Microactuators and Sensors for Microfluidics and Lab on a Chip applications

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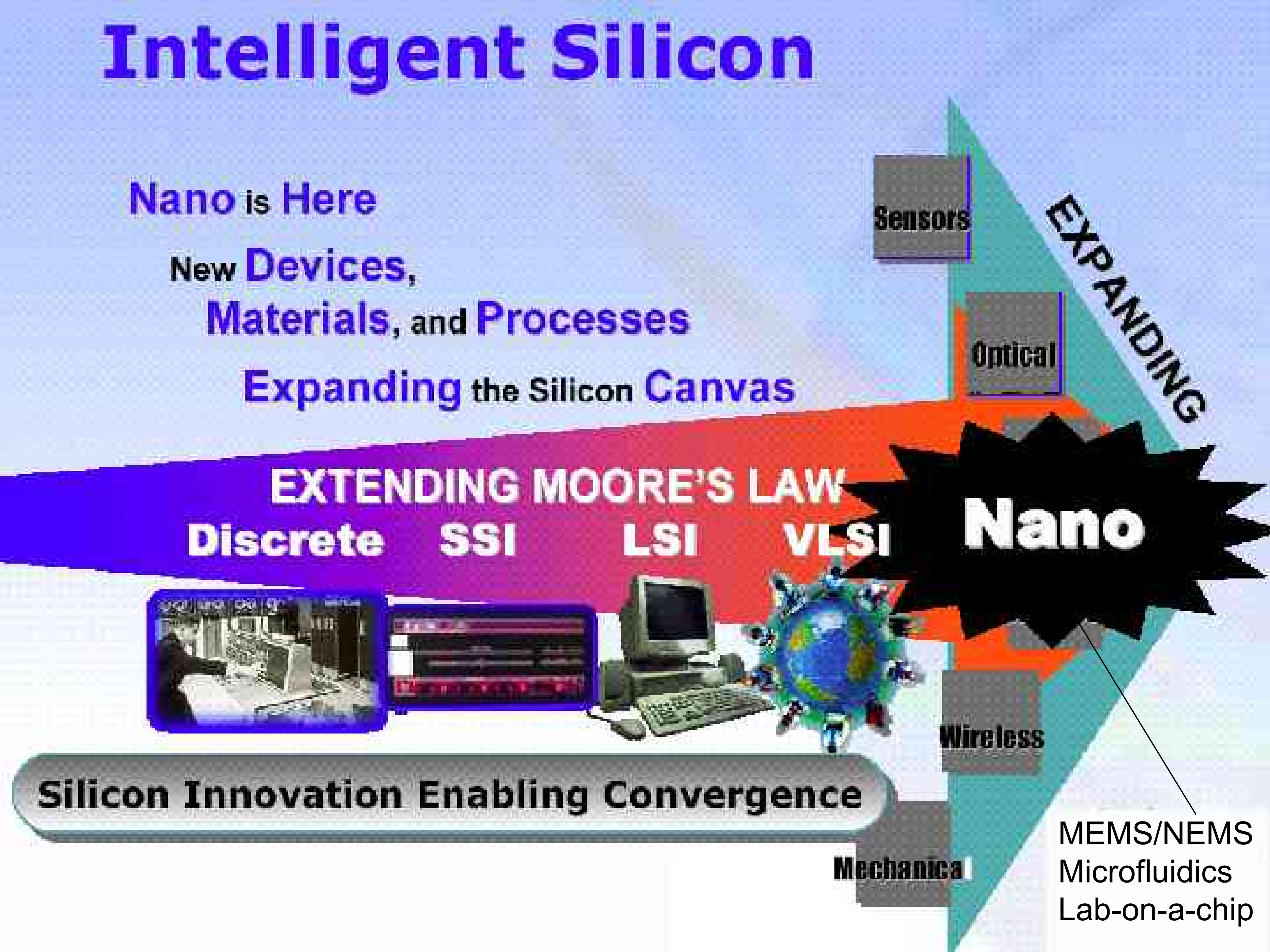
Slides 20-56 are contributed by Michael Ramsey (Oak Ridge)

General reference: Nanoelectromechanics in Engineering and Biology, by M. P. Hughes

Current Status of Electronics

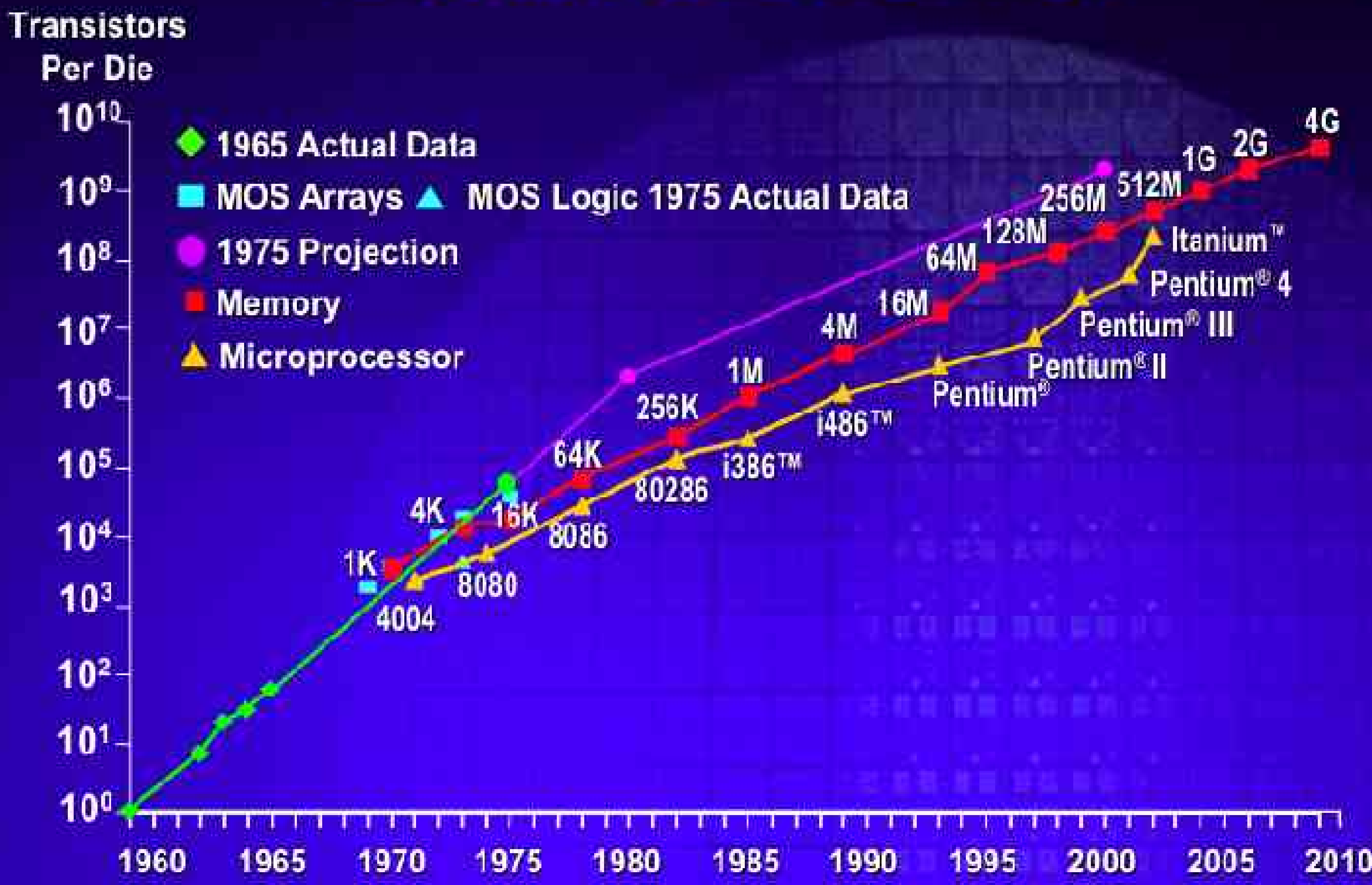
- The current status of the integrated circuits
  - Device size ~ 10 nm
  - Integration Level ~ 10^9/chip
  - Power ~ 100 W Leakage ~ 20 W
  - Other features: Power Supply ~1.5 V


Intelligent Silicon
Nano is Here
New Devices,
Materials, and Processes
Expanding the Silicon Canvas
EXTENDING MOORE'S LAW
Discrete
SSI
LSI
VLSI
Nano
EXPANDING
Sensors
Optical
Wireless
Mechanical
Silicon Innovation Enabling Convergence
MEMS/NEMS
Microfluidics
Lab-on-a-chip

