Channeling 2014

Naples, Italy

CHANNELING

and

ADVANCED ELECTRONIC MATERIALS

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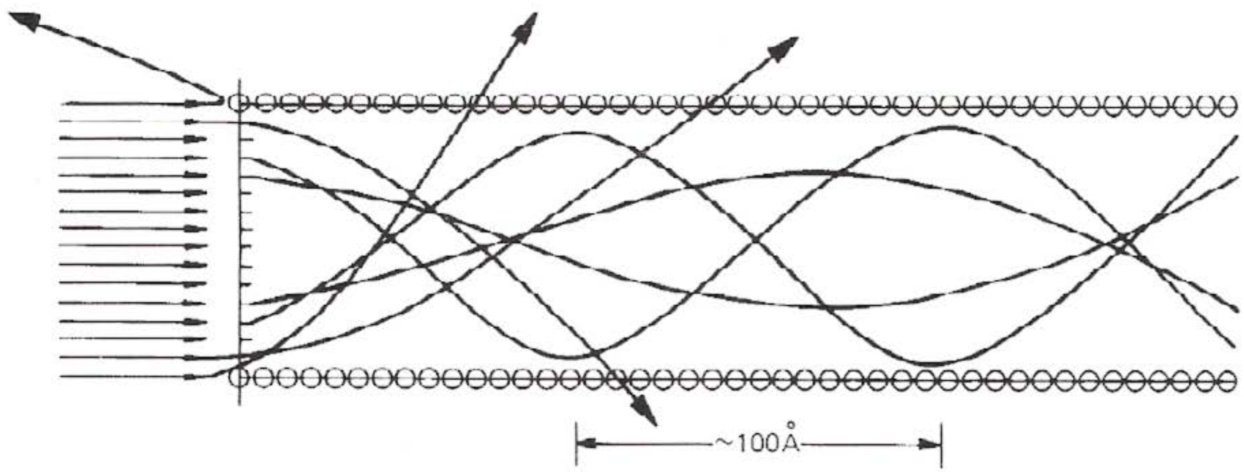
THE AGENDA

1. Some history
2. The channeling tool
3. Current electronics materials research

CHANNELING



And the Nobel Prize for the discovery of channeling goes to:

Chalk River (John Davies)—anomalous ranges in single crystals

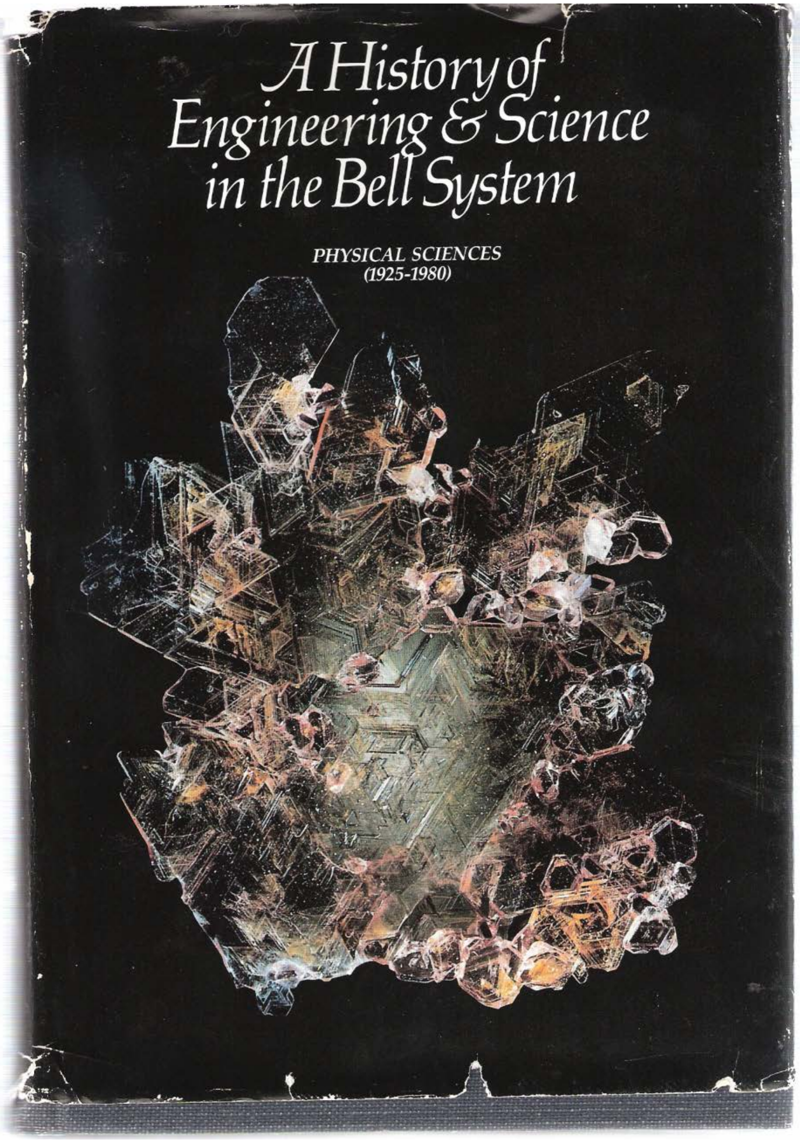
Oak Ridge (Mark Robinson and Dean Oen)-anomalous ranges in computer simulations

Harwell (Mike Thompson), orientation dependence of (p,n) reaction in single crystal Cu, blocking patterns through Au

Bell Labs/ Harwell (Walt Gibson, Geoffrey Dearnaley);—dE/dx through thin silicon, at high energy

AND

Aarhus University (Jens Lindhard, et al) –for explaining it all– early in the game!



Pg 297:
..Nuclear lifetime measurements developed by W. Gibson and K. . O Nielsen of Aarhus

Pg 301:
…Feldman and J. U. Andersen of Aarhus University compared analytical and computer simulations..

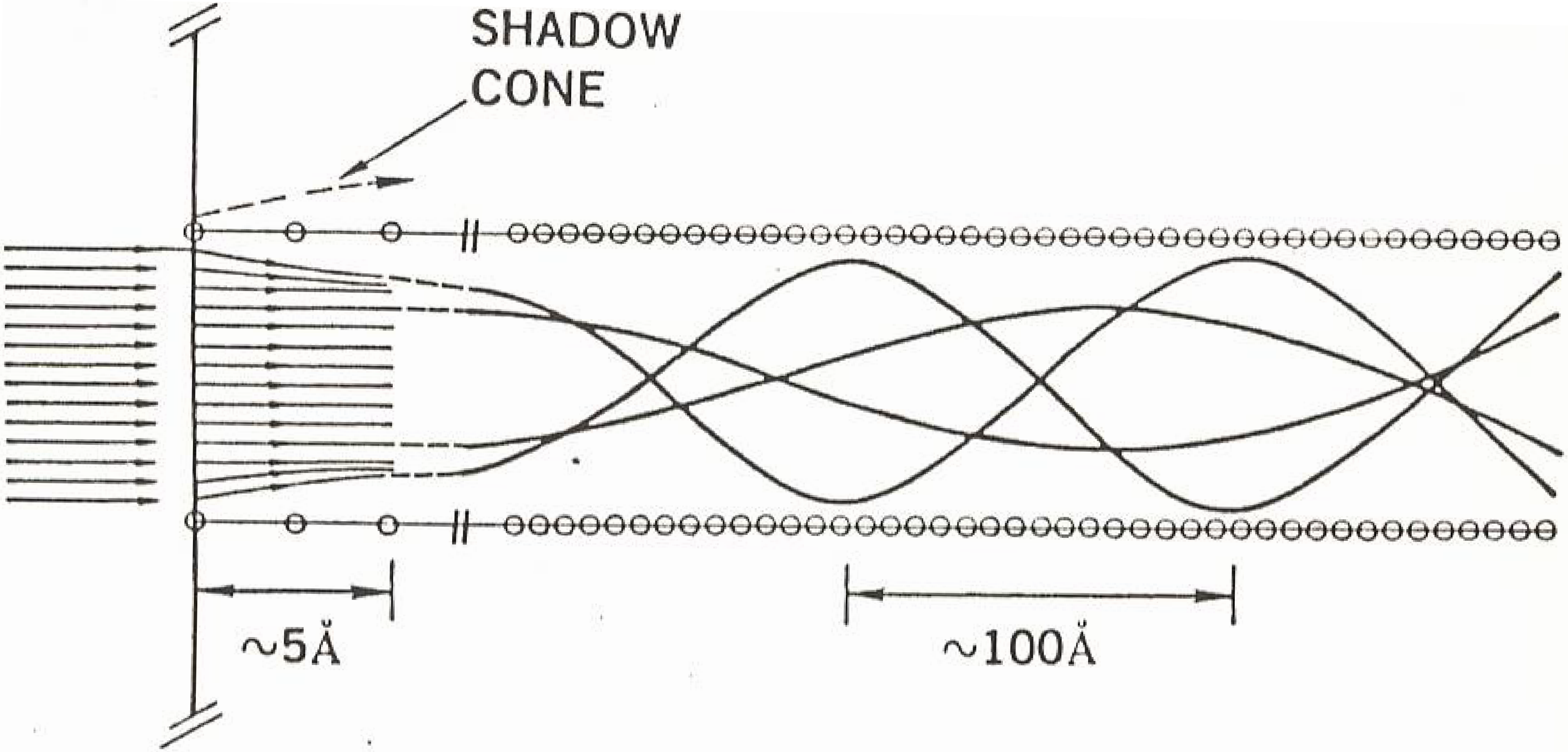
Pg 303:
In 1968 W.M Gibson spent a year at Aarhus and carried out some of the first..lattice location of implanted ions in silicon

VISITING AARHUS MEANT YOU ALSO MET SOME OF THE INTERNATIONAL STARS OF THE FIELD

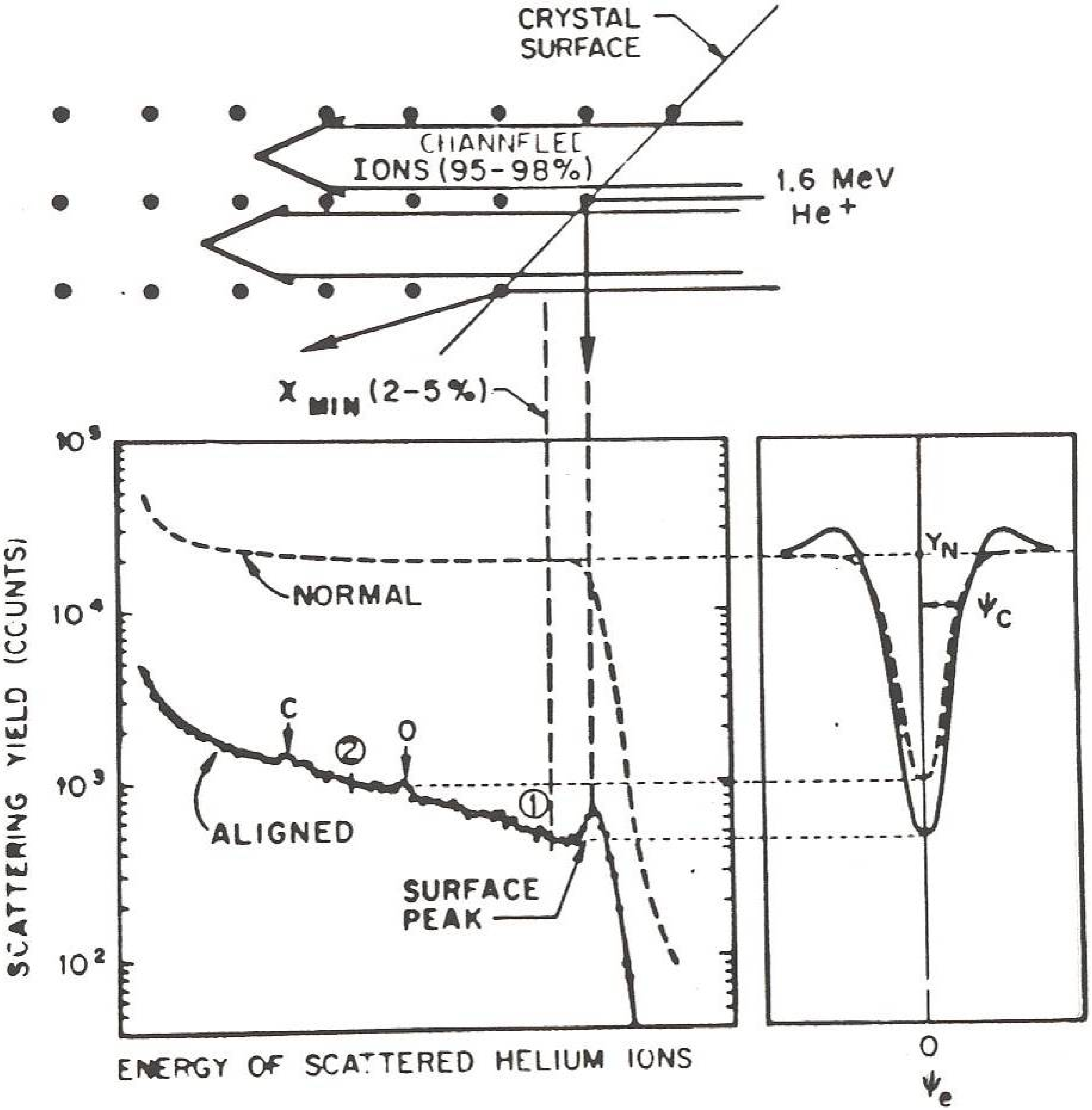
Jens Ulrik Andersen, Jens Lindhard, Susan Toldi , John Davies

THE BIG THREE +


5 8'96



SHADOW
CONE
~5Å
~100Å



CRYSTAL SURFACE
CHANNELED IONS (95-98%)
1.6 MeV He +
X MIN (2-5%)
10⁵
10⁴
10³
10²
SCATTERING YIELD (COUNTS)
NORMAL
C
2
O
1
ALIGNED
SURFACE PEAK
ENERGY OF SCATTERED HELIUM IONS
Y N
ψ C
0
ψ e

Channeling of Positrons

J. U. Andersen* and W. M. Augustyniak
Bell Telephone Laboratories, Murray Hill, New Jersey 07974

and

E. Uggerhøj
Institute of Physics, University of Aarhus, 8000 *Aarhus C, Denmark*
(Received 7 July 1970)

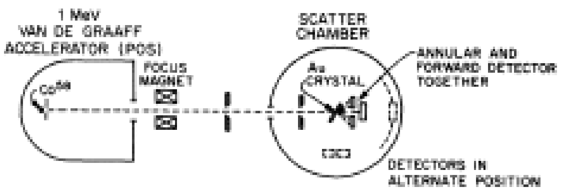


FIG. 2. Experimental arrangement.

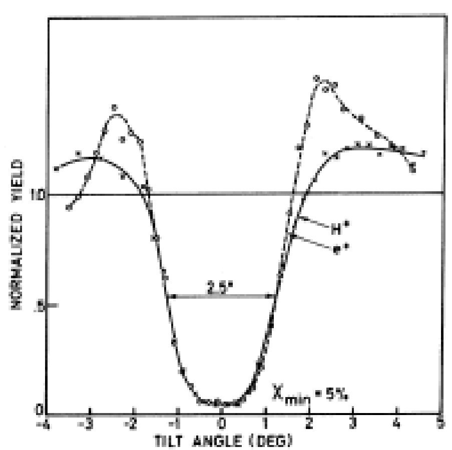


Fig. 4. Comparison of positron and proton dips along the ⟨110⟩ axis. The abscissa scale for the proton dip has been scaled from 1 to 0.67 MeV (see text).

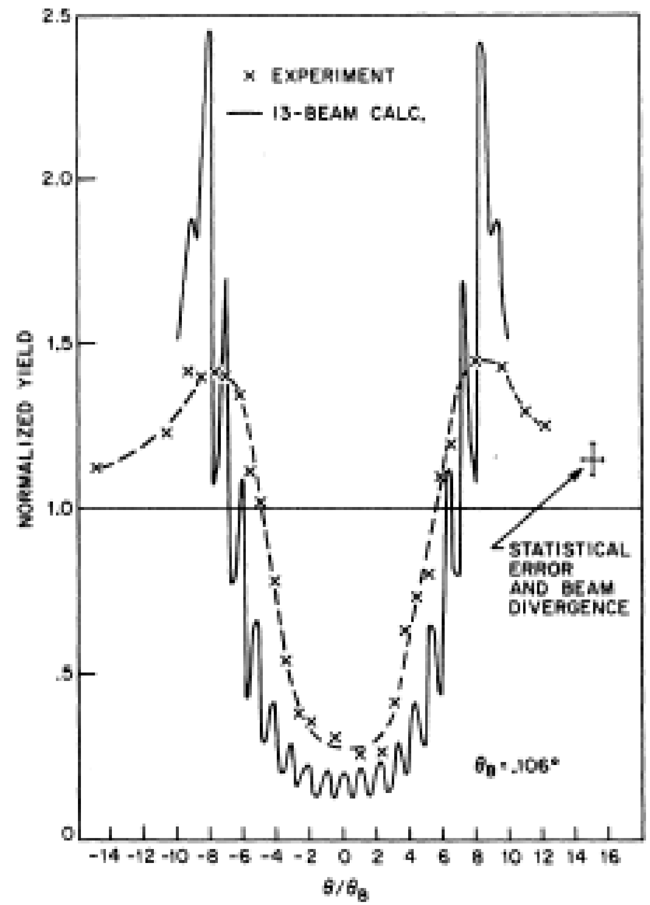
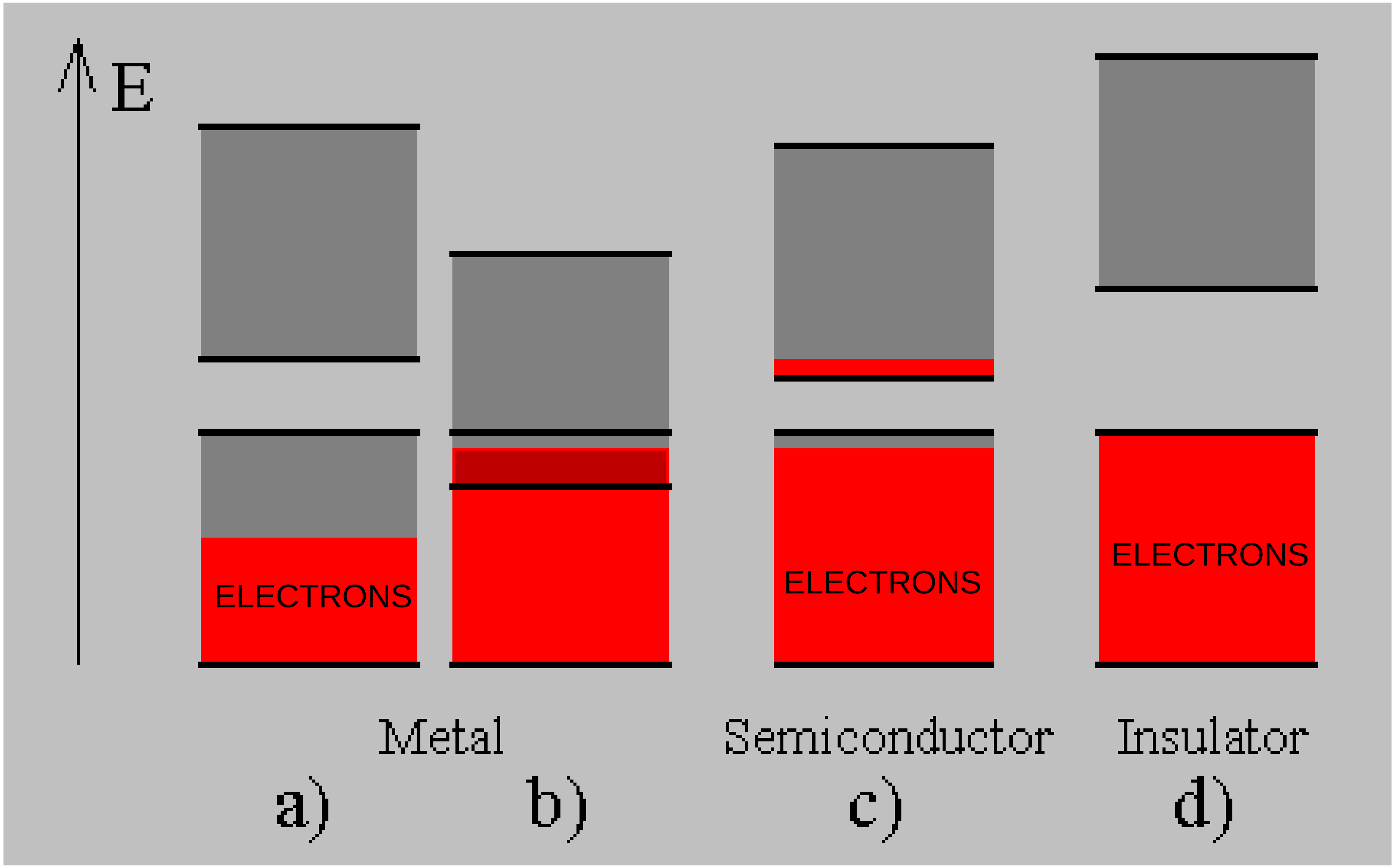


FIG. 6. Comparison of measured dip for a {111} plane with a 13-beam calculation. The planar spacing is $d_p = 2.35$ Å. θ_B denotes the Bragg angle; $\theta_B = \lambda/2d_p$.

