Self-Assembled $TiSi_x$ Nanostructures formed by Chemical Vapor Deposition

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invent

QSR

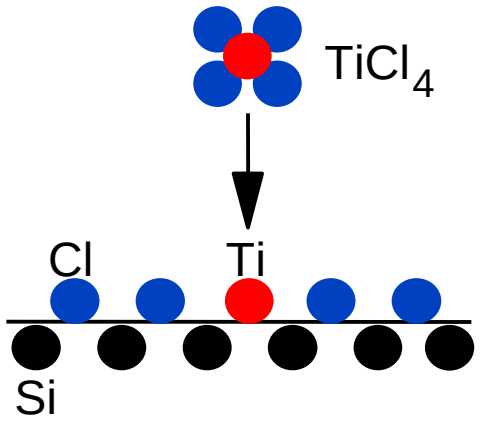
Outline

- Motivation
- Ti deposition
- Island formation during deposition
- Island modification during annealing
- Nanowire growth
- Nanowire alignment

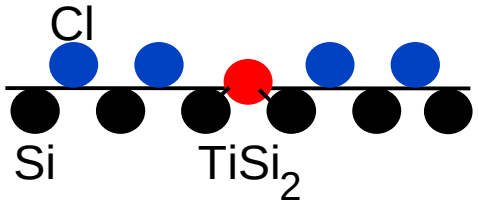
Moore's (Second) Law and Self Assembly

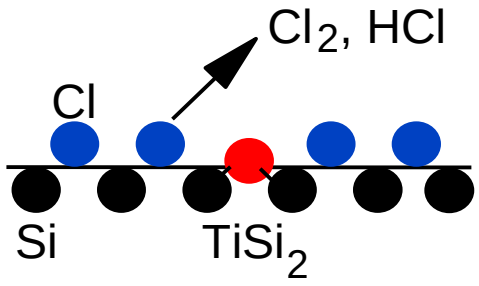
- The **cost** of IC fabrication facilities continues to increase
- Much of cost relates to **lithography** of very small features
- Using **self-assembly** to form the smallest features can potentially reduce the escalating cost
- **Coarser lithography** can be used to position the fine features formed by self-assembly
- Features formed **thermodynamically** will have large numbers of defects
- Coupling self-assembly with a **defect tolerant computer architecture** is attractive

Deposition from $TiCl_4$

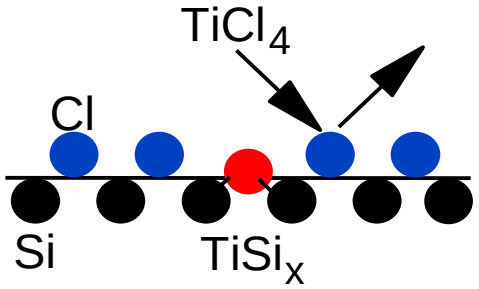


Higher Temperatures (T>700°C)

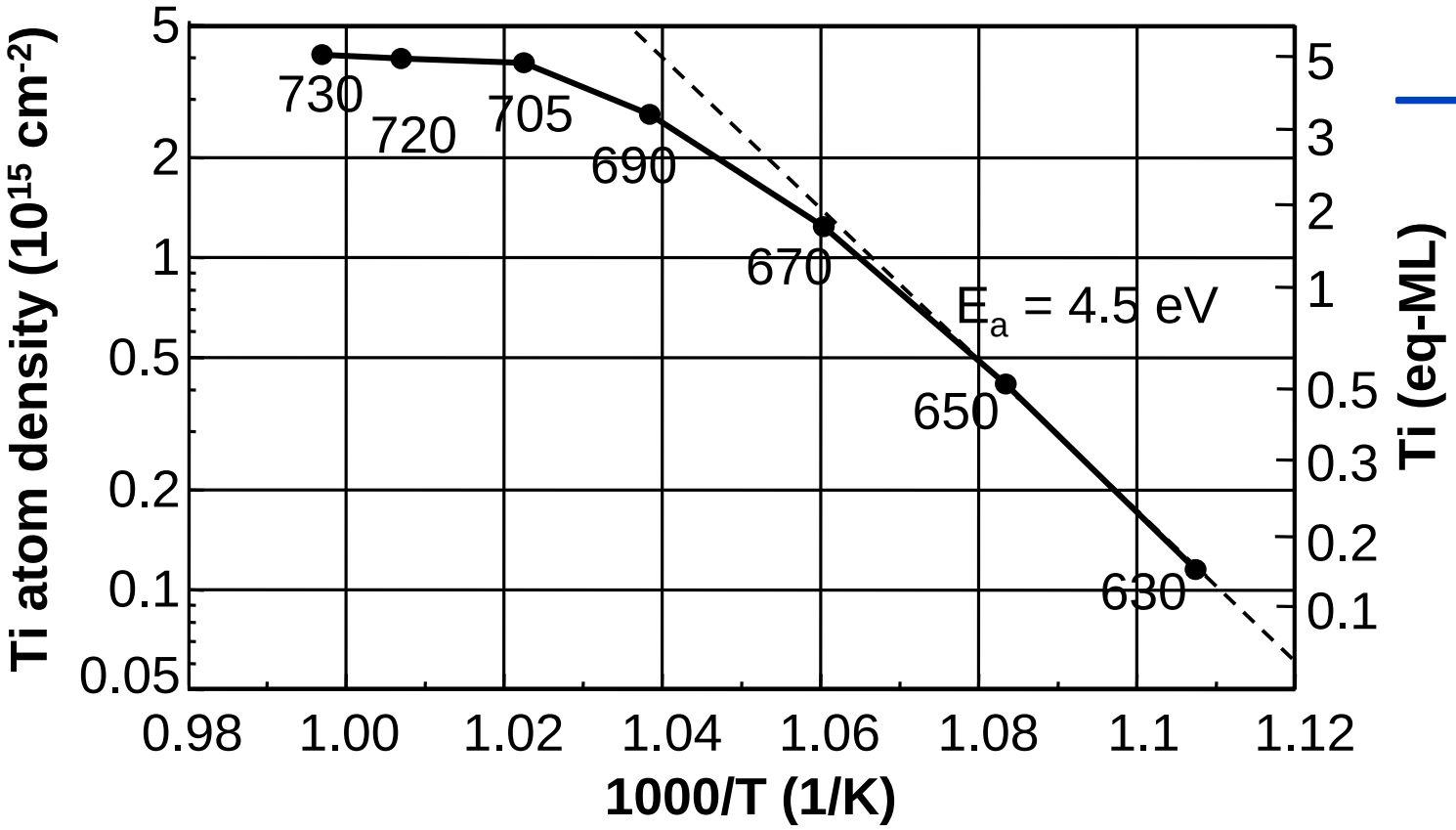




Lower Temperatures (T<700°C)



