Epitaxy for Physics Research and Device Applications:

and other
Research activities in the Semiconductor Materials Research Laboratory

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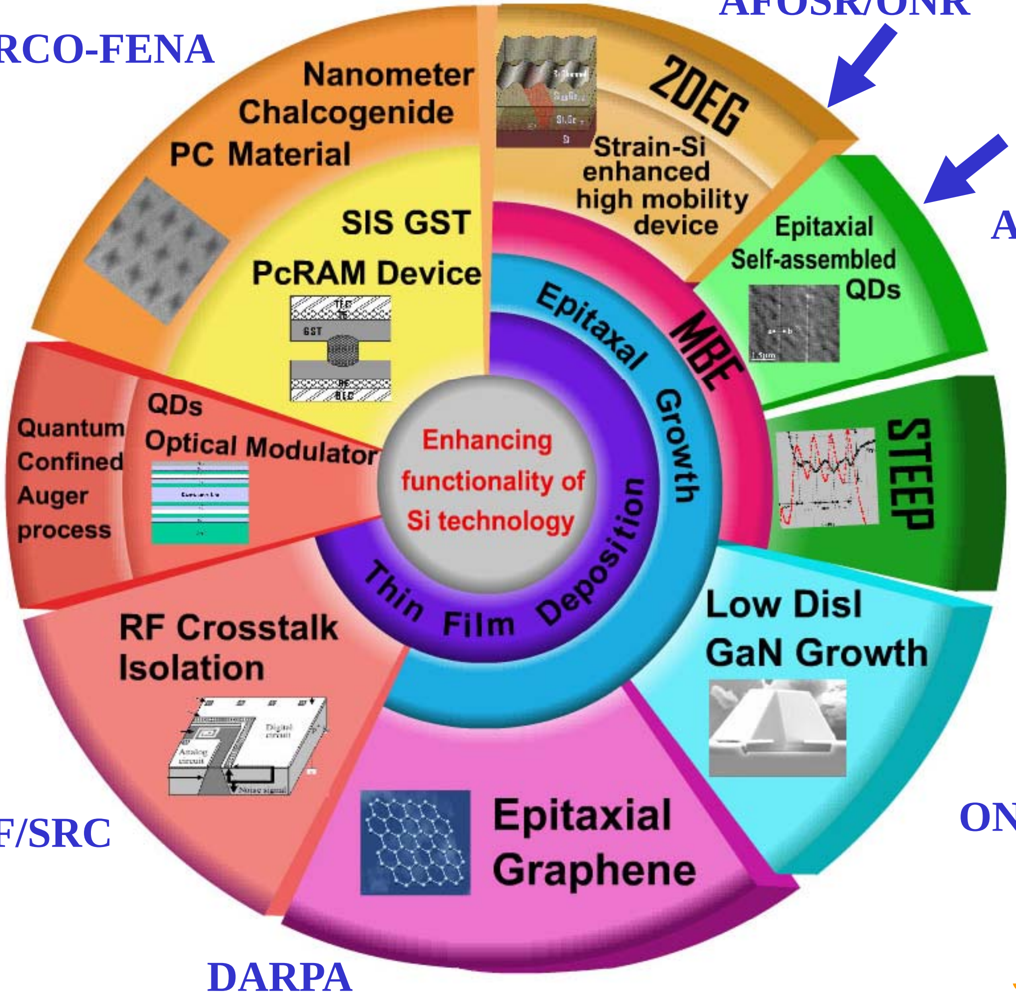
Outline



MARCO-FENA

AFOSR/ONR

ARO

DARPA

ONR

DARPA

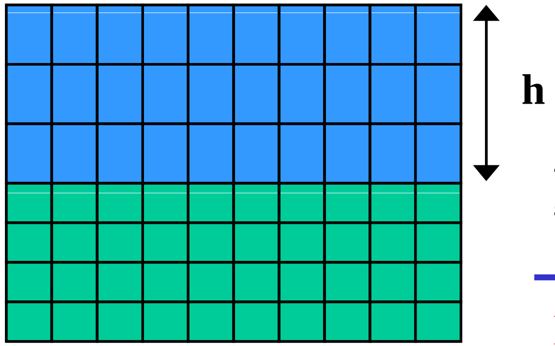
NSF/SRC

ARO

Epitaxy of Semiconductors for Physics Research and Device Applications

Fundamentals of Epitaxy

Hetero-epitaxy

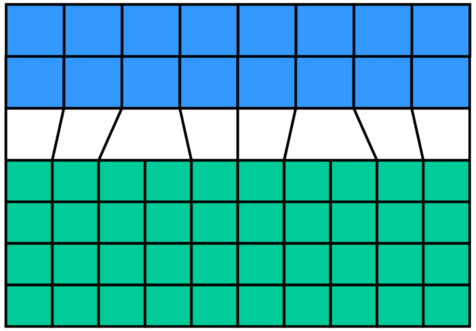


$$E_{\varepsilon} = B\varepsilon^2 h$$

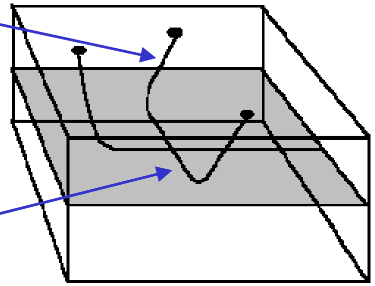
$$\textit{where} \qquad B = 2Y_s \frac{1+\nu}{1-\nu}$$

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

Plastic relaxation of misfit strain

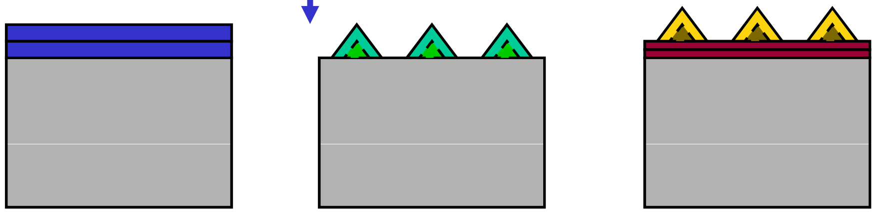


The importance of dislocation dynamics



2DES

Elastic relaxation of misfit strain



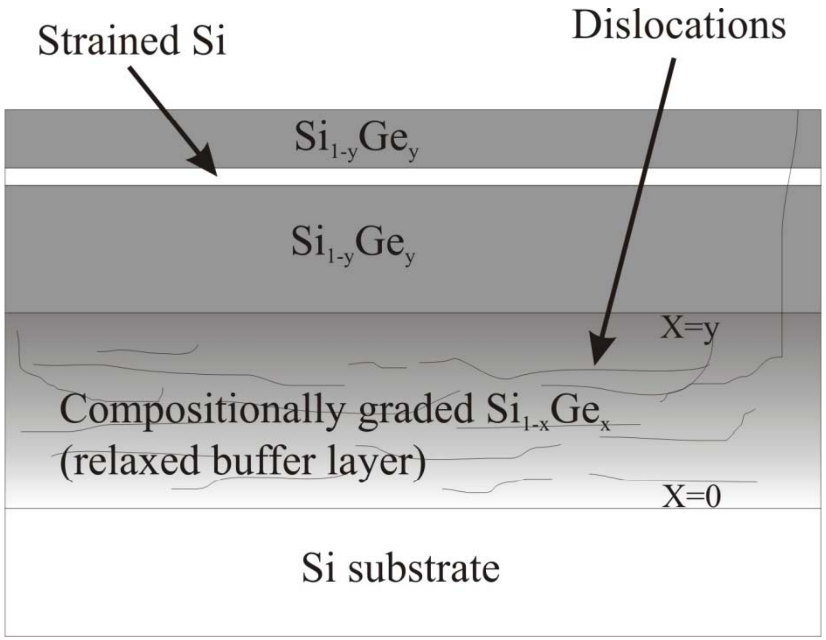
Self-assembled quantum dots

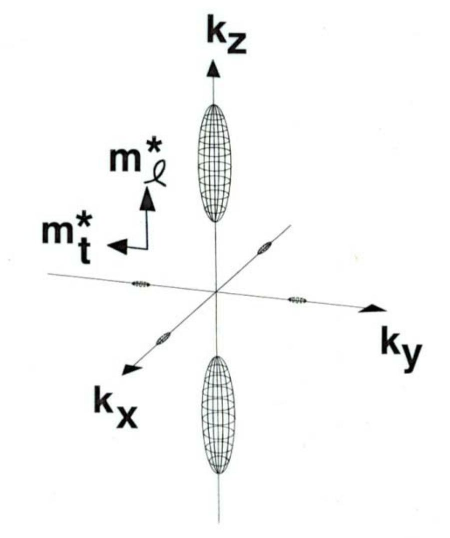
2D Electron System in Strained Si

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

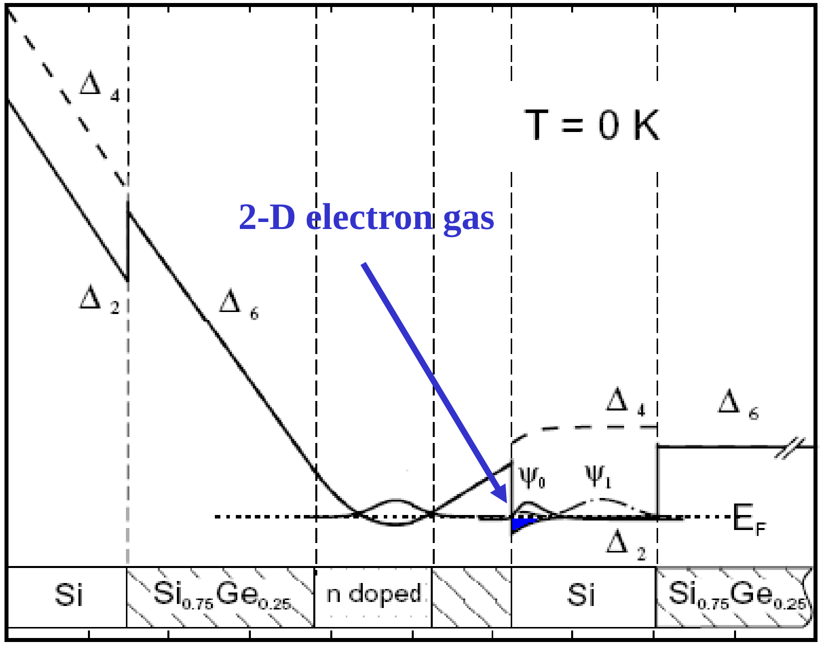
Other collaborations: Marc Kastner (MIT); Jagadeesh Moodera (MIT magnet lab)