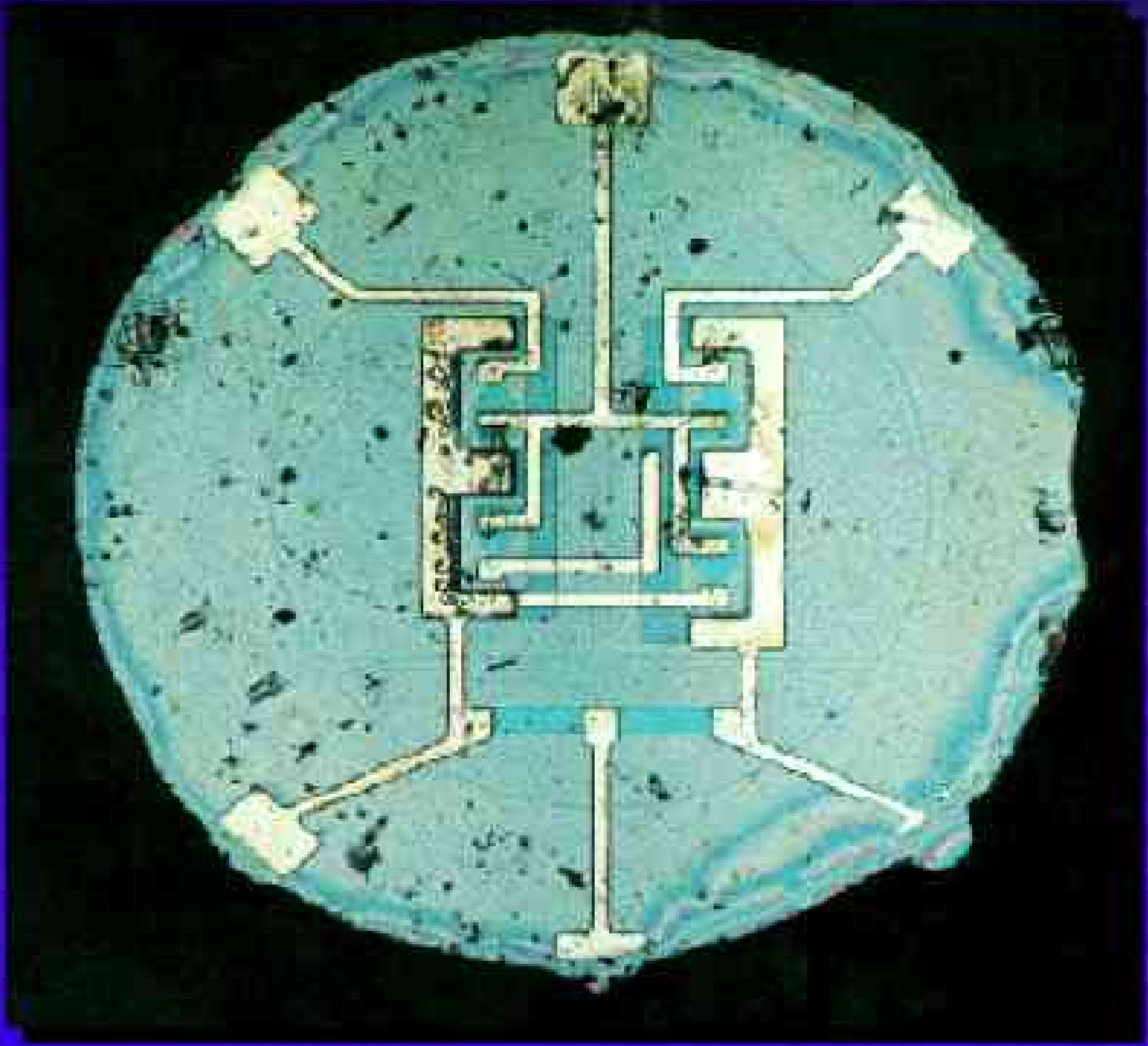
Worldwide Semiconductor Revenues

Average Transistor Price By Year

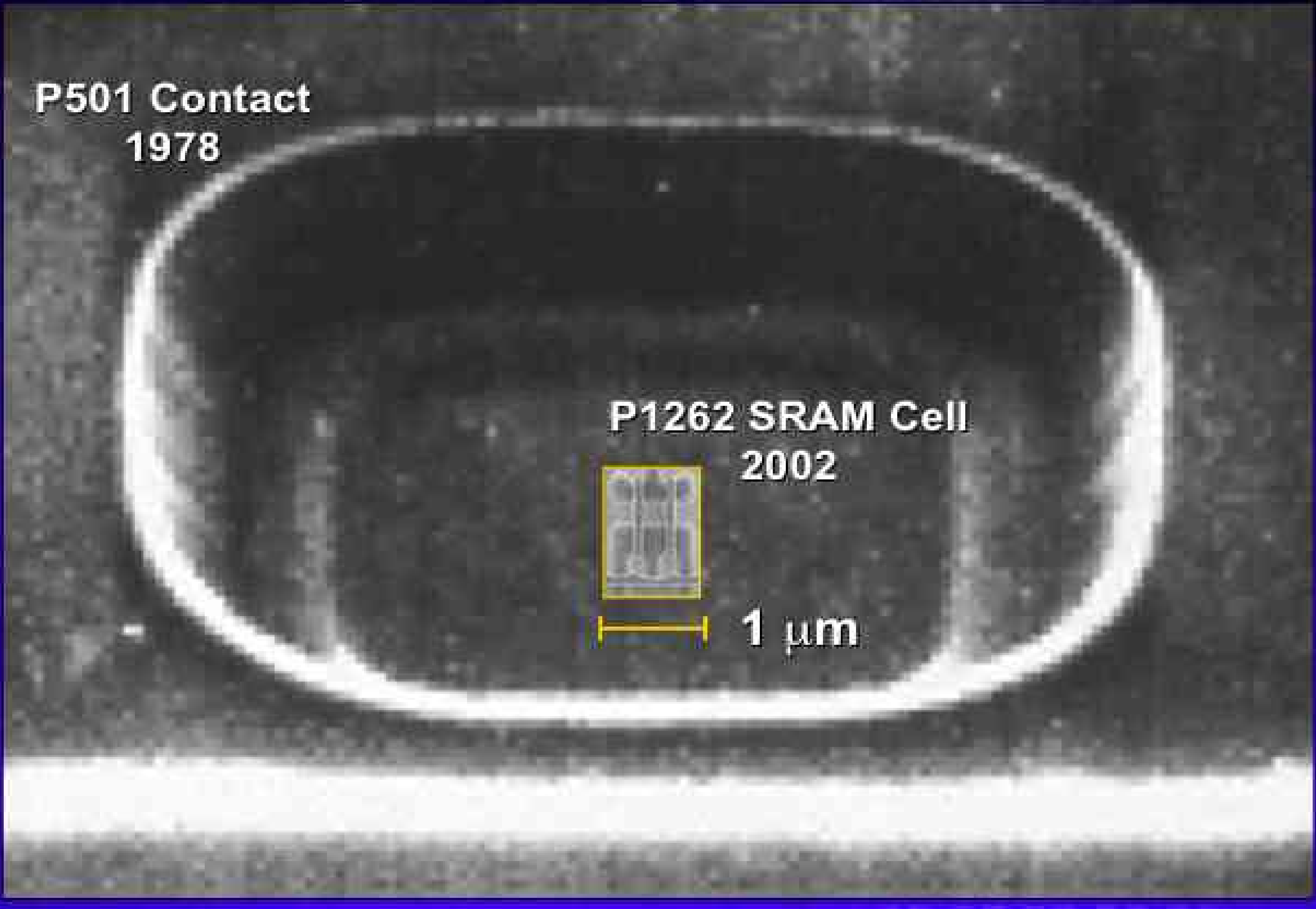
Integrated Circuit Complexity



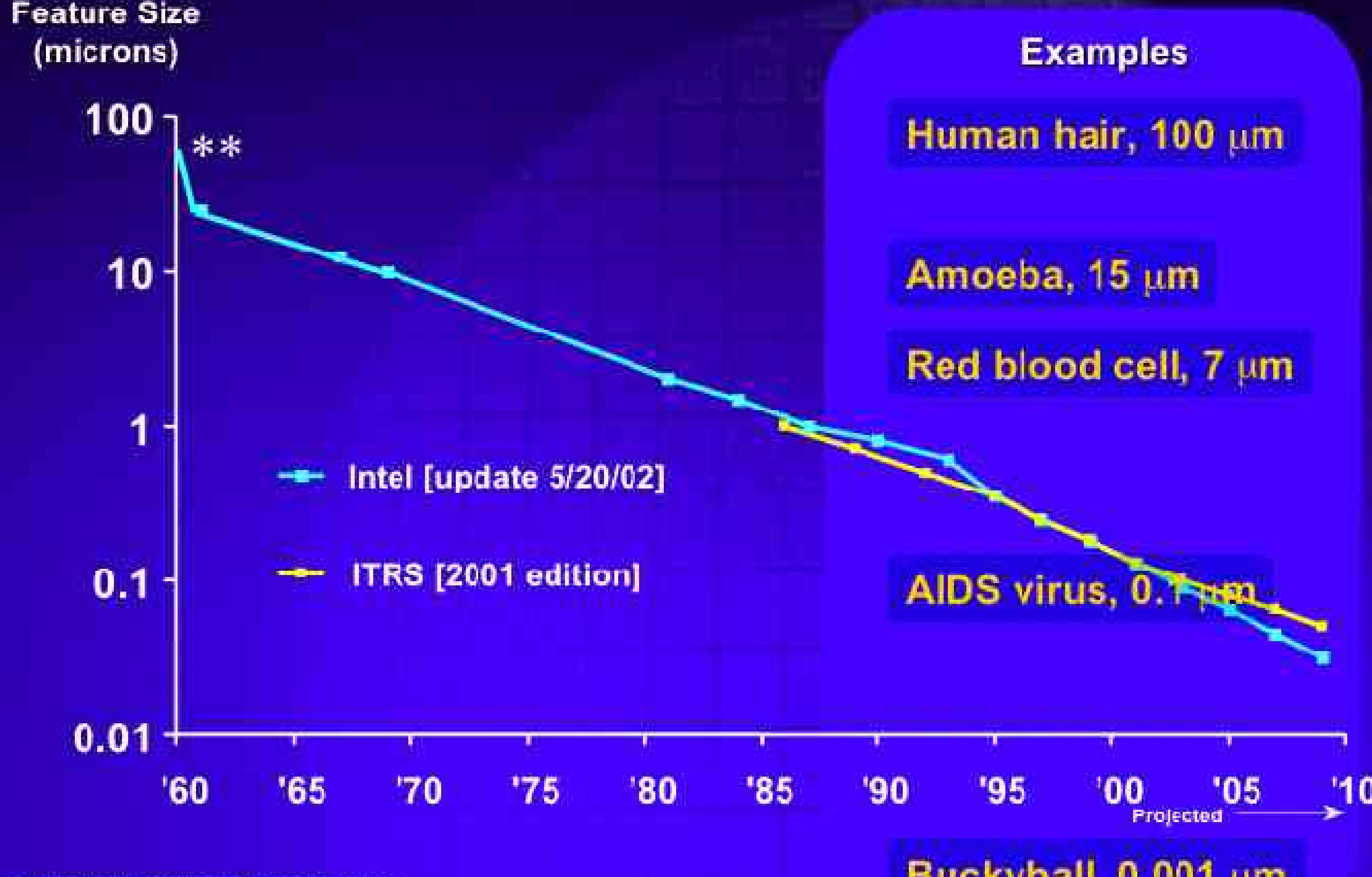
The First Planar Integrated Circuit, 1961



1 μm² SRAM Cell

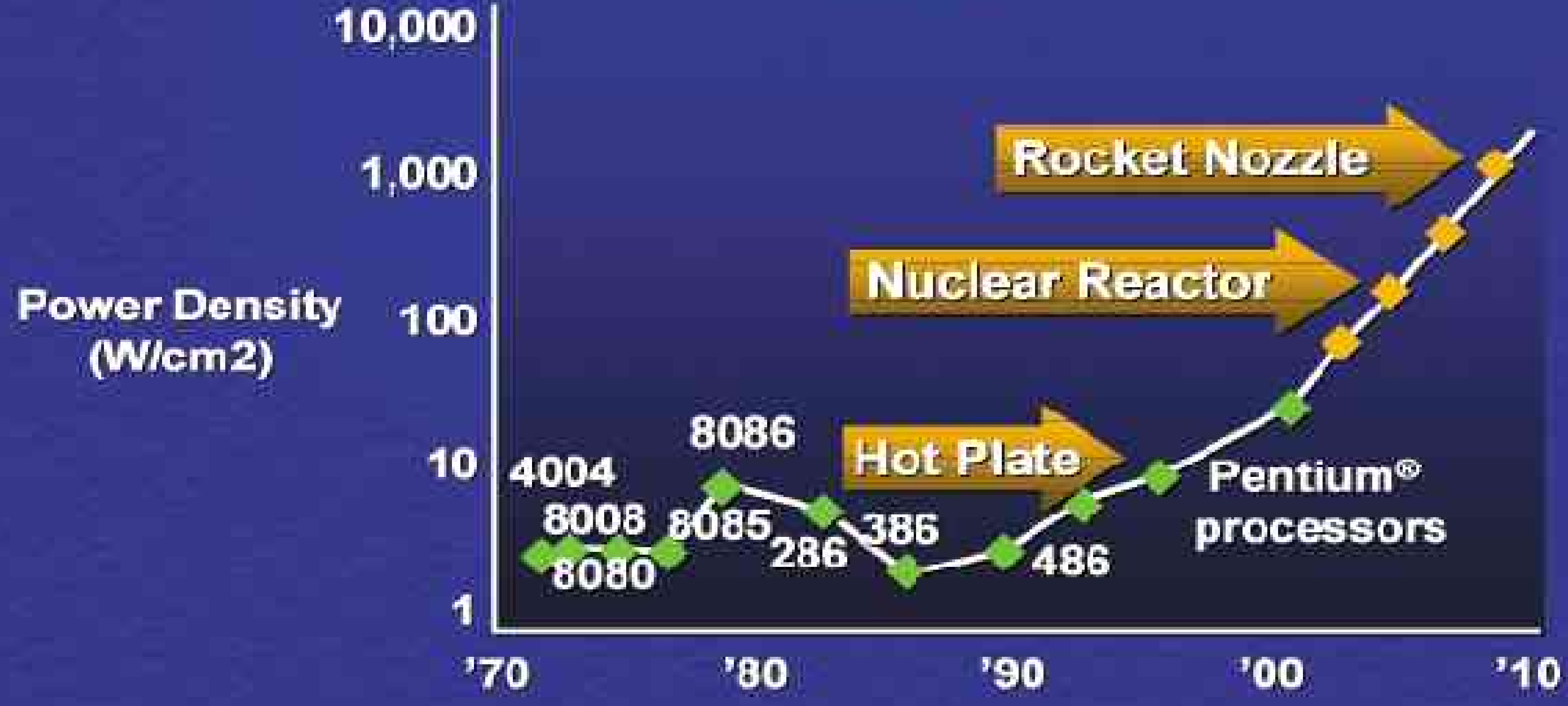


Minimum Feature Size



** Planar Transistor; remaining data points are ICs
Source: Intel, post '95 trend data provided by SIA
International Technology Roadmap for Semiconductors (ITRS)
^ [ITRS DRAM Half-Pitch vs. Intel "Lithography"]

