Microactuators and Sensors for Microfluidics and Lab on a Chip applications

Massood Tabib-Azar
Case Western Reserve University
Cleveland, Ohio 44106

Partially supported by grants from NIST, WPAFB, and SRC

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

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

Functional Elements

I/O
- pipette
- inkjet
- electrospray

filters
- physical
- polymeric
- SPE

reactions
- stopped flow
- continuous flow
- thermal cycling

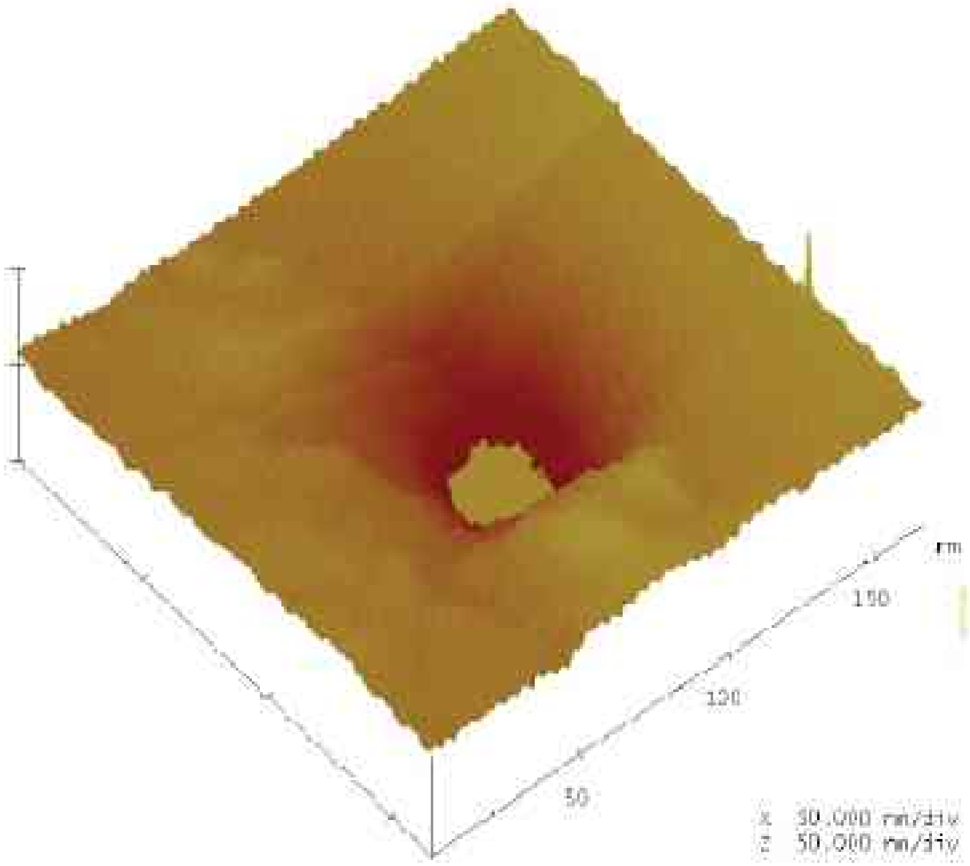
separations
- electrophoretic
- chromatographic
- sizing
- heterogeneous

cytometry
- immunoassay
- staining
- cell sorting

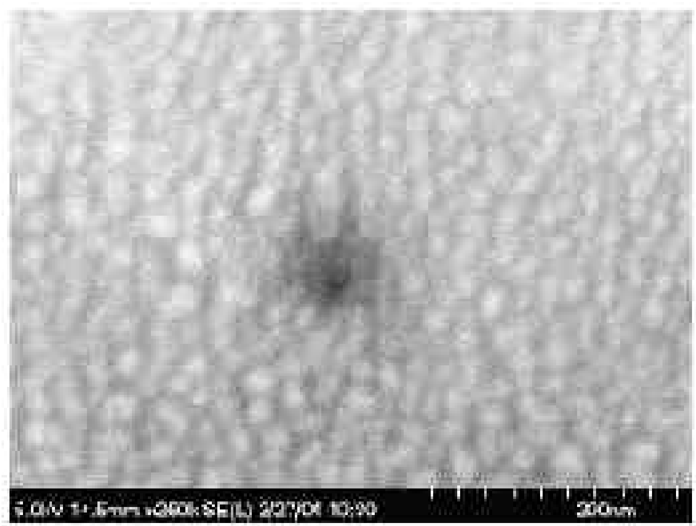
detection
- fluorescence
- absorbance
- refractive index
- scattering
- electrochemical
- MS

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

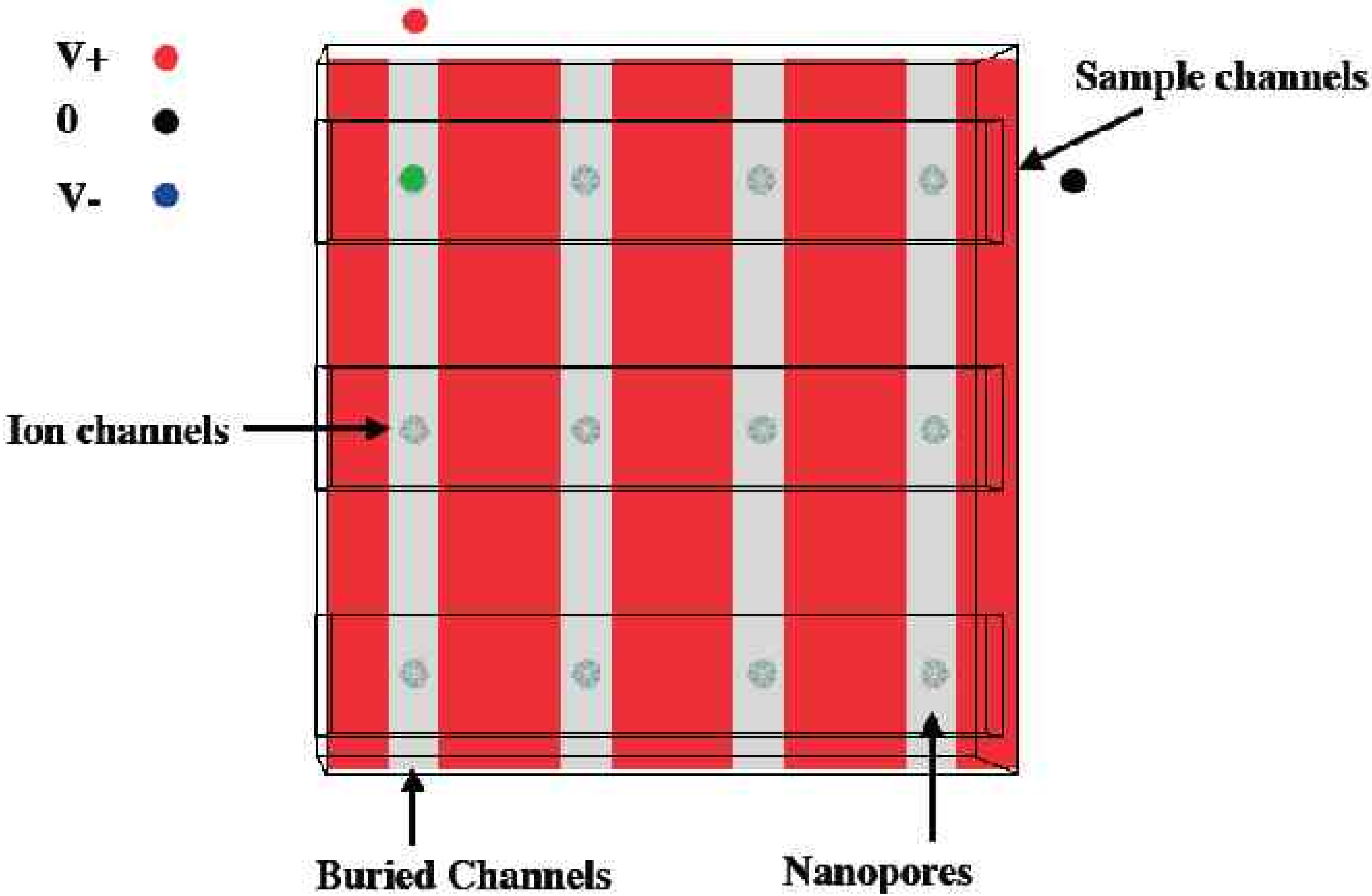


AFM Image



SEM Image

Addressable Ion Channel Arrays



Fundamental Questions

- Can nanoscale channels be fabricated to molecular dimensions?
- What is the dimensional stability of a molecular scale channel?
- Can interfacial characteristics be sufficiently controlled
- What are the characteristics of fluid transport in molecular scale channels?
- How can such fluids/molecules be probed experimentally? ←

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 ←

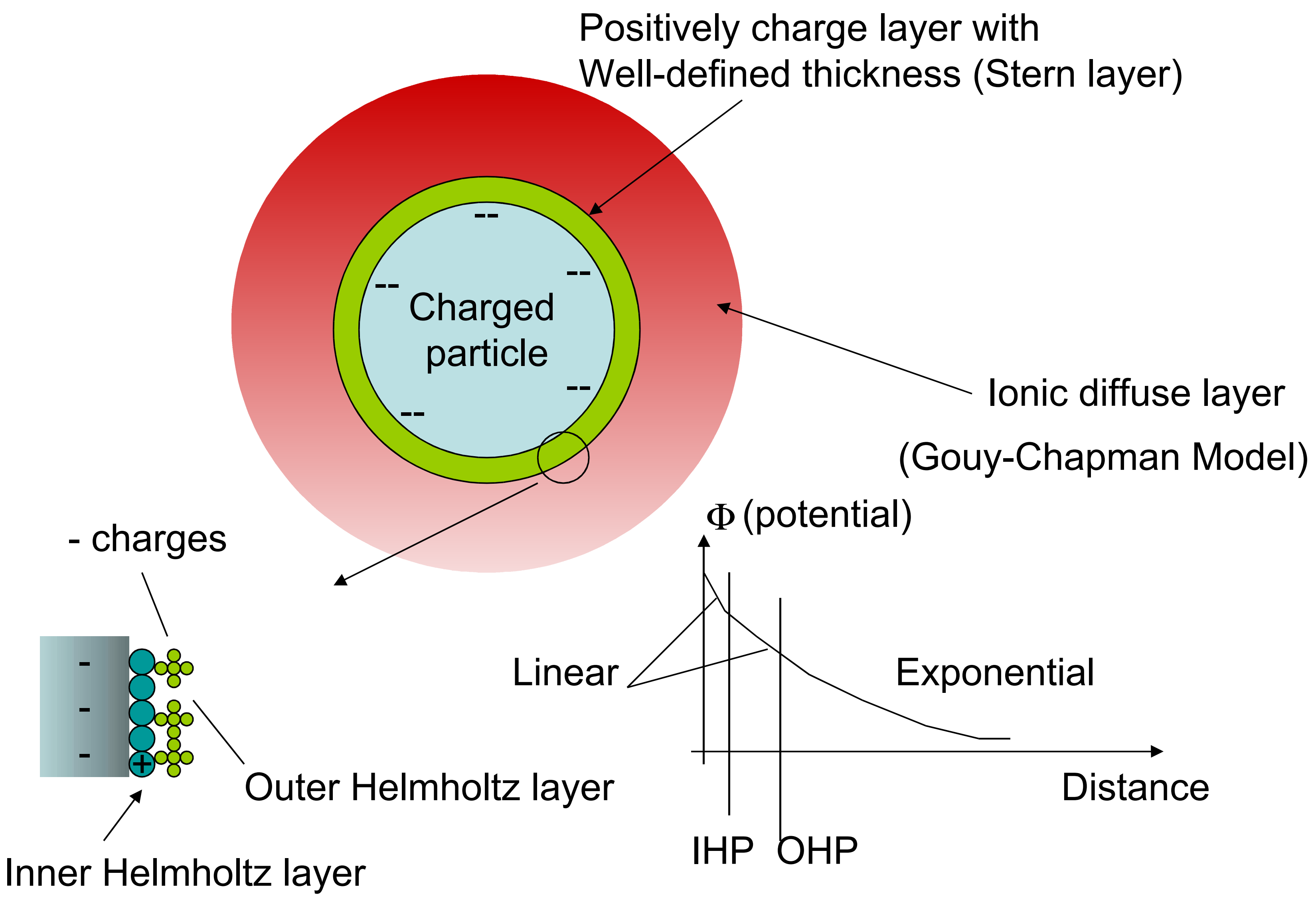
Needs

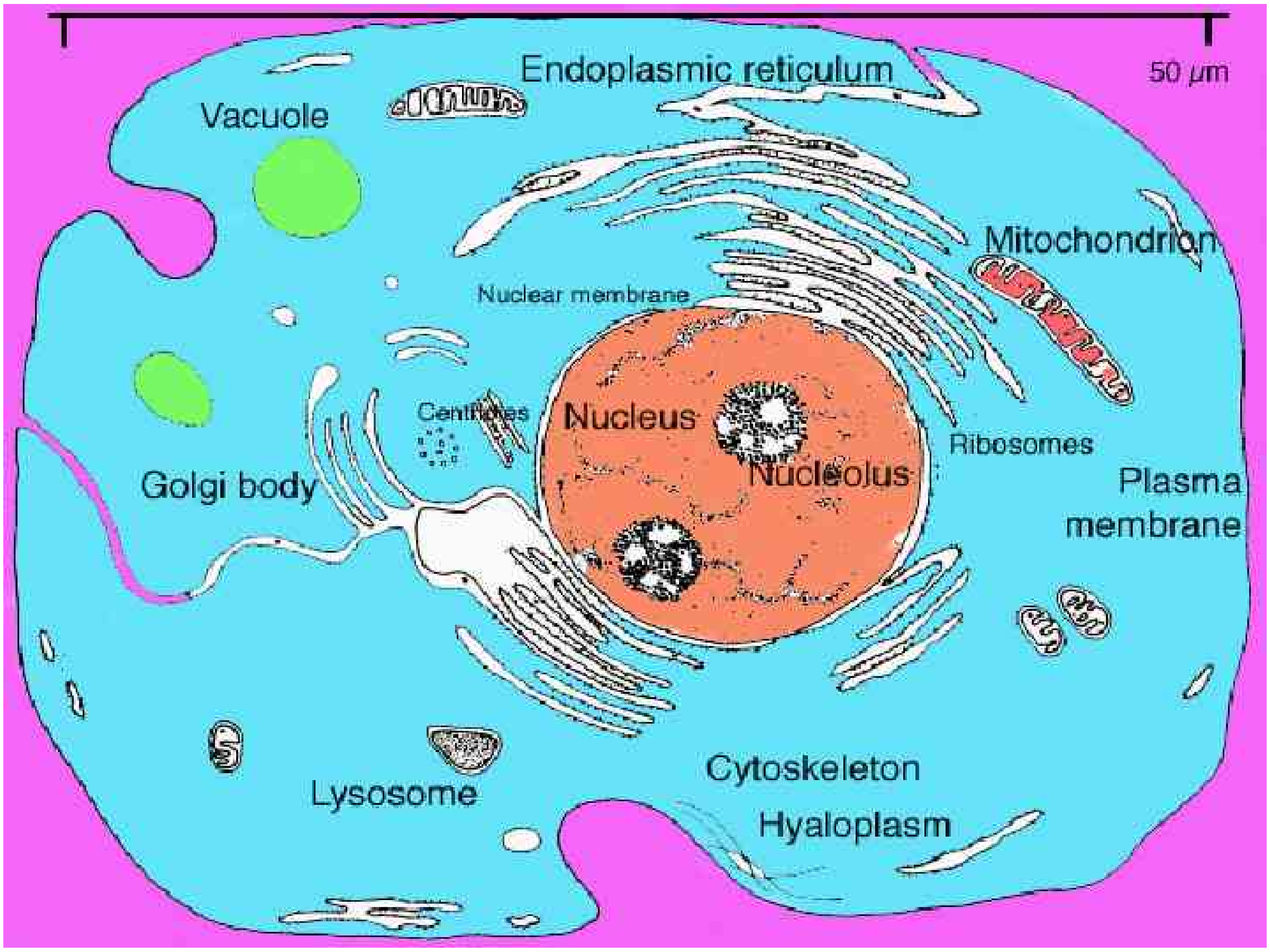
- Materials
  - Micro- and nanoscale fabrication
  - Interfacial chemistry
- Nanoscale transport
  - Fluids
  - Polymers
  - Experiment and simulation benchmarking
- Sensors
  - Integrated flow sensors
  - Integrated voltage sensors
  - Ultrasensitive analyte detectors
    - Non-selective
    - Selective

Future Directions

- Biochemistry integrated with HP separations
  - Single cell assays
  - Protein manipulations
- Nanofluidics
  - Low dimensional fluid transport
  - Molecular transport ($r_g > h$)
  - Single molecule manipulation, detection, and characterization
- Chemical synthesis
- Handheld microfabricated mass spectrometers

Electric Double Layer

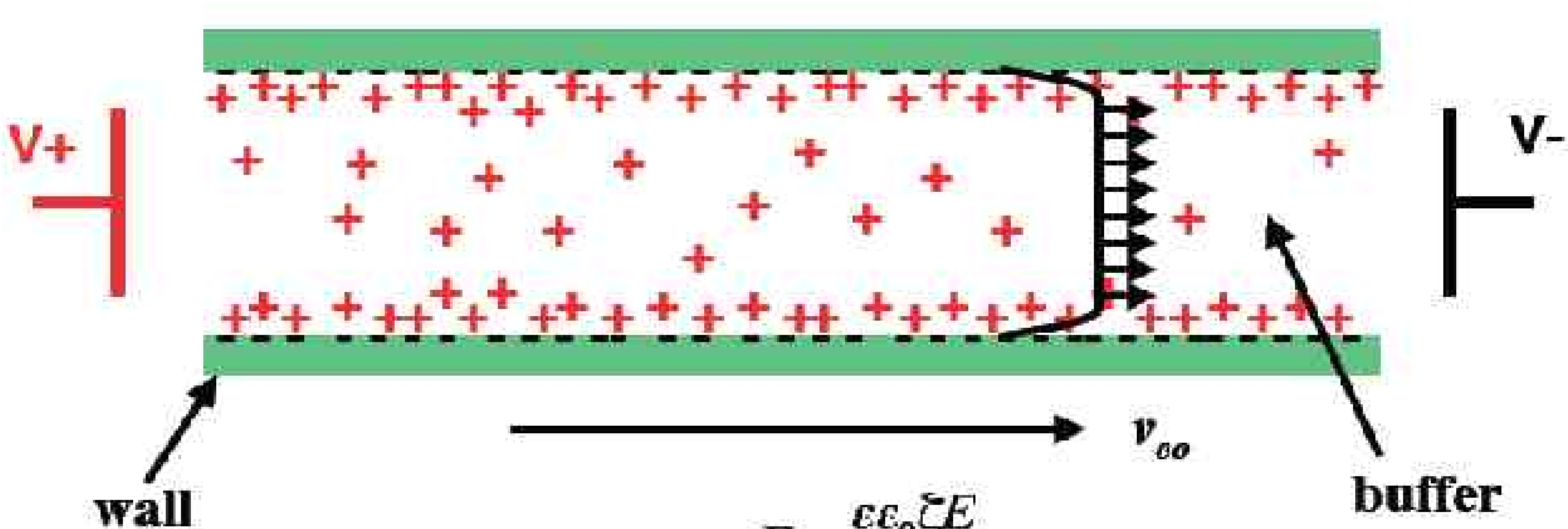



50 μm
Endoplasmic reticulum
Vacuole
Mitochondrion
Nuclear membrane
Centrioles
Nucleus
Ribosomes
Nucleolus
Golgi body
Plasma
membrane
Cytoskeleton
Lysosome
Hyaloplasm

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

Electrokinetic Transport



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

eo: electroosmosis

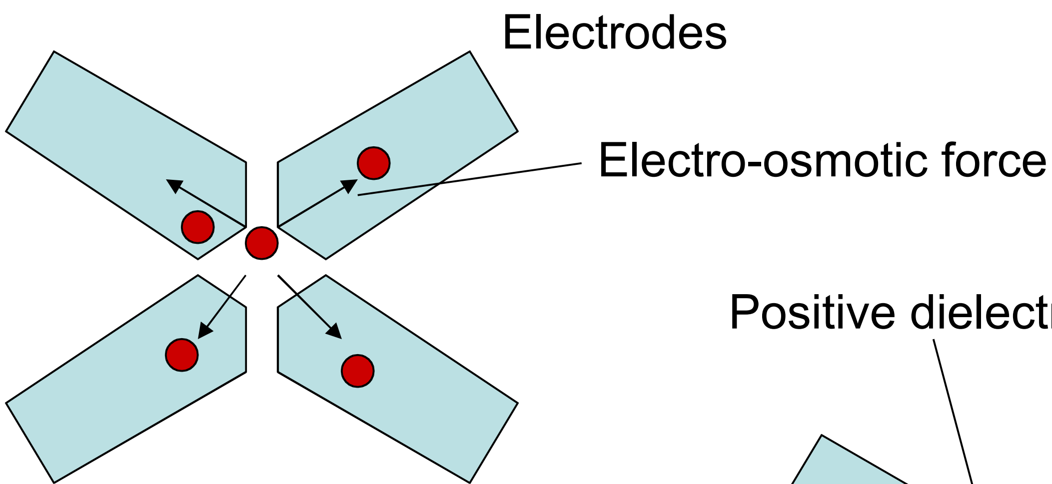
$$v_{ep} = \mu_{ep} E = \frac{ezE}{6\pi\eta r}$$