- 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%;



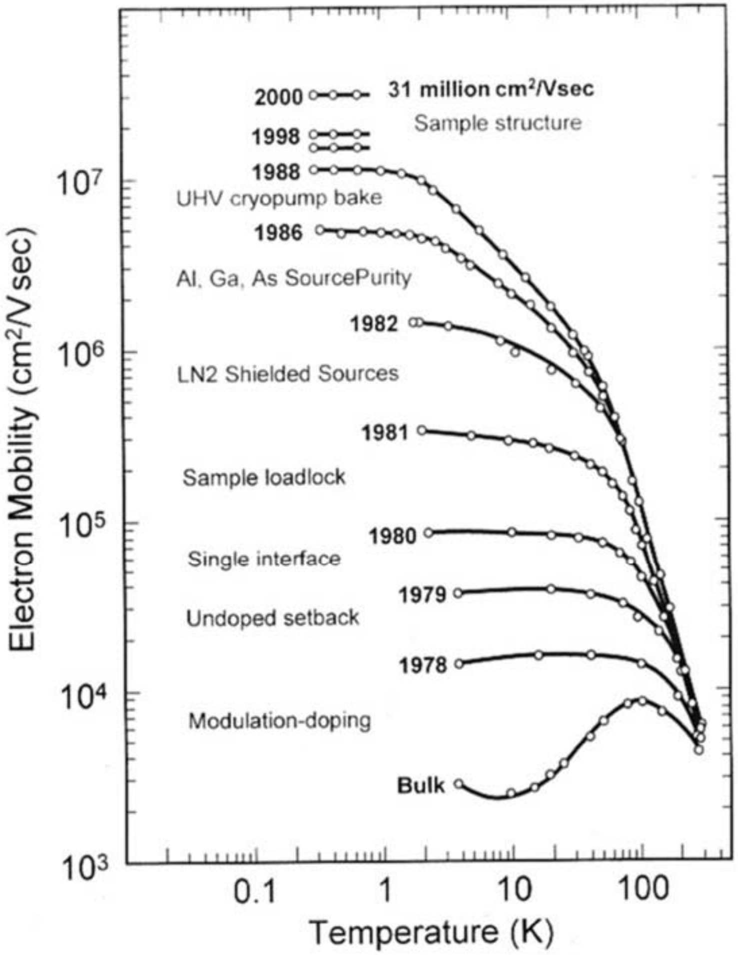


Modulation Doped 2DES



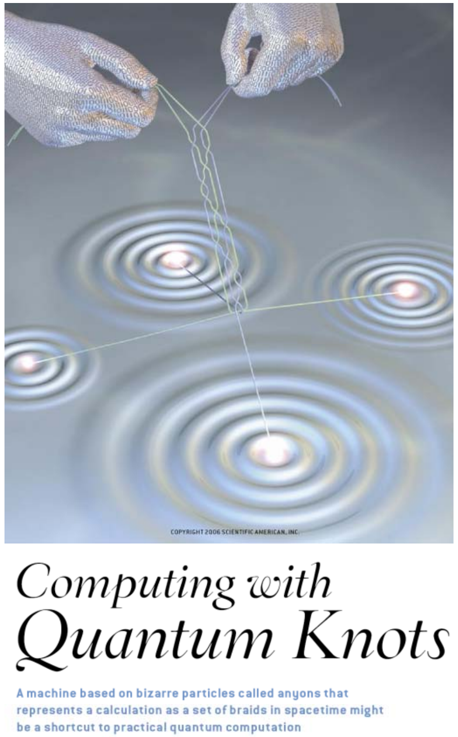
2-D electron gas

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;

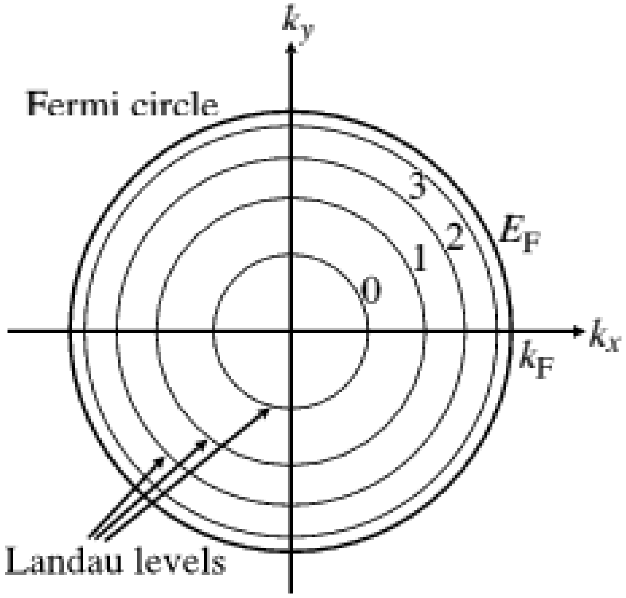


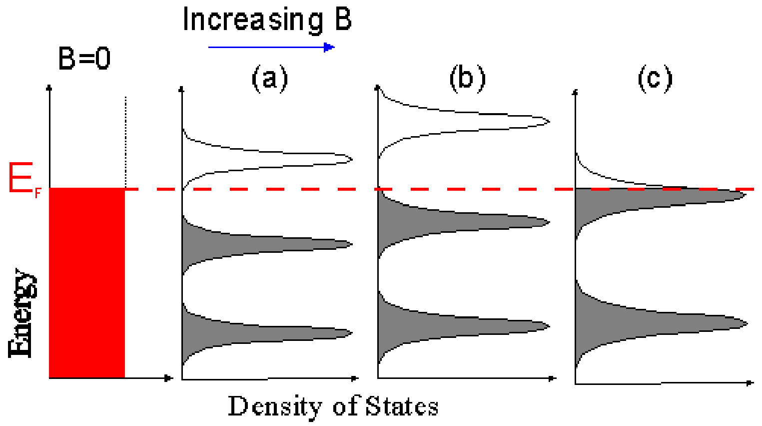
Computing with
Quantum Knots

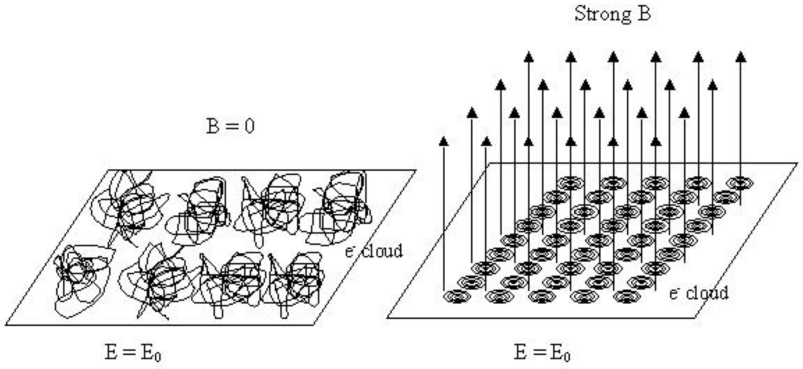
A machine based on bizarre particles called anyons that represents a calculation as a set of braids in spacetime might be a shortcut to practical quantum computation

Scientific American, p.56, April 2006,

Integer Quantum Hall Effect: electron localization







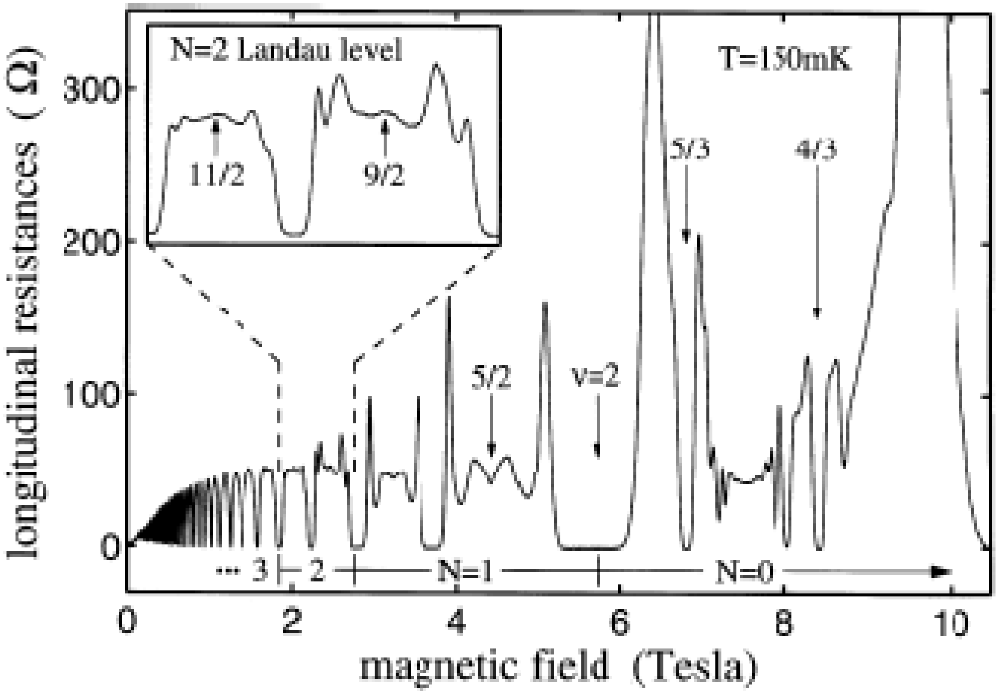
2D density of states of electrons (B=0):

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

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)