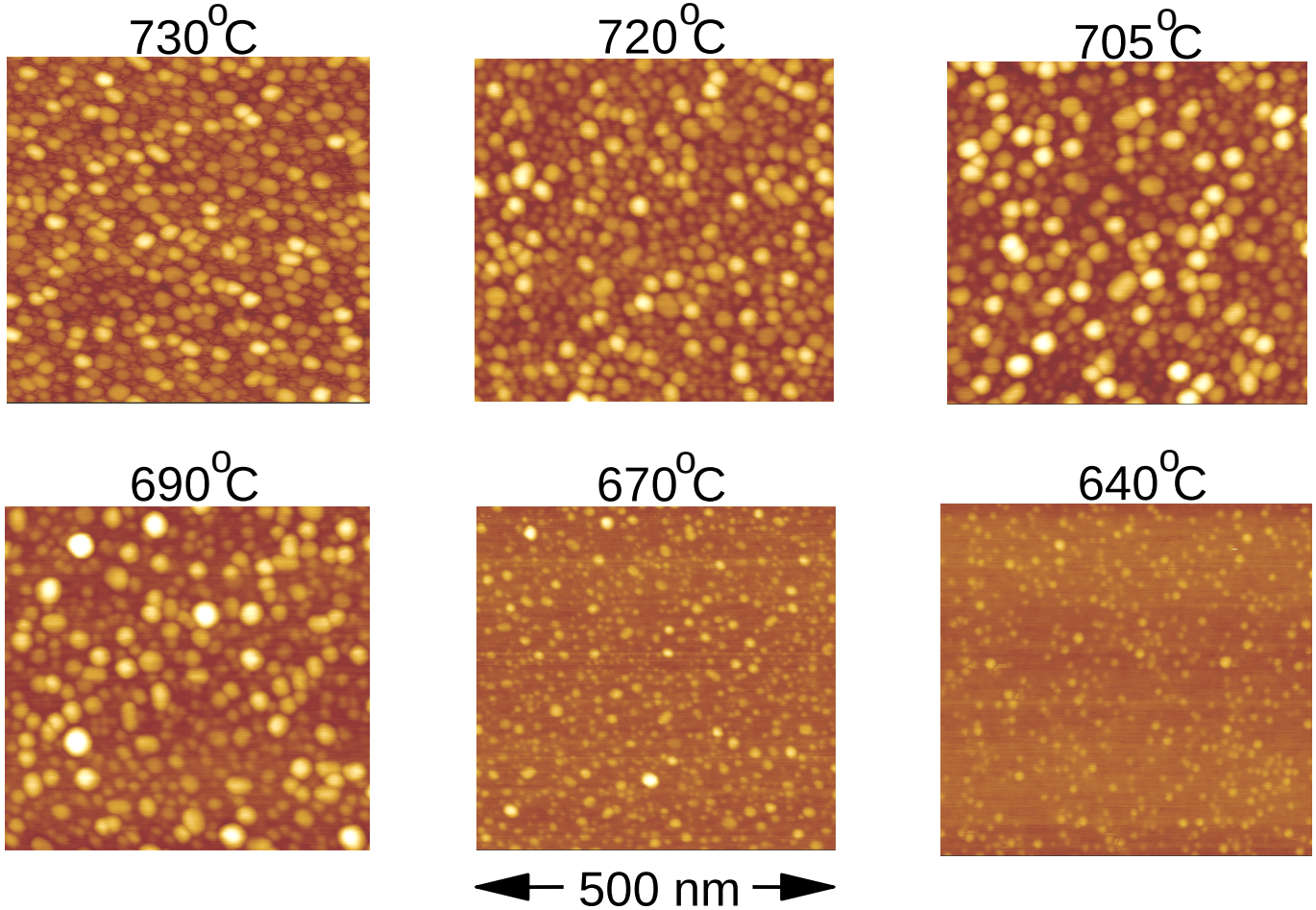
Ti Deposition Rate



Controlled submonolayer deposition by varying deposition temperature (10 s depositions)