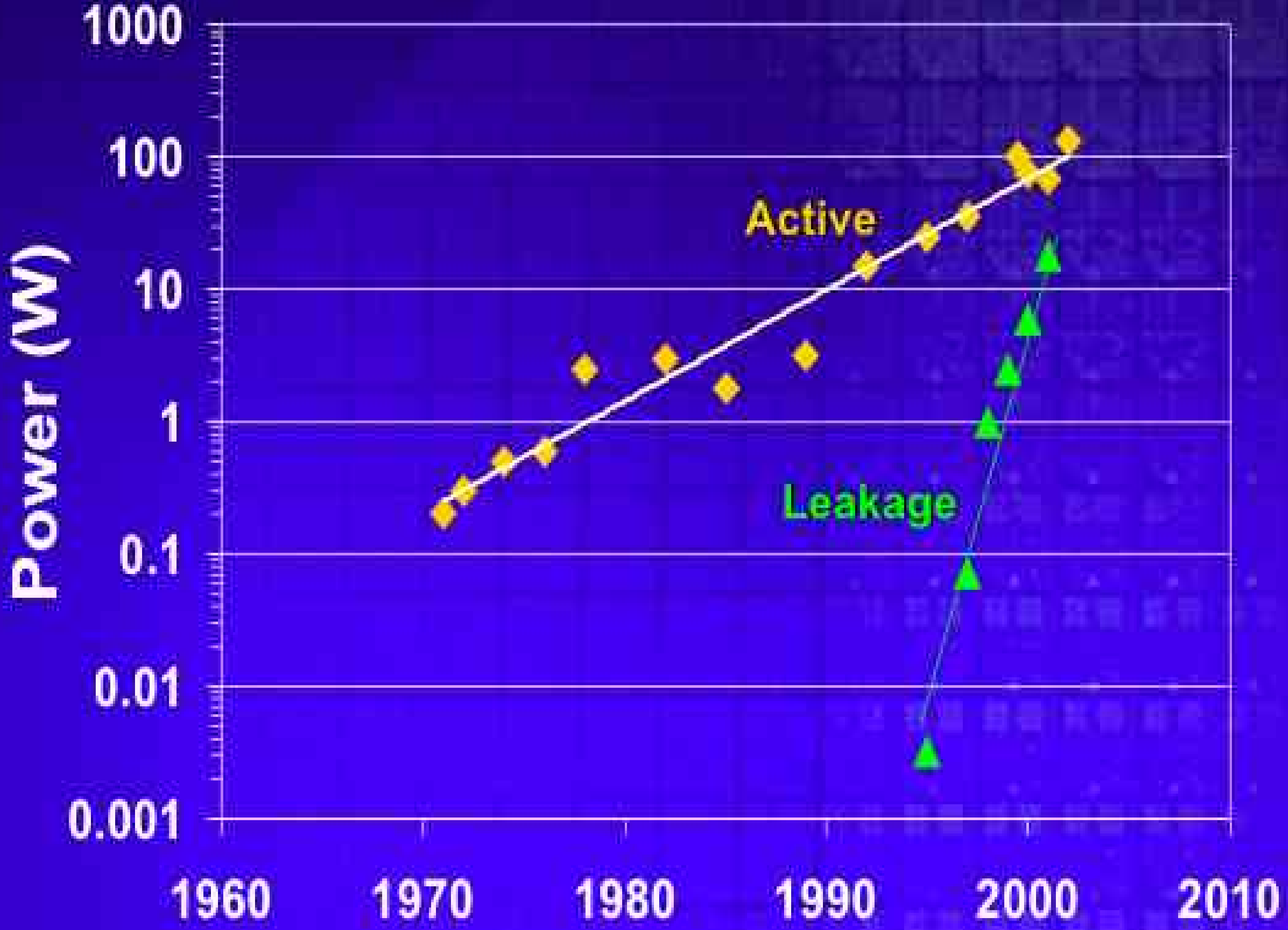
Power Density Will Get Even Worse



Need to Keep the Junctions Cool

- Performance (Higher Frequency)
- Lower leakage (Exponential)
- Better reliability (Exponential)

Processor Power (Watts) - Active & Leakage



New Materials, Devices Extend Si Scaling

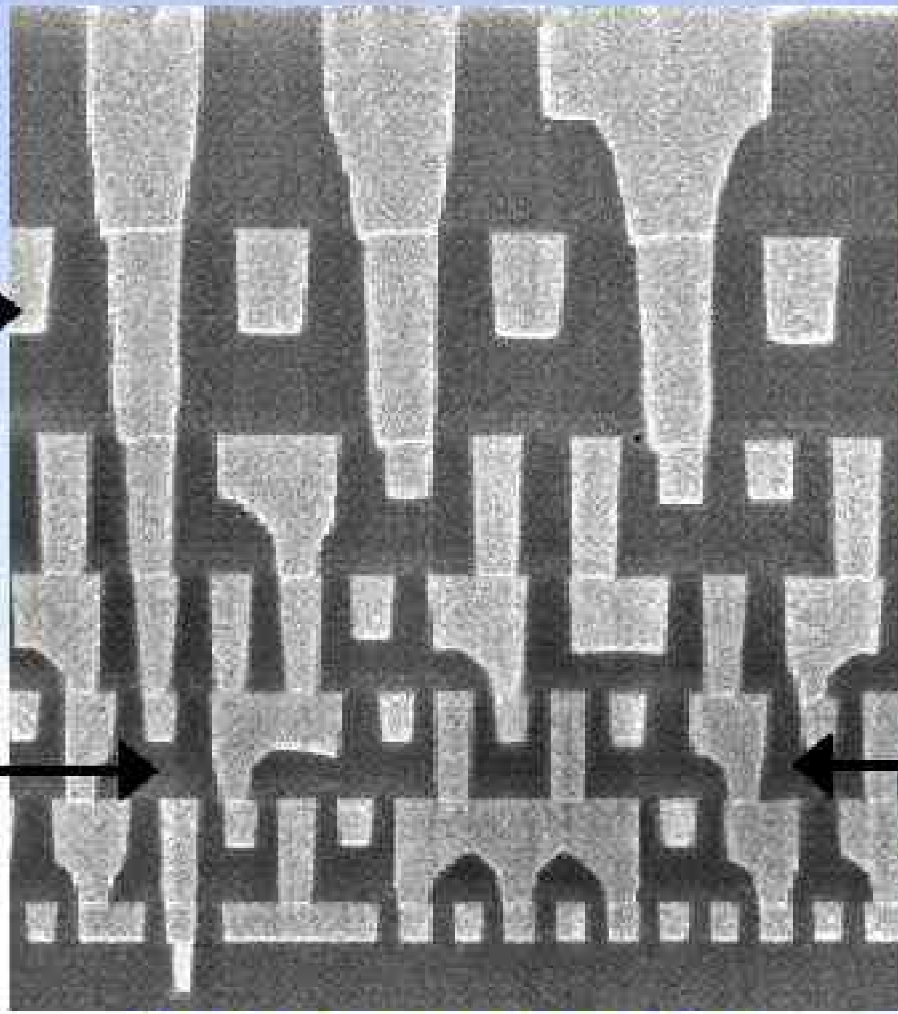
Changes Made

Metal lines

Al → Cu

Insulating dielectric

SiO_2 → SiOF → CDO (low-k)



Future Options

Ultra Low-k Dielectric

Interconnects

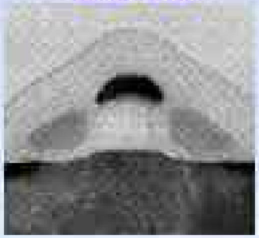
Source: Intel

Intel Nano Transistors

90nm Node
2003

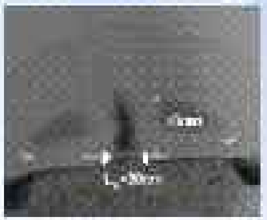
50nm Length
(IEDM2002)

65nm Node
2005



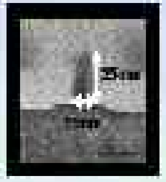
30nm Prototype
(IEDM2000)

45nm Node
2007



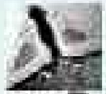
20nm Prototype
(VLSI2001)

32nm Node
2009



15nm Prototype
(IEDM2001)

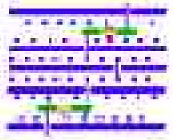
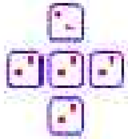
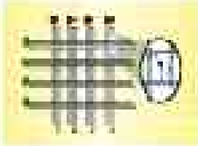
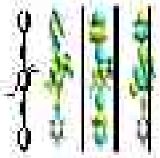
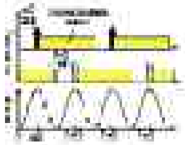
22nm Node
2011