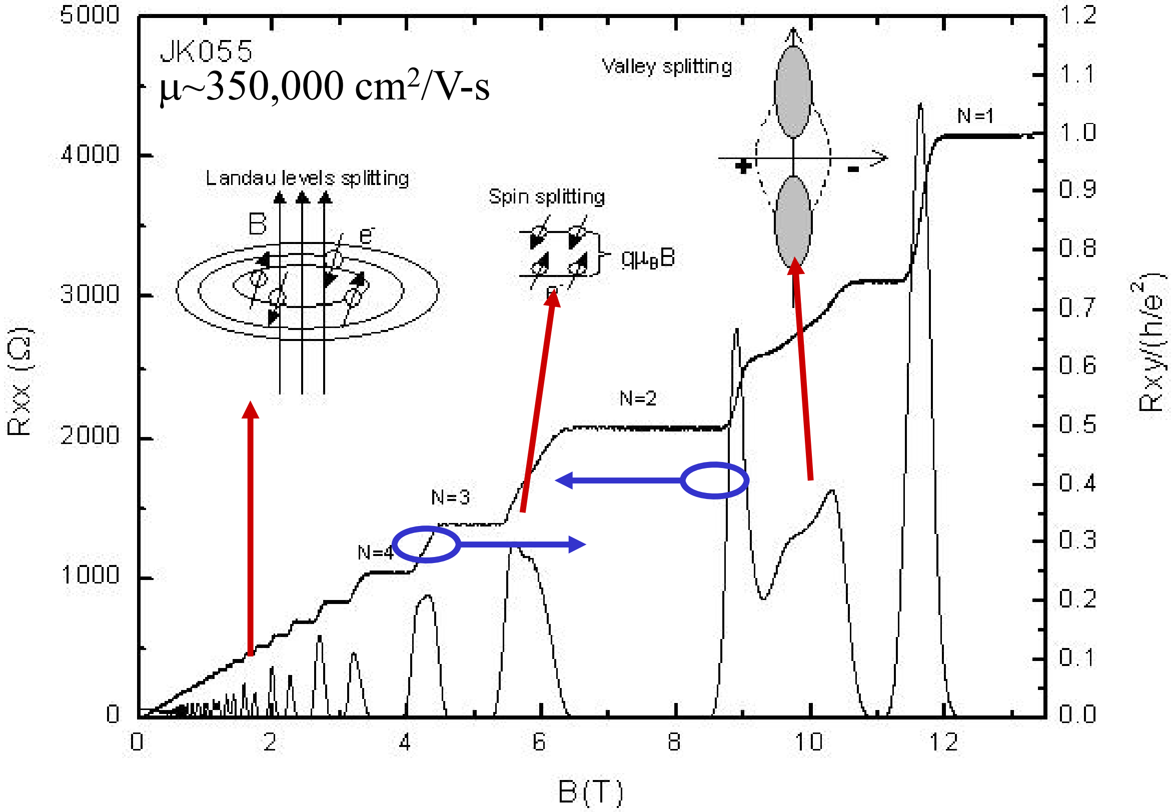
μ~11,000,000 cm^2/V-s
2DES in GaAs/AlGaAs

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 ever higher μ: identifying the dominant scattering mechanism

Semiconductor Materials Research Lab

The quest for lower 2DES density

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

The dimensionless density parameter:

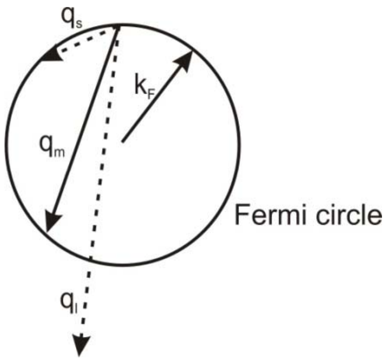
$$r_s = E_{e\text{-}e}/E_F$$

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.

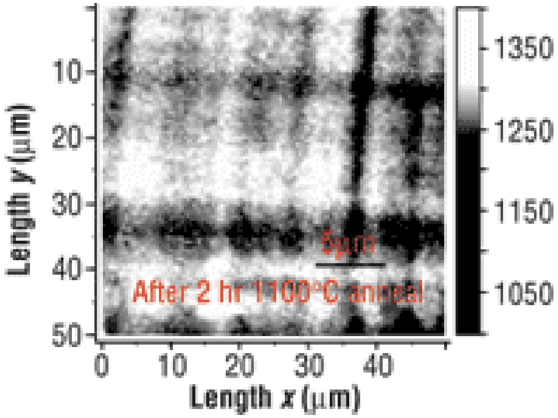


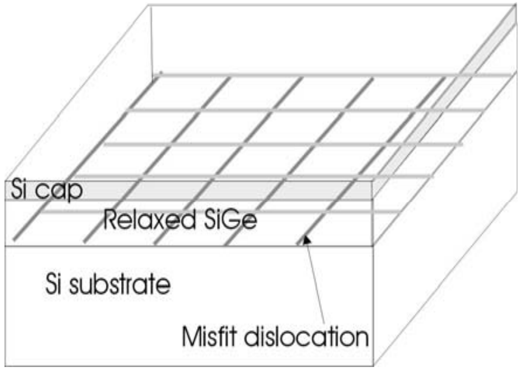
- The factors that could limit the achievable carrier density;
  - Localization induced by impurities and other inhomogeneity in the sample;
  - The uniqueness of 2DES in strained Si: another source for poor homogeneity.

The Challenges in Achieving Low 2DES Density

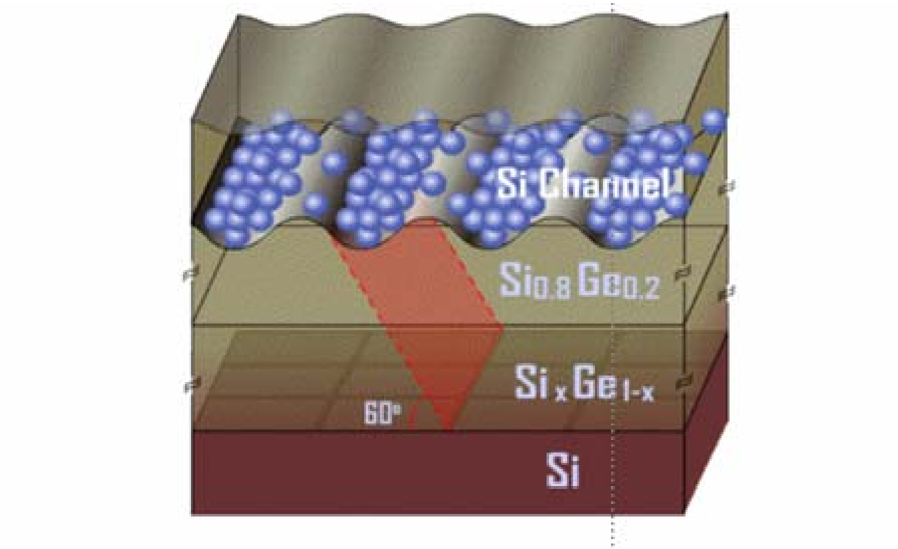
Raman Mapping of SSOI

(Mark Kennard, SOITEC)





Deformation potential calculation



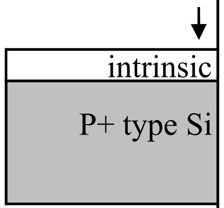
Amplitude of potential undulation: 7 meV
Spatial correlation: ~1 um;
Lower limit of carrier density : 5~6x10^{10}cm^{-2}

Alternatives: avoid dislocation

An alternative method for fabricating dislocation-free strained Si

Oxidation of poro

Epitaxial g
(100 nm~4



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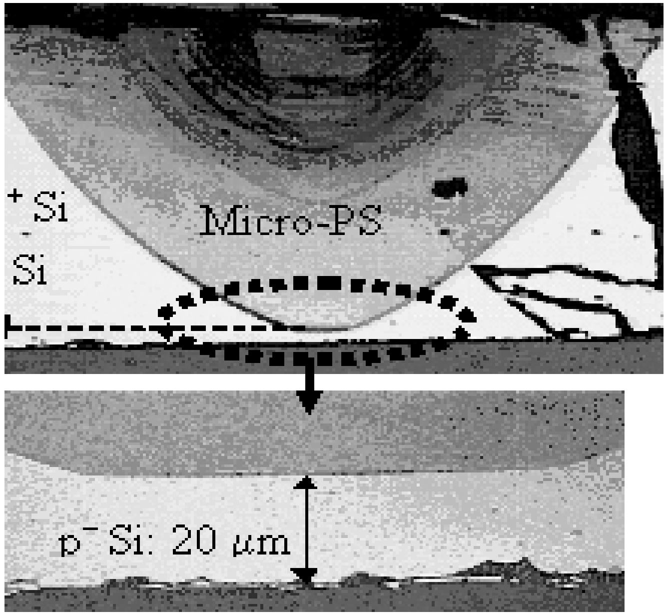
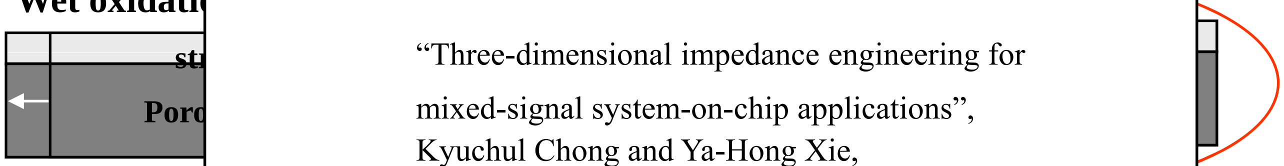
Platinum Film

trate



“Three-dimensional impedance engineering for mixed-signal system-on-chip applications”,
Kyuchul Chong and Ya-Hong Xie,
in “Si-based RFIC”, W.Z. Cai, Editor, p.153-216,
Transworld Research Publishers, publisher, 2006;