ABOUT THE SAME TIME THE SILICON REVOLUTION BEGINS!

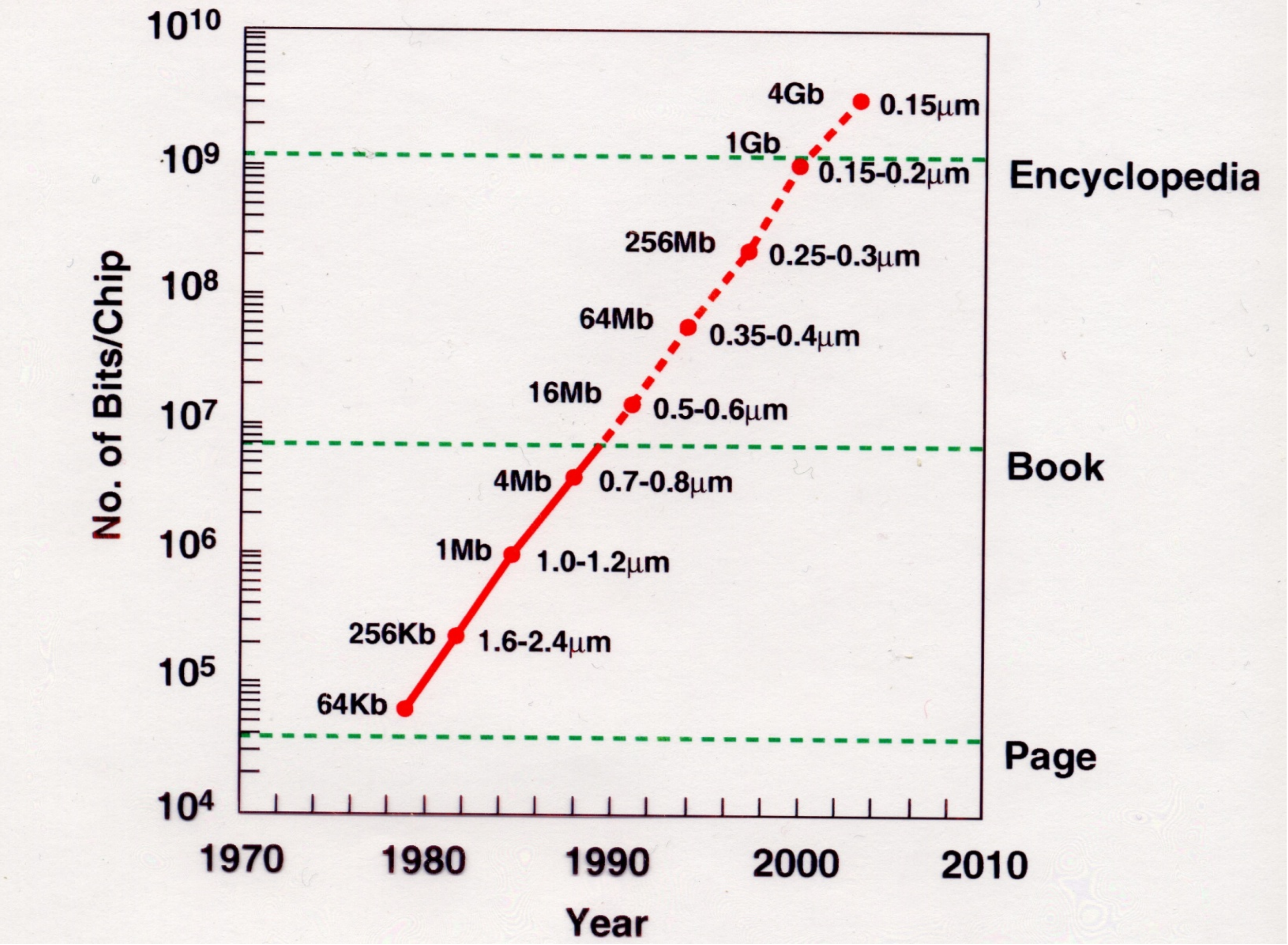
Enabled by the most basic particle solid interaction
ion implantation!

MATERIALS AND THE CONCEPT OF BANDS

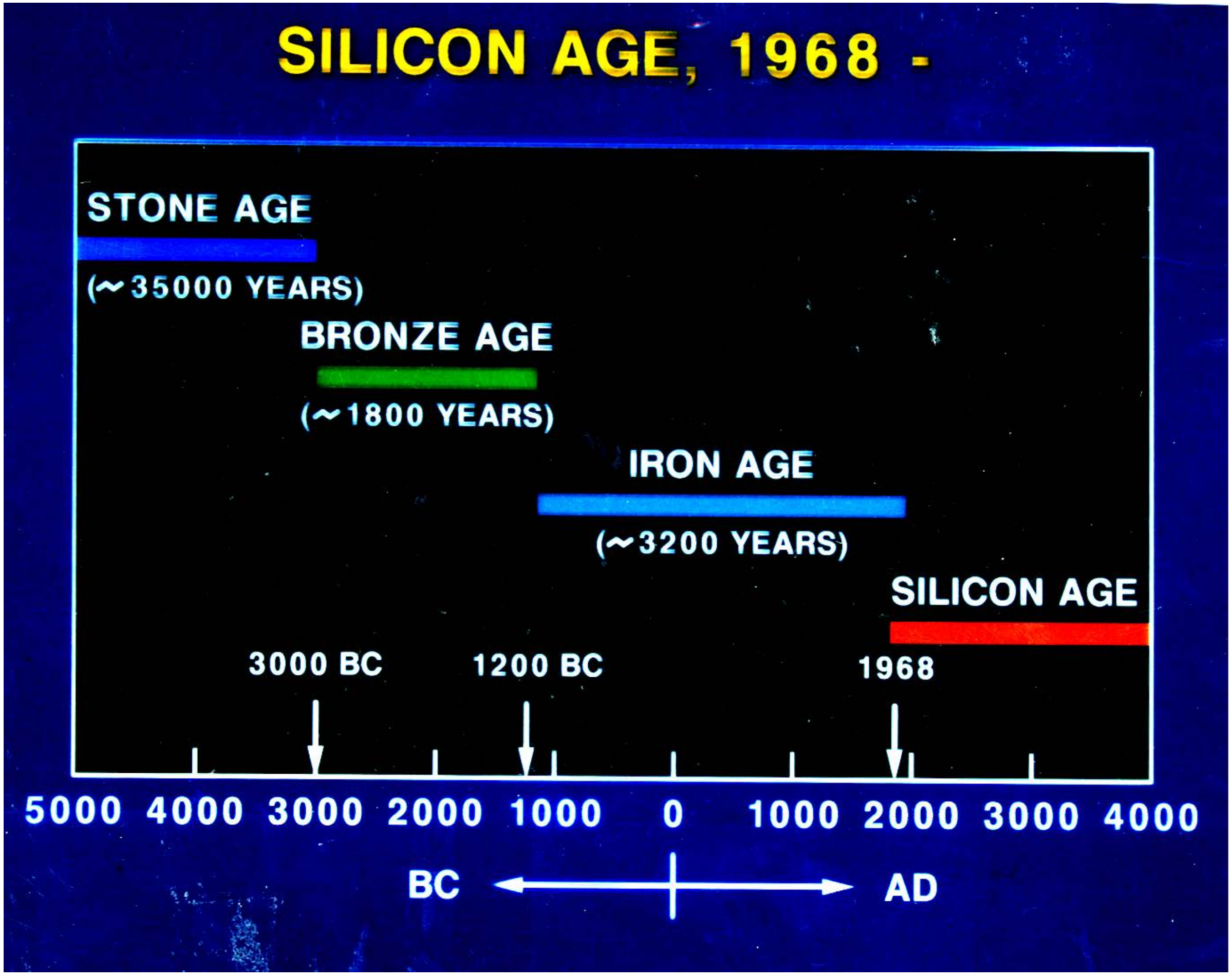


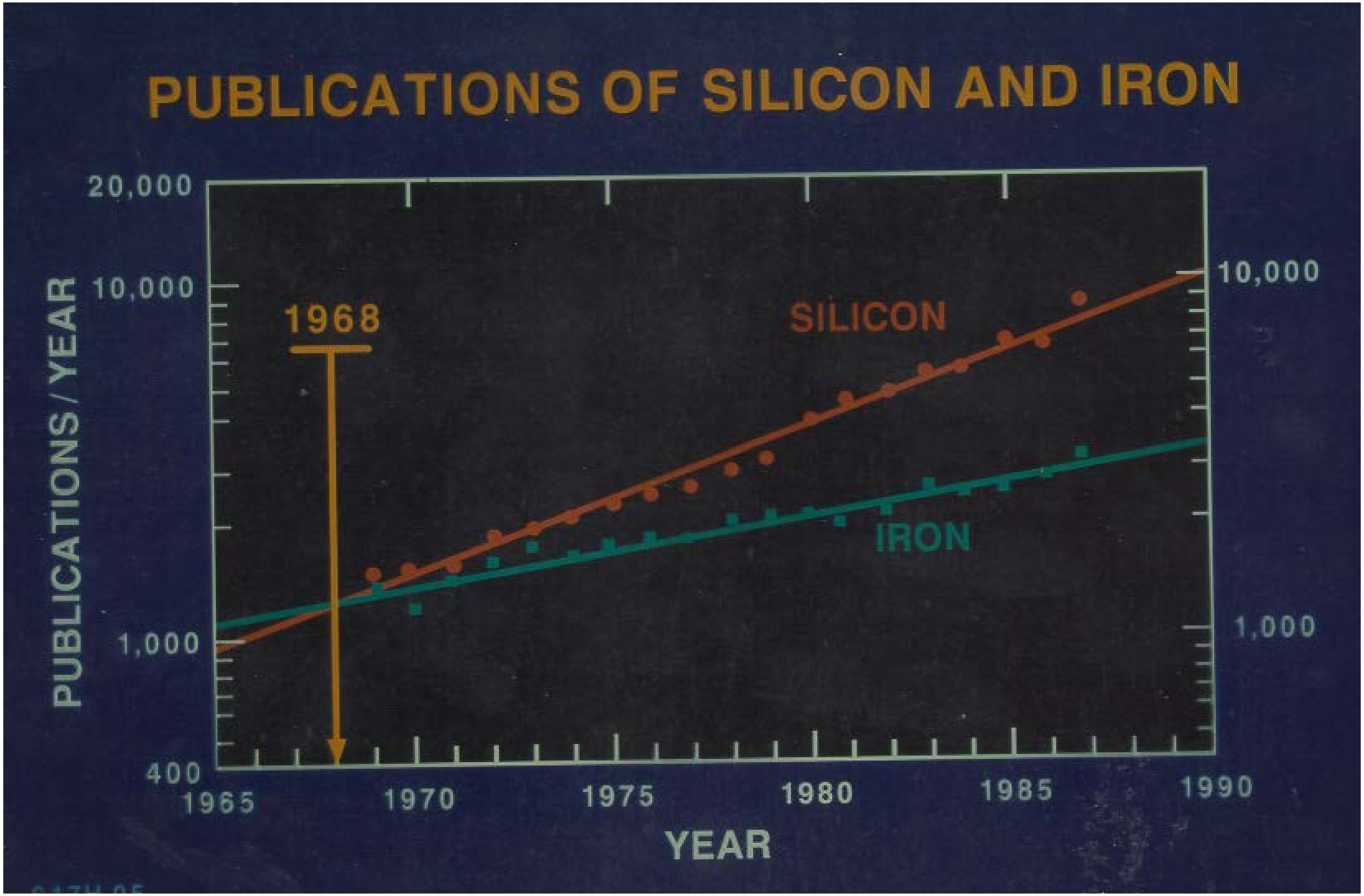
"We call him the semi-conductor - he only works part time."

MOORE'S LAW – THE SPEED OF A CPU DOUBLES EVERY 18 MONTHS

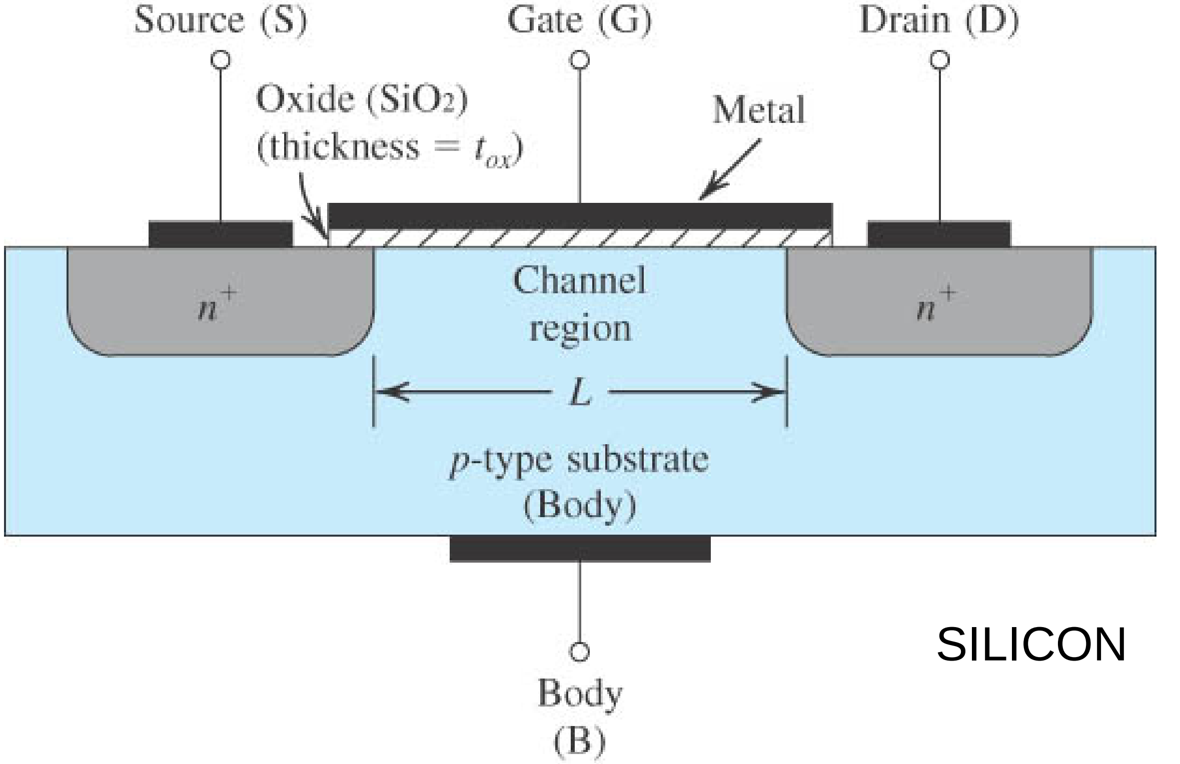


AGES OF CIVILIZATION




PUBLICATIONS OF SILICON AND IRON
PUBLICATIONS / YEAR
20,000
10,000
1,000
400
10,000
1,000
1965
1970
1975
1980
1985
1990
YEAR
1968
SILICON
IRON

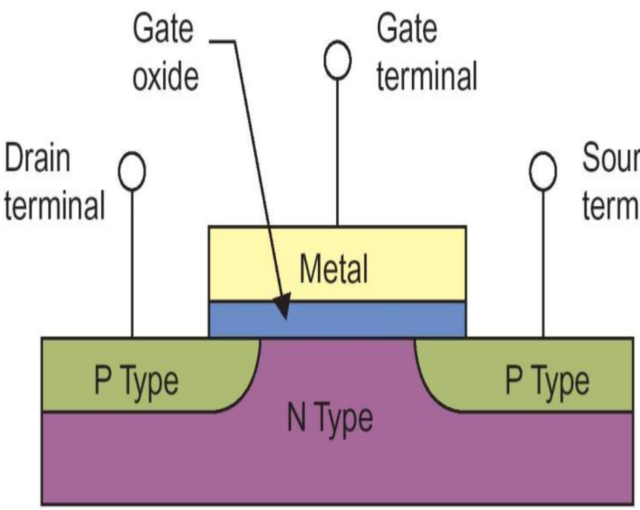
Device Structure

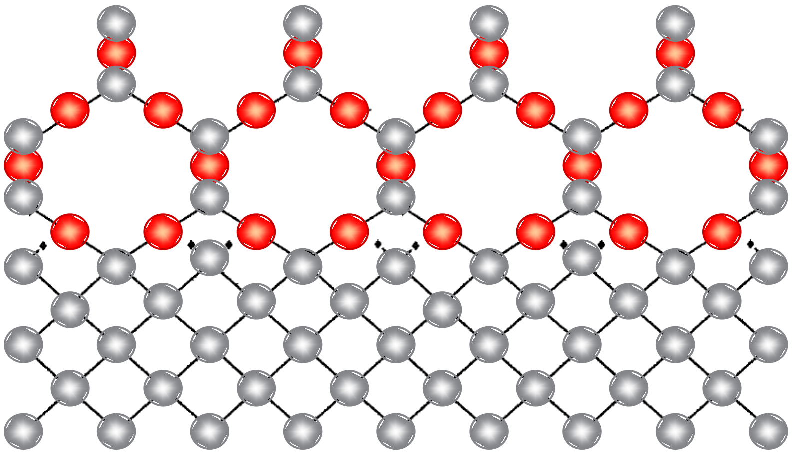


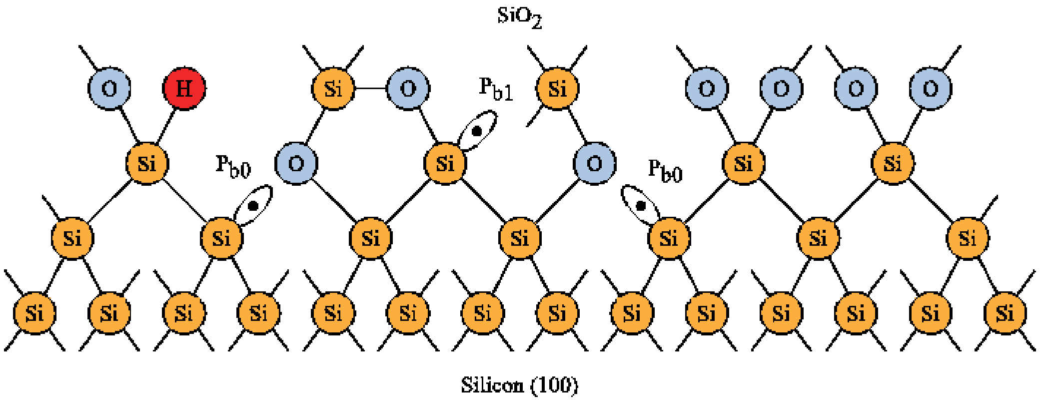
(b)

SILICON

Classic Si
Metal-Oxide-Semiconductor Field Effect Transistor
MOSFET



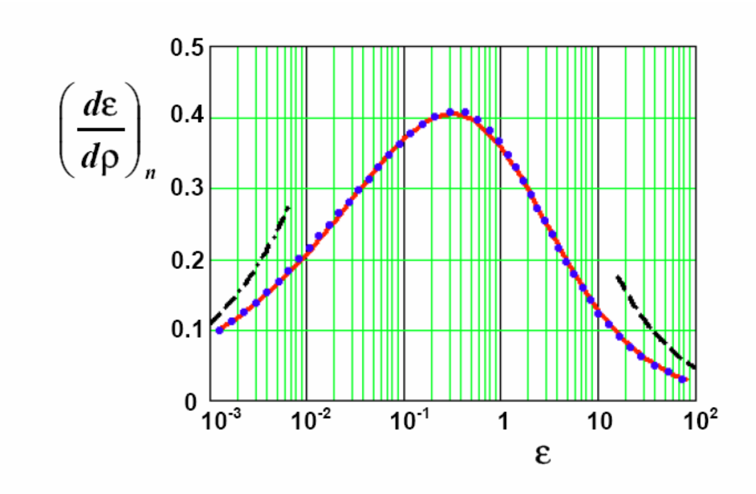




I. INTRODUCTION

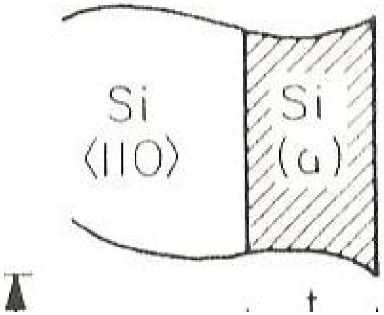
Ion implantation is one of the most important processing tools in Si integrated circuit technology. Its discovery by Ohl at Bell Laboratories in 1952 and subsequent development in industrial, governmental, and university laboratories to become a work horse of the industry makes fascinating reading. Today ion beams are ubiquitous in Si technology

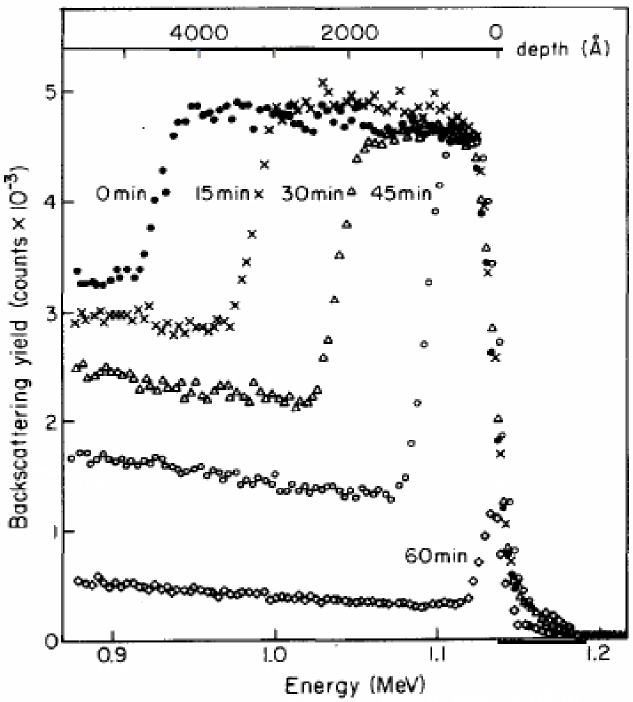
.

