From Hubert's Museum to Science at Small Scales

Stephan von Molnár

MARTECH – Florida State University

Nanoscience and Quantum Computing Teachers' Conference

UC Santa Barbara, March 25, 2006

Collaborators

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Jim Zheng (ECE, FSU/FAMU)

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DARPA BioMotors Program

NSF NIRT

FSU Research Foundation

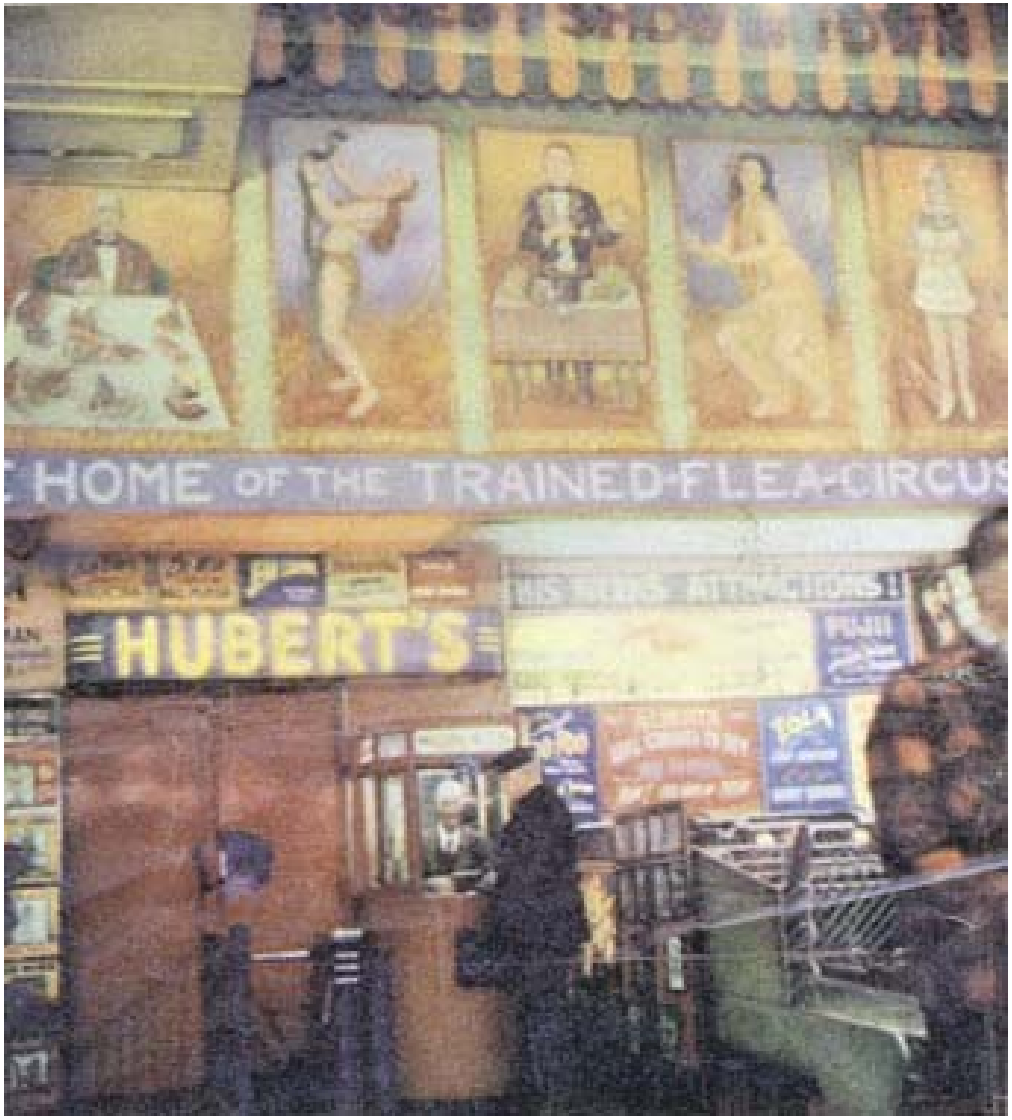
Outline

I. Background and Introduction

II. Magnetic Sensors

III. Electric Sensors

IV. Patterning and Controlled Activation of Biomotors



NY City, circa 1947

Lord's Prayer on the head of a pin

Physics At Small Scales

Can we put a physics book on the ***head of a pin***?

An encyclopedia?

- ***Book:*** 10" × 10" X **1000 pages =** 10^5 □" **≡ Area of all pages**

- ***Head of Pin:*** $D = \frac{1}{16}"$ $\quad A = \pi \frac{D^2}{4} = \frac{3.14}{4} \times \frac{1}{16} \times \frac{1}{16} \approx 3 \times 10^{-3}$ □"

$$\therefore \frac{10^8}{3} \approx 3 \times 10^7 \approx 30 \times 10^6$$

Increase Linear Dimension by ~ **5.5×10^3**

- ***Encyclopedia Britannica:***

$$25 \text{ volumes} \equiv \frac{25 \times 10^5 \;\square"}{3 \times 10^{-3} \;\square"} \quad \mathbf{\sim 8 \times 10^8}$$

or ~ **3×10^4** magnification in linear dimension

Resolving Power of Eye ~ $\frac{1}{120}''$

To put E.B. on the pin, demagnify by 3 x 10⁴

$$\therefore \frac{1}{120}'' \times 2.54\frac{cm}{''} \times \frac{1}{3\times10^4} \sim$$ **70 – 80 Å**

Å = 10^{-8} cm

$$\approx \frac{75}{3} \approx$$ **25 atoms across**

diameter of atom

Thus **A ~ 625 Atoms**

Plenty of information if we were able to manipulate atoms !!!

Units

- **1 μm** = 1 micrometer = 10^{-6} meters
- **1 nm** = 1 nanometer = 10^{-9} meters
- **1 Å** = 1 Angstrom = 10^{-10} meters

- 10^3 = 1,000 (thousand) ≡ KILO
- 10^6 = 1,000,000 (million) ≡ MEGA
- 10^9 = 1,000,000,000(billion) ≡ GIGA
- 10^{12} = 1,000,000,000,000 ≡ TERA

RICHARD P. FEYNMAN

"There's Plenty of Room at the Bottom"
APS Meeting, December 26, 1959

Reprinted in: Journal of Microelectromechanical Systems 1, #1, 60 (1992)

Feynman goes on…

What about all the written knowledge in the world?

***As of 1959*:**	**~ 9 M volumes**	**/**	**Library of Congress**
	~ 5 M "	**/**	**British Museum Library**
	~ 5 M "	**/**	**National Library of France**

~ 25 M volumes → 1 M ***pin heads***

1000 *pin heads* × 1000 *pin heads* →

$$\frac{1}{16}'' \times 1000 = 62.5''$$

Thus $\left(\frac{62.5''}{36''}\right)^2 \approx 3$ □ **yds.**

What about volume information storage?

Assume: Each letter requires 6 or 7 bits {some order of dots and dashes}

Each bit ≡ dot or dash of metal (5 × 5 × 5 ~ 100 Atoms)

Estimate # of bits necessary for 25M volumes — ***Feynman*** says 10^{15}

Thus - # of Atoms necessary is 10^{17}

But – density of metal is ~ $10^{22} – 10^{23}$ atoms/cm^3

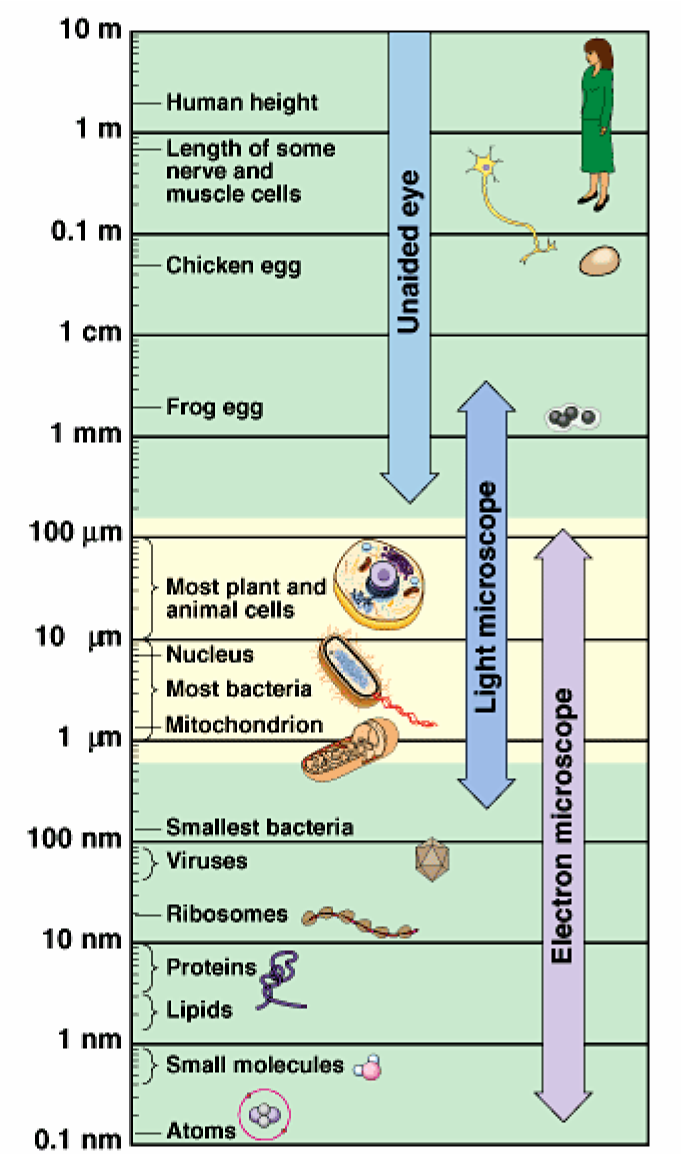
THUS WE ONLY NEED A LITTLE CUBE
$1/100^{th}$ OF A CM ON EACH SIDE ⇒A PIECE OF DUST

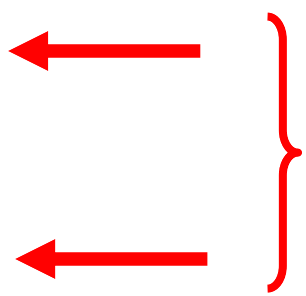
For ***all*** the written knowledge in the world (1959)

⬇

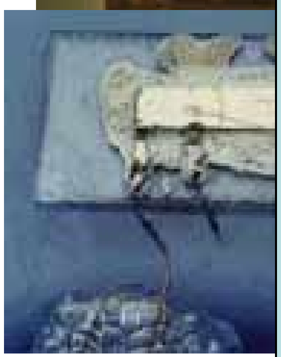
BIOLOGY KNOWS THIS!! Genetic makeup is carried in minute quantities of material

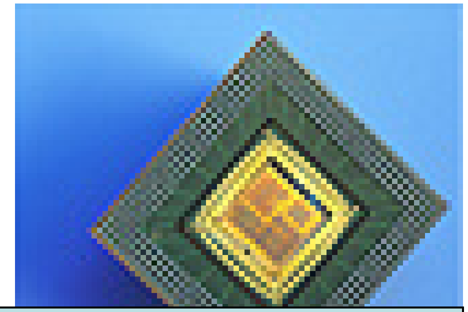
The nano scale

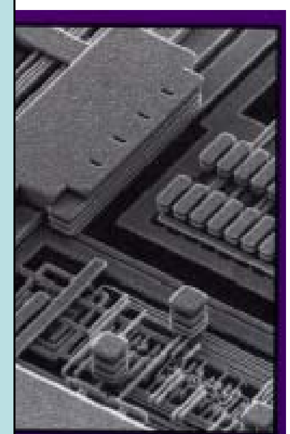




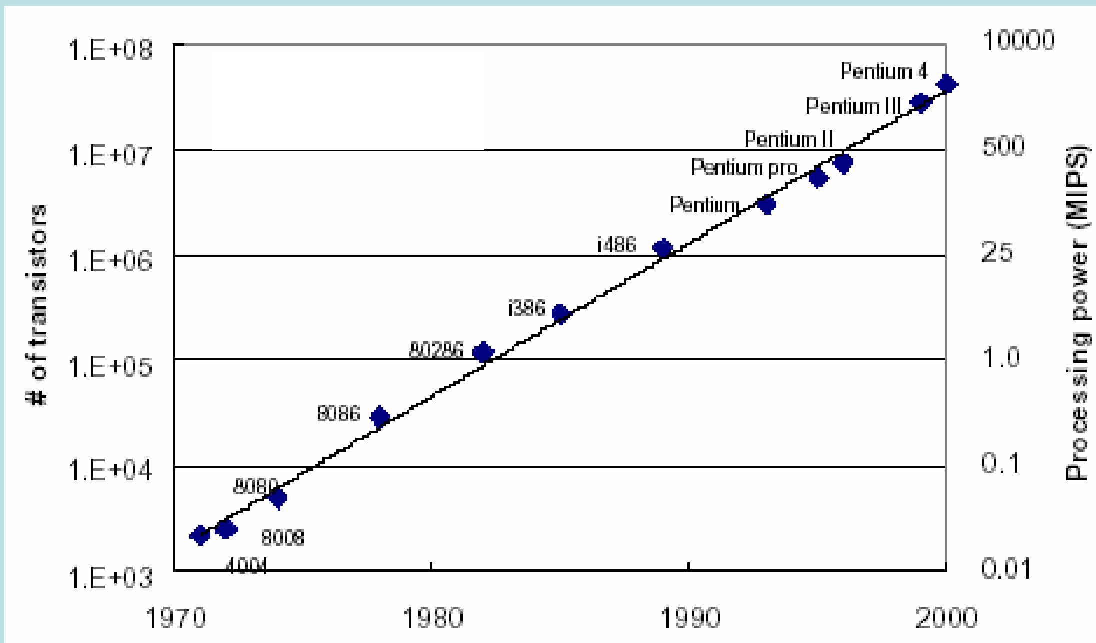
Phenomena in objects with 1-100 nanometers