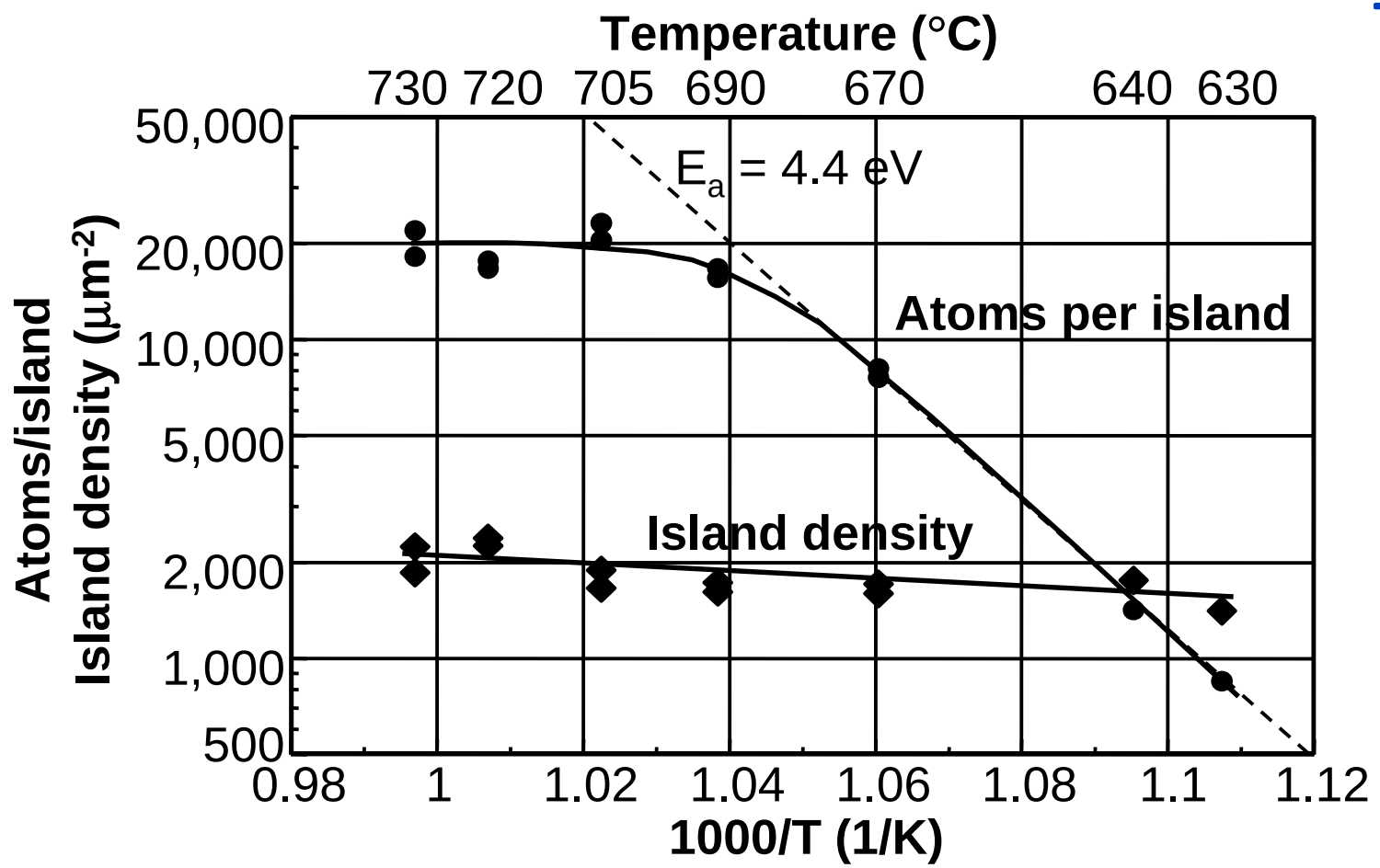
Islands after Deposition

Large (7%) lattice mismatch → island formation

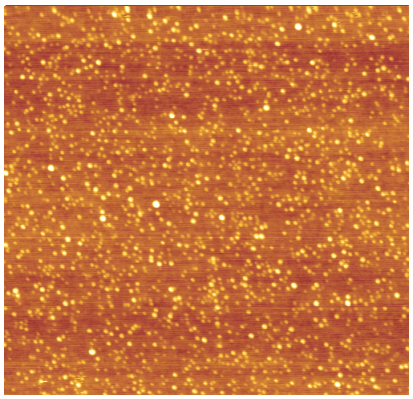


Atomic-Force Micrographs

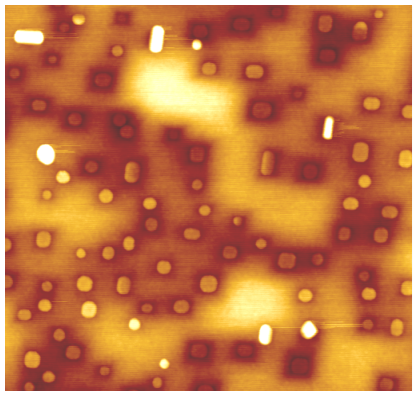
Island Density and Size after Deposition

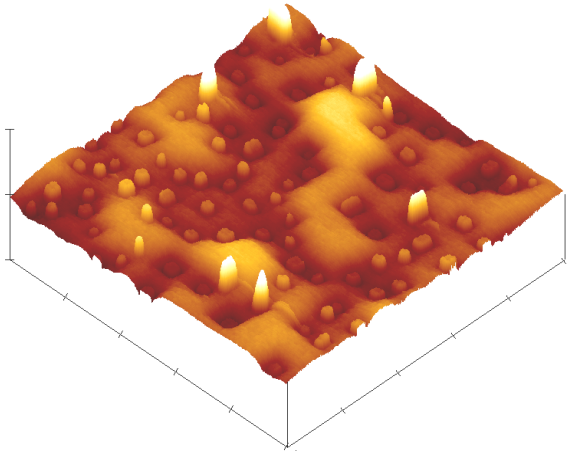


Annealing of CVD $TiSi_x$ Islands



Deposition at 640°C



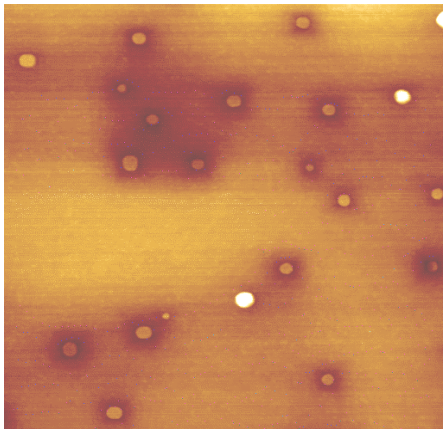


Annealing at 920°C

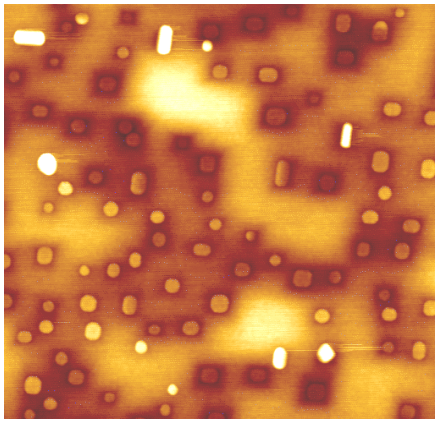
During annealing

- Amount of Ti on surface remains the same
- Island density decreases
- Islands take characteristic shapes

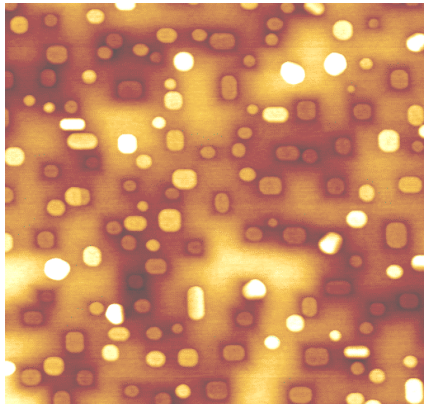
Islands after Annealing
$TiSi_2$ on Si(001)



3×10^{14} Ti/cm^2



1.5×10^{14} Ti/cm^2



3×10^{15} Ti/cm^2

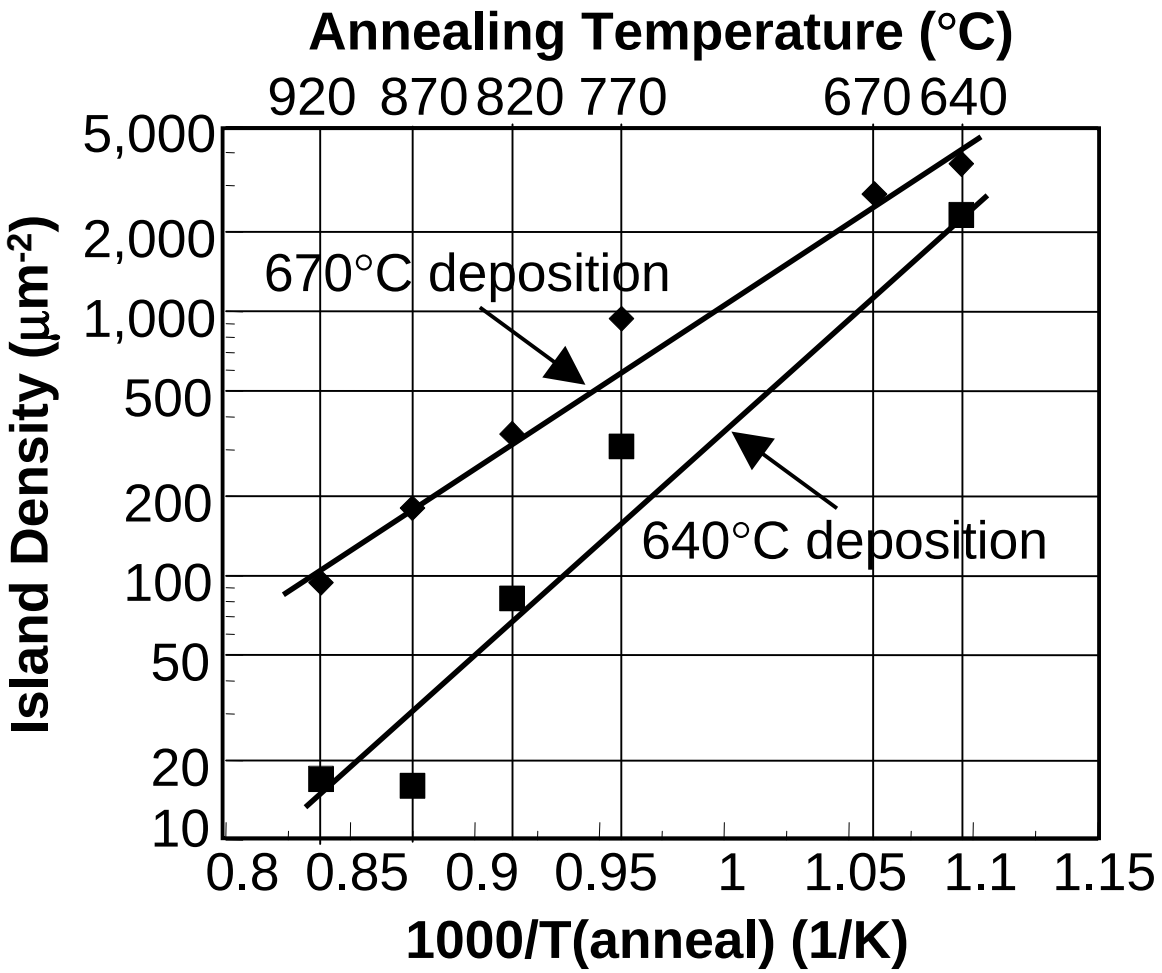
(1 μm × 1 μm images)