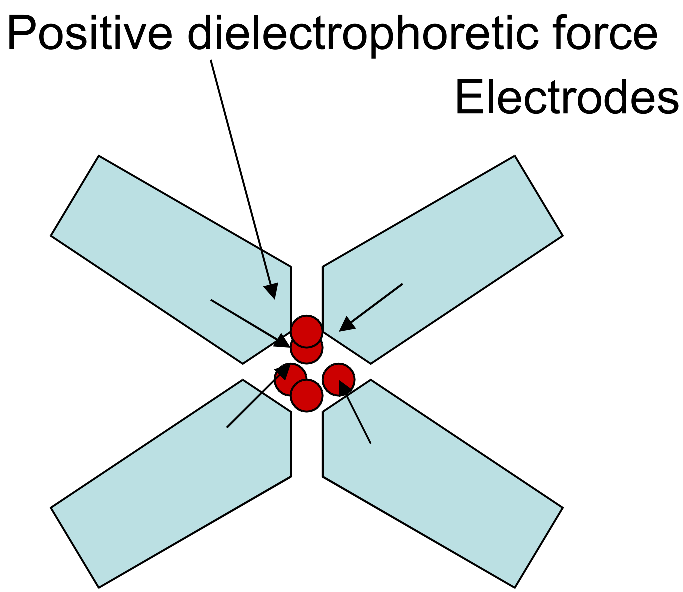
ep: electrophoresis

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

η: viscosity

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

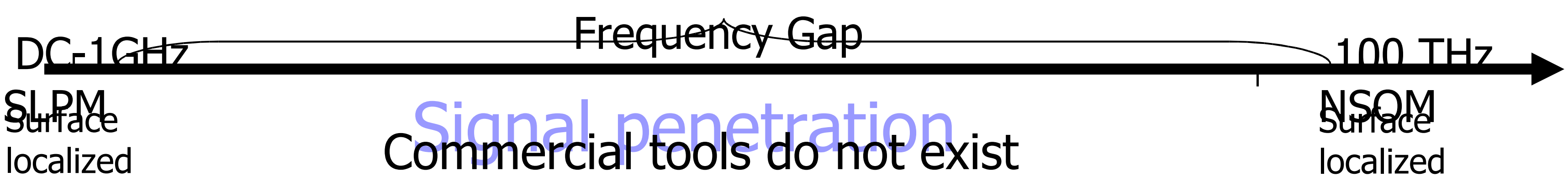




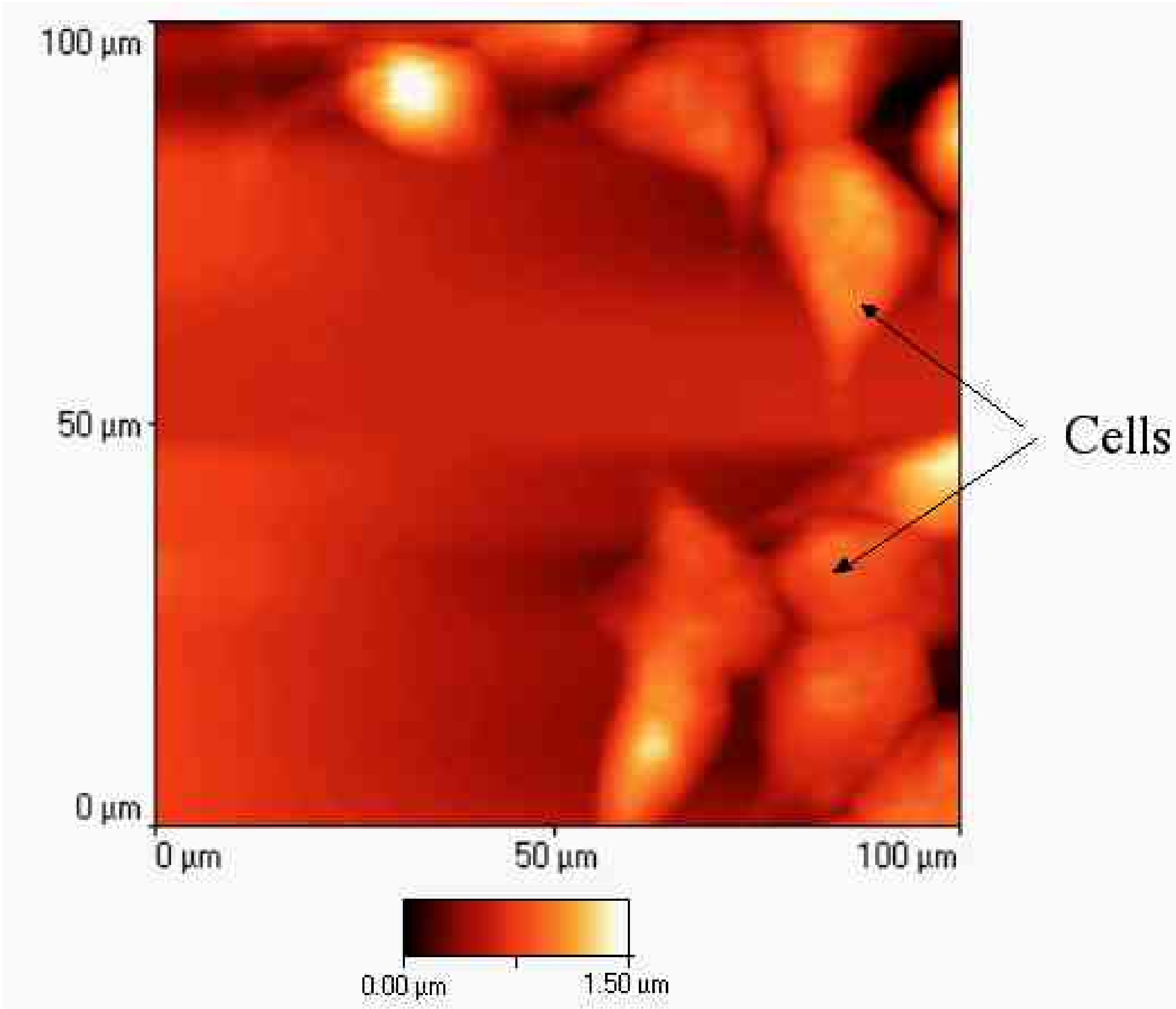
Negative dielectrophoretic force arises when ε_{real} becomes negative

Existing Tools

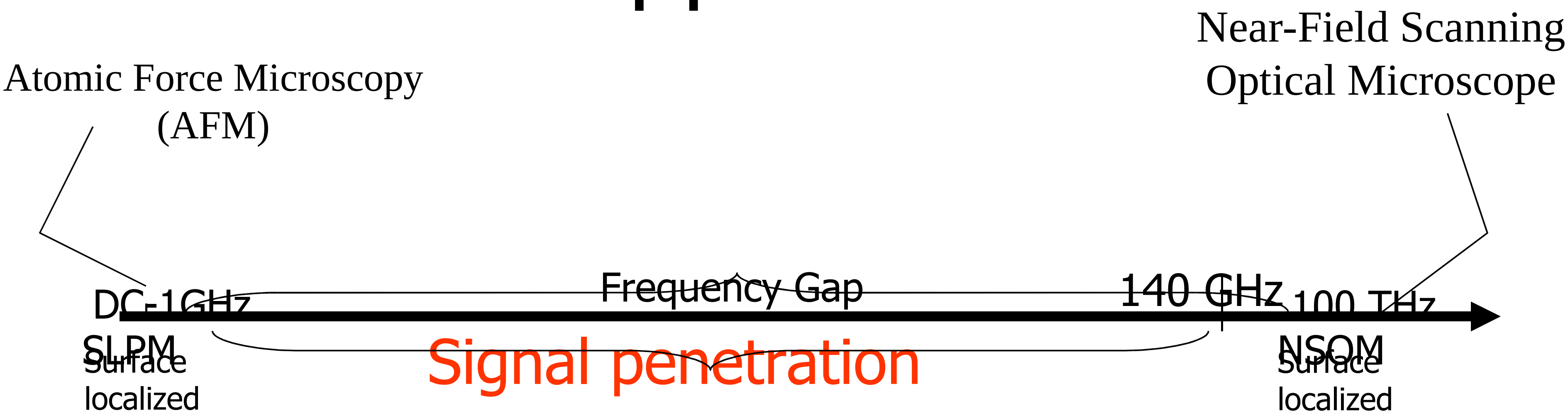
- Scanning local probe microscopy offers nearly atomic resolution:
  - Scanning tunneling microscopy (STM)~1Å
  - Atomic force microscopy (AFM)~ 10Å
  - AFM-related techniques>10Å
    - Magnetic force microscopy (MFM)
    - Scanning capacitance microscopy (SCM)
  - Near-field scanning optical microscopy (NSOM)~ 50Å



Atomic Force Microscopy (AFM) of Cells



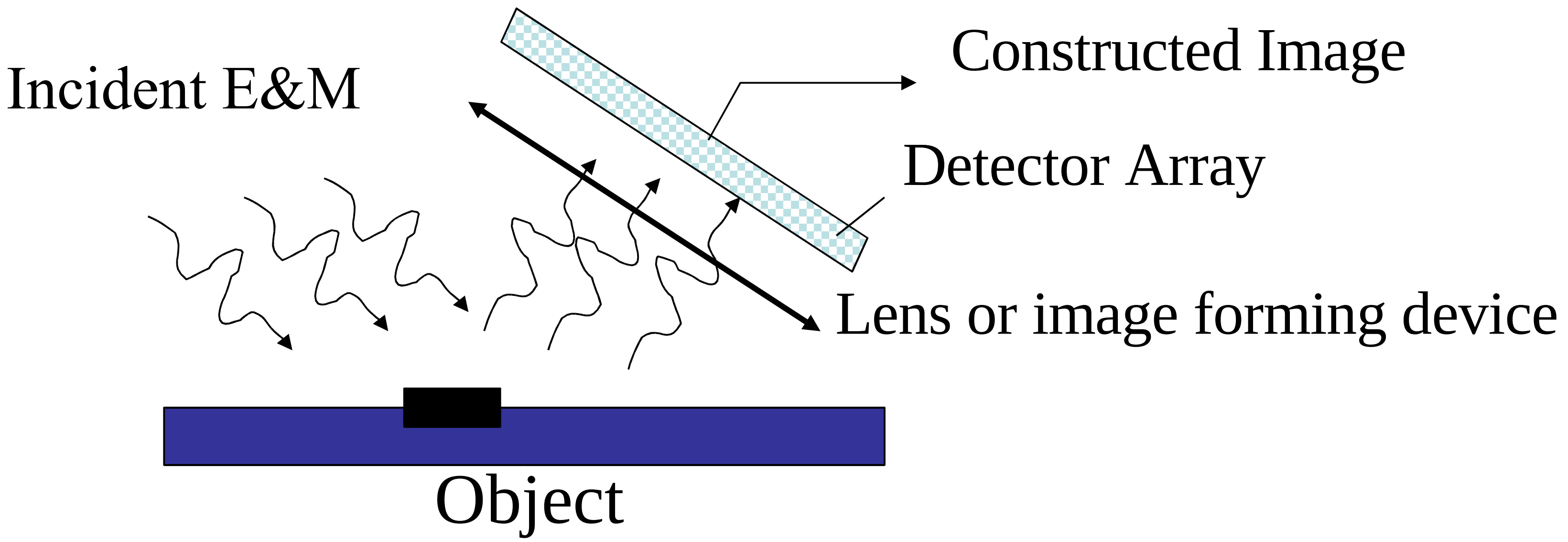
Approach



Scanning Evanescent Microwave Probe (SEMP)
Non-ionizing
Sub-surface sensitive
Nearly atomic resolution
Conductivity and permittivity information
Compatible with AFM and NSOM
Hyperspectral
Components are commercially available
Non-contact and does not require conducting sample

Challenging

Traveling wave imaging

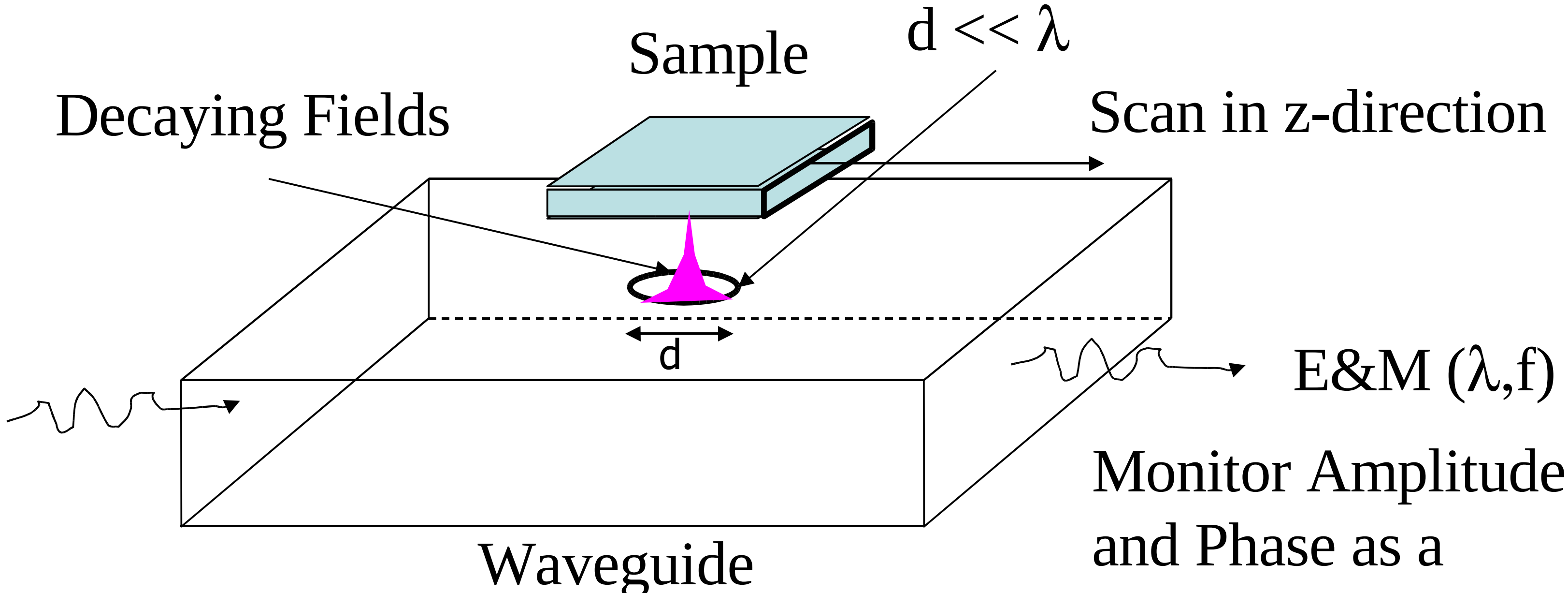


Resolution ~ Wavelength of incident E&M (λ)

Advantage: One shot imaging

E&M: electromagnetic wave

Decaying, or Evanescent Wave Imaging



Monitor Amplitude and Phase as a function of "z"

Resolution ~ d<< λ

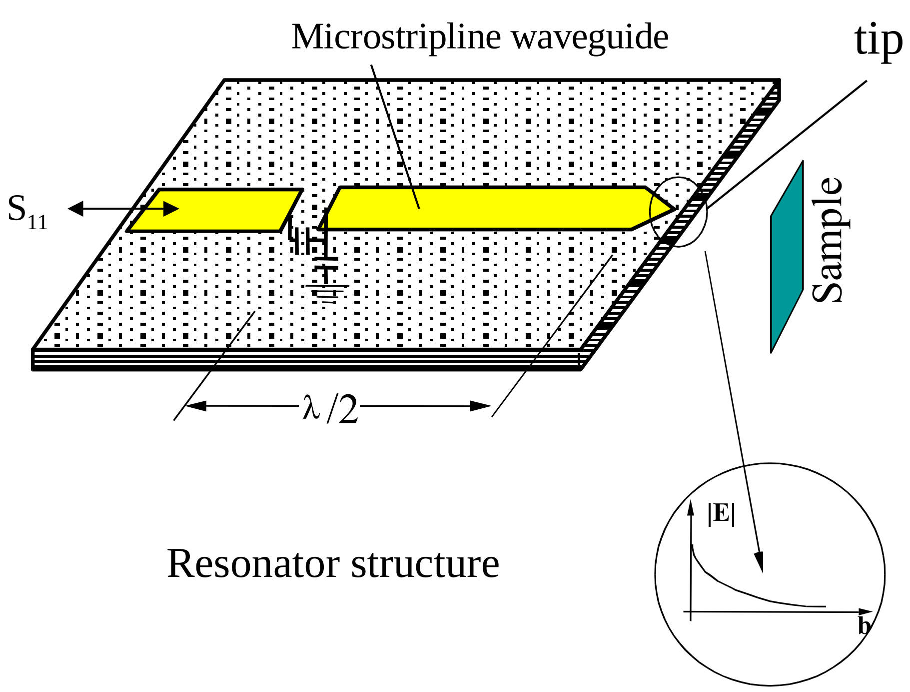
Disadvantage: Point by point imaging

λ: wavelength of E&M

d: diameter of the waveguide opening

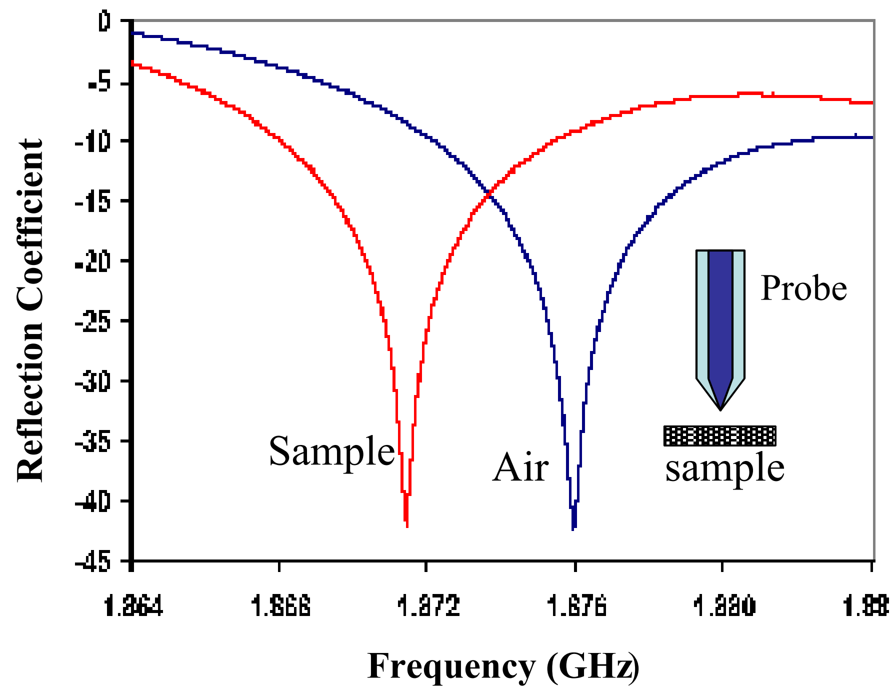
Scanning Evanescent Microwave Microscopy

- **Evanescent fields are produced at the tip of a resonator**
- **Interaction between evanescent microwave field and sample**
- **Monitoring the resonance change of the probe resonator**