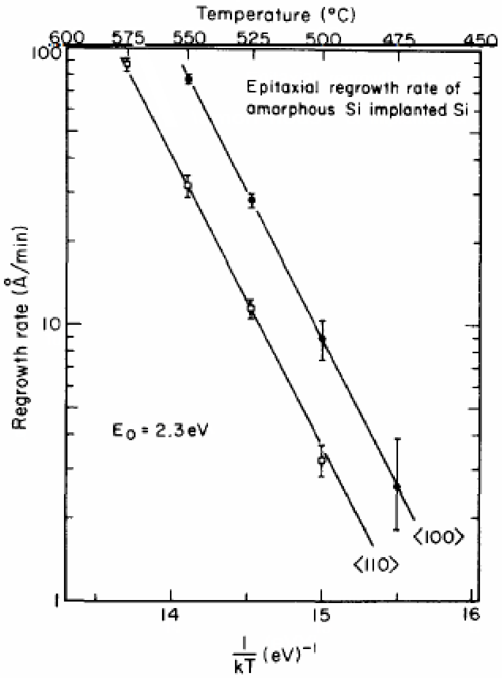


From Picraux, Poate, Mayer et al--1997

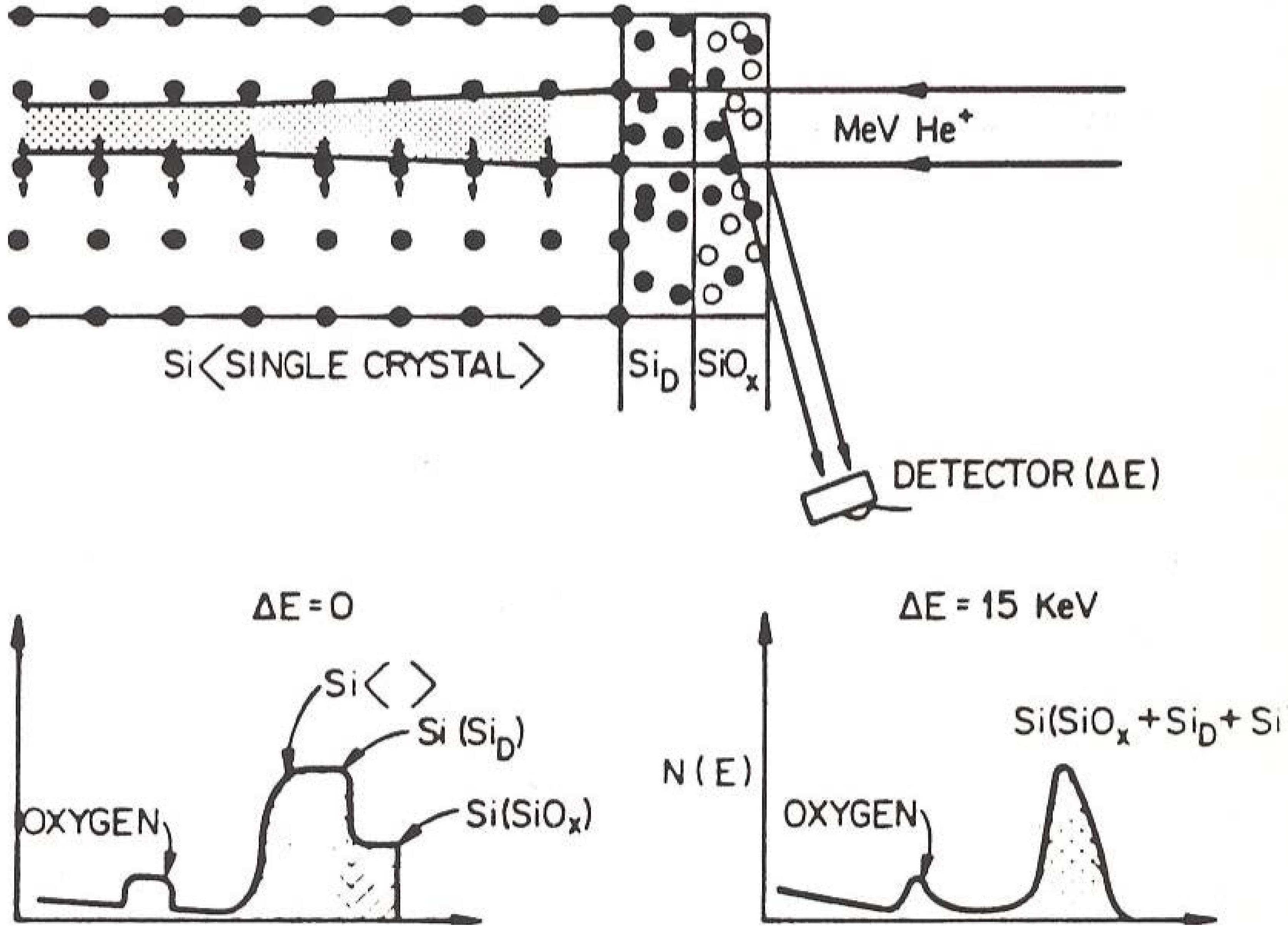
SOLID PHASE
EPITAXIAL RE-GROWTH



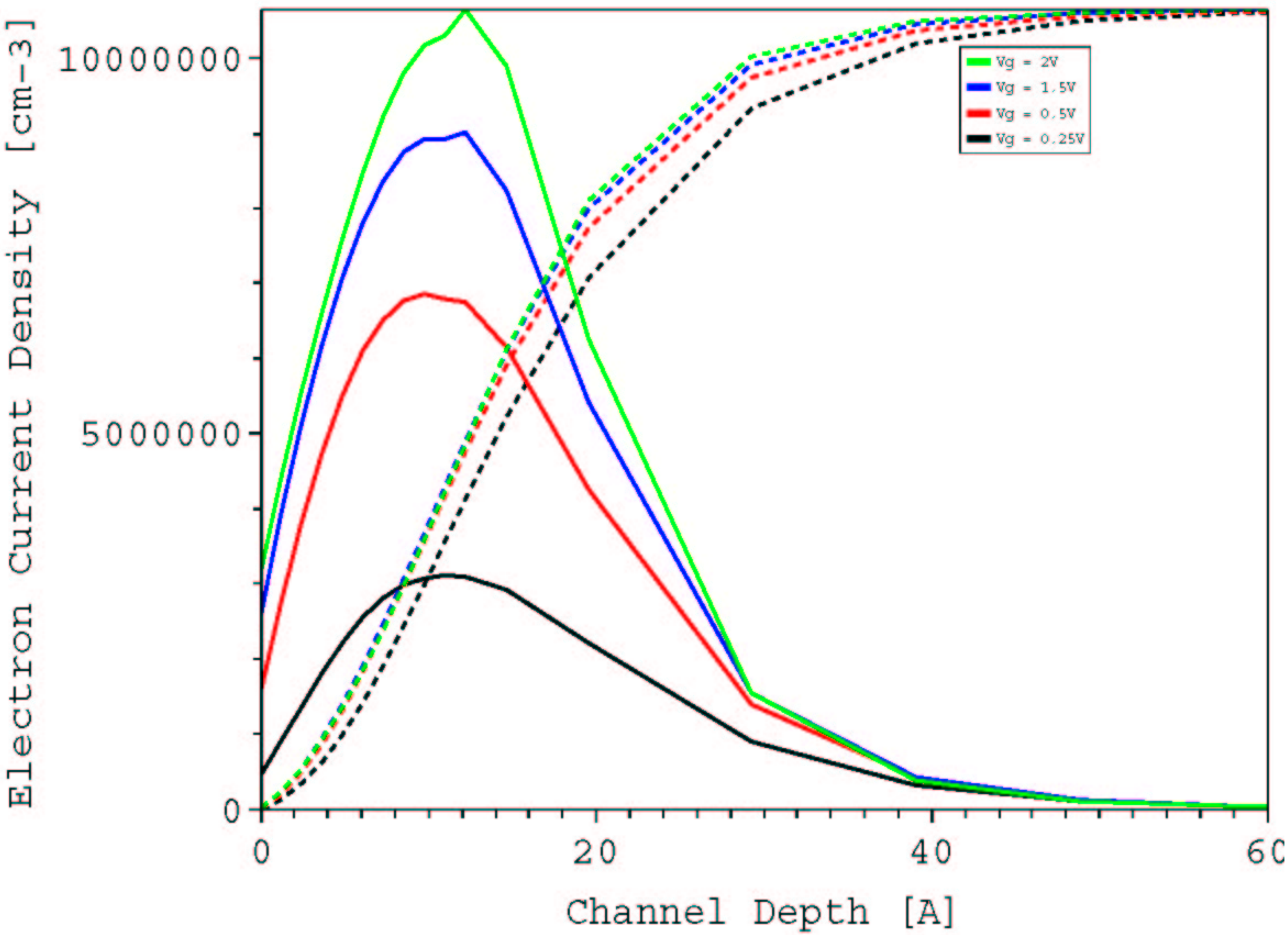




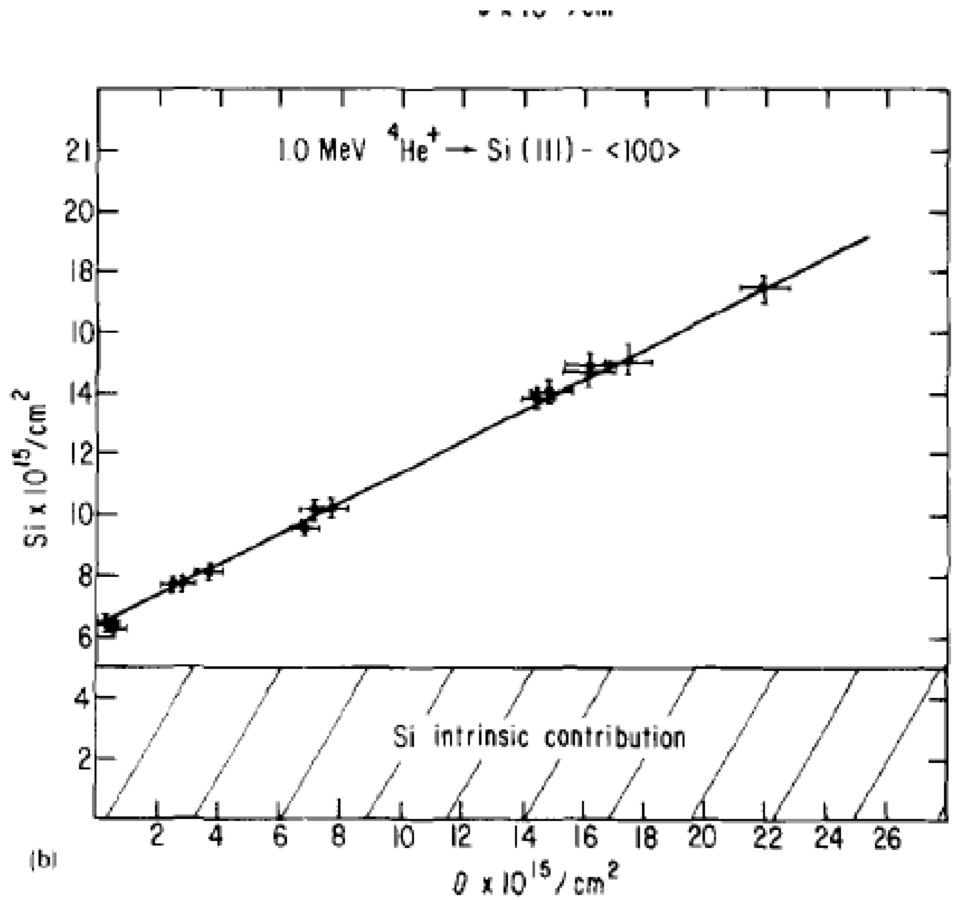
Mayer, Csepregi, Sigmon, Physics Let (1975)



MeV He⁺
Si⟨SINGLE CRYSTAL⟩
Si_D
SiO_x
DETECTOR (ΔE)
ΔE = 0
Si⟨ ⟩
Si (Si_D)
OXYGEN
Si(SiO_x)
ΔE = 15 KeV
N (E)
Si(SiO_x + Si_D + Si
OXYGEN



Vg = 2V
Vg = 1.5V
Vg = 0.5V
Vg = 0.25V
Electron Current Density [cm-3]
10000000
5000000
0
0
20
40
60
Channel Depth [A]

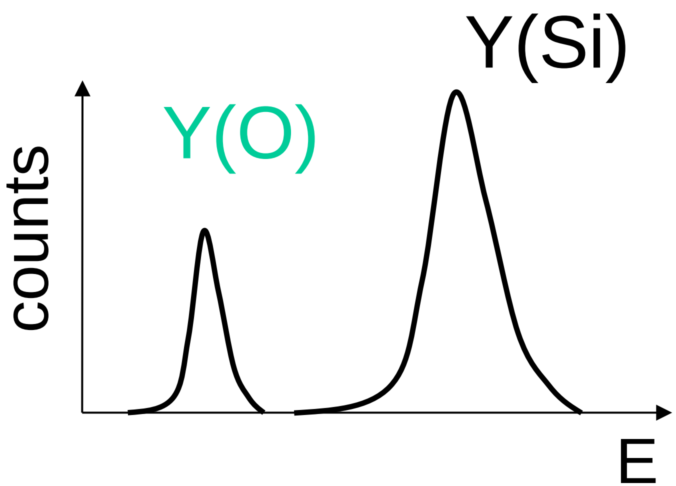


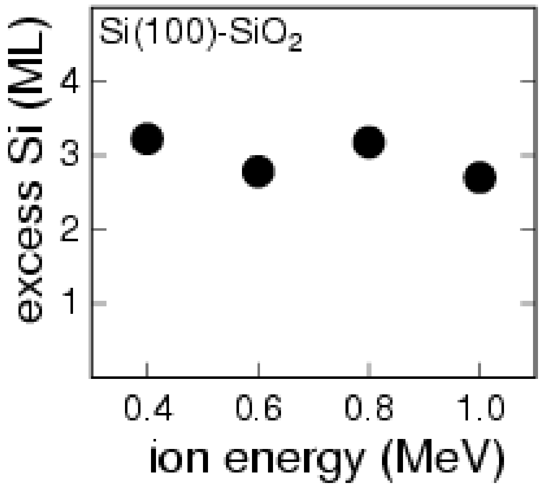
Haight and Feldman,

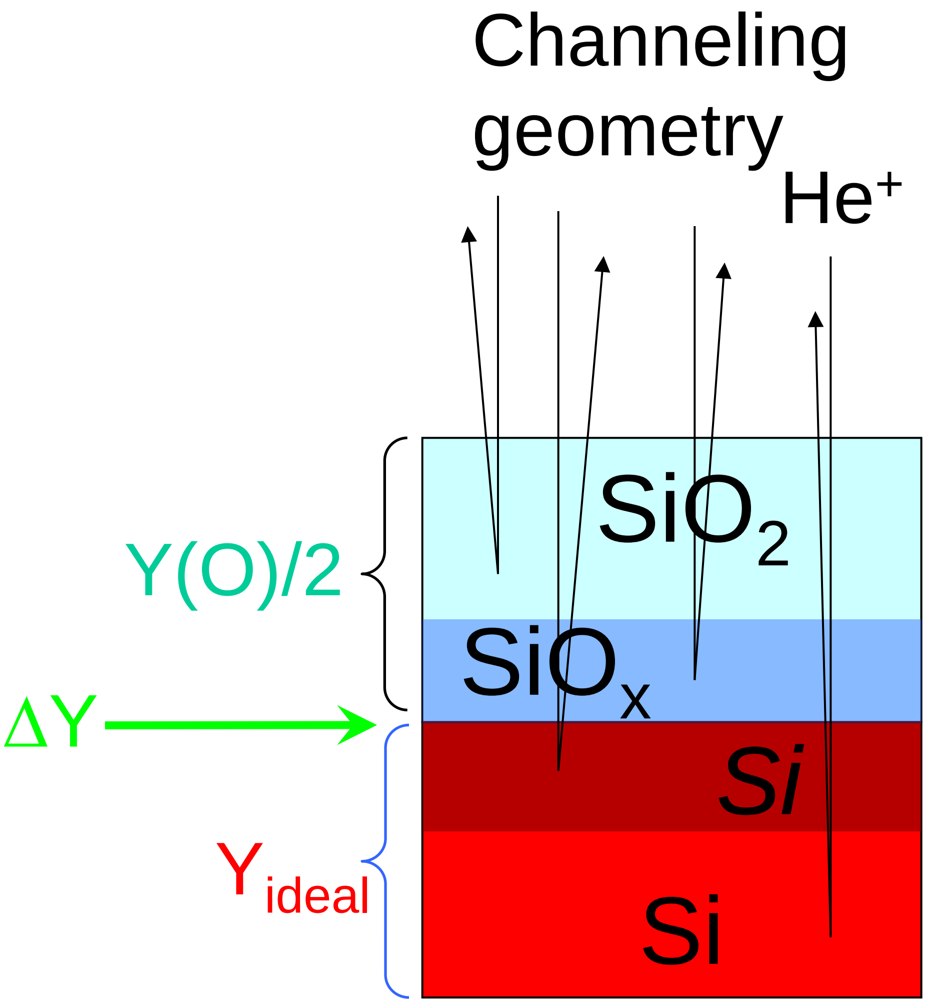
J. Appl. Phys., Vol. 53, No. 7, July 1982

