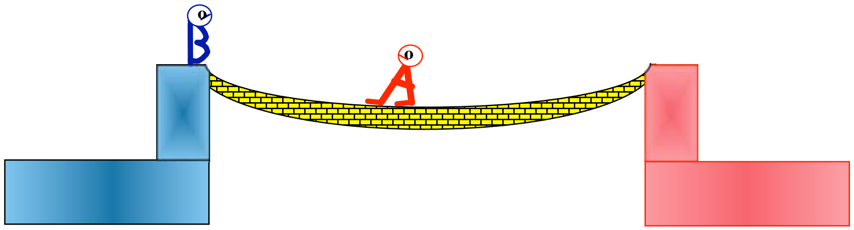
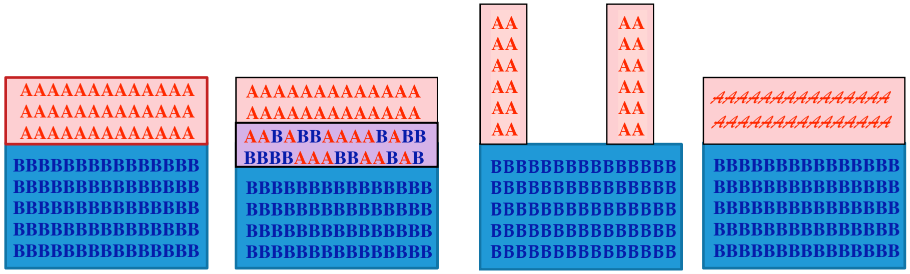
Building Atomic Bridges Between Dissimilar Materials

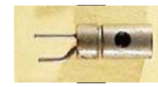


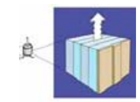


Professor Marjorie Olmstead, Department of Physics olmstd@uw.edu

Miniaturization

1930's	1960's	1990's	2020's
Victrola	Tabletop Turntable	Walkman	



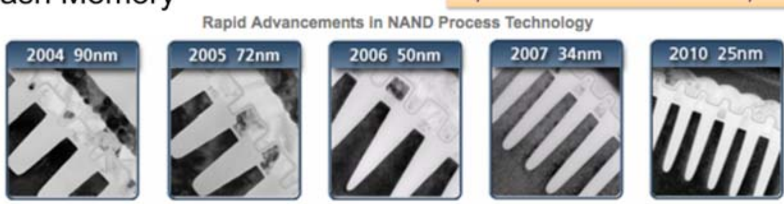


Vacuum Tube	Transistor	Heterostructure Laser
L ~ 5 mm	L ~ 5 μm	L ~ 5 nm

Inside your I-Pod …

Flash Memory

http://www.micron.com/innovations/process_tech/index

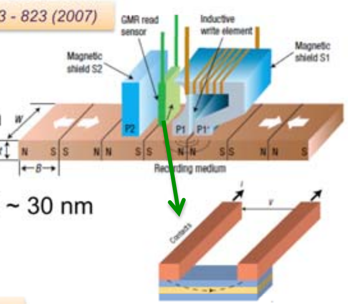


GMR Read Head

Nature Materials 6, 813 - 823 (2007)

W ~ 100 nm

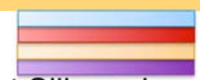
B ~ 30 nm

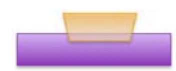


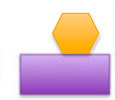
Field Effect Transistors

Intel Press Release on cnet.com

Future Devices – Interfaces Matter

- ➢ Silicon Based Nanoelectronics: 
  - o Join Silicon with things that do what Silicon doesn't do
- o Increase speed:
  - ✧ Strain electron channel by adding Germanium

  Islands and Interdiffusion 
- o Modulate Light:
  - ✧ Add layers of compound materials

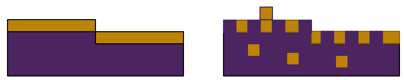
  Interface Compounds and Crystal Symmetry 
- o Add Magnetic Effects
  - ✧ Transition-metal doped oxides and semiconductors

  Unwanted Reactions and Phase Segregation

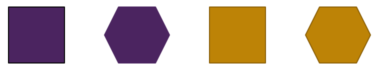
Questions to Answer

When you grow A on B …

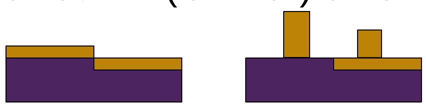
- Is there intermixing?



- How does B's structure influence A's ?



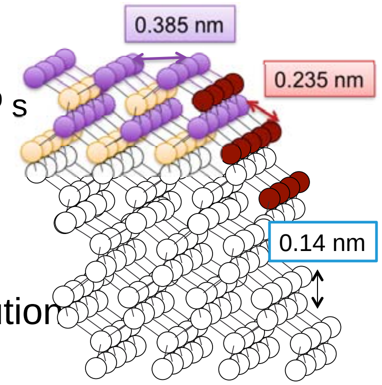
- Does A form a flat film (laminar) or form islands?



- Does A have new properties ?

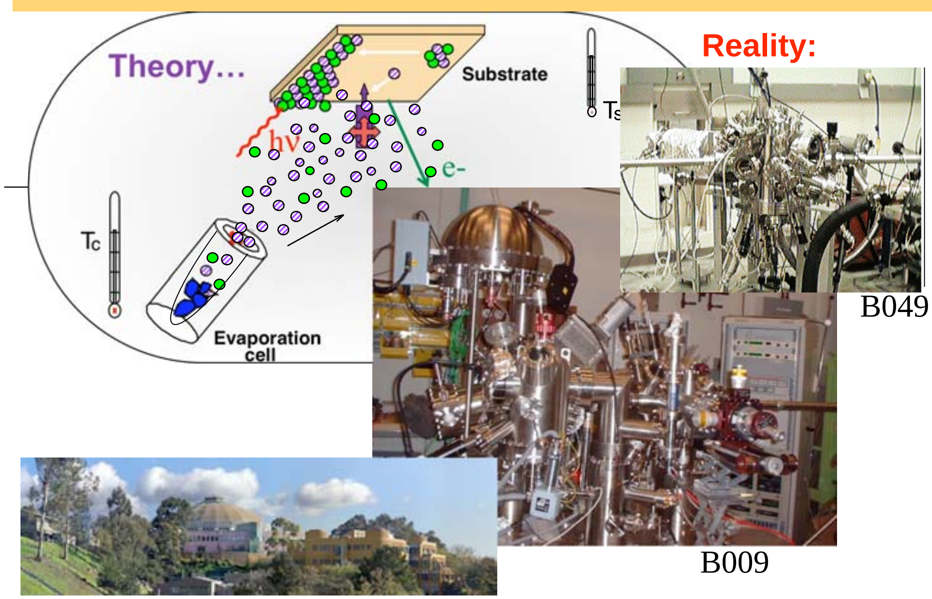
How can we answer these questions?