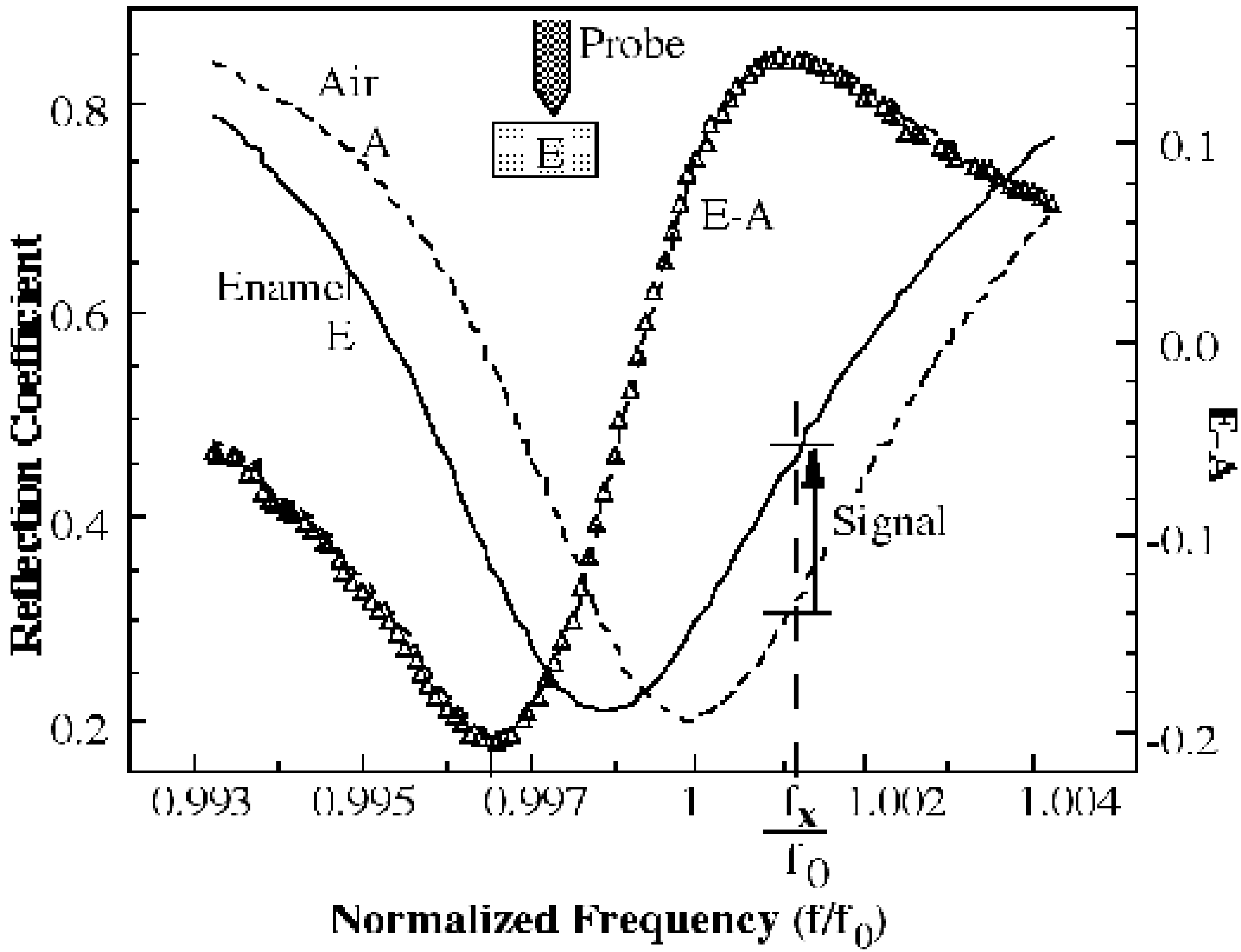


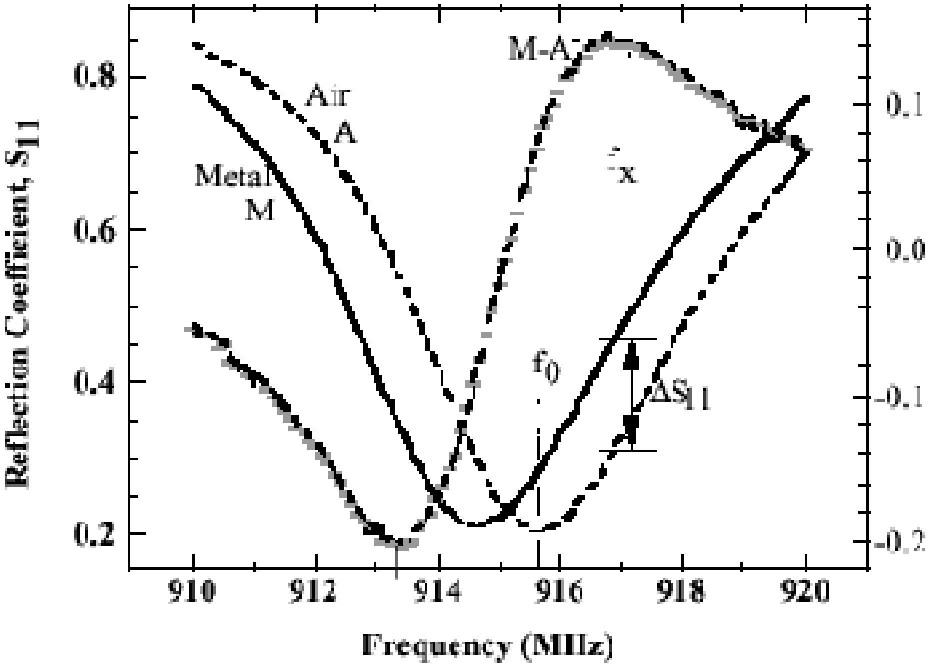
Resonator structure

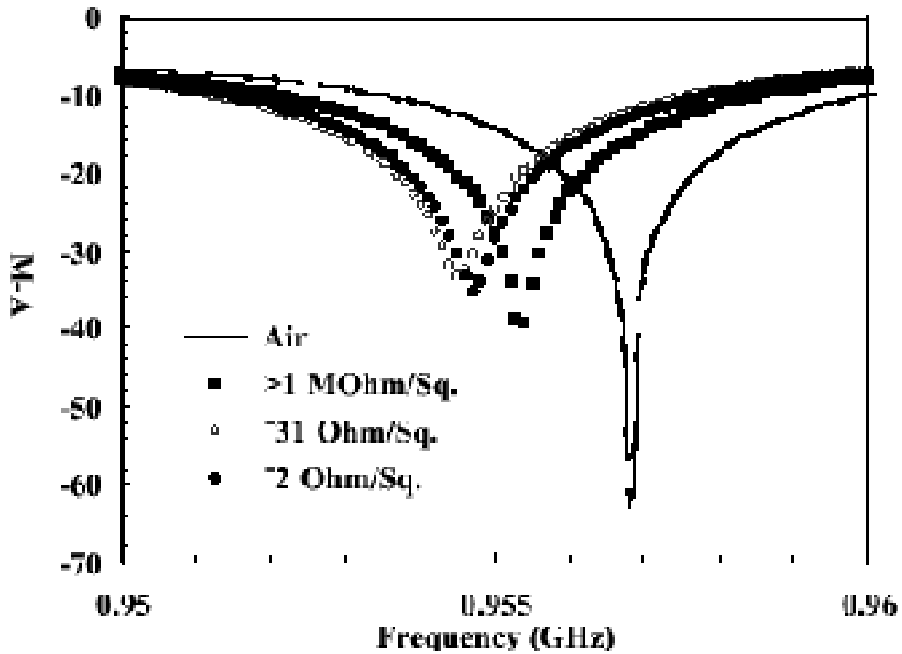
Active Probe Region

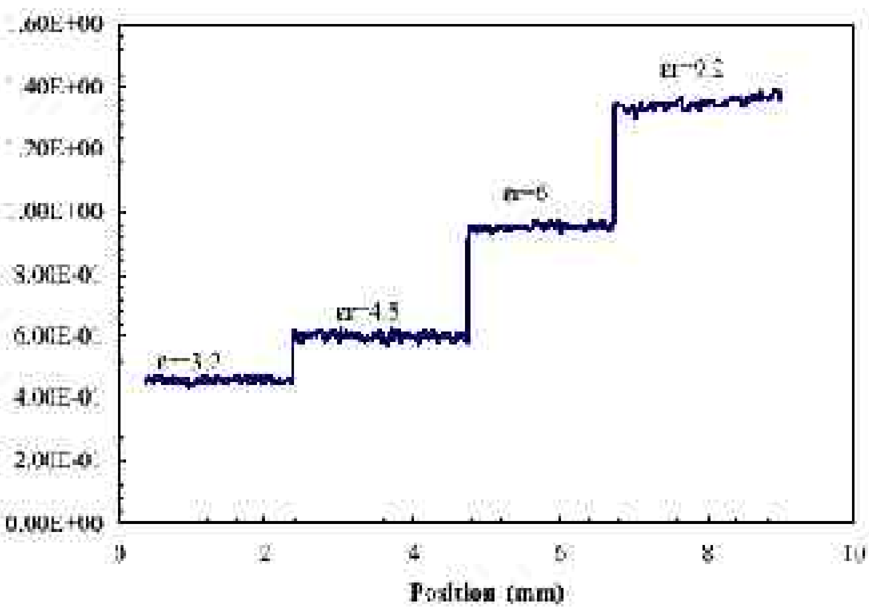


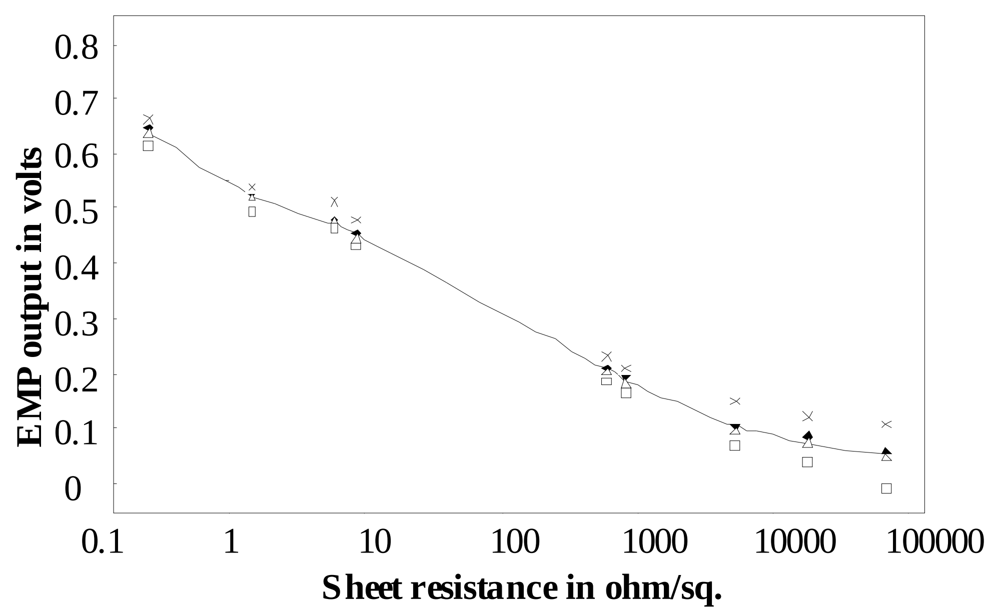
S_{11} Spectra of Human Molar Enamel




Reflection Coefficient, S11
Frequency (MHz)
0.8
0.6
0.4
0.2
910
912
914
916
918
920
0.1
0.0
-0.1
-0.2
M-A
Air
A
Metal
M
f0
ΔS11
M-A


0
-10
-20
-30
-40
-50
-60
-70
0.95
0.955
0.96
Frequency (GHz)
Air
>1 MOhm/Sq.
731 Ohm/Sq.
72 Ohm/Sq.


Position (mm)
0
2
4
6
8
10


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
EMP output in volts
0.1
1
10
100
1000
10000
100000
Sheet resistance in ohm/sq.

Experimental Arrangement

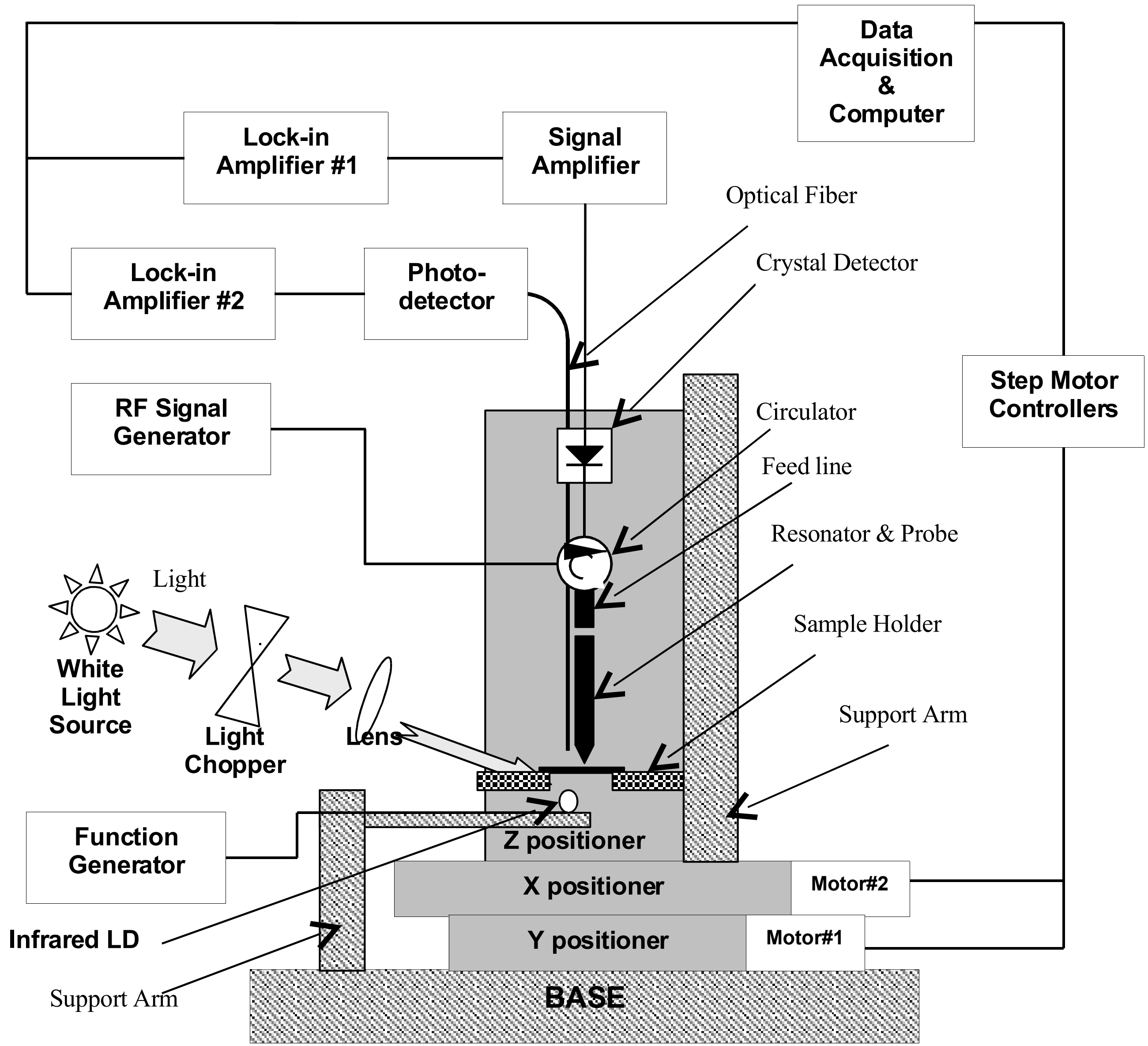
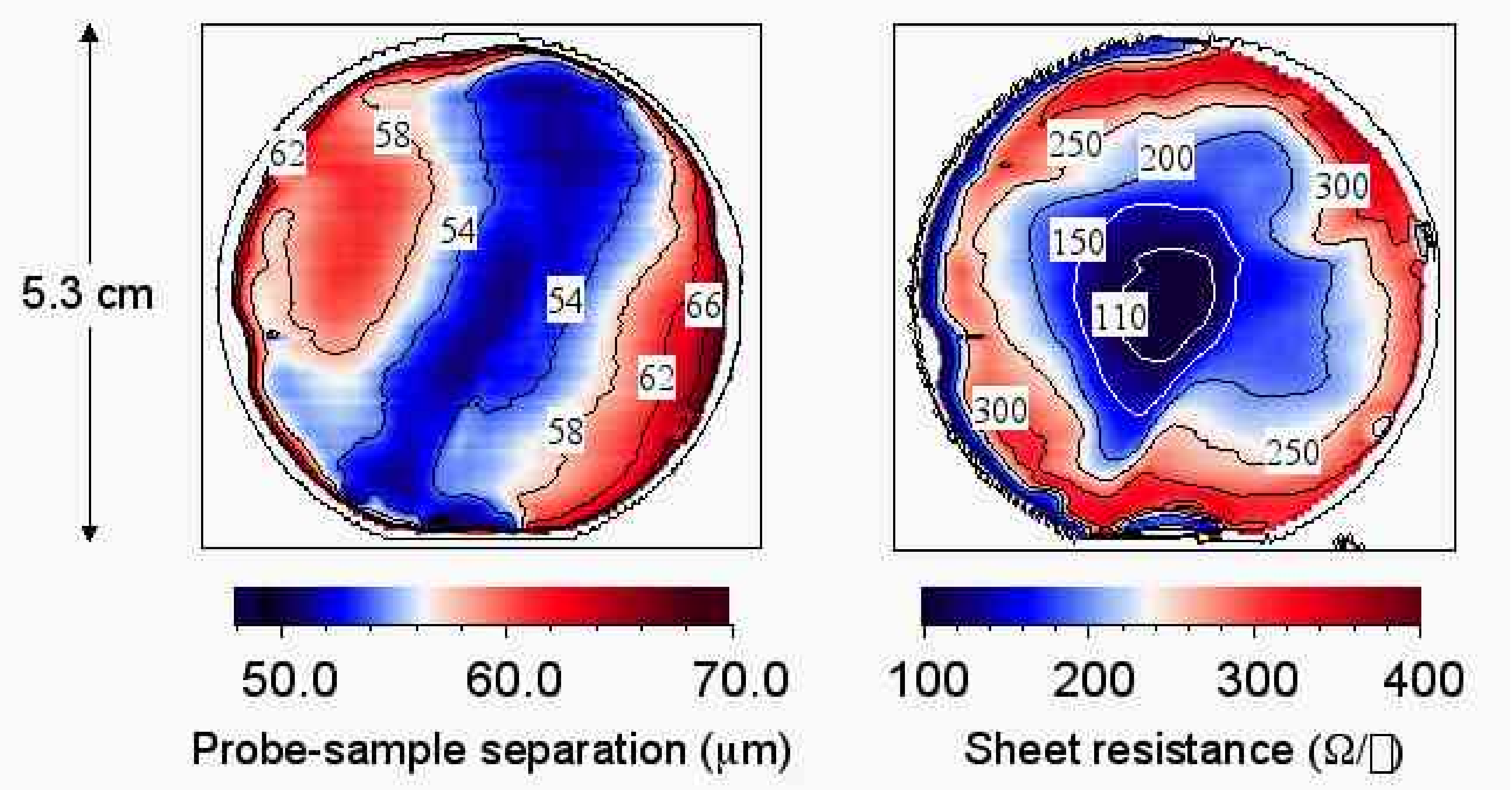


Fig. Schematic of the experimental setup

SEMP IMAGES: Topography & Sheet Resistance



Sample: $YBa_2Cu_3O_{7-\delta}$ thin film on 2” sapphire wafer

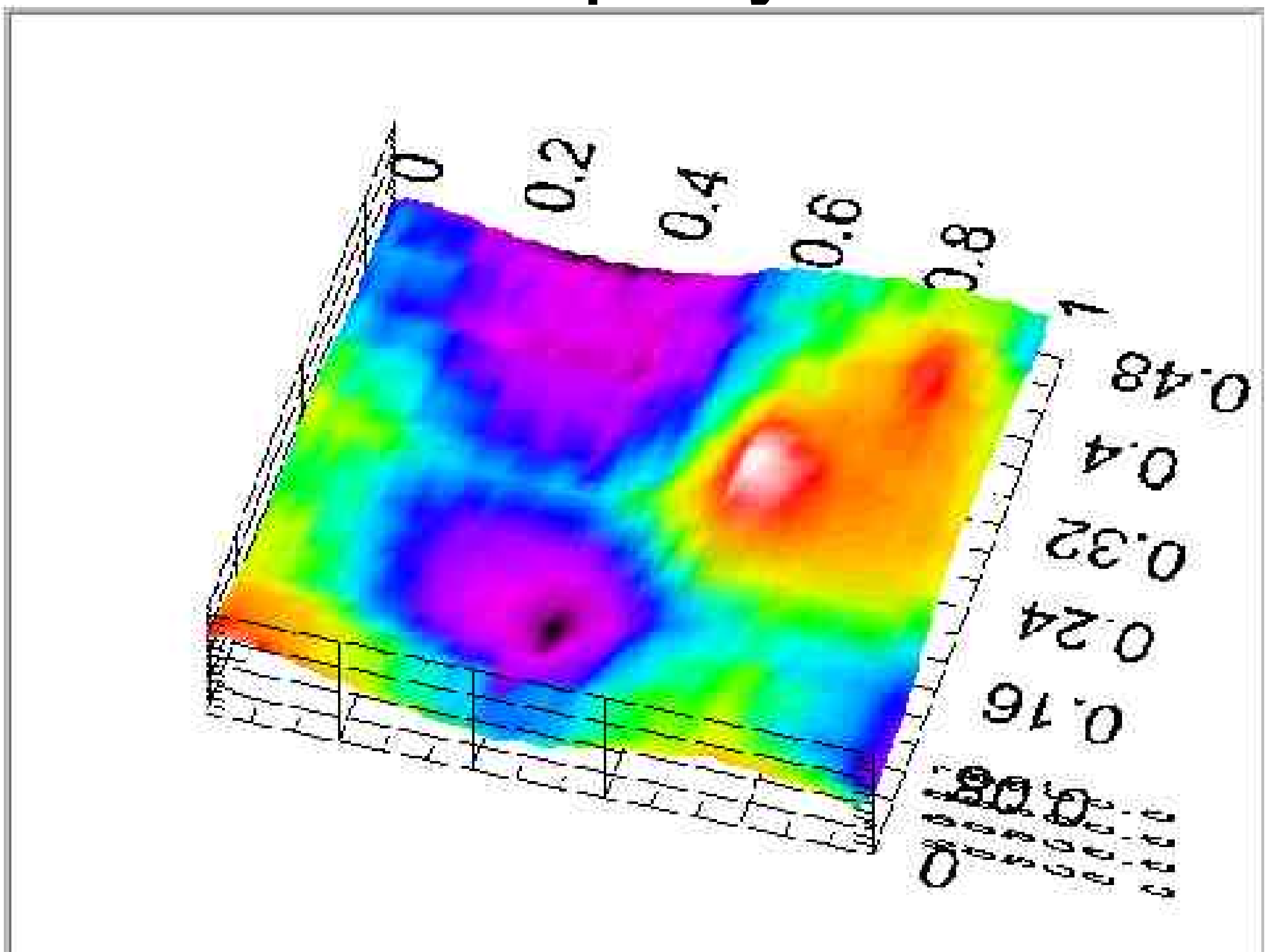
Frequency: 7.5 GHz

Temperature: 300 K

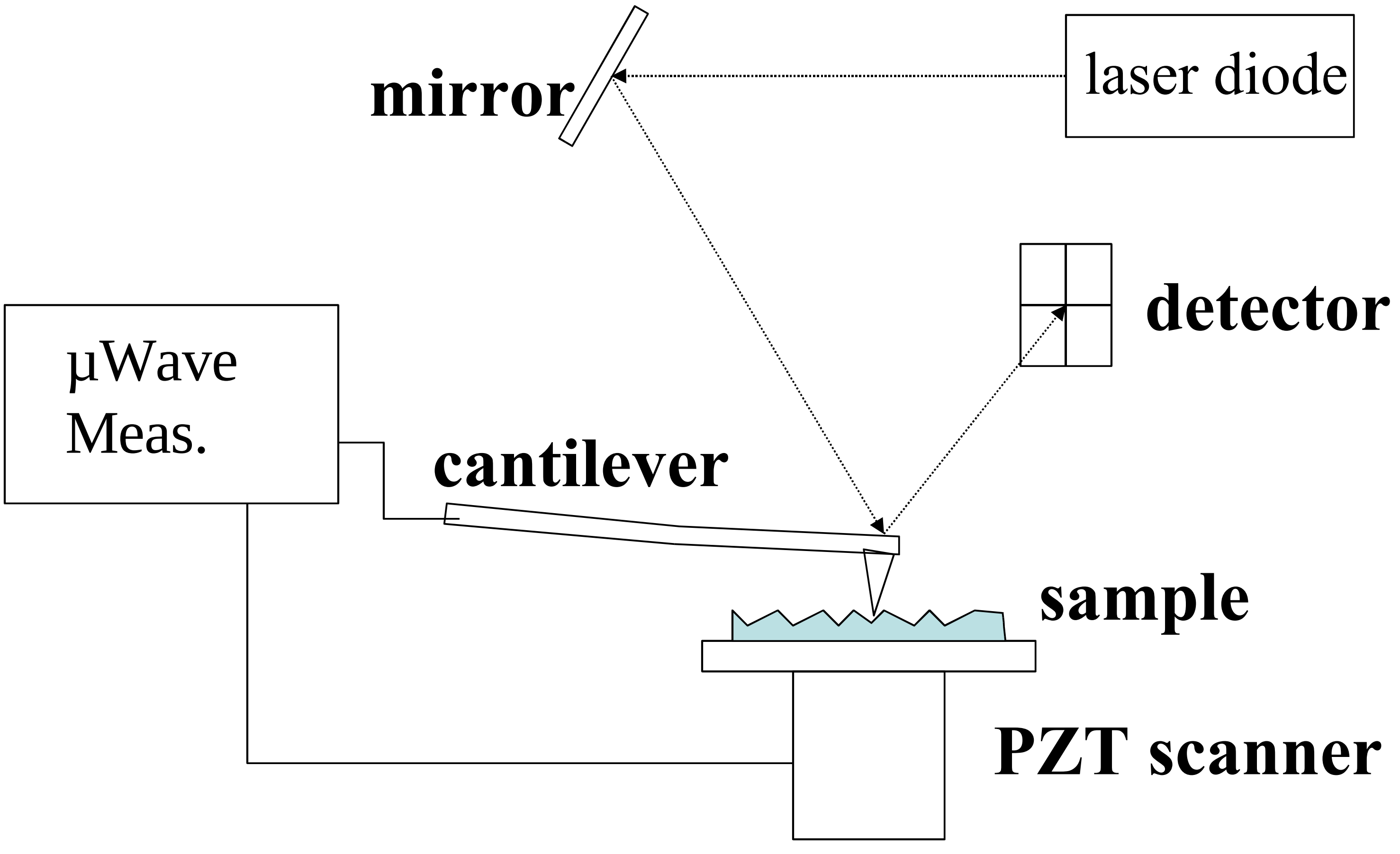
500 μm probe, in non-contact mode

Appl. Phys. Lett. **72**, 861 (1998)