Wet oxidati



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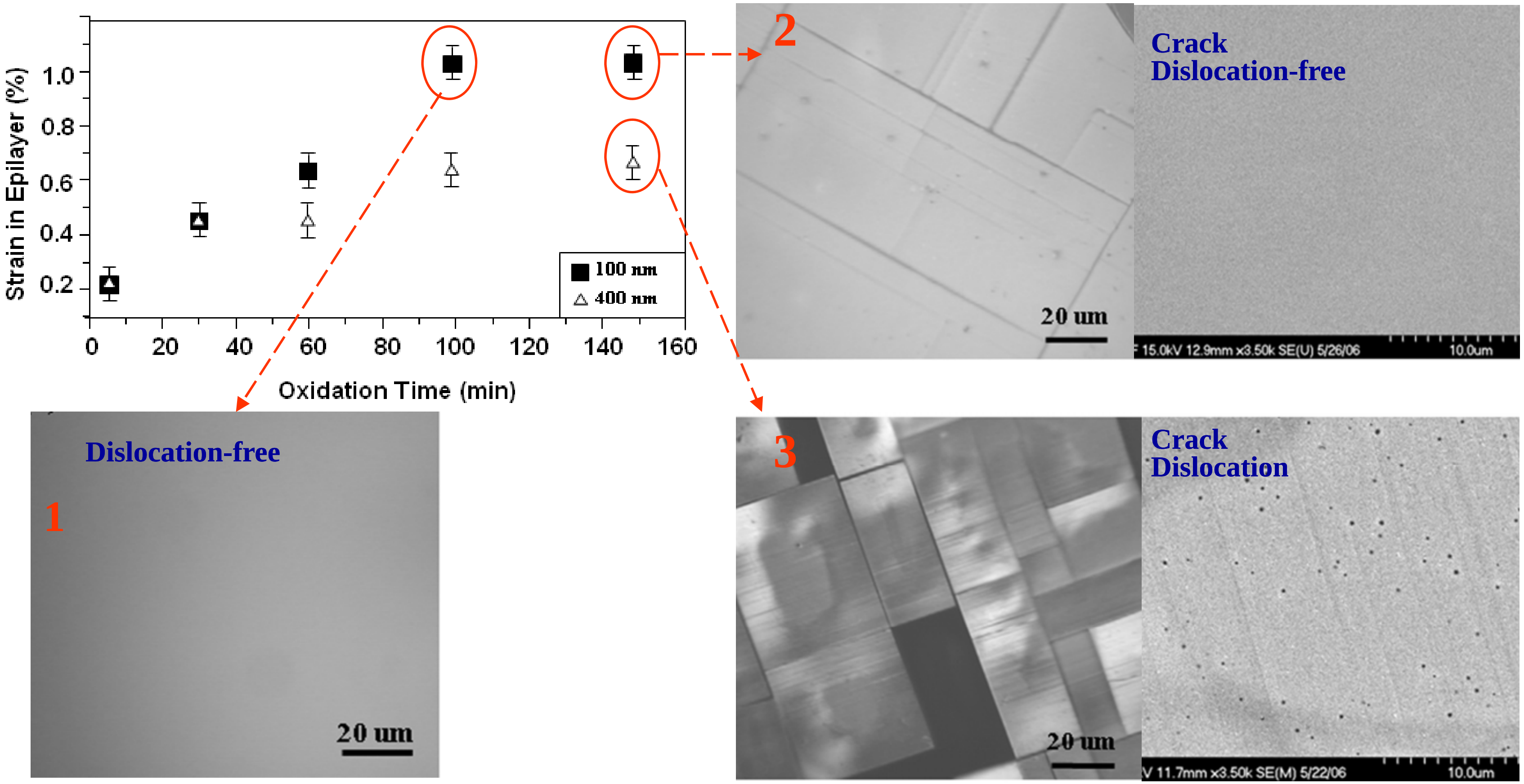
An alternative method for fabricating dislocation-free strained Si

After defect etch



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

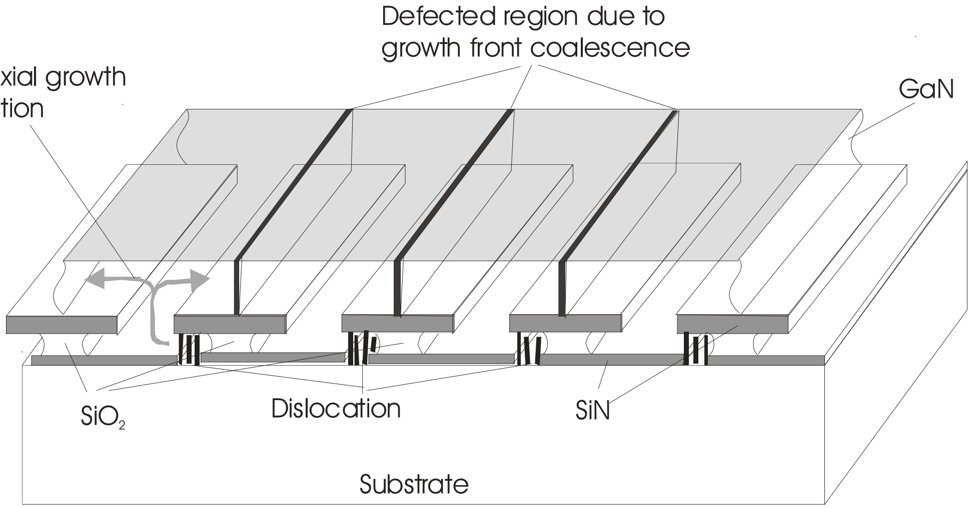
Summary of 2DES in Strained Si

- 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.

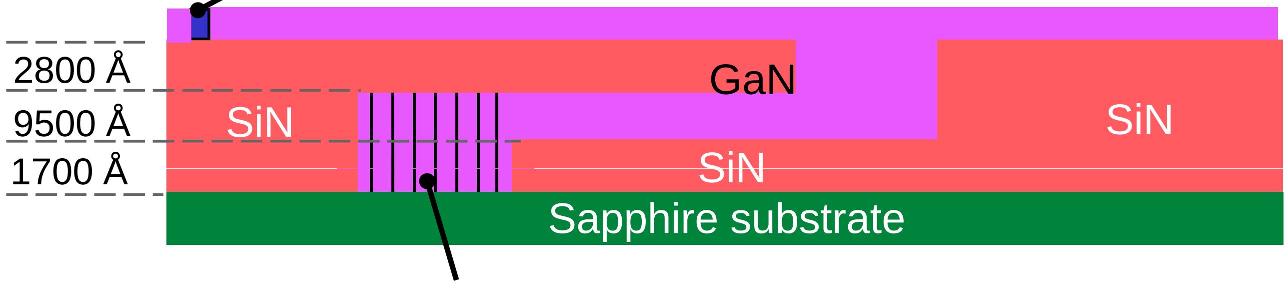
and other Epitaxy related
Research activities in the Semiconductor Materials Research Laboratory

Selective-Epi of GaN using Patterned Substrates

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



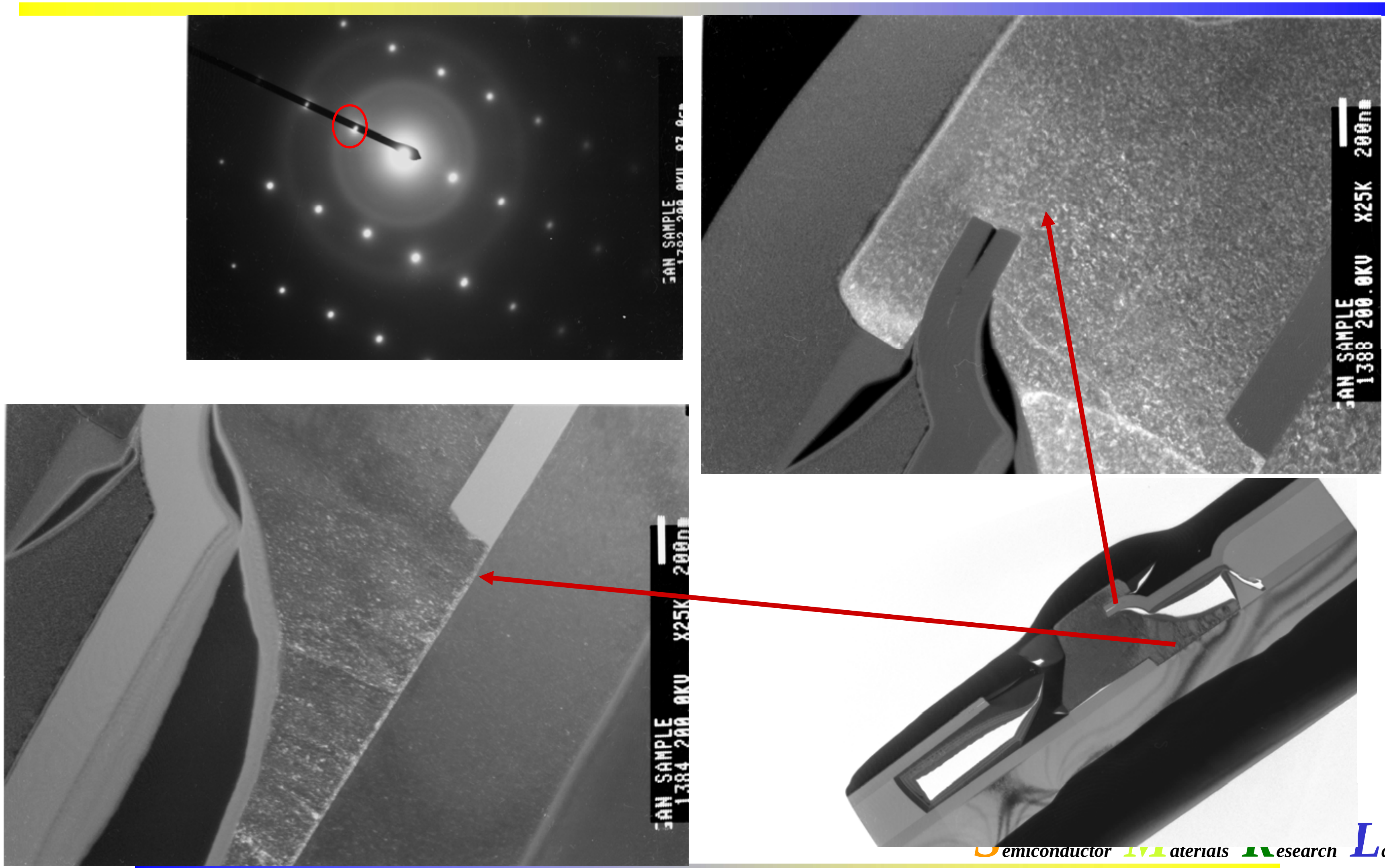
The undesirable coalescence front



High threading arm dislocation density

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

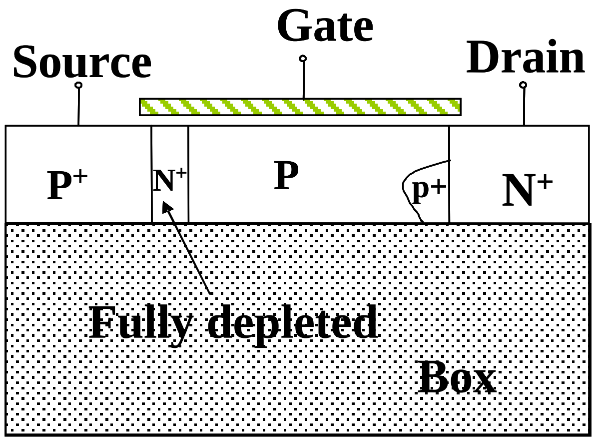
Dark-field Transmission Electron Micrographs of GaN on Sapphire