- Ultrahigh Vacuum
  - o Atmospheric pressure: Surface atoms hit once each 10^{-9} s
  - o 1 layer/second = 1 micron/hour
  - o Work at ~ 10^{-13} atmospheres, grow ~ few layers / minute
- Microscopy with sub-nm resolution
  - o Atomic spacing ~ 0.2 – 0.4 nm
- Atom-specific structural information
  - o Elemental distribution perpendicular to growth direction



Silicon Lattice

How it's done …



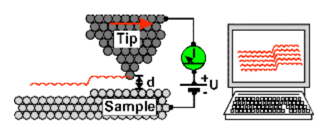
B049

B009

Synchrotron Source-Berkeley

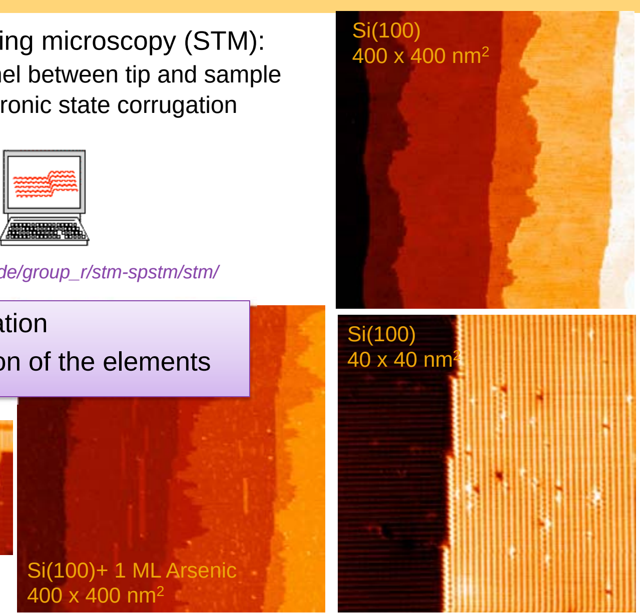
Experimental tools: Microscopy

- Scanning tunneling microscopy (STM):
  - o Electrons tunnel between tip and sample
  - o Measure electronic state corrugation

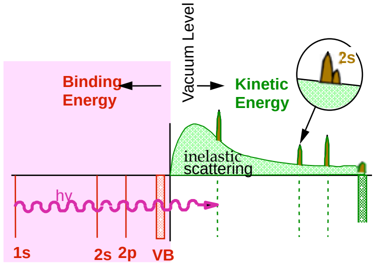


http://www.nanoscience.de/group_r/stm-spstm/stm/

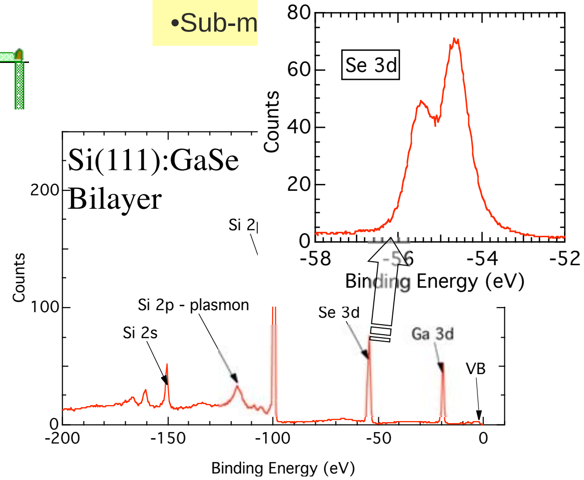
- Real space information
- No direct information of the elements



Experimental Tool: Photoemission Spectroscopy



•Element-specific
•Environment-specific
•Sub-m



•Intra-Atomic
- Atomic Potential
- Chemical Bonding
- Other Excitations

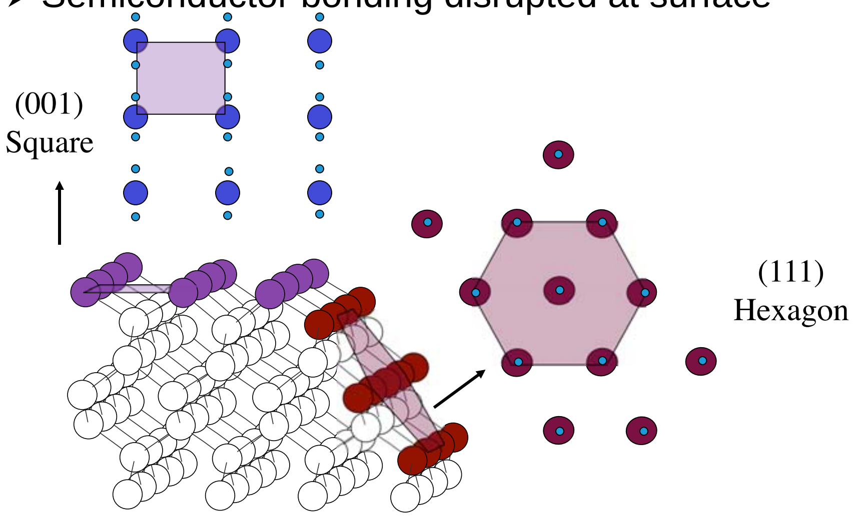
•Extra-Atomic
- Electrostatic Potential
- Polarization Screening
- Inelastic Scattering

A Few Intrinsic Factors in Heteroepitaxy

- **Surface Structure** -- Symmetry, Defects
  - o **GaSe vs Ga_2Se_3/Si**: Substrate control of crystal structure
- **Chemical Reaction** – Interface Compound Formation
  - o **TiO_2/Si**: Buffer layer inhibition of interface reaction
- **Impurity Incorporation** – Solubility Limits, Phase segregation
  - o **Cr** and **Mn**-doped **Ga_2Se_3/Si**: Concentration-dependent structure

