Physicists in the Semiconductor Industry

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Outline

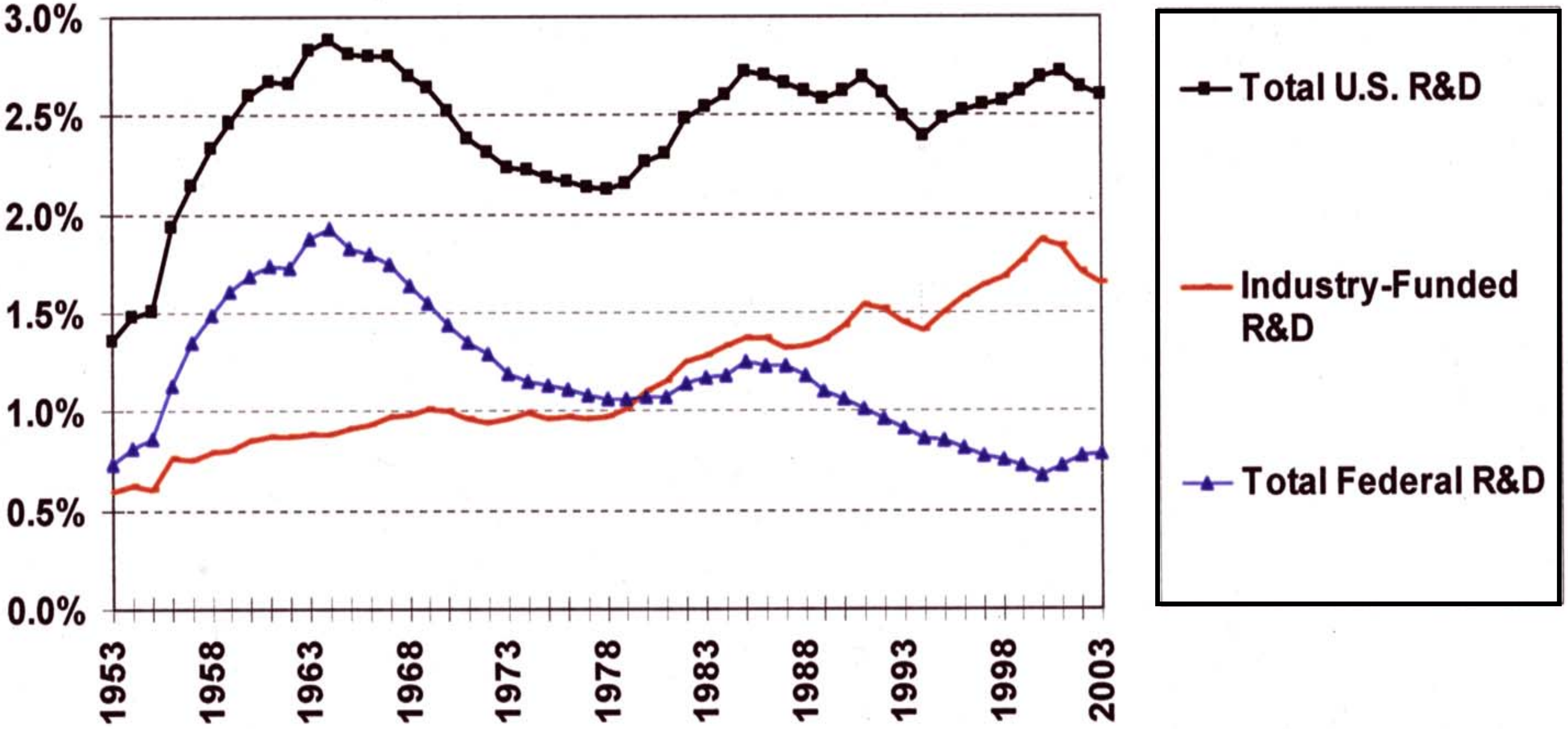
- Introduction
  - R&D funding in the US
  - evolution of semiconductor technology

- Physics research in the semiconductor industry
  - current materials issues in Si CMOS technology
  - materials characterization issues

- Physicists in the semiconductor industry
  - requirements
  - career paths

U.S. R&D as Percent of Gross Domestic Product

Total, Industrial, and Federal R&D - 1953-2003



Source: NSF, Division of Science Resources Statistics. 2002 and 2003 data are preliminary. R&D funded by other sources (universities, nonprofits, etc.) included in Total U.S. R&D. Includes defense and nondefense R&D.