After annealing

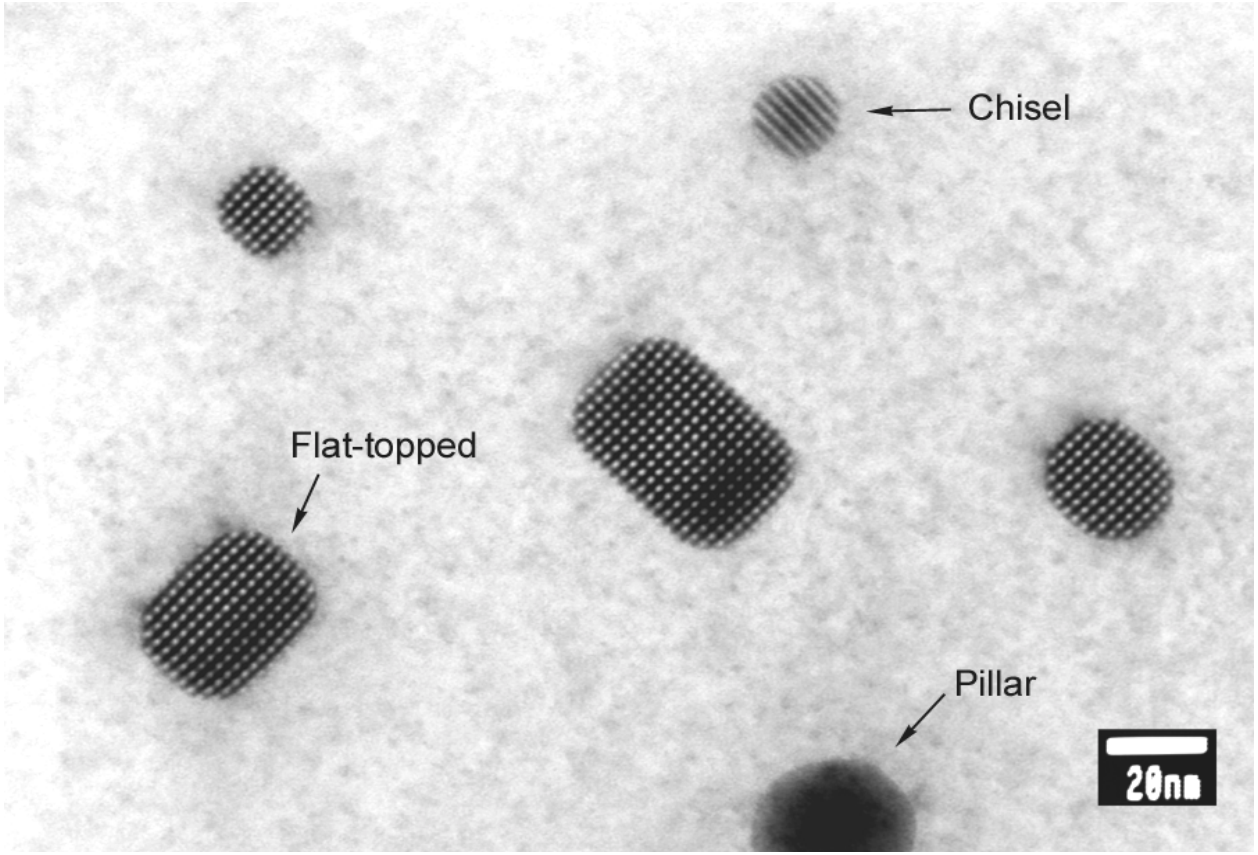
Island size depends only weakly on the amount of Ti

Island density increases with increasing amount of Ti

Island Density after Annealing



Plan-View TEM: $TiSi_2$/Si(001) Three Island Types



Most numerous islands

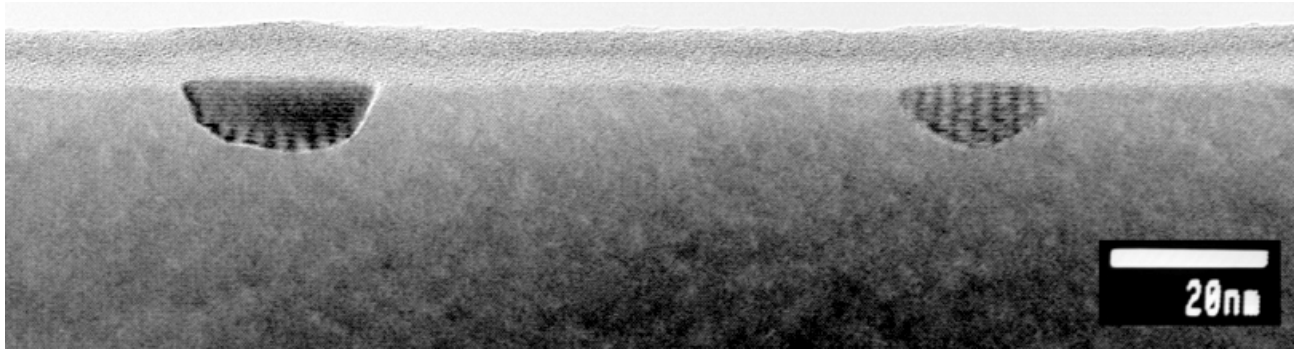
- Flat-top
- Square or rectangular
- Mostly recessed into surrounding surface

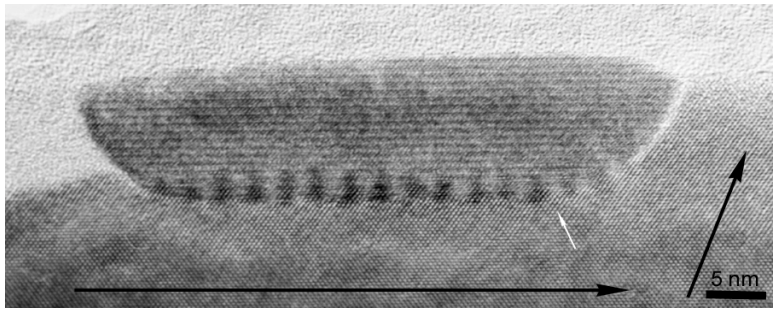
(C49 $TiSi_2$)

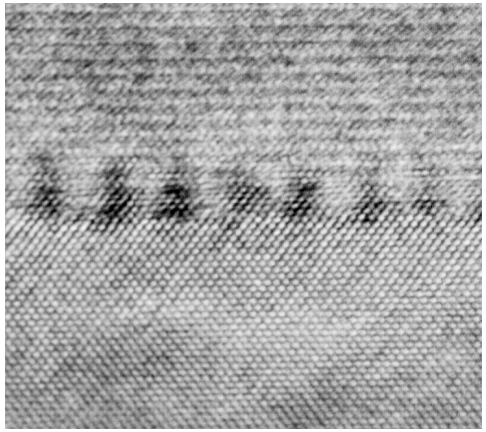
Transmission electron micrograph courtesy of
D. P. Basile and M. Wong of Agilent Technologies

Cross-Section TEMs: $TiSi_2$/Si(001)

Embedded Islands







Islands mainly recessed into the surrounding Si surface

The period of the structure at the $TiSi_2$/Si interface corresponds to the difference in lattice constant.