Surface Symmetry

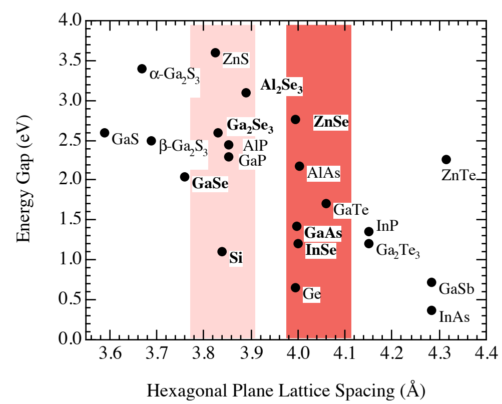
- Semiconductor bonding disrupted at surface



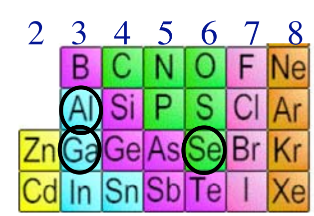
Silicon Crystal (Diamond structure)

Optoelectronics Heteroepitaxy

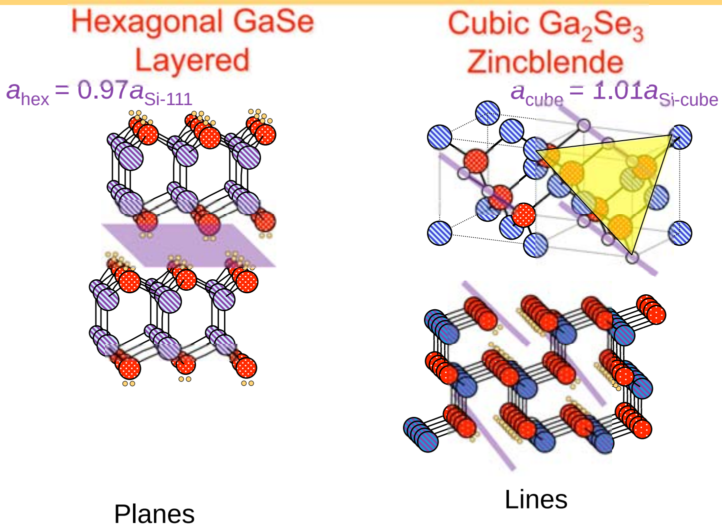
- Optical Band Gap vs. Lattice Parameter



- GaSe, Ga_2Se_3, Al_2Se_3
  - – Matched to Si
  - – Non-linear optics
  - – Direct band gap
  - – Anisotropic
  - – Cool growth physics
  - – Useful material??