- Speed:
- Size: 1
- Cost: $

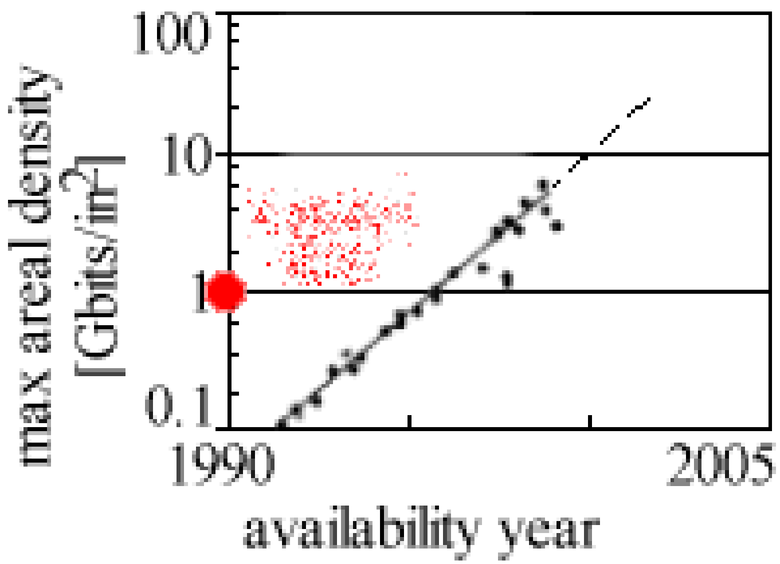


Moore's Law: Power of Miniaturization

ansistor

- Density: 2 kb/in^2
- Speed: 70 kb/s
- Size: ϕ24″ x 50
- Capacity: 5 Mb

- Density: 100 Gb/in^2
- Speed: > 200 Mb/s
- Size: ϕ2.5″ x 2
- Capacity: > 400 Gb



Outline

I. Background and Introduction

II. **Magnetic Sensors**

III. Electric Sensors

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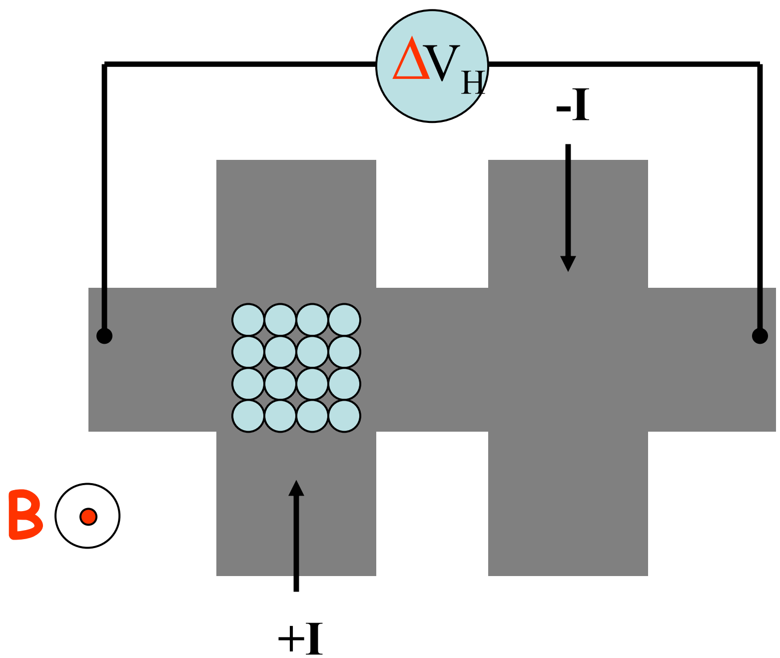
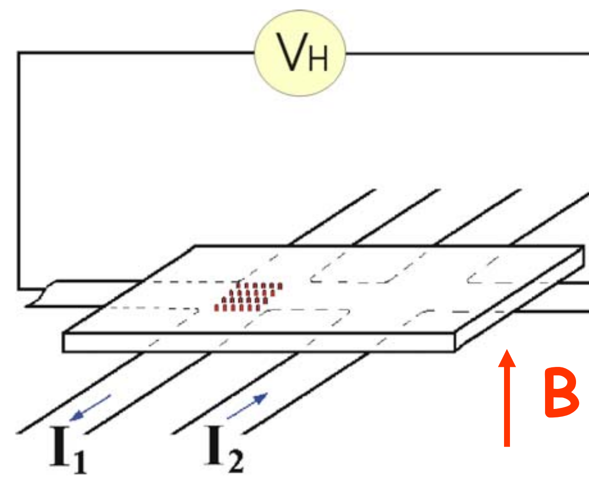
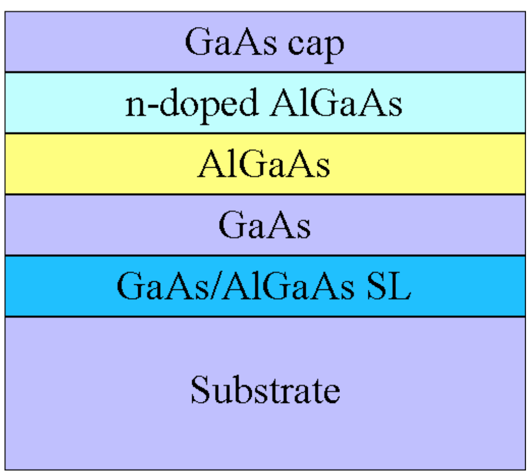
Goran Mihajlovic, Pradeep Manandhar

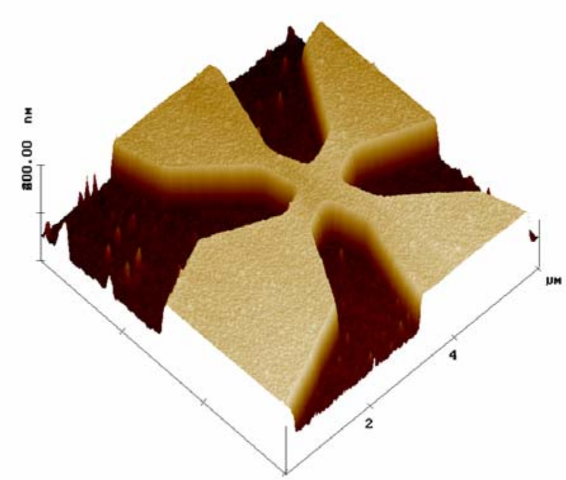
Materials by: Hideo Ohno (Tohoku University)
Gerald Sullivan, Mark Field (Rockwell)

µ-Hall magnetometry: gradiometry

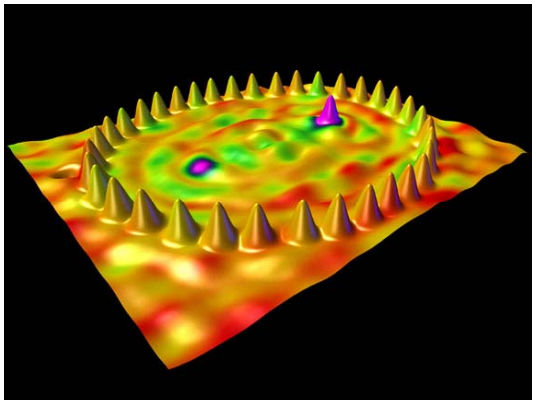








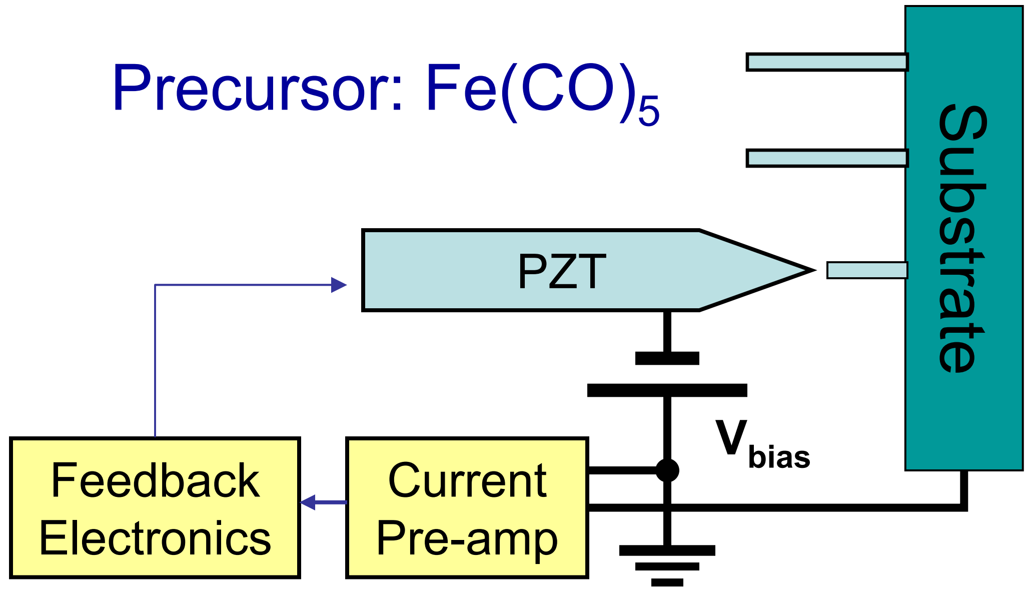
STM and Nanofabrication



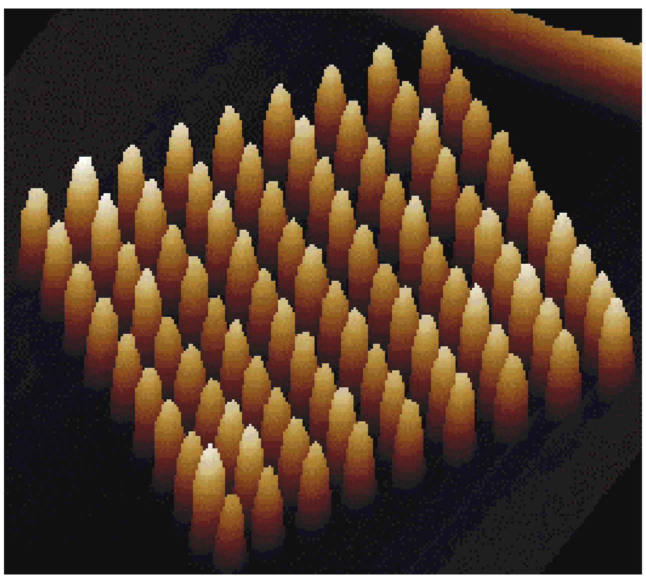
Single atom manipulation,
D. M. Eigler, IBM

STM assisted Chemical Vapor Deposition

Precursor: $Fe(CO)_5$



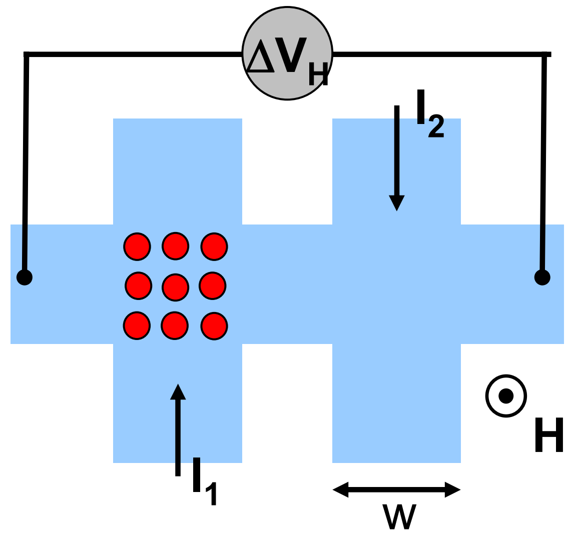
- **McCord and Awschalom, APL, (1990)**
- **Kent, Shaw, von Molnár, and Awschalom, Science, (1993)**

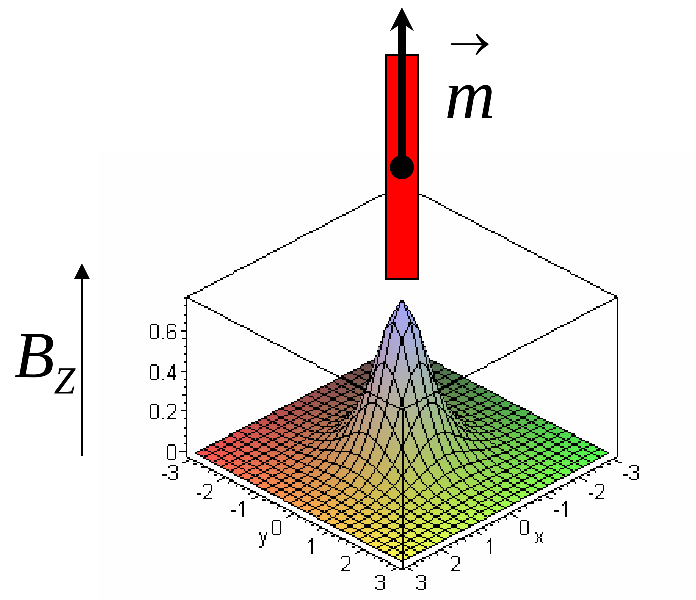


←An array of Fe nanomagnets fabricated with STM
spacing: 300 nm

TEM of STM fabricated Fe fiber

Improve moment sensitivity by miniaturization





moment sensitivity: $m_{min} = C^{-1} \cdot B_{min}$

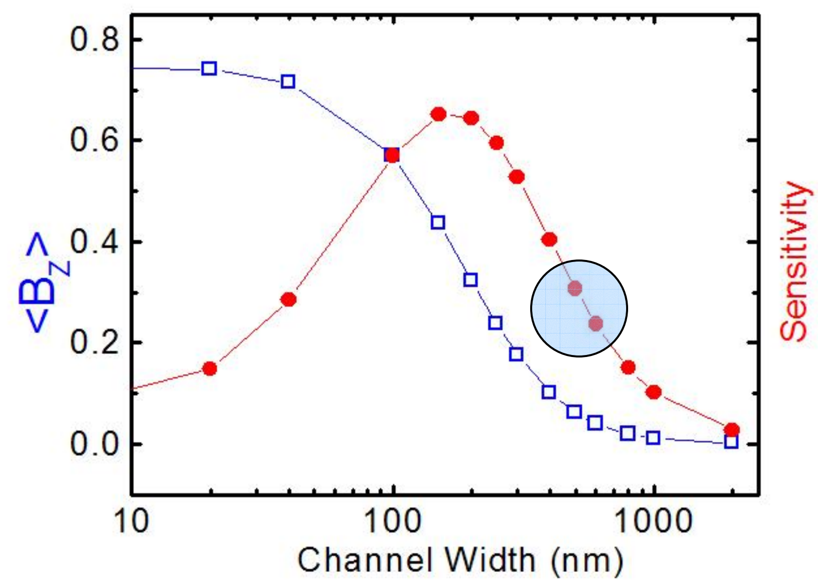
- **field sensitivity:** $B_{min} \propto w^{-1}$
- **coupling coefficient:** $C = \langle B_Z \rangle / m$