Ion-scattering experiments

$$\Delta Y = Y(Si) - Y(O)/2 - Y_{ideal}$$

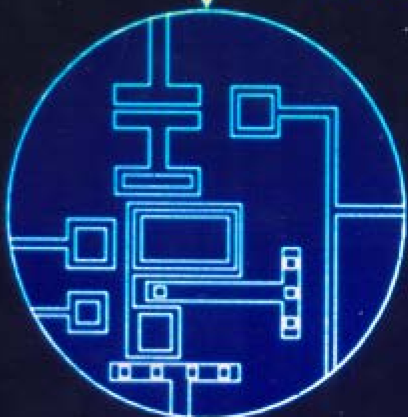






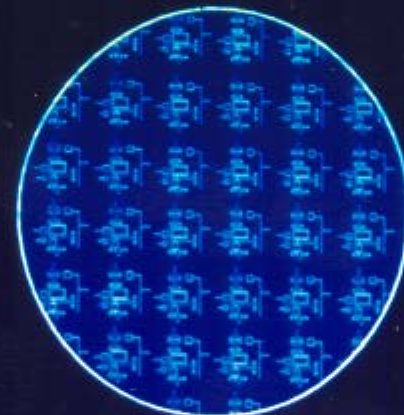
ADVANCES IN TRANSISTOR LITHOGRAPHY

Cross section of human hair



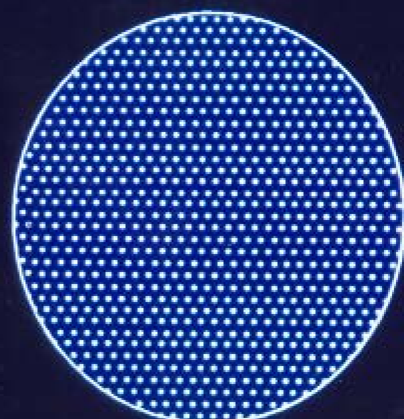
10 micron
design rules
(5 transistors per
human hair)

1970



1 micron
design rules
(500 transistors
per human hair)

1985



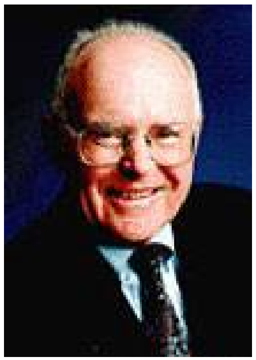
2000

0.1 micron design rules
(50,000 transistorss per human hair
Hair = early micro computer)

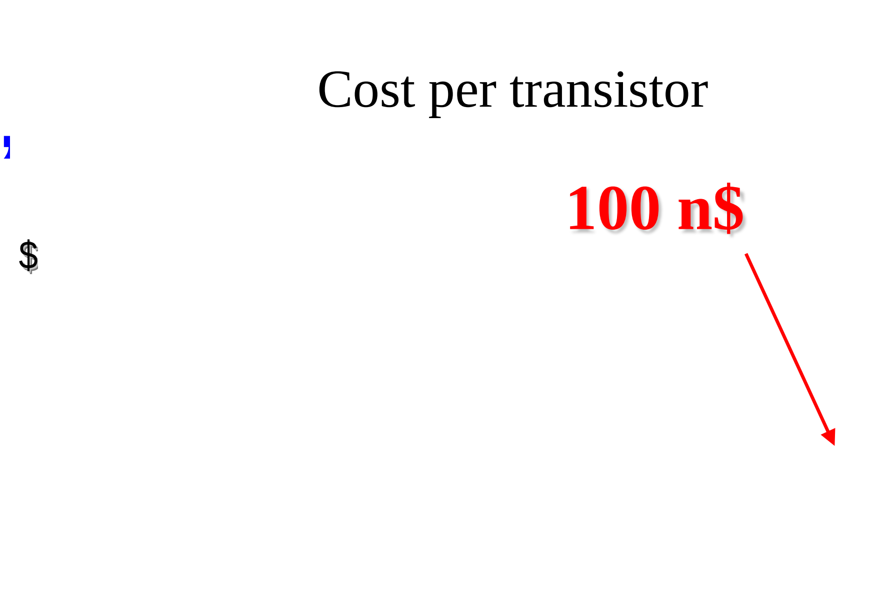
AT&T

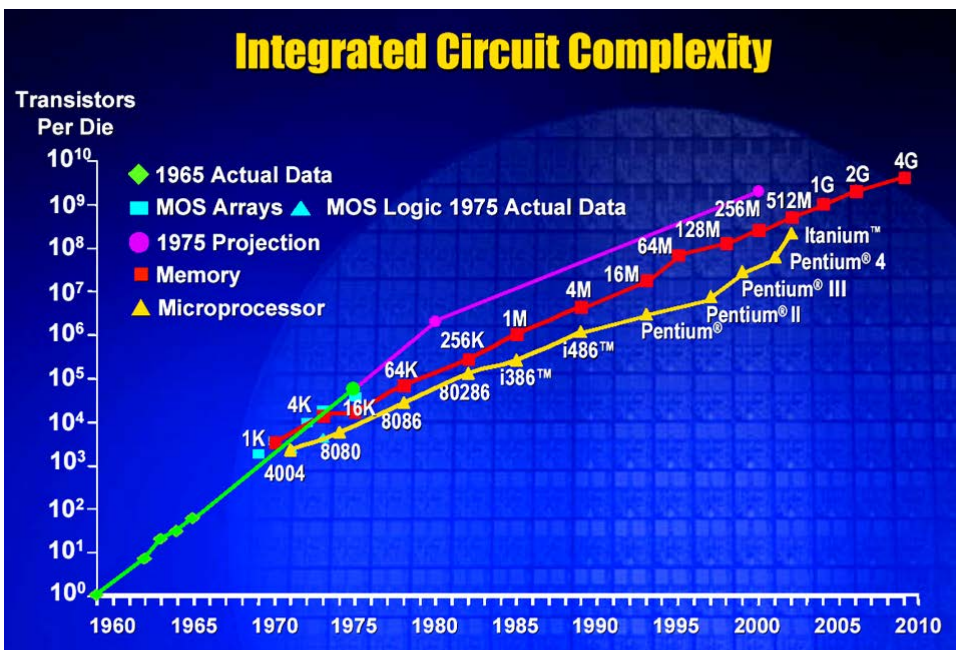
Moore's Laws

of computer scaling: small, faster, cheaper, gazillions



Gordon Moore, Intel founder





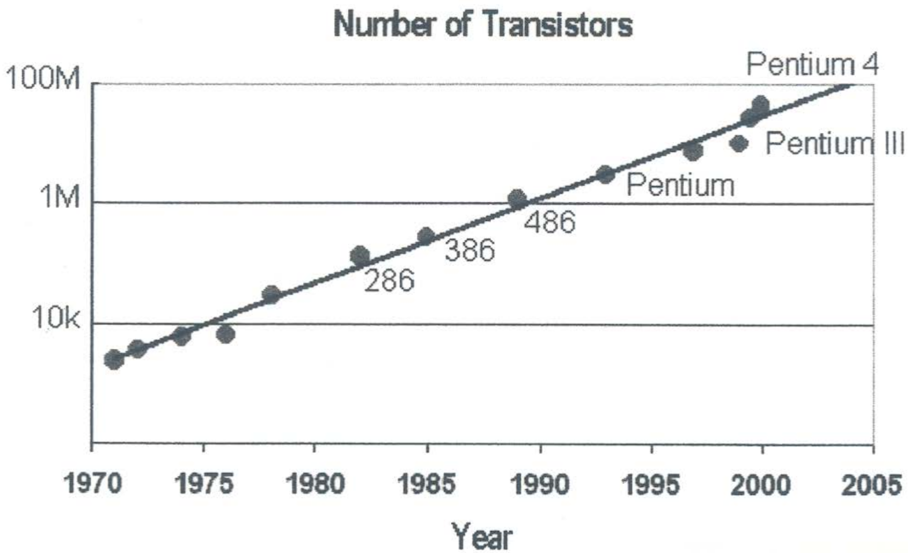
FABRICATION SUCCESS

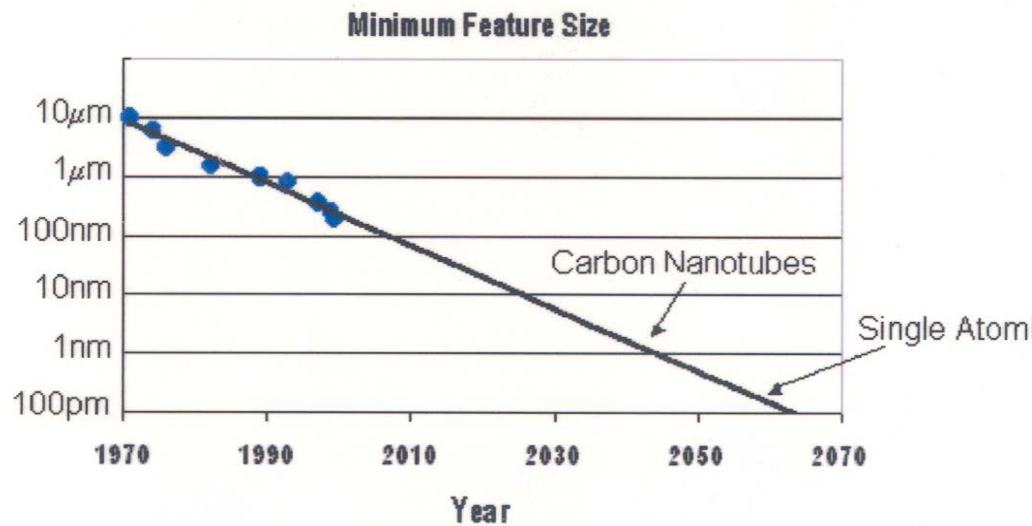
Oxidation and the high quality semiconductor oxide interface

Ion implantation and precision manufacturing

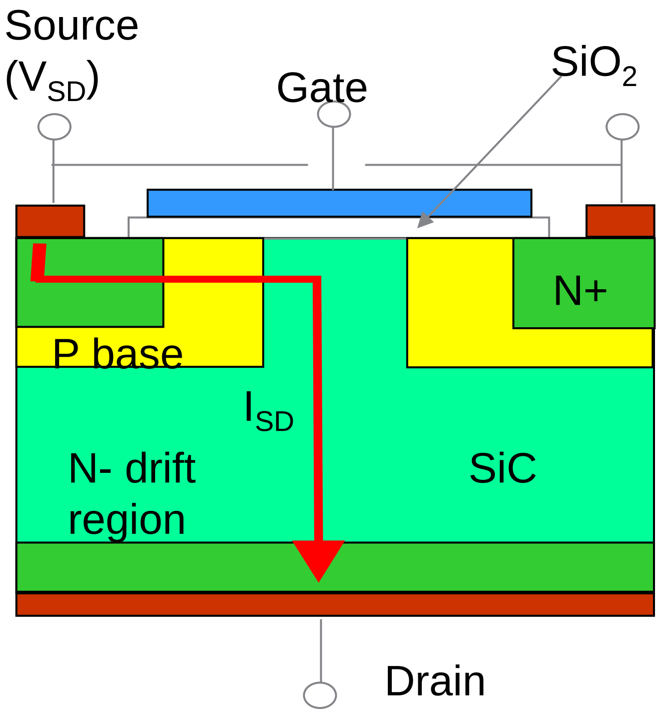
Lithography

END OF SILICON?





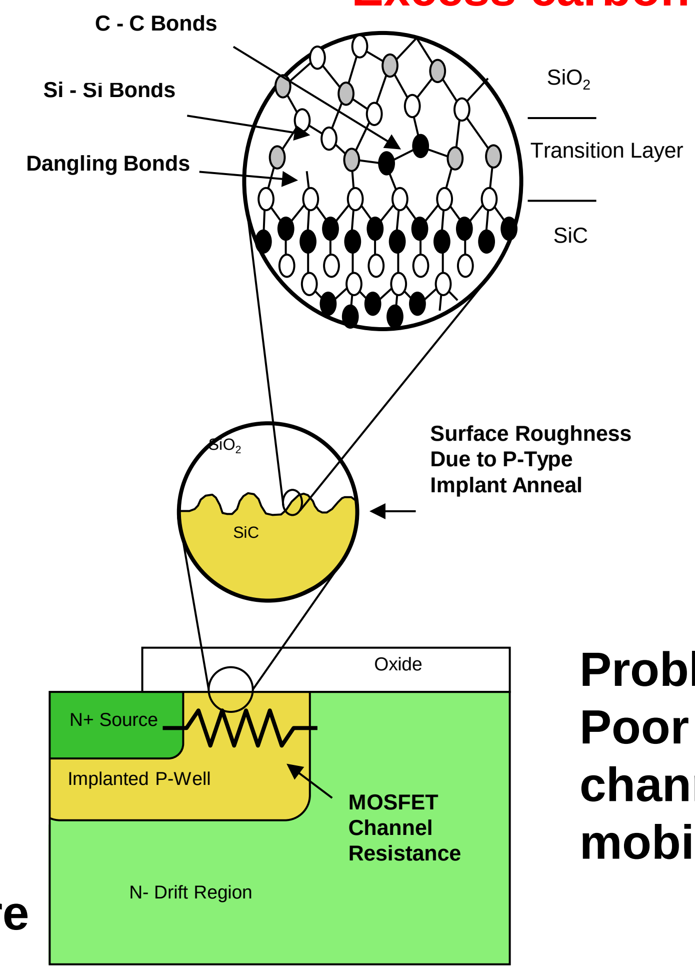
Silicon Carbide Power Devices-Energy Efficiency



- High breakdown field
- High thermal conductivity

High voltage and High temperature applications

Excess carbon ?