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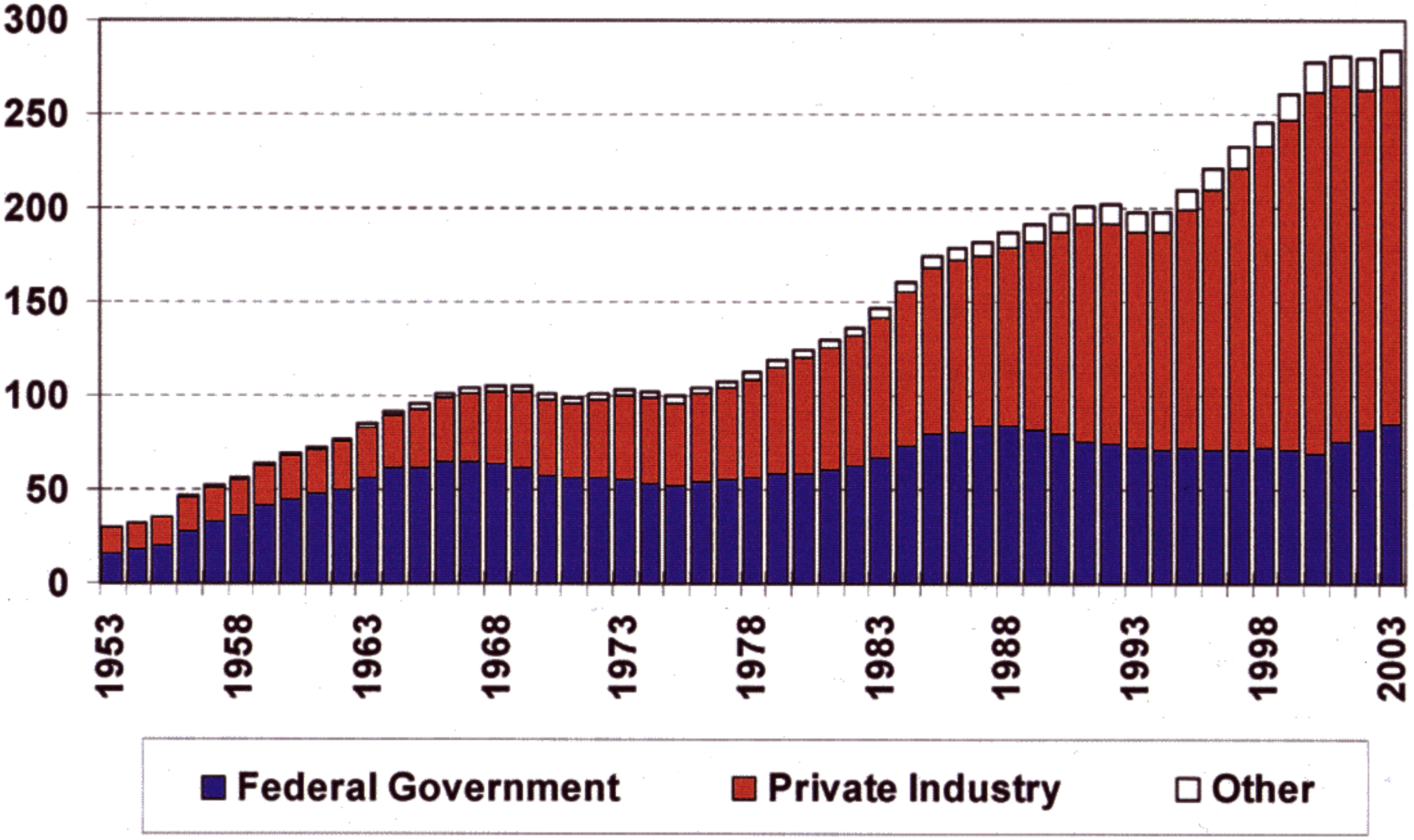
U.S. R&D Funding by Source, 1953-2003

expenditures in billions of constant 2003 dollars



Source: NSF, Division of Science Resources Statistics. (Data for 2002 and 2003 are preliminary.)
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Information Technology Enabled by Semiconductor Technology

Highlights in the evolution of semiconductor technology:

electron discovered	1898	
semiconductor properties understood	1920's and 30's	
bulk crystal growth methods	high quality crystals	
point contact transistor	1947	Ge
junction transistor	1948	Ge
photovoltaic device (solar cell)	1954	Si
fully transistorized computer	1954	10^6 operations/sec, 800 transistors
integrated circuit invented	1958	Si
diode laser	1962	GaAs
Si memory chips available	1971	1024 bits
first microprosessor	1971	2300 transistors
epitaxial crystal growth methods	1970s	layered semiconductor heterostructures - study of quantum effects - quantum effect electronic devices
Apple II	1977	1st assembled PC (not a kit)
IBM PC	1981	
Cray-2 (supercomputer)	1985	10^9 logic operations/sec
World Wide Web	1990	proposal for standard addresses
GPS completed	1993	24 Navstar satellites/atomic clocks
Pentium III processor	1999	9.5 million transistors

Moore's Law -- in 1965 Gordon Moore predicted that the number of components on the most complex chips would double every year for 10 years

Exponential increases in performance for >30 years!