$\Rightarrow$ **miniaturization**

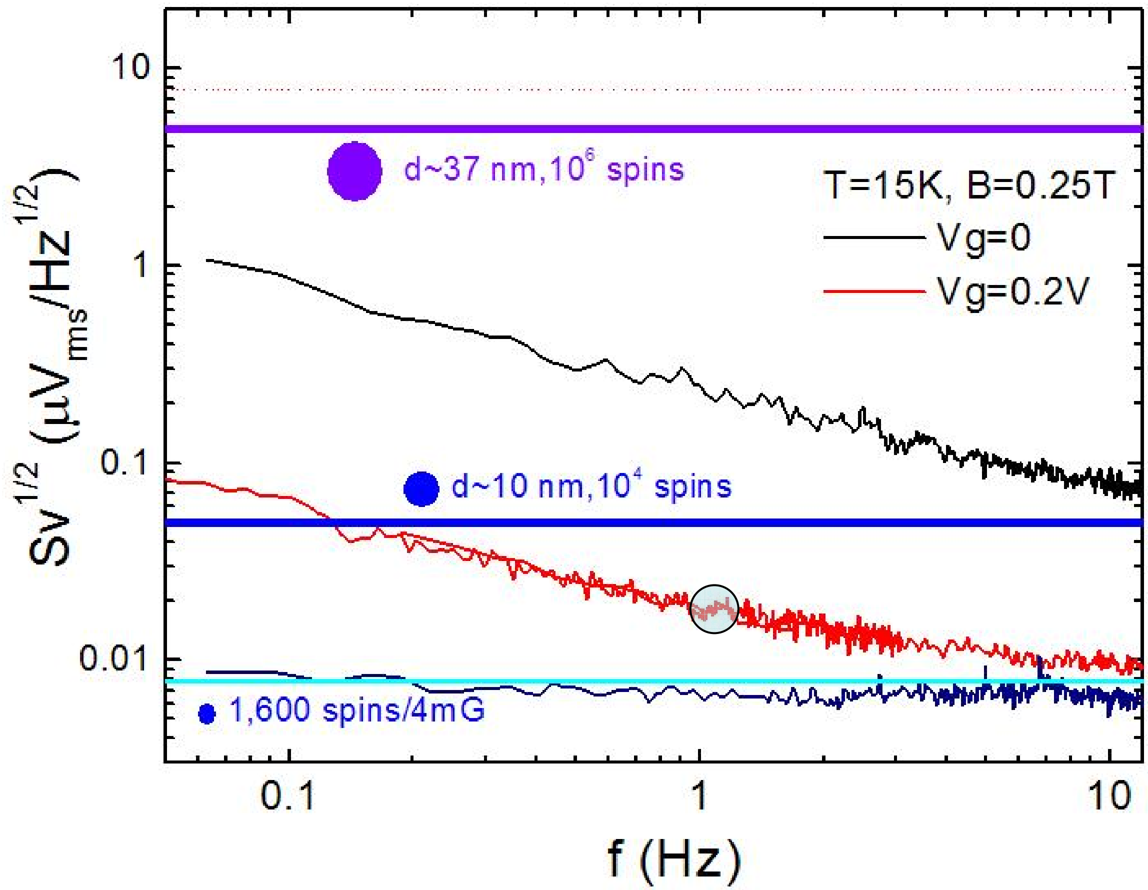
However:

- mesoscopic effects
- 1/f noise and telegraph noise

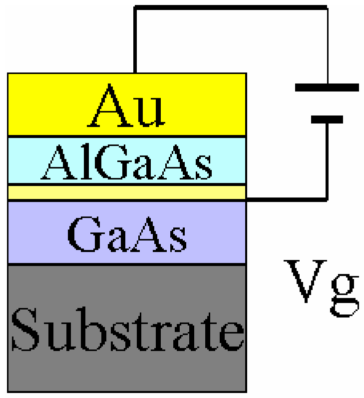
$\Rightarrow$ *systematic* noise studies



μ-Hall magnetometry: noise reduction



Signals estimated for a dipole placed at the center of a Hall cross of active area of ~0.5X0.5 μm^2



Moment sensitivity:

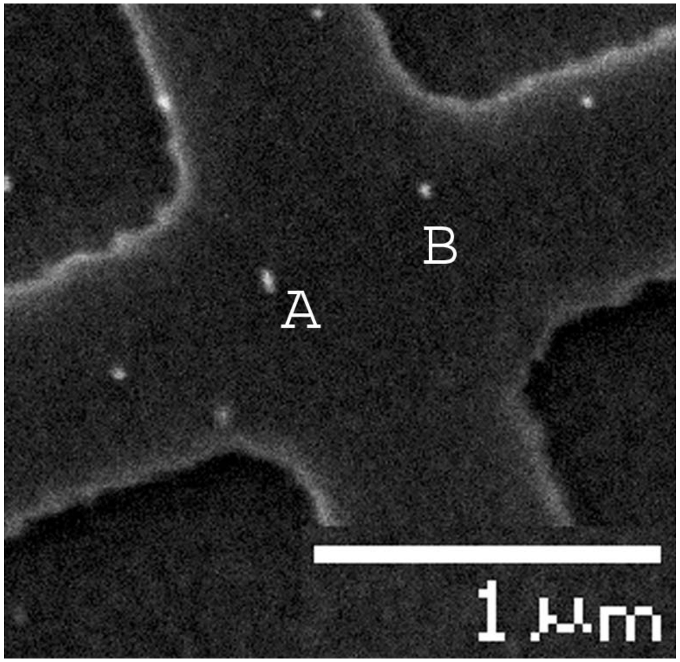
$\sim 10^4\ \mu_B/\sqrt{Hz}$

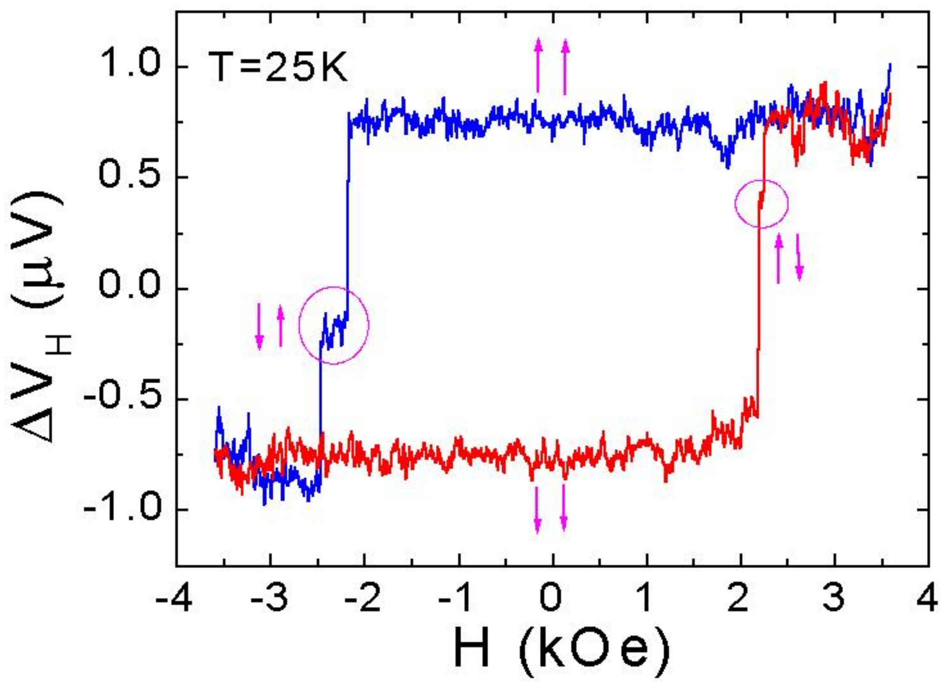
$\sim 10^{-16}$ emu

@ B=0.25 T

Li *et al*, PRL 2004

Multi-domain Nanoparticle

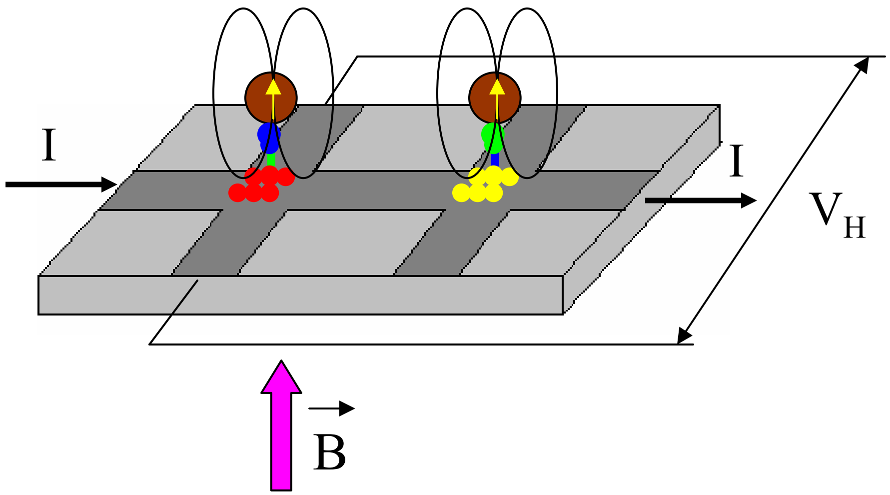




The multi-domain magnetic state of a larger Fe nanoparticle (d ~ 10 nm) or **both particles A and B** is resolved via high sensitivity Hall magnetometry.

Li *et al*, PRB 2005

µ-Hall Sensor Biological Sensing Scheme



target molecule (analyte)

receptor molecule

magnetic particle (label) functionalized with receptor molecule

$$V_H = R_H I B_z$$

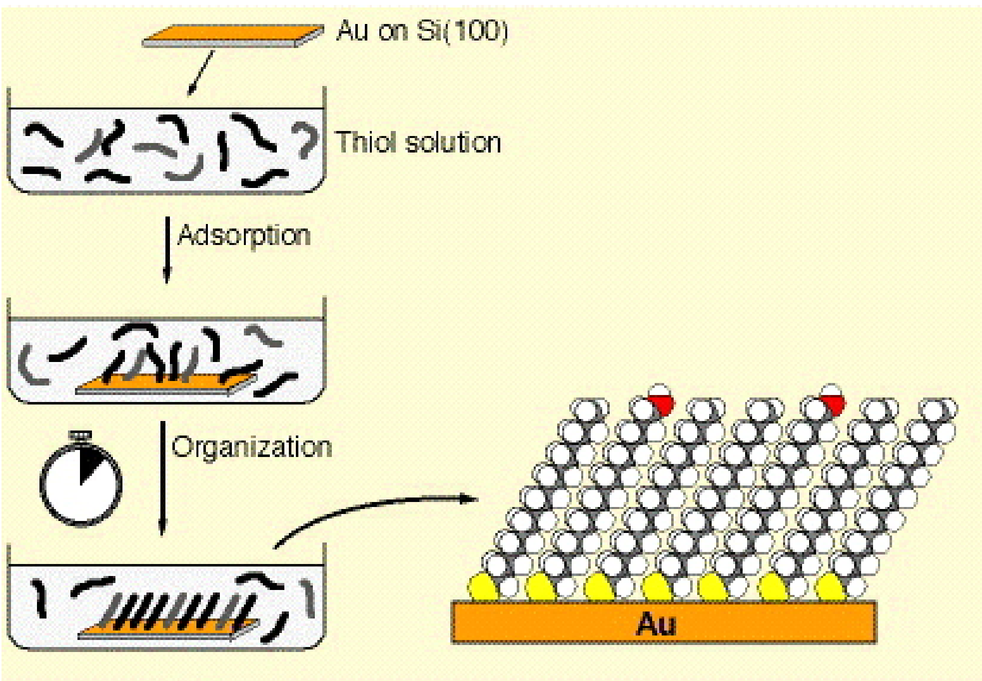
Main advantages over non-magnetic and substrate free sensing schemes

- integration of multiple sensors on a single chip
- detection of low concentrations of molecules, possibly **<u>single molecule detection</u>** if:

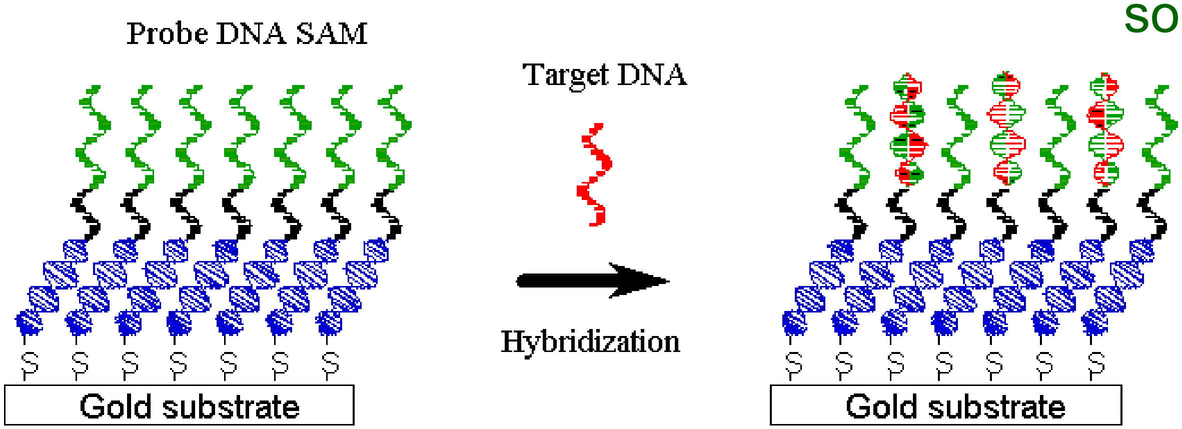
a) size of the label is comparable to the size of the analyte

b) sensor is sensitive enough to detect the small stray magnetic field from the label