Transmission electron micrographs courtesy of
D. P. Basile and M. Wong of Agilent Technologies

Ti-Catalyzed Si Nanowires

Possible interconnections
for molecular electronics

Forming wires

1) Form nuclei

Expose to vapor $TiCl_4$ at 600-700°C

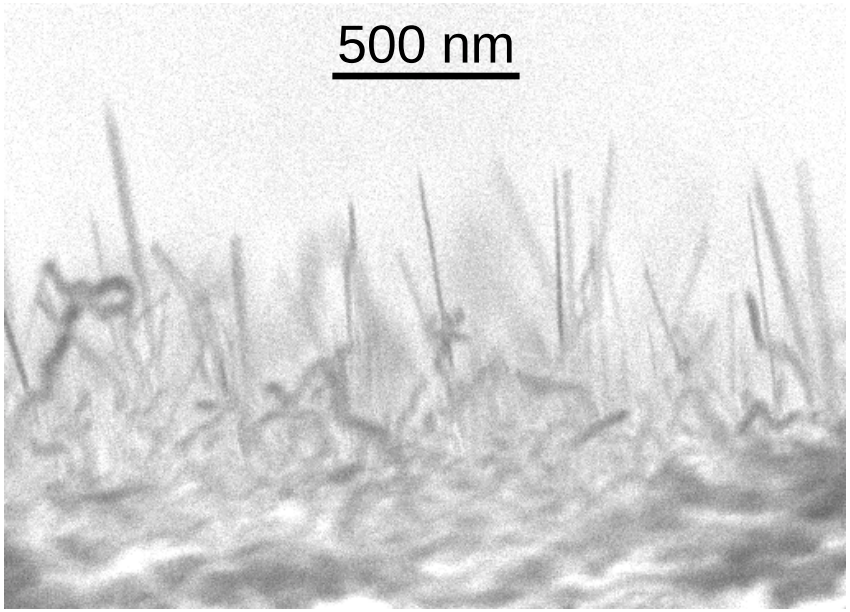
$TiSi_x$ islands form on Si(001)

by strain energy from lattice mismatch

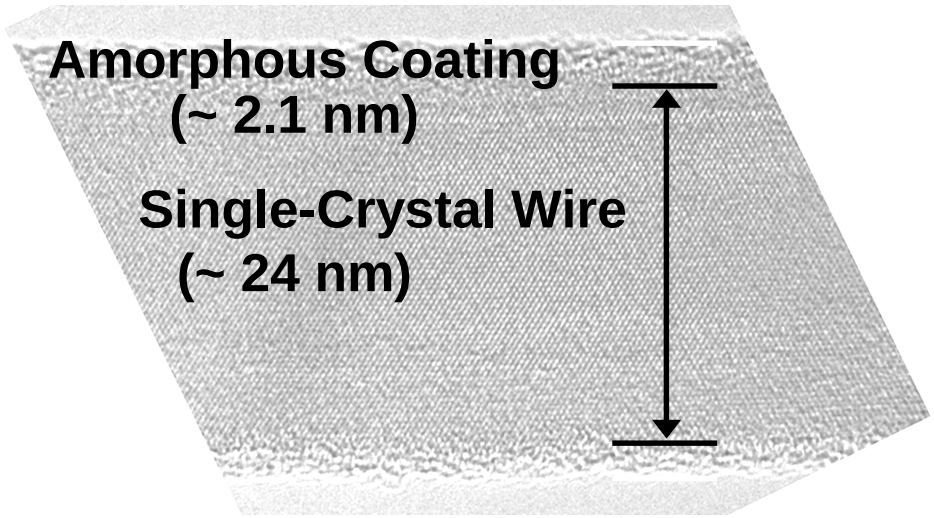
2) Form nanowires

Expose to vapor SiH_4 or SiH_2Cl_2 at 600-700°C

Ti-Catalyzed Si Nanowires



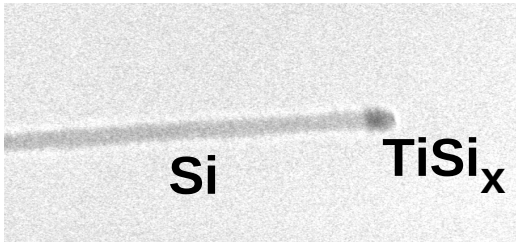
Shallow-angle scanning electron micrograph

