The Silicon Valley Career of a UIUC Physics Ph.D.

Alan Stivers, Ph.D.

UIUC, 1979

Disclaimer!

None of the work I will describe was done without the help and advice of many, many people.

Outline

- Introduction: me, you and my employer
- Forces driving my career
- My first job
- Technology transfer problems
- Case study: Resolution of transfer problems and the after-effects
- Overall learning
- Q&A

Me

- Grew up in Silicon Valley
- Physics Education: AB at UC Berkeley, MS and PhD at UIUC
  - Ph.D. advisor: Prof. C. T. Sah
- Intel Career: 1979 to 2008
  - Started in Quality Assurance doing Voltage Contrast Electron Beam Probing
  - Moved to Components Research (CR) to do advanced process development
    - Chemical vapor deposition of polycrystalline-Si, Si_3N_4, $TiSi_2$
    - Multichip packaging
    - Silicon selective epitaxial deposition
    - Advanced silicides
    - Alternating phase-shift masks for 193nm lithography
    - Extreme ultra-violet masks for 13.4 nm lithography
  - **Things you learn always carry forward. They are all arrows in your quiver.**

You, from my perspective

- You are being groomed to be the sharp end of the spear that advances science and technology.
- You may become the person that points that spear where it does the most good.
  - People with our training often start out as individual contributors, but often transition to leading other people.
- You will find:
  - A big future for science and technology. The show is only starting.
  - Later in your careers, technology will start to catch up with the physics you learn in grad school.
  - Relationships matter, including the ones you make here.

My Employer for 28 Years: Intel Corporation

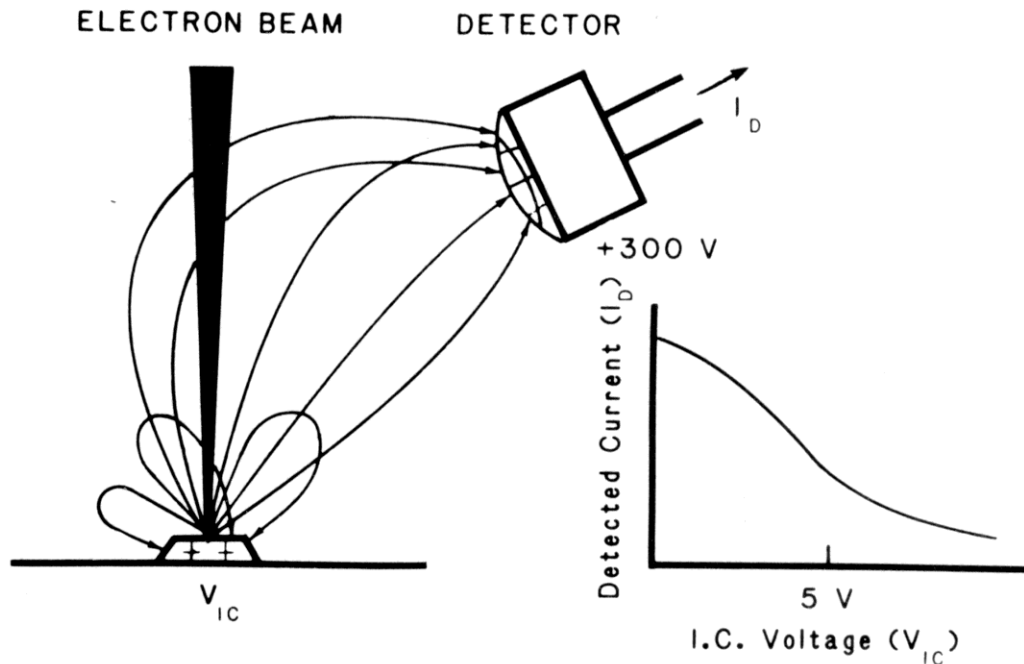
- Founded in 1969 by Gordon Moore and Robert Noyce
- Key inventions: Si gate SAMOS (at Fairchild), dRAM, EPROM, µP
- Employees: 15k in 1979, 84k in 2008, 107k today
- Annual revenue: $69B today
- Highly disciplined culture
  - Get lots done but not for everyone
- Great management IMHO: “Conviction Required” philosophy
- I was lucky to be there during its growth.

Two Driving Forces in my Career

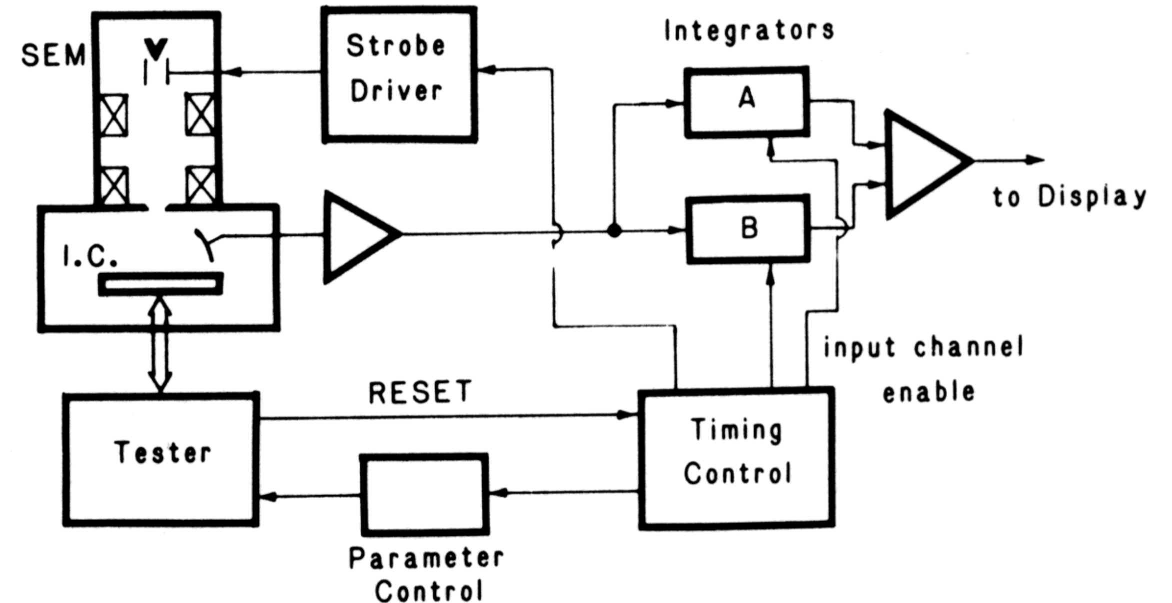
- Decision Making Using the Scientific Method
  - Test hypotheses with data.
  - Unsaid: beware of opinions, especially those expressed forcefully.
  - Modified in industry: restricted to internally accepted practices and standards.
    - Standardization restricts decision space but simplifies and speeds decision making.
    - Makes maximum use of an organization's knowledge base
    - **Key Benefit: Allows easy insertion of new learning into that knowledge base**
- Semiconductor Scaling, *i.e.*, You Always Can Do Better!
  - Smaller means faster: higher current drives lower capacitance
    - ➢ More applications and sales
  - Smaller means cheaper: more product per wafer means lower cost per product
    - ➢ More applications, sales and profits
  - Smaller means you need fewer factories to supply the market
    - $5B to $10B savings up front if one factory doesn't need to be built
    - ➢ More jobs for engineers to work on faster scaling

