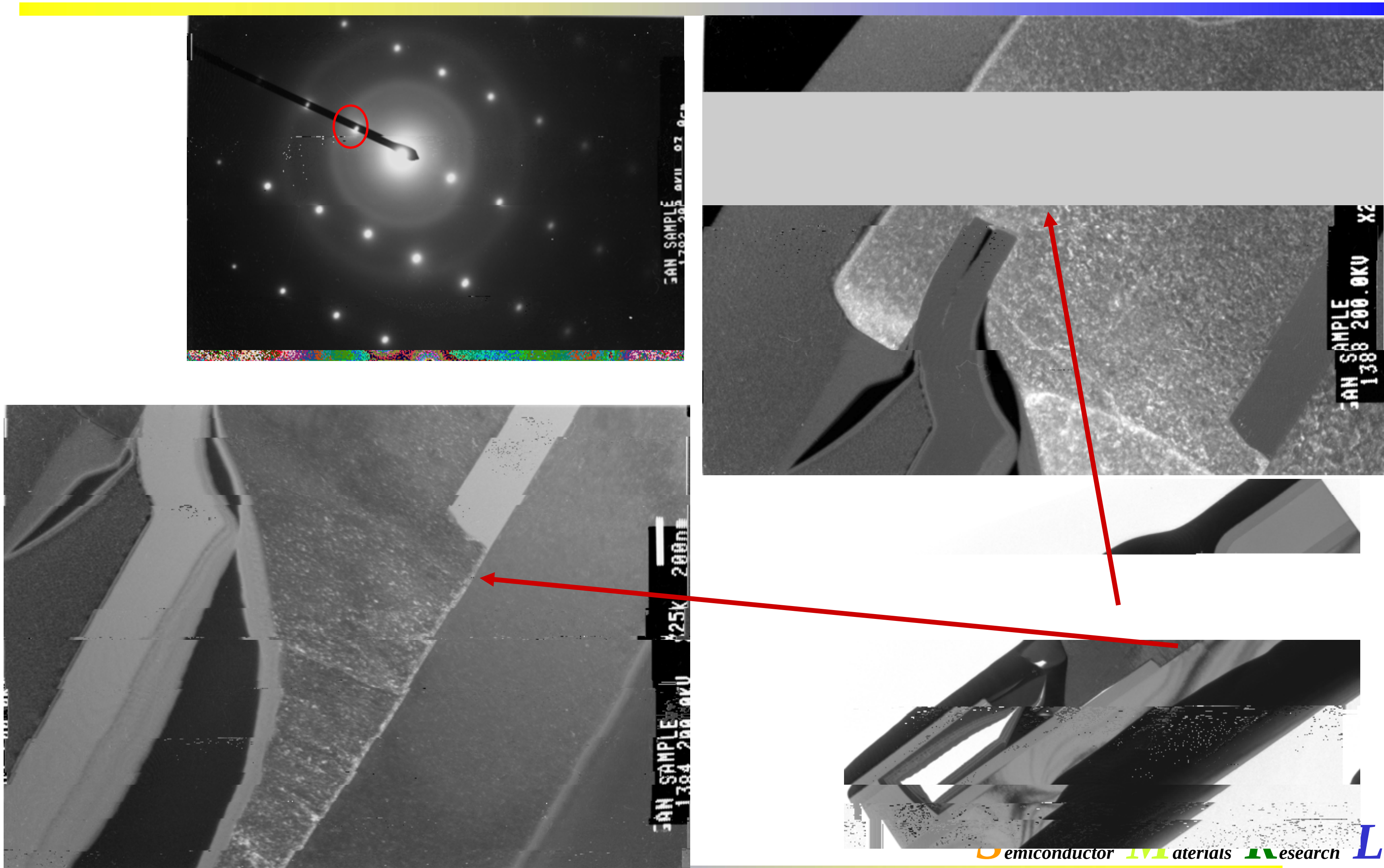
in collaboration with S.J. Chang, Y.K. Su & groups at National ChengKung University, Taiwan





U.S. Patent Number 6,495,385, December 17, 2002: "Hetero-integration of Dissimilar Semiconductor Materials," Y.H. Xie