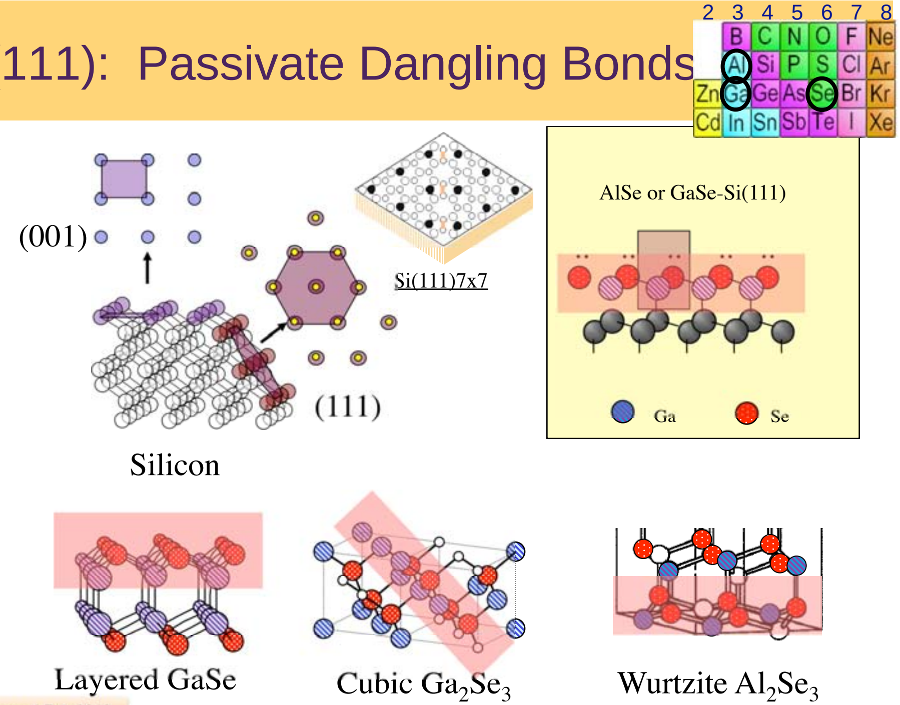


Gallium Selenide Crystal Structure

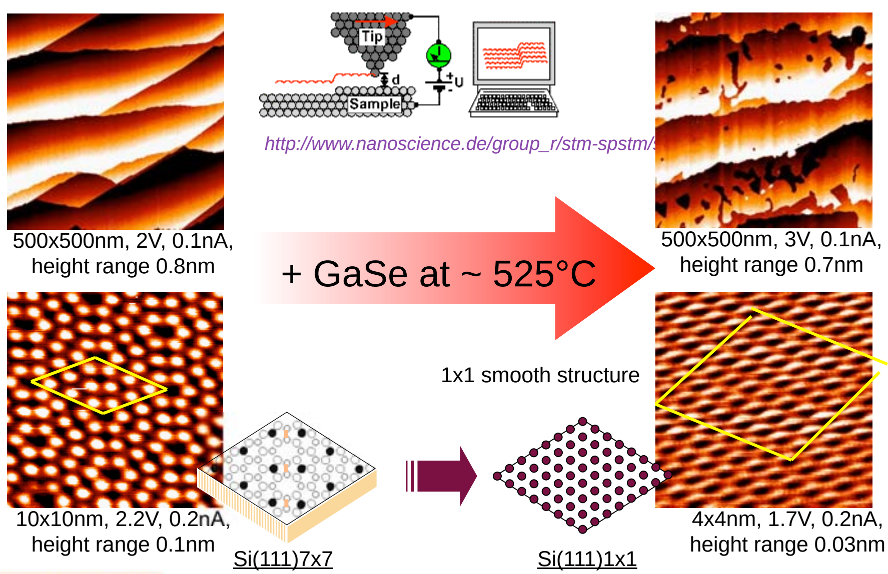


Flexible Bonding Configuration: Vacancies and Lone Pairs

Si(111): Passivate Dangling Bonds



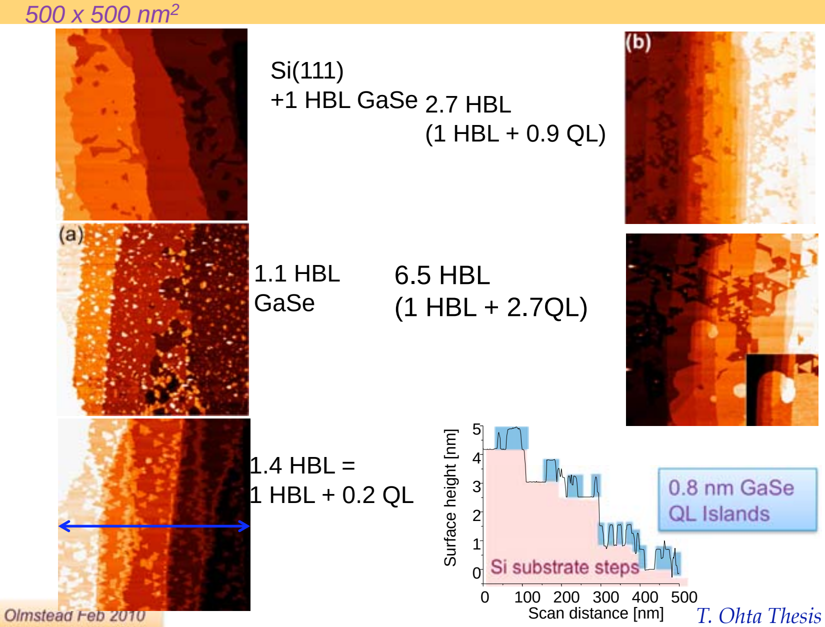
GaSe Bilayer on Si(111)7x7



PRB Feb 2004

GaSe Nucleation and Growth on Si(111)

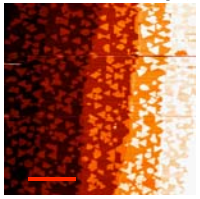
500 x 500 nm²



T. Ohta Thesis (UW) 2004.

Nucleation on Si(111):GaSe Hexagonal, Layered GaSe

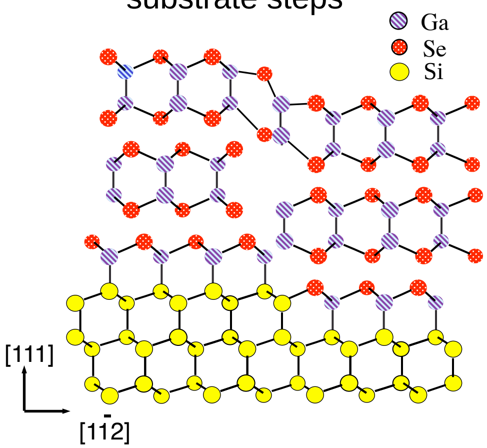
1.1QL on bilayer (3.2HBL coverage)



2.7QL on bilayer (6.5HBL coverage)

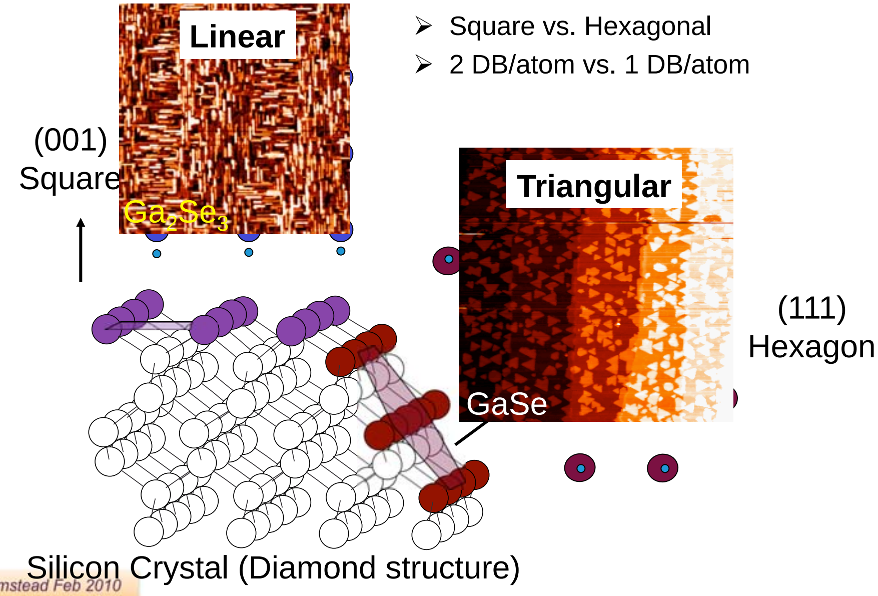
Scale bar 100 nm

- Triangular Islands
- 1 QL high (0.8 nm)
- "Carpet on steps" over substrate steps



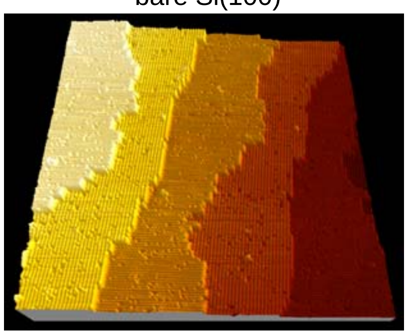
Change Symmetry: Si(001) vs. Si(111)

- Square vs. Hexagonal
- 2 DB/atom vs. 1 DB/atom



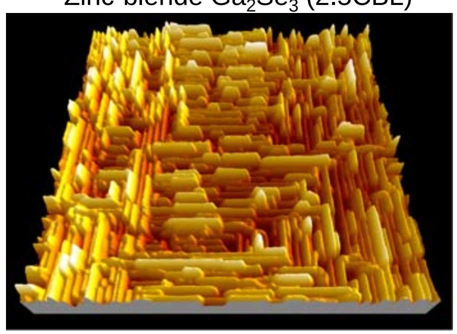
Growth on Si(001)

bare Si(100)

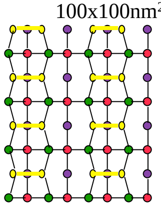


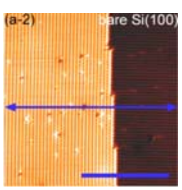
$100x100nm^2$, -2V, 0.1nA

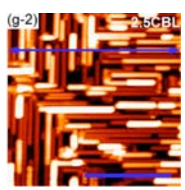
Zinc-blende Ga_2Se_3 (2.5CBL)