My First Job: Voltage Contrast Electron Beam Probing

Sample voltage affects secondary emission: +V pull electrons away from detector → dark electron image

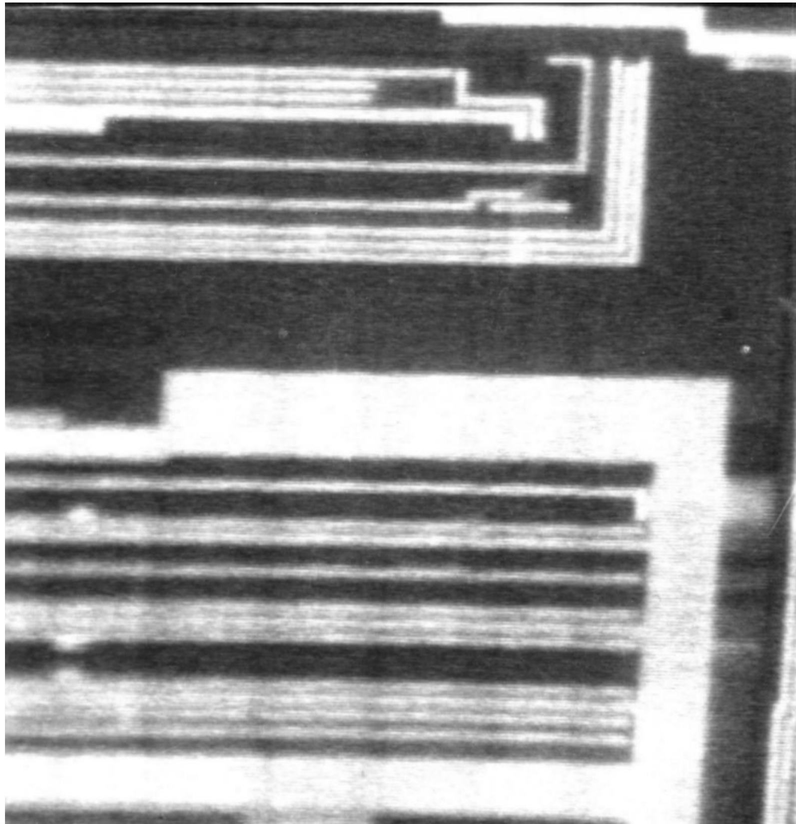


Stroboscopic electron beam control for freeze action images of operating circuit

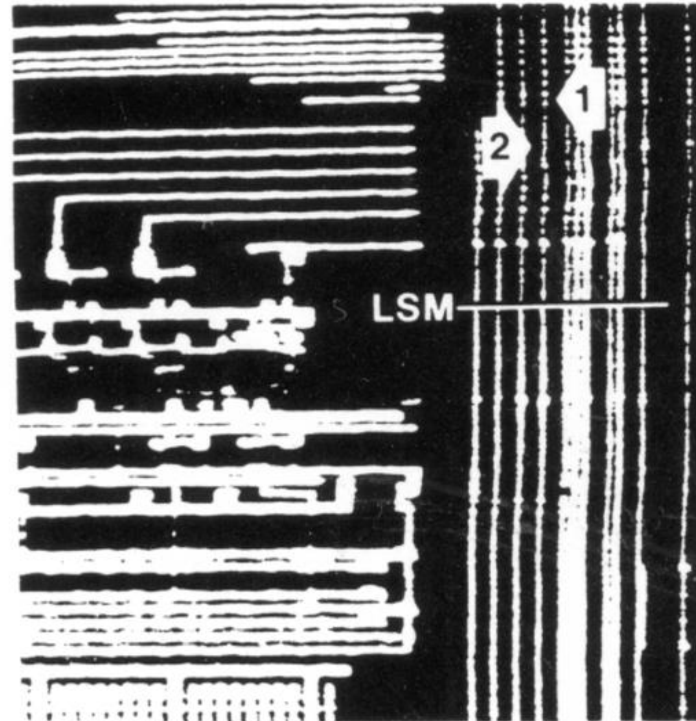


Voltage Contrast Applications

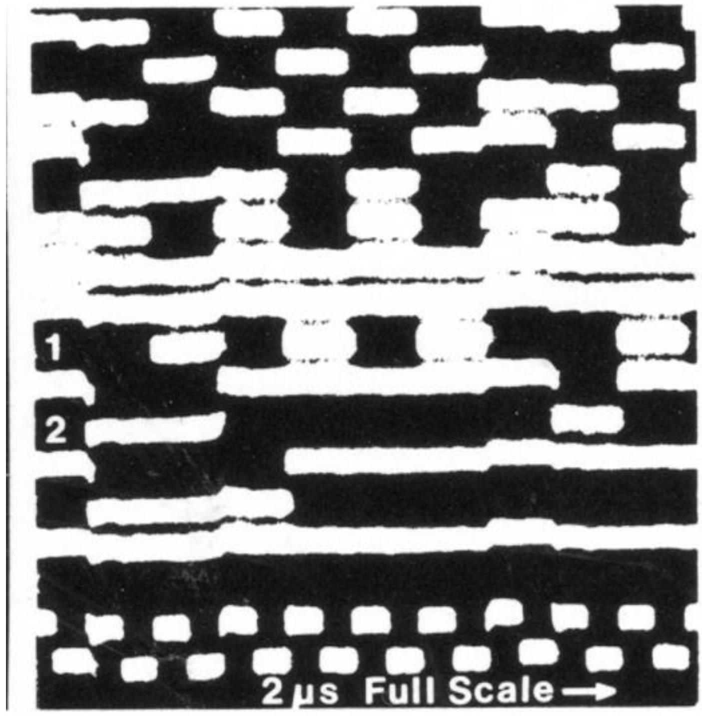
Stroboscopic VC freezes action on an operating 80286



Stroboscopic image



Logic State Map:
x-axis time, y-axis space



Accomplishments

- Working with Quality and Reliability Engineers
  - Failure analysis of several products
- Working with Chip Designers
  - Identification of design defects in logic circuits
  - Identified the last design error keeping Intel's then lead product, the 80286, from release (1982 at 8MHz clock).
    - My lab then moved to be in the same building as the chip designers.
  - Identified speed limiting elements of logic circuits
    - ➢ Enabled higher speed versions (to 12.5 MHz) to be released.

Learning from this project

- A new technique is only as powerful as its application
  - My customer’s application was Intel’s then lead product, 80286.
