High-Q Mechanical Resonators Based on Carbon Nanotubes

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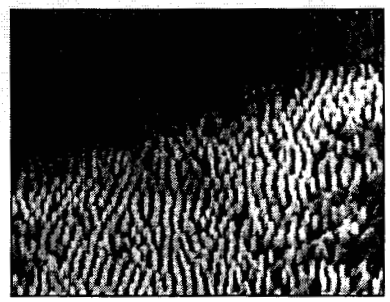
Brown University

Douglas Adam, Rob Young

Northrop Grumman

suspended nanotube

NT array with electrode



DARPA NMASP PI Meeting Talk

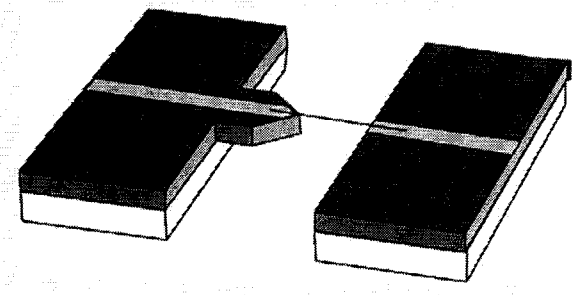
Orlando, Florida, 2/20/03

Goals / Approach

- **Demonstrate high-Q mechanical oscillators aimed at signal processing and based on carbon nanotubes: 1) a tunable nanotube resonator and 2) a nanotube array RF filter**

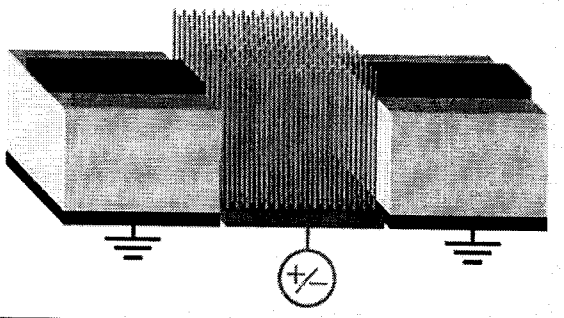
A single horizontal nanotube device for narrow-band detection:

Tunable Nanotube Resonator

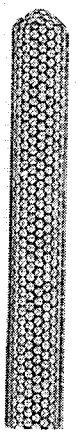


A vertical nanotube array device for high-Q RF power signal processing:

Nanotube Array RF Filter



- **Parallel efforts to develop both *in-plane* single nanotube resonators as well as *vertical array* power devices**
- **Basic fabrication approach:**
  - **Use carbon nanotubes due to excellent mechanical, thermal, and electrical properties**
  - ***Grow nanotubes in situ with integrated electrodes***



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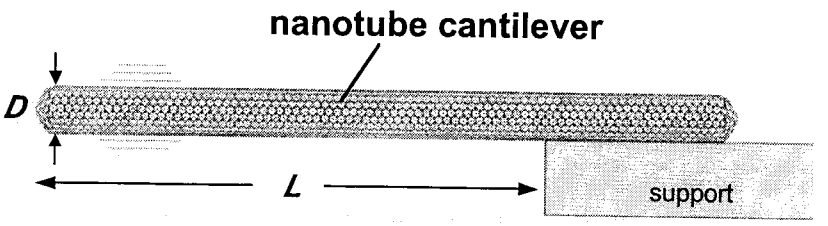
Nanotube mechanical resonators

- **Fund. cantilever resonant frequency, f_0, given by:**

$$f_0 = \frac{(1.875)^2}{8\pi}\frac{1}{L^2}\sqrt{D^2 + D_i^2}\sqrt{\frac{E_b}{\rho}}$$

Poncharal et al., Science (1999)



Length:	500 nm	200 nm	100 nm	50 nm
fo:	213 MHz	1.3 GHz	5.3 GHz	21.3 GHz

10 nm OD SWNT, Eb = 1 TPa, β1=1.875, ρ = 1.33 g/cm3

- ***Resonant frequencies can range from MHz to GHz***

- **<u>Nanotubes enable high f_0 *and* small force constants</u>**
  - Small k gives high sensitivity to input signals, low power operation, improved tunability (<u>M. Roukes</u>, Sensor and Act. Workshop, Hilton Head, 2000)
  - Natural nanoscale dimensions allow large aspect ratios and GHz f_0 without *heroic* lithography effort: $f_0 \alpha (D/L^2)$ and $k \alpha (D/L)^3$
  - But, also get increased sensitivity to environmental effects…

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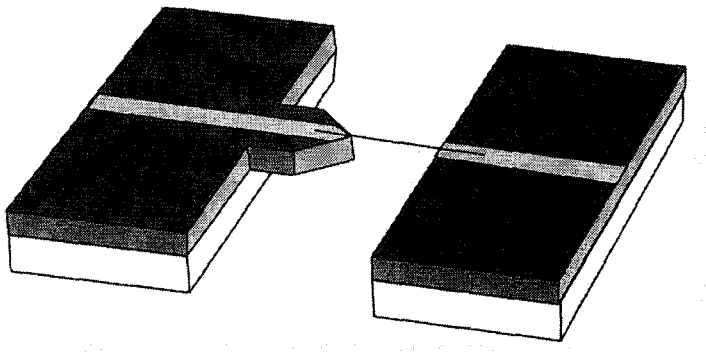
Tunable nanotube resonator