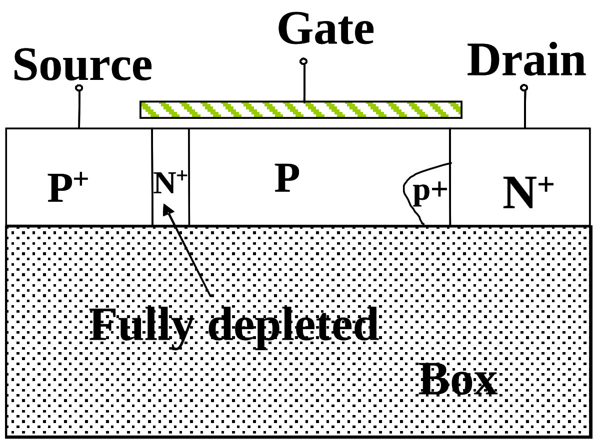
Dark-field Transmission Electron Micrographs of GaN on Sapphire



Scalable Silicon Tunnel Transistor Technology for Low Power Circuits (S2T3)

DARPA STEEP Program

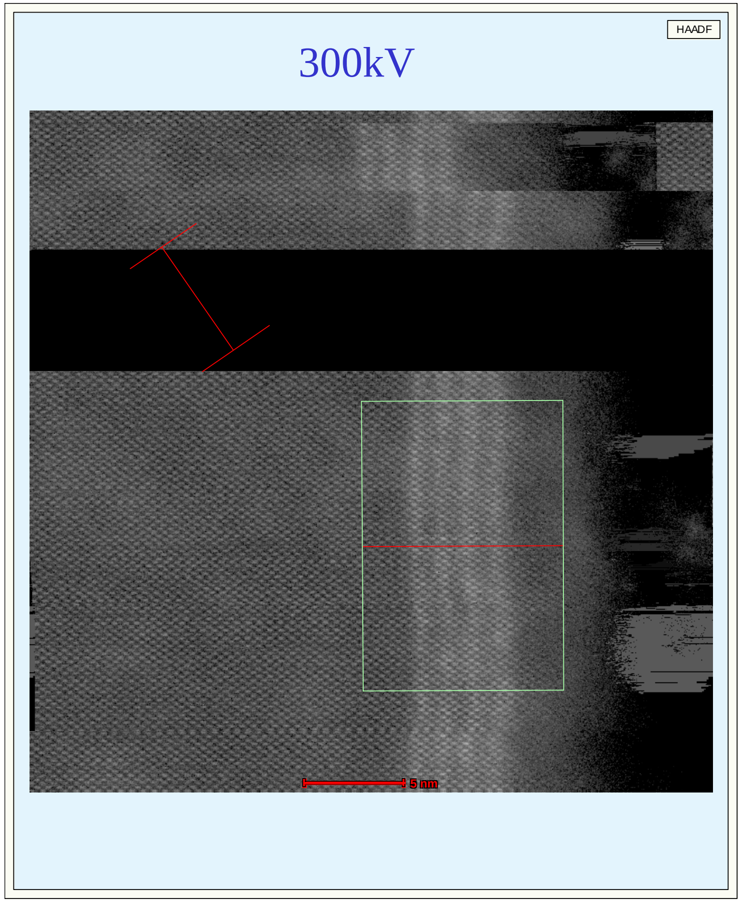
Jason Woo, PI, EE UCLA

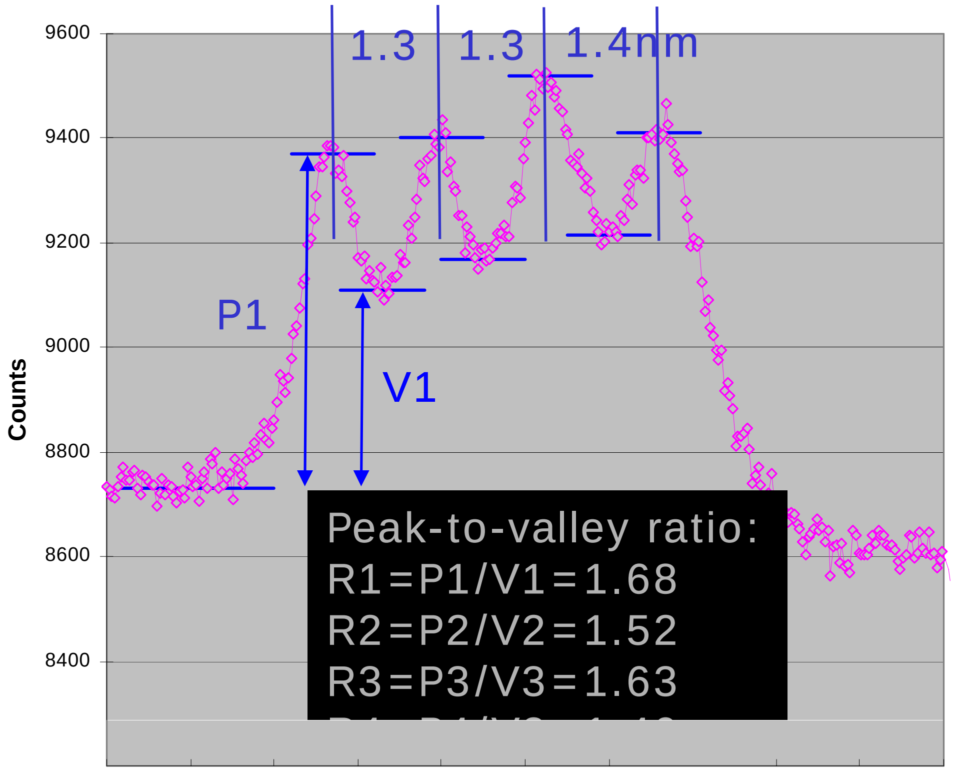


Requirements:
- Carrier concentration as high as possible;