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

DARPA STEEP Program

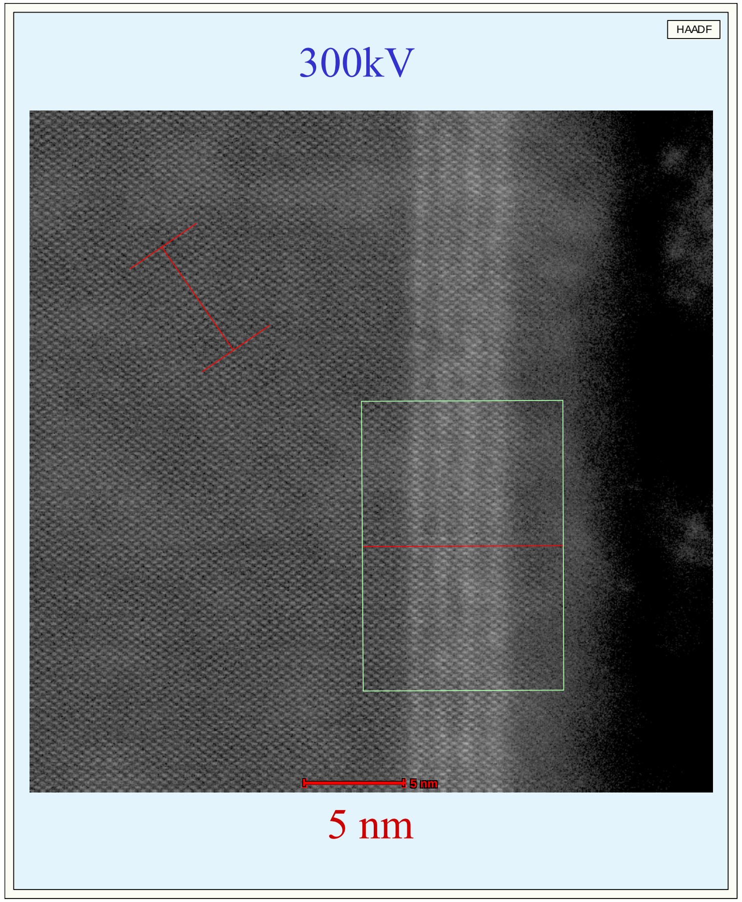
Jason Woo, PI, EE UCLA

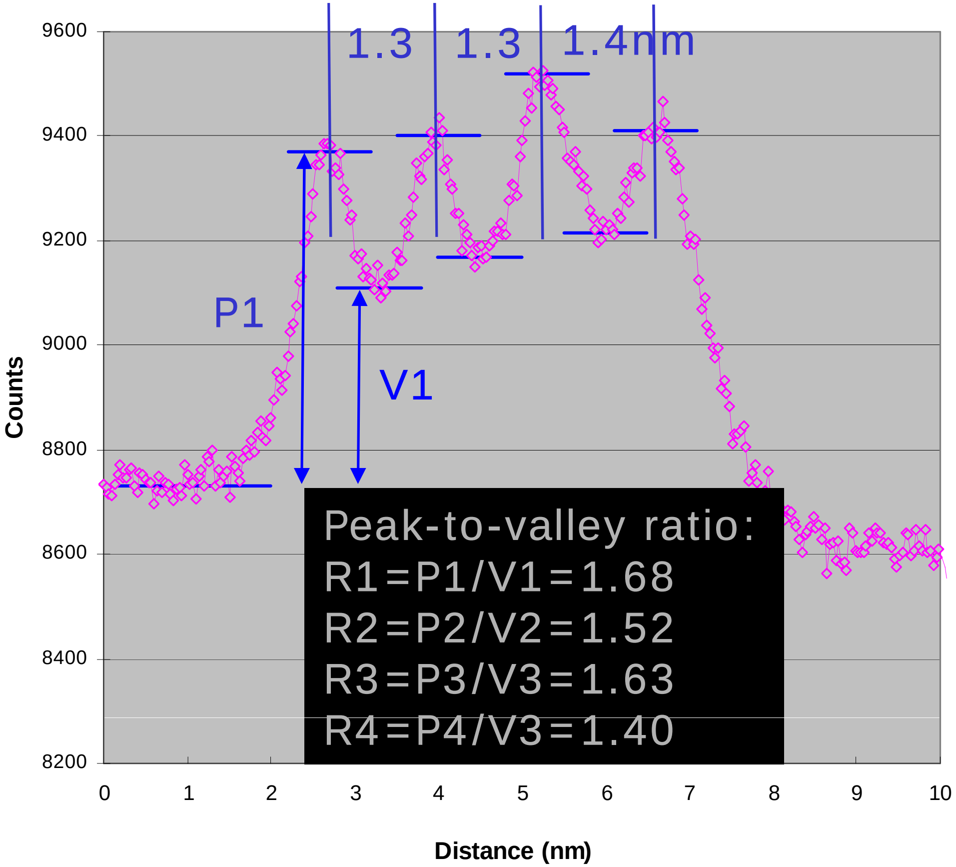


Requirements:
- Carrier concentration as high as possible;
- Abrupt doping concentration gradient.

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)

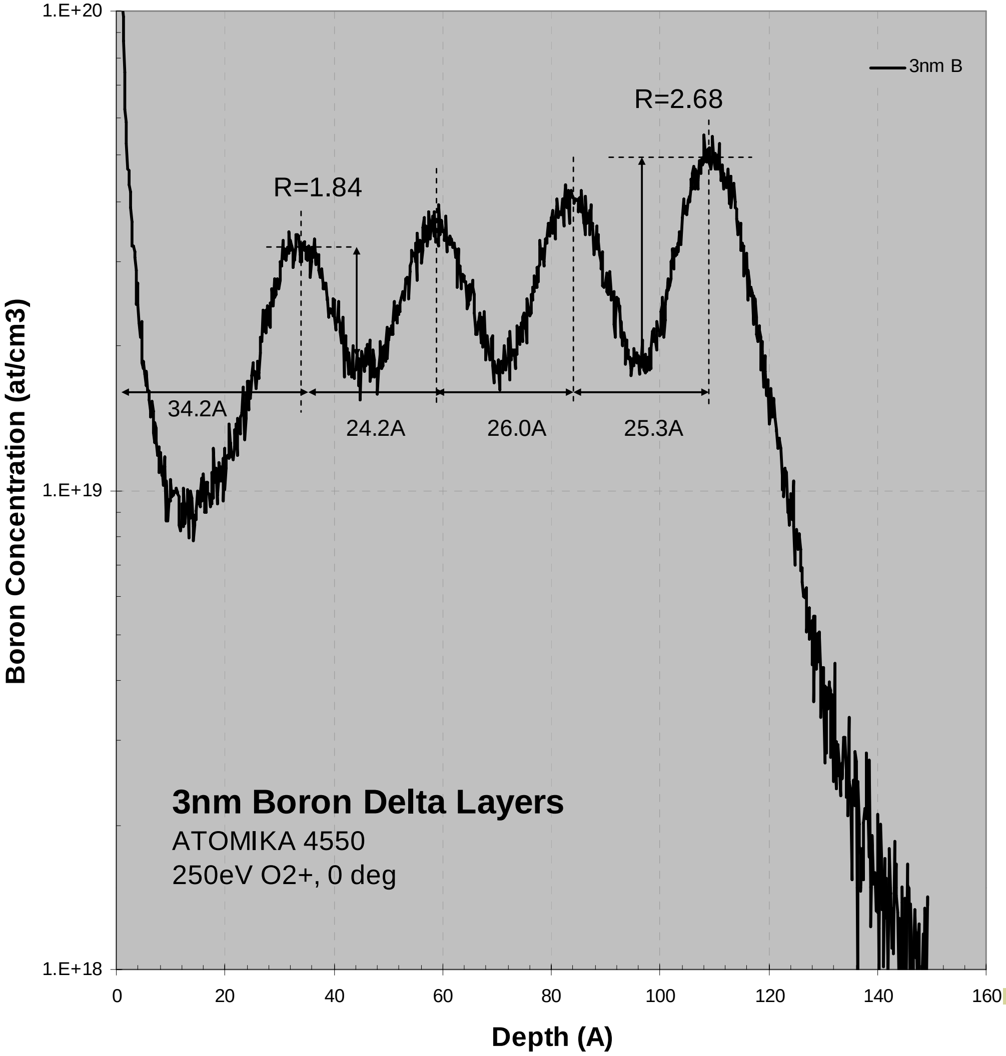




Peak-to-valley ratio:
R1=P1/V1=1.68
R2=P2/V2=1.52
R3=P3/V3=1.63
R4=P4/V3=1.40

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;