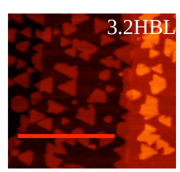


$100x100nm^2$, 5.4V, 0.09nA





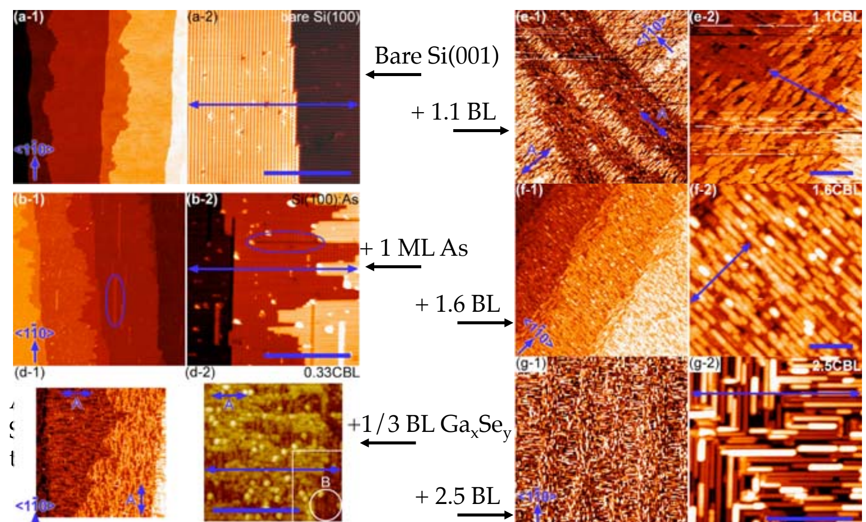




on Si(111)

Nanorod Nucleation and Growth

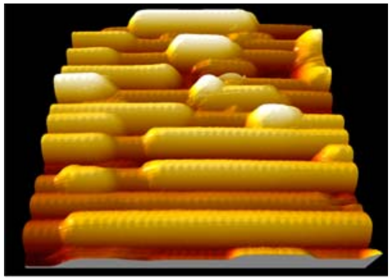
Large scale 500x500 nm^2 Scale Bar 25 nm



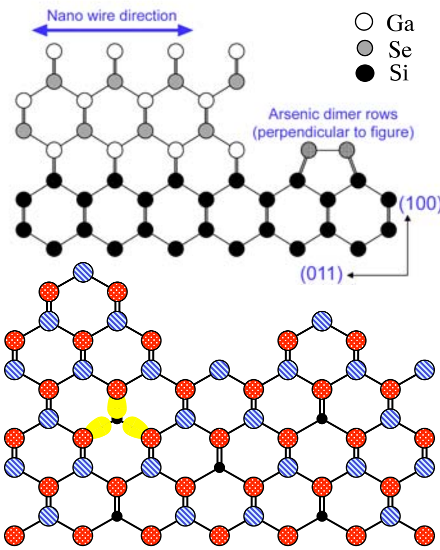
Ga_xSe_y islands perpendicular to As dimer rows

Sharp, narrow nanoridges. Shape stable with further growth

Ga_2Se_3 Nanoridge Structure ←→ Growth



-5.4 V, 0.09 nA, 20x20nm²

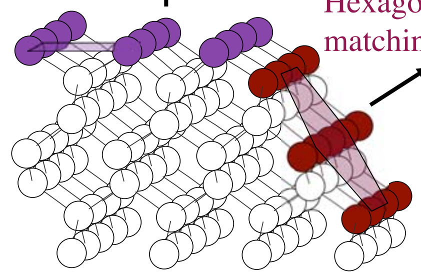


- 1 Ga-Se bilayer high
- Corrugation = Ga-Ga distance
- Rods perp. to As dimer rows
- Lateral shift between layers

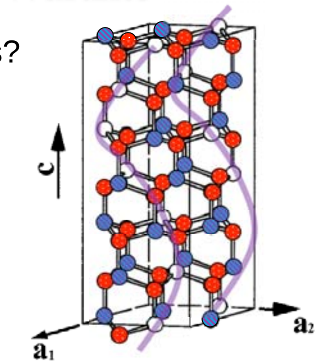
T. Ohta et al, PRL 2005.

Al_2Se_3 on Si(001):As

- Bulk Al_2Se_3 is hexagonal
  - o Can we induce cubic?
  - o Does intermixing still occur?
  - o Do vacancies align for nanoridges?



Hexagonal Al_2Se_3
Wurtzite

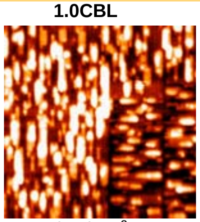


Helices

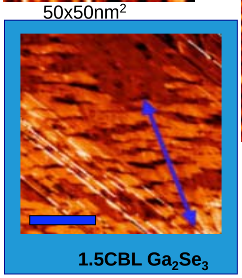
C. Lu thesis

Al_2Se_3 Growth on Si(001):As

1.0CBL

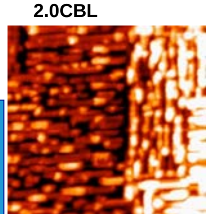


50x50nm²



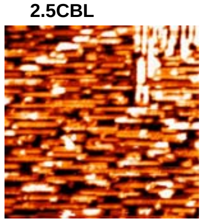
1.5CBL Ga_2Se_3

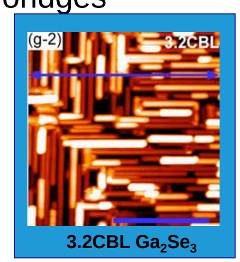
2.0CBL



- Initial growth
  - o Cubic symmetry
  - o Incipient nanoridges

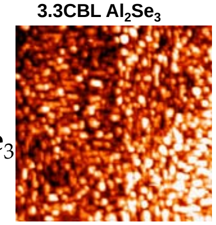
2.5CBL





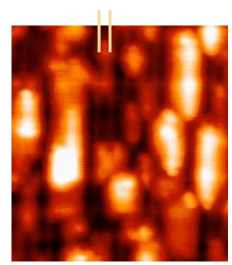
3.2CBL Ga_2Se_3

3.3CBL Al_2Se_3



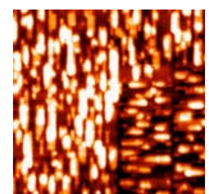
- Thin: Al_2Se_3 nanoridges sharper than Ga_2Se_3
- Thicker: Al_2Se_3 disorders, Ga_2Se_3 orders