- Abrupt doping concentration gradient.

Materials science challenge:
- High dopant concentration while maintaining 100% in substitutional sites;
- Minimize diffusion while maintaining "good" crystalline quality in terms of point defects.

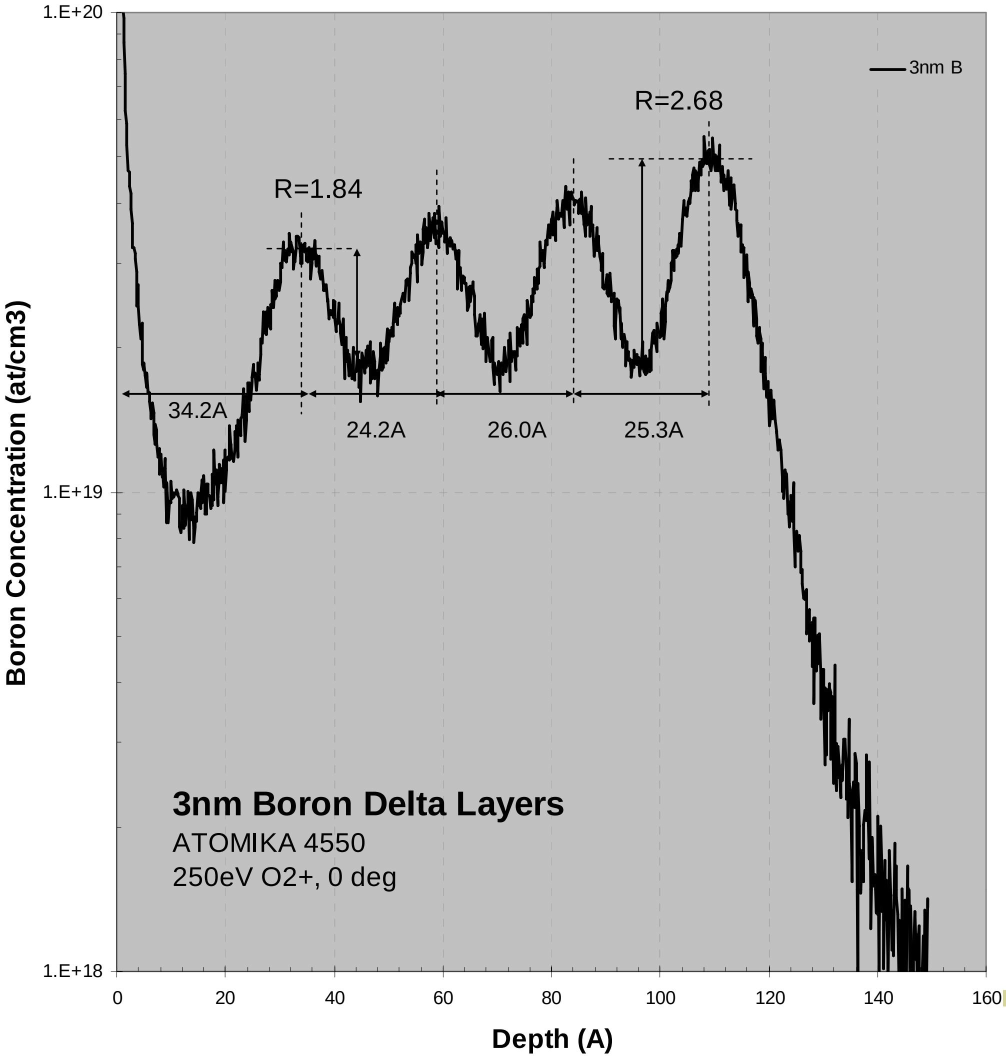
HRTEM of Ge Spikes Separated by 1 nm Si on Si (001)