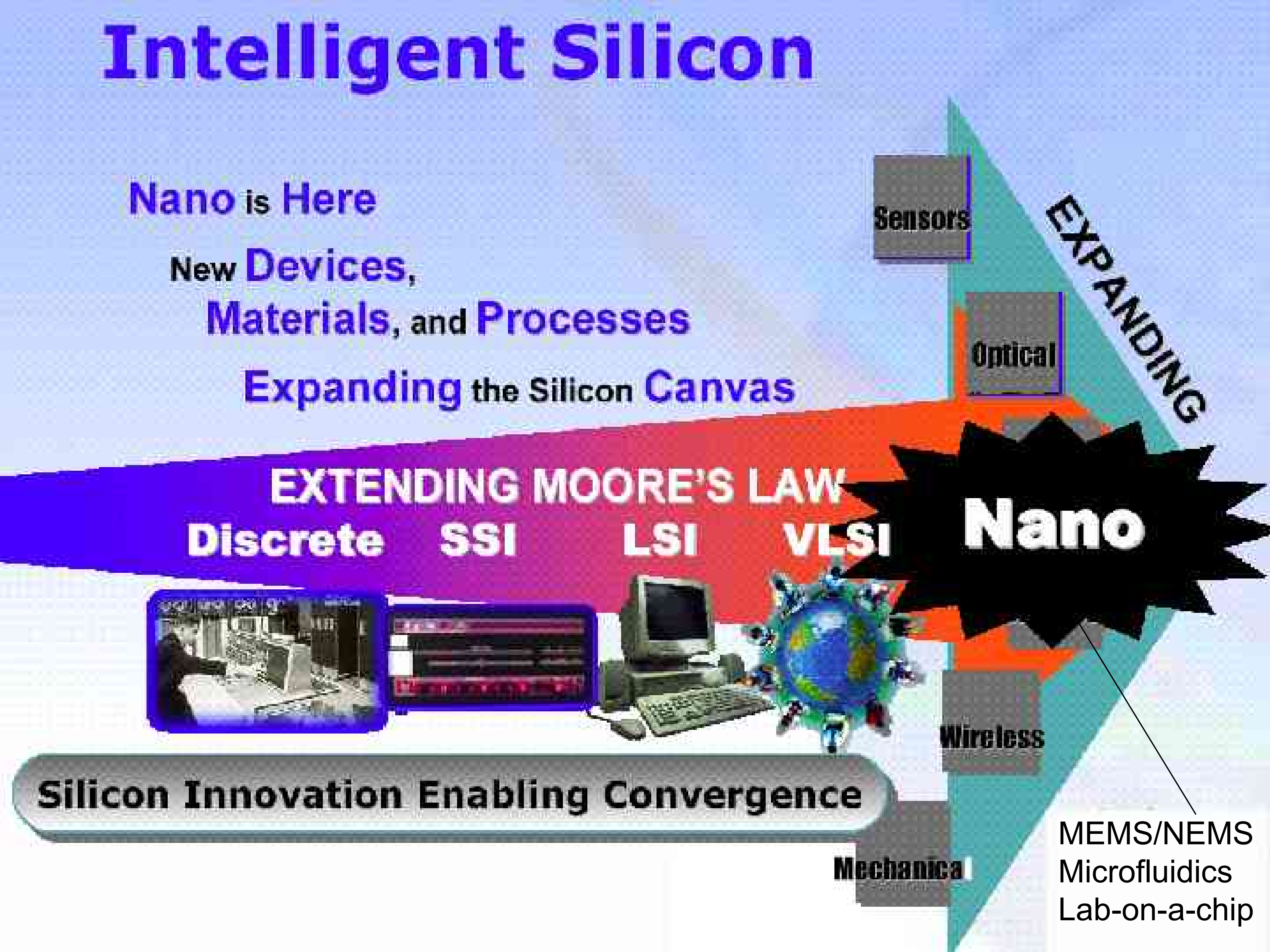
10nm Prototype
(ITJ 2002)

Increasing leakage

Emerging Research Architectures

Architecture	3-D Integration	Quantum Cellular Automata	Defect Tolerant Architecture	Molecular Architecture	Cellular Nonlinear Networks	Quantum Computing
						
Device Implementation	CMOS with dissimilar material systems	Arrays of quantum dots	Intelligently assembles nanodevices	Molecular switches and memories	Single electron array architectures	Spin resonance transistors, NMR devices, Single flux quantum devices
Advantages	Less interconnect delay. Enables mixed technology solutions	High functional density. No interconnects in signal path	Supports hardware with defect densities >50%	Supports memory based computing	Enables utilization of single electron devices at room temperature	Exponential performance scaling, Enables unbreakable cryptography
Challenges	Heat removal, No design tools, Difficult test and measurement	Limited fan out, Dimensional control (low temperature operation), Sensitive to background charge	Requires pre-computing test	Limited functionality	Subject to background noise, Tight tolerances	Extreme application limitation, Extreme technology
Maturity	Demonstration	Demonstration	Demonstration	Concept	Demonstration	Concept

~2009? ← 2015++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MEMS/NEMS
Microfluidics
Lab-on-a-chip

Microfabricated Chemical Measurement Systems

- Lab-on-a-Chip
  - Microfabricated fluidic circuits for chemical analysis
- Nanofluidics
- Micro Ion Trap Mass Spectrometry
- Micro Ion Mobility Spectrometry

Lab-on-a-Chip: Objectives

- Integrate multiple steps of a measurement or synthesis protocol into a microfabricated fluidic device
- Utilize existing laboratory principles taking advantage of scaling where possible
- Design devices that can be mass produced

Lab-on-a-Chip: Benefits

- Automation
- Reagent consumption reduced 10^4 - 10^6
- Speed - 10^2
- High quality data
- Scale up at low cost
- Inexpensive/disposable devices (chips)
- Standardized platforms
- CAD/A - Rapid prototyping

Applications

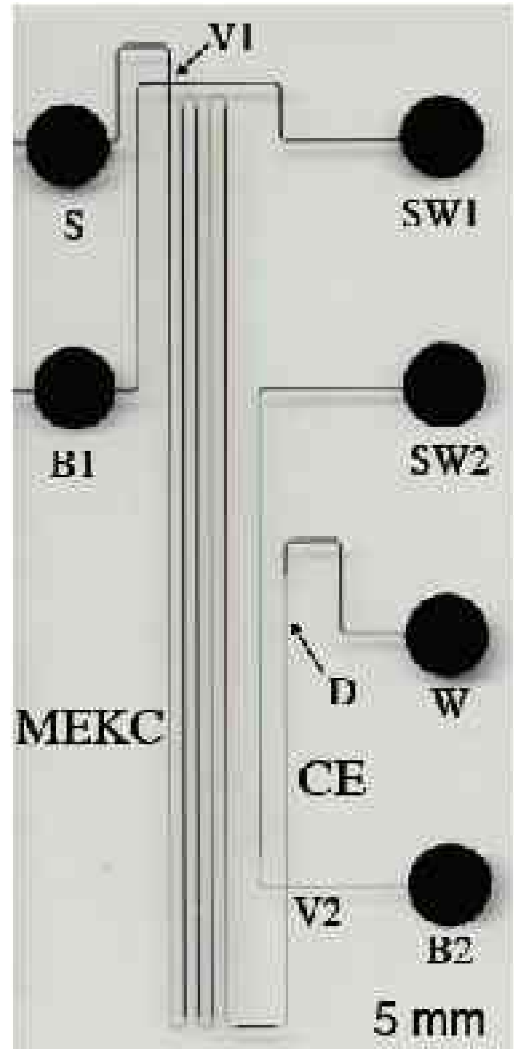
- In-situ Measurements
  - Process Control
  - Environmental Monitoring
- Field Analysis
  - Environmental Monitoring
  - Forensics
- Medical Diagnostics
  - Point-of-Care
  - Emergency Care
  - Closed-Loop Monitoring/Dosing
- High-throughput Laboratory Analysis
  - Combinatorial Discovery
  - DNA Sequencing
  - Proteomics

Synthesis Applications

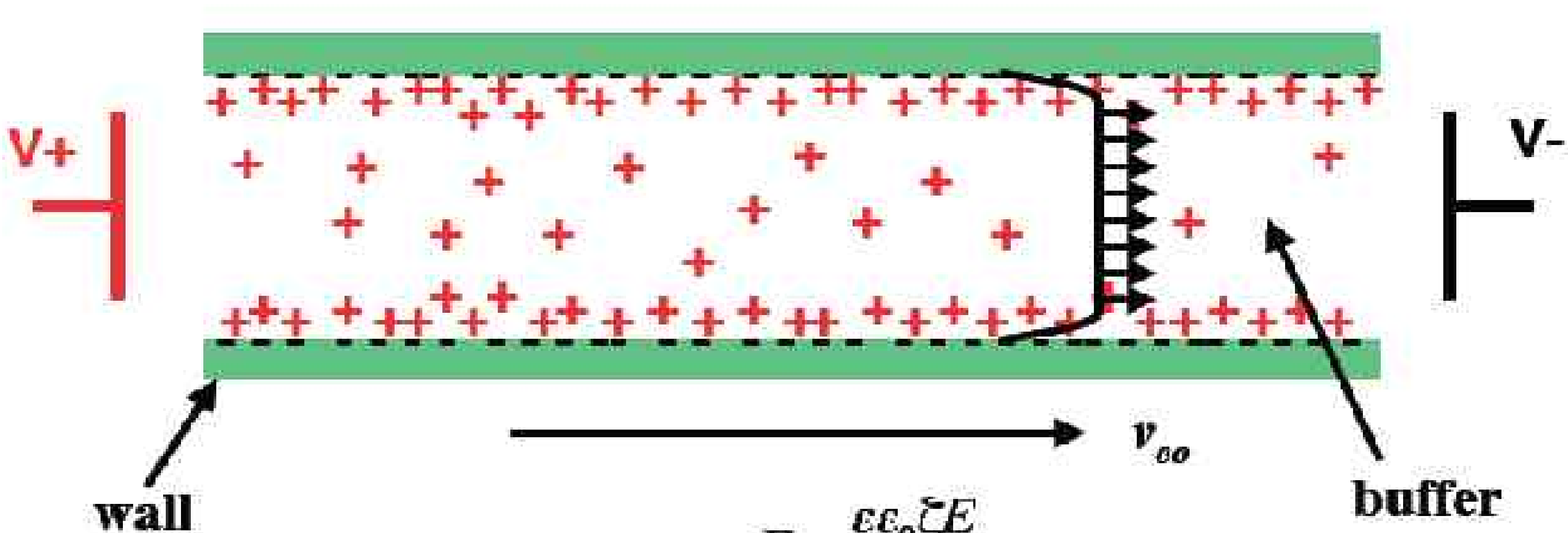
- Materials Discovery
  - Vaccines
  - Coatings
  - Electronics
- Just in time production
  - Hazardous materials
- Production development/optimization
  - Pharmaceuticals
  - Materials

Microfluidic Devices

- Materials
  - Silica (and other silicon related)
  - Plastics (polymers)
- Dimensions (channels)
  - 20-100 µm wide
  - 0.05-30 µm deep
  - 1-20 cm^2 substrates
- Volumes
  - 1 fL - 1 nL manipulations
  - 1-100 µL reservoirs
- Fluid transport
  - electrokinetic
  - pressure
  - surface tension



Electrokinetic Transport



$$v_{eo} = \mu_{eo} E = \frac{\varepsilon \varepsilon_0 \zeta E}{4\pi\eta}$$

eo: electroosmosis

$$v_{ep} = \mu_{ep} E = \frac{ezE}{6\pi\eta r}$$

ep: electrophoresis

$$v_{eff} = \mu_{eff} E = \left(\mu_{eo} + \mu_{ep}\right) E$$

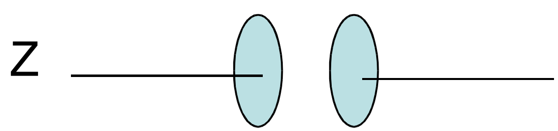
η: viscosity

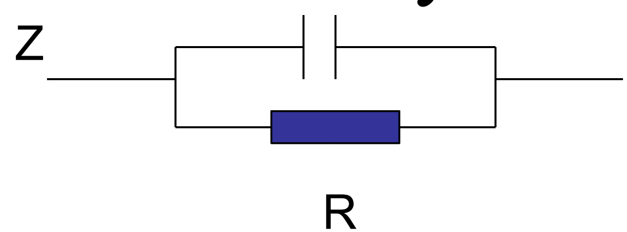
Electrokinetic Forces

Force	AC or DC	Origin (Force)
Electrophoresis	DC	Caused by charge in E-field (**QE**)
Dielectrophoresis (DEP)	AC/DC	Caused by induced dipole in field gradient (**Qd. ∇E**)
Electro-osmosis	AC/DC	Caused by interaction between double layer charges and tangential E-field
Electrorotation	AC	Caused by dipole lag in rotating E-field (Torque=Dd X E)
Traveling wave DEP	AC	Caused by dipole lag in traveling E-field
Electro-orientation	AC/DC	Caused by interaction between dipole and electric field