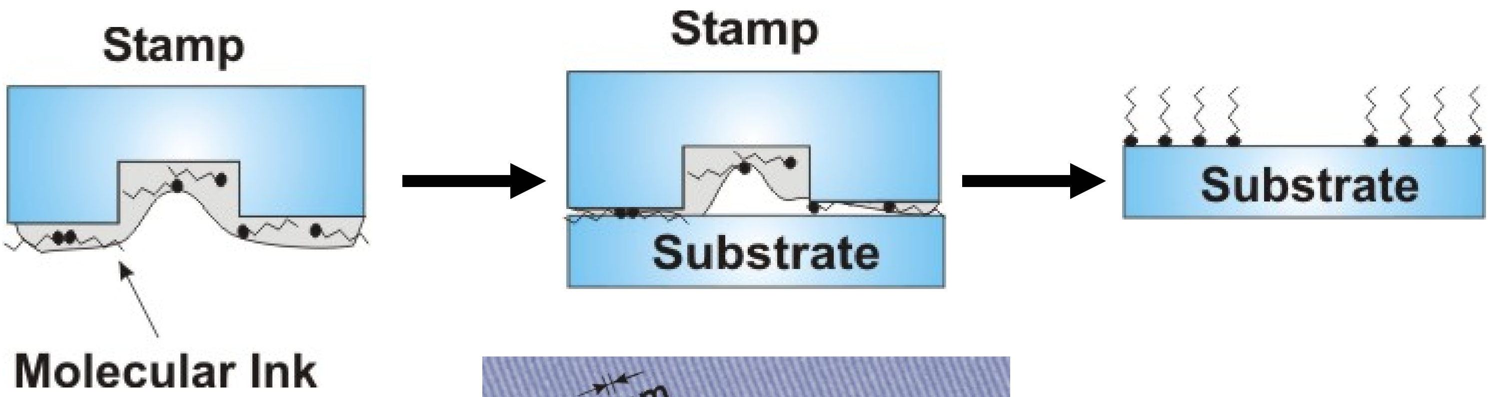
Self-Assembled Monolayer (SAM)

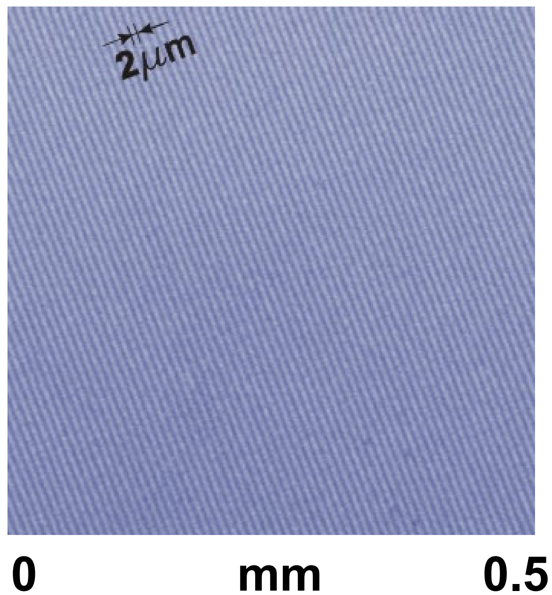


- SAM: ordered monolayer of organic molecules on a solid substrate via self assembly
- Wide variety of chemical end groups and solid-state substrate
- Convenient pathway for integrating organic/solid materials and for chemical and biological functionalization of solid-state substrates



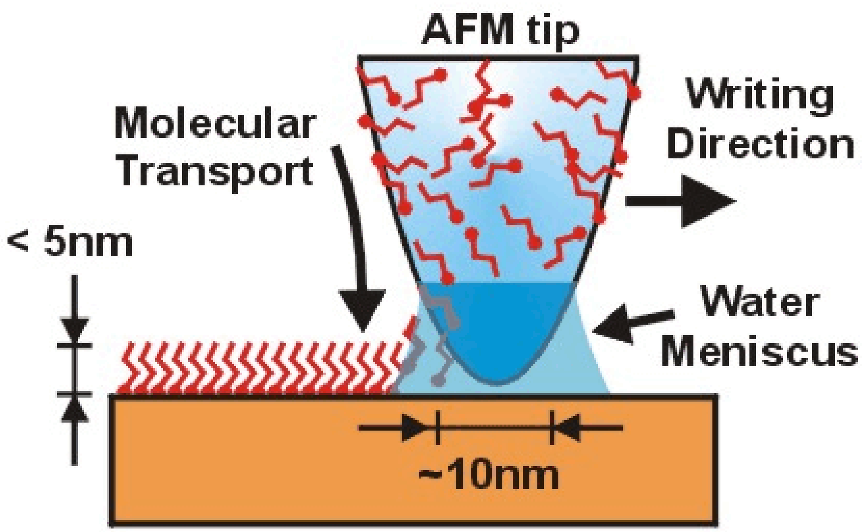
SAM patterning: μ-contact printing

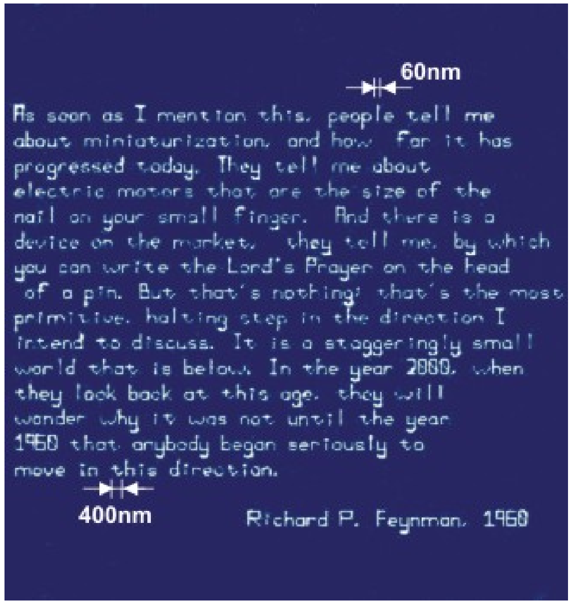




Rapid microscale patterning of soft materials over large surface areas

Dip-Pen Nanolithography (DPN)





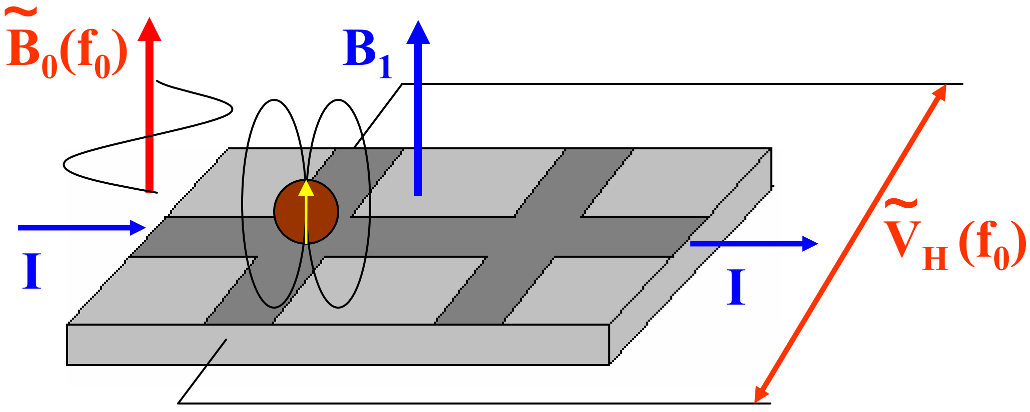
16-mercaptohexadecanoic acid patterns on Au

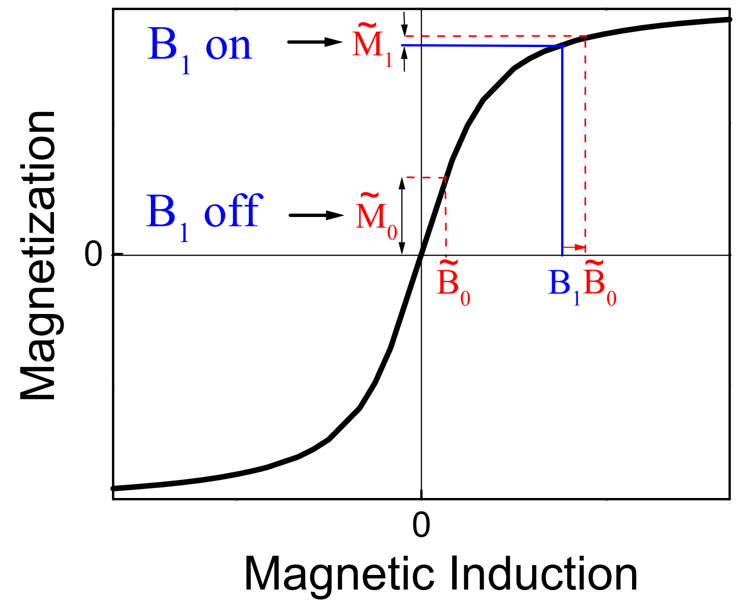
nanoscale patterning of soft materials with high spatial registry

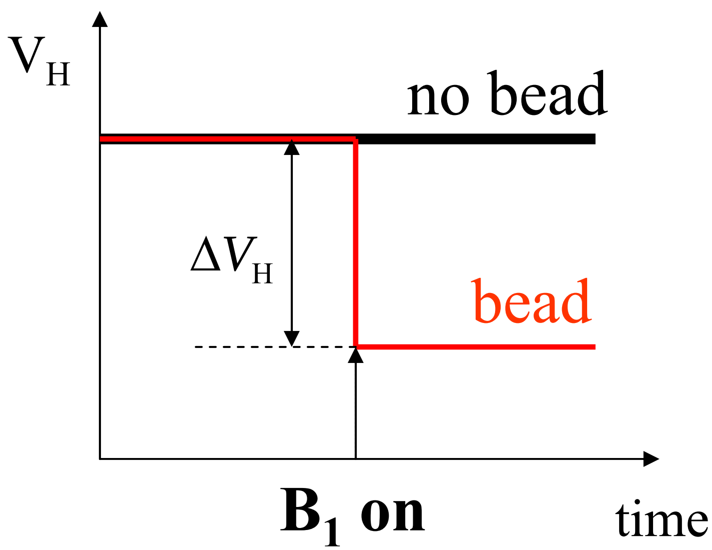
S. Hong, C. A. Mirkin, *Science* 2000.

μ-Hall magnetometry: ac detection

Superparamagnetic particles – magnetic only when exposed to an external field



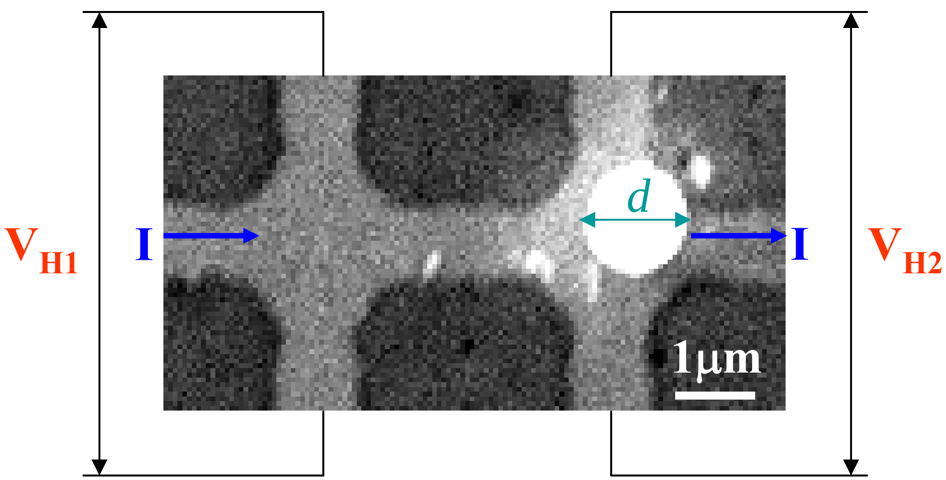


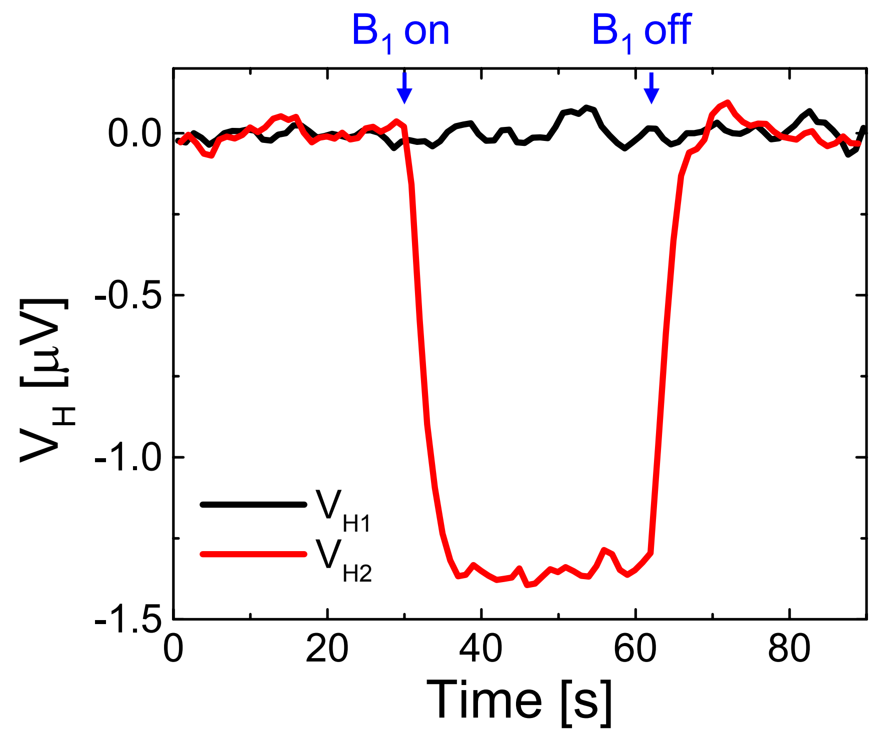


$$\Delta V_H = R_H I C \Delta M \quad , \quad \Delta M = M_0 - M_1$$

Room Temperature Operation

G. Mihajlović et al., Appl. Phys. Lett. **87**, 112502 (2005)





<u>superparamagnetic bead:</u> $d \sim 1.2$ μm

Fe_3O_4 nanoparticles in a spherical latex matrix

(Sigma Chemical CO)

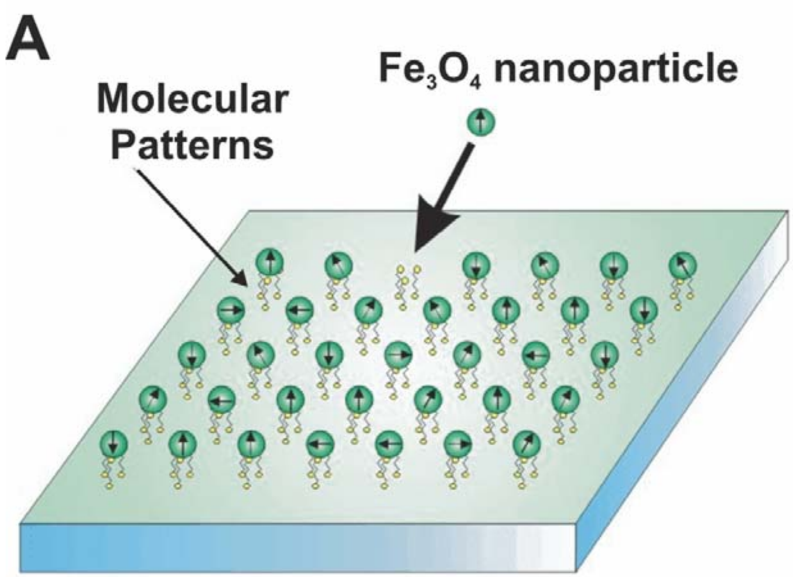
Detection parameters: I = 10 μA, R_H = 616 Ω/T, B_0 = 26.3 G, B_1 = 470 G, f_0 = 83.7 Hz, τ = 1s