Pushing the Limit on the Abruptness of Compositional Transition

collaboration with Intel @ Oregon



B spikes separated by 3 nm using SIMS with trailing edge slope > 2 nm/dec;

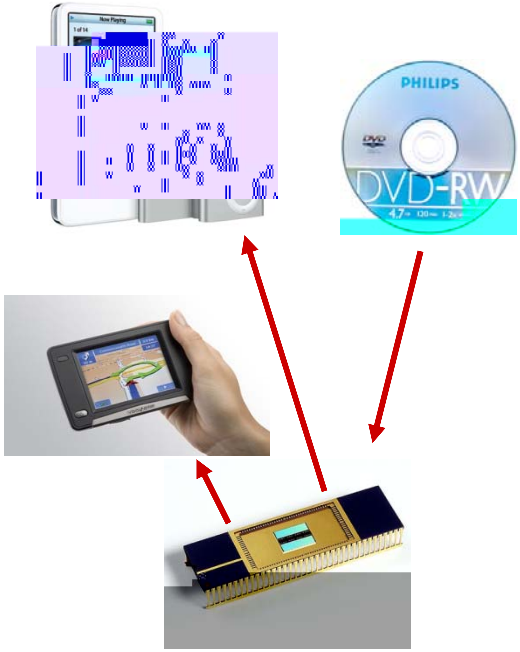
Semiconductor Materials Research Lab

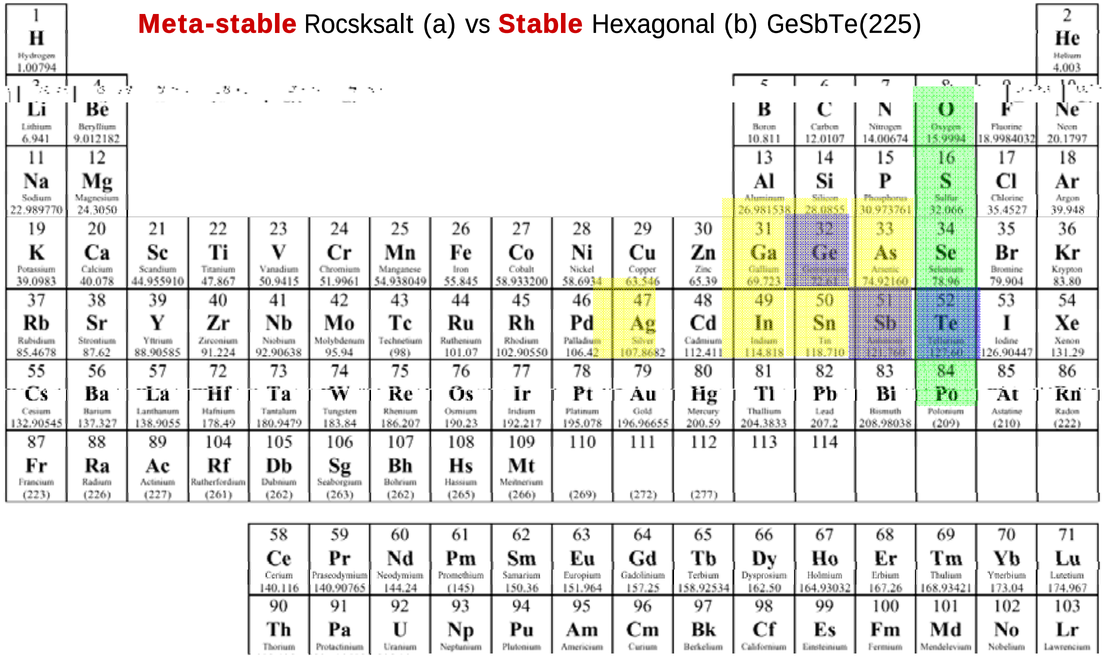
The rise of graphene

and other Non-epitaxy

Research activities in the Semiconductor Materials Research Laboratory

Understanding the Scaling Limit of PcRAM Technology of Chalcogenide Materials





A.L. Lacaita / Solid-State Electronics 50 (2006) 24–31, Phys. Rev. Lett. 96, 055507 (2006)

Characteristic features: significant difference in optical and electrical properties between amorphous and poly-crystalline states.

From optical memory to electronic memory: the size of the programming volume.