- Measurement is only one part of the solution
  - You need the expertise and resources of your customers
- Be close to your customers
  - Even being across the street hinders application
- Always be ready to go the extra mile. Their deadlines are your deadlines.
- Learning enabled a successful electron beam-based repair technology for alternating phase-shift masks 15 years later for Intel’s 65nm process.

Intel Technology Transfer Problem History

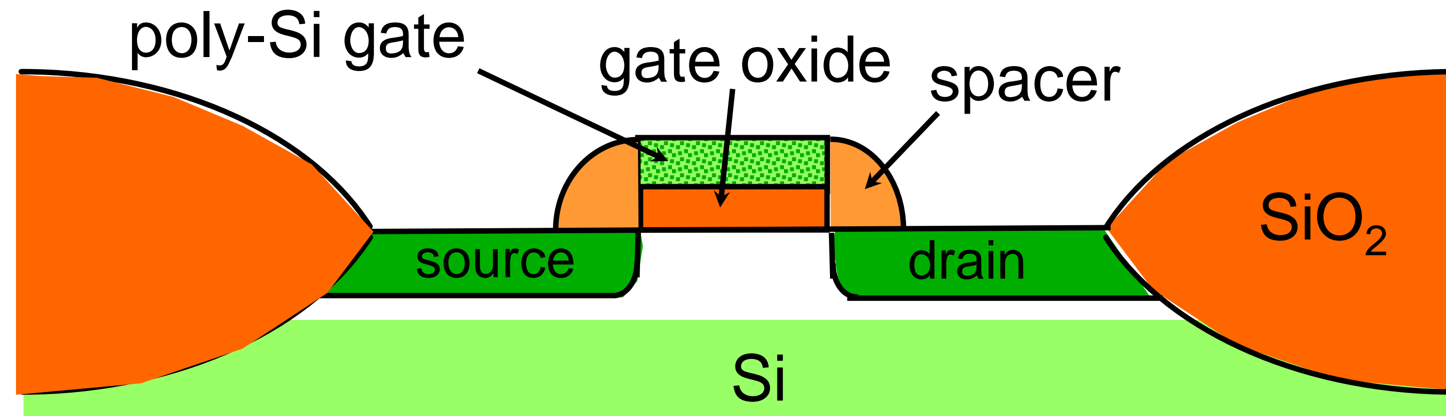
- At Fairchild: R&D-to-manufacturing transfer problems
- At Intel
  1. Do R&D in the factory:

     Plus: no transfer needed   Minus: R&D lowered product output
  2. R&D done in separate factory and Copy Exactly transfer methodology begun
     - Large R&D lab/factory
     - Process, toolset, materials, procedures, specs all copied exactly to manufacturing.
     - Very successful
  3. Later, D became more difficult. Need to do more advance work
     - Pathfinding (advanced development) started to look at next technology generation.
     - Components Research (CR) started to look several generations out.
  - Again needed to solve the problem: how to transfer R to D?