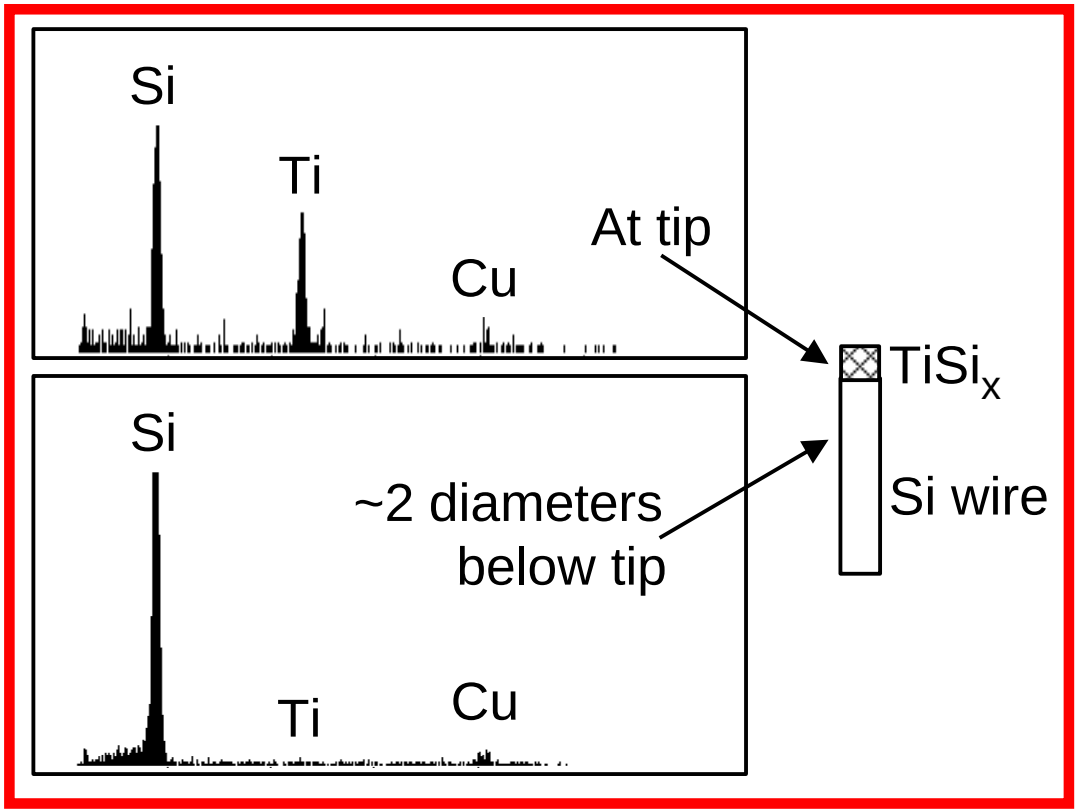


High-resolution transmission electron micrograph

Micrographs courtesy of Tor Hesjedal
Stanford University

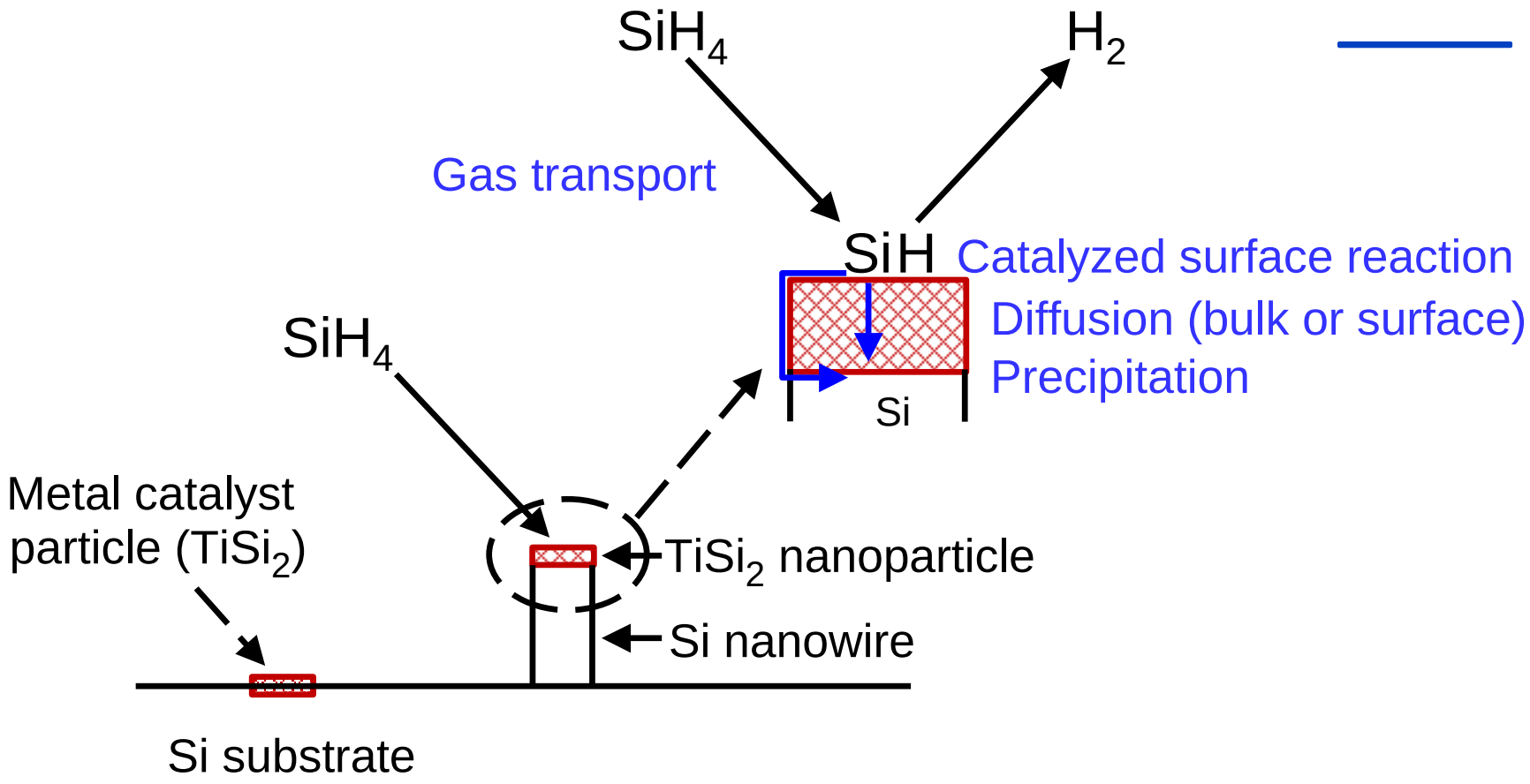
Single-Crystal Si Wire with $TiSi_x$ at Tip





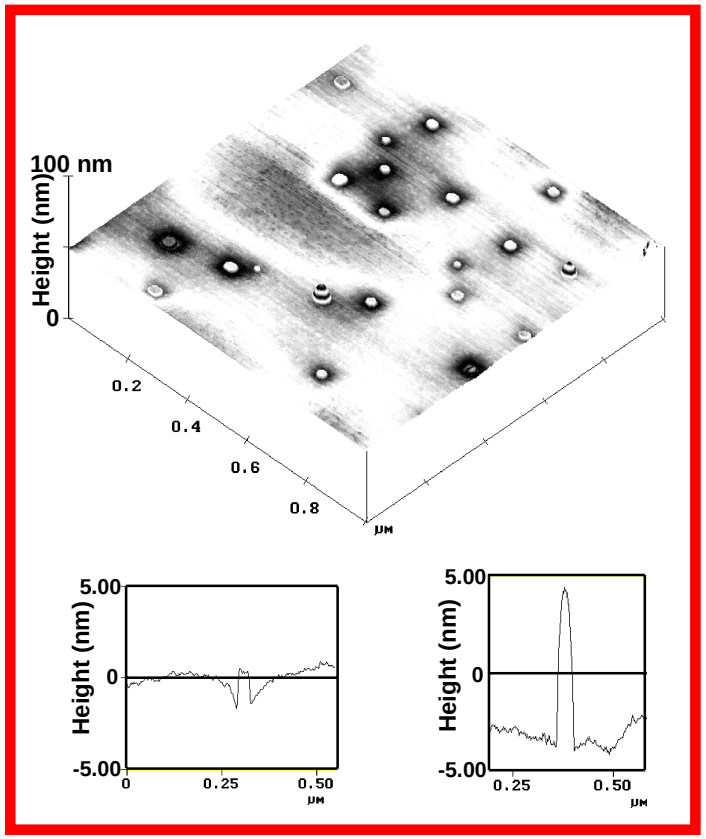
EDS analysis courtesy of
Tor Hesjedal, Stanford University, and
David Basile, Agilent Technologies