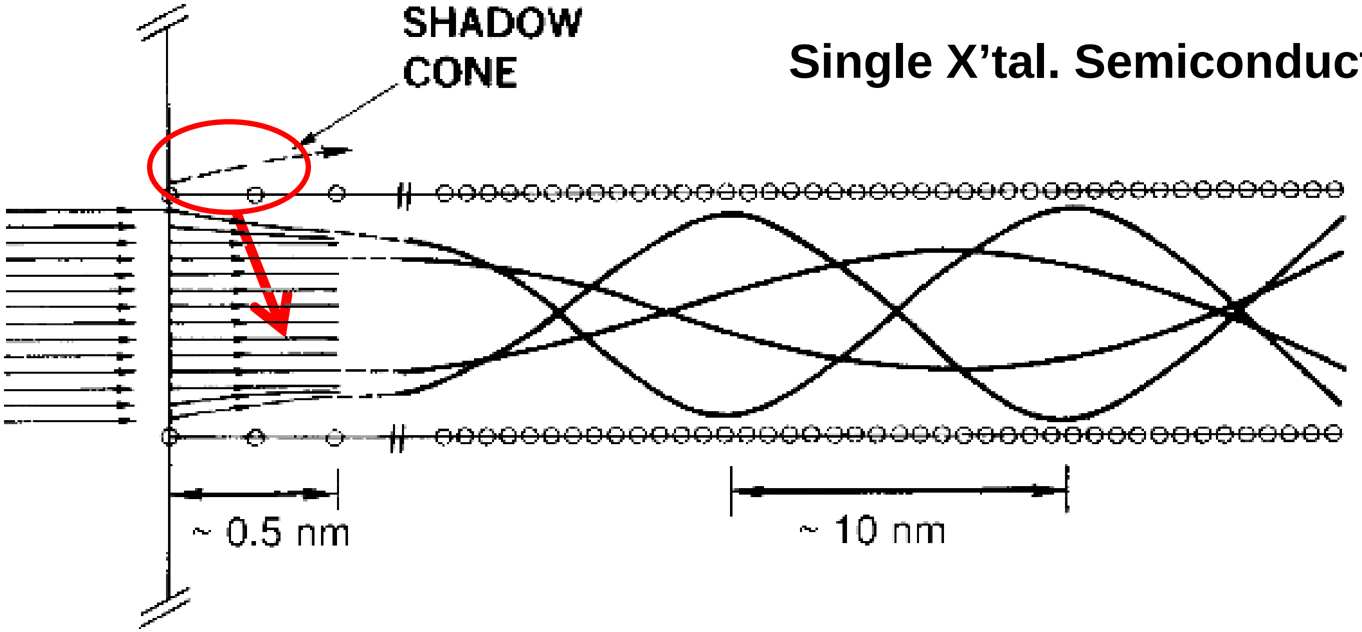


Problem: Poor channel mobility

Channeling – shadow cone

Single X'tal. Semiconductor

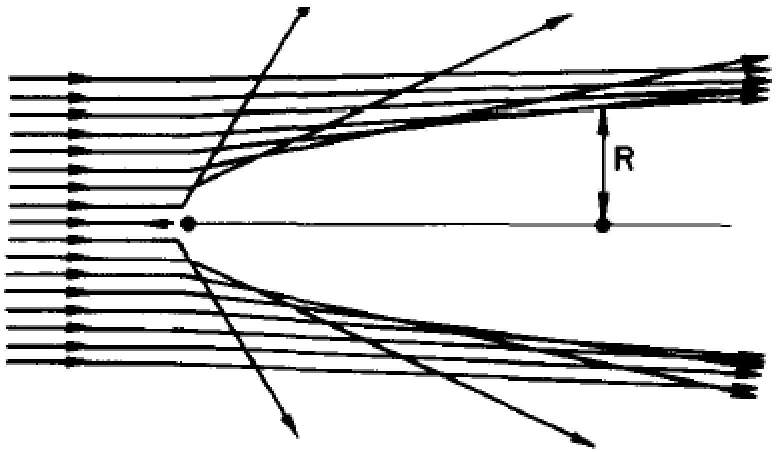
100 Kev
He Beam



Channeling – two body shadow cone

$$R_C = 2(Z_1 Z_2 e^2 d/E)^{1/2}$$

$$I_C = 1 + [\exp(-R_C^2/2\rho^2)](1 + R_C^2/2\rho^2)\,.$$

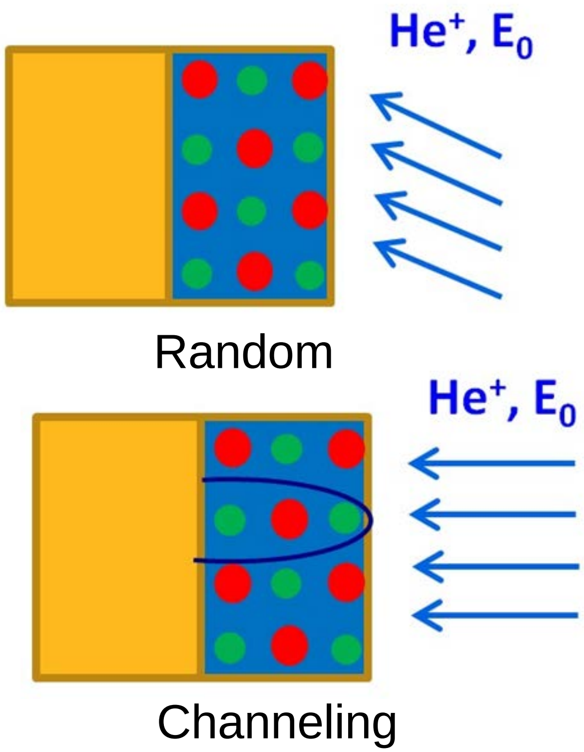


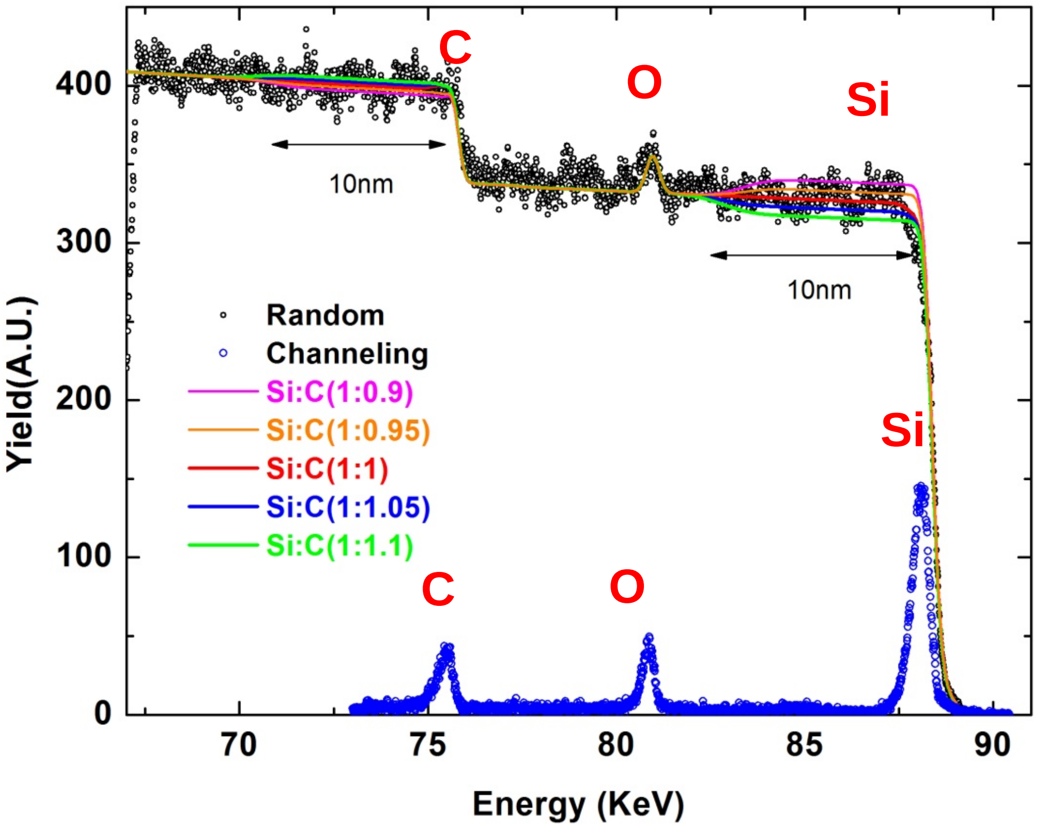
ρ = relative thermal displacement

Modelling of many atoms is used for more complete analysis

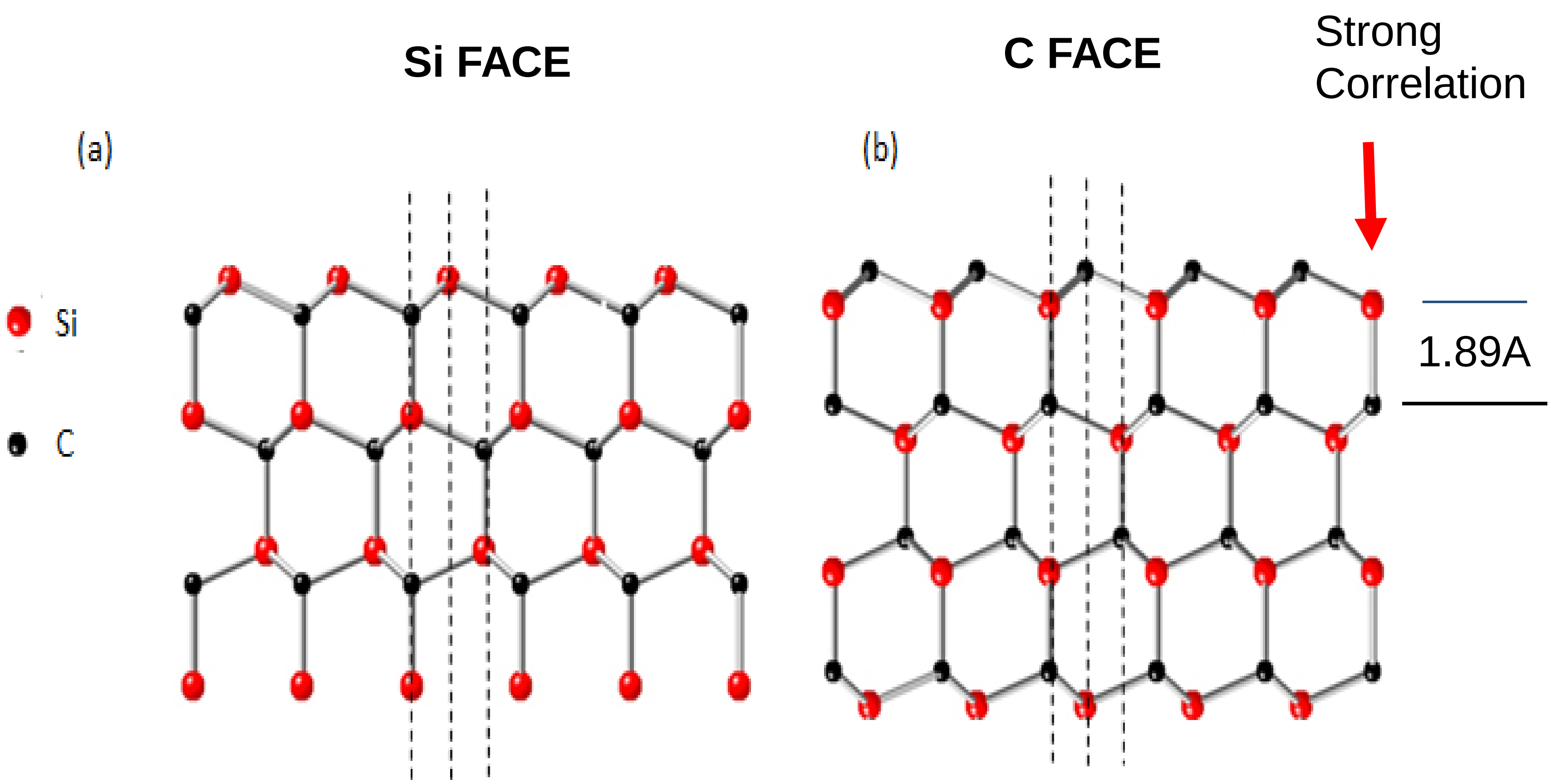
Stensgaard et al, Surf Sci., 1978

SiC: Channeling & Random-----MEIS



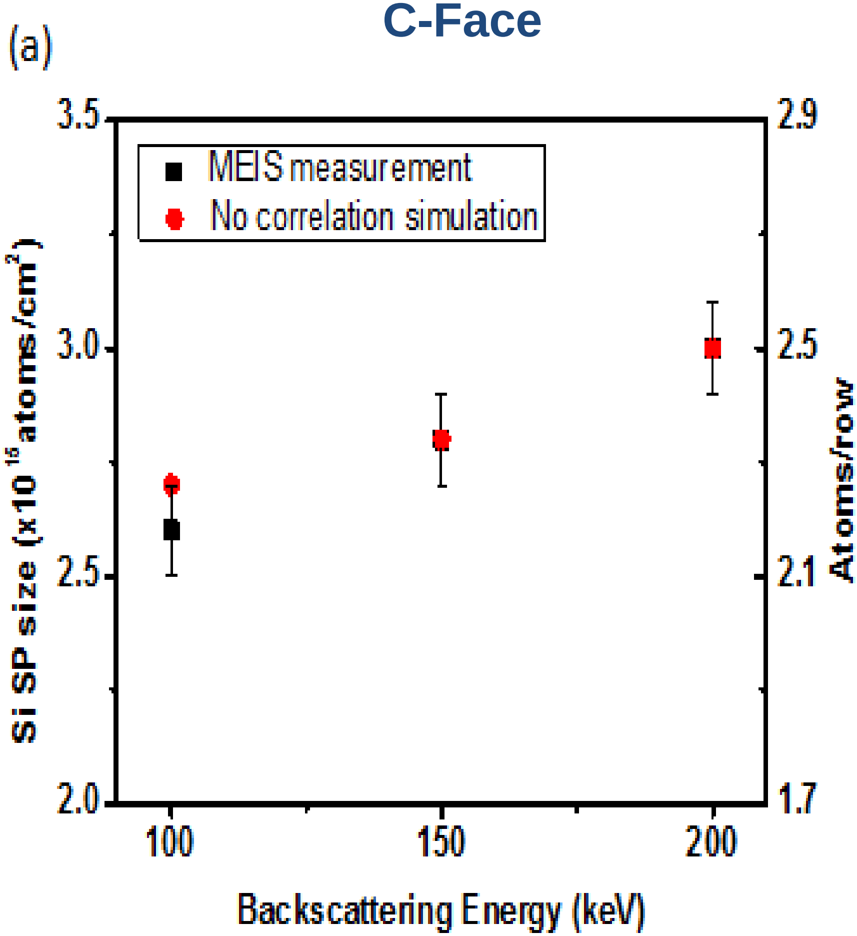


surface peak measured in channeling gives information of the first few monolayers and their crystal structure

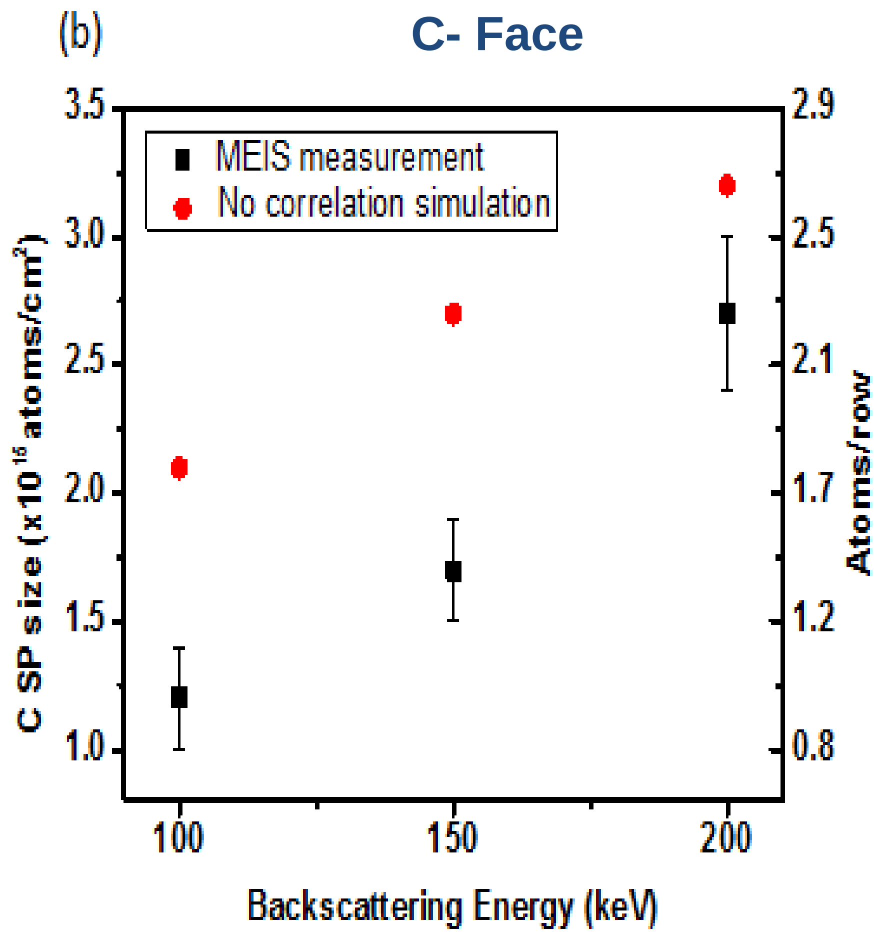

Si FACE
C FACE
Strong
Correlation
(a)
(b)
Si
C
1.89A

SURPRISING! SURFACE INTENSITY<<THEORY

Si Surface Peak C-Face



C Surface Peak C- Face



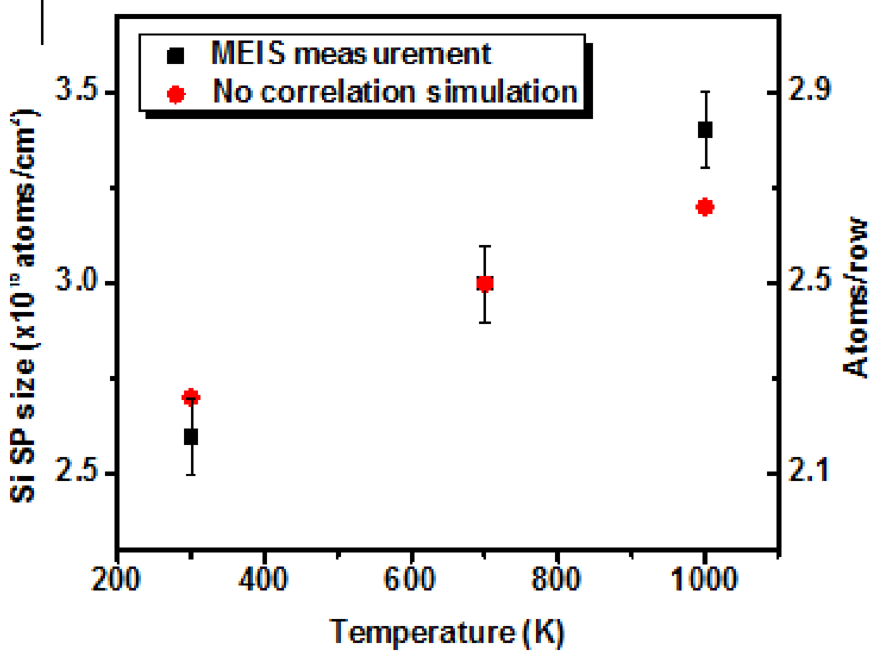
No Correlation effect

Correlated vibrations

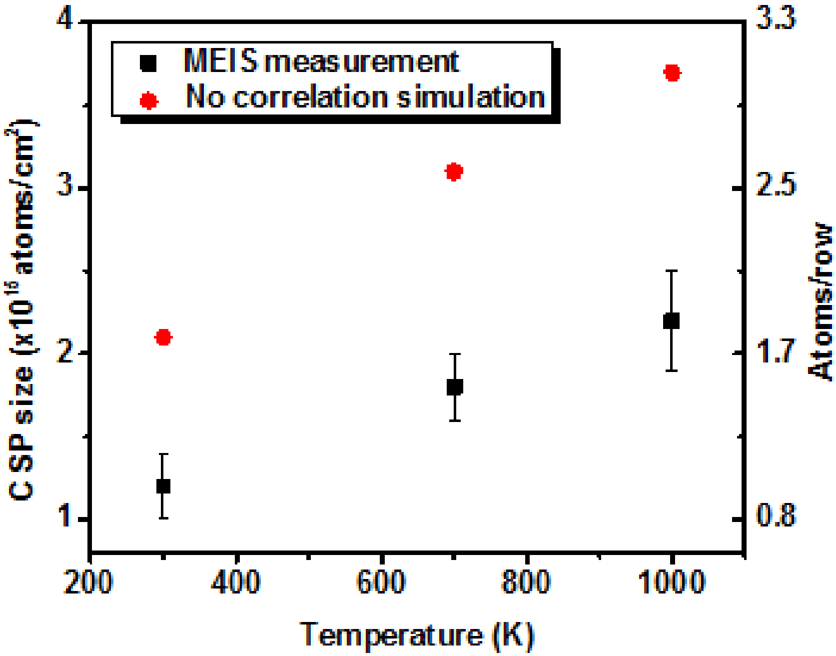
TEMPERATURE DEPENDENCE

Higher temperature>more low energy phonons= longer wavelenths
Longer wavelengths> more correlation

Si SP C-face-correlations not expected



C SP C-face-correlations expected



RUTGERS

SILICON CARBIDE THERMAL VIBRATION CORRELATIONS

CORRELATION IN THERMAL VIBRATIONS-

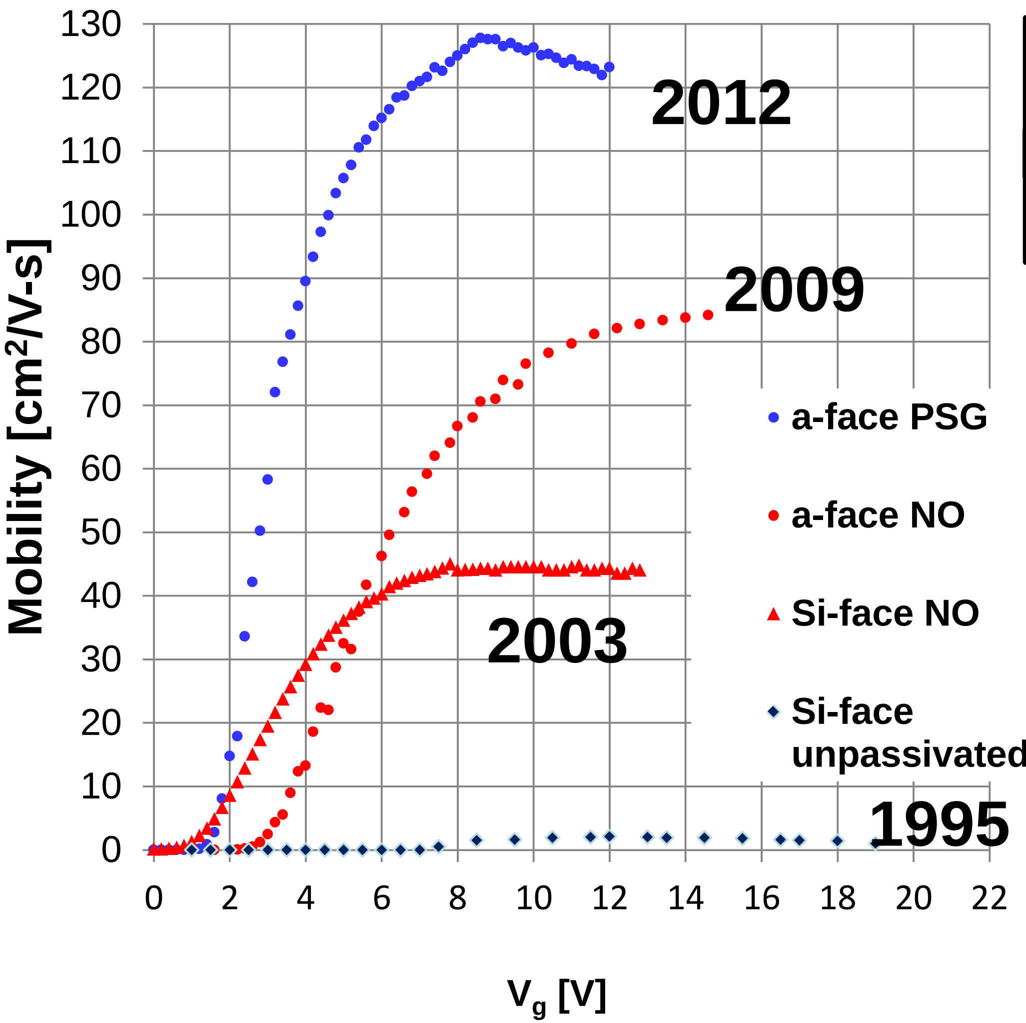
- ARE OBSERVED

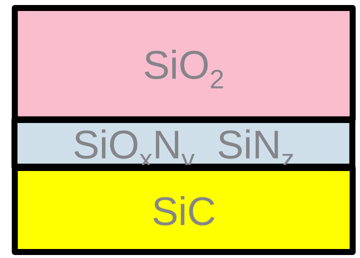
- SiC MAY REPRESENT THE LARGEST CORRELATION EFFECT IN SIMPLE MATERIALS.