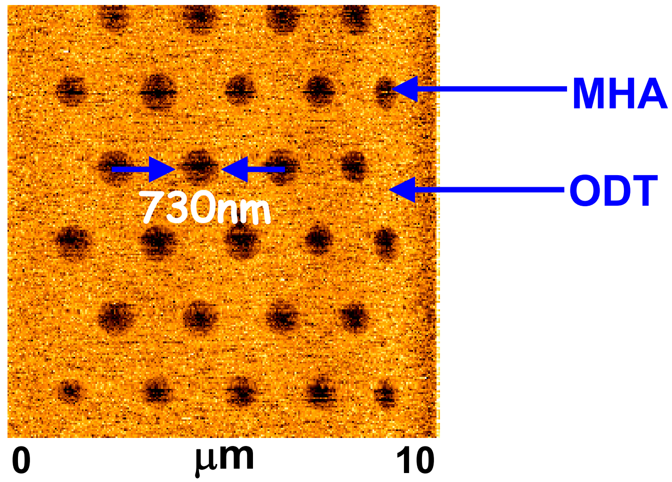
Detected signal and noise level: ΔV_H = 1.35 μV, V_{HN} = 29 nV, S/N = 33.3 dB (46.5)

Detected change in the stray magnetic field: B_{det} = 2.2 G

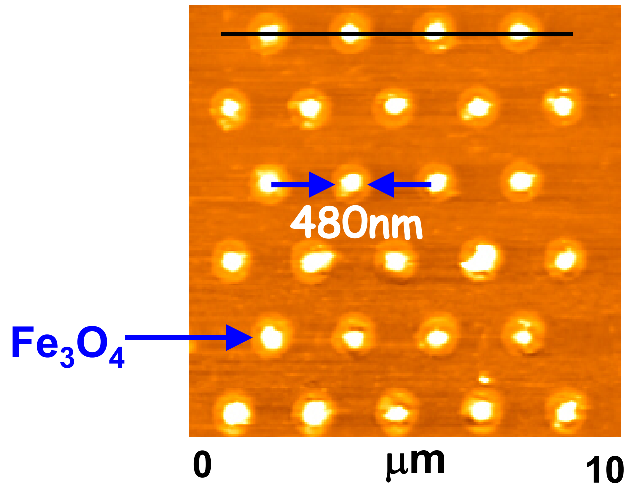
Nanoscale Functionalization

Selective functionalization with high spatial registry by DPN





LFM image of MHA/ODT DPN patterns

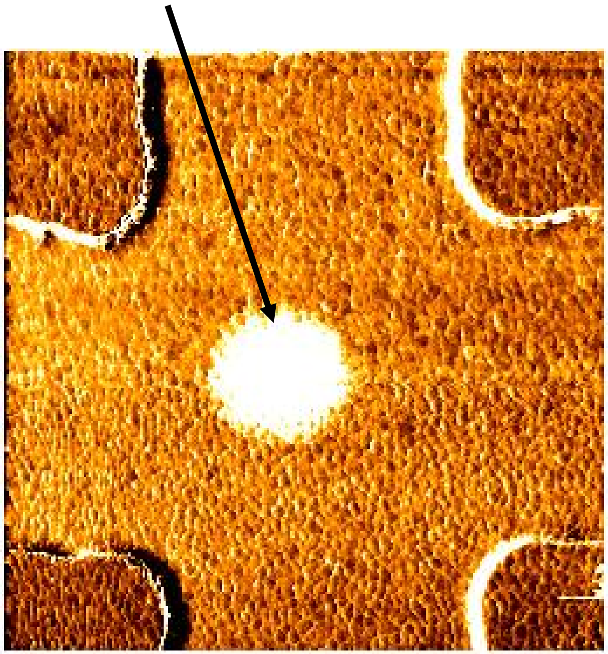


Topogaphy image of Fe_3O_4 assembled on MHA

Superparamagnetic Fe_3O_4 nanoparticles self-assemble onto MHA patterns

Functionalization of Hall sensor

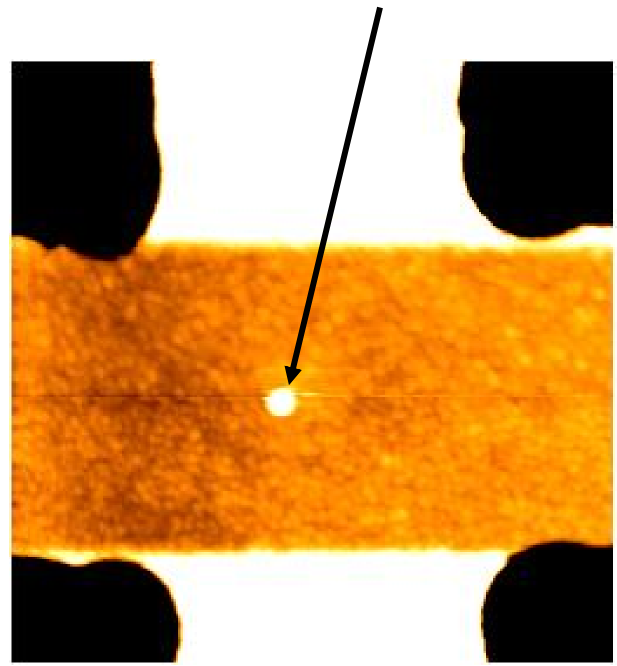
MHA pattern by DPN



0 μm 4

LFM Image

Fe_3O_4 nanoparticles assembled on MHA



0 μm 4

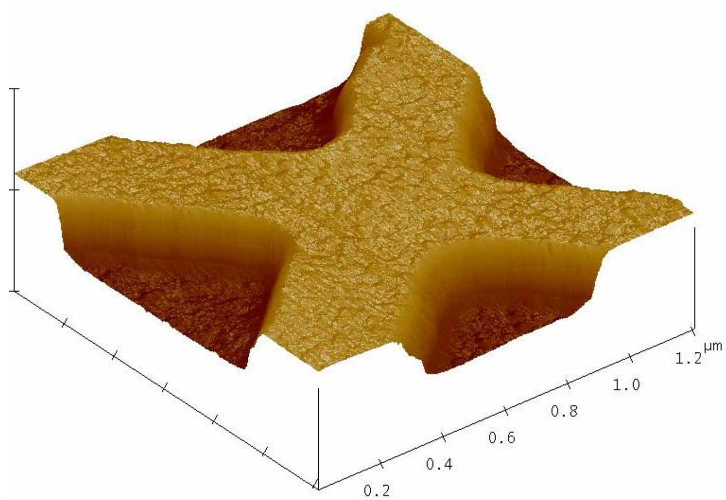
Topography Image

What's next?

Further Improvement in Sensitivity

Goal: to demonstrate the suitability of InAs quantum well Hall sensors for detection of superparamagnetic nanoparticles with sizes approaching those of the smallest biological entities

fabrication: e-beam lithography + photolithography, etching, thermal evaporation and SiO_2 deposition



detection method: phase-sensitive single Hall cross method used for immobilized superparamagnetic bead

prediction: single Co nanoparticle ~10 nm in diameter should be detectable with a 0.3 µm × 0.3 µm Hall sensor

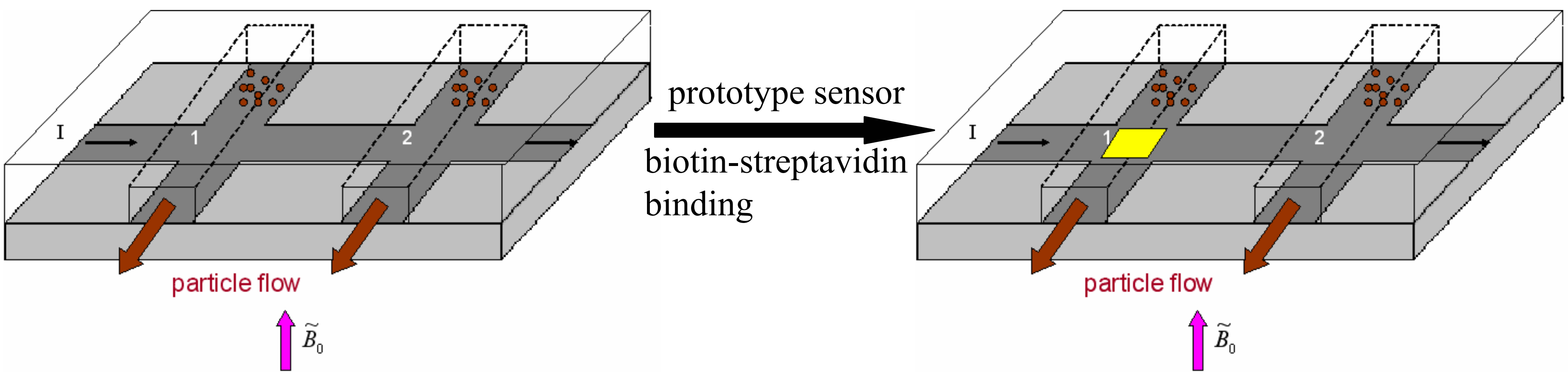
What's next?

Integration with Microfluidics   Sensor Arrays

Goals: (a) to demonstrate the suitability of InAs quantum well micro-Hall sensors to operate in biological (aqueous) environment

(b) to demonstrate the principle of multiple sensors on a single chip

(c) to study quantitative relation between the sensor signal and number of particles in the Hall cross area, i.e. potential for quantitative detection of biological molecules



optimize for using with blood samples to demonstrate the detection of intracellular proteins associated with heart attack

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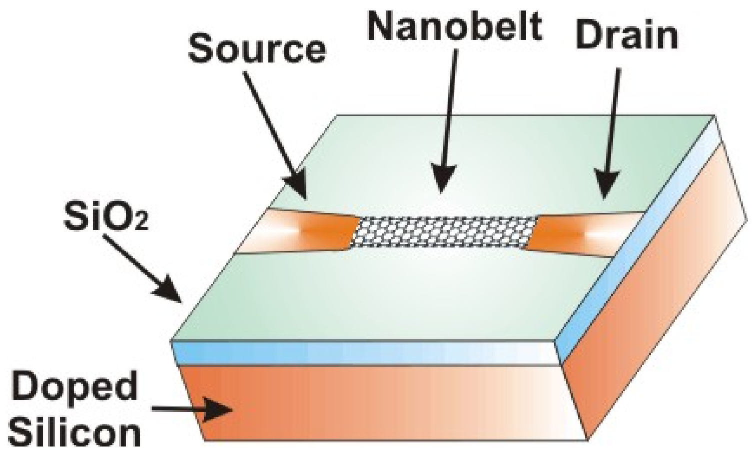
Yi Cheng, Fang Wang

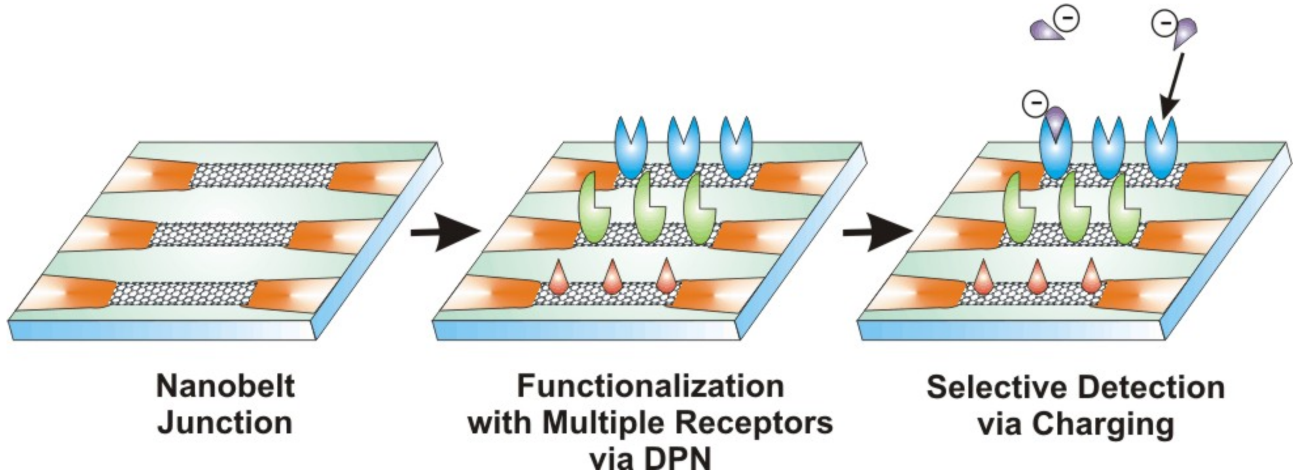
Materials by: Hideo Ohno (Tohoku University), Gerald Sullivan, Mark Field (Rockwell)