The Topics of Research of Our Group

1. The minimum size required for the existence of 3 distinguishable phases in chalcogenide materials (amorphous, FCC, and HCP);

2. The phase change kinetics as a function of the volume: the effects of interface and surface;

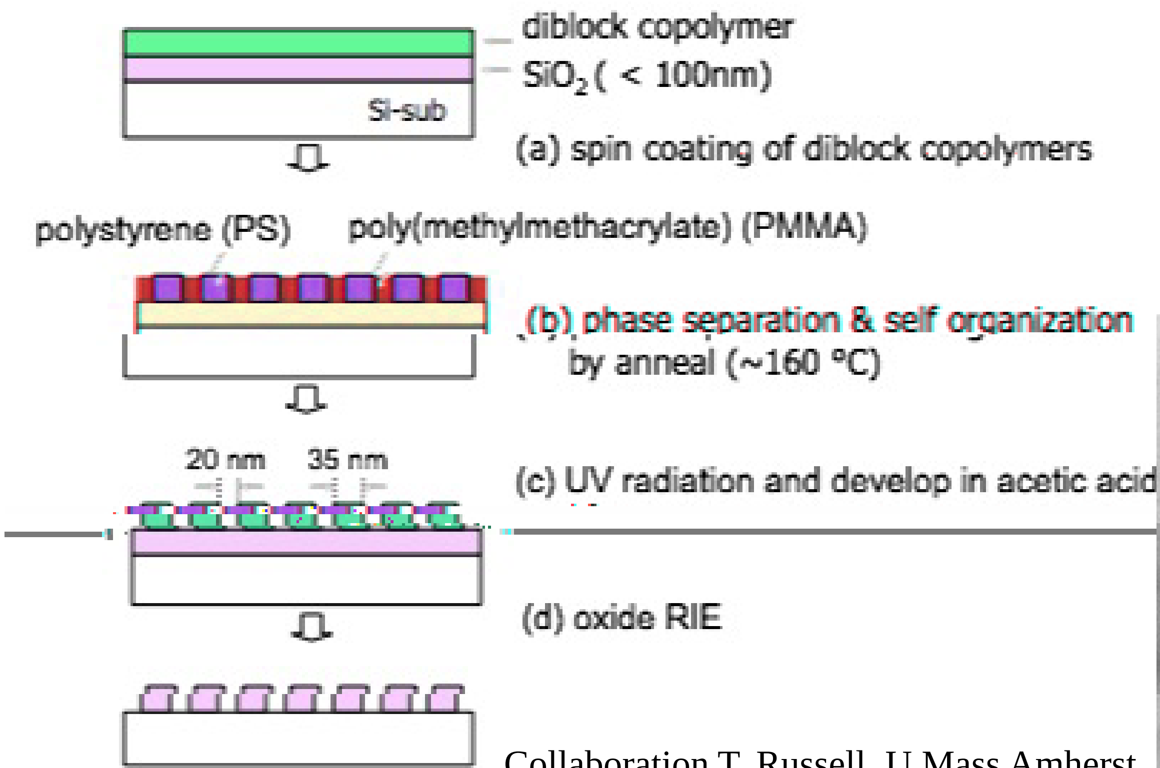
3. The cross-over from nucleation dominated crystallization process to growth dominated regime with reducing volume;

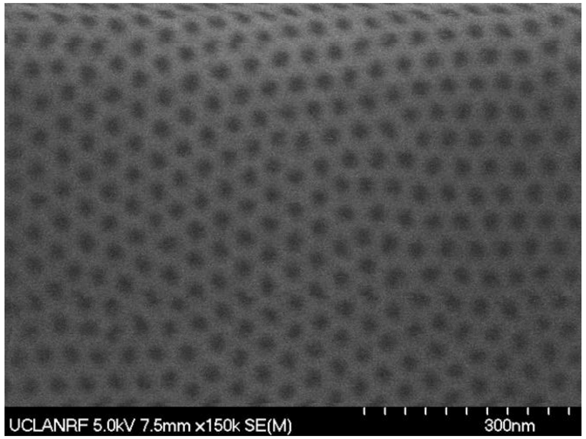
4. Assessment of thermal proximity effect and the implication on technology scaling limit.