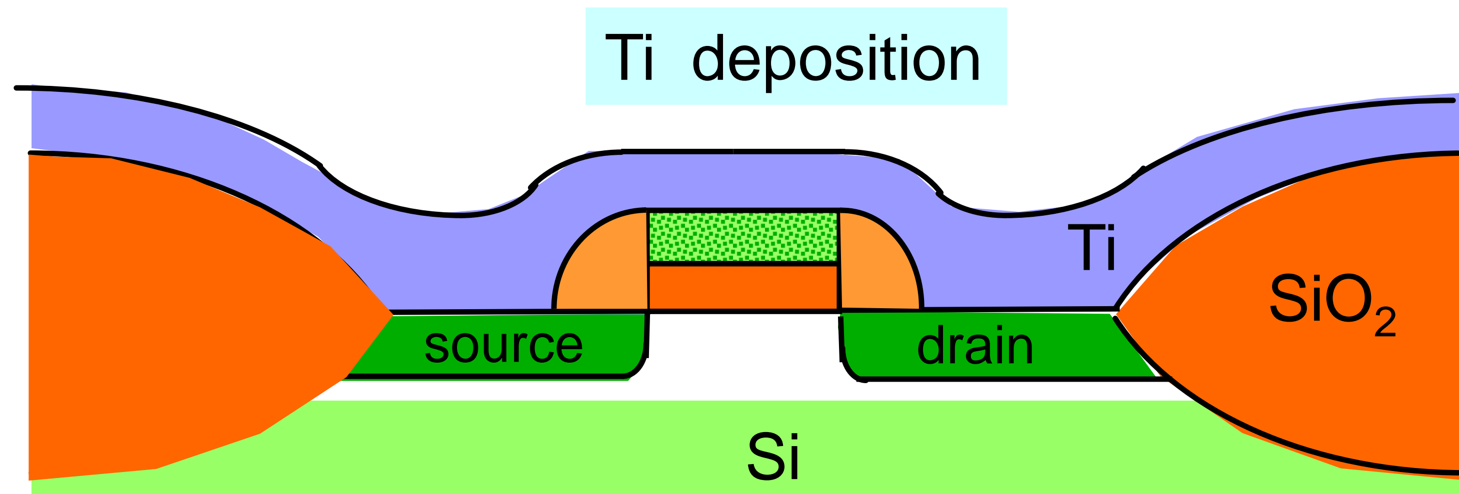
Case Study of a Successful R → D Transfer

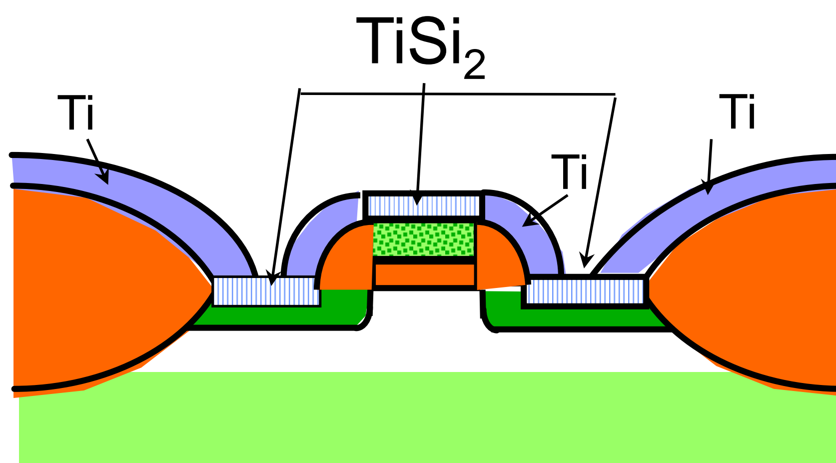
- At first, Components Research (CR) had difficulty transferring results to Technology Development (TD). CR perceived as a problem child.
  - Management puts CR and TD under the same senior manager.
  - CR must "sell" its projects to TD.
- My boss and I decided on an advanced silicide project and this was approved by TD.
  - There were early signs of scaling limits in the then current $TiSi_2$ process.
- We decided to explore:
  - New materials/same process: NiSi, PdSi and PtSi
  - Same material/new process: Selective $TiSi_2$ Chemical Vapor Deposition
- Got TD OK along with agreement on key qualities to optimize

Self-Aligned Silicide (SALICIDE) Process Flow



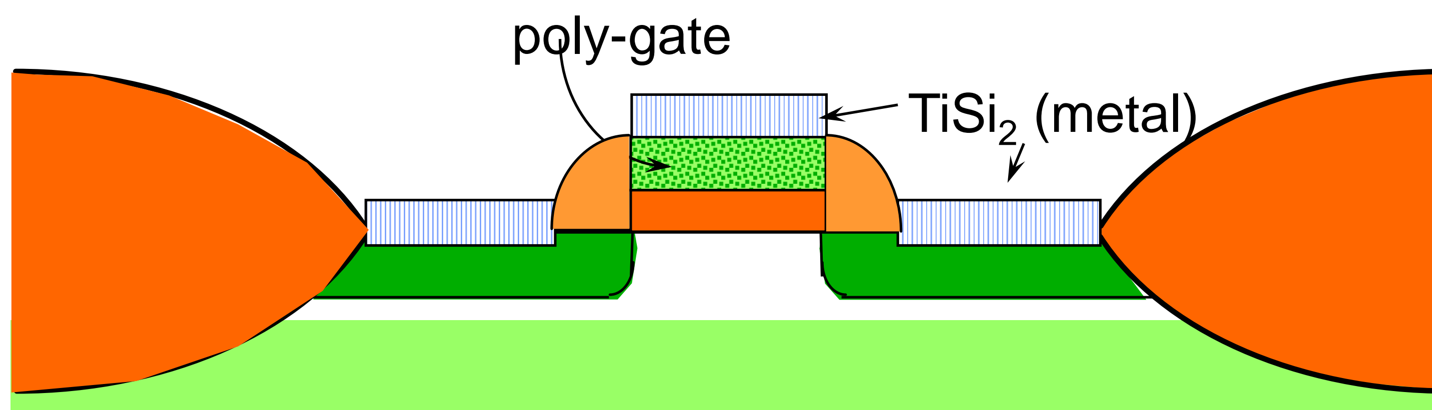
Ti deposition





Heat treatment reacts Ti with Si
No reaction with SiO_2 or SiN
Get $TiSi_2$ only over S/D and gate