Nanoscale FET as biosensor

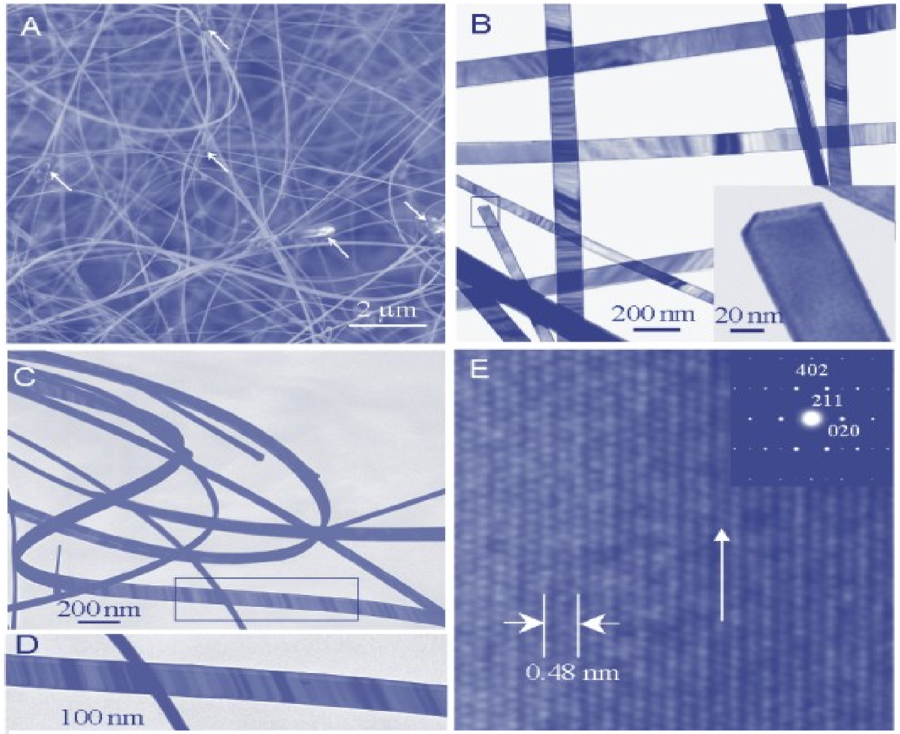


Sensing of biological species via measurement of conductance change of a nanoscale FET channel

Cui *et al*, Science, 2001

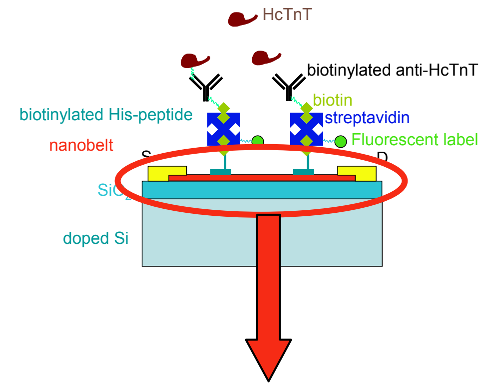


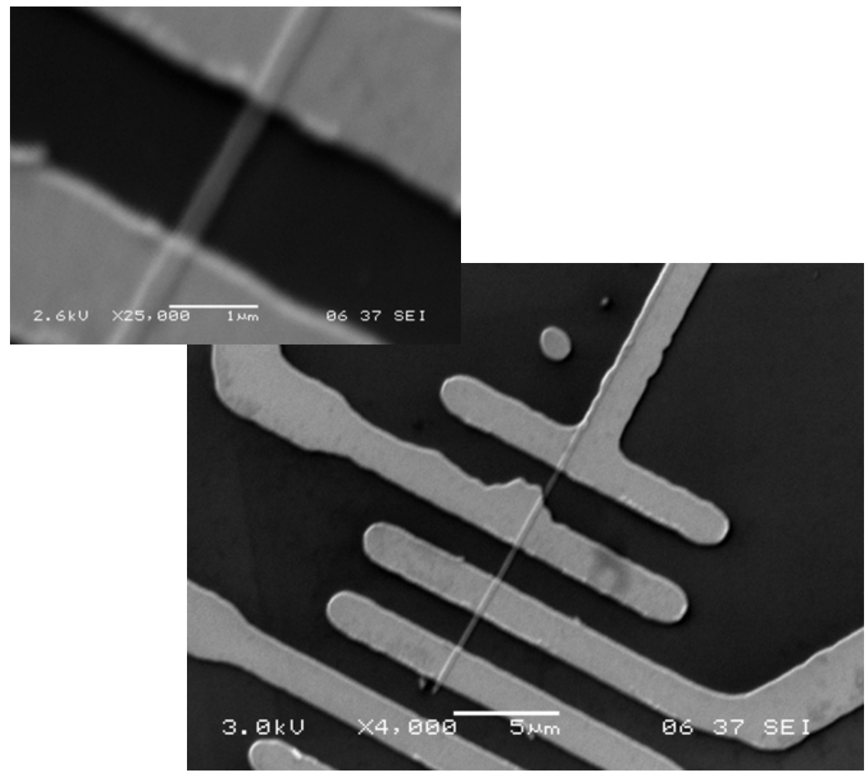
Nanobelt FET: material and device



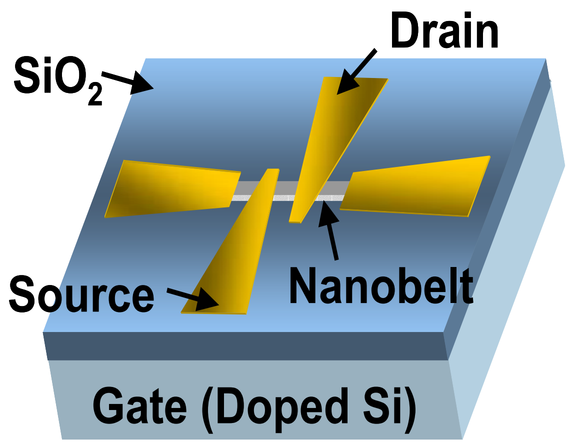
Nanobelt structure of SnO_2. (A) SEM image of as-synthesized nanobelt. (B)-(D) TEM images of straight and twisted nanobelts. (E) High resolution TEM image of nanobelt showing its crystalline structure.

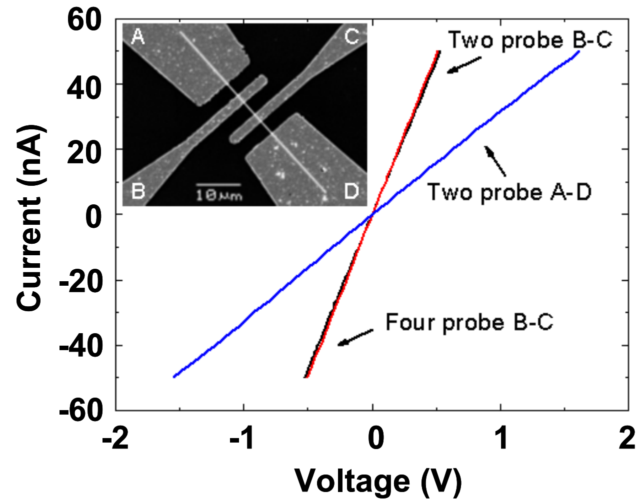
Pan, Dai, and Wang, Science, 2001



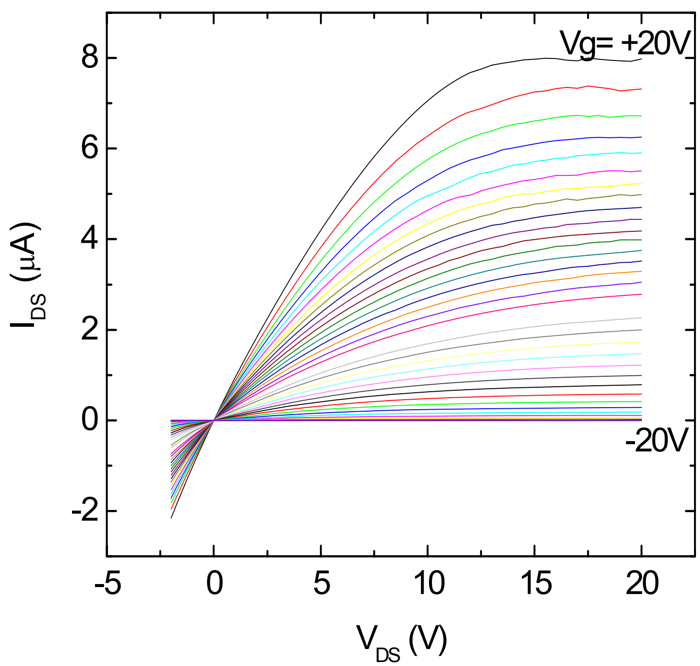


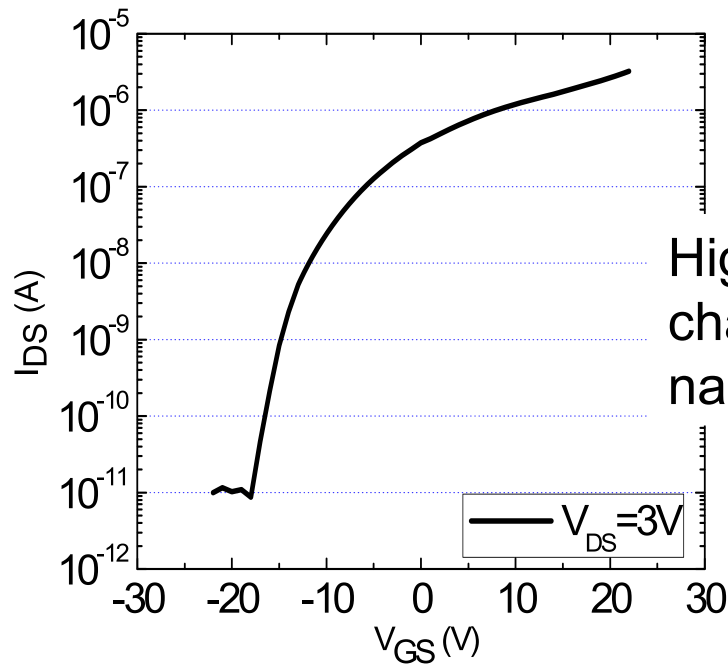
High-performance channel-limited nano FET