Work in progress

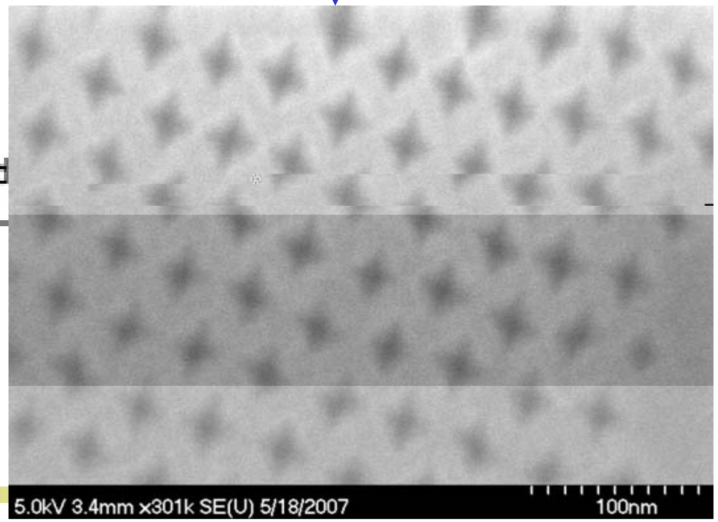
Nano-Patterning: the prerequisite for our research