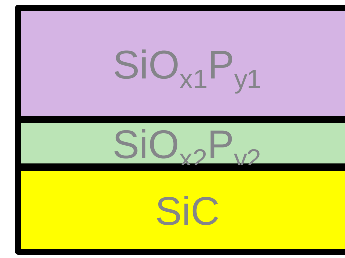
- SMALL LATTICE CONSTANT, STRONG BONDING GIVE RISE TO A 30% EFFECT IN THE SURFACE SCATTERING

- IMPLICATION: CORRELATIONS NEED TO BE INCLUDED IN QUANTITATIVE SURFACE SCATTERING

Mobility of SiC MOSFET vs. Passivation







NO (nitric oxide) and PSG (phosphosilicate glass) highly increase the inversion layer mobility of SiC/SiO_2 MOSFETS

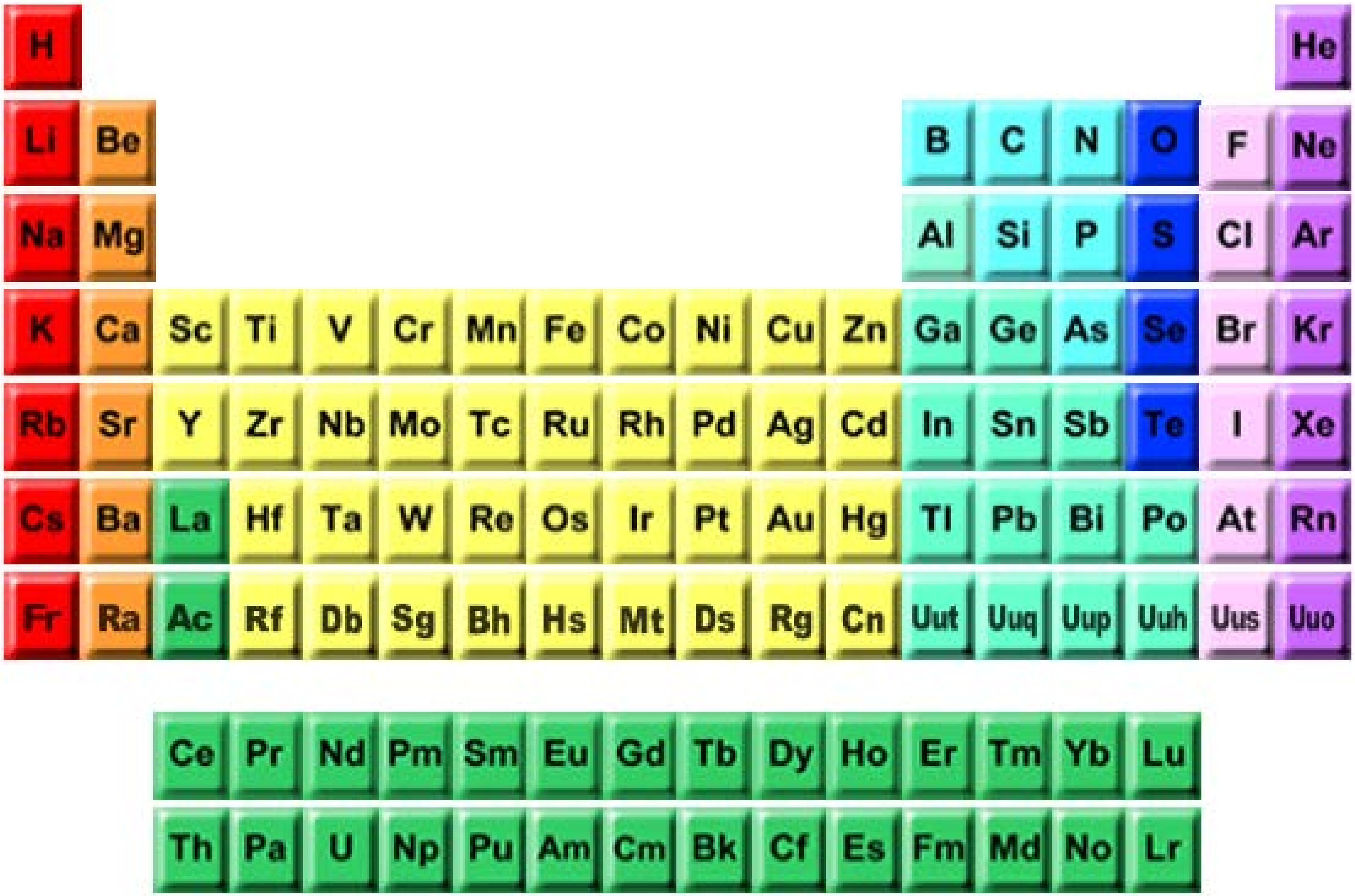
ROZEN *et al*, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 58, NO. 11, 2011
Gang Liu et.al IEEE ELECTRON DEVICE LETTERS, 2013

THE MATERIALS REVOLUTION

Computational materials science

Emergent materials with unanticipated properties

Quantum materials –lower dimensionality, atomic dimensions

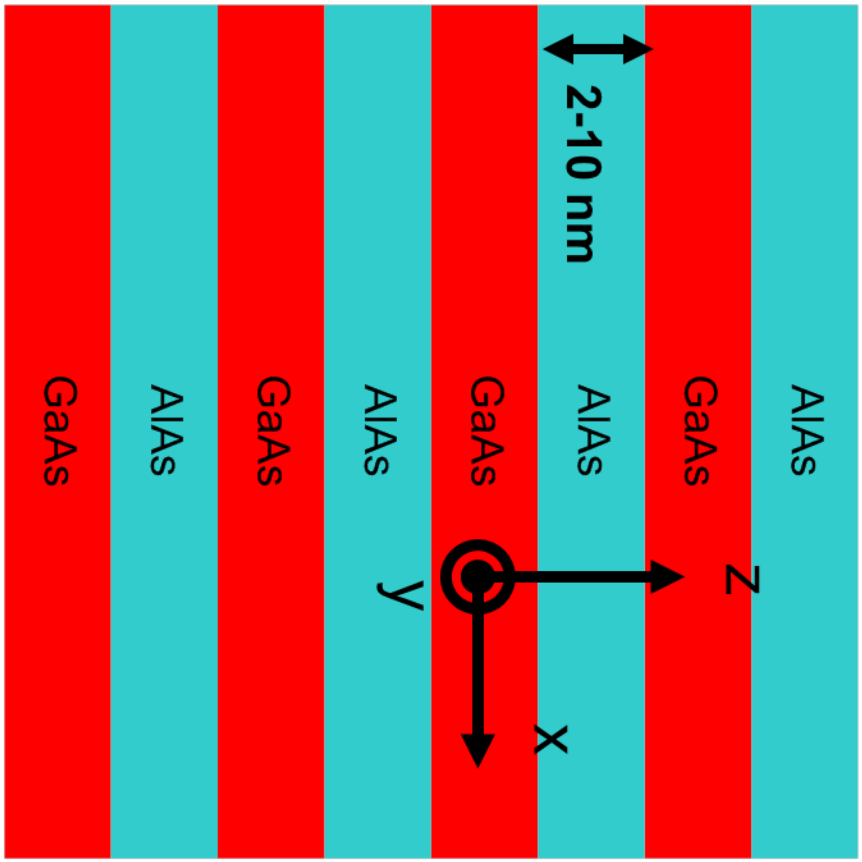


(select an element)

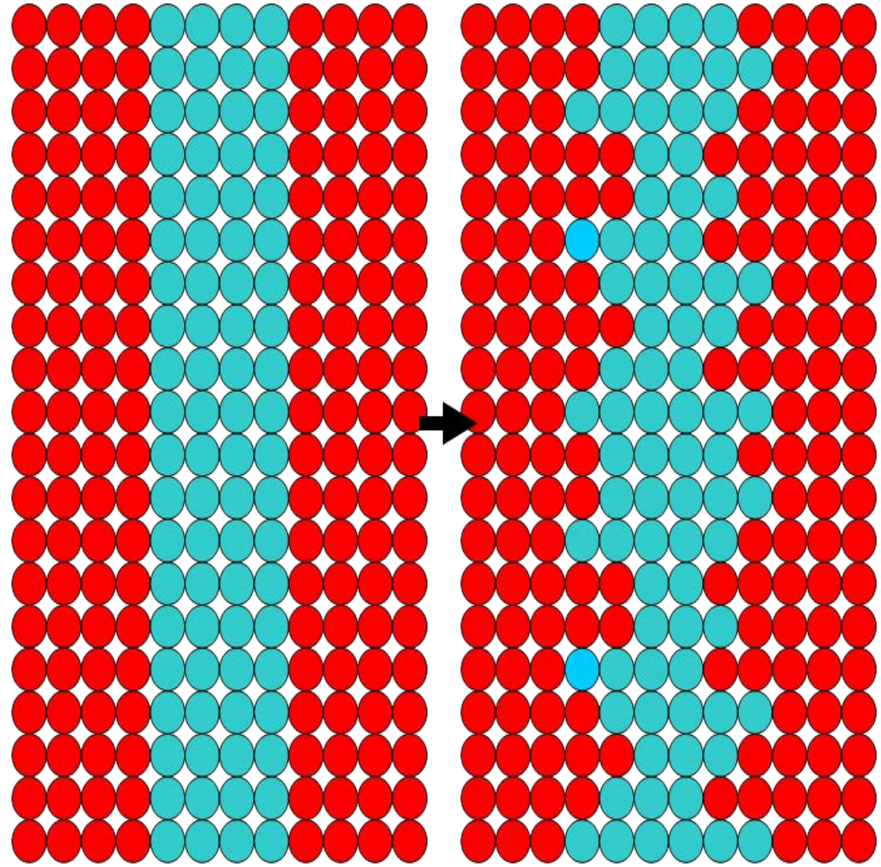
NOW CREATE !

GaAs/AlAs Superlattice

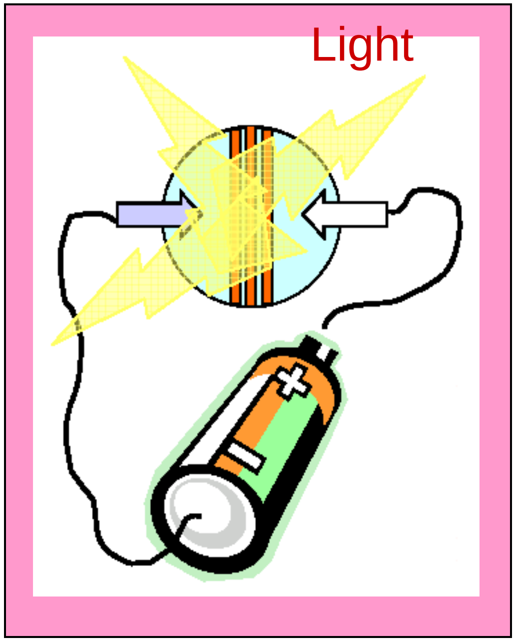
Superlattice

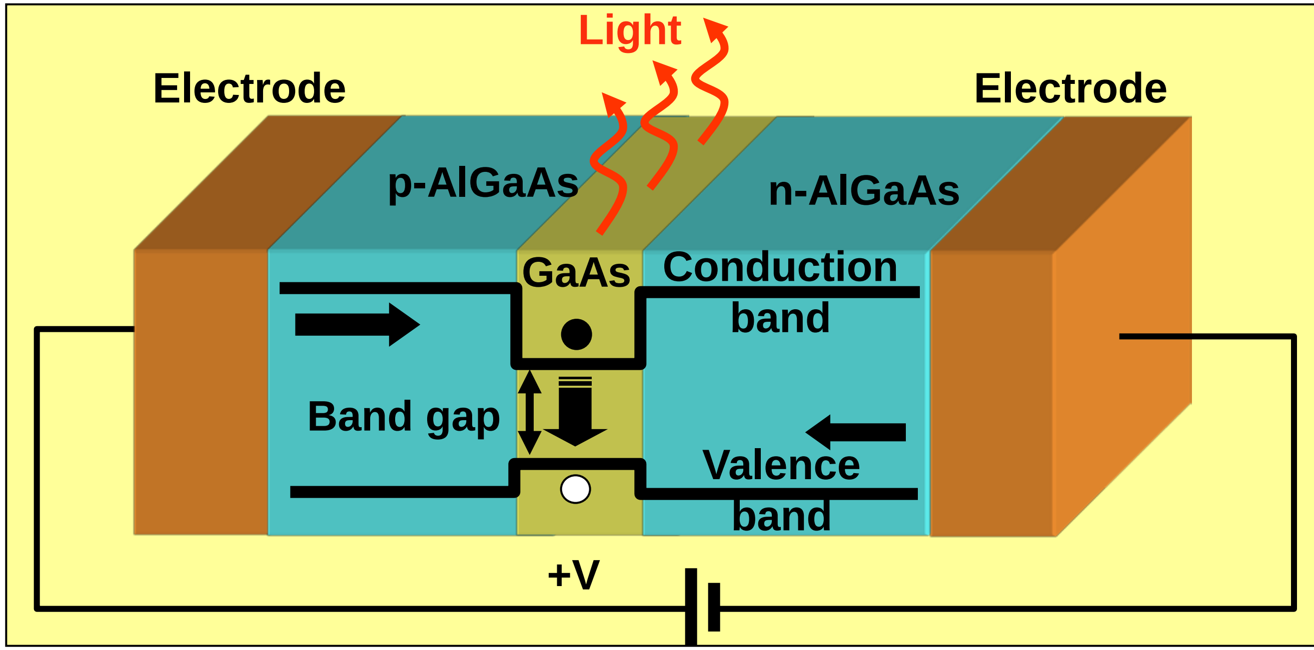


Quantum Well Intermixing



Application of QWs — Diode Laser

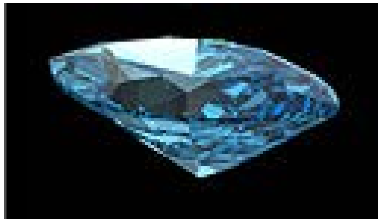


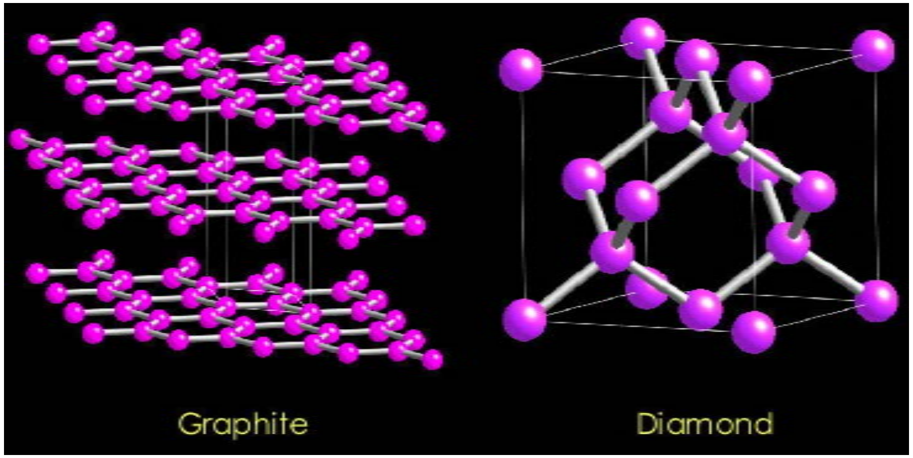


Disadvantages:

- Emission wavelength depends on material
- Very difficult to generate more than one color per laser
- Difficult to generate long wavelength, i.e., colors in the mid- to far-infrared region

COMPLEXITY
as in the arrangement of carbon atoms





The arrangement of carbon atoms determined the properties of the material!
In modern materials science, the arrangements are determined by the scientist!

The family of carbon compounds

Properties of the family

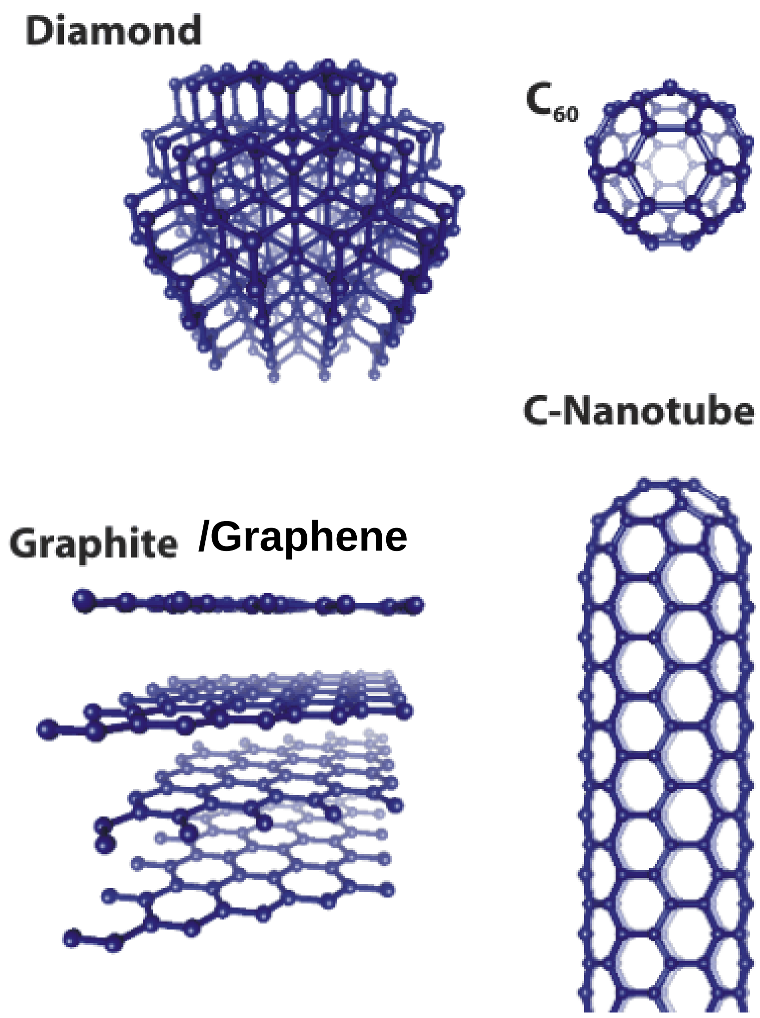
Mechanical
C-C bond strength: ~ 600 kJ/mol
stiffness of sp^2 orbitals: ~ 1 Tpa

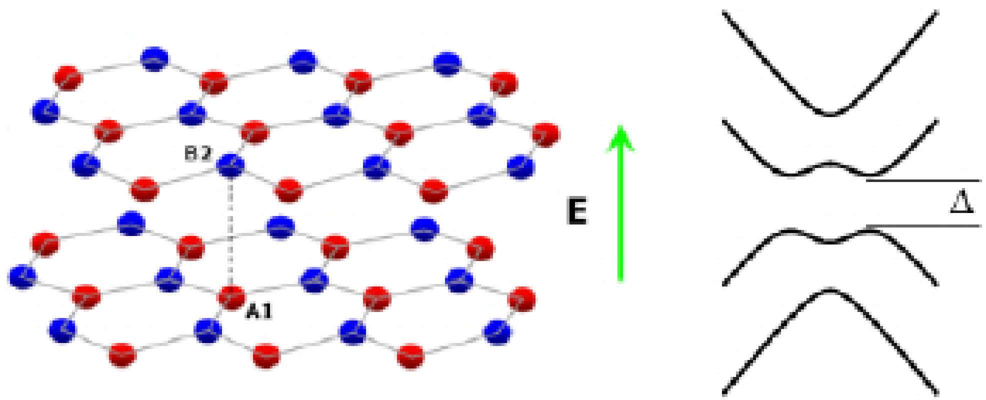
Thermal
conductivity of diamond: 3300 W/m/K

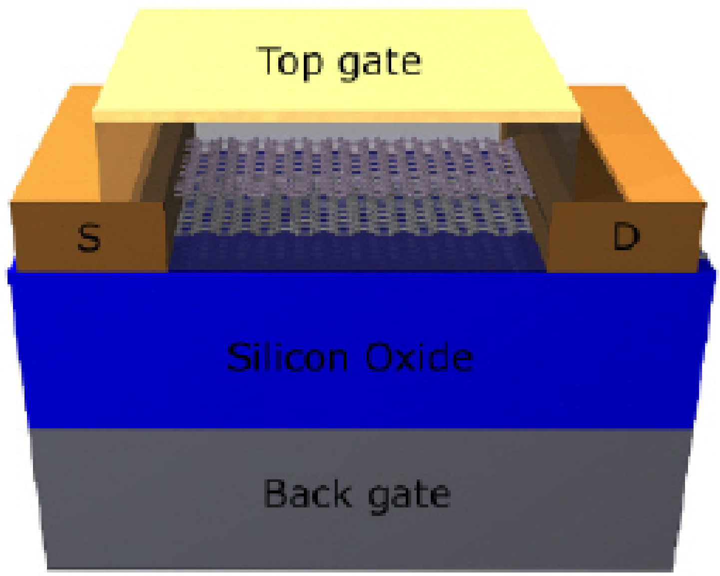
Electronic
semimet. (graphite) - insul. (diamond)

Chemical
inert (graphite) - reactive (amorphous C)

- **Unique about C-Nanotubes**
- Dimensionality
  aspect ratios up to 1:1,000,000
- Electronic variety
  semiconducting - metallic
- Surface-volume ratio
  specific surface area: ~1000 m^2/g




B2
A1
E
Δ

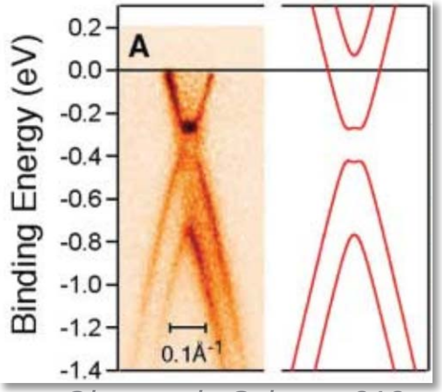

Top gate
S
D
Silicon Oxide
Back gate

The Challenge of Graphene

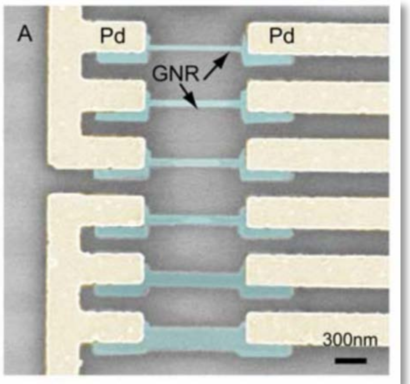
Graphene electronics requires a room temperature compatible band gap.