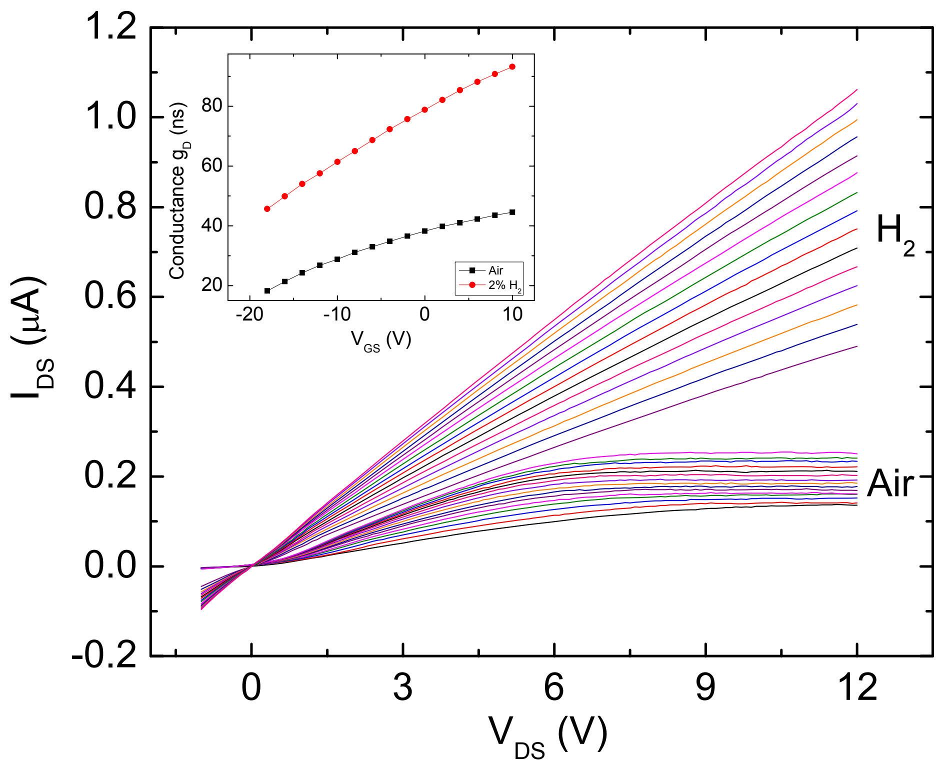
Low-resistance Ohmic contacts

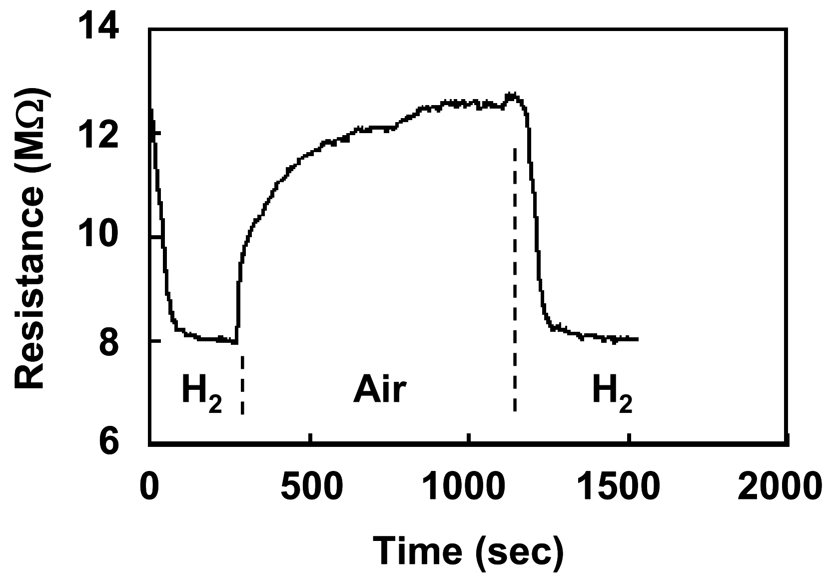




High-performance channel-limited nanobelt FET

Room-temperature H_2 sensing

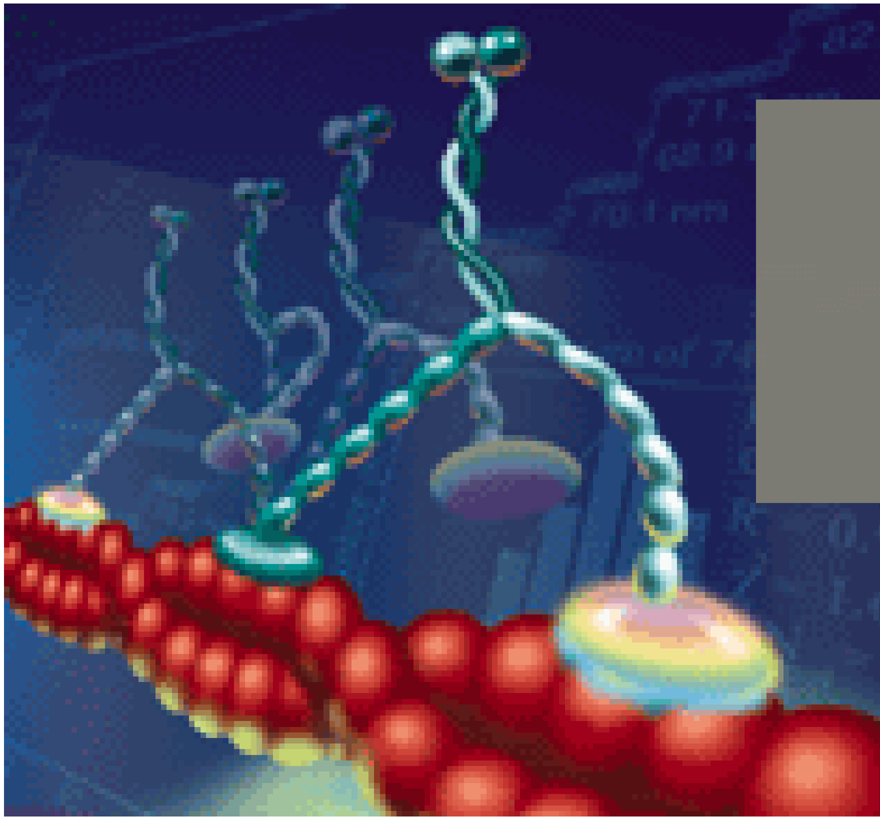


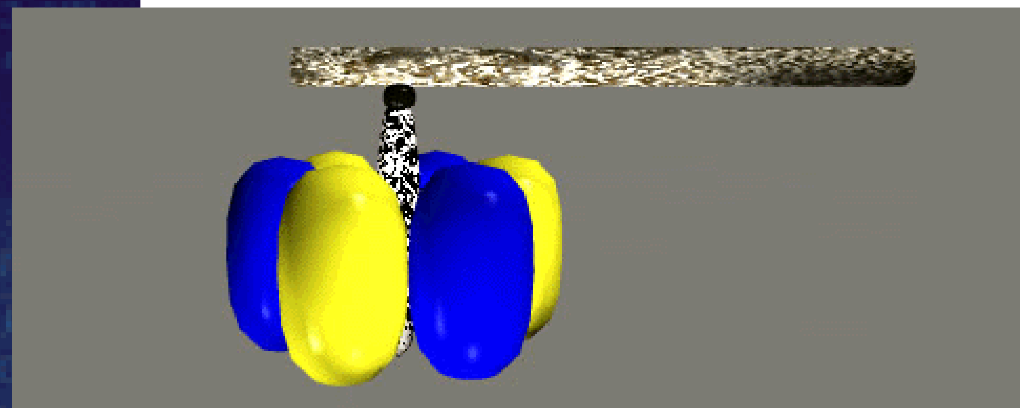


Outline

Pradeep Manandhar, Ling Huang, Jad Jaber, Goran Mihajlovic, Nicholas Brunet

Biomolecular motors





ATPase rotary motor

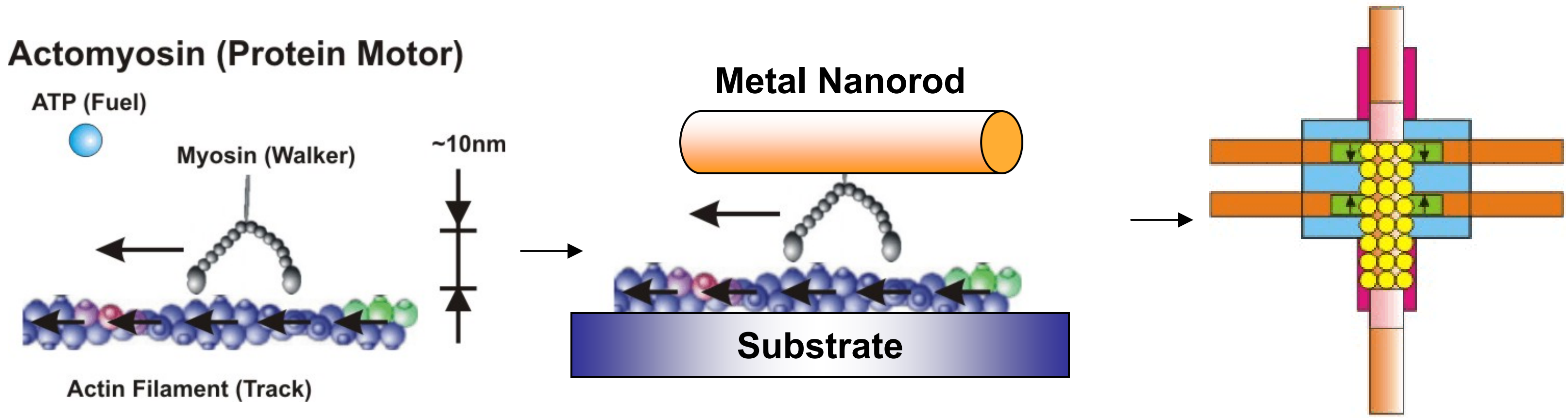
Montemagno *et al*., Science, 2000

actomyosin linear motor

- **Small motor size (~10nm)**
- **High fuel efficiency (>60%)**

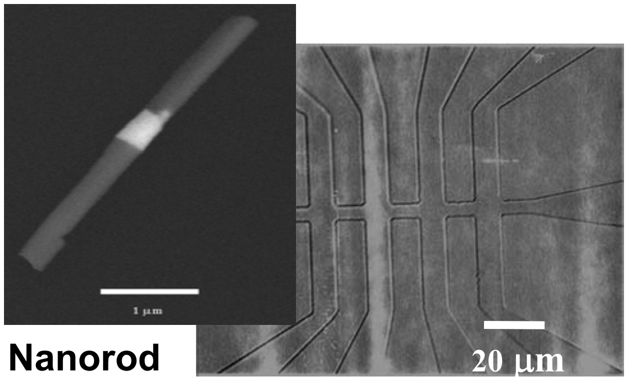
Can we generate mechanical motion with biomolecular motors?

Proposed bio-mechanical device



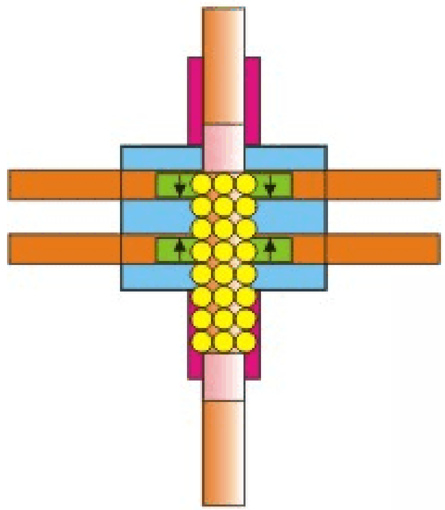
Bi-directional linear nanoactuator driven by actomyosin motors