Requirement: large area uniform coverage of nanometer dimension features



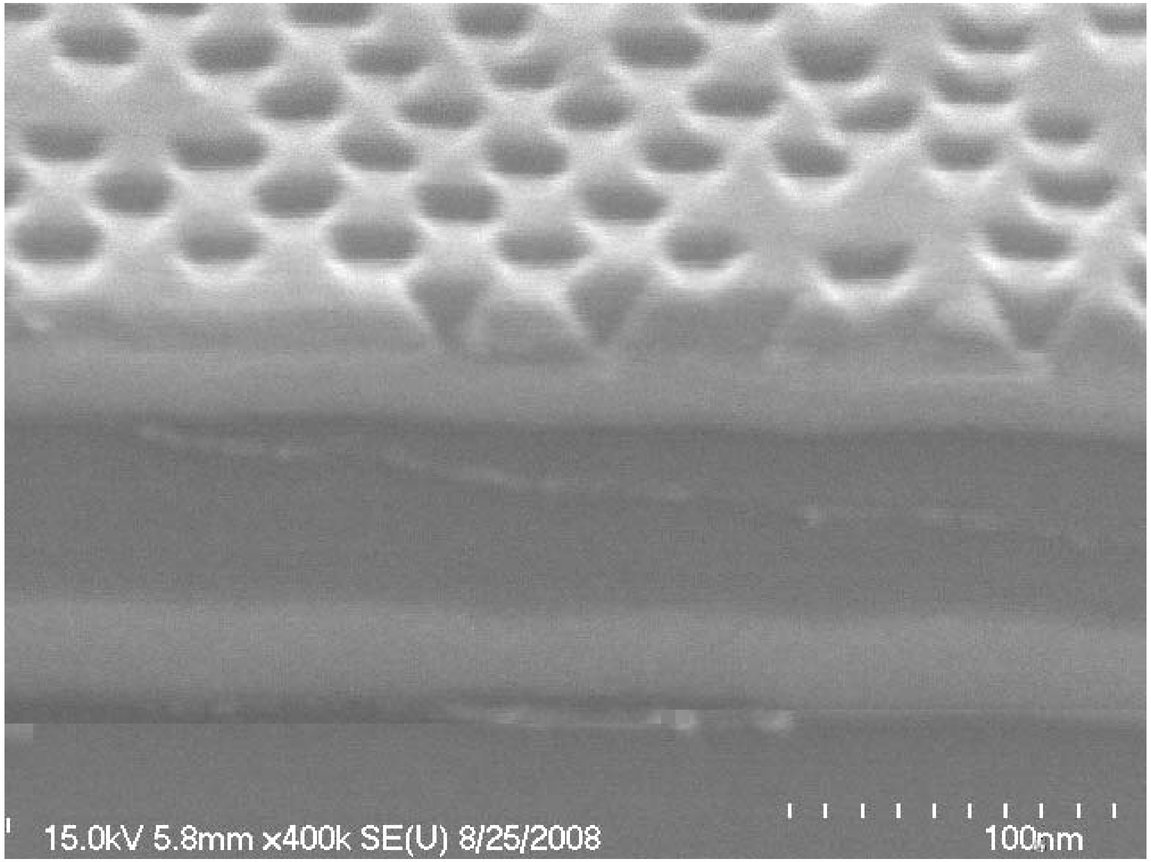


KOH



Collaboration T. Russell, U Mass Amherst

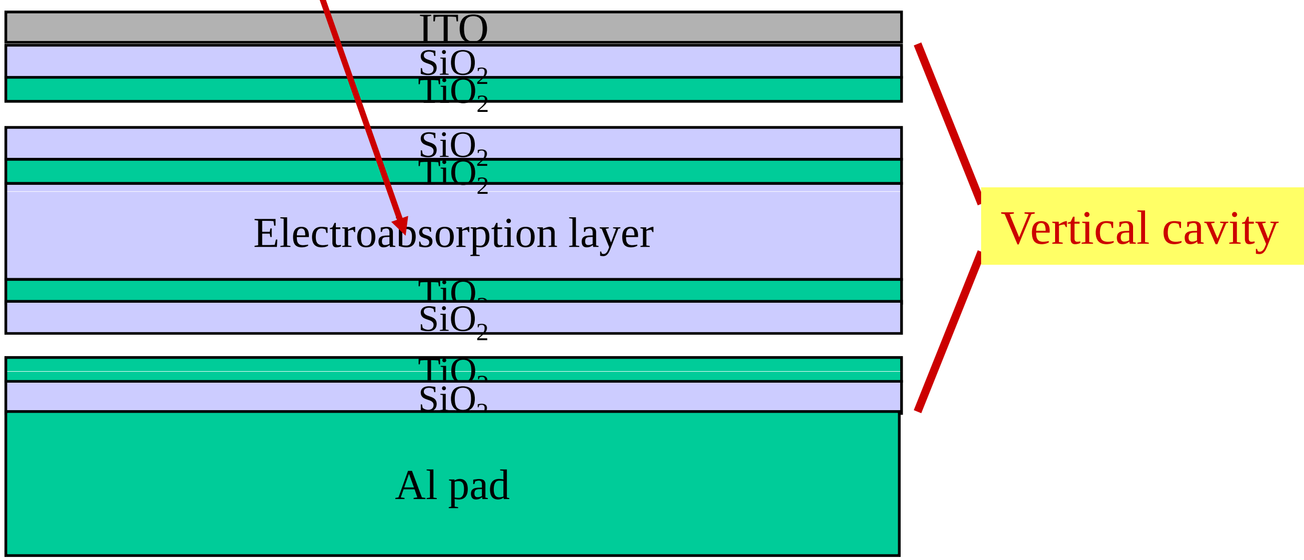
Nano-Patterning: the prerequisite for our research



A Quantum Dot Based Electro-optic Modulator

Schematics of Our Quantum Dot Based Modulator Structure

- Using **semiconductor quantum dots** operating near saturation absorption as the electro-absorption medium;
- Employing a dielectric vertical cavity for signal (both the pumping light intensity and the modulation effect) amplification;
- A capacitor as opposed to a current injection device from the circuit perspective;
- Inherently compatible with 2D array architecture.