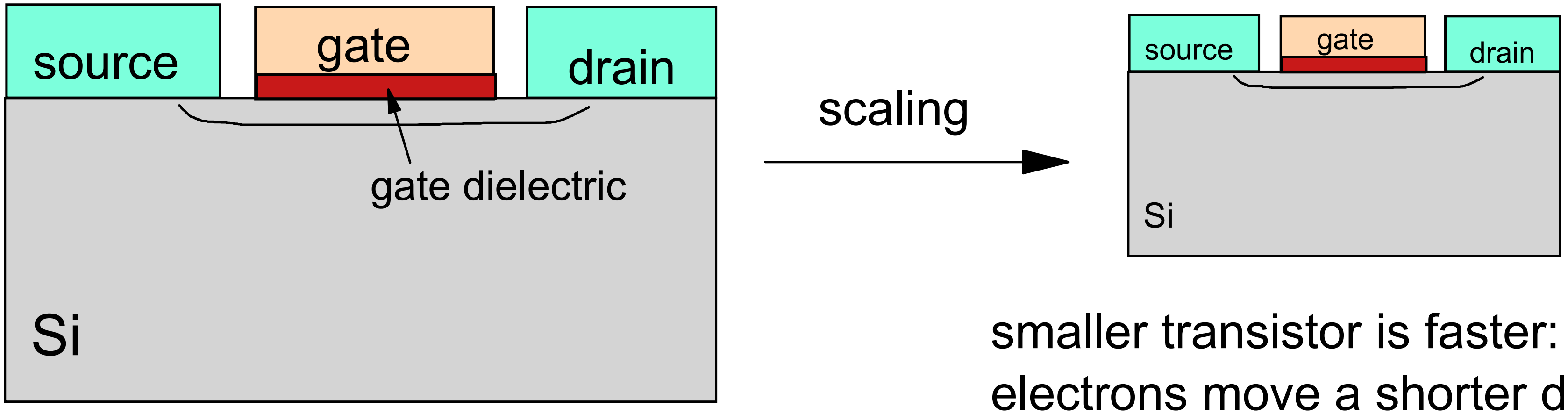
Transistor performance increases primarily due to scaling --
reduction in the size of individual devices

Key factors in overall performance increase of ICs:

50% -- improvement in lithograpy (determines size of smallest features)
25% -- larger chip size
25% -- innovations in fabrication methods/new materials

components/chip increases faster than cost/chip ==>
exponential decrease in cost/function fuels information age!

Faster Computers Need Faster Transistors

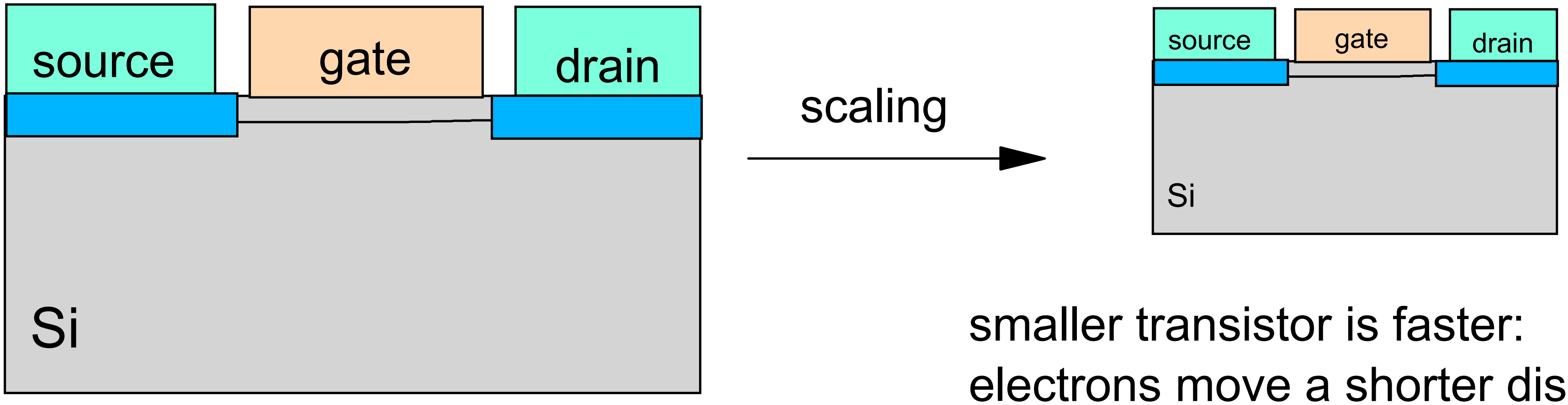


smaller transistor is faster:
electrons move a shorter distance

- standard gate dielectric in SiO_2
  - tunneling current increases as layer becomes thinner
  - leads to high power consumption in IC

- find a <u>new gate dielectric material</u> with larger dielectric constant
  - the physical thickness of the layer can be larger
    ==> reduced tunneling current in scaled devices