Mechanism of Nanowire Growth

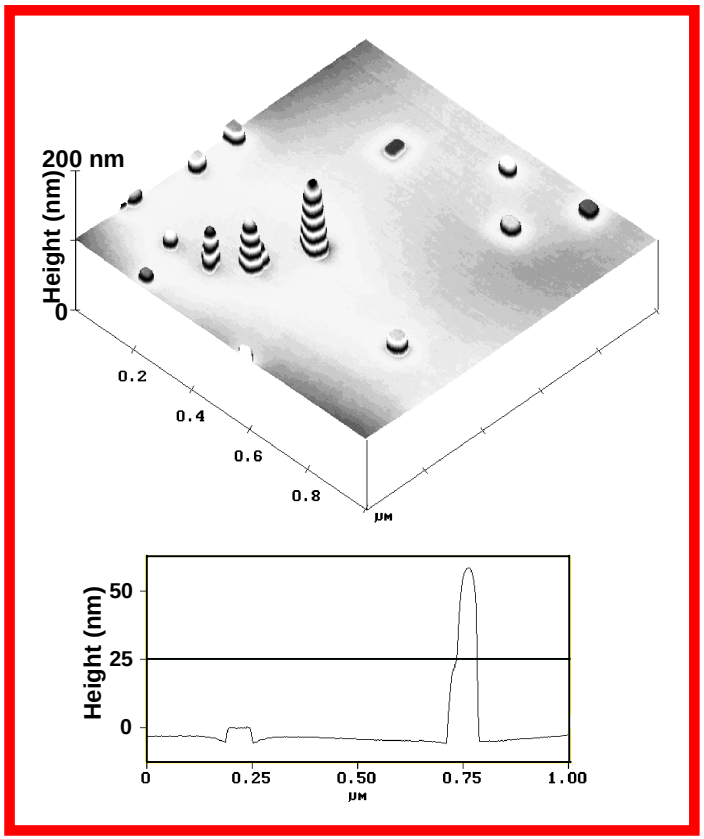


Surface-Reaction-Rate-Limited Growth

Initial Stage of Wire Growth



Subsequent Stage of Wire Growth

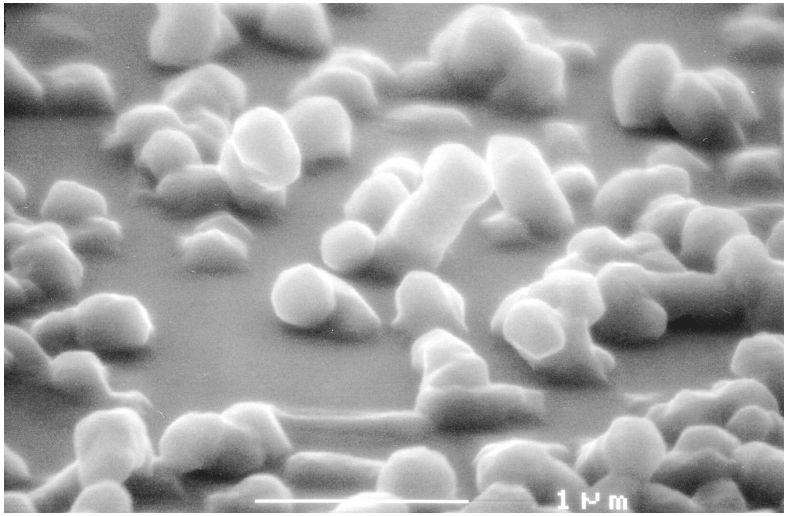


Higher Temperature

Uncatalyzed growth rate significant

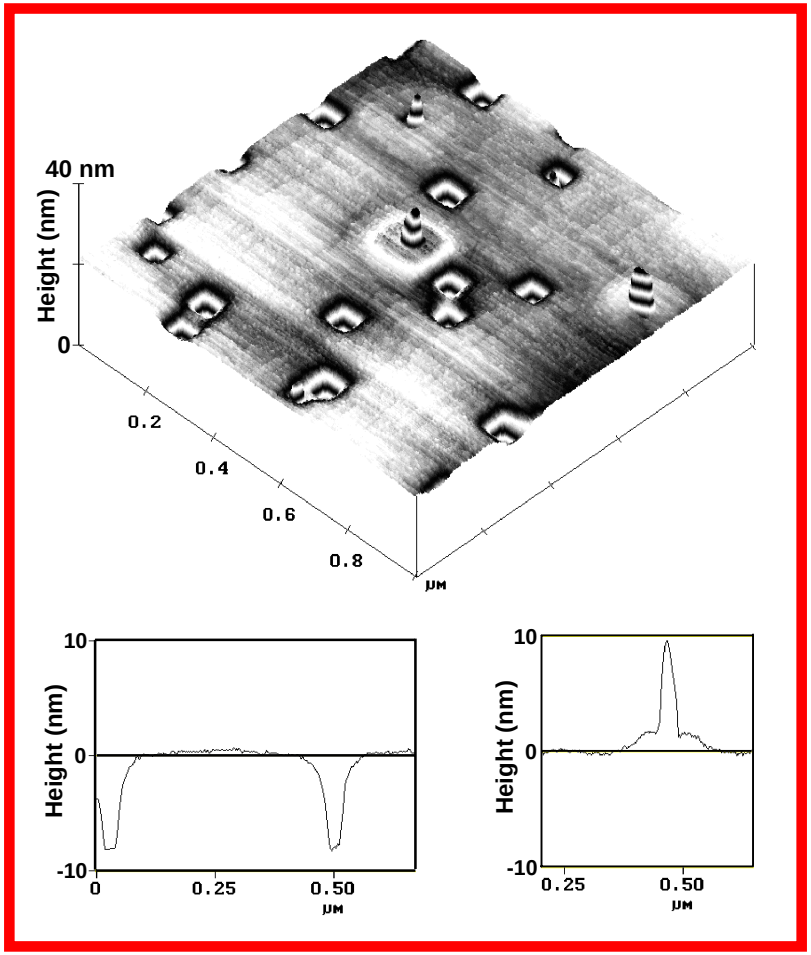
Surface-Reaction-Rate Limited

SiH_2Cl_2 at 920°C



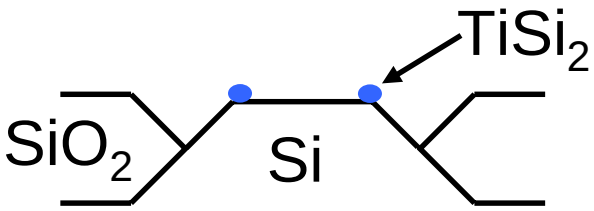
Mass-Transport Limited

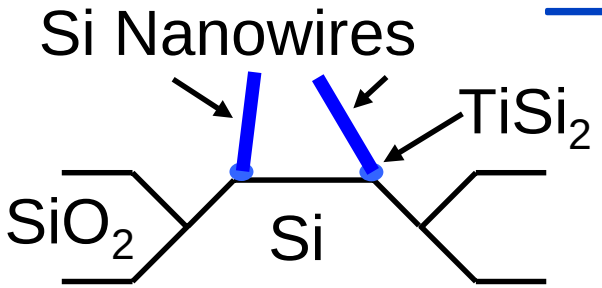
SiH_4 at 920°C

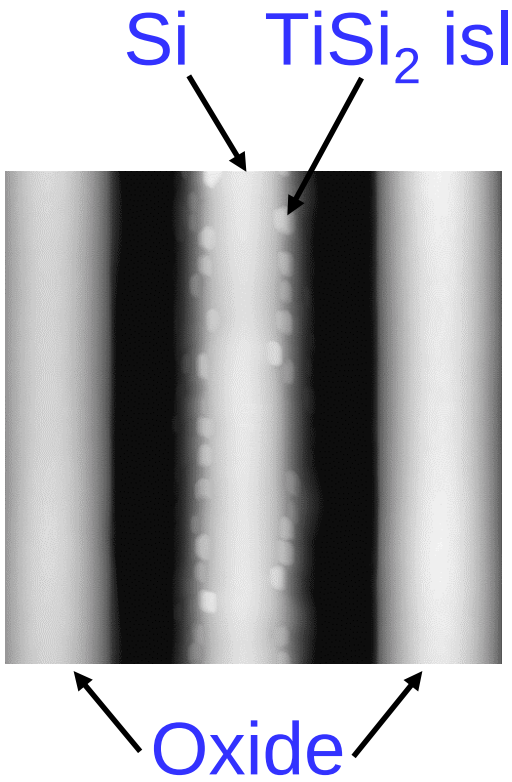


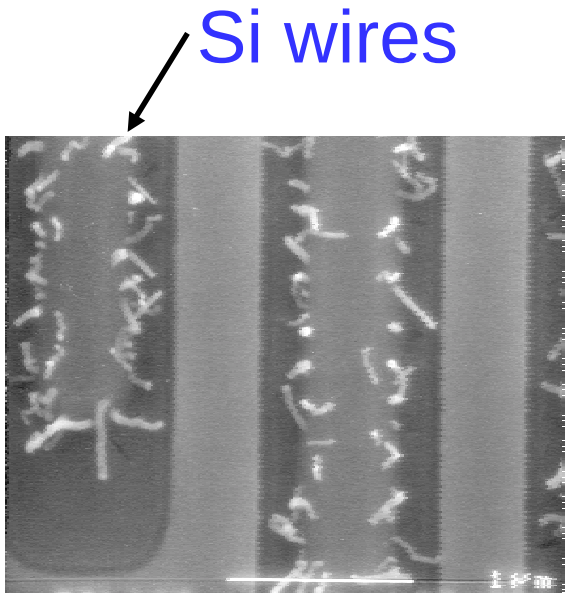
Positioning Islands and Nanowires

Oxide-Patterned Si Substrate



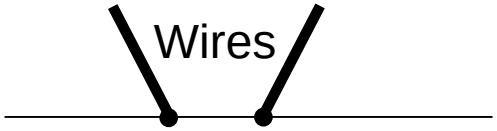


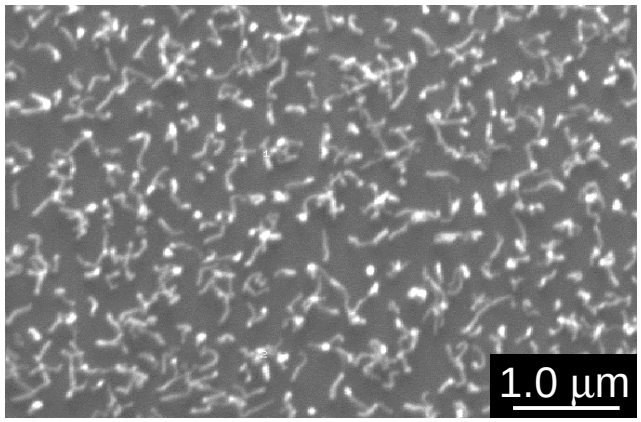




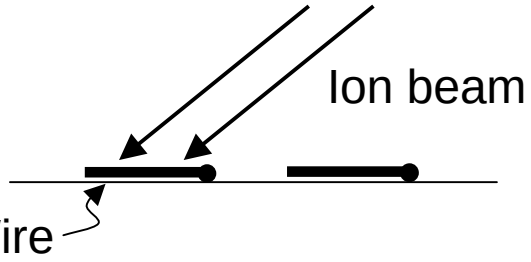
