From Hubert's Museum to Science at Small Scales

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MARTECH – Florida State University

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

An encyclopedia?

- **Book:**
  
  \[
  \begin{array}{c}
  \text{10"} \\
  \times 1000 \text{ pages} = 10^5 \text{"} \equiv \text{Area of all pages}
  \end{array}
  \]

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

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

  Increase Linear Dimension by \( \approx 5.5 \times 10^3 \)

- **Encyclopedia Britannica:**
  
  \[
  25 \text{ volumes} \equiv \frac{25 \times 10^5 \text{"}}{3 \times 10^{-3} \text{"}} \equiv \sim 8 \times 10^8
  \]

  or \( \sim 3 \times 10^4 \) magnification in linear dimension
Resolving Power of Eye $\sim \frac{1}{120}$ "

To put E.B. on the pin, demagnify by $3 \times 10^4$

$$\therefore \frac{1}{120} \text{ "} \times 2.54 \frac{cm}{"} \times \frac{1}{3 \times 10^4} \sim 70 - 80 \text{ Å}$$

Å $= 10^{-8} \text{ cm}$

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

diameter of atom

Thus $A \sim 625 \text{ Atoms}$

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

• **10³** = 1,000 (thousand) ≡ KILO
• **10⁶** = 1,000,000 (million) ≡ MEGA
• **10⁹** = 1,000,000,000 (billion) ≡ GIGA
• **10¹²** = 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

Thus

\[
\frac{1"}{16} \times 1000 = 62.5"
\]

Thus \( \left( \frac{62.5"}{36"} \right)^2 \approx 3 \square \text{ yds.} \)
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 $\frac{1}{100}$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

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Moore's Law: Power of Miniaturization
Density: 2 kb/in²
Speed: 70 kb/s
Size: φ24” x 50
Capacity: 5 Mb

Density: 100 Gb/in²
Speed: > 200 Mb/s
Size: φ2.5” x 2
Capacity: > 400 Gb
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Goran Mihajlovic, Pradeep Manandhar

Materials by: Hideo Ohno (Tohoku University)
Gerald Sullivan, Mark Field (Rockwell)
µ-Hall magnetometry: gradiometry

\[ \Delta V_H \]

\[ B \]

\[ V_H \]

\[ I_1 \]

\[ I_2 \]

GaAs cap
n-doped AlGaAs
AlGaAs
GaAs
GaAs/AlGaAs SL
Substrate

B
STM and Nanofabrication

STM assisted Chemical Vapor Deposition

Precursor: Fe(CO)₅

• Mc Cord 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:** \( m_{\text{min}} = C^{-1} \cdot B_{\text{min}} \)
- **field sensitivity:** \( B_{\text{min}} \propto w^{-1} \)
- **coupling coefficient:** \( C = \langle B_Z \rangle / m \)

⇒ **miniaturization**

However:
- mesoscopic effects
- 1/f noise and telegraph noise

⇒ **systematic** noise studies
µ-Hall magnetometry: noise reduction

Moment sensitivity:
\[ \sim 10^4 \mu_B/\sqrt{\text{Hz}} \]
\[ \sim 10^{-16} \text{ emu} \]
@ B=0.25 T

Signals estimated for a dipole placed at the center of a Hall cross of active area of \( \sim 0.5 \times 0.5 \mu m^2 \)

Li et al, PRL 2004
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**

![Diagram of µ-Hall sensor with magnetic particles and receptor molecules]

- **target molecule (analyte)**
- **receptor molecule**
- **magnetic particle (label) functionalized with receptor molecule**

\[ V_H = R_H IB_z \]

**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 **single molecule detection** 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)

nanoscale patterning of soft materials with high spatial registry

μ-Hall magnetometry: ac detection

Superparamagnetic particles – magnetic only when exposed to an external field

\[ \Delta V_H = R_H IC \Delta M \]

\[ \Delta M = M_0 - M_1 \]
superparamagnetic bead: \( d \sim 1.2 \ \mu m \)
Fe\(_3\)O\(_4\) nanoparticles in a spherical latex matrix
(Sigma Chemical CO)

Detection parameters: \( I = 10 \ \mu A, R_H = 616 \ \Omega/T, B_0 = 26.3 \ \text{G}, B_1 = 470 \ \text{G}, f_0 = 83.7 \ \text{Hz}, \tau = 1 \ \text{s} \)

Detected signal and noise level: \( \Delta V_H = 1.35 \ \mu V, V_{HN} = 29 \ \text{nV}, \text{S/N} = 33.3 \ \text{dB} (46.5) \)

Detected change in the stray magnetic field: \( B_{\text{det}} = 2.2 \ \text{G} \)
Selective functionalization with high spatial registry by DPN

Superparamagnetic Fe₃O₄ nanoparticles self-assemble onto MHA patterns
Functionalization of Hall sensor

MHA pattern by DPN

Fe$_3$O$_4$ nanoparticles assembled on MHA

LFM Image

Topography Image
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 $\mu$m × 0.3 $\mu$m Hall sensor

What’s next?
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

Integration with Microfluidics

Sensor Arrays

What’s next?

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

- Actomyosin linear motor
- ATPase rotary motor

Montemagno et al., Science, 2000

- 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

Actin Nano-patterns

Fish Myosin Motility

Temperature
Rapid Motility Control

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

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

\[ R = R_0 + \alpha T \]

\[ R_0 = (1068.1 \pm 0.4) \, \Omega \]

\[ \alpha = (1.903 \pm 0.007) \, \Omega/\degree C \]
Thermal activation of protein motors

Mihajlović et al., APL 2004

thermal activated behavior of motor motility

rapid reversible on-off control of protein motors
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