Faster Computers Need Faster Transistors



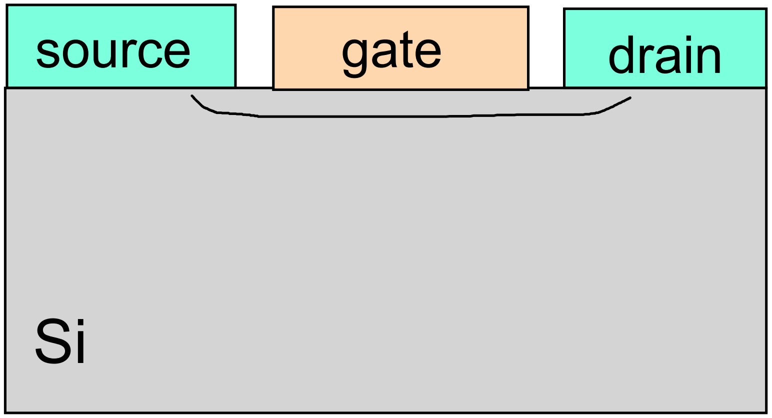
smaller transistor is faster:
electrons move a shorter distance

- dopant atoms are implanted to form source and drain regions
  - dopant diffusion is hard to control at nm dimensions
  - lateral diffusion can lead to shorted devices
    - e.g. transient enhanced diffusion is a problem

- need to understand dopant diffusion better

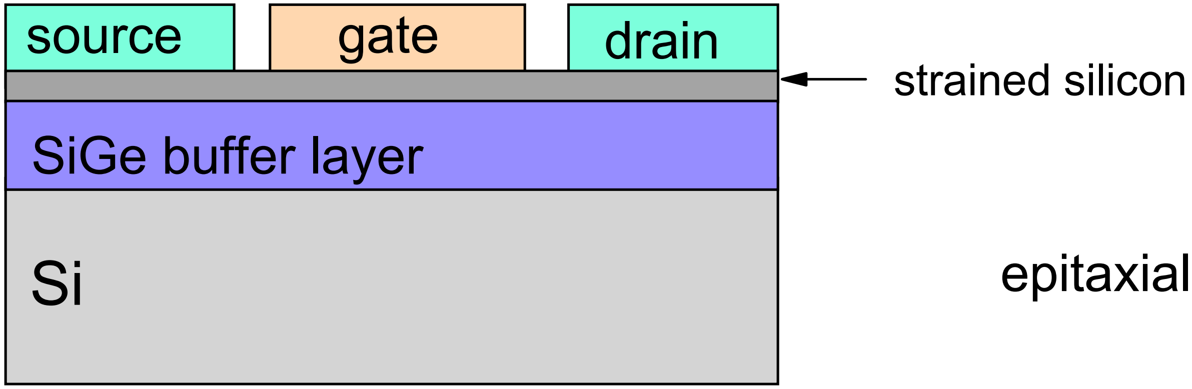
- need <u>new characterization methods</u> for dopant distribution

Faster Computers Need Faster Transistors



find a new material in which charge carriers have higher mobility

($v = \mu E$, where mobility, μ, is a function of effective mass, m^*)



epitaxial SiGe/Si heterostructure

Materials Requirements for CMOS

- desired physical characteristics
    - e.g., dielectric constant, electron mobility

- compatible with fabrication processes
    - high processing temperatures (up to 1000 °C)
    - similar thermal expansion coefficient

- reliability
    - integrated circuit should last 10 years

- manufacturablity

- cost

===> physics is just the beginning!!

Characterization/Metrology Issues

- must be able to characterize what you make!
  - structural characterization
    - electron microscopy (SEM, TEM)
    - x-ray difraction (lattice parameter/strain)
    - x-ray reflectivity (film thickness and roughness)
    - spectroscopy ellipsometry (film thickness)
    - Raman spectroscopy (strain)
  - Chemical Characterization
    - secondary ion mass spectrometry
    - Aujer electron spectroscopy
    - Rutherford back scattering
  - electrical characterization
    - carrier mobility
    - charge density at interfaces
    - resistivity
    - device characteristics

- automated measurements needed in manufacturing!
  - fast data collection
  - data management
  - collaborations with equipment companies

New Characterization Methods: Electron Holography

- electron beam is split to obtain phase information as well as amplitude information

- obtain electrical potential from phase information

- demonstrated use to image dopant distribution in short-gate CMOS devices
    - quantative measurement of dopant profile in device
    - learn about dopant diffusion