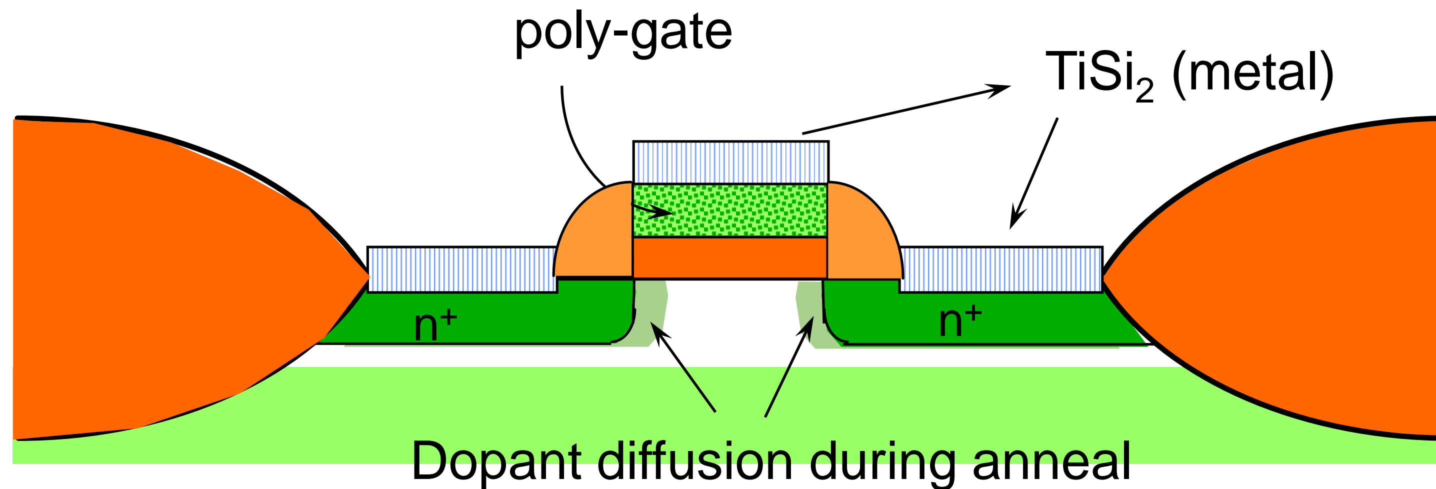
SELF-ALIGNED PROCESS!
SCALABLE!



Selective etch to remove only unreacted Ti.
Use H_3PO_4

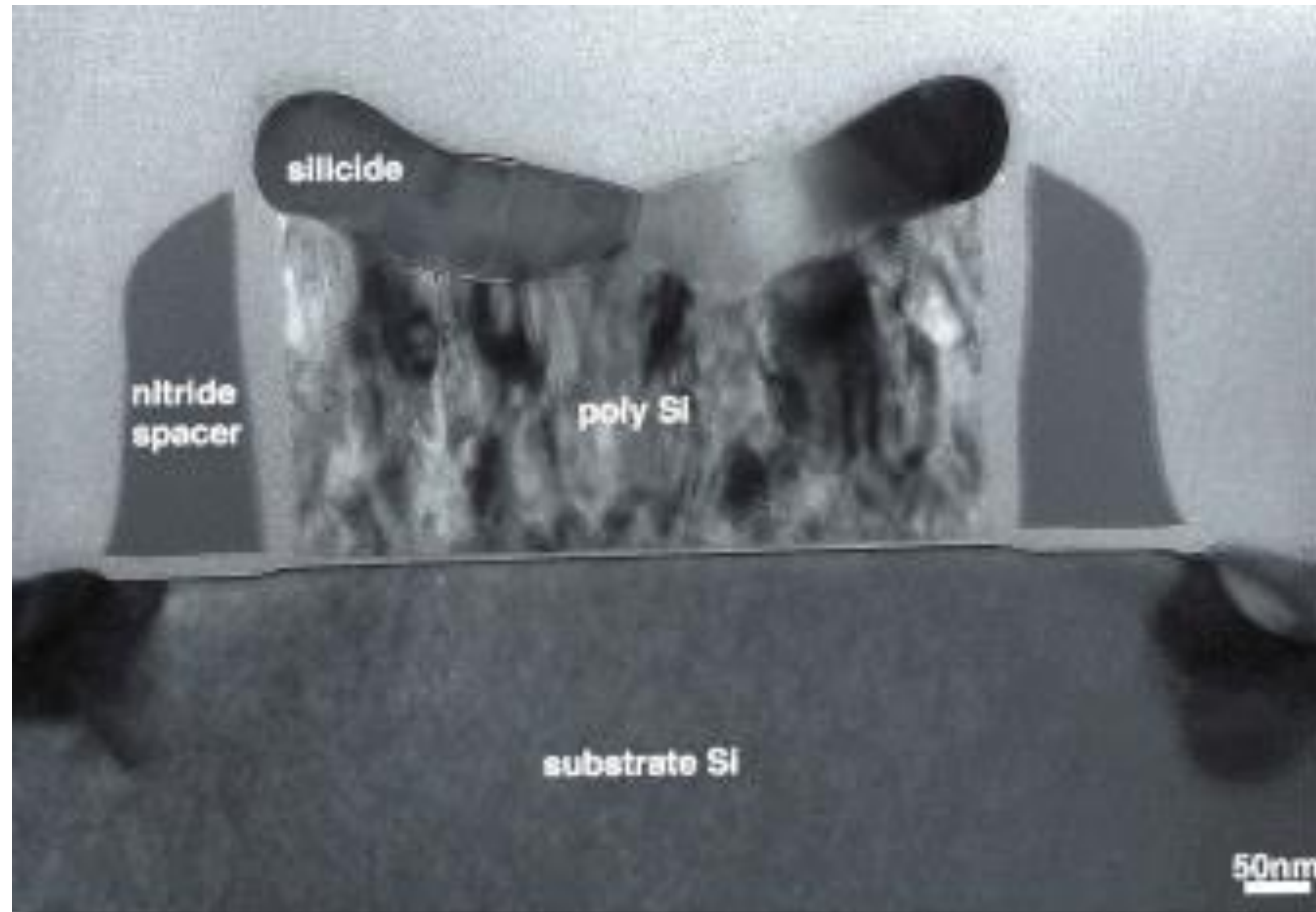
- Metal silicides are metallic.
- They lower the sheet resistance of S/D and the poly-gate
- Lower resistance → Higher current → Faster circuit

Issue: Anneal required for low-resistivity $TiSi_2$ structure transition



- $TiSi_2$ C49-to-C54 crystal structure transition requires a thermal anneal.
- Done after S/D formation – diffusion softens junction edges and lowers performance → 10% performance loss on 180nm generation n-channel devices.
- Transition needs longer/hotter anneal as line width approaches $TiSi_2$ grain size
- SCALING LIMIT! Need to find a new alternative.