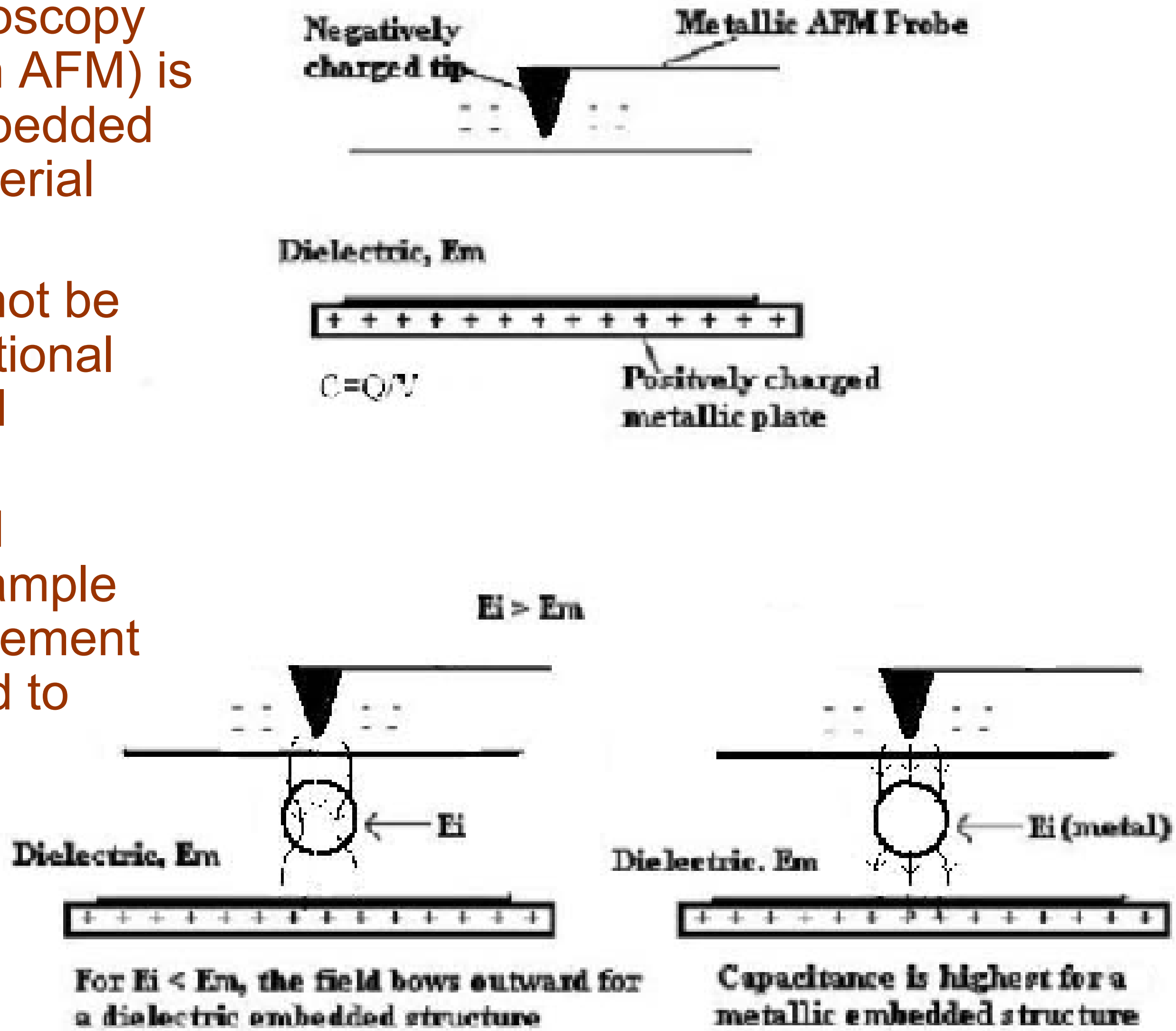
SEMP Image of Mold Release De-Bond with Two Bubbles in Epoxy



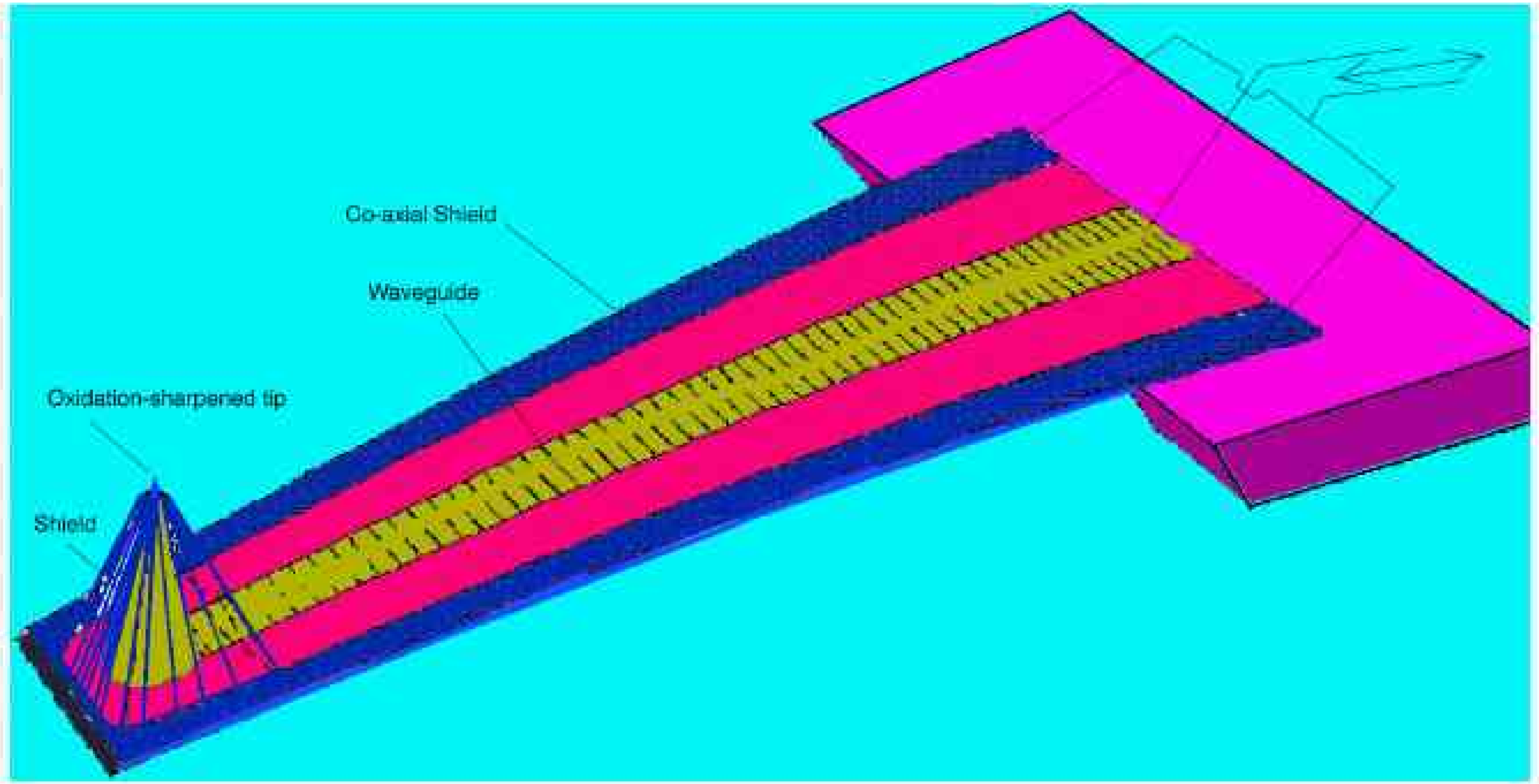
SEMP Integrated with AFM Setup



- Impedance spectroscopy (performed with an AFM) is used to image embedded structures in a material
- These embedded nanoparticles cannot be detected with traditional AFM topographical probing.
- A.C. signal applied between tip and sample results in a displacement current that is used to detect embedded structures.



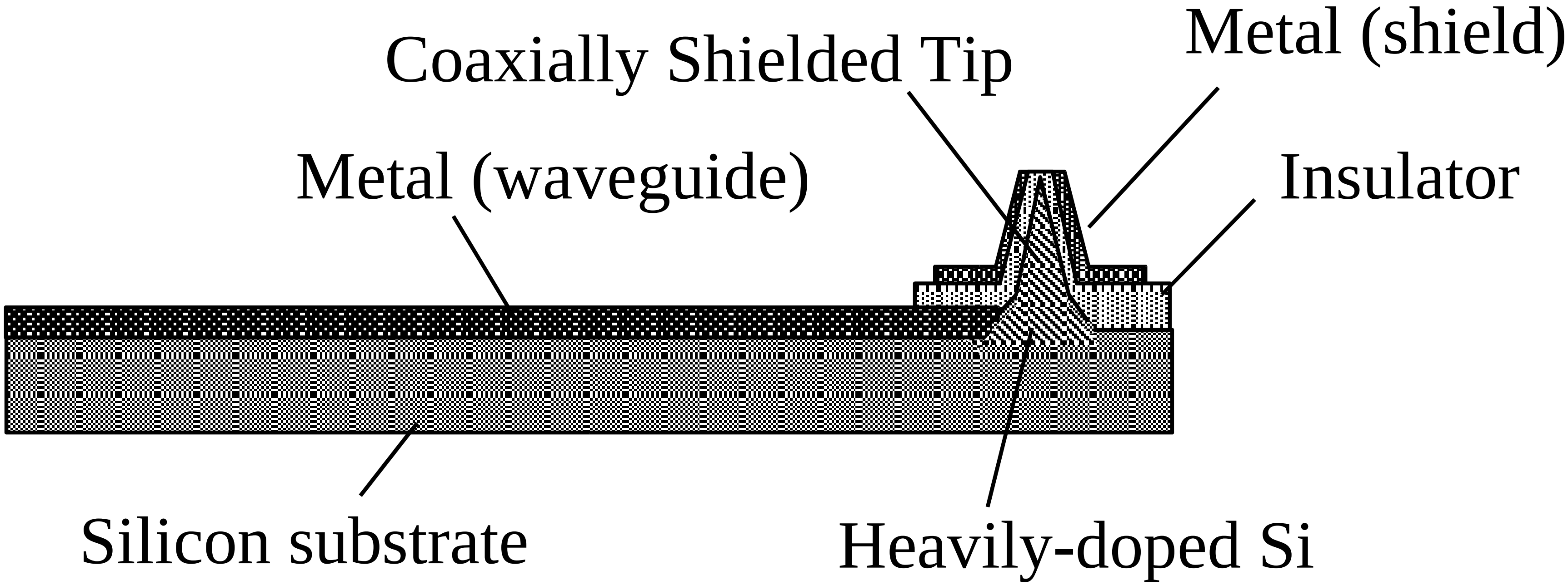
AFM-Compatible SEMP tip



- No cutoff frequency with coaxial geometry
- Shielded to limit Coulomb interactions and increase electric-field resolution
- Orthogonal, simultaneous probing of topography/field

SEMP-AFM Combined Imaging

Probe Cross Section



Mechanical Design

$$E = \frac{E_{si} t_{si} + E_{LTO} t_{LTO} + E_{Al} t_{Al}}{t_{si} + t_{LTO} + t_{Al}}$$

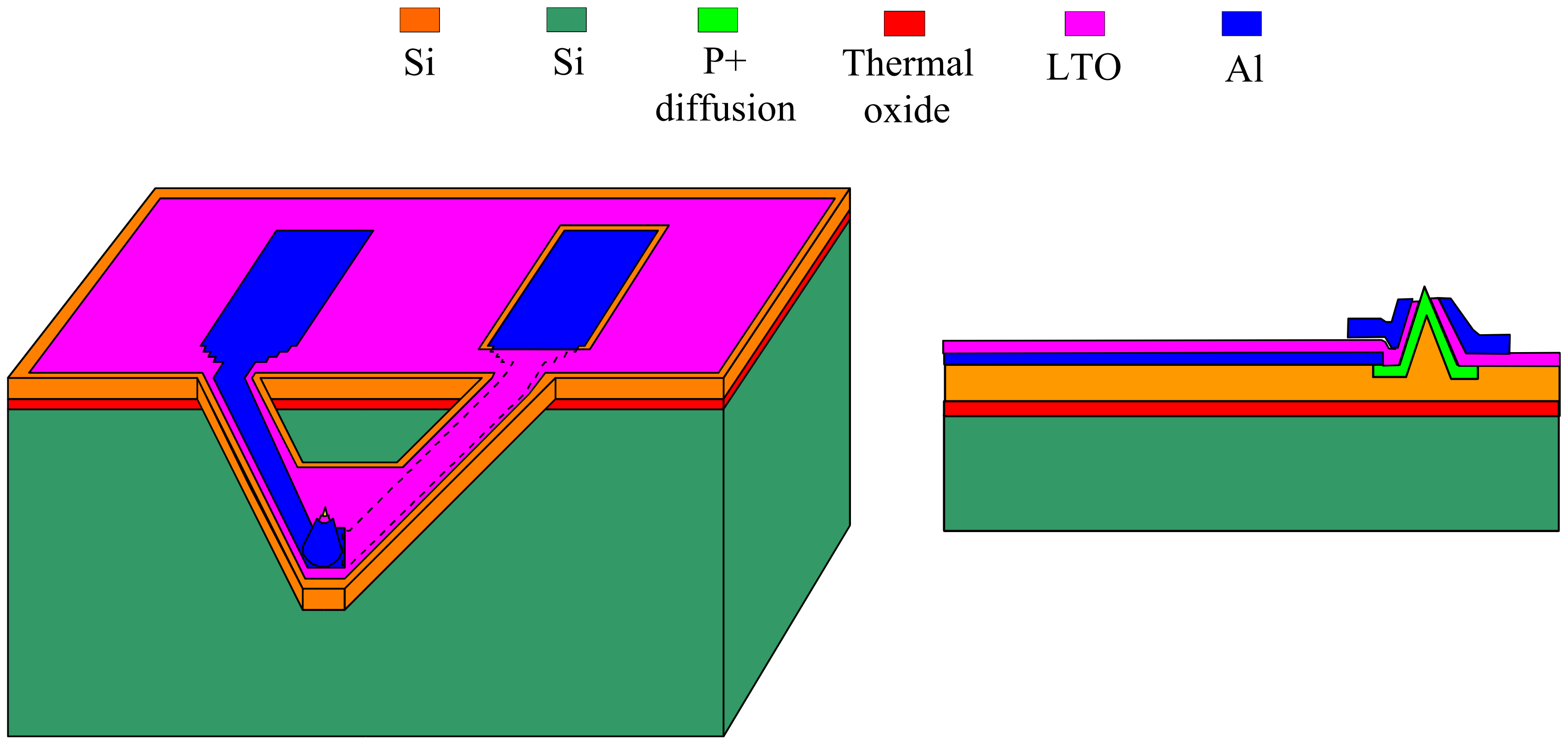
$$\rho = \frac{\rho_{si} t_{si} + \rho_{LTO} t_{LTO} + \rho_{Al} t_{Al}}{t_{si} + t_{LTO} + t_{Al}}$$

$$K = \frac{6EI}{L^3} = \frac{EW}{2}\left(\frac{t}{L}\right)^3$$

$$f_0 = \frac{3.52}{\pi} \frac{t}{L^2} \sqrt{\frac{E}{12\rho}}$$

W = 50 μm	L = 300 μm		L = 450 μm		L = 1000 μm	
	t = 3 μm	t = 5 μm	t = 3 μm	t = 5 μm	t = 3 μm	t = 5 μm
Spring constant (N/m)	5.84	21.7	1.73	6.42	0.16	0.59
Resonant frequency (KHz)	95.5	150	42.5	66.5	8.60	13.5

Scanning Near-field Microwave Microscope Probe



(a)

Three dimensional view of an SNMM probe

(b)

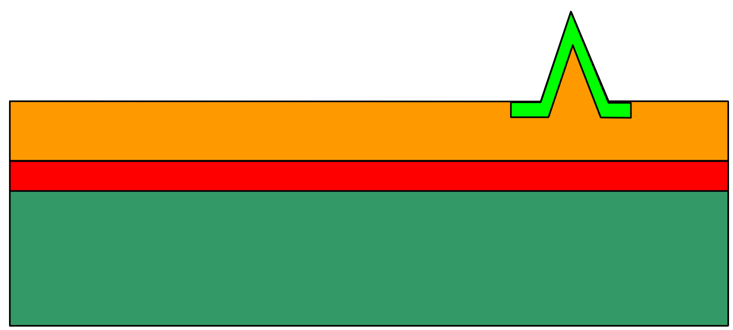
Cross-section view along a waveguide arm

Microfabrication: Tip Formation

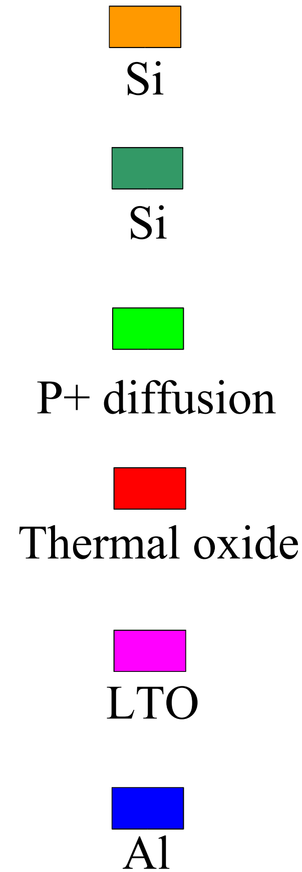
Thermal oxidation
Lithography
Oxide etching
Plasma etching tip

(a)

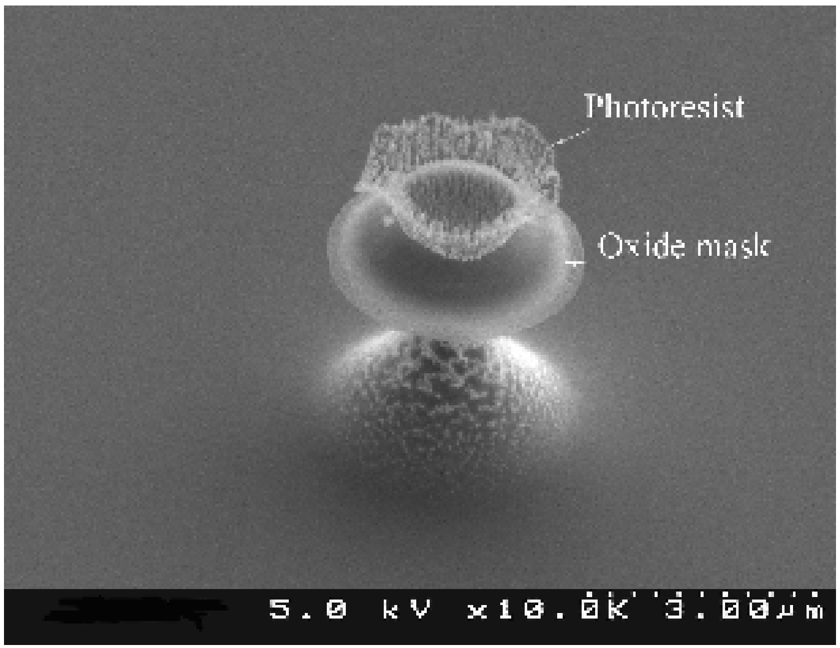
Oxidation sharpening
Lithography
Oxide etching
P+ ion implantation

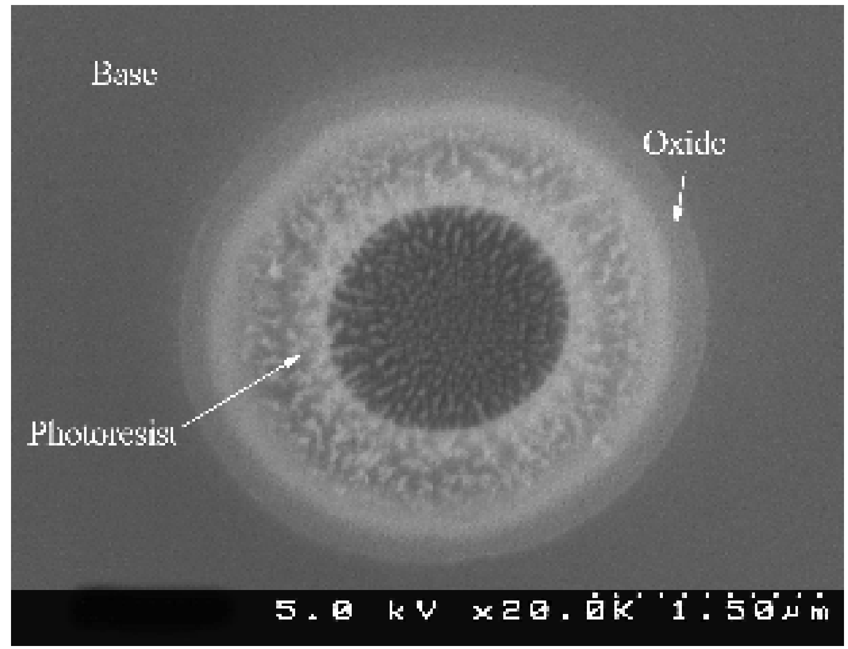


(b)