- developed as routine method for failure analysis

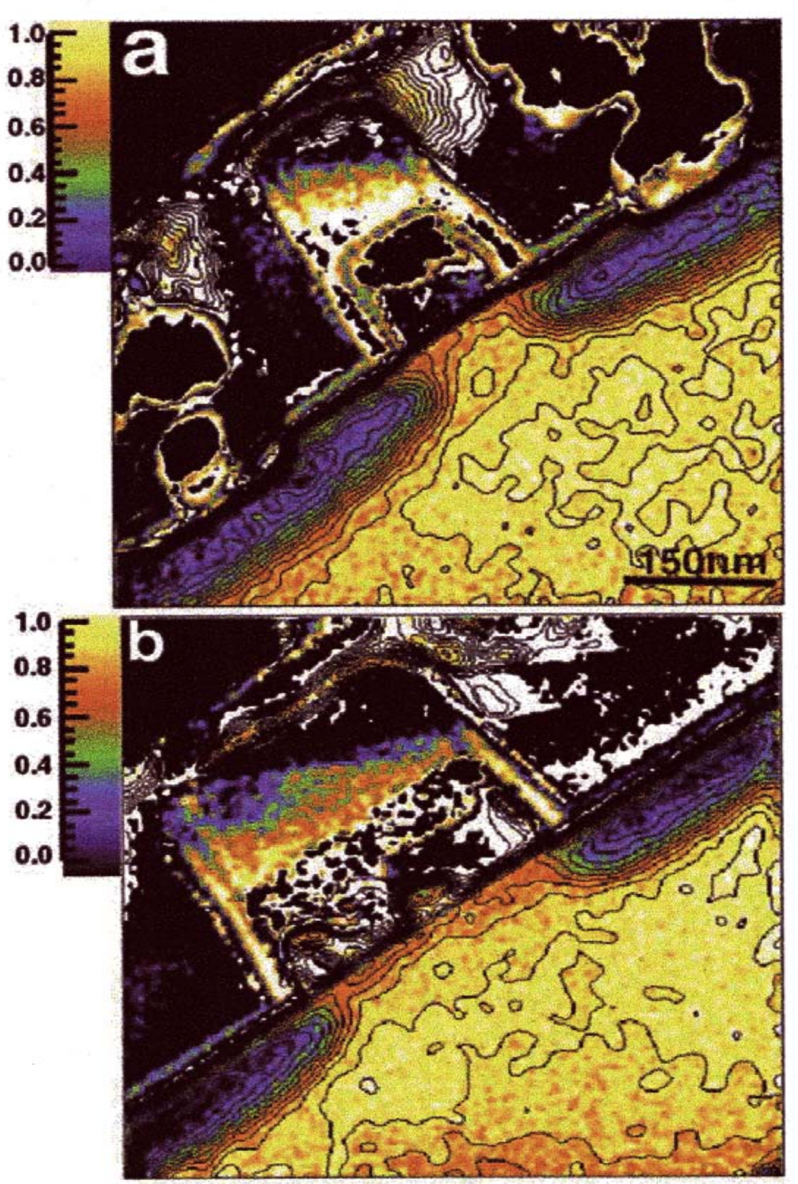


FIG. 2 (color). Reconstructed 2D maps of the electrostatic potential variation in (a) 0.13 μm and (b) 0.35 μm devices. The contour step is 0.1 V.

IBM - Arizona State U. collaboration

- Gribelyuk, et al., Phys. Rev. Lett. **89**, 25502 (2002)
- M.R. McCartney, et al. Appl. Phys. Lett. **80**, 3213 (2002).

Improved Scanning Transmission Electron Microscopy

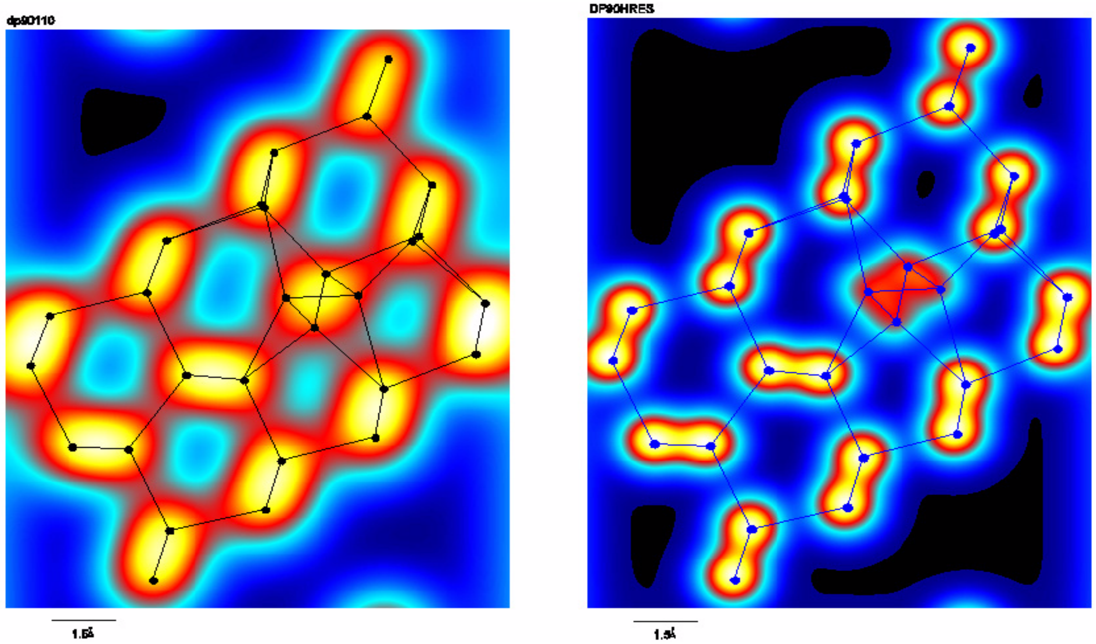
- high spatial resolution structural imaging plus electron energy loss spectroscopy for electronic structure