- Suspended nanotube bridge provides high-Q resonant element
- *Nanotube length strongly dependent on charge injection* (Baughman et al., Science 1999)
- DC bias can be used to control the length and hence the stress on suspended tube, and thereby control the resonant frequency (f_o)



Suspended NT bridge with integrated electrodes. The length change of a biased NT enables such a structure to serve as a *high-Q tunable resonator.*

- An additional RF bias will change the length at the RF frequency and cause the tube to oscillate
- Conversely, the oscillation of the nanotube (NT) will produce an oscillating current signal proportional to amplitude giving a <u>direct</u> readout of vibration
- Functions primarily as narrow band detector - <u>not for power handling</u>

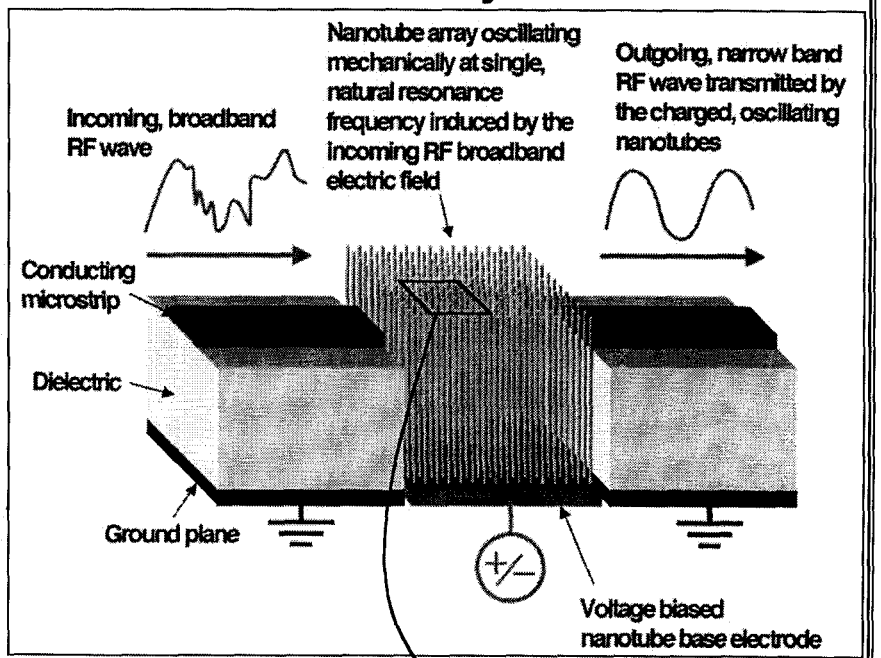
Nanotube resonator offers tunability with simple, direct electromechanical conversion

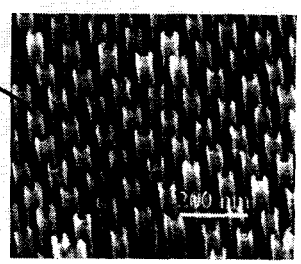
JPL Proprietary

Nanotube array RF filter operation

- ***Array of tubes needed for RF power handling***
- **Nanotube array embedded in microstrip waveguide**
- **Conducting nanotubes reflect RF at all frequencies except f_0**
- **At f_0 RF wave couples to nanotubes via Coulomb forces**
- **In turn, mechanical oscillation of charged tubes couples via Coulomb forces to output**
- **λ >> array dimensions so tubes vibrate in unison**
- **Acts as narrow-band bandpass filter, passband set by Q of array --> uniformity critical**
- ***Array averaging gives improved resistance to environmental effects and array phase locking may enable Q enhancement***

Nanotube Array RF Filter





NT array-J.Xu et al.

JPL Proprietary

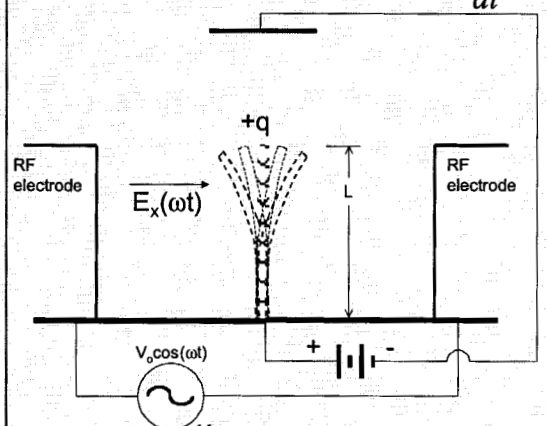
NT resonator modeling - Highlights

- **Modeling is progressing – developing Equations of Motion and approximate circuit models for coupling to nanotube resonators:**

Selected example – *Northrop Grumman analysis*:

1-D Eq. Of Motion charged "wheat stalk" nanotube.

Newton's Law: $F_{tot} = Ma = M\frac{d^2x}{dt^2} = -kx - M\beta x^3 - 2M\lambda\frac{dx}{dt} + qE_{xo}\cos(\omega t)$



Linear spring cantilever:

$$k = \frac{3EI}{L^3} \qquad I = \frac{\pi}{4}(R^4 - R_i^4)$$

Zero non-linear spring $\beta = 0$

Viscous damping:* $\frac{2\lambda}{\omega_R} = \frac{1}{Q}$

$$Q = \frac{\frac{\mu}{\pi\rho R^2} + \Gamma_r(\omega_R)