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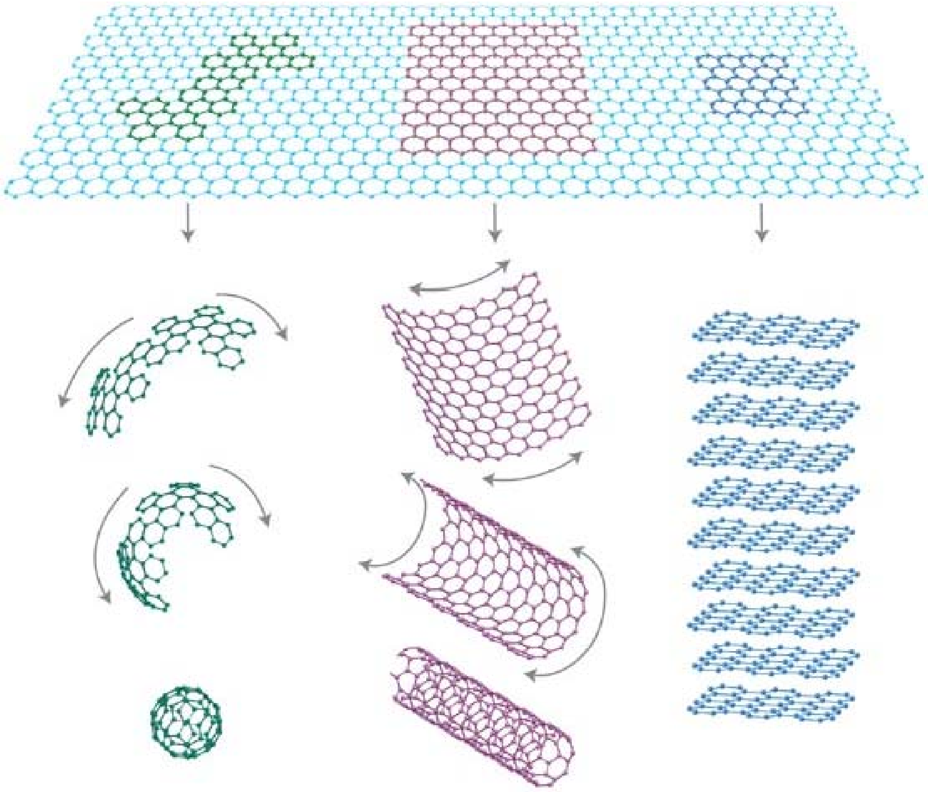
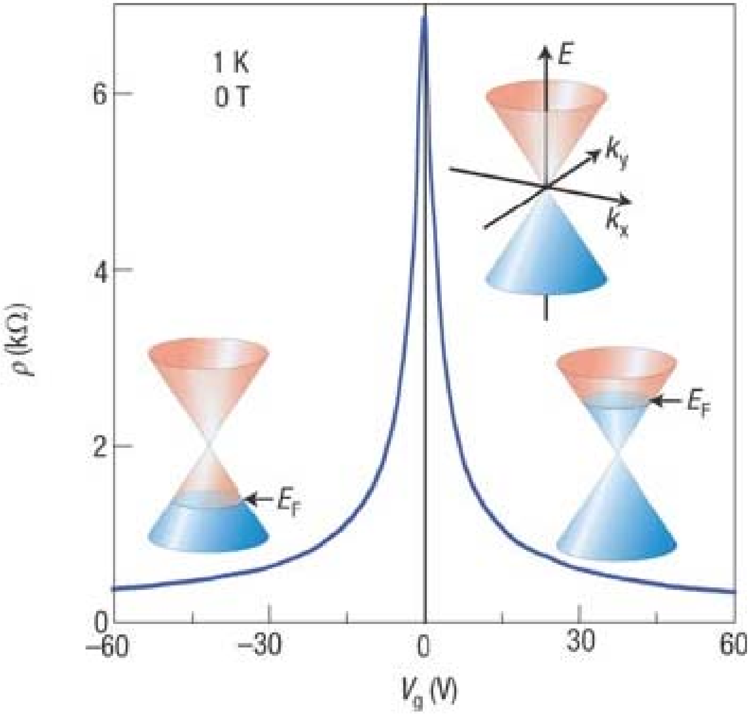
The rise of graphene

Jason Woo, PI, EE UCLA

The unique feature: highly anisotropic material



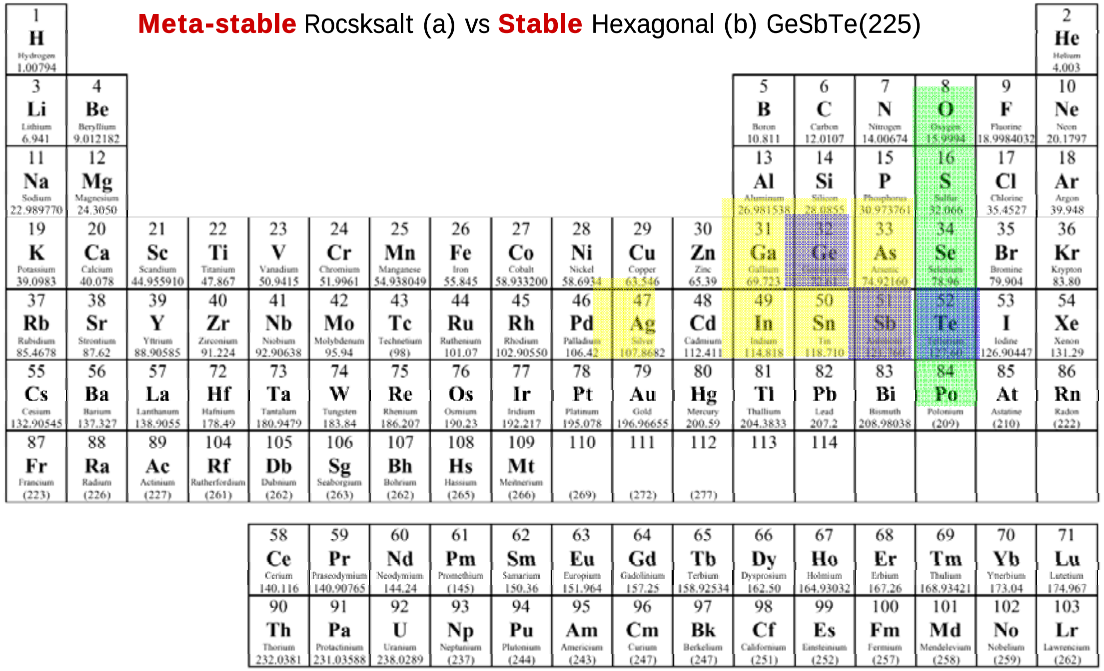
A. K. Geim1 and K. S. Novoselov, Nature Materials 6, 183 - 191 (2007)



The Challenge:
Wafer scale fabrication with
uniform (1 monolayer) thickness

and other Non-epitaxy
Research activities in the Semiconductor Materials Research Laboratory

Understanding the Scaling Limit of PcRAM Technology of Chalcogenide Materials



Meta-stable Rocsksalt (a) vs **Stable** Hexagonal (b) GeSbTe(225)

1 H Hydrogen 1.00794																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050											13 Al Aluminum 26.981538	14 Si Silicon 28.0855	15 P Phosphorus 30.973761	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955910	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 Co Cobalt 58.933200	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 La Lanthanum 138.9055	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.078	79 Au Gold 196.96655	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 (269)	111 (272)	112 (277)	113	114				

58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

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

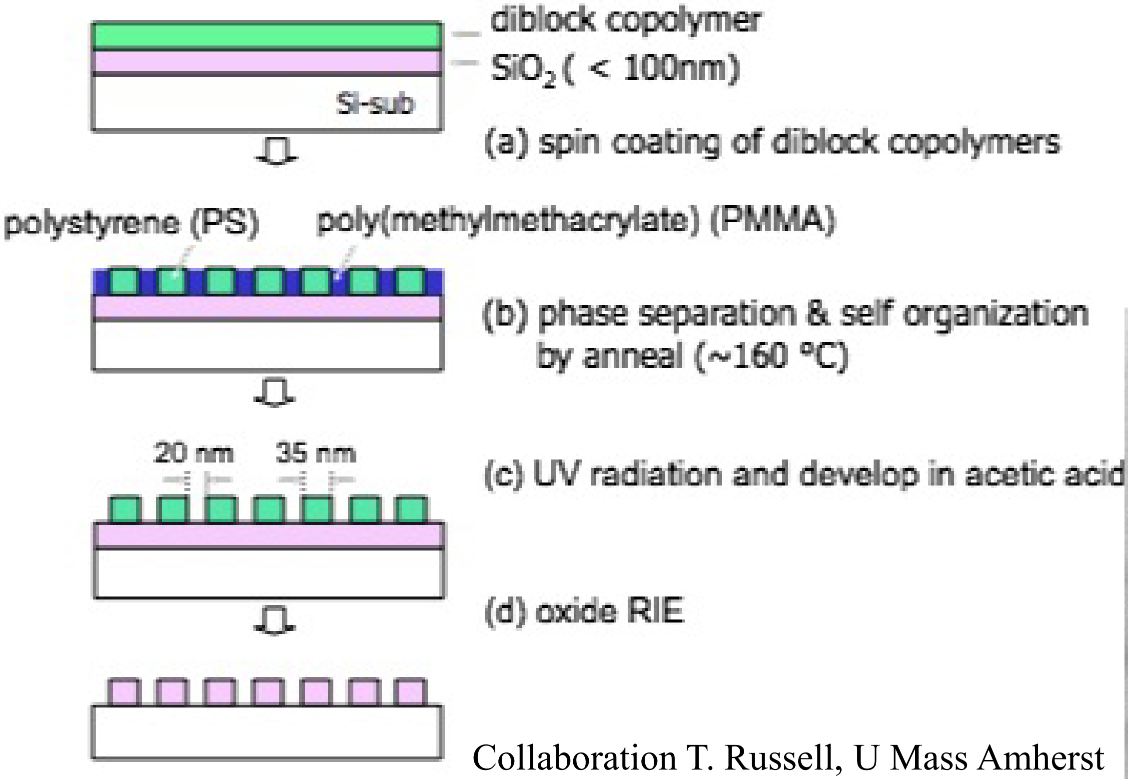
1. The minimum size required for the existence of 3 distinguishable phases in chalcogenide materials (amorphous, FCC, and HCP);
2. The phase change kinetics as a function of the volume: the effects of interface and surface;
3. The cross-over from nucleation dominated crystallization process to growth dominated regime with reducing volume;
4. Assessment of thermal proximity effect and the implication on technology scaling limit.