- recently achieved sub-Angstrom (0.078 nm) probe size by means of a computer controlled aberration correction system
  - allows imaging of single atoms, clusters of a few atoms, single atomic layers, single column of atoms in a semiconductor

90° Partial Dislocation Structure

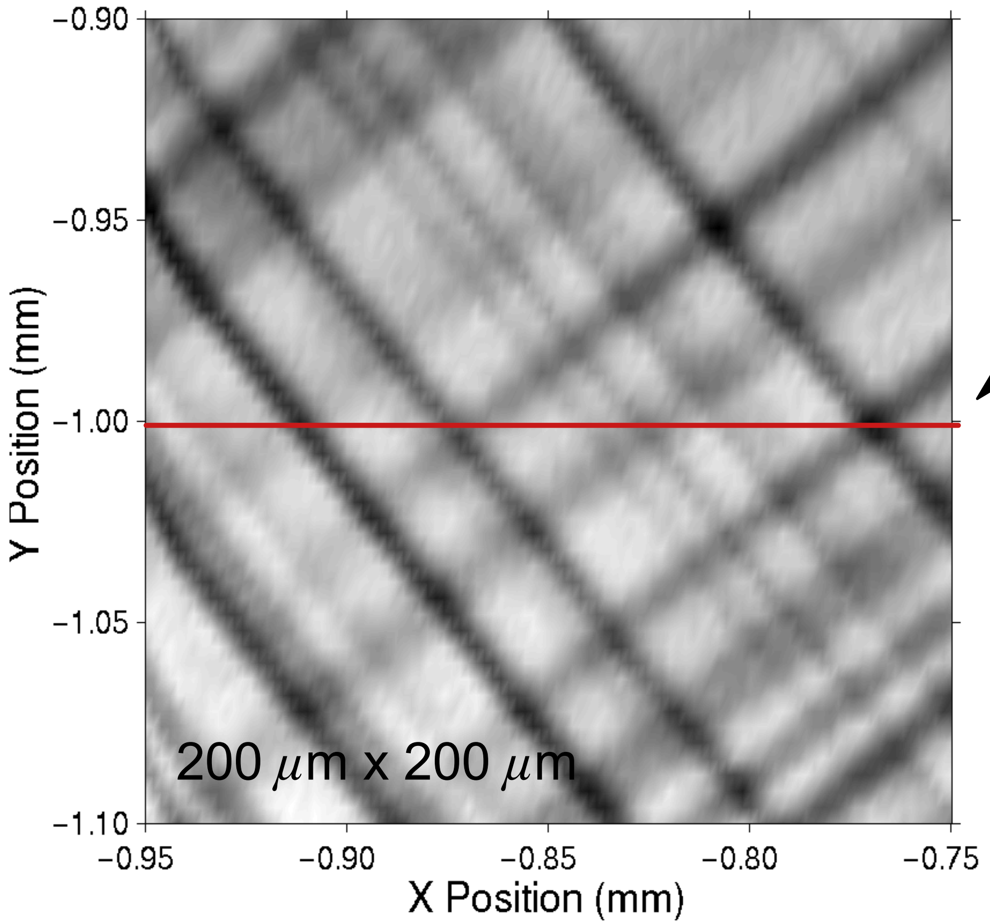
On the left: Model calculation showing a proposed structure for an important defect in the silicon crystal, viewed using a 2 Angstrom (0.2 nanometers) resolution. Atom columns are indicated by the dots. Near neighbor connectivity of the atoms is indicated by the lines. Bright areas indicate strong scattering of the 2 Angstrom electron beam.

On the right: The same structure viewed with a 1 Angstrom diameter beam. Details in the four column group (red) will become apparent.



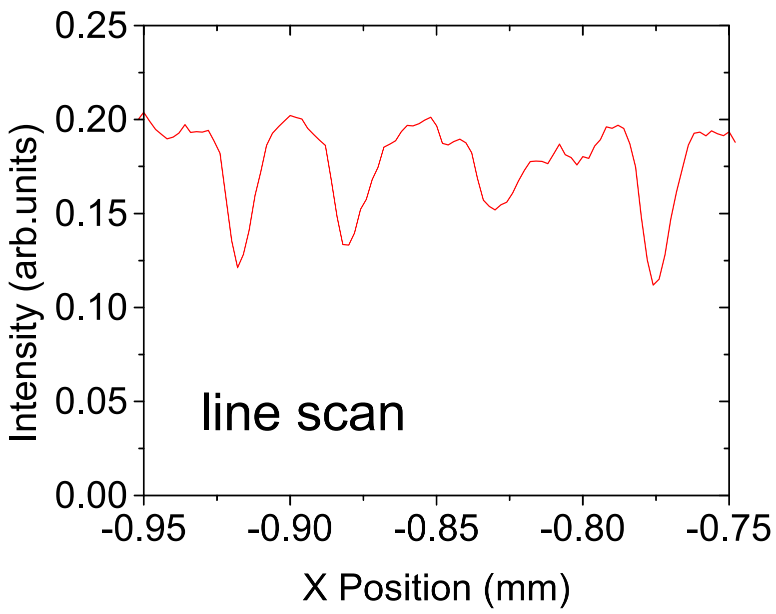
P.E. Batson et al., Nature **418**, 617 (2002).
P.E.Batson, Ultramicroscopy **96**, 239 (2003).