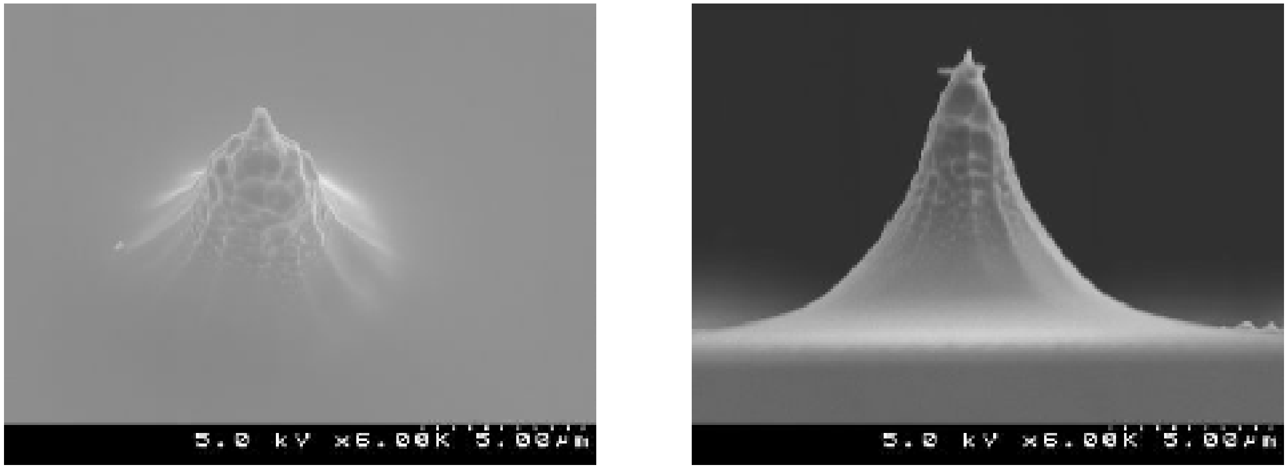


Si Tip after Plasma Etching

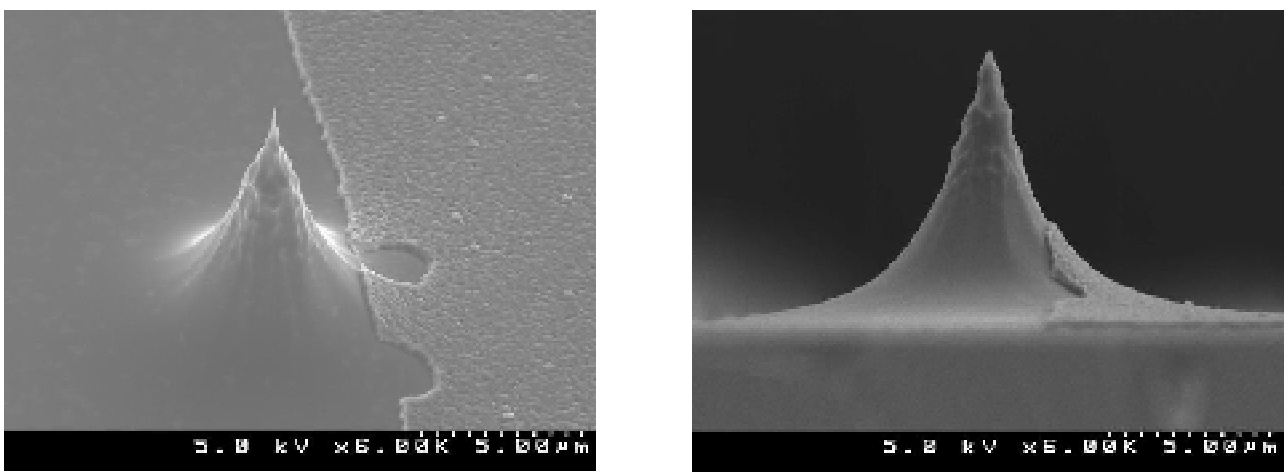




Si Tips before and after Oxidation Sharpening



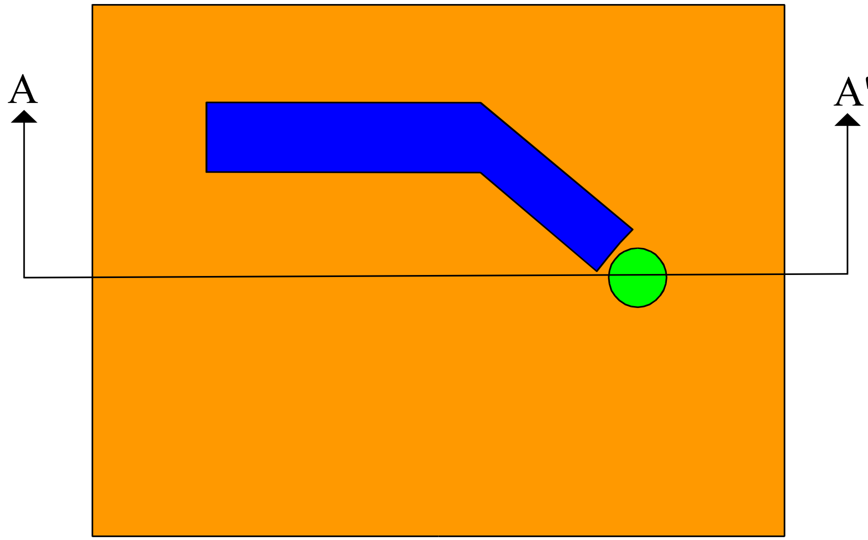
(a) Before oxidation sharpening



(b) After oxidation sharpening

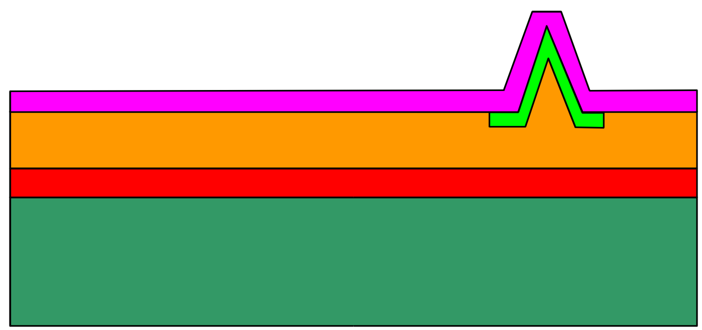
Microfabrication: Waveguide

Metal deposition
Lithography
Metal etching

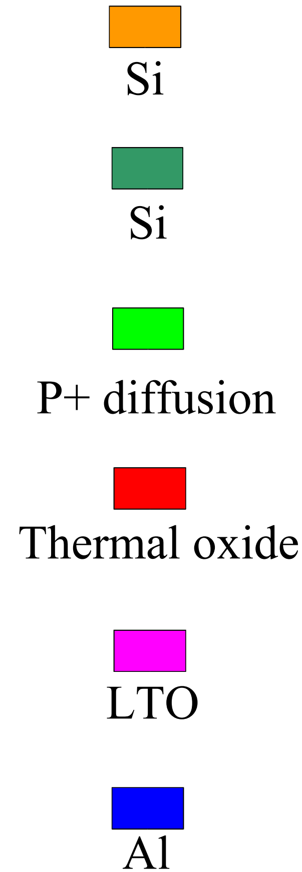


(c)

LTO deposition



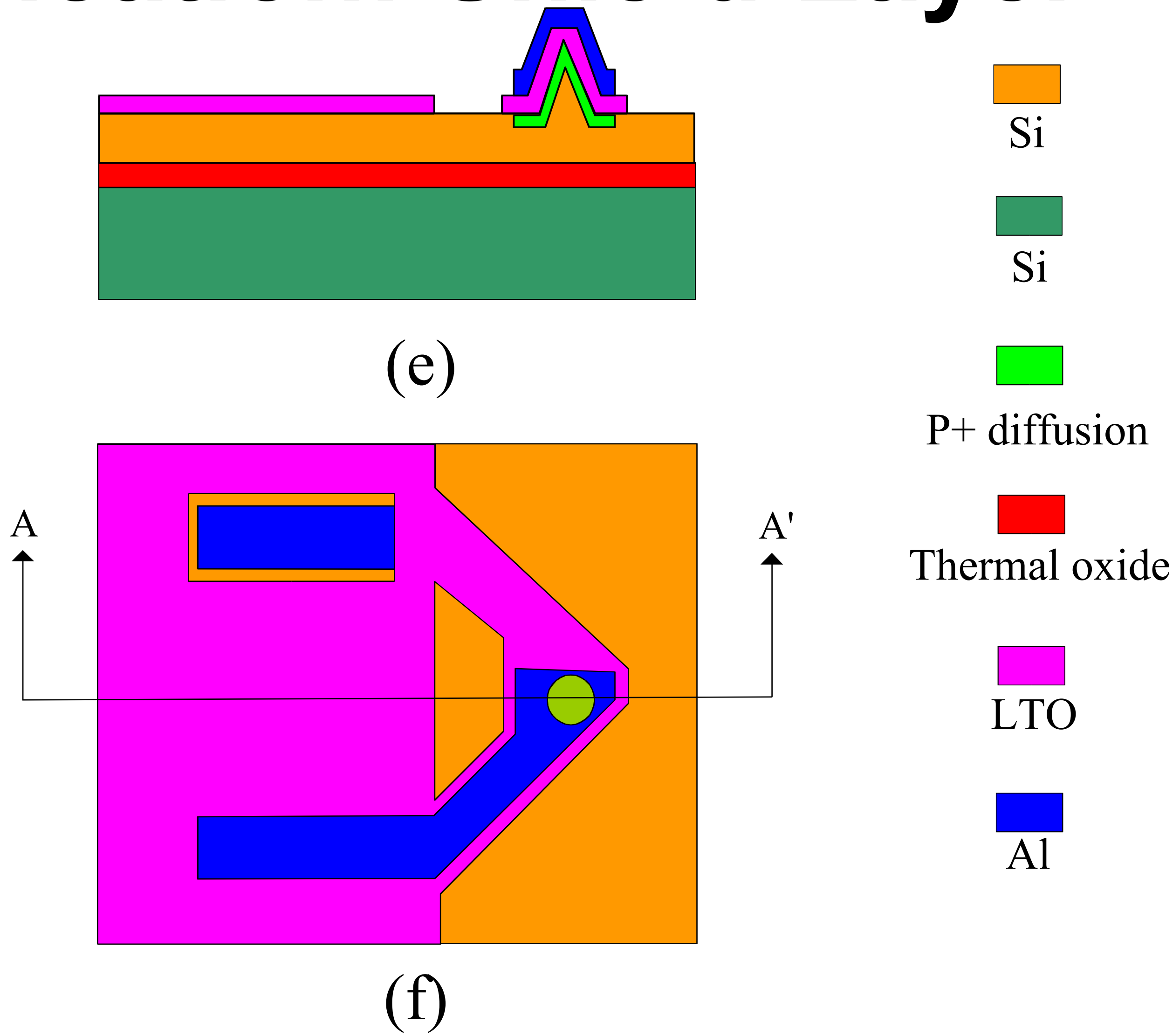
(d)



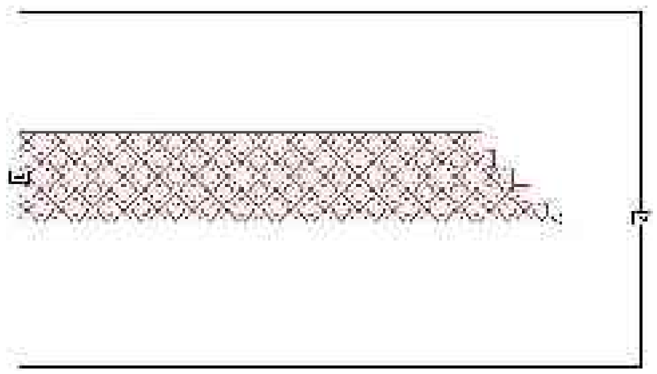
Microfabrication: Shield Layer

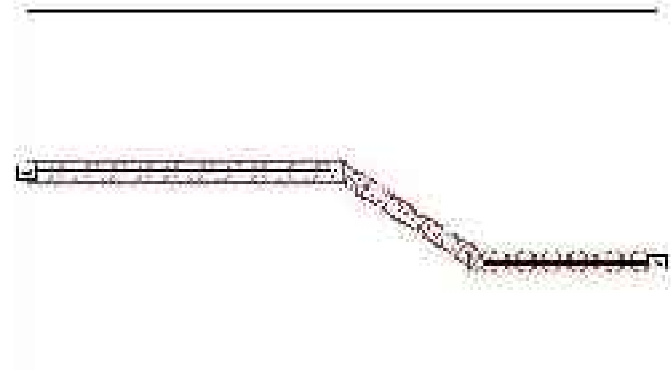
Metal deposition
Lithography
Metal etching
Lithography
LTO etching

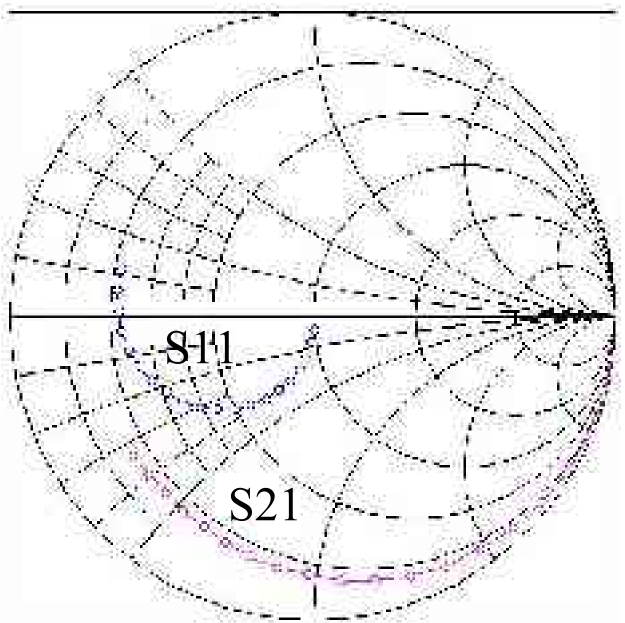
Top view
after step (e)

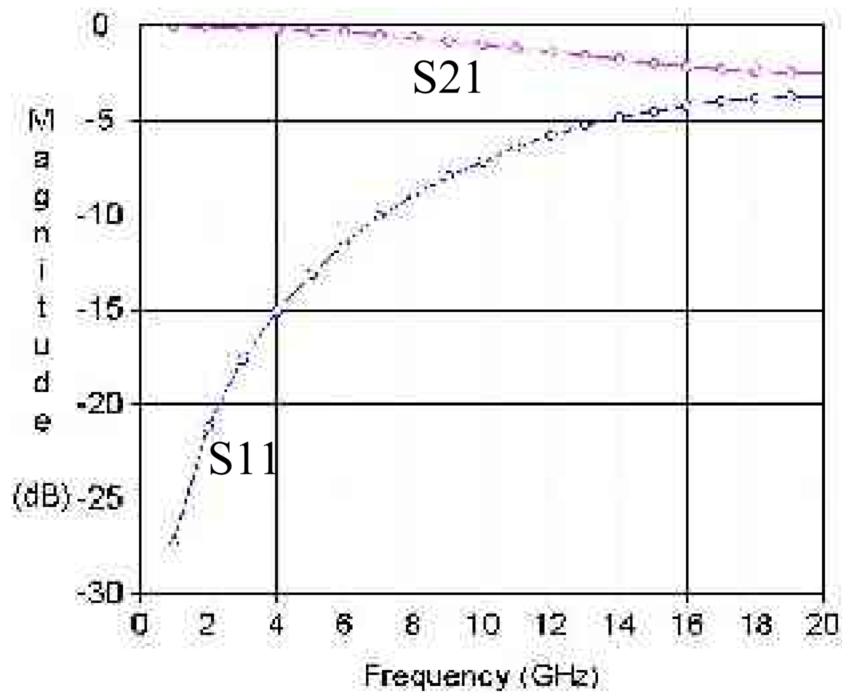


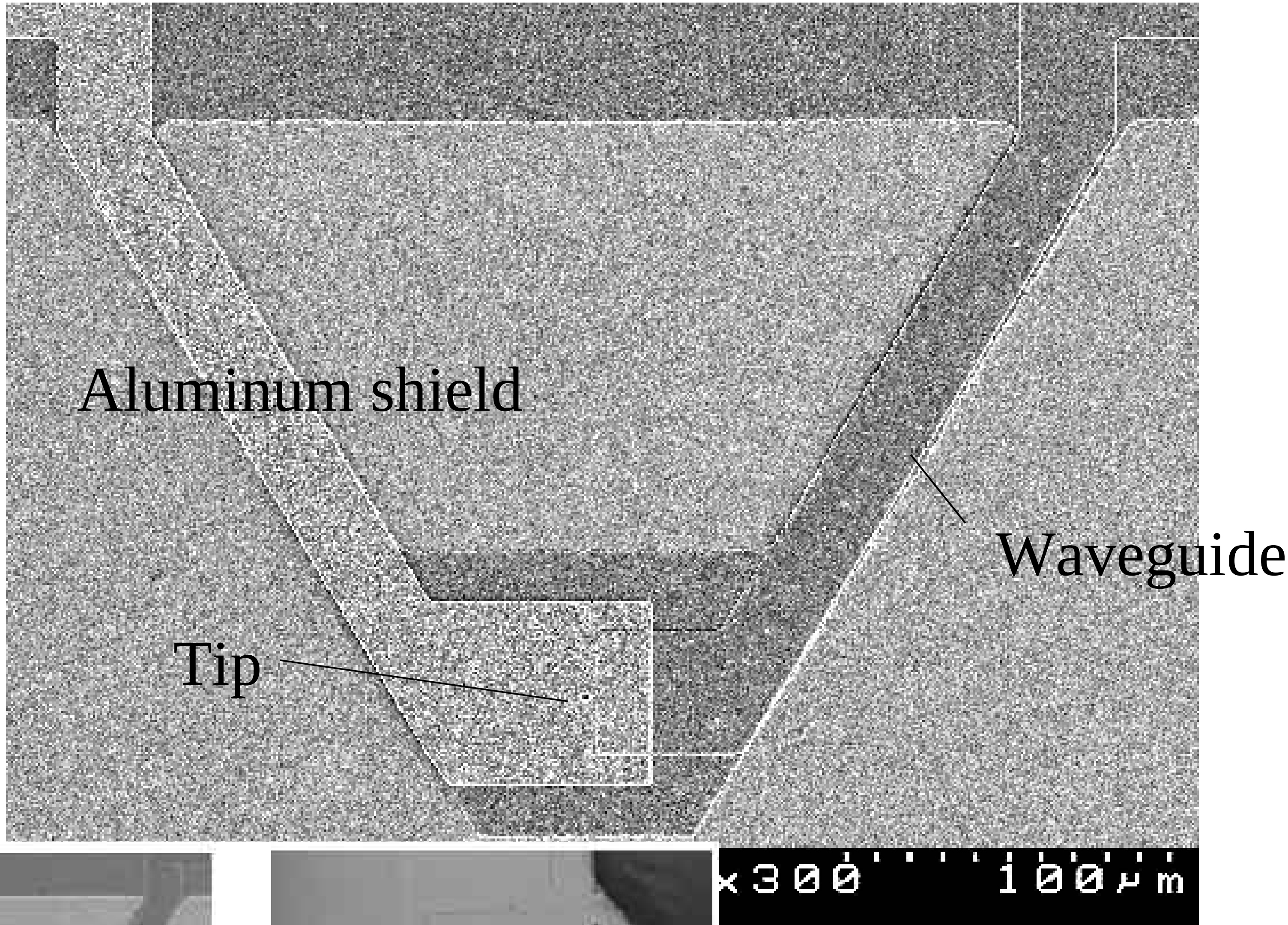
Microwave Design

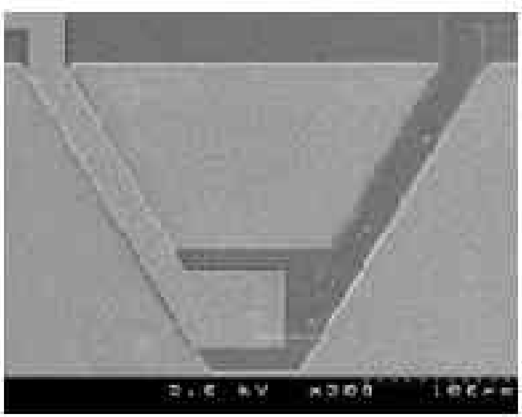




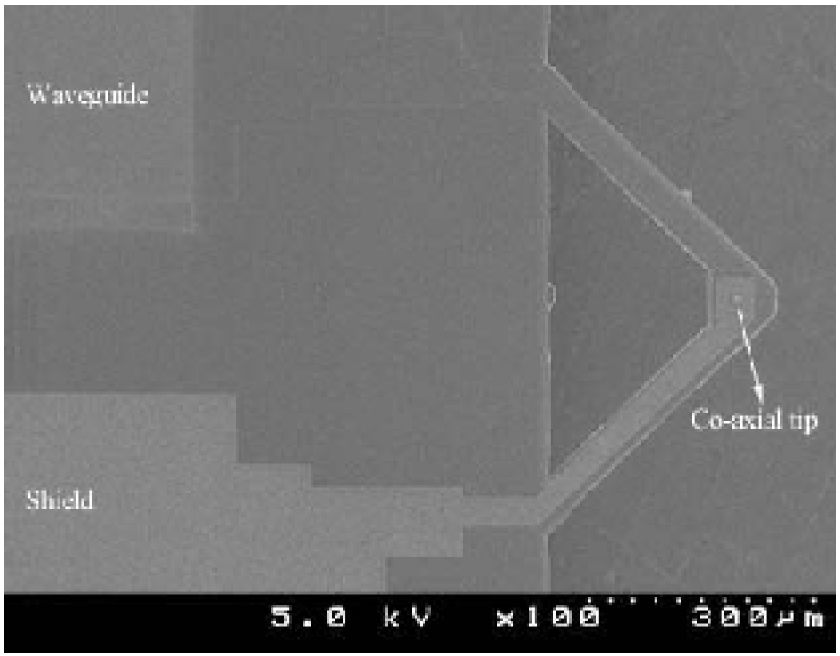


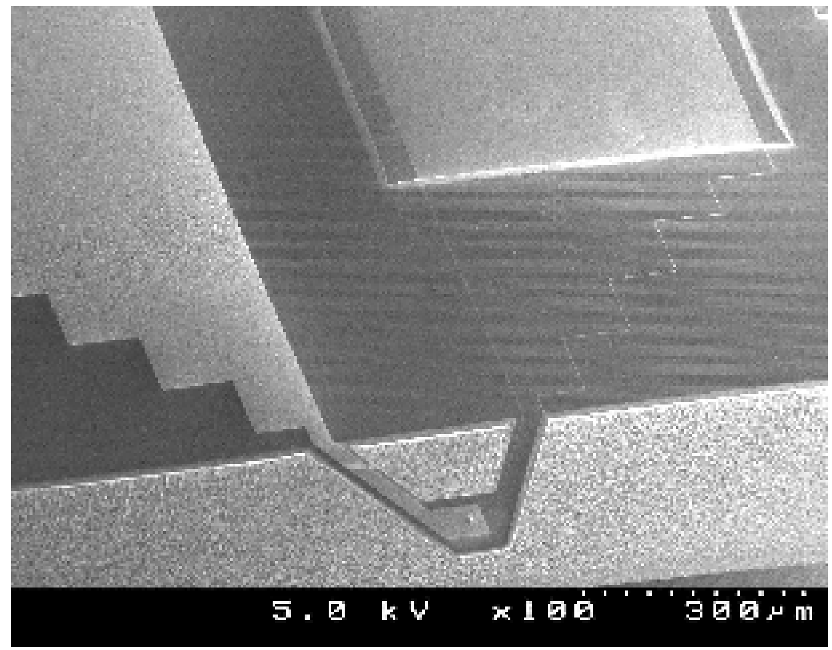



Aluminum shield
Waveguide
Tip
×300 100µm



Released SNMM Probes

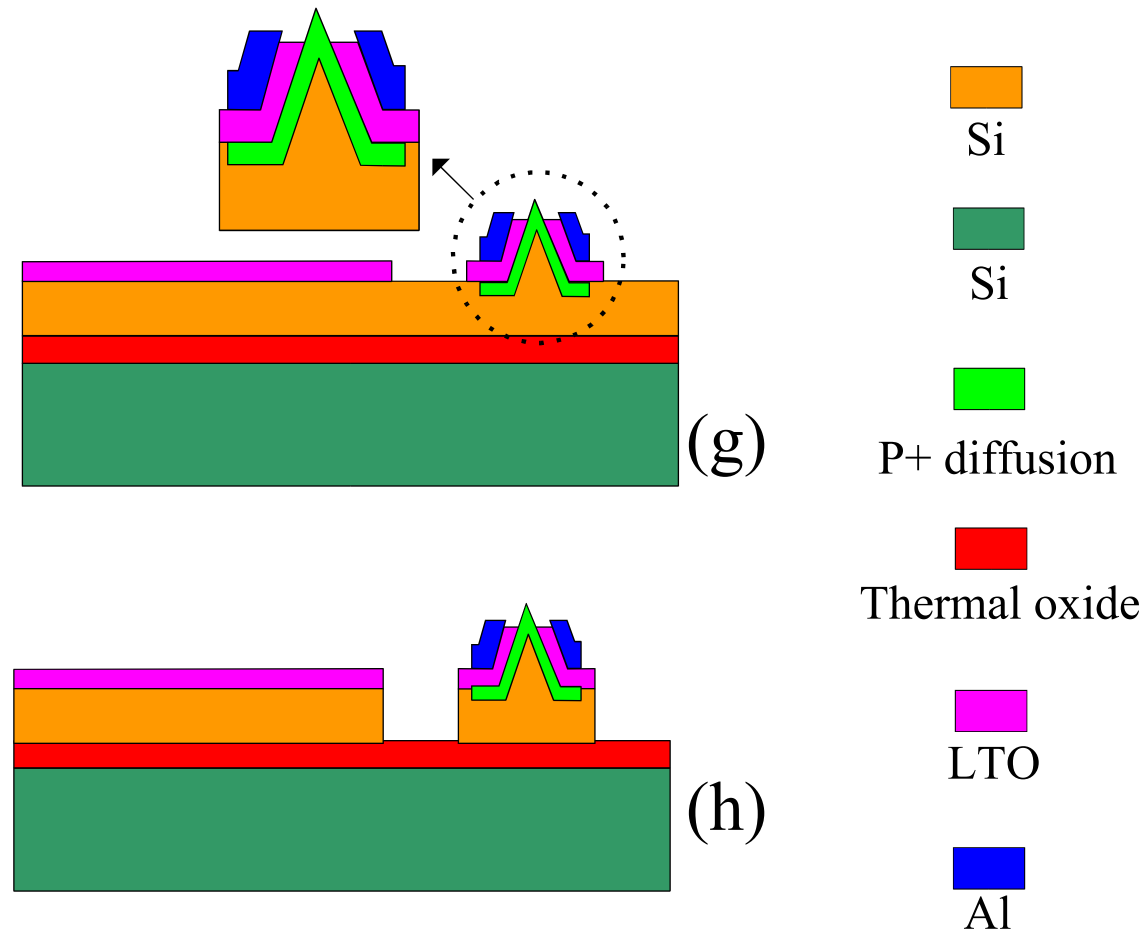




Microfabrication: Tip Exposure

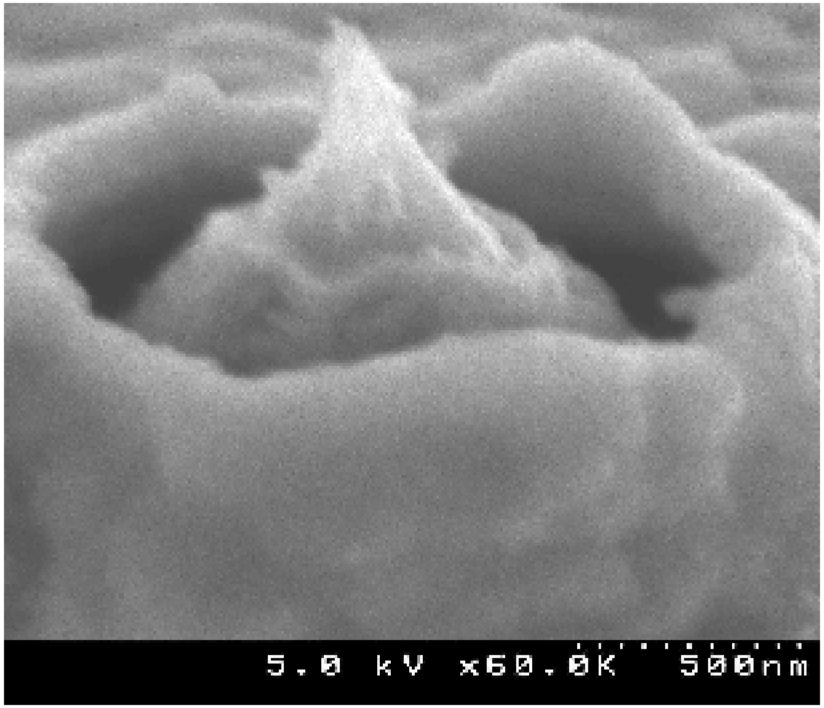
PR coating
Tip exposure
Metal etching
LTO etching