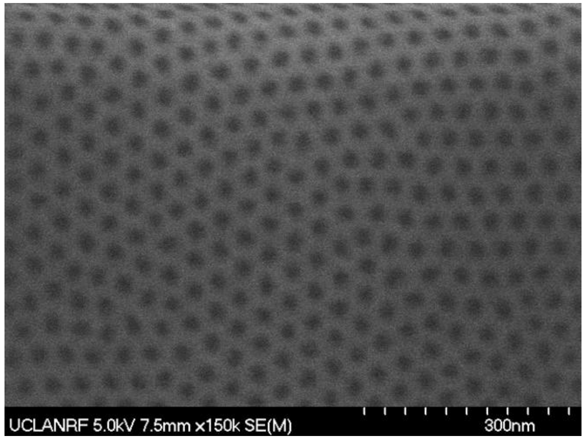
Work in progress

Nano-Patterning: the prerequisite for our research

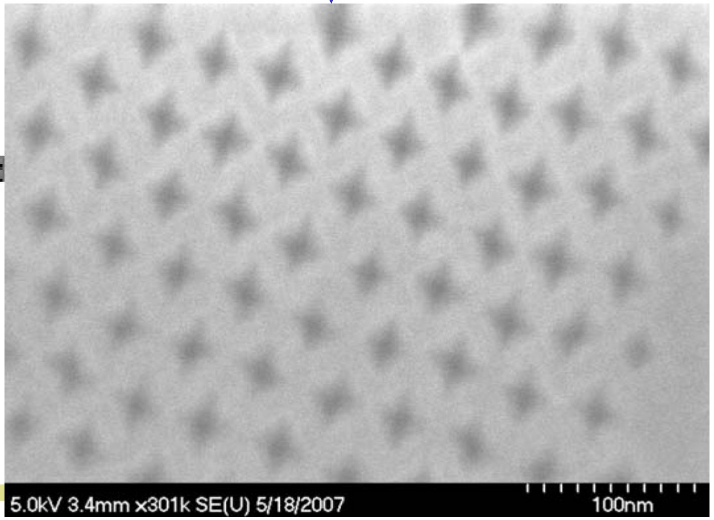
Requirement: large area uniform coverage of nanometer dimension features

Process Schematics of di-block copolymer patterning



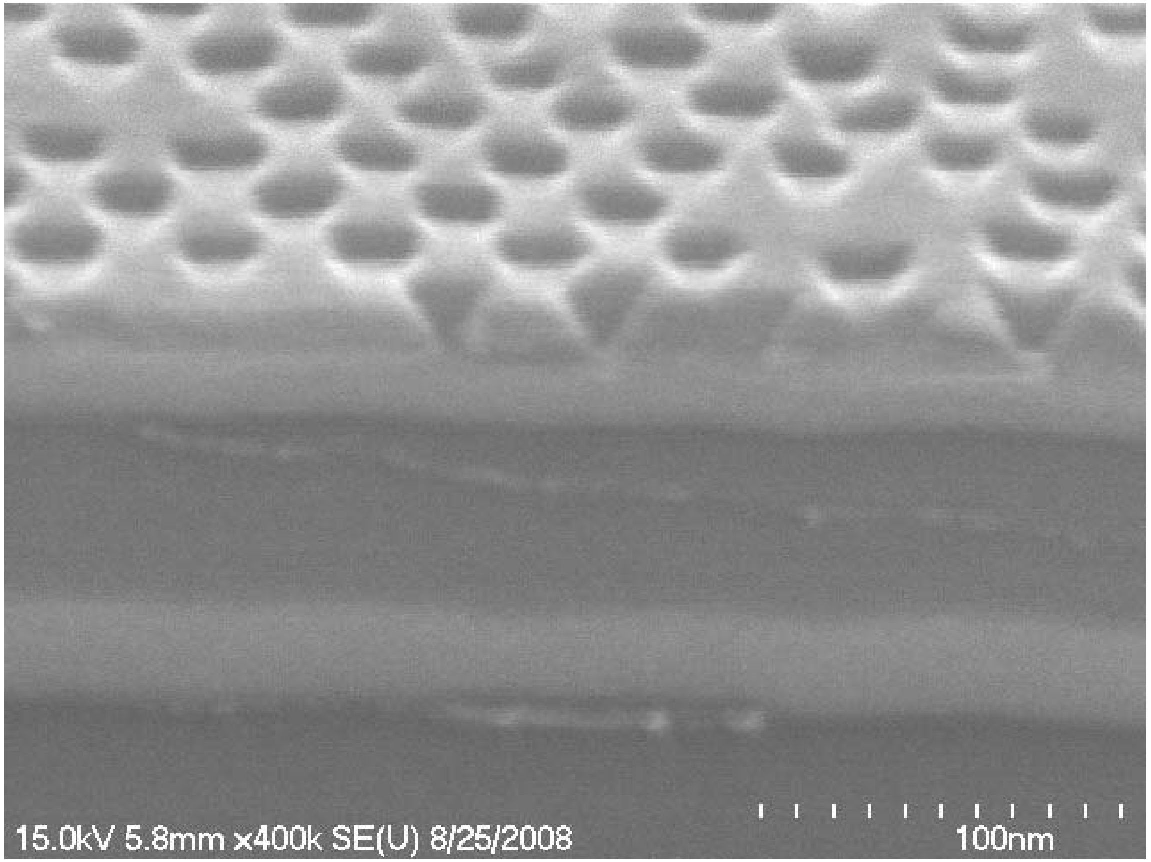


KOH



Collaboration T. Russell, U Mass Amherst

Nano-Patterning: the prerequisite for our research



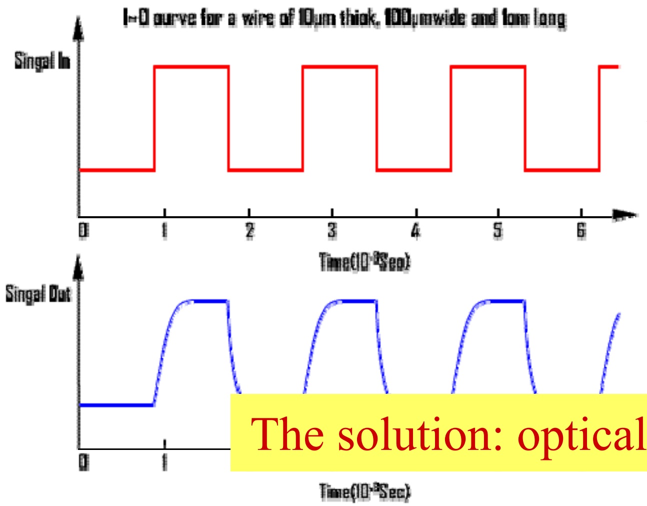
A Quantum Dot Based Electro-optic Modulator

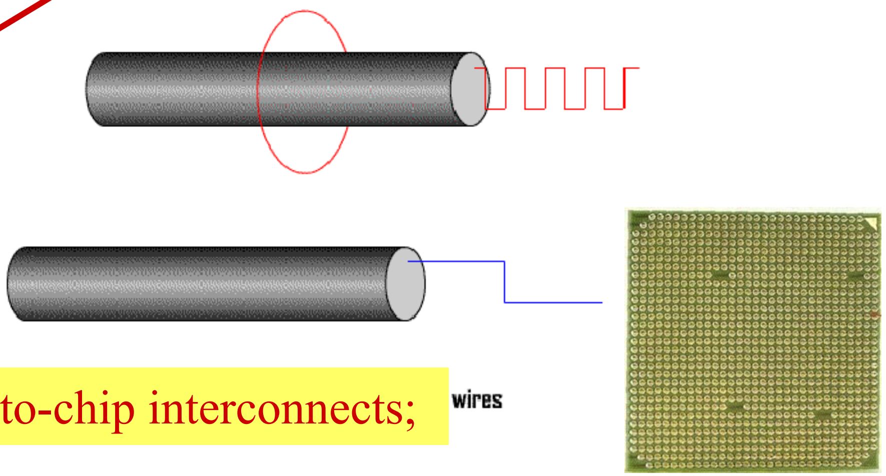
for chip-to-chip optical interconnects

- The non-zero R, L, and C in each real electrical wire;
- For high frequency or bit rate, electrical interconnects are prone to data skew and crosstalk with an ultimate bit rate limit:

$$B \approx \frac{A}{l^2} \times 10^{15} (bps)$$

- The rate limit B is determined by the aspect ratio of the interconnects and is <1 Gbps for typical chip interconnect geometry;



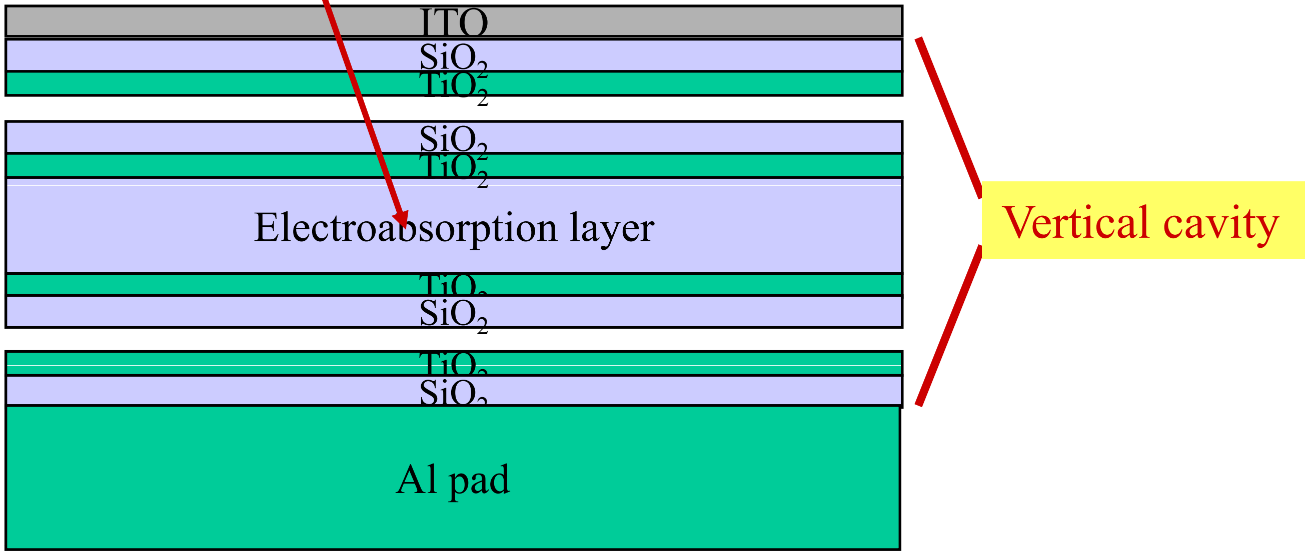


The solution: optical chip-to-chip interconnects;

“Limit to the bit-rate capacity of electrical interconnects from the aspect ratio of the system architecture”, D.A.B. Miller and H.M. Ozaktas, J. Paral. Distrib. Comput., v.41, 42 (1997).