X-Ray Microdiffraction: Image Dislocations in SiGe Layers

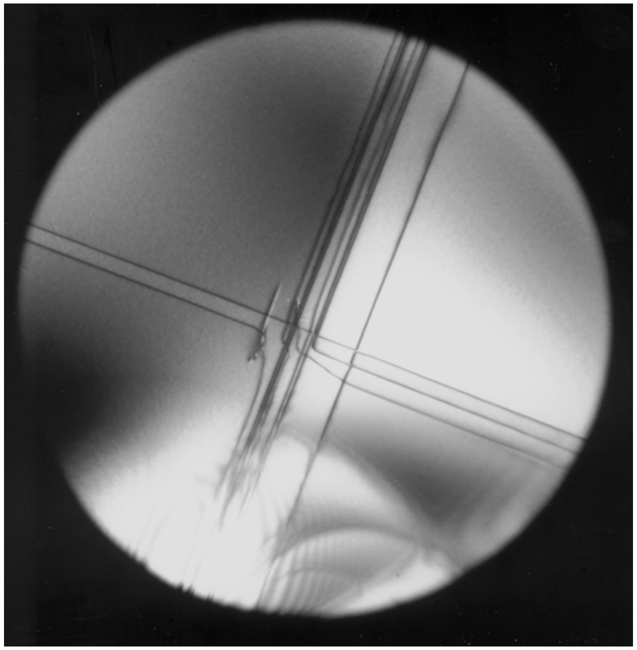


scanning microtopograph

dark features are >7 nm wide!



XTEM shows that features are dislocation pile-ups, not individual dislocations!