Interface Structure and Orientation

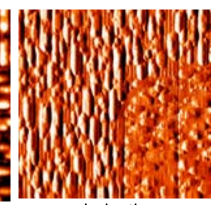


15x20nm²

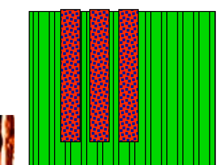
- Al_2Se_3 ridges form || As dimer rows

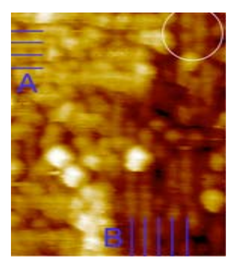


50x50nm²



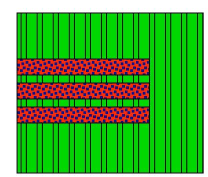
derivative





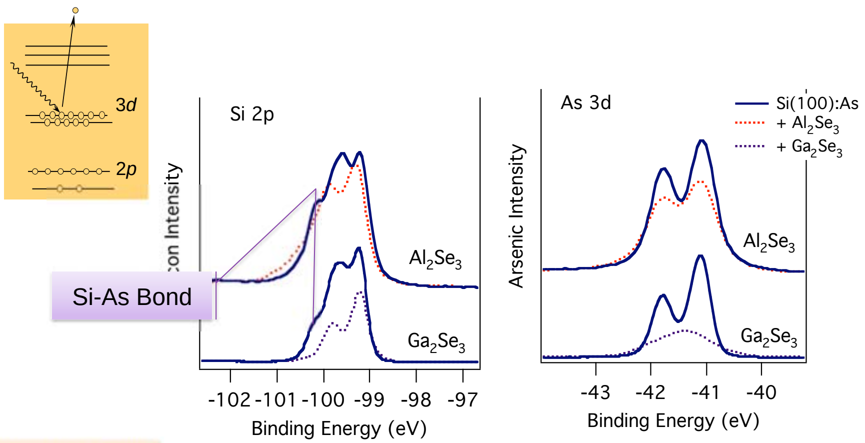
15x20nm²

- Ga_2Se_3 ridges form ⊥ As dimer rows



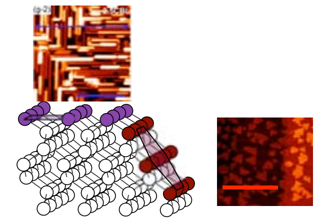
Why? Different Reactivity

- Ga_2Se_3: As interdiffuses into Ga_2Se_3
- Al_2Se_3: As stays bonded to Si



A Few Intrinsic Factors in Heteroepitaxy

- **Surface Structure** –
  Symmetry, Defects



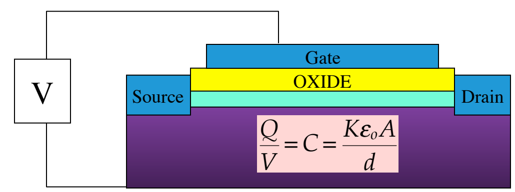
- **Chemical Reaction** – Interface Compound Formation
  - o **TiO_2/Si**: Buffer layer inhibition of interface reaction
- **Impurity Incorporation** – Solubility Limits, Phase segregation
  - o **Cr** and **Mn**-doped **Ga_2Se_3/Si**:
    Concentration-dependent structure

Chemical Reactions: Good or Bad?

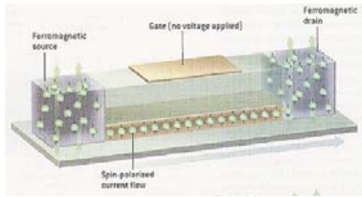
- Bad
  - o Wrong properties for desired application
  - o Passivate to the point nothing wets the surface
- Good
  - o Unzip surface reconstruction
  - o Satisfy electron counting at interface
  - o Special properties of unique material

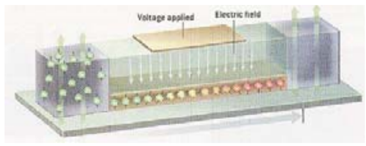
TiO_2: Heteroepitaxial Oxide on Silicon

- High K dielectric for transistor as area shrinks



- Ferromagnetic semiconductor for spin-transistor

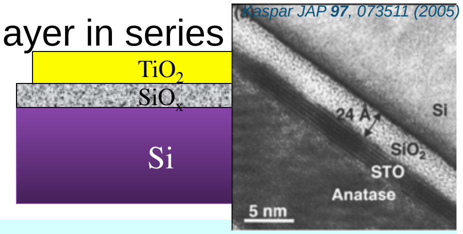




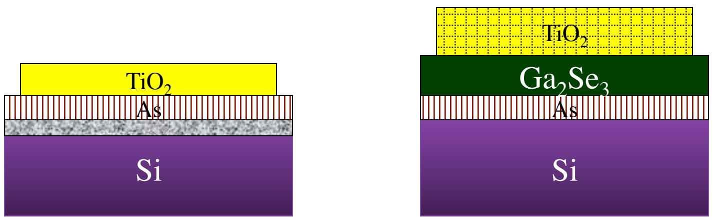
Rashbah effect: Voltage rotates spin

TiO_2 Problem: Unwanted SiO_2

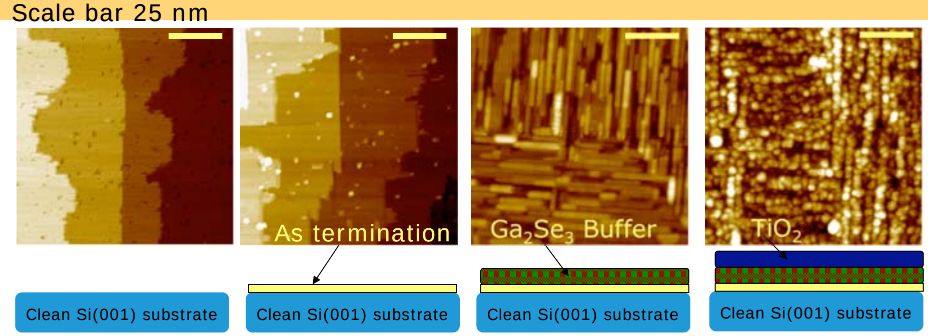
- Low dielectric constant layer in series
  - o Large capacitance
- Amorphous interface
  - o scatters spin-polarization