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.

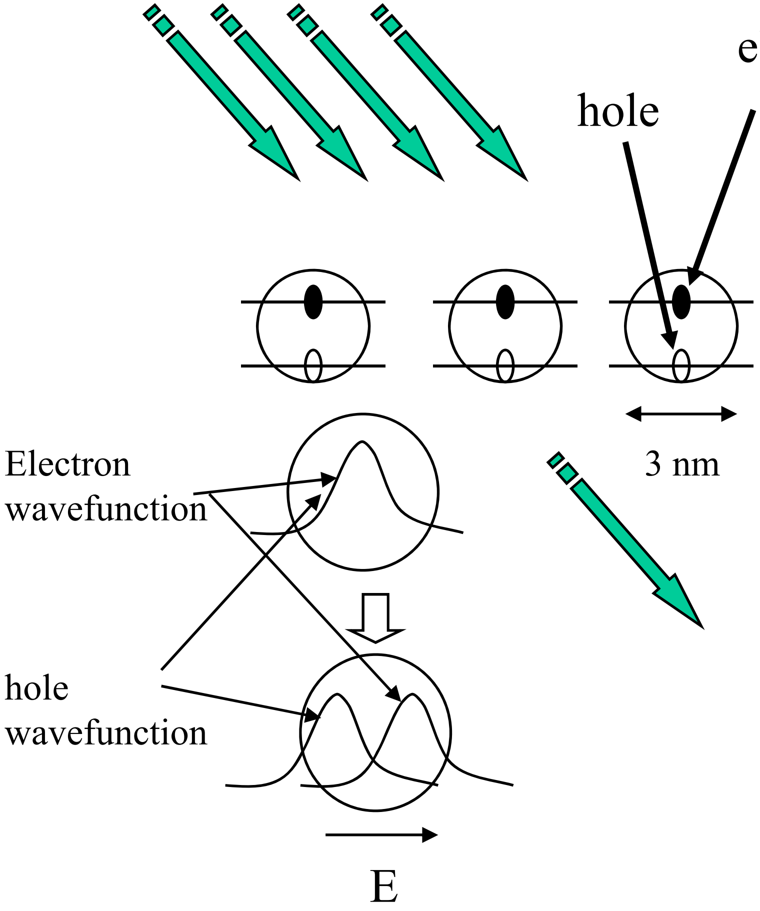


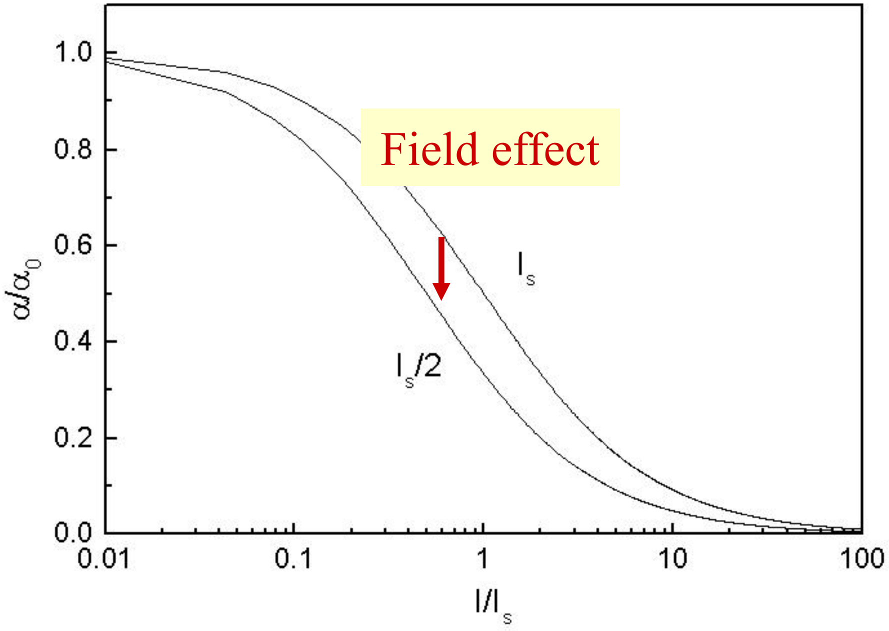
The function of the vertical cavity: amplification.

Quantum Dot Absorption under External Electric Field

Saturation absorption of QDs

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



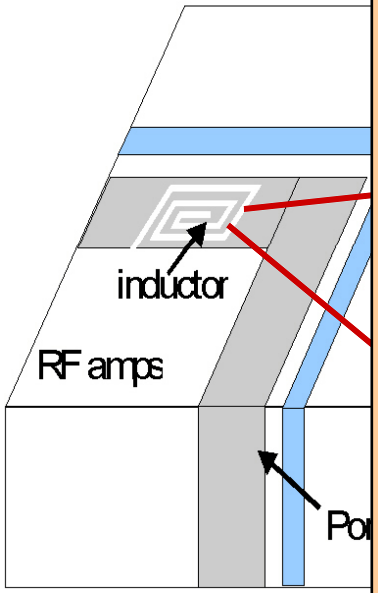


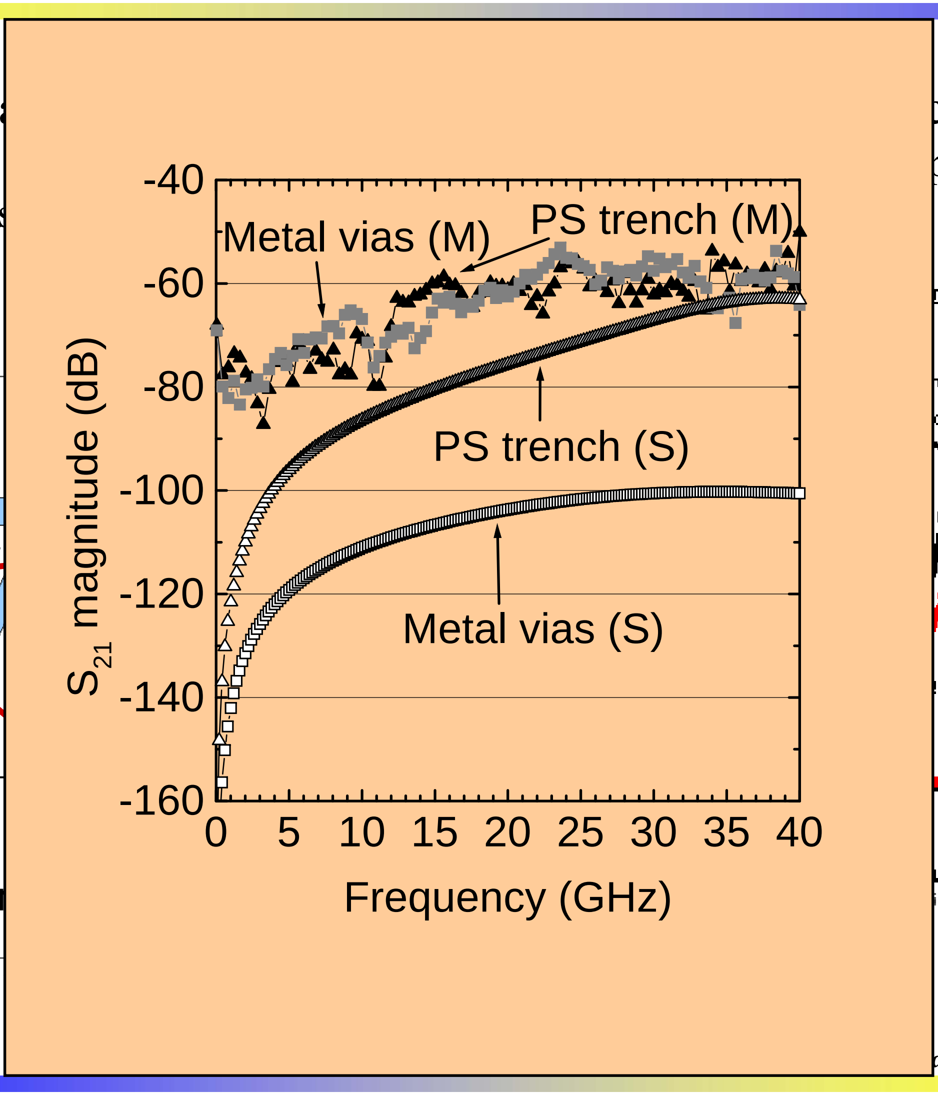
RF Crosstalk Isolation Technology

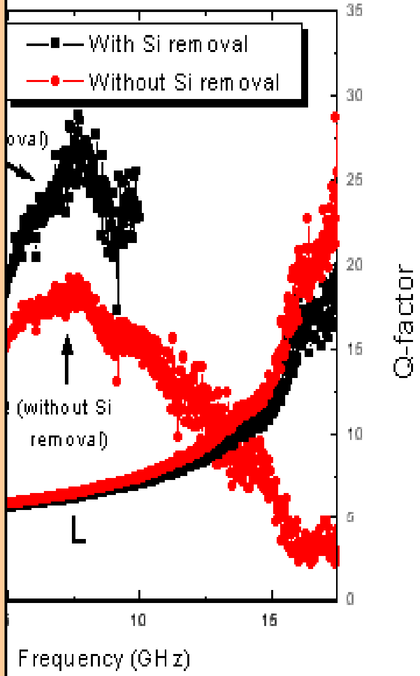
Substrate impedance engineering

Substrate imped circuit applications:

- Integration of pacitors;
- RF crosstalk is







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