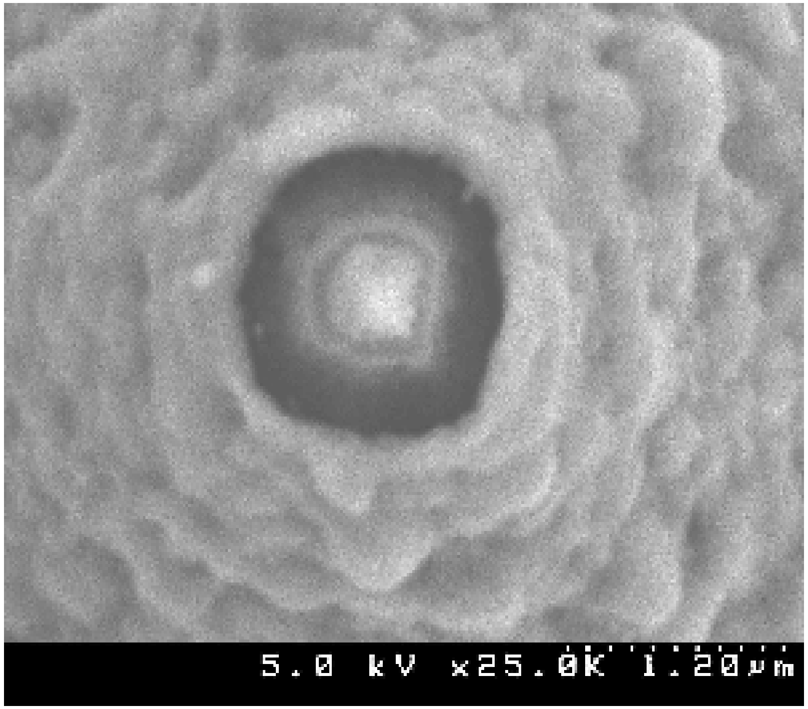
Lithography
Si RIE



Y. Wang and M. Tabib-Azar, "Microfabricated Near-field Scanning Microwave Probes," Electron Devices Meeting, IEDM '02. Digest. International, IEEE, pp. 905-908 (2002).

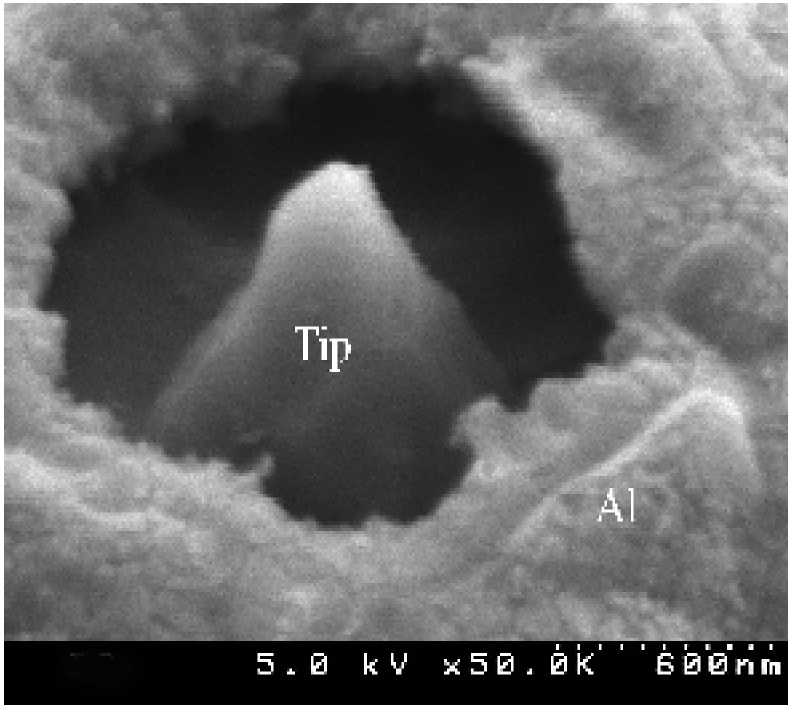
Co-axially Shielded Tip (2)





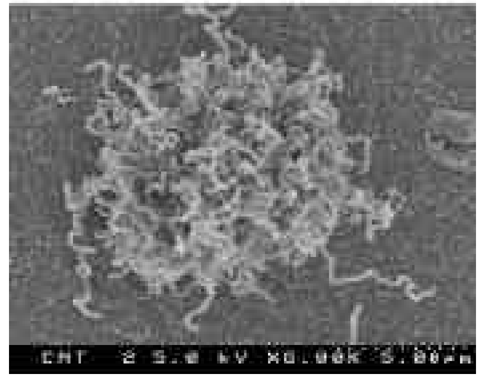
Y. Wang and M. Tabib-Azar, “Microfabricated Near-field Scanning Microwave Probes,” Transducers '03