After more than a decade of research, producing a **significant** band gap remains the fundamental challenge

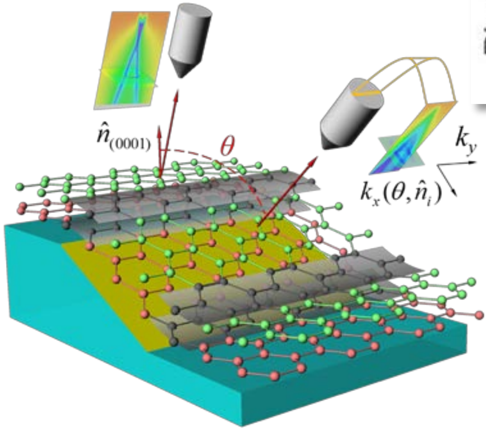
- Chemistry
- Strain
- Confinement



Ohta et al., Science 313 (2006)

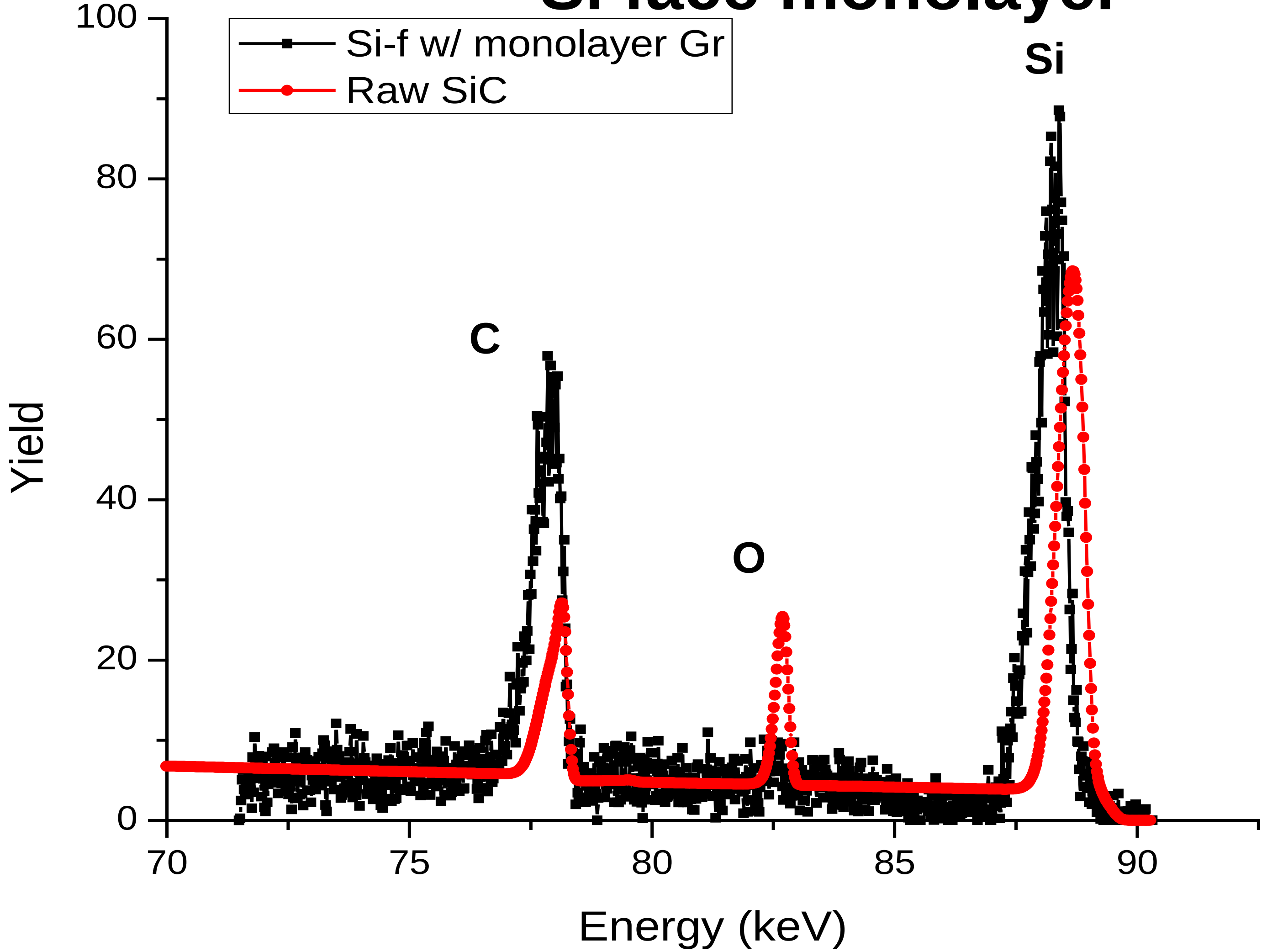


Chen et al., Physica E 40 (2007)



Hicks et al. Nature Phys. 9, 49 (2013).

Si face monolayer



Si: 3.2 x 10^{15} atoms/cm^2
C: 9.7 x 10^{15} atoms/cm^2

→ C from Gr 6.5 x 10^{15} atoms/cm^2

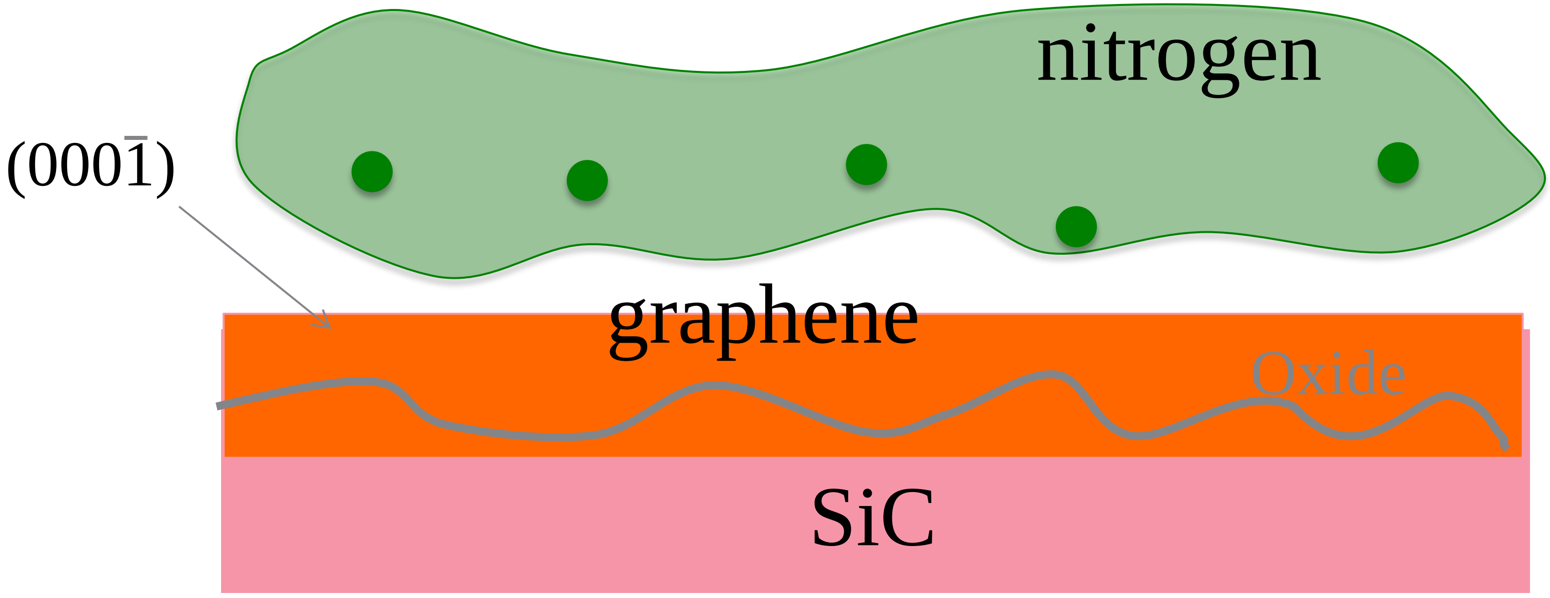
Nitrogen Modification of Epitaxial Graphene Formed on SiC

Edward H Conrad,[1] Feng Wang,[1] Gang Liu,[2] Sara Rothwell,[3] Leonard C. Feldman,[2] and Phil Cohen[3]

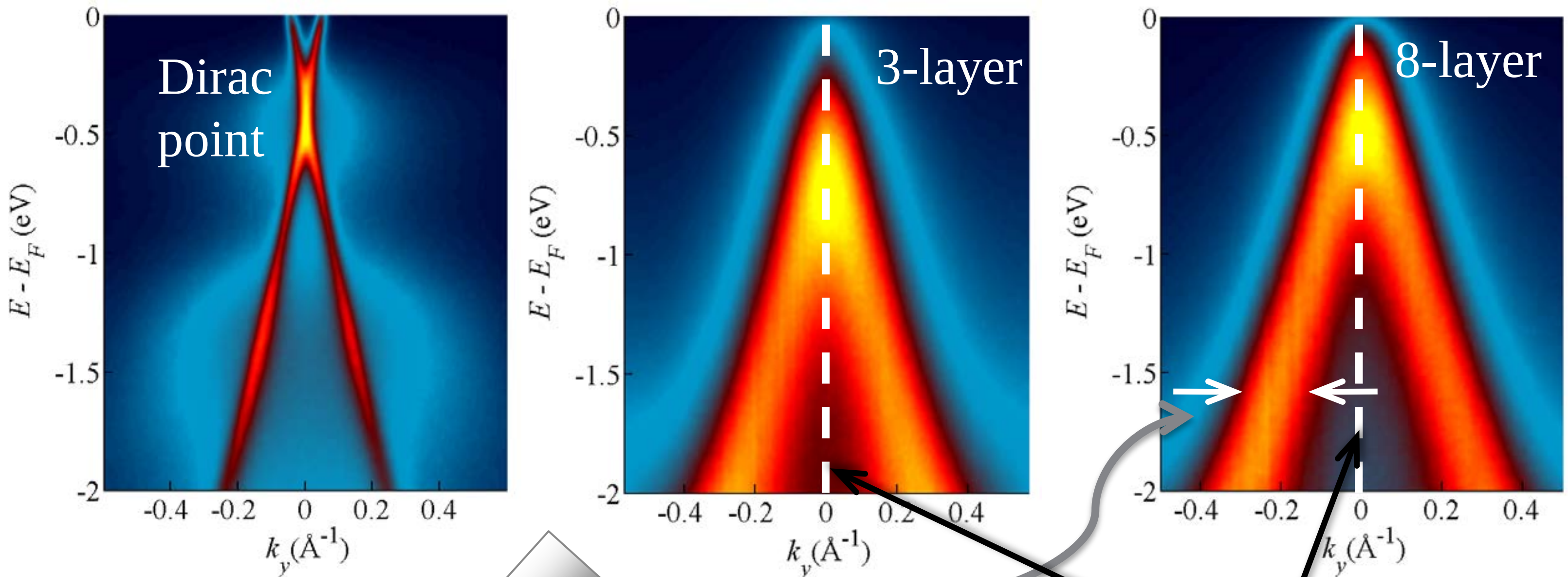
1. School Physics, Georgia Tech
2. Institute for Advanced Materials Devices and Nanotechnology, Rutgers University
3. Dept. of Electrical and Computer Eng., Univ. of Minnesota

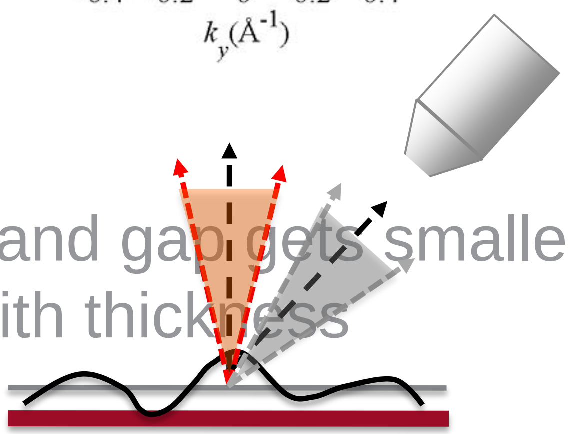
Nitrogen-Induced Strain Confined Graphene

Capable of producing large band gaps (> 0.7eV)

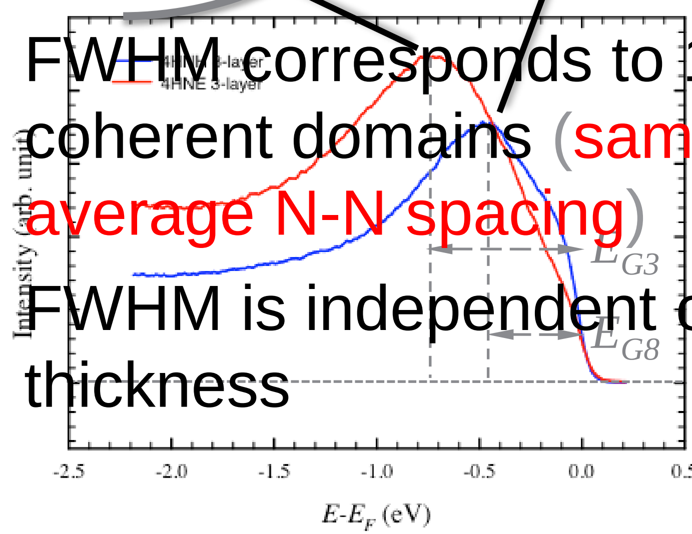


Angle resolved photoemission buckled graphene





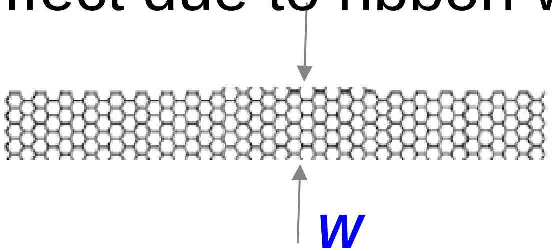
- Band gap gets smaller with thickness



- FWHM corresponds to 1-2nm coherent domains (same as average N-N spacing)
- FWHM is independent of layer thickness

Origin of gap

- Finite size effect due to ribbon width



$$E_{gap} \sim 1\ eV\cdot nm/W$$

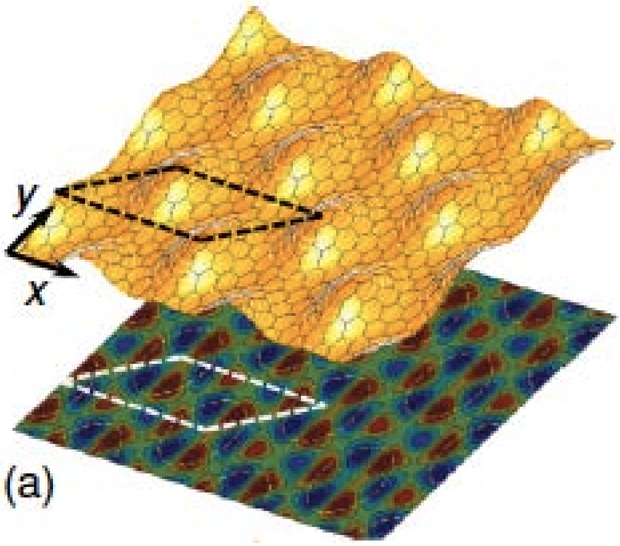
Nakada et al., PRB 54 (1996)

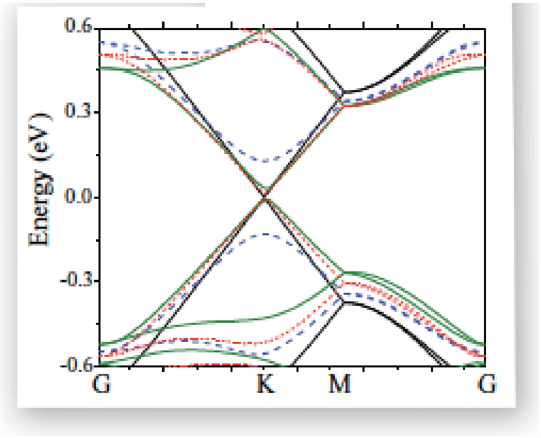
- quasi-periodic Strain

PHYSICAL REVIEW B **83**, 195436 (2011)

Gaps tunable by electrostatic gates in strained graphene

T. Low,[1,2] F. Guinea,[3] and M. I. Katsnelson[4]





High-mobility Ambipolar Field-Effect Transistors (FETs) based on Transition Metal Dichalcogenides (MoS_2, WSe_2)

V. Podzorov and M. E Gershenson
(*Dept. of Physics and IAMDN, Rutgers U.*)

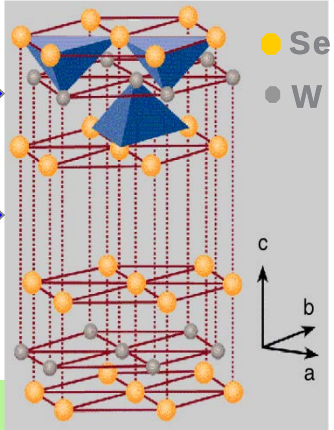
V. Podzorov *et al.*, *Appl. Phys. Lett*. **84**, 3301 (2004)

Layered Inorganic Semiconductors:

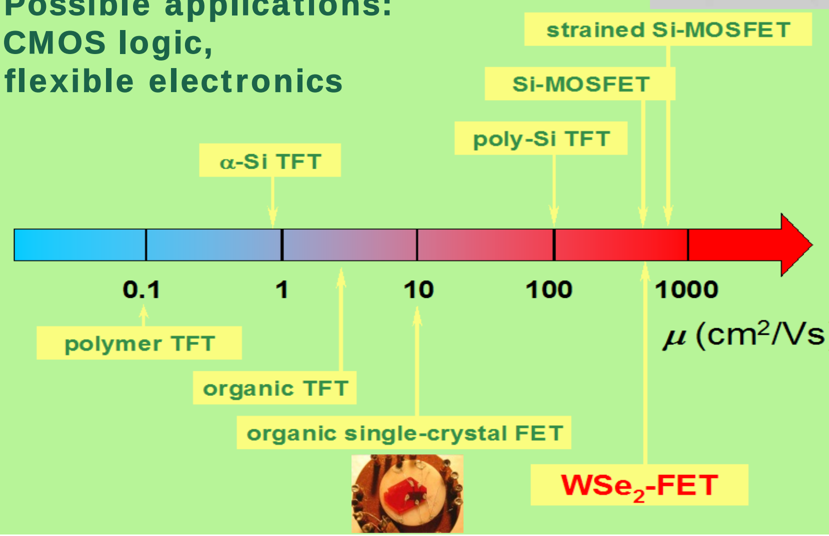
Transition metal dichalcogenides combine the "best of both worlds" (organic and inorganic):

covalent / ionic bonds within layers (≡ high mobility)

van der Waals interlayer bonding (≡ low density of surface states)