Ti Salicide Gate and Source/Drain



Quick Project History and Information Flow 1

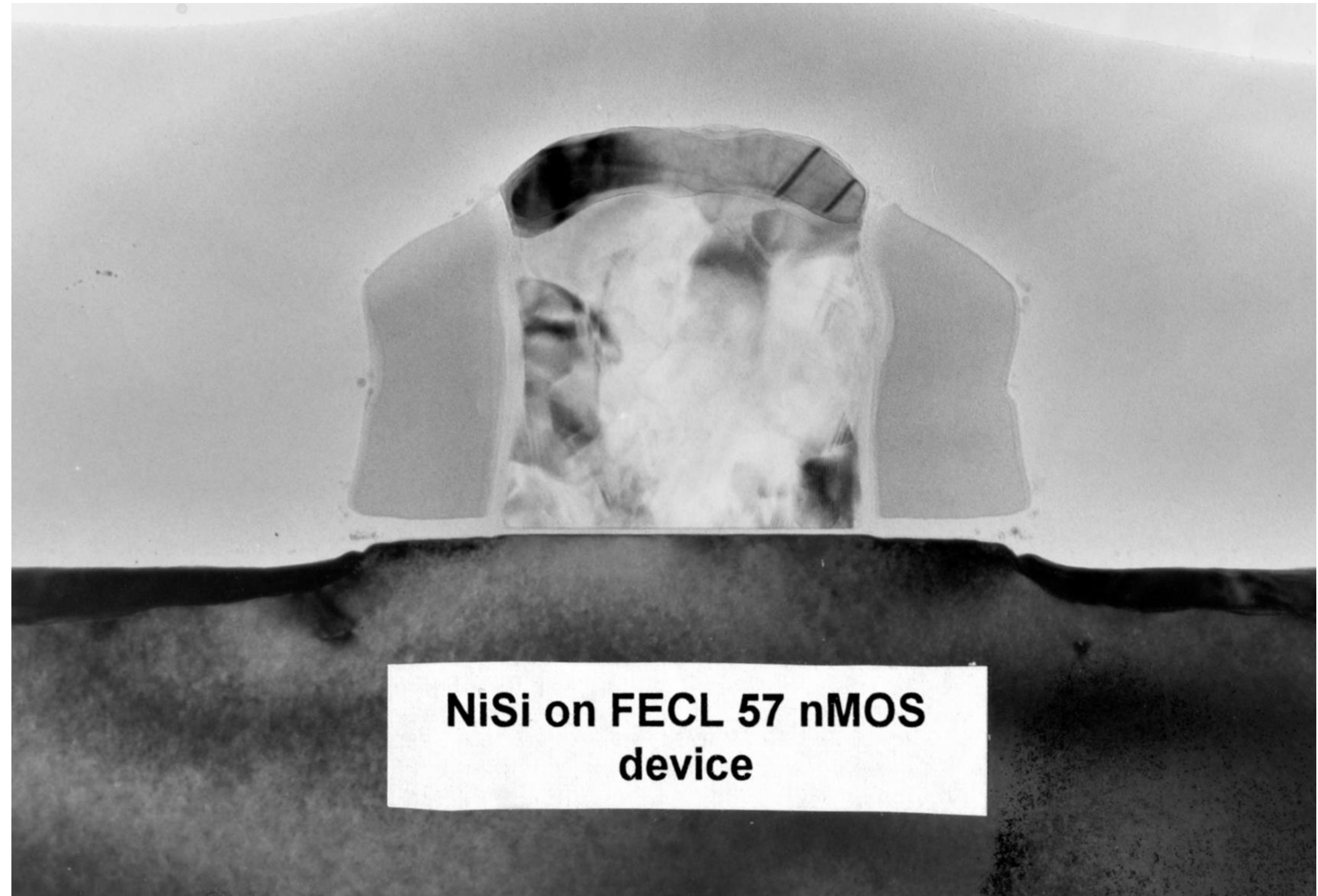
- Initial requirements provided by TD — TD → CR
- Narrowed down options in our California lab using materials measurements. NiSi worked best in our test devices.
- Developed a basic NiSi process in California with the help of Applied Materials.
- Weekly flights to TD site, attended meetings, reviewed data, lunch, one-on-one discussions. Developed a trusting relationship with TD — TD → CR
- Began to understand current process and speed of change at TD — TD → CR
  - *High rate of learning means understanding of requirements always changing*
  - *The goalposts are always moving!*

Quick Project History and Information Flow 2

- Ran simple experiments at Development site to quantify performance loss due to salicide anneal of $TiSi_2$. Quantified scaling limit. D → R → D
- Ran NiSi experiments at the Development site using our NiSi process inserted into the Development process. Used their tools and testing and compared against Development controls. Demonstrated 15% performance improvement *vs*. 30% overall TD performance goal. R → D
- Development adopts NiSi as a worthwhile option.
- A research engineer (not me) is transferred to Oregon to continue the development R → D

TEM x-section of early device with NiSi

- Test device designed for TEM cross-section.
- Good silicide formation on S/D and gate using a low temperature process.
- From 1997 on older process (250 nm node)