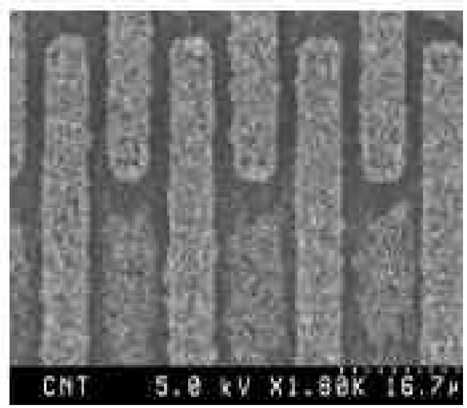
Coaxially shielded tip

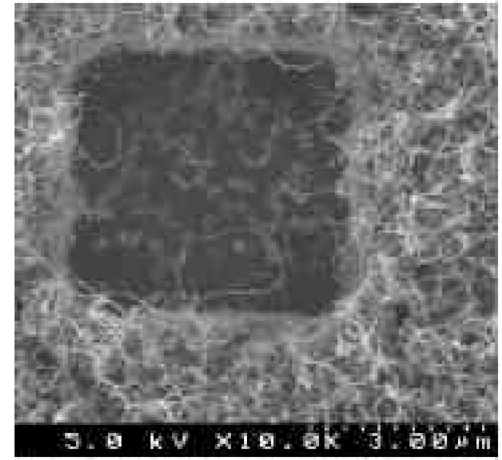


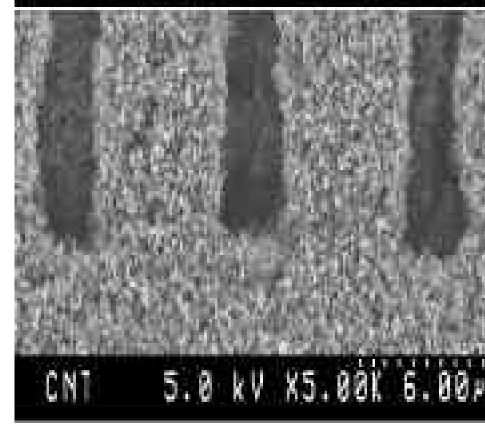
Carbon Nanotubes & Nanospheres

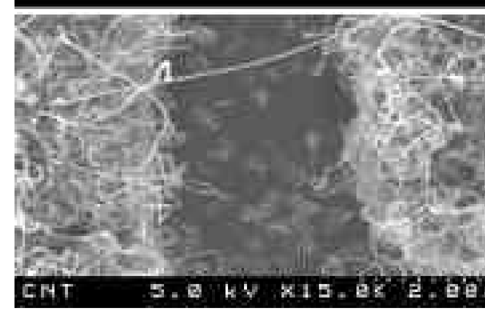
Self-Assembled on Electrodes

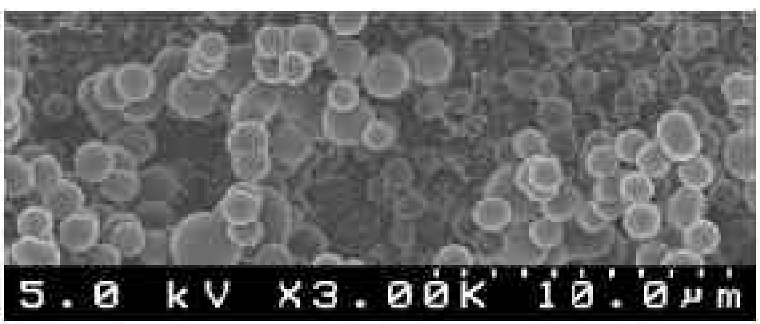


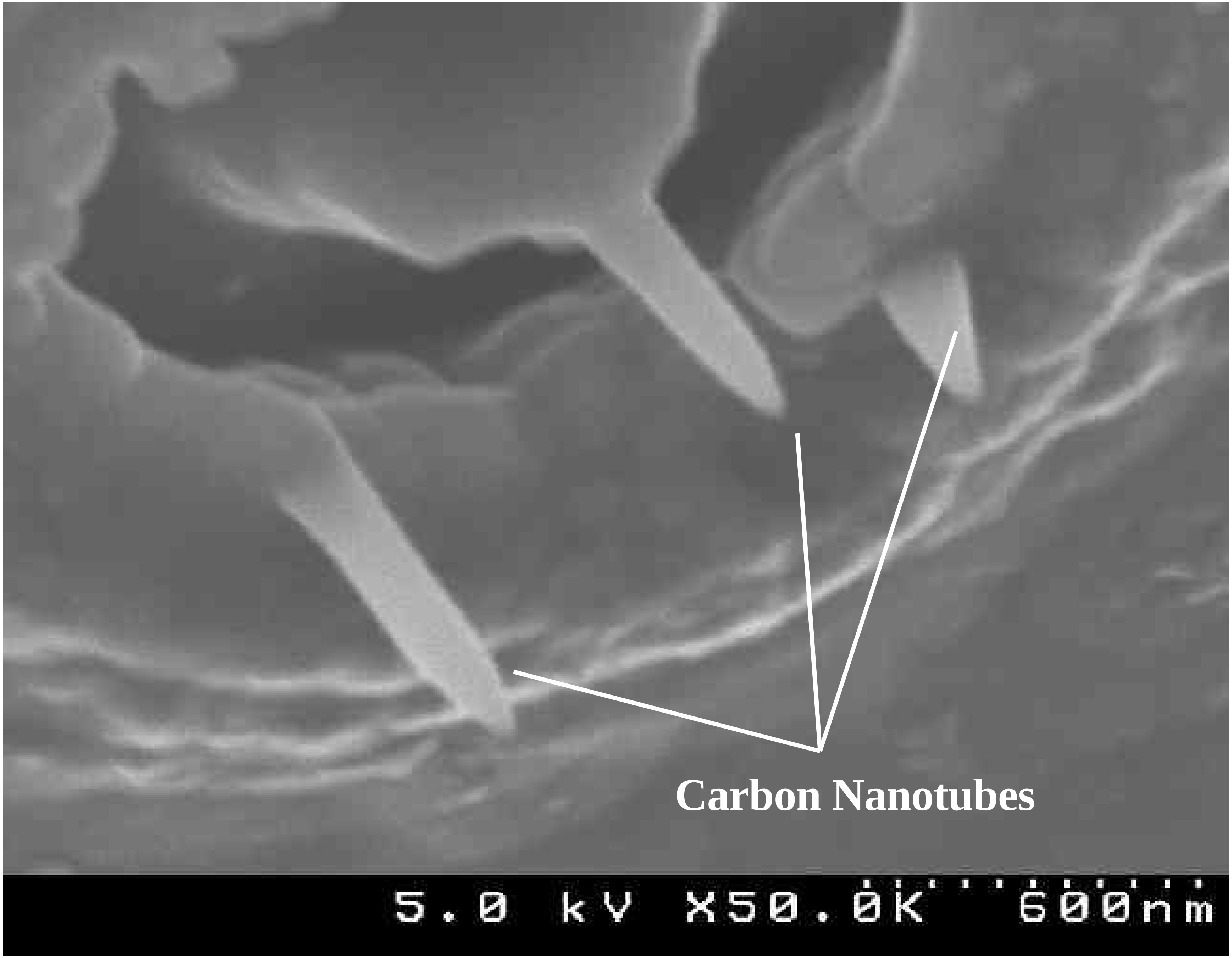






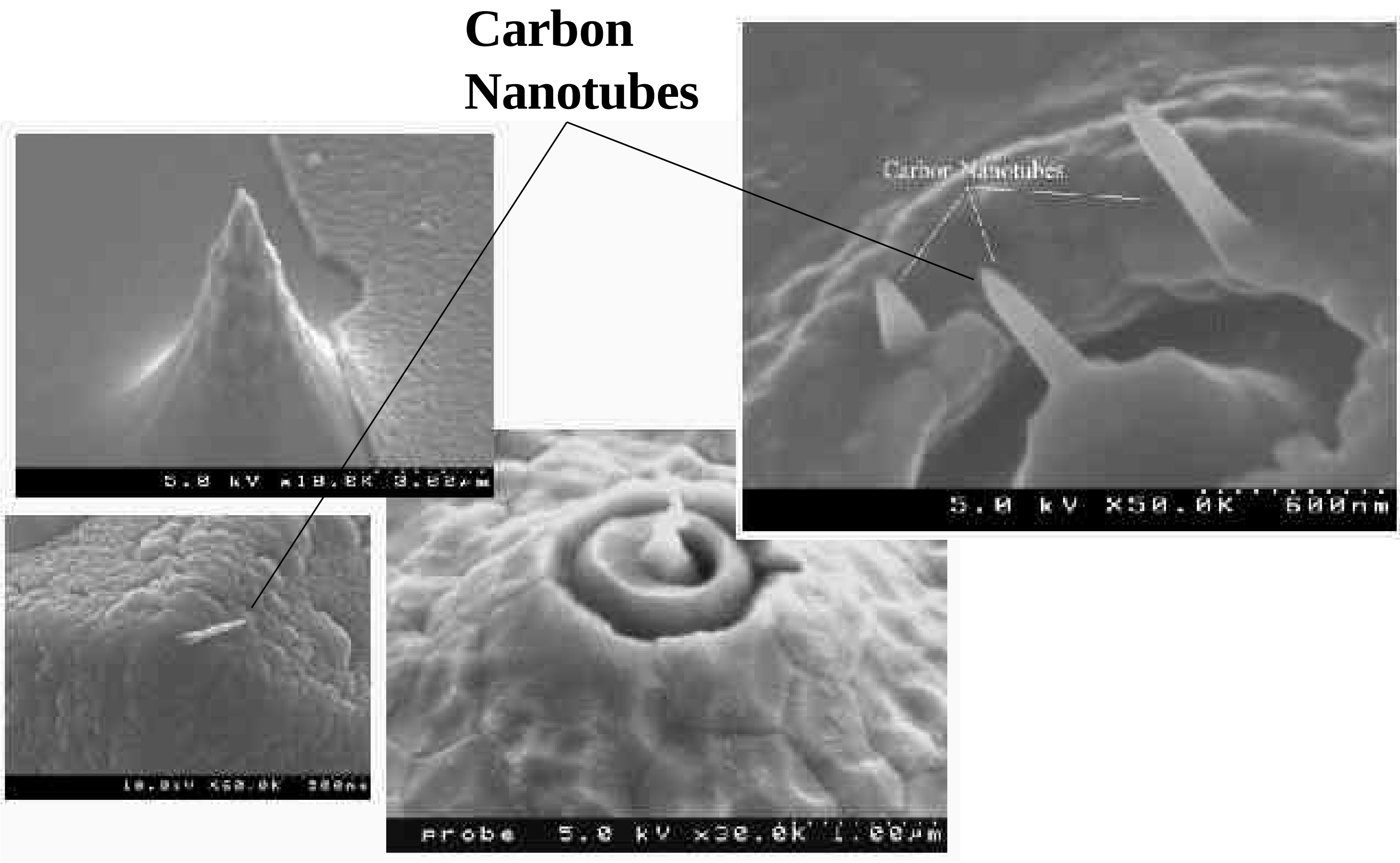




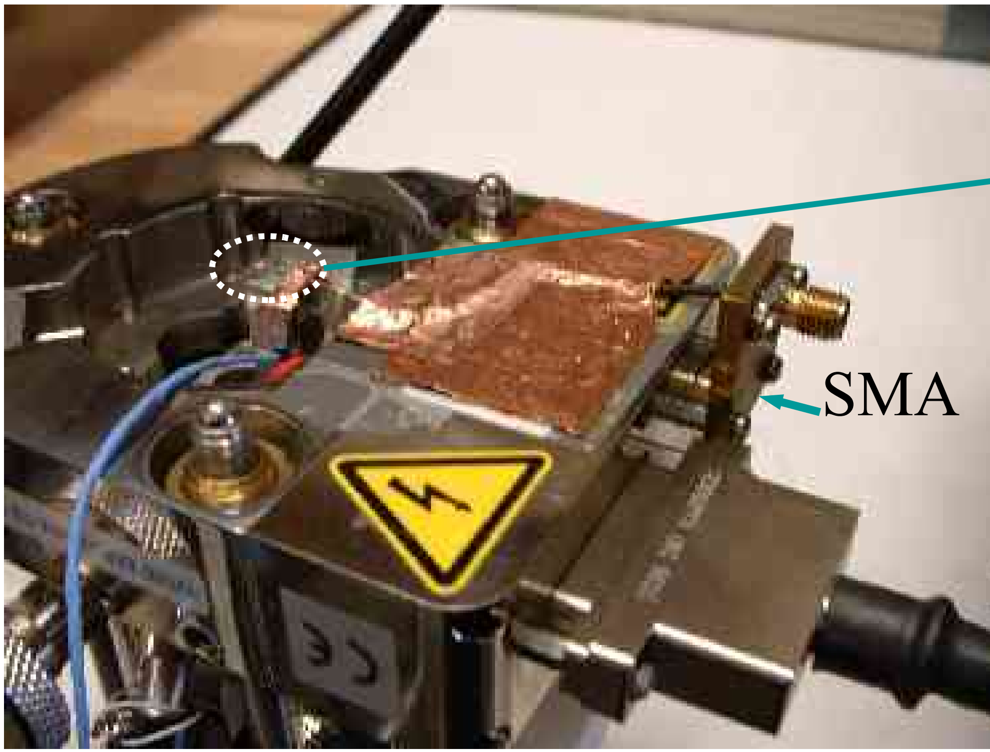


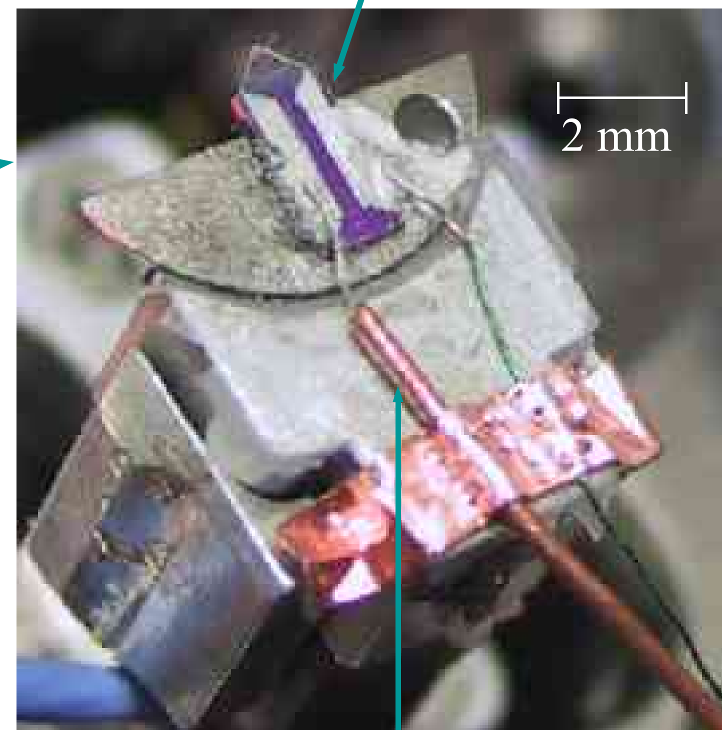
Carbon Nanotubes
5.0 kV X50.0K 600nm

Nano-Device Characterization

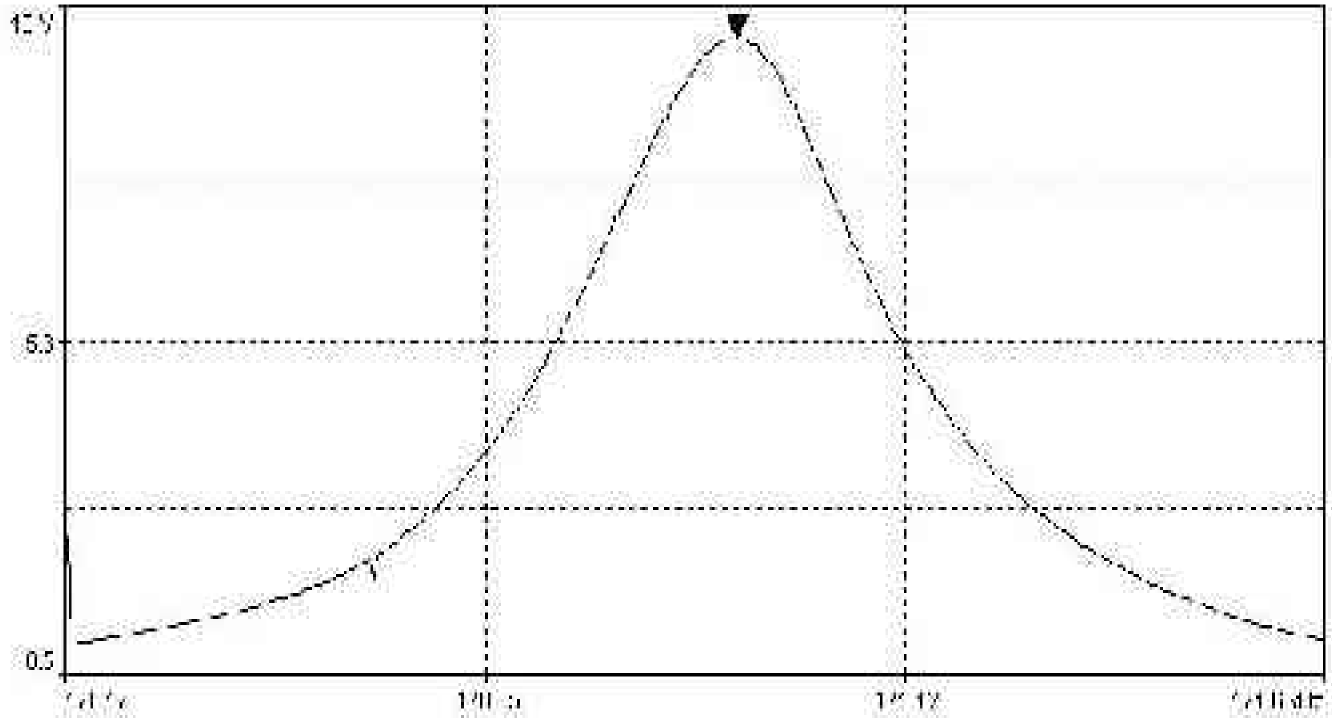


AFM Head – Microwave Tip Assembly



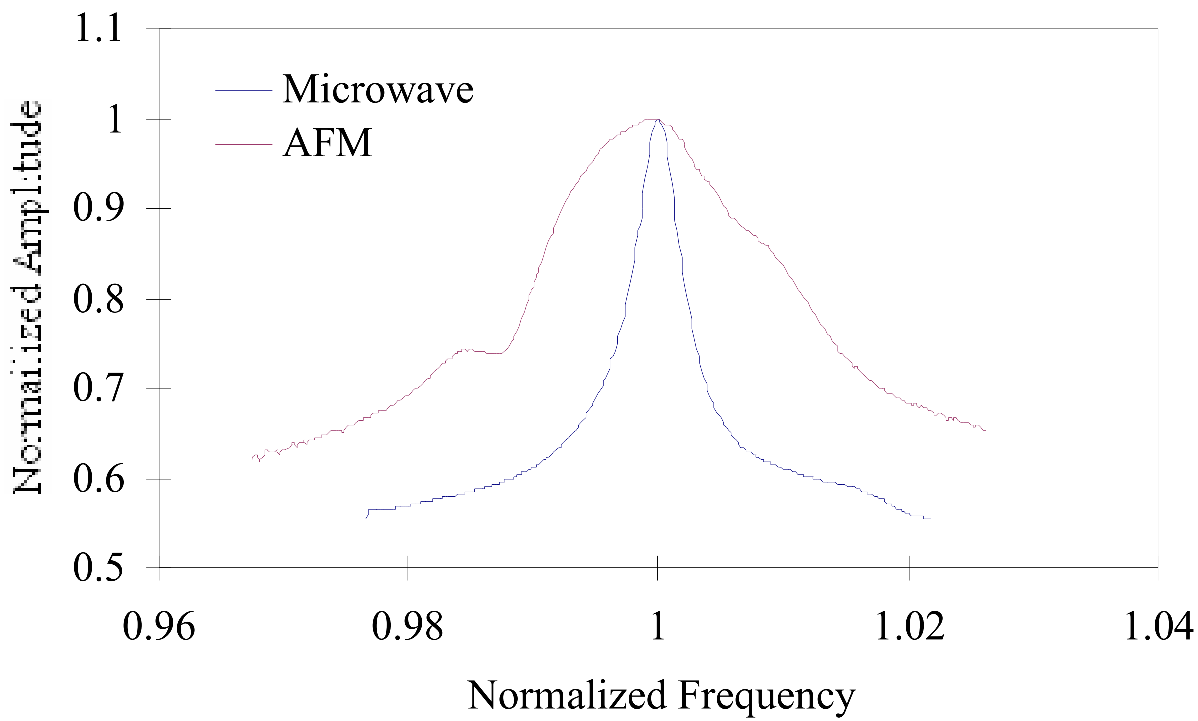


Mechanical Oscillation Spectrum



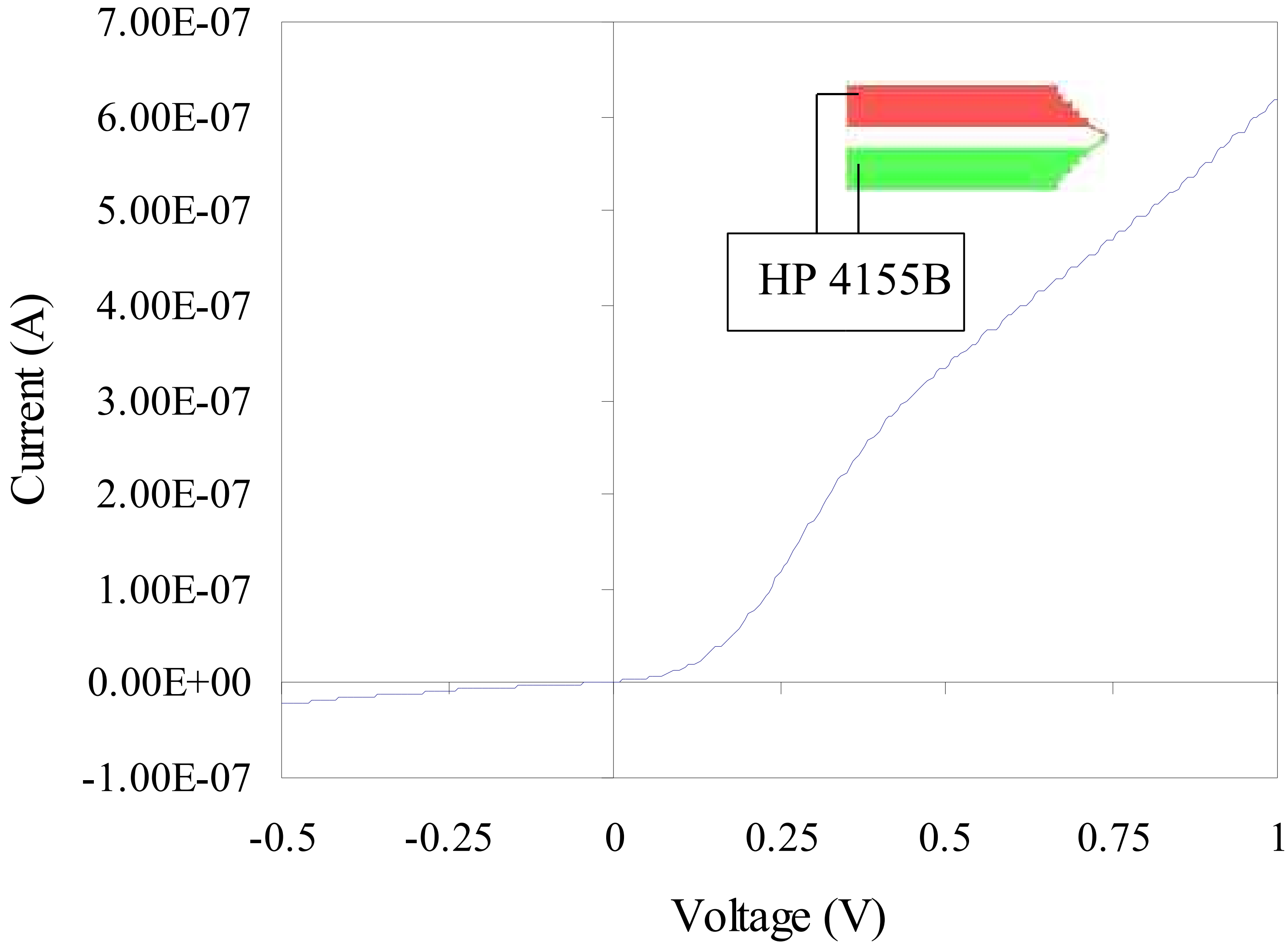
Measured resonant frequency is 170.92 KHz, and quality factor is 317. The design value is 150 KHz with L = 300μm, W = 50μm, and t = 5μm.

AFM-Compatible SEMP tip

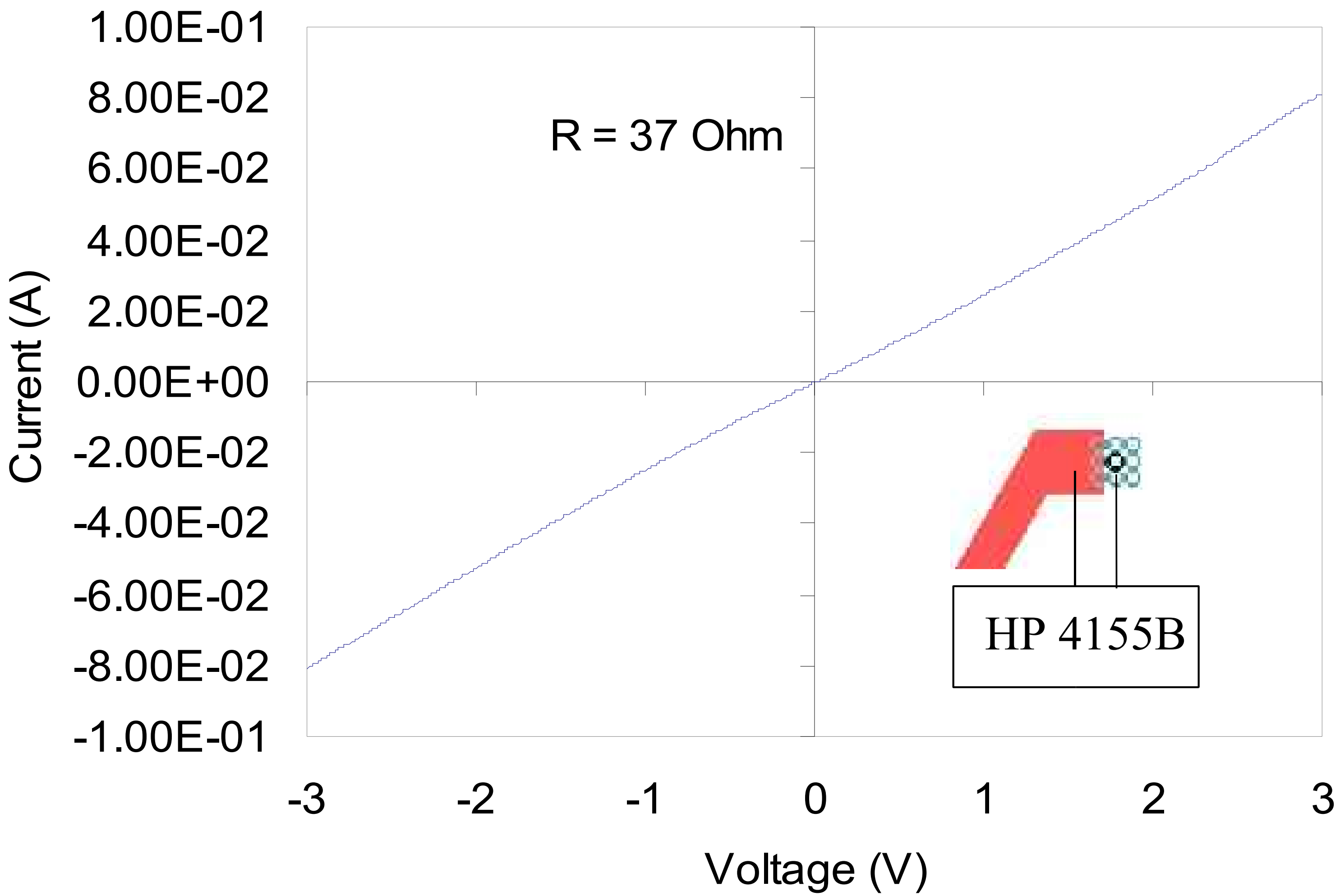


Explorer™ AFM System

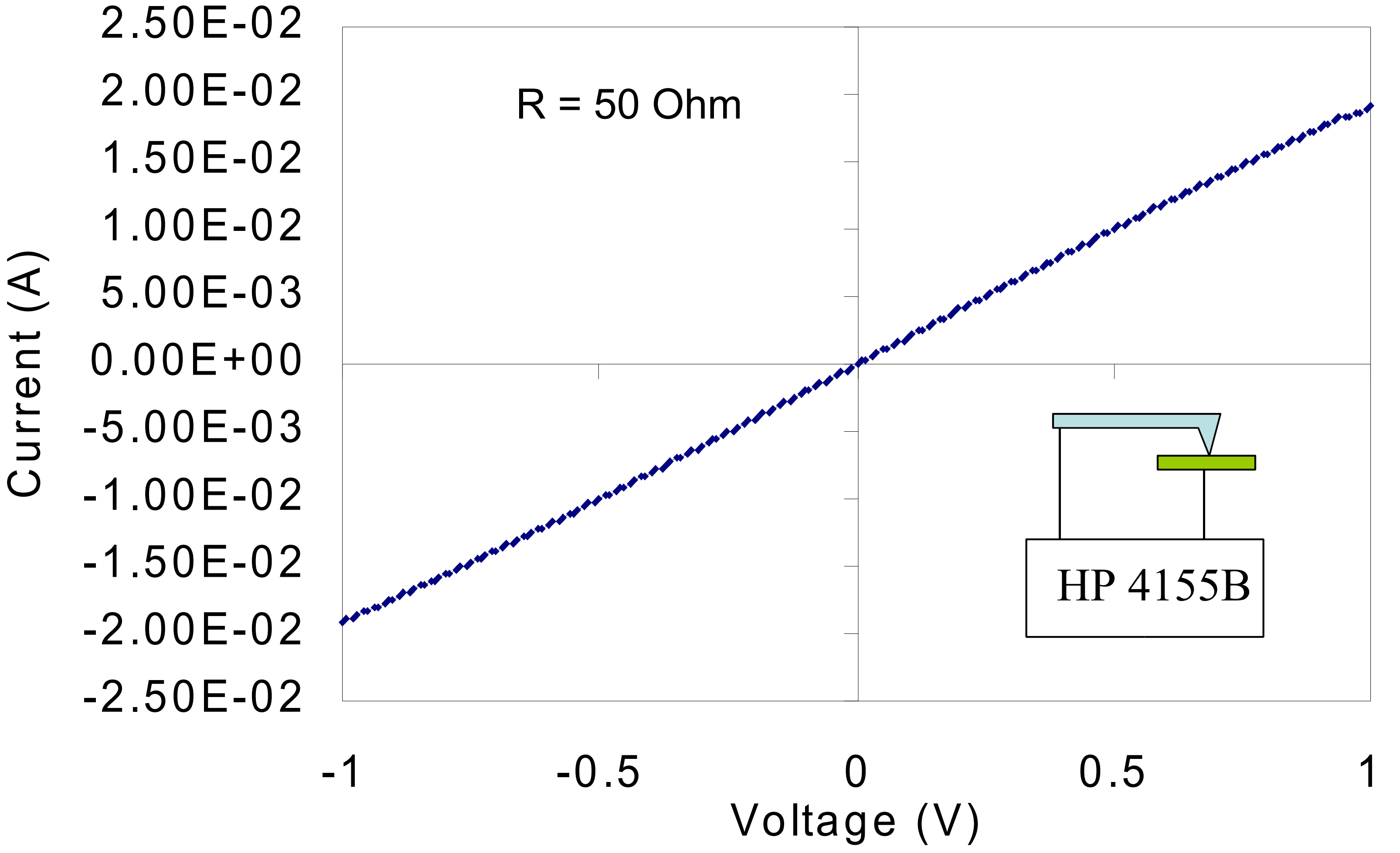
DC Conductivity between A Waveguide and A Shield



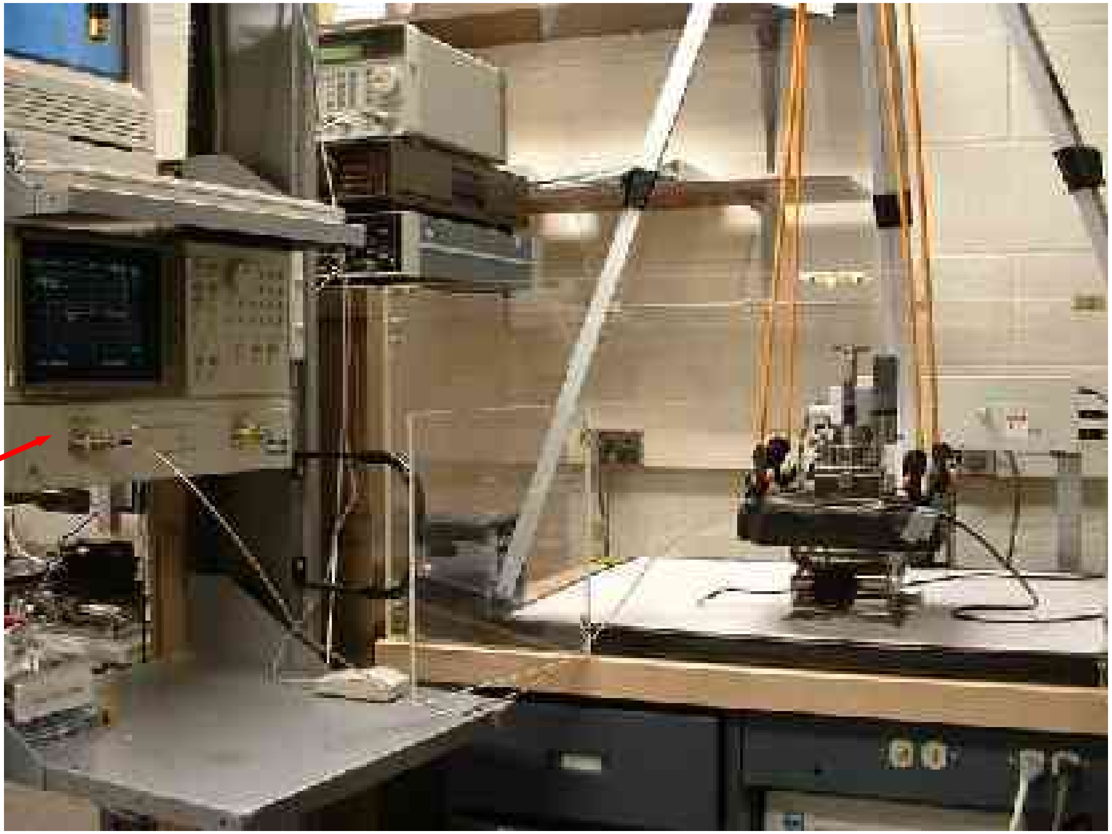
DC Conductivity between A Waveguide and An Implanted Tip Region