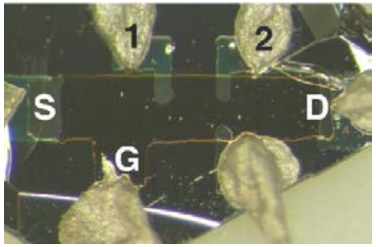


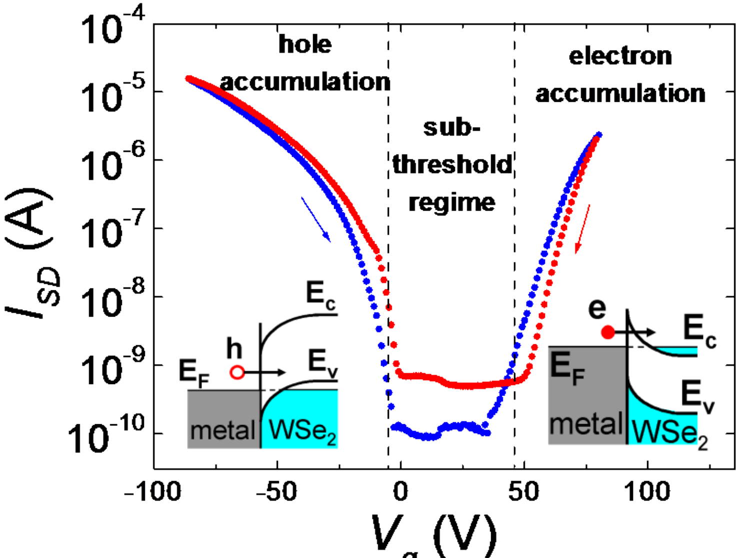
Possible applications:
CMOS logic,
flexible electronics

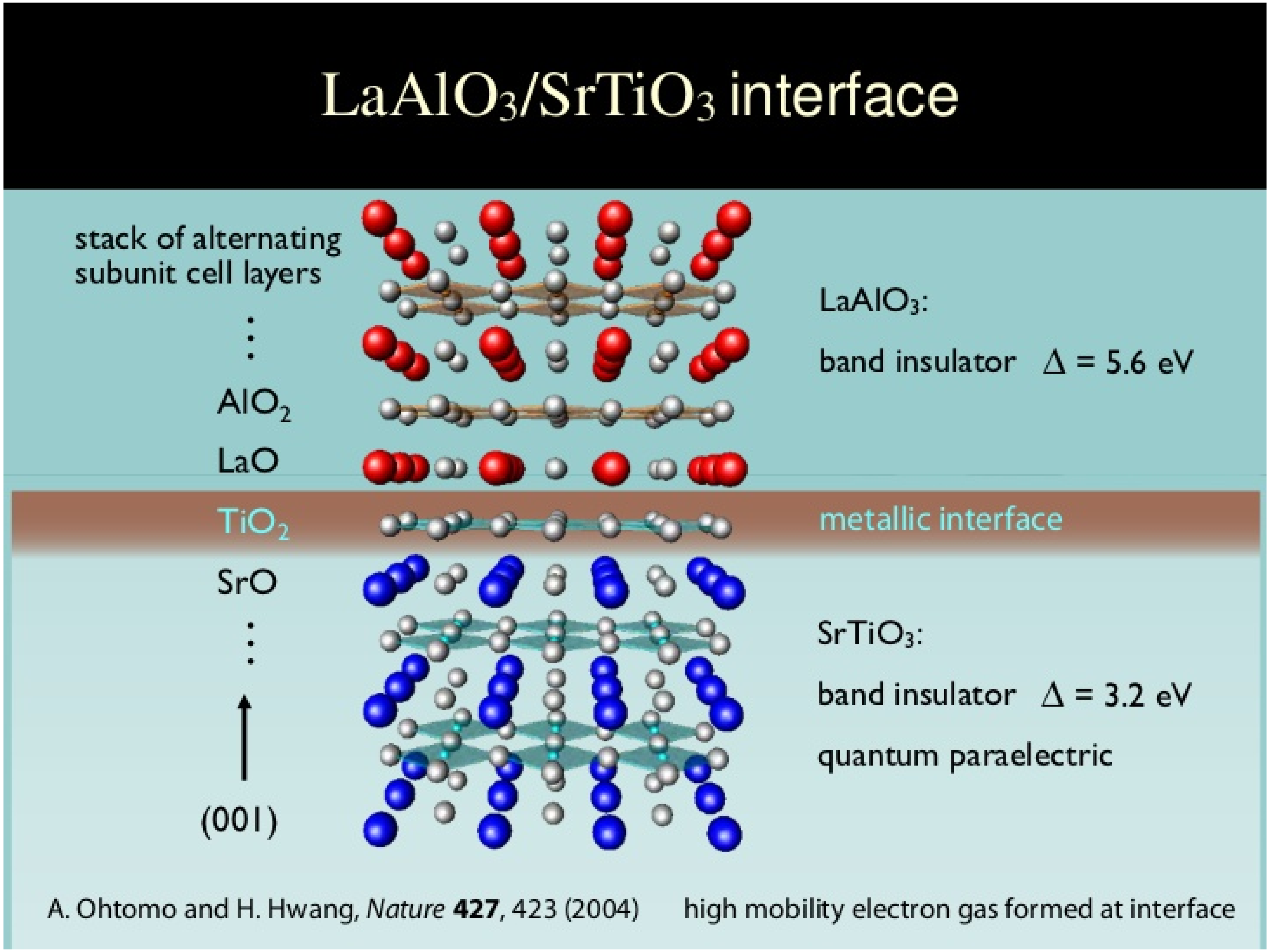


Unique characteristics of WSe2 FETs:

- **High Mobility ~ 500 $cm^2V^{-1}s^{-1}$ (comparable to Si MOSFETs)**
- **Ambipolar operation**
- **Mechanical flexibility**
- **Gap of ~ 1.5 eV**

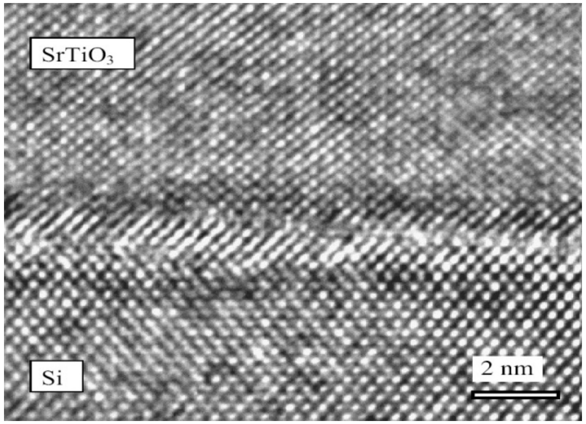




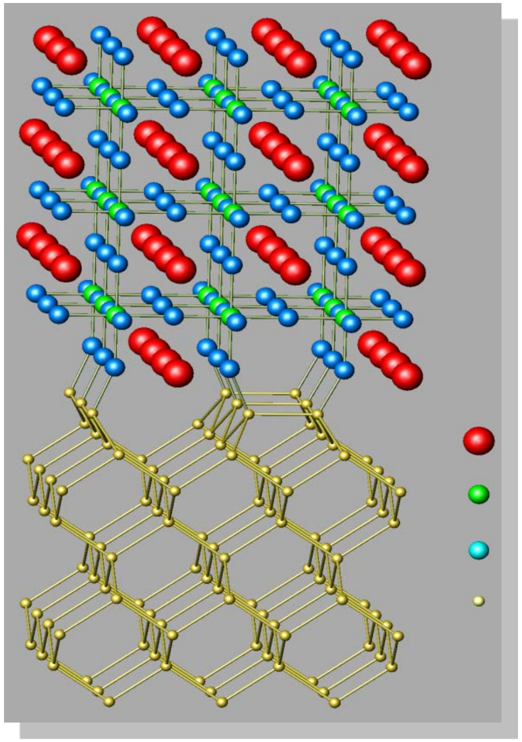

LaAlO3/SrTiO3 interface
stack of alternating subunit cell layers
AlO2
LaO
TiO2
SrO
(001)
LaAlO3:
band insulator Δ = 5.6 eV
metallic interface
SrTiO3:
band insulator Δ = 3.2 eV
quantum paraelectric
A. Ohtomo and H. Hwang, Nature 427, 423 (2004)
high mobility electron gas formed at interface

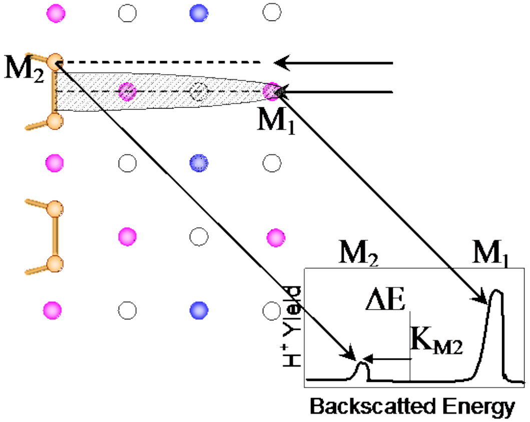
Epitaxial STO on Silicon

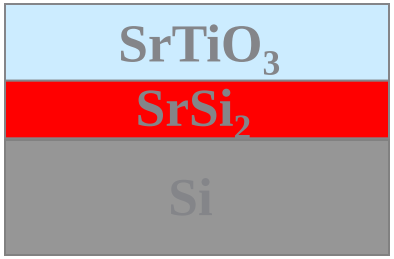
An ideal problem for MEIS: composition and structure in a thin film (heavy Z on light Z substrate)

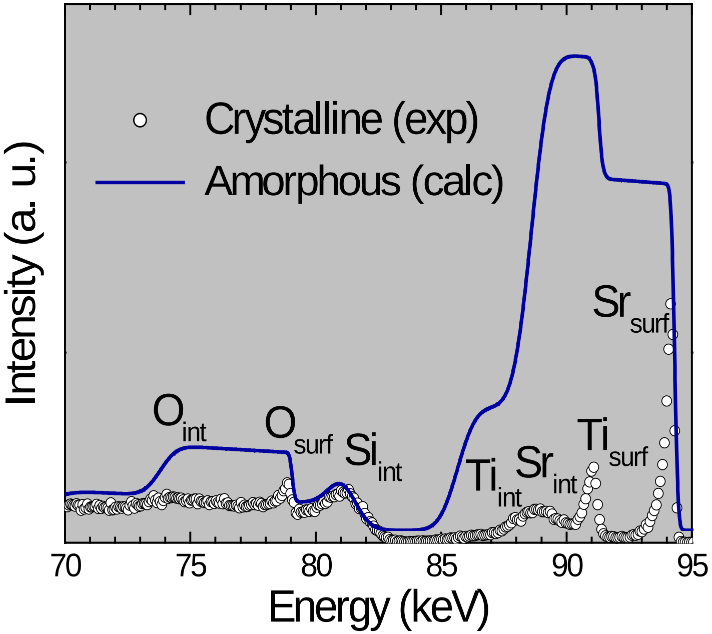


High-resolution TEM image of the interface between the $SrTiO_3$ film and Si(001)



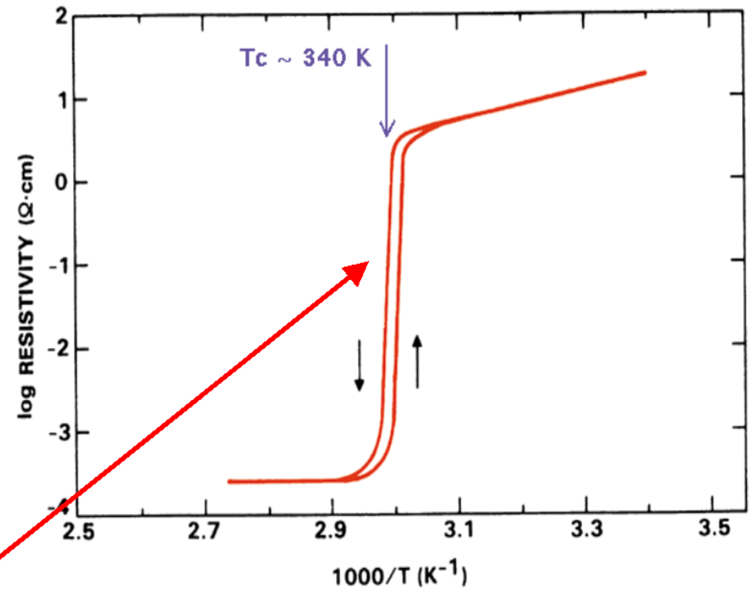






VO_2 metal-insulator transition

- First seen in films in 1960s
- First-order phase transition
- Structural rearrangement
- Gives Δ(conductivity)~10^4-10^5
- Large change in optical T, R
- Can be triggered by laser
- Entropy cost $\Delta S \sim 1.6 k_B$/V ion
- Antiferromagnetic above T_C

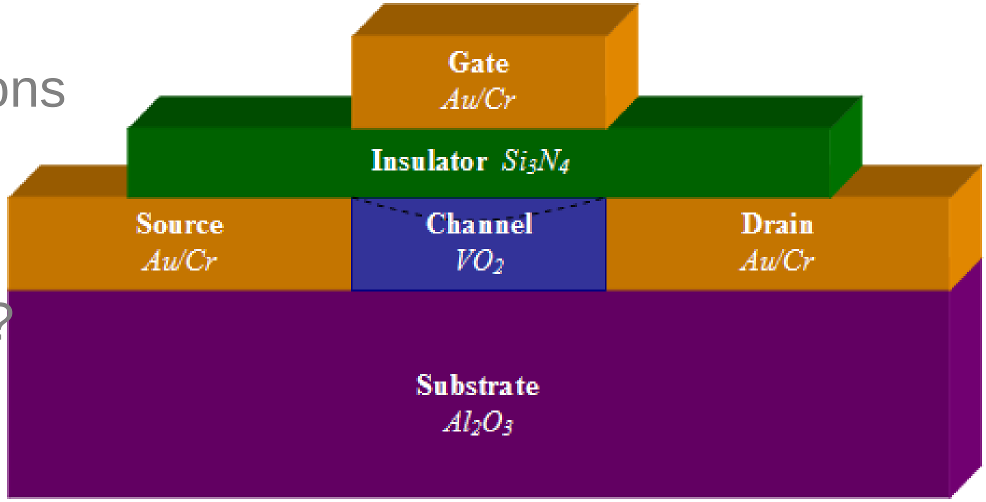


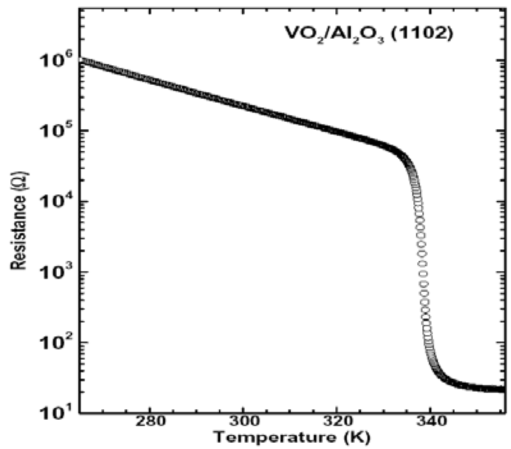
Hysteresis loop; typical first order transition feature.

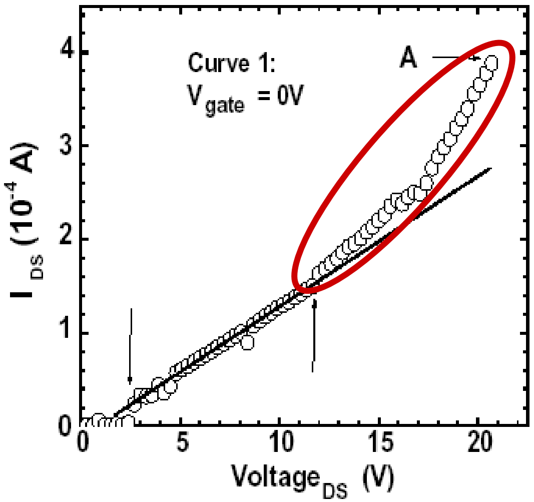
Temperature dependence of resistivity in VO_2 films.

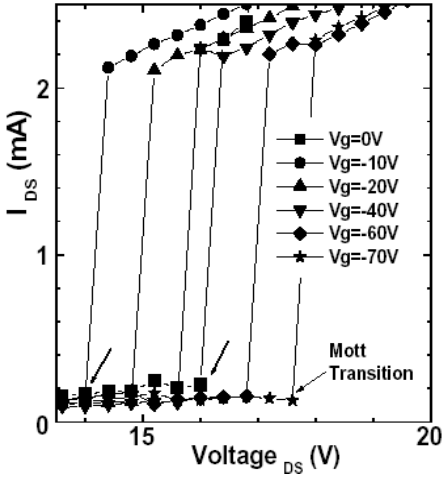
VO_2 Transistor

- An actual device:
  - $V_{D\ trans} = f(V_G)$ inducing collisions
- Still not answered:
  - What is the speed in this case?
  - What is the effect of E_{field} only?



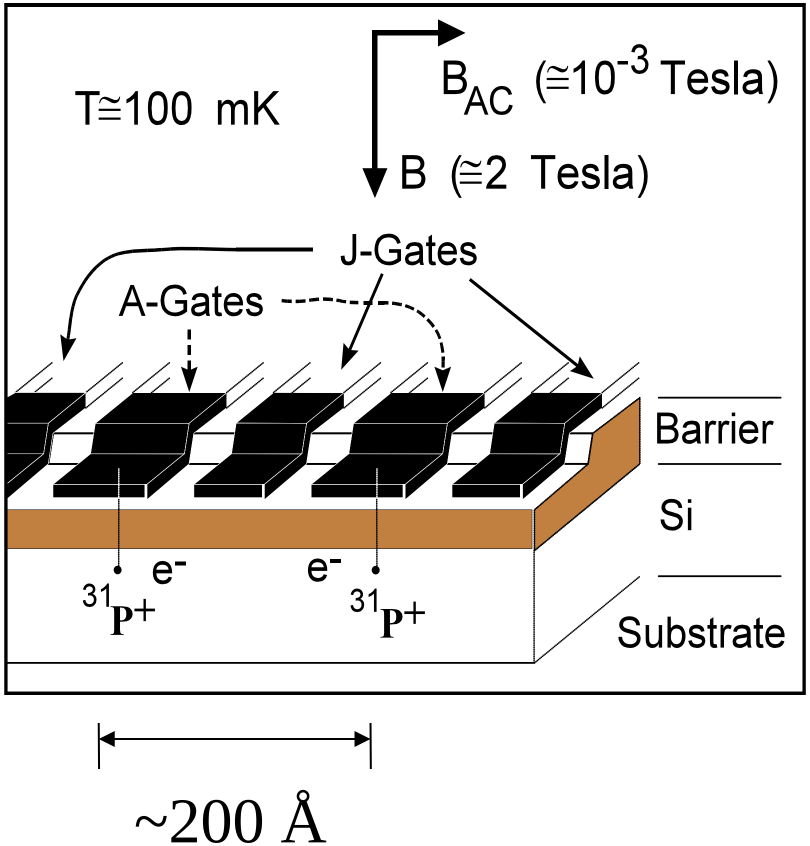


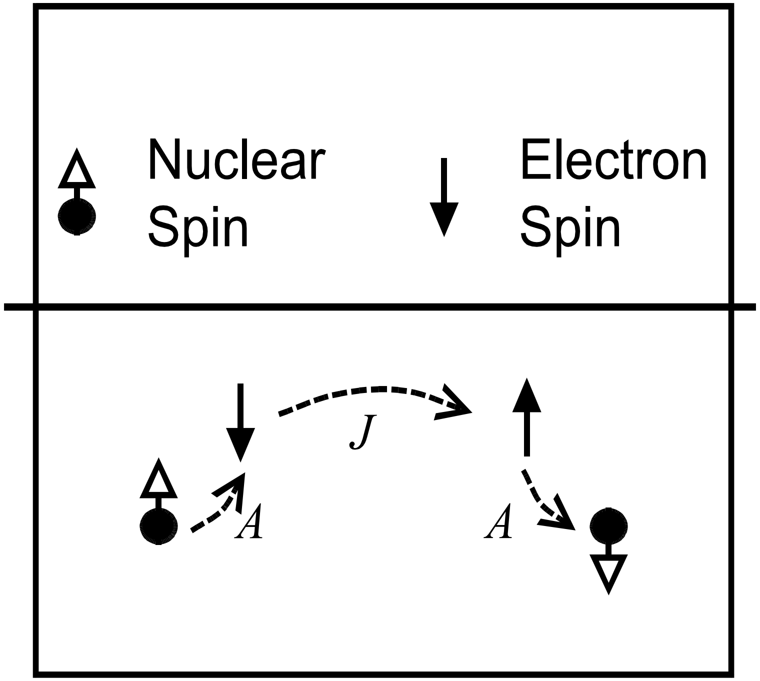




A Silicon-based nuclear spin quantum computer

B. E. Kane, Nature, May 14, 1998





Channeling is one tool in the on-going materials revolution

THANK YOU

Collaborators:
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