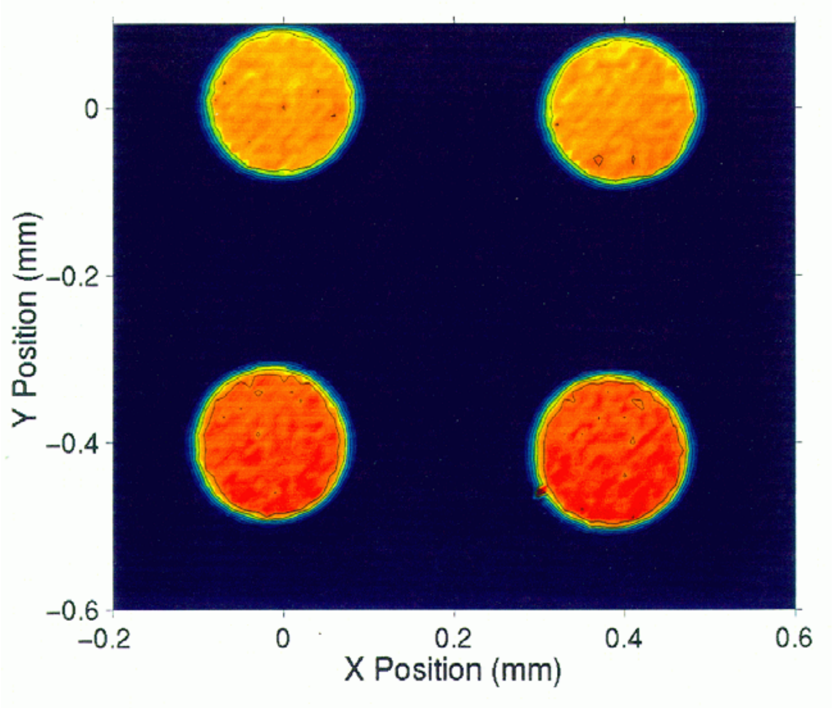


TEM image diameter = 6.7 μm

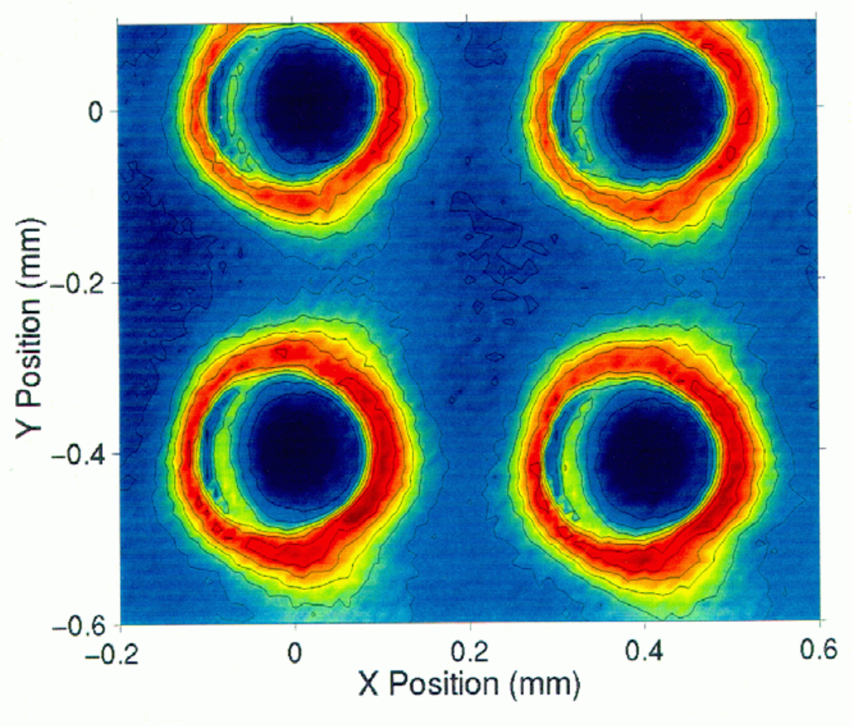
P.M. Mooney, et al., Appl. Phys. Lett. 79, 2363 (2001).

X-Ray Microdiffraction: Measure Strain at Small Features

190 μm-diameter polycrystalline Ni dots on a Si(111) substrate



Ni K_α fluorescence



intensity of Si 333 peak

- diffracted intensity is increased at edge of dot
- enhancement due to kinematic (not dynamic) diffraction from strained Si regions
- extends 120 μm beyond edge of dot (long range effect)
- similar effect seen for smaller SiGe/Si features

I.C. Noyan, et al., APL 74, 2352 (1999).
C.E. Murray, et al., APL 83, 4163 (2003).

Requirements for PhD Researchers

- strong scientific or technical background
    - PhD in physics, chemistry or engineering

- creativity/innovation

- interest in solving problems
    - research in industry is mission oriented
    - important to apply knowledge to future products

- leadership
    - technical leadership
    - project leadership
        - convince others to work on your ideas
    - management of research/development

- communications skills
    - speaking and writing

- ability to work with people in interdisciplinary teams

Research Staff Member: Pat Mooney

- research in semiconductor defects
  - electronic states of defects (DLTS)
  - strain relxation in lattice mismatched structures (XRD)
- project leader
  - various projects related to SiGe/Si materials and devices
- active in research community
  - organizing national and internations conferences
  - editorial boards of journals
  - American Physical Society
    Chair, Division of Materials Physics
    Councillor, Forum of Industrial and Applied Physics

- primary responsibility is doing research

Research Management: Tom Theis

Resarch Staff Member:

- research on transport in semiconductors
- manager of III-V semiconductor epitaxy group
- manager of III-V semiconductor epitaxy and device groups
- manager of semiconductor research department
- manager of CMOS materials research department

Director of Physical Sciences Department (executive)

- responsible for Research Division physical sciences research strategy and planning (includes research at Watson, Almaden and Zurich labs)

Technology Management: Bernie Meyerson

Research Staff Member:

- research on growth of Si and SiGe films at low temperature
  - invented UHVCVD
- manager of SiGe materials group
  - demonstrated SiGe heterojunction bipolar transistor
- manager of SiGe materials and device groups
  - iniated development of IBM's analog and mixed signal circuits for telecommunications applications

Director of Communications Technology Department

included groups in both the Research and the Microelectronics Divisions

Vice President and Director of Communications Research and Development Center

included departments in both the Research and the Microelectronics Divisions

Vice President and Chief Strategist, IBM Technology Group

responsible for product development activities in microelectronics

many science and engineering researchers move into technology management!

Services Management: Francoise LeGoues

Research Staff Member

- materials physics using electron microscopy methods
- manager, physical sciences electron microscopy group
- technical assistant to Director of Mathematical Sciences Department (research executive responsible for utilities industry)

Marketing Division

- worked to initiate research activities related to utilities industry
- managed IBM customer center (established to show new research products to customers

Director, Inovation and Technology, IBM Global Services Division

- linkage between research, IBM Global services and Customers
- impact of technology on customers
- organizational transformation through technical innovation

uses technical background for work with IBM customers

Summary

Research in the semiconductor industry

- mission oriented -- e.g., faster/lower power ICs
- applied physics research
  - new materials are is essential
  - new characterization methods are essential

Physics PhDs are sought for

- innovation/creativity
- ability in problem solving
- interest in applications of research for products
- scientific and technical **leadership**
  - research management
  - technology management
  - marketing and services management