Aligning Nanowires Using an Ion Beam

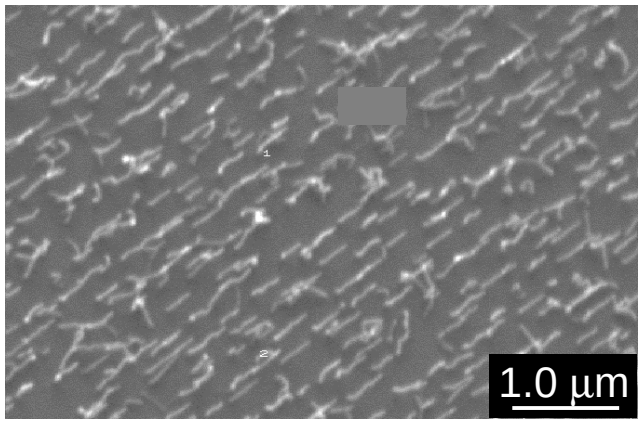
Sparse array: after deposition





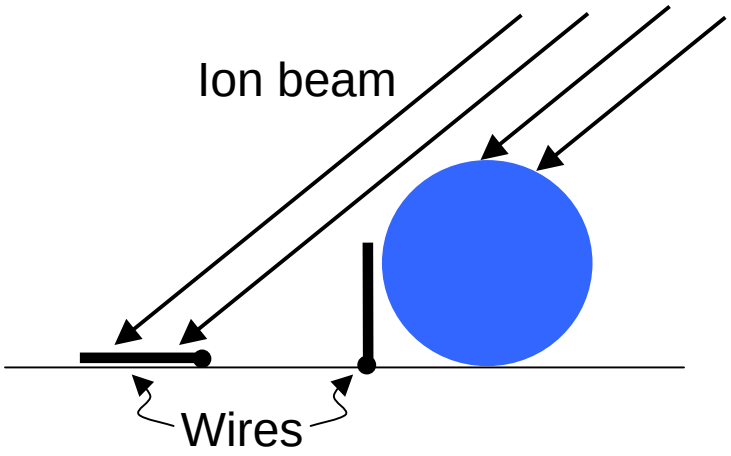
Sparse array: after alignment



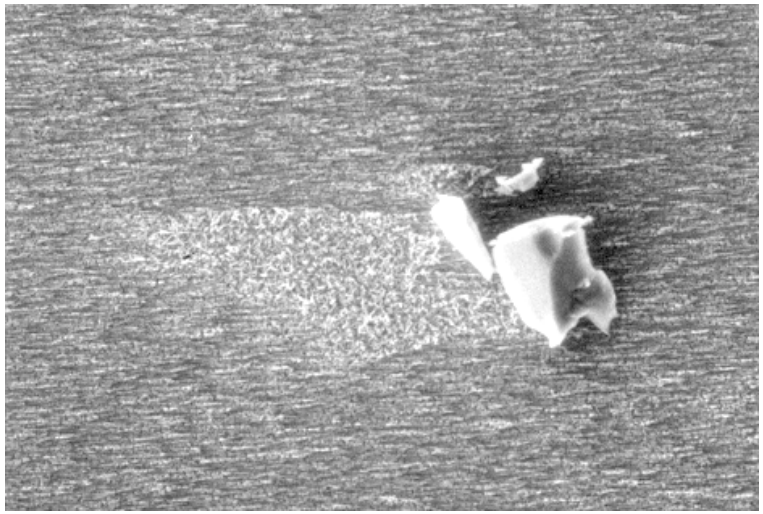


Aligning Nanowires Using an Ion Beam

Shadowed wires



Dense array after shadowed alignment



Summary

- **Ti deposition**
  - Rate decreases as temperature decreases
- **Island formation** during deposition
  - Size decreases as temperature decreases
  - Density varies only weakly with temperature
- **Island modification** during annealing
  - Islands coarsen
- **Nanowire growth**
  - Ti catalyzes SiH_4 and SiH_2Cl_2 decomposition
  - Ti remains at tip of growing wire
- **Nanowire alignment** using an ion beam