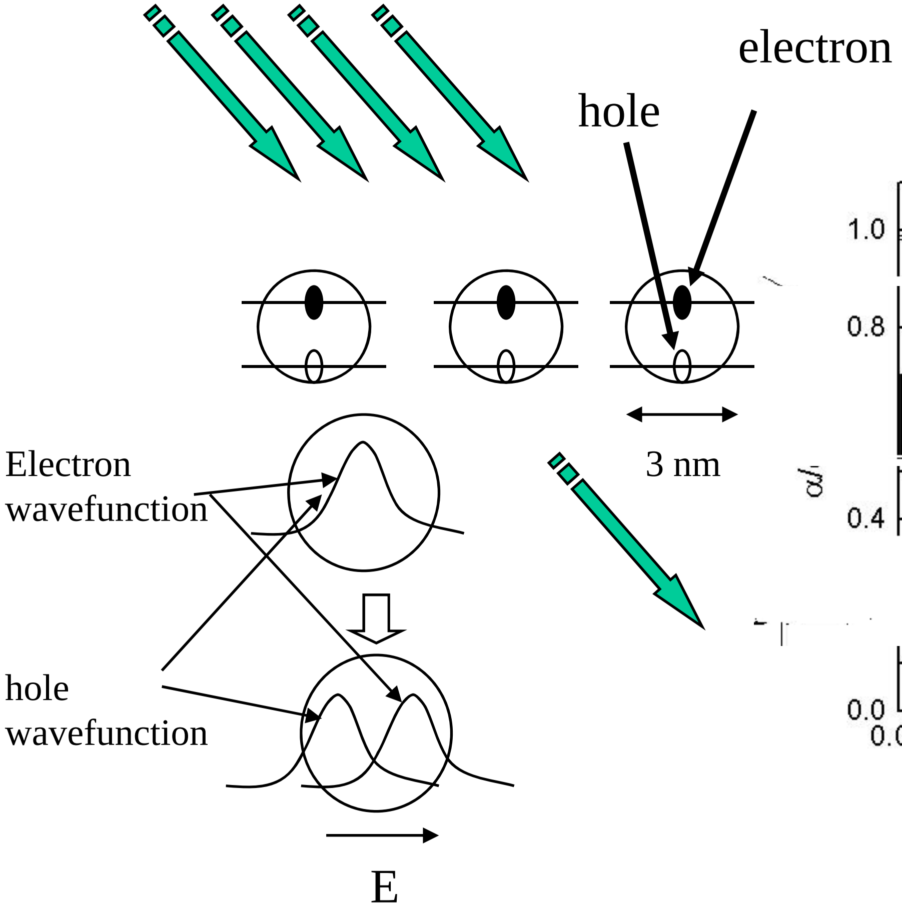


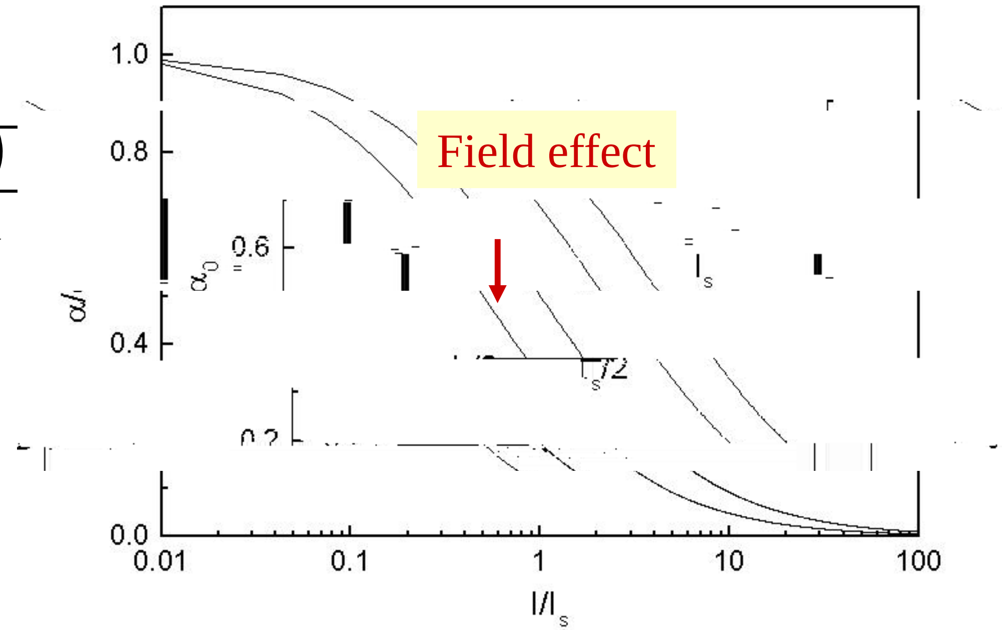
The function of the vertical cavity: amplification.

Quantum Dot Absorption under External Electric Field

Saturation absorption of QDs

$$\alpha = \frac{\alpha_0}{1 + I / I_s}$$





RF Crosstalk Isolation Technology

Substrate impedance engineering

Substrate impedance engineering for Si mixed-signal integrated circuit applications:

- Integration of higTQBT0 1 gsq0 65ati4gTQBT0 97.8 275.7tsive6 12217054.00275D.8(nte63ation compone

Acknowledgement

- **Graduate students**:

  Karen Li, Jae-Young Lee, Janet Wen Feng, Jian Liu, Jeehwan Kim, Bin Shi, Ke Sun, P. Sam Chang, Engdu Workneh, Seife Wooldeyesus, Albert Lipson;

- **Postdoctoral fellows:**

  ZuoMing Zhao, HyungJun Kim; JoonYeon Chang, YoungMin Kim, Oksana Hulko;

- **Collaborators:**

  Chander Radhakrishnan, Mike Lo and Harold G. Monbouquette (Chem. E. UCLA)

  Keji Lai, Tzu-Ming Lu, Daniel Tsui (Princeton University)

  Ryu, Tom Russell (U. Mass Amhurst)

  Larry MingJoo Lee, E.A. Fitzgerald (MIT)

  Y.D. Jhou, S.J. Chang (NCKU)

  Aaron Gin, Alec Talin and JianYu Huang (CINT)

- **Funding agencies:**

  AFOSR, NSF, DARPA, SRC, ARO, ONR