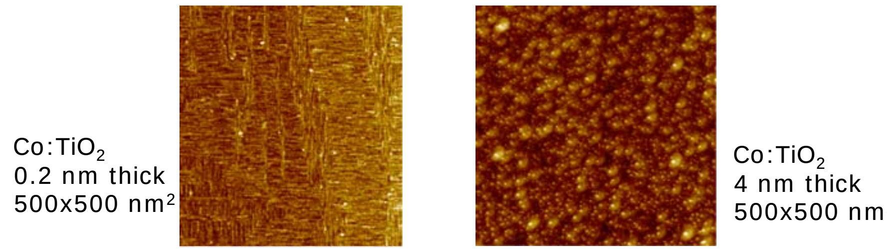


Solution: Nanoscale Buffer Layer

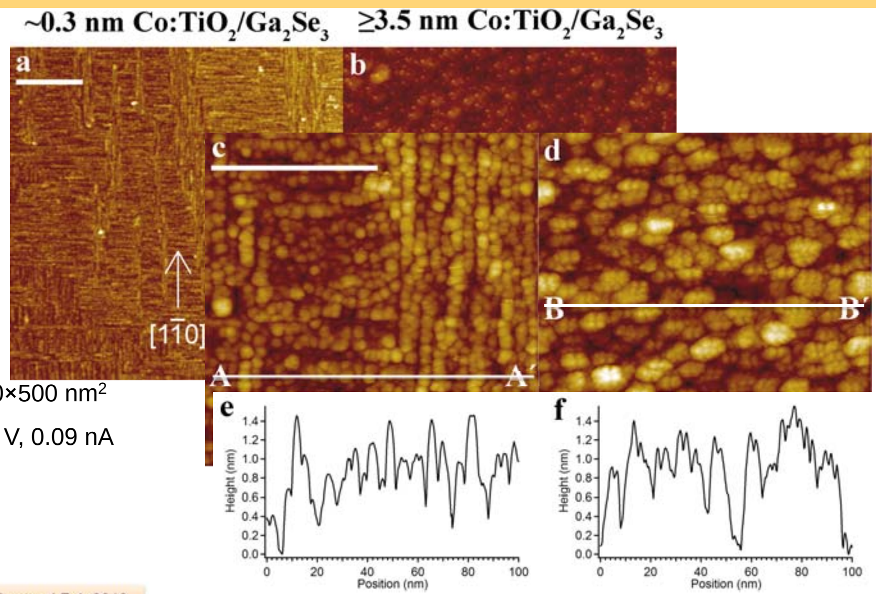


Scanning Tunneling Microscopy





$Co:TiO_2/Ga_2Se_3/As/Si(001)$

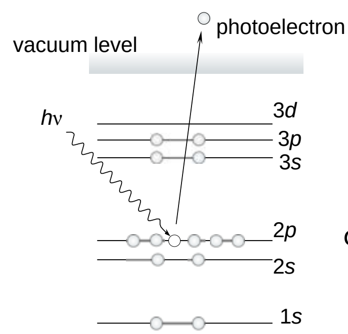


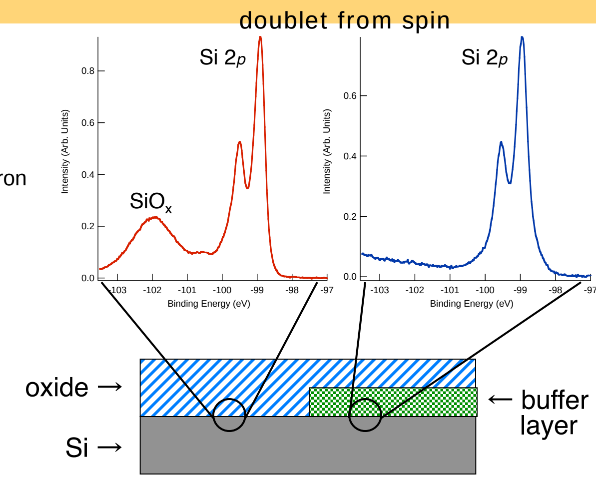
500×500 nm^2

2.8 V, 0.09 nA

Photoemission - Si Chemistry

Element specific
Chemical environment





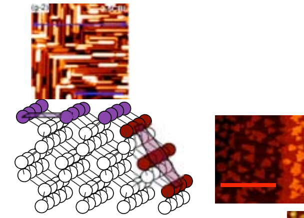
Lend valence electrons to Oxygen --
Remaining electrons are more tightly bound

A Few Intrinsic Factors in Heteroepitaxy

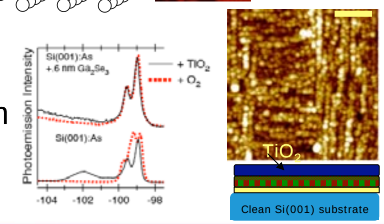
- **Surface Structure** -- Symmetry, Defects
  - o **GaSe vs Ga_2Se_3/Si**: Substrate control of crystal structure
- **Chemical Reaction** – Interface Compound Formation
  - o **TiO_2/Si**: Buffer layer inhibition of interface reaction
- **Impurity Incorporation** – Solubility Limits, Phase segregation
  - o **Cr** and **Mn**-doped **Ga_2Se_3/Si**: Concentration-dependent structure

A Few Intrinsic Factors in Heteroepitaxy

- **Surface Structure** – Symmetry, Defects



- **Chemical Reaction** – Interface Compound Formation

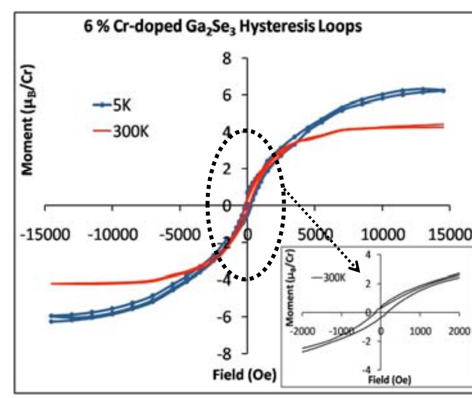


- **Impurity Incorporation** – Solubility Limits
  - o **Cr** and **Mn**-doped **Ga_2Se_3/Si**: Phase segregation

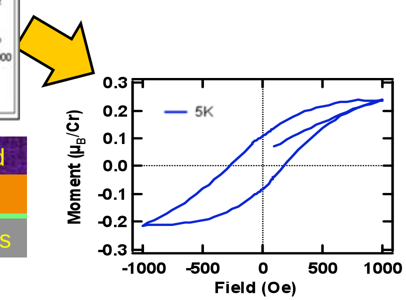
Can we Make the Buffer Layer Magnetic?