Polarization, Relaxation and Dispersion

- $Z^{-1}=R^{-1}+X_c$ Resistance: $R=d/\sigma A$
- Reactance: $X_c= 1/\omega C$
- $C=\varepsilon^{*}A/d$
- $\varepsilon^{*}=\varepsilon_0\varepsilon_r-j\sigma/\omega$ ↗ Includes both dielectric and conductivity effects





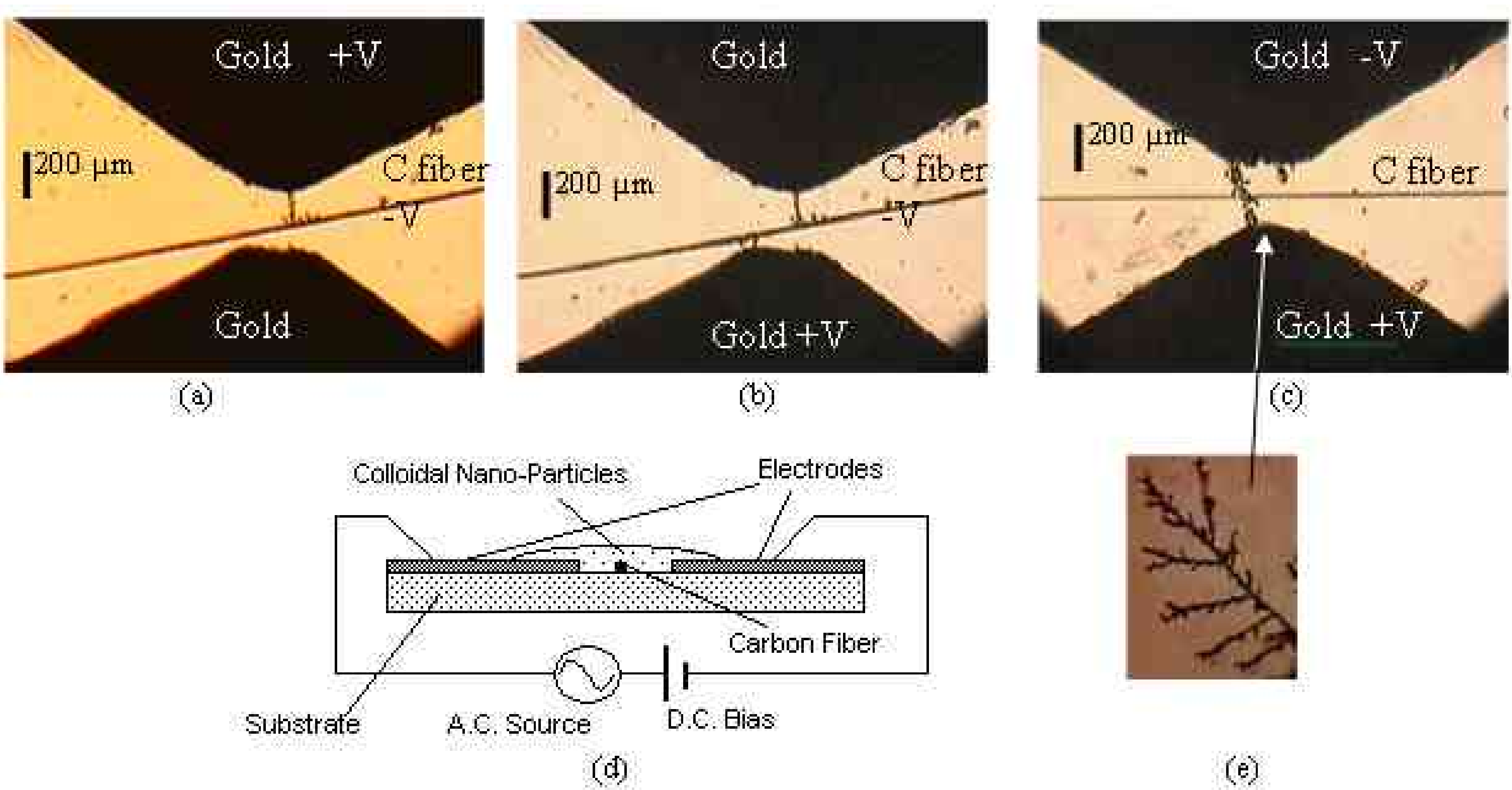
ω ↙0 σ dominates, ω ↙8 ε_r dominates in between there is a transition↙ dispersion

Dispersions

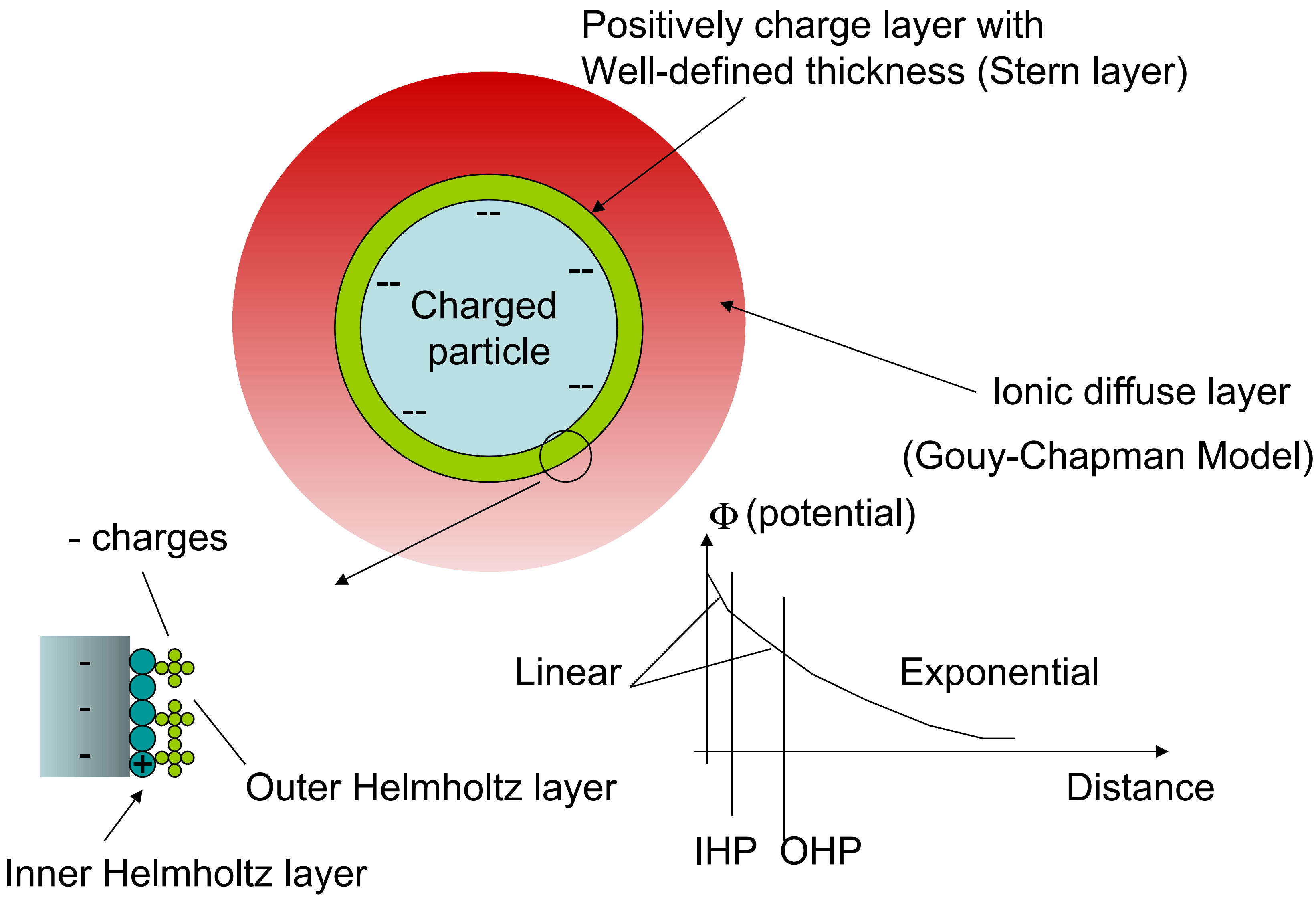
- Internal dispersion:
  - Debye relaxation
- Dispersion at the interface between two different materials:
  - Maxwell-Wagner relaxation

- These and other dispersions results in frequency dependence of forces on nano-particles