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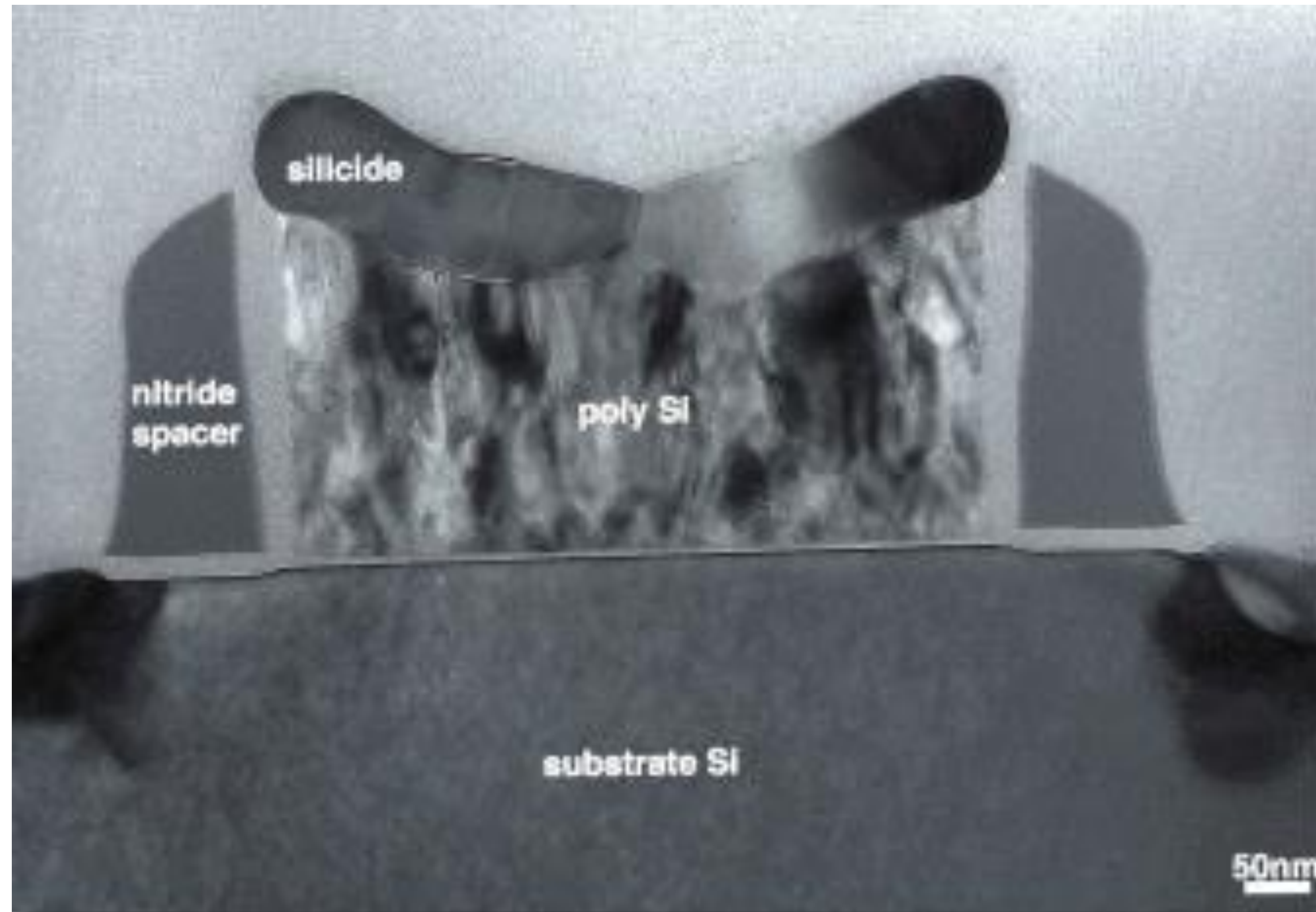


Intel Corporate Response to this Work

- Development spent 4+ years developing a high-yield NiSi process.
  - $CoSi_2$ used in 180nm and 130nm technologies, a process acquired when Intel bought Digital Equipment Corp to settle a patent dispute.
  - NiSi was first used in manufacturing in the 90nm technology.
  - NiSi was preferred over $CoSi_2$ due to its compatibility with SiGe used in raised source/drain process and the strained Si process.
    - ***This was impossible to predict when we started.***
- Organizational Change: Most of CR moved to Oregon to work closely with TD (1997-8)
  - Subsequent big CR contributions in high-k dielectric (45 nm technology) and tri-gate process (FINFET, 22 nm process)

NiSi in Manufacturing

90nm/65nm nodes: NiSi on SiGe S/D and gate

45nm/32nm nodes: NiSi on SiGe S/D. Metal gate over high-k dielectric requires no silicide.

22nm node:

No silicide used on tri-gate device.

Transistor Innovations Enable Technology Cadence

2003	2005	2007	2009	2011
90 nm	65 nm	45 nm	32 nm	22 nm
Invented SiGe Strained Silicon	2nd Gen. SiGe Strained Silicon	Invented Gate-Last High-k Metal Gate	2nd Gen. Gate-Last High-k Metal Gate	First to Implement Tri-Gate

50nm

Metal

High-k

SiGe

SiGe

Silicon

Strained Silicon

High k Metal gate

Tri-Gate

From 2011

Tri-Gate Achievement Results from Long Term Commitment to Research

Pathfinding

Internal Research

CE! transfer

Development

Manufacturing

Tri-Gate Invented

Tri-Gate Selected for 22nm node

2002 — Single-fin transistor demonstrated

2003 — Multi-fin transistor demonstrated

2006 — Tri-gate SRAM cells demonstrated

2007 — Tri-gate RMG process flow developed

Tri-gate optimized for HVM

Tri-Gate Mfg

Bringing innovative technologies to HVM is the result of a highly coordinated internal research-development-manufacturing pipeline