DC Conductivity between the Tip and An Au Sample

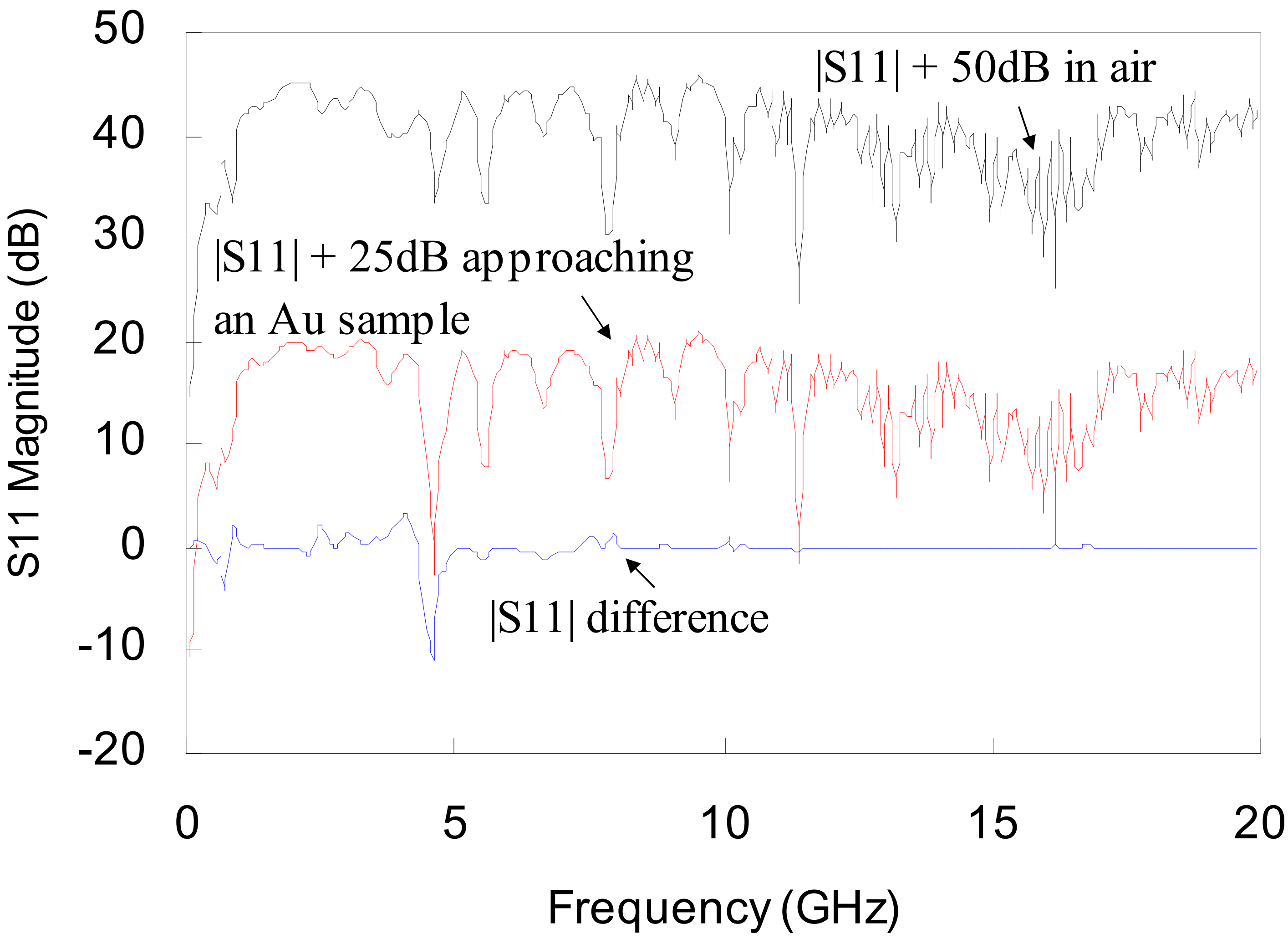


Microwave Measurement Setup

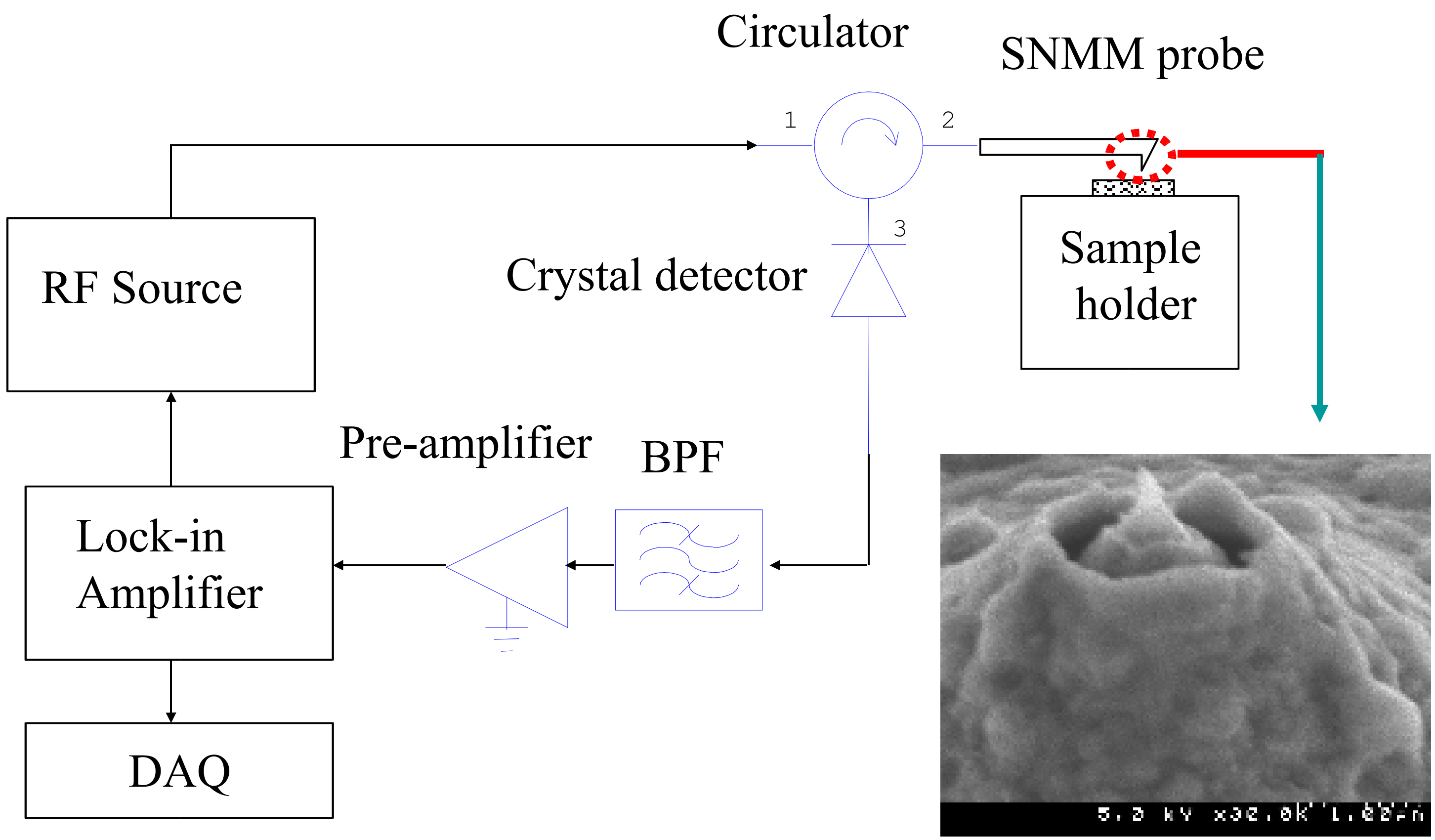


Network
Analyzer
HP 8720C

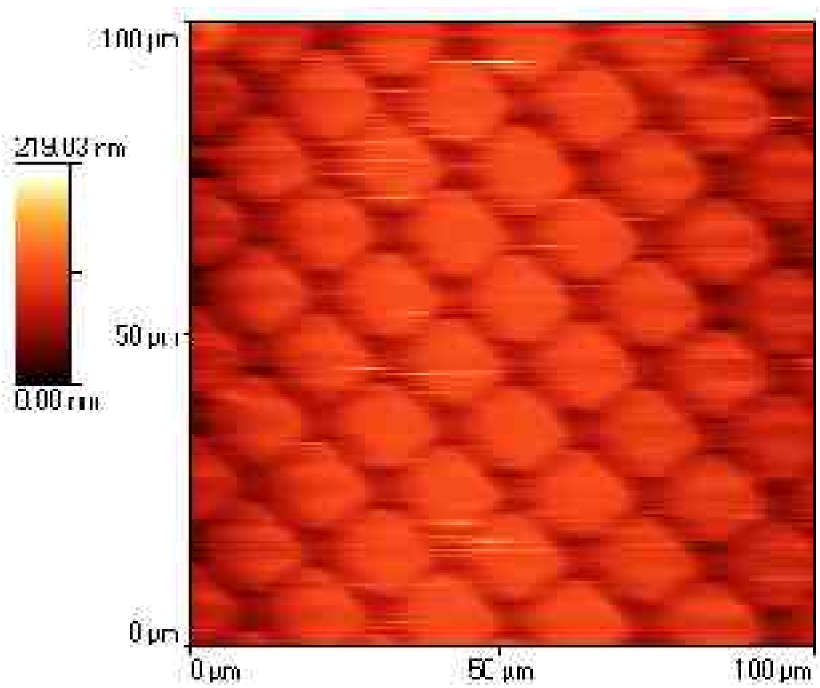
S11 Measurements in Air and over An Au Sample



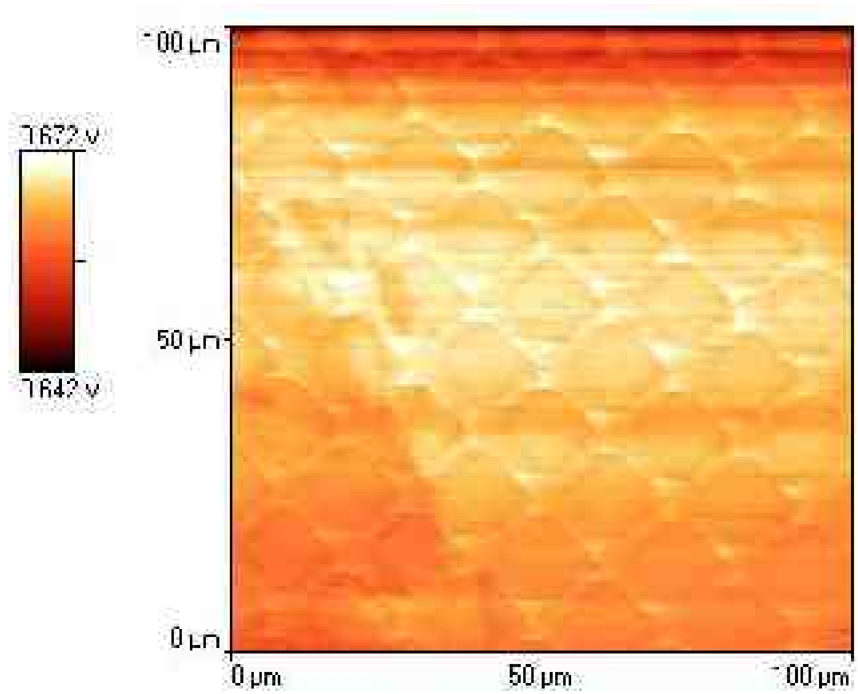
Schematic of the Image Scanning Circuit



Simultaneous AFM and Scanning Near-field Microwave Images (2.8 GHz)

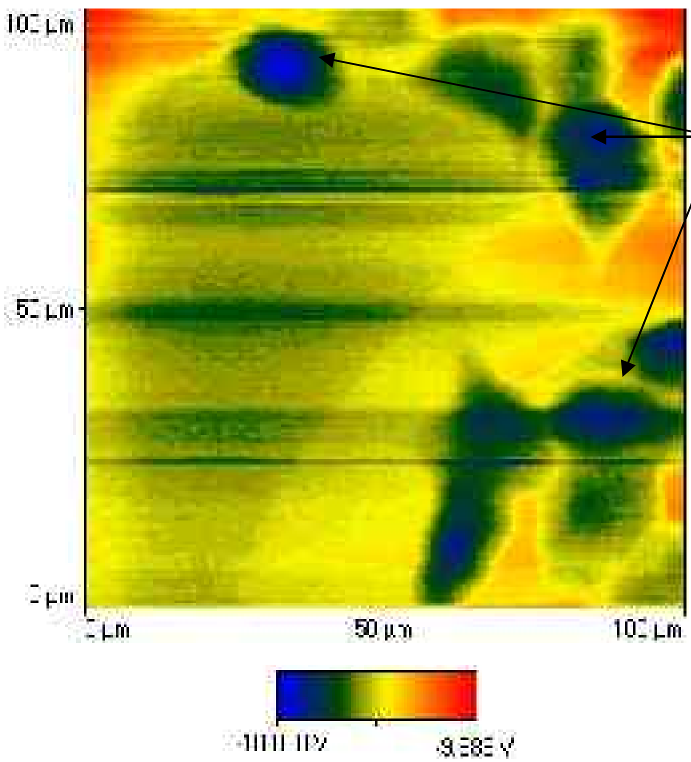


Contact AFM

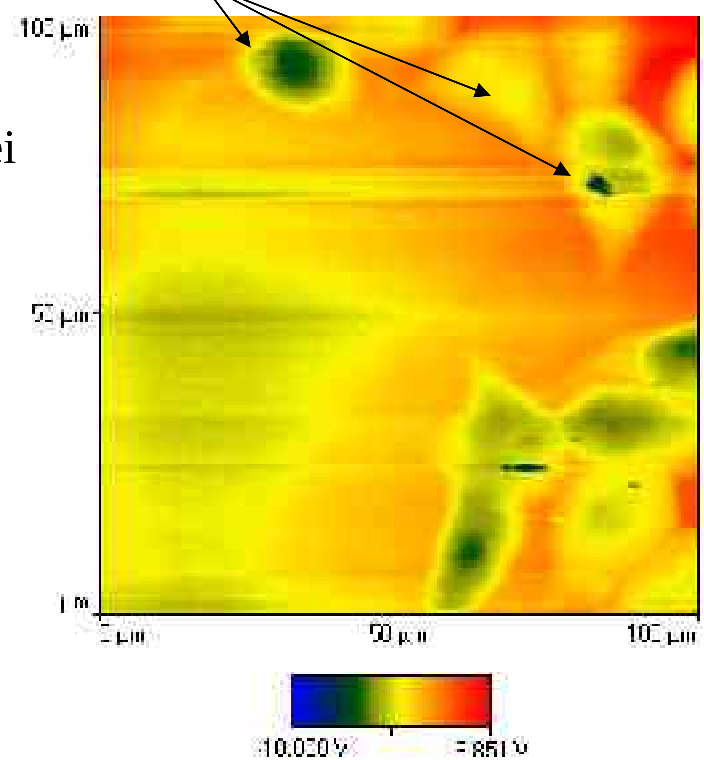


Microwave Image

Use microwave AFM to see inside the cell

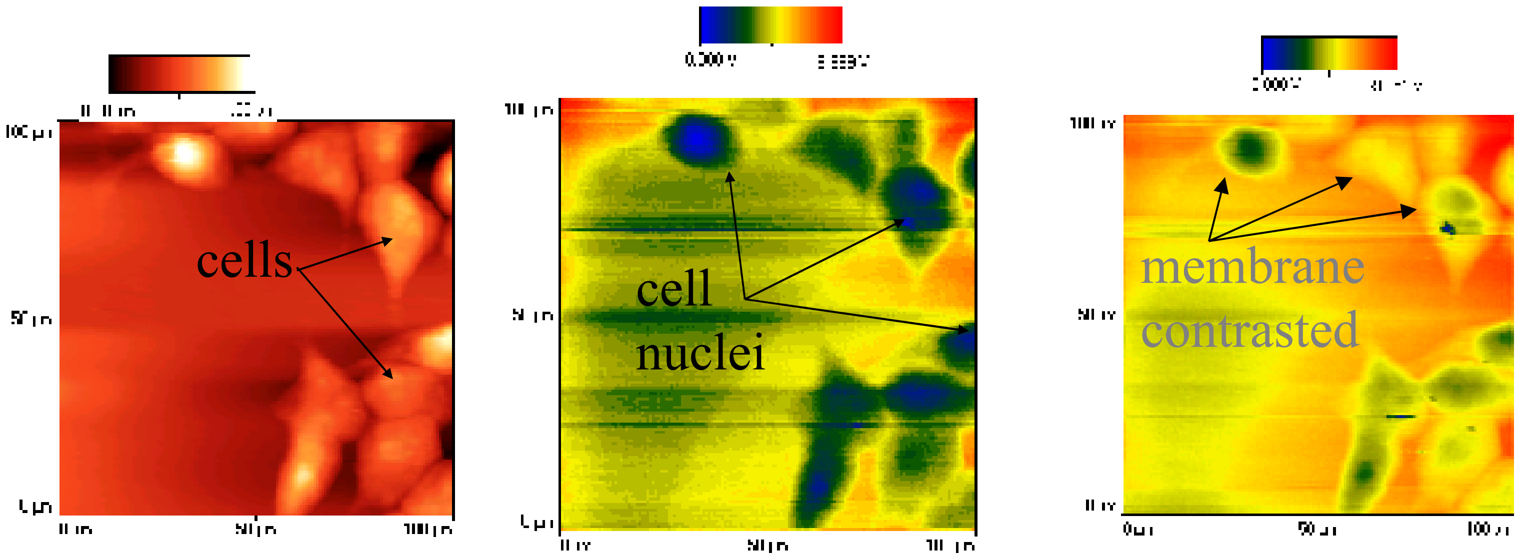


Microwave AFM amplitude



Microwave AFM phase

Significance of Scanning Near-field Microwave Microscope 1.8 GHz)



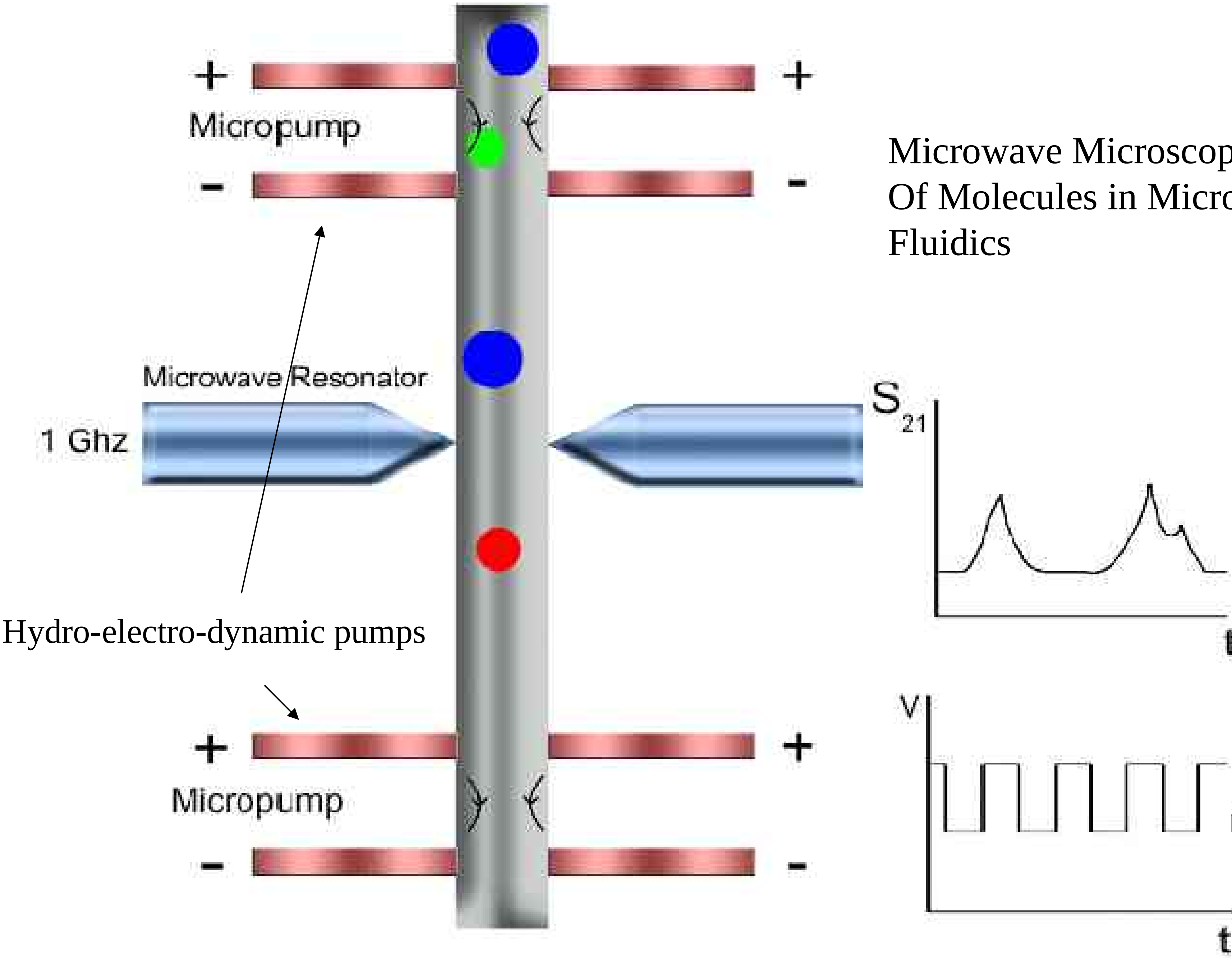
(a) AFM topography

(b) SNMM amplitude

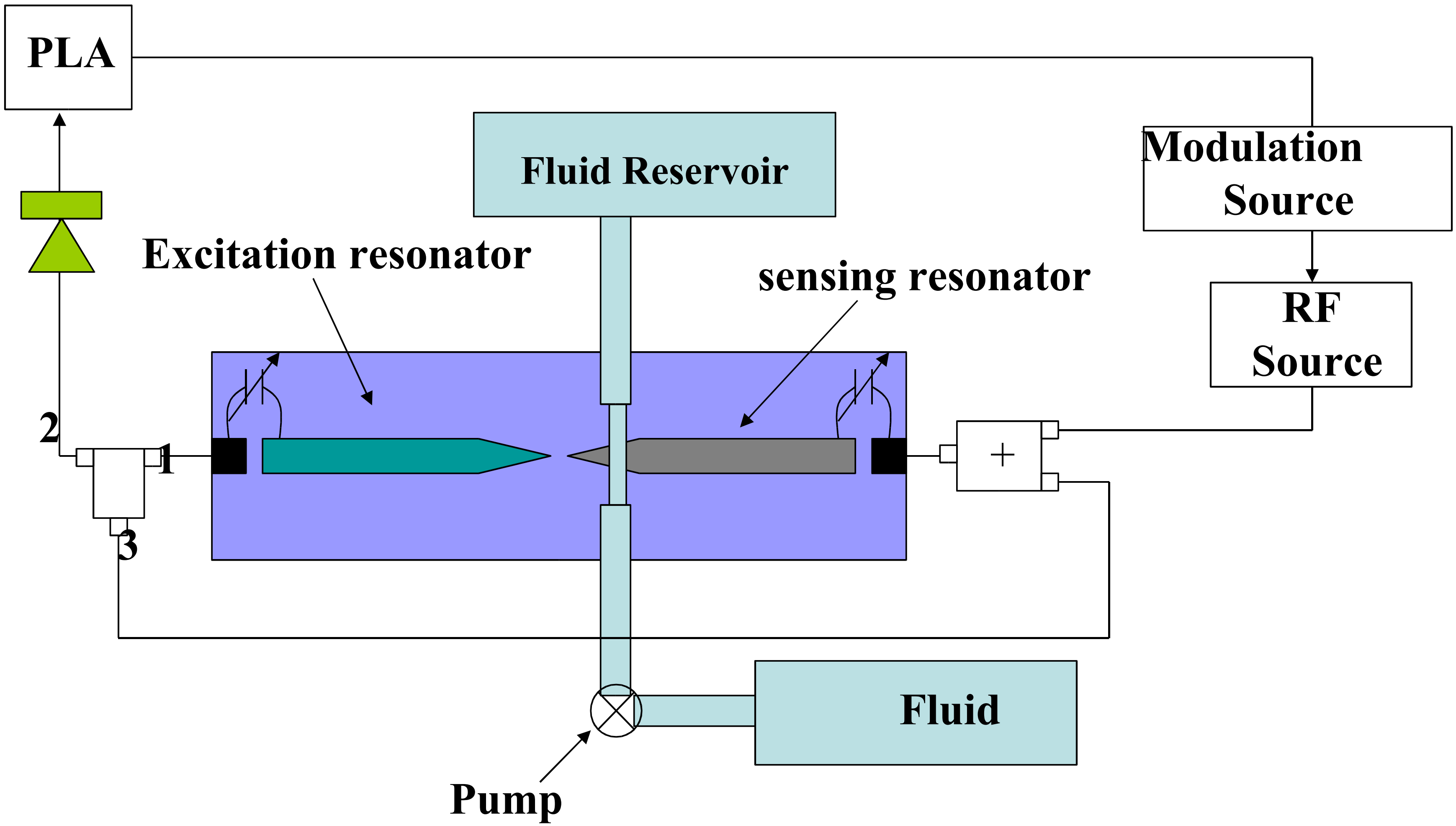
(c) SNMM phase

Commonly used

Microwave Microscopy Of Molecules in Micro-Fluidics



Micro-Fluidic: Experimental Arrangement



Detection of Cavitation bubbles using SEMP
<0.1 µm Bubbles