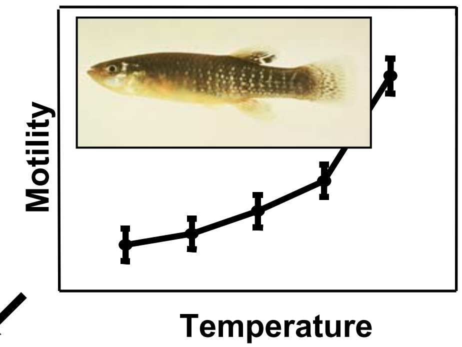
Elements of the bio-nano-actuator



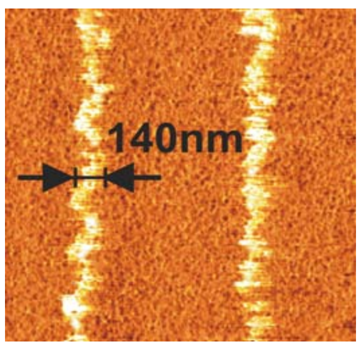
Nanorod

Room Temp. Hall Sensor

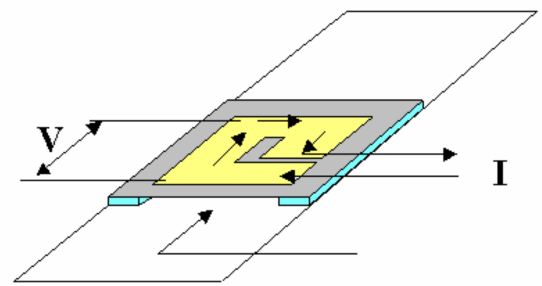




Fish Myosin Motility

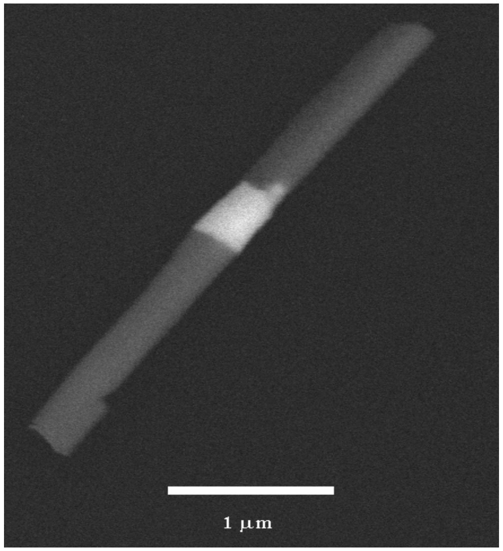


Actin Nano-patterns

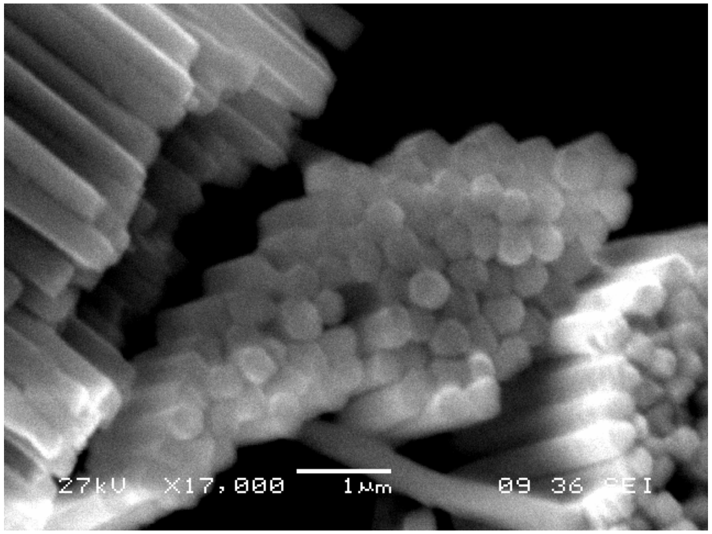


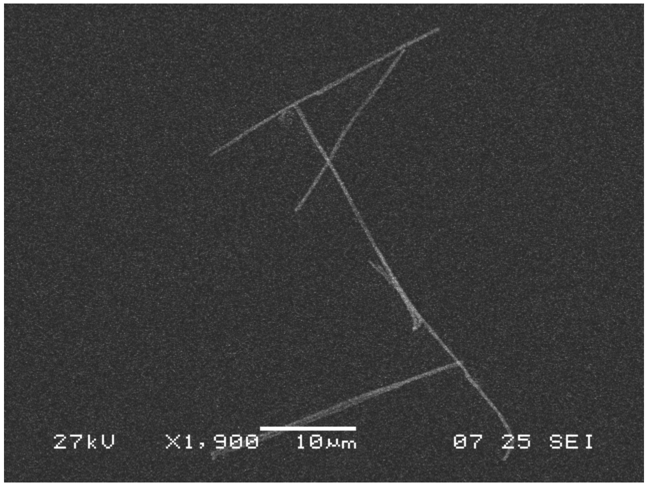
Rapid Motility Control

Magnetic nanorods



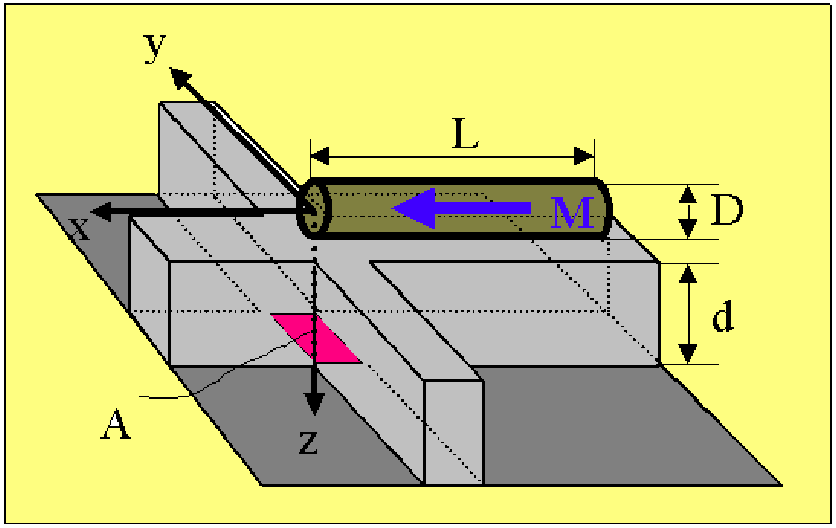
Ni/Au/Ni nanorods

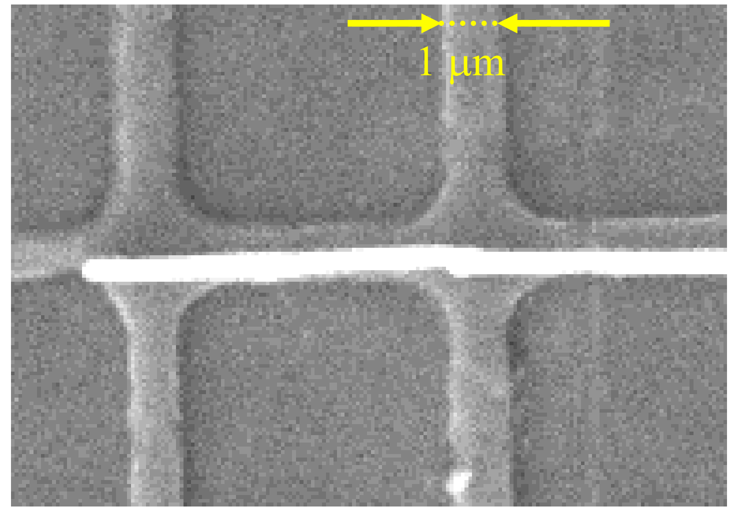


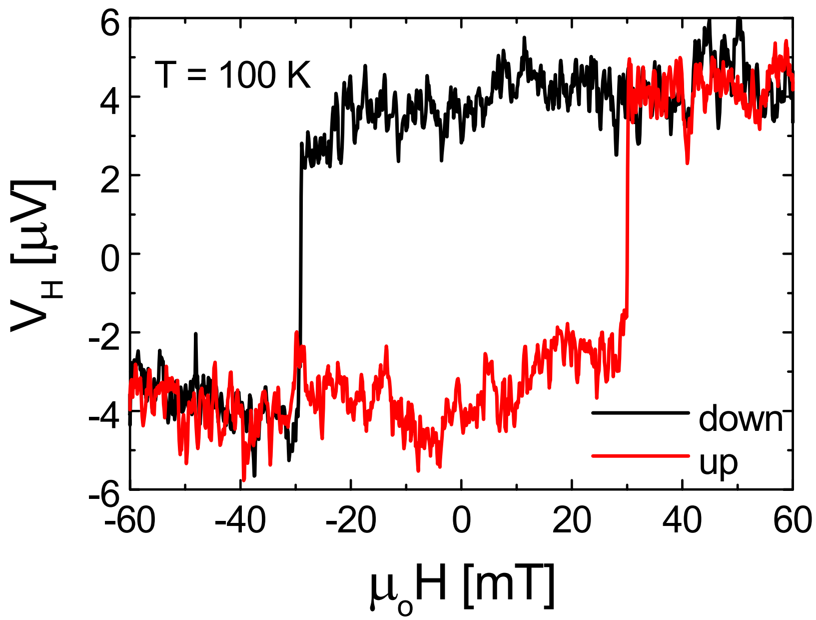


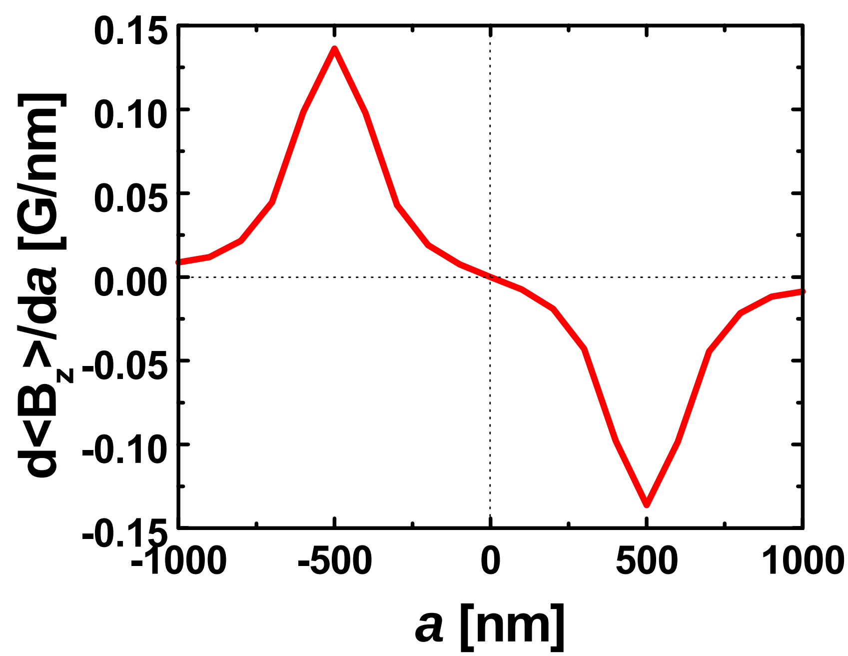
Ni nanorods

μ-Hall Gradiometer: nanoscale position sensor for magnetic nanowire



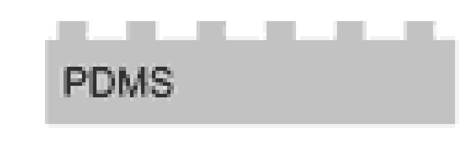


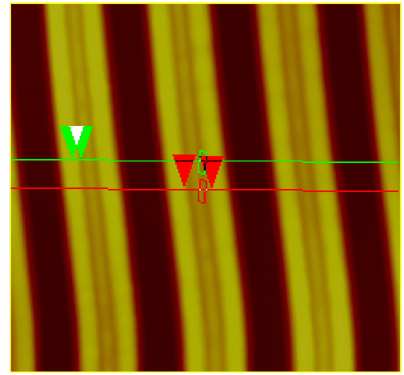


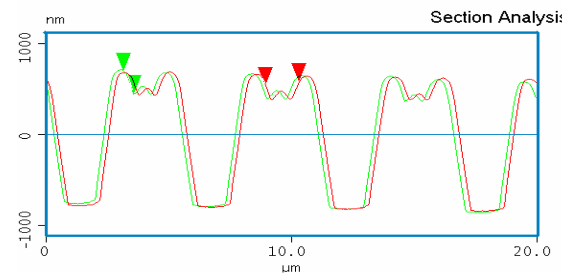


Action Filaments taking a Random Walk

Chemical + Physical Tracks







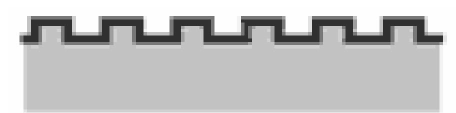
The stamp

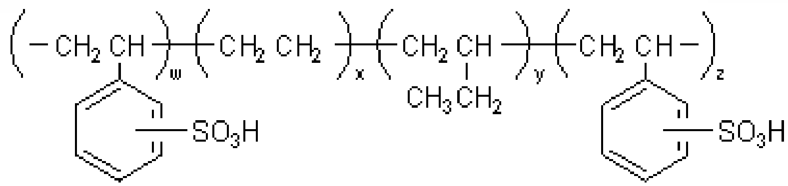
Horizontal distance 1.37 µm

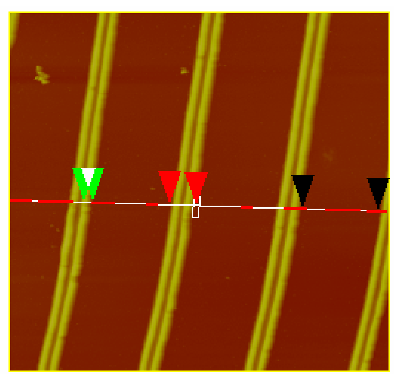
Vertical distance 250 nm

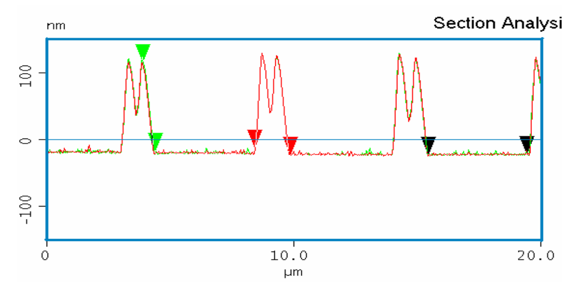
The surface: coat with PAH, then:

Inking with PEBSS









Jaber *et al.*, Nano Lett., 2003

Actin motility and confinement

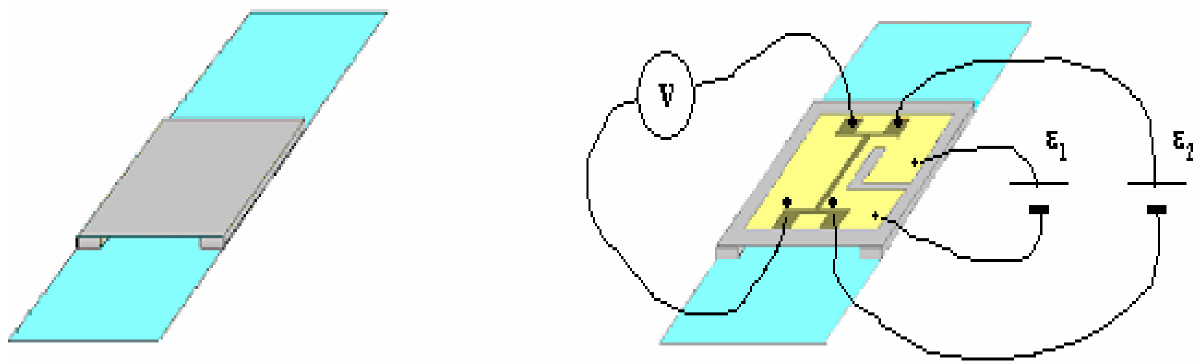
PEBSS barrier

(light)

PAH terminated
multilayer channel

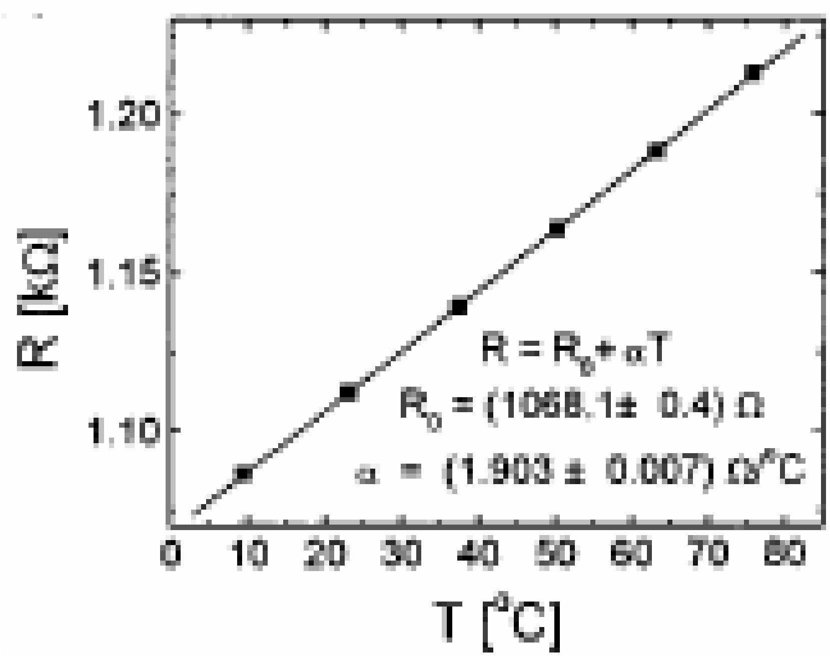
(dark)

Temperature dependence of actomyosin motility



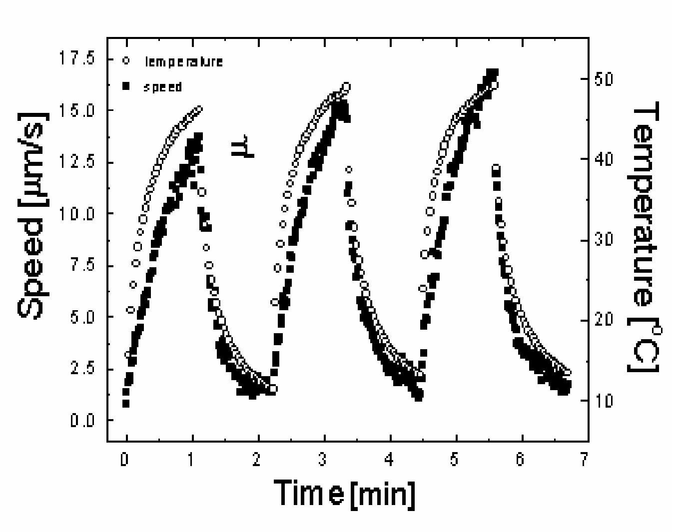
conventional flow cell

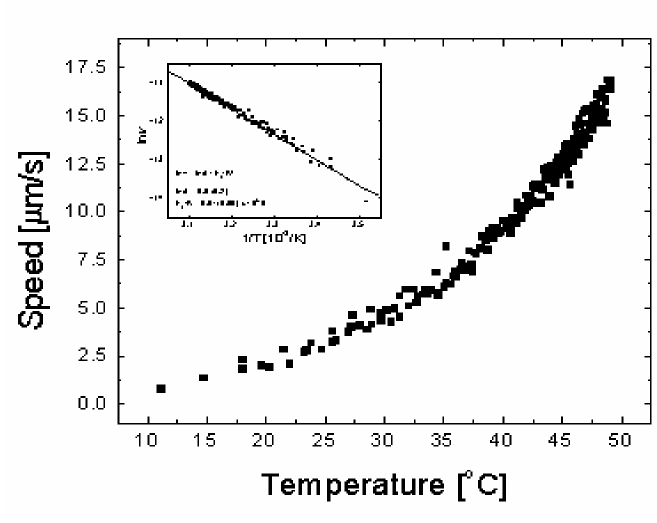
flow cell with local temperature control



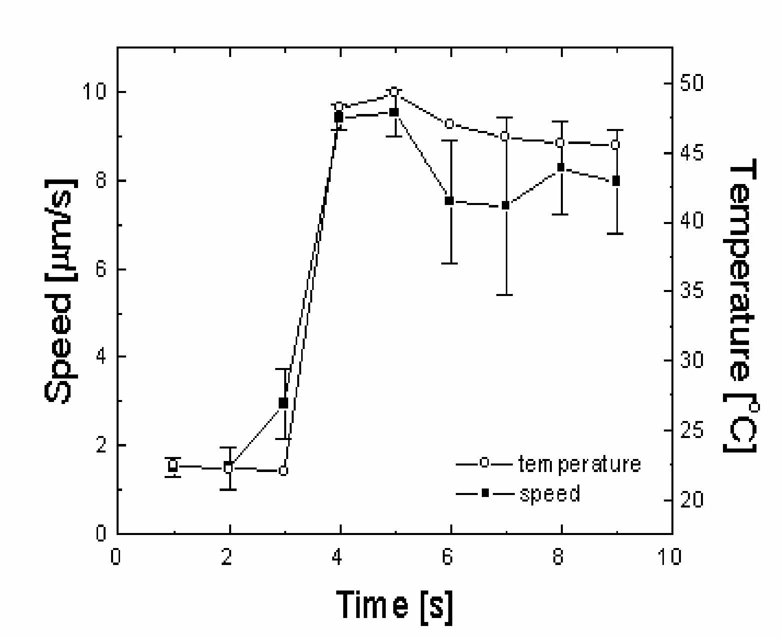
Electrically controlled flow cell with on-chip electric heater and thermometer

Thermal activation of protein motors





thermal activated behavior of motor motility

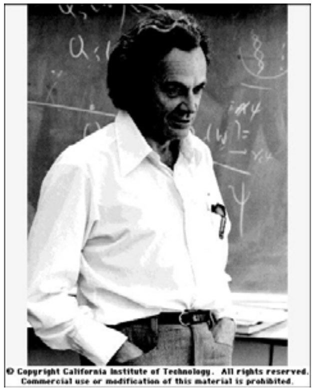


rapid reversible on-off control of protein motors

Mihajlović *et al.*, APL 2004

We've come a long way, baby!….but

As the man said



Richard Feynman –

"There's Plenty of Room at the Bottom"

1959 APS March Meeting