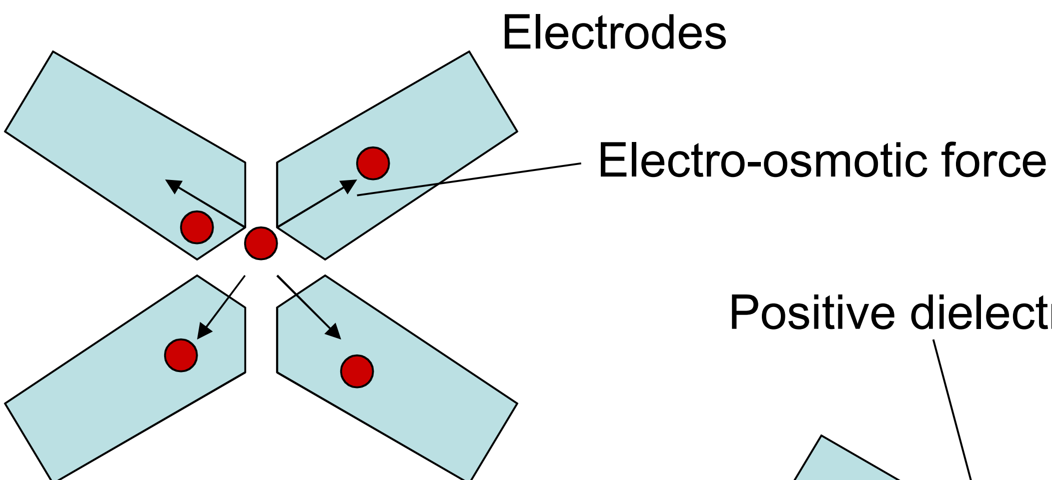
Dielectrophoresis/Electrophoresis

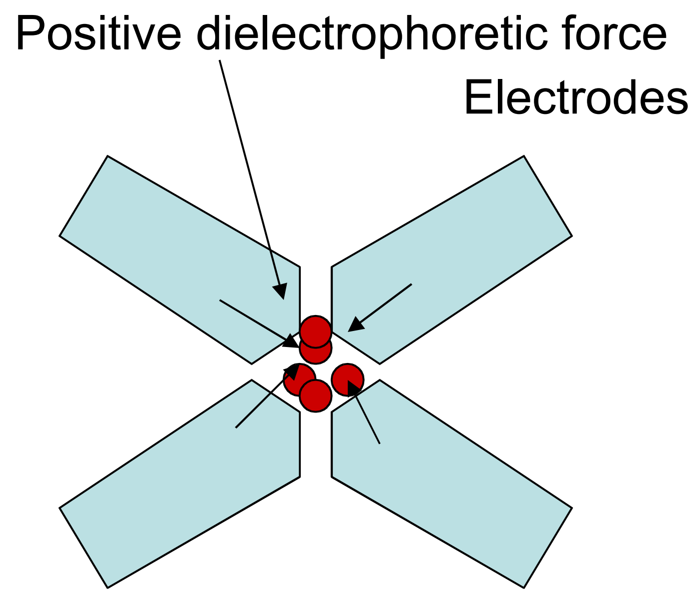


Electric Double Layer



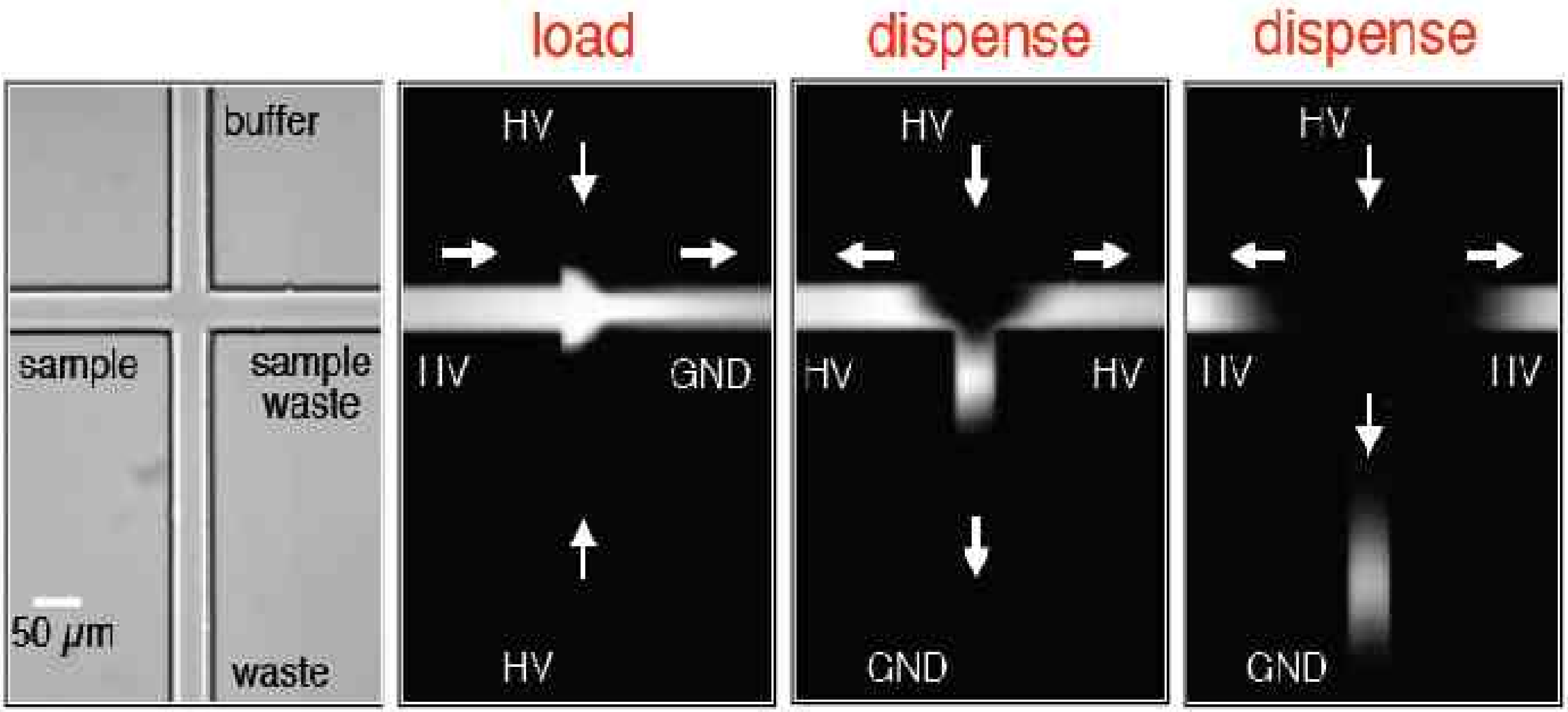
- Negative dielectrophoresis
- Positive dielectrophoresis
- Brownian motion, dielectrophoretic, and electro-osmotic balance





Negative dielectrophoretic force arises when ε_{real} becomes negative

Constant Volume (Pinched Valve)



Anal. Chem. 66, 1107 (1994)

Functional Elements

I/O
- pipette
- inkjet
- electrospray

filters
- physical
- polymeric
- SPE

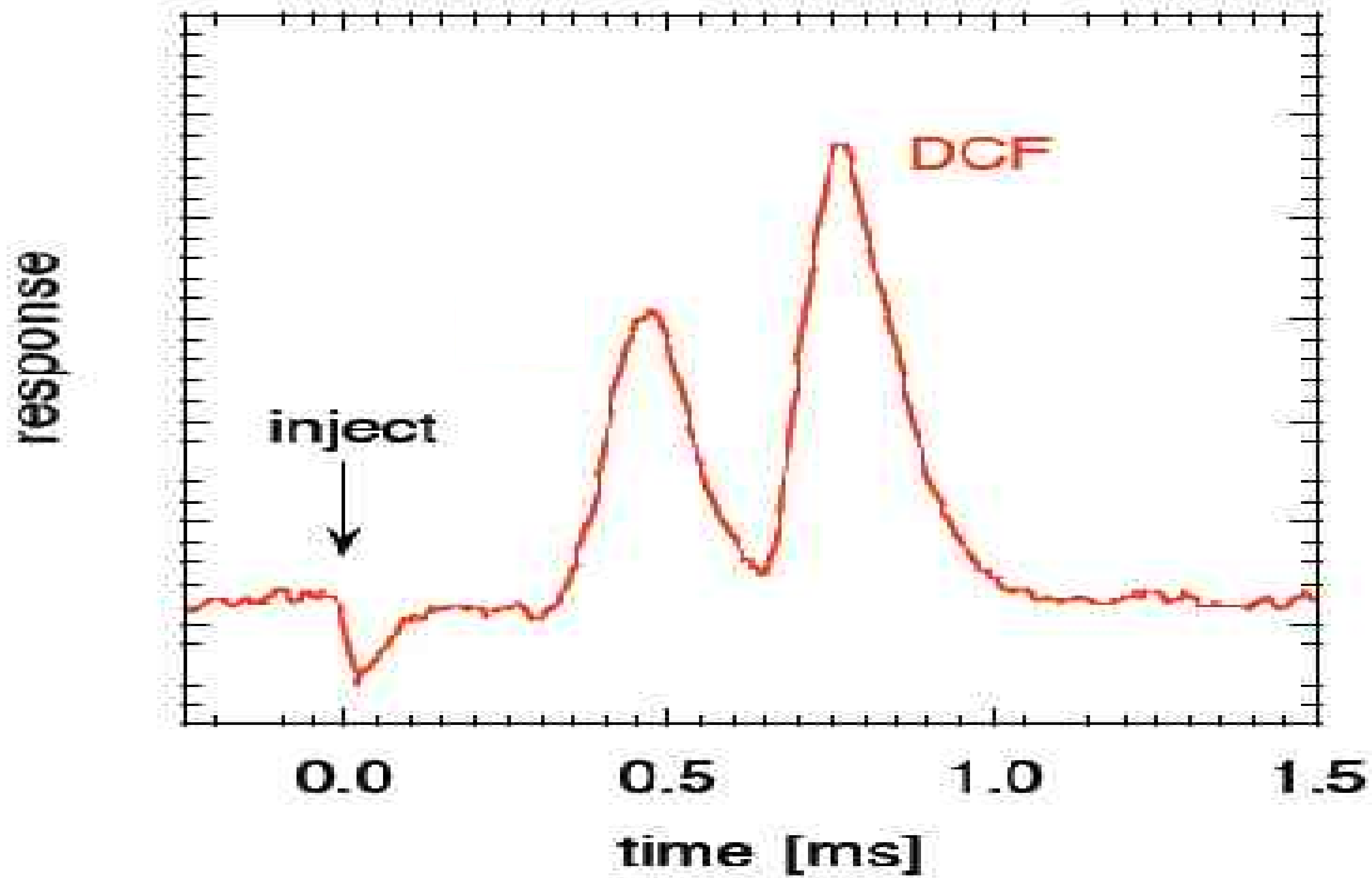
reactions
- stopped flow
- continuous flow
- thermal cycling

separations
- electrophoretic
- chromatographic
- sizing
- heterogeneous

cytometry
- immunoassay
- staining
- cell sorting

detection
- fluorescence
- absorbance
- refractive index
- scattering
- electrochemical
- MS

Sub-Milisecond Electrophoresis

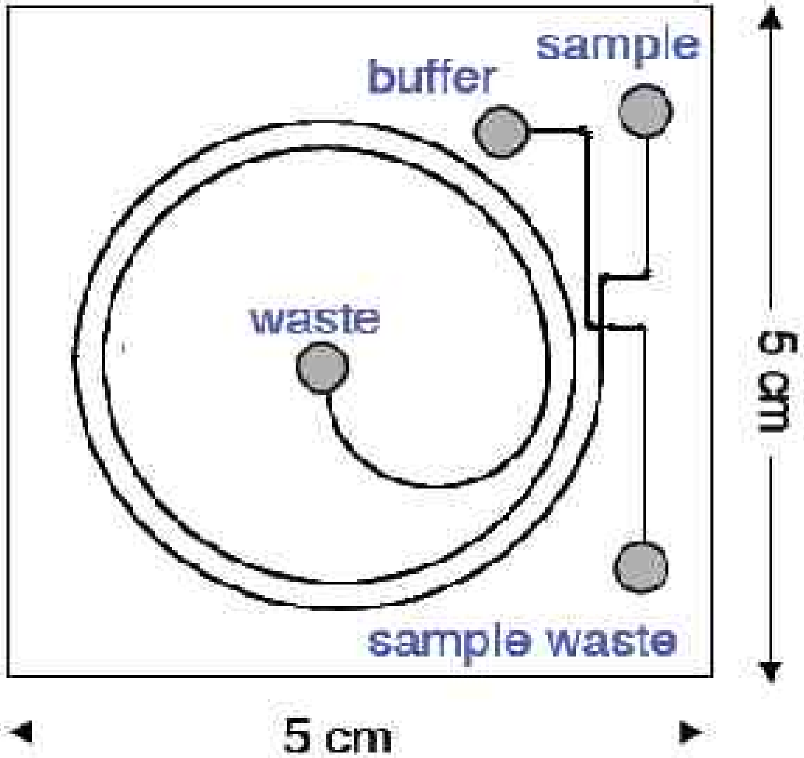


L_{sep} = 200 μm

E_{sep} = 53 kV/cm

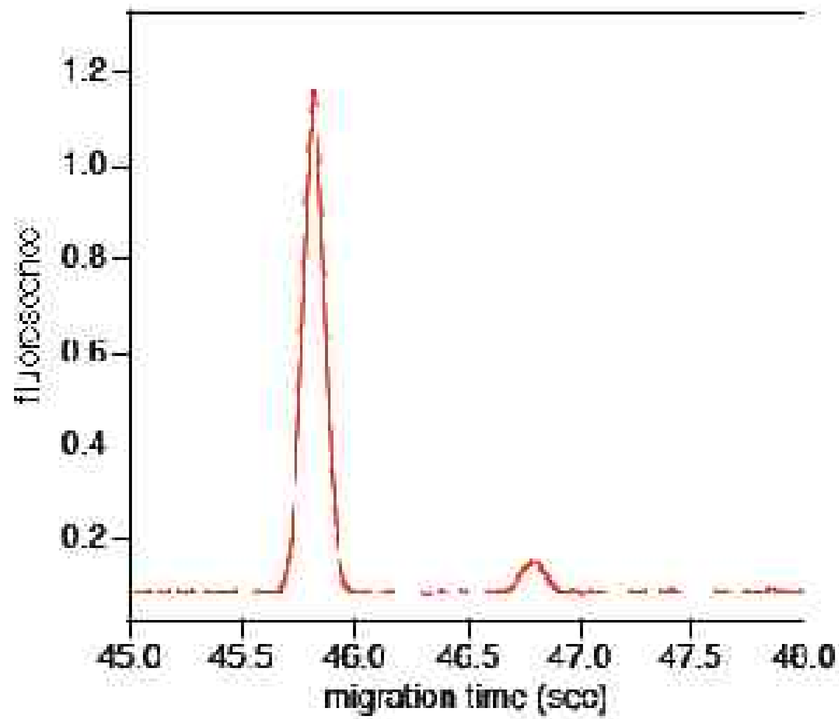
Anal. Chem., 70, 3476 (1998)

Very High Efficiency Separation



L = 25 cm

Anal. Chem., 72, 5814 (2000)



Dichlorofluorescein
N = 1,100,000
L_D = 22.2 cm
E_{sep} = 1360 V/cm
Buffer: 20 mM Boric Acid
/100 mM TRIS (pH 9.2)

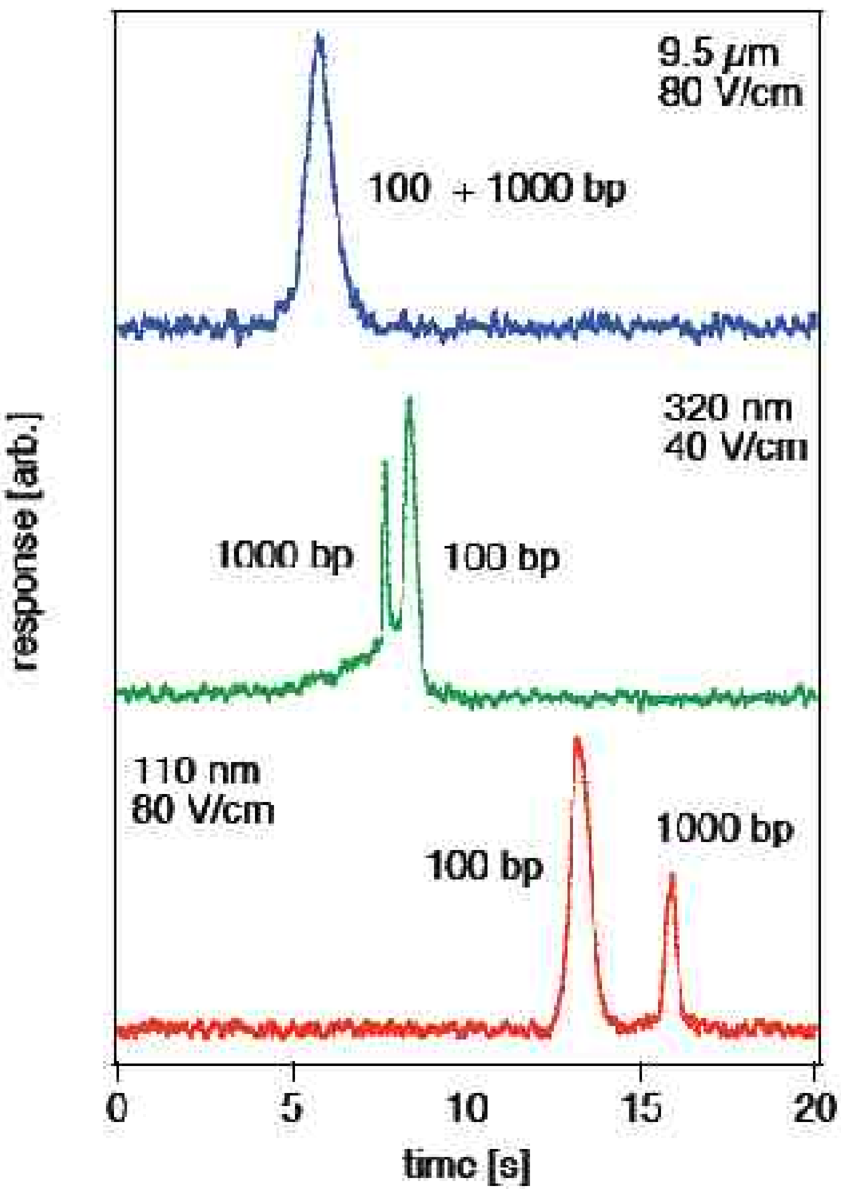
Electrokinetically Actuated Segmented Flow

Field Free
Pumping
of
Segmented
Flow

Nanofluidics will be Enabling

- Emulation and interface to biological systems
  - Artificial cells
    - Biological and chemical sensing
- Molecular characterization
  - Molecular counting
  - DNA sequencing
  - Protein and peptide sizing
- Fabrication (synthesis) of single molecules
  - Heterogeneous polymers
  - Complexes with controlled substitution
- Hardened (self-repairing) electronics
  - Fluidic-based molecular electronic gates
  - Molecular-based memories

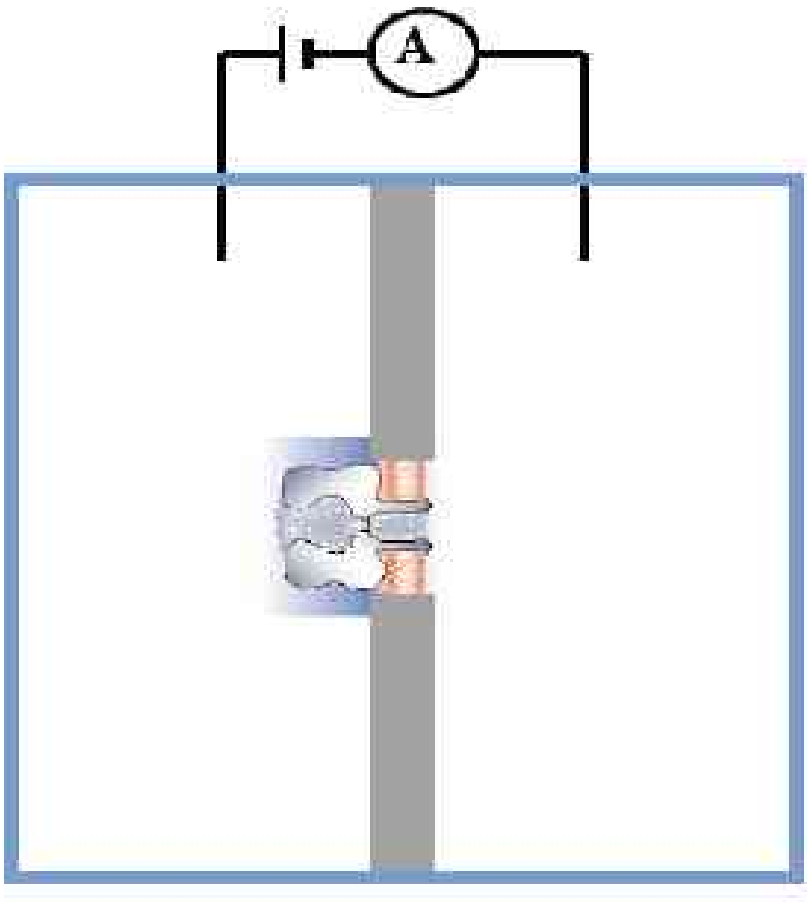
Electro Hydrodynamic Separation of DNA



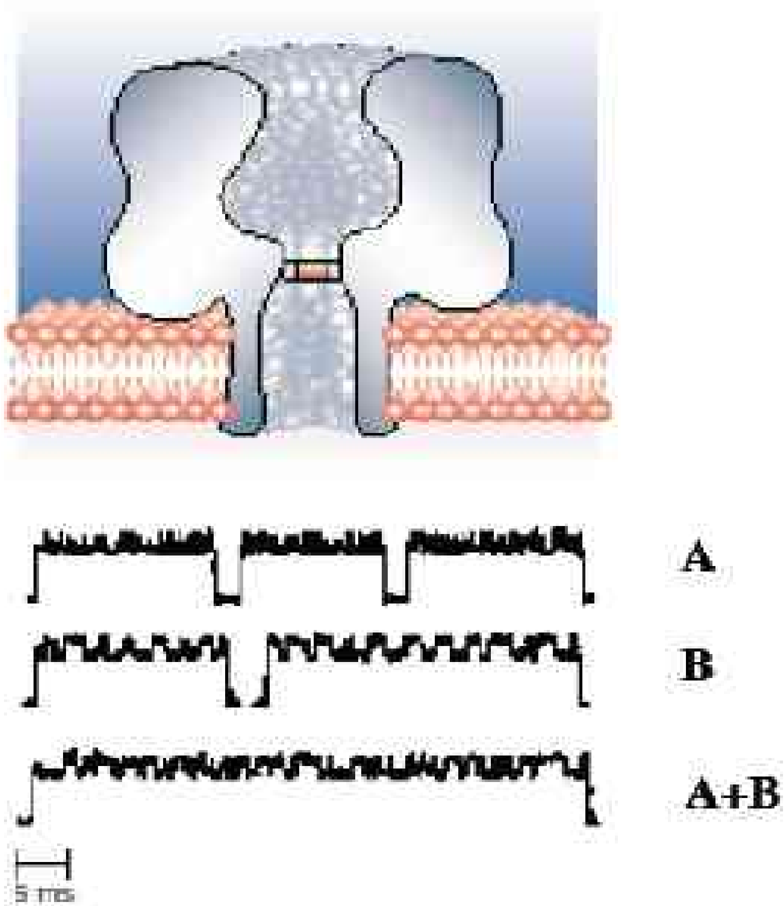
radius of gyration
25 nm (100 bp)
75 nm (1000 bp)

$R_g \approx h$

Stochastic Chemical Sensing with Ligand Gated Ion Channels

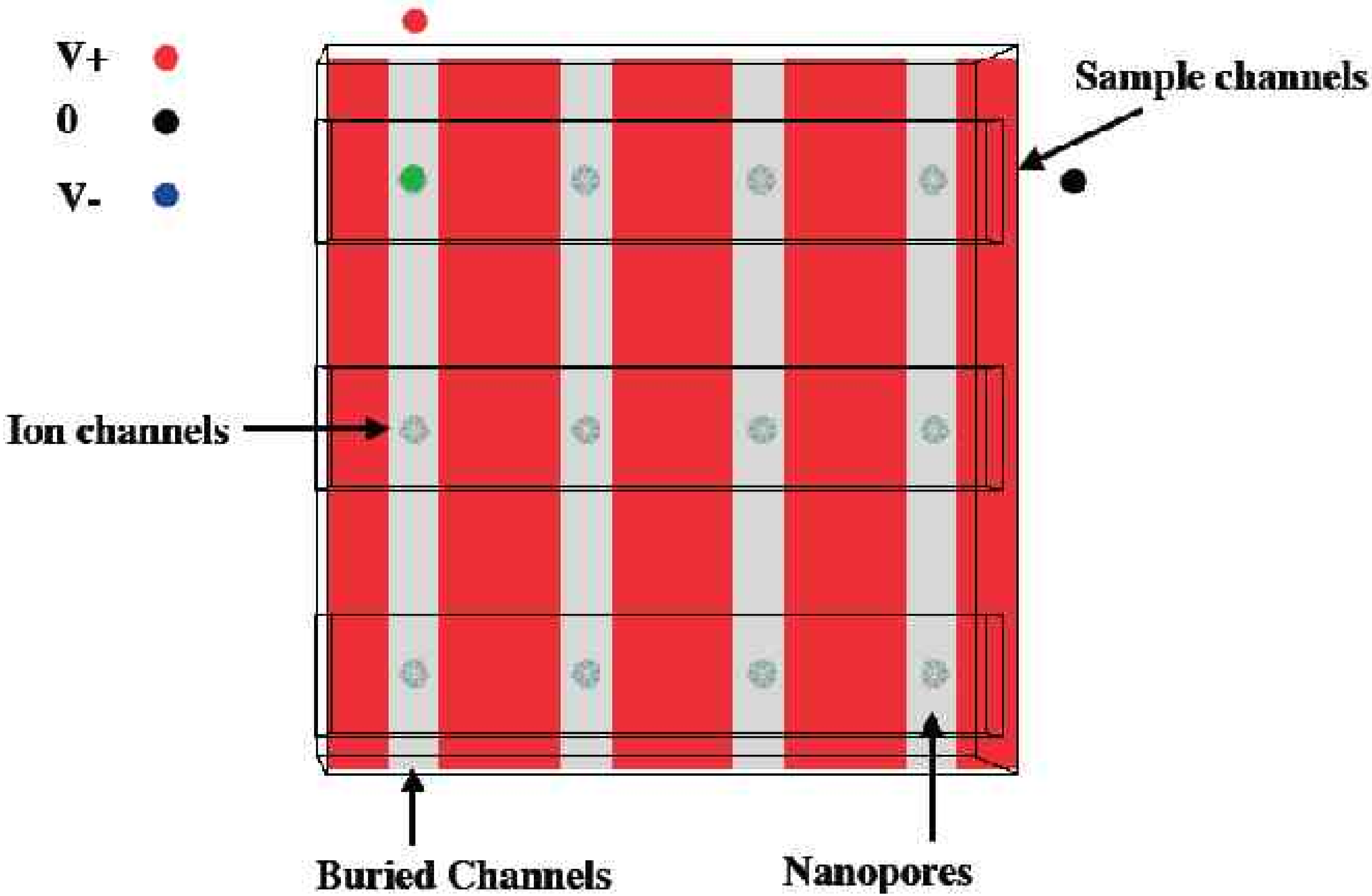


Planar Lipid Bilayer Apparatus



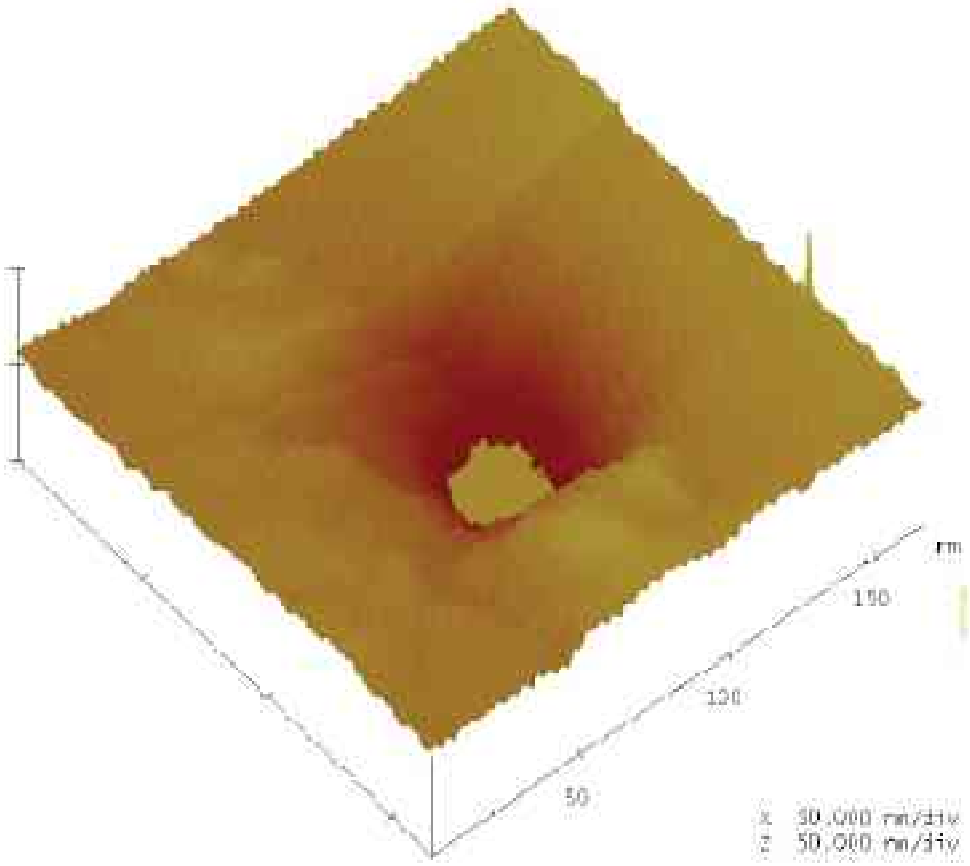
H. Bayley, P. S. Cremer, Nature, 413, 226 (2001).

Addressable Ion Channel Arrays

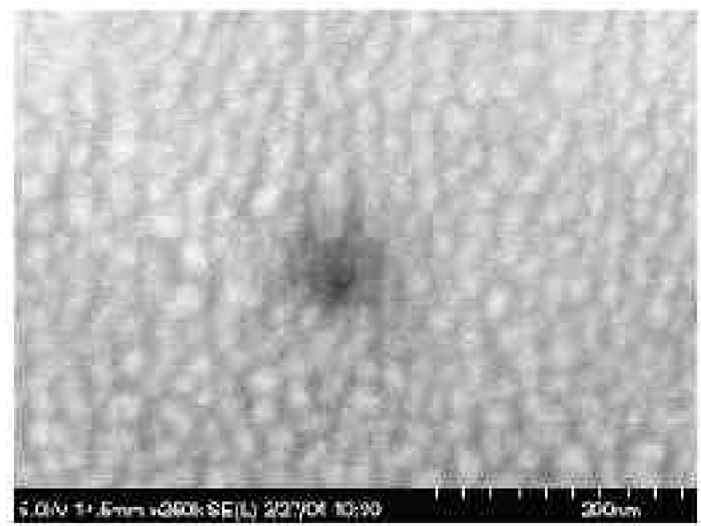


FIB Milled Nanochannels in SiO2 Membranes

- 40-nm thick SiO_2 membrane
- 500 µS FIB dwell time, 70 pA
- AFM tip: r = 40 nm; $\theta_{1/2}$=35
- Estimated diameter ≈ 50 nm



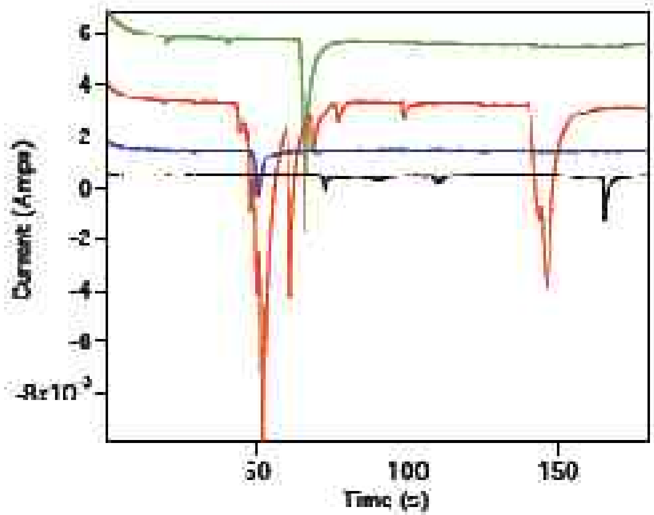
AFM Image



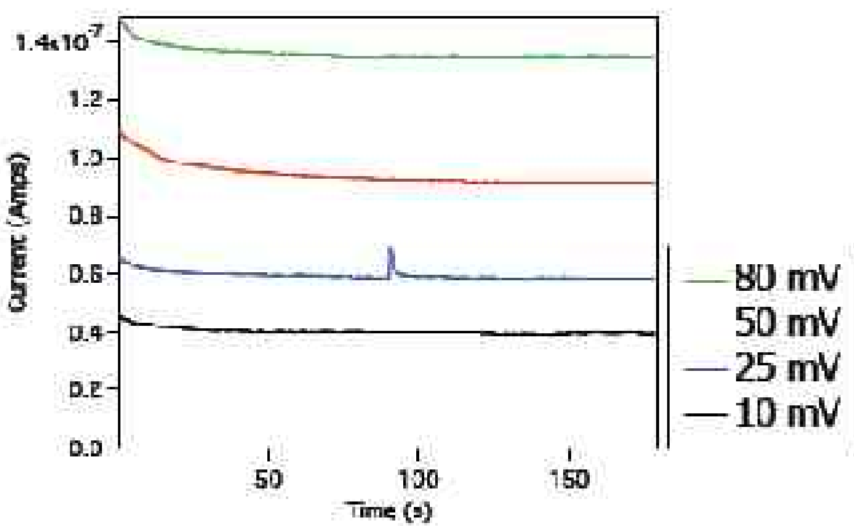
SEM Image

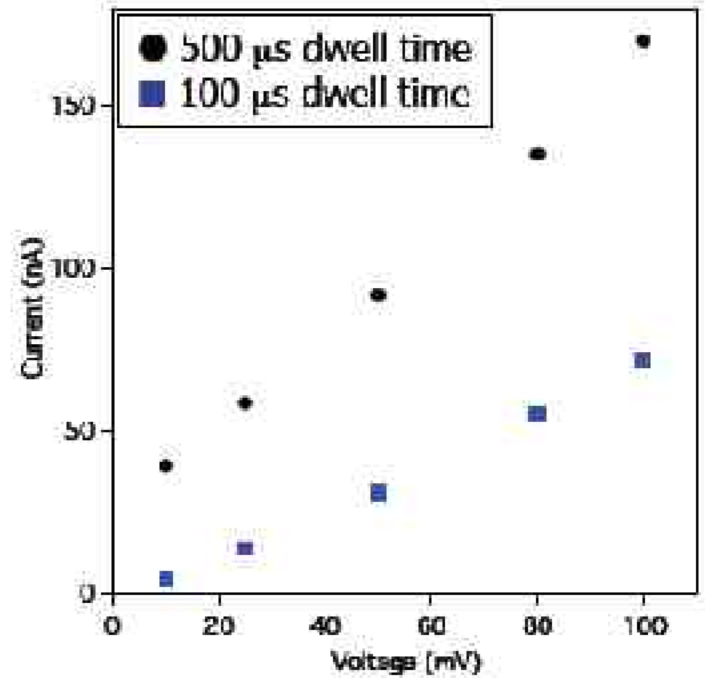
Conductance Measurements

100 µS dwell time



500 µS dwell time





Electrolyte: 1 M KCl