From 2011

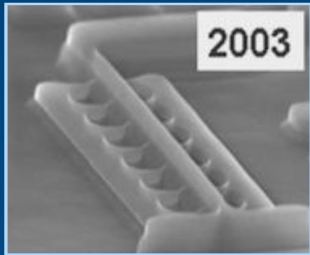
Tri-Gate Achievement Results from Long Term Commitment to Research

E! transfer

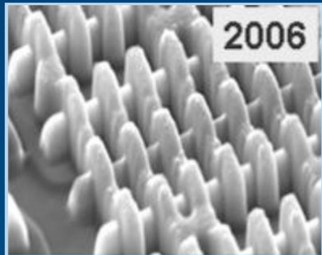
Manufacturing

22nm node

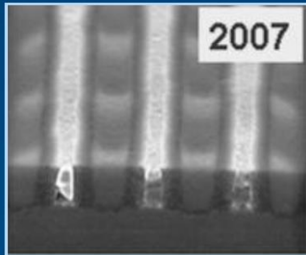
Single-fin transistor demonstrated



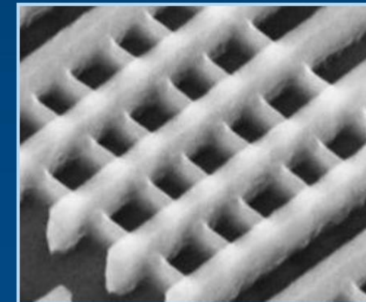
Multi-fin transistor demonstrated



Tri-gate SRAM cells demonstrated



Tri-gate RMG process flow developed



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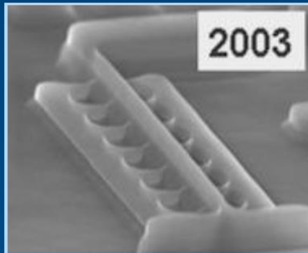
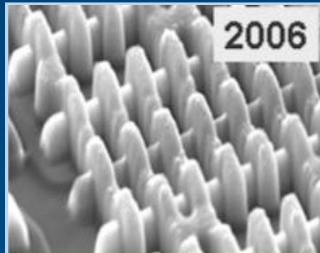


Multi-fin transistor demonstrated



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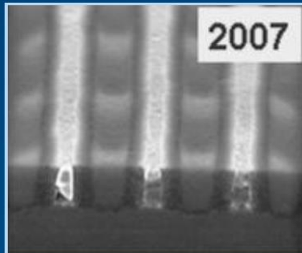
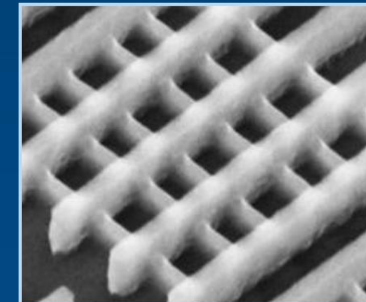


Tri-gate RMG process flow developed


Tri-gate optimized for HVM

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Tri-Gate Achievement Results from Long Term Commitment to Research

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CR Went From Problem Child to Competitive Advantage

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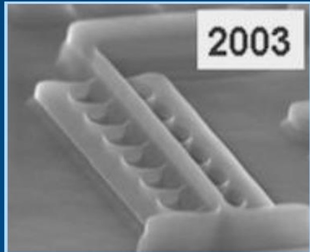
Tri-Gate Selected for 22nm node

Single-fin transistor demonstrated



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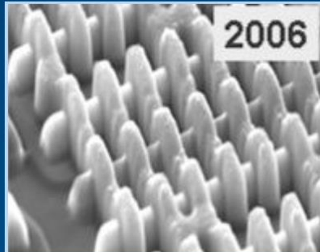

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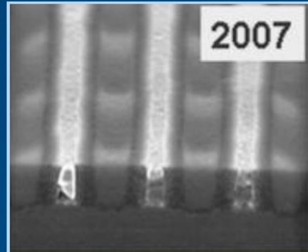

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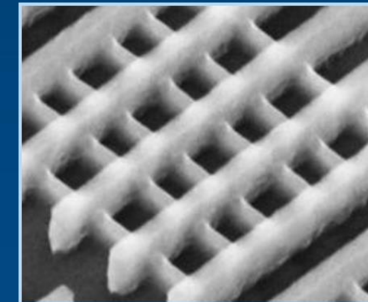

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Some theories on why transfers from R to D fail

- Staff falls short:
  - Research engineers not doing a complete enough job
    - **Trying to do a "complete" job will ensure your failure**
  - Research engineers not working hard enough
    - **Researchers cannot schedule progress. Work on several options.**
- Organization or management falls short:
  - Administrative barriers and organizational territoriality
  - Dislike or distrust between members of different organizations.
  - "Not invented here" attitude on the part of the receiving organization.
- Buzzword-dependent theories:
  - People or organizations not "entrepreneurial" enough.

At least at Intel, all untrue

Key Methods for Success

- Understand and adopt the customer's methods, especially their decision-making process
  - ***No one really has the time to redo results, so just do it their way.***
- Transfer information, not a finished process or product
  - ***Enable your customer to finish the process or product.***
- Work constantly at transferring intermediate research results and getting ***feedback*** to direct future research.
- Extract learning from research work that the customer does not adopt.
  - Example: Selective CVD $TiSi_2$ learning aided selective CVD SiGe development.
- Shamelessly use your contacts and your UIUC pedigree.

Learning to Lead

- Leadership is learned over many years. It is most critical and beneficial when working across organizations.
- A leader is simply a servant with a vision.
  - Help solve their problem.
  - Spend lots of time with your customers to learn what they know and how they did it, to develop trust and communicate your vision.
  - Leadership is way more interesting than authority. Don't confuse the two.
  - You can start serving and leading on Day One.
- You need to take responsibility for the transferability of your work.
- Capable people are willing to help with a good new idea.
- Your co-workers and managers value leadership.
- ***Everyone in this room should expect to lead at some point.***

Thank you for your attention