- Doping with transition metals
  - o Mn-doped GaAs
    - Ferromagnetic below –100 °C
  - o Cr-doped GaN or TiO_2
    - Ferromagnetic at room temperature
    - Needs defects to work – impurity phases?

Ferromagnetism in Cr-doped Ga_2Se_3

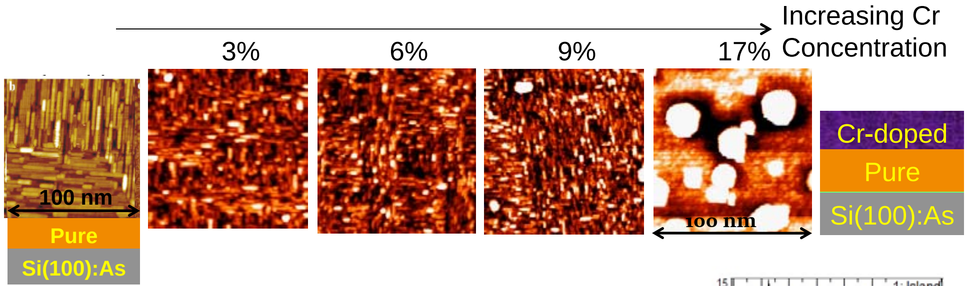


- Adding Chromium to Ga_2Se_3 makes it a ferromagnet at room temperature

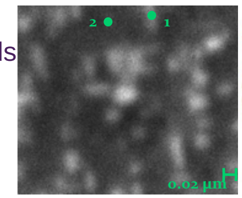


E.N.Yitamben et al., submitted to PRL 2010

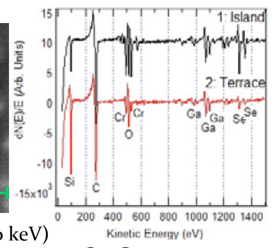
Surface morphology (solubility limit?)



- ❖ Low Cr Incorporates into Nanorods
- ❖ Higher Cr Nucleates Islands
- ❖ Islands are Cr-rich
  - ❖ New Compound?



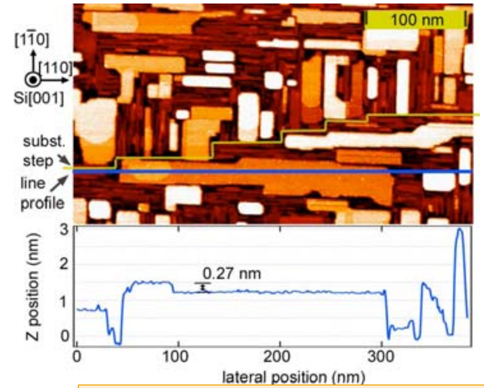
SEM image (FOV: 0.3 µm, 20 keV)

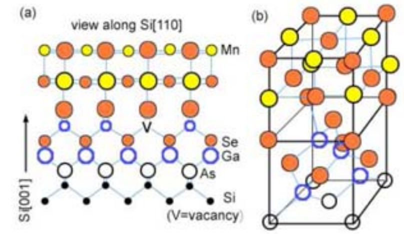


$$\frac{Cr:Ga_{island}}{Cr:Ga_{terrace}} = 1.7$$

E.N.Yitamben et al., PRB 80, 075314 (2009)

Mn doping – leads to MnSe



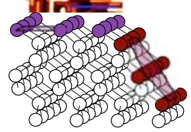


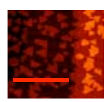
8 % Mn – Segregates to pure MnSe islands on Ga_2Se_3 substrate

T. Lovejoy, et al APL 95 (2009) 241907

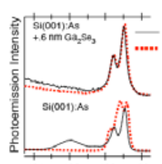
A Few Intrinsic Factors in Heteroepitaxy

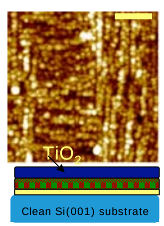
- ➢ **Surface Structure** -- Symmetry, Defects



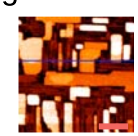


- ➢ **Chemical Reaction** – Interface Compound Formation

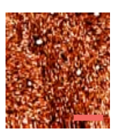




- ➢ **Impurity Incorporation** – Phase Segregation

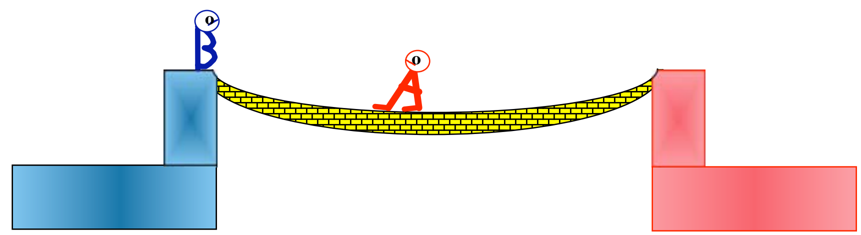


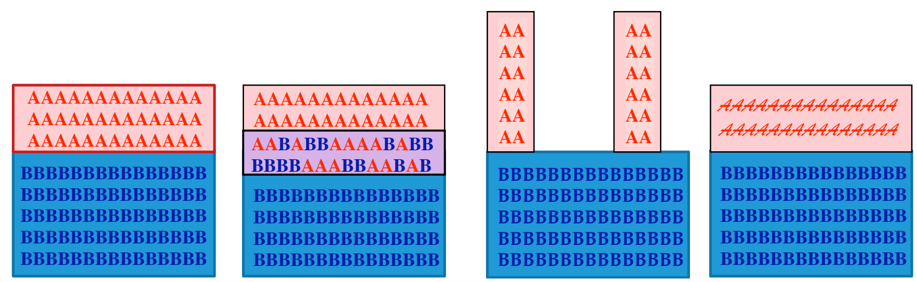
9 % Mn



9 % Cr

Building Atomic Bridges Between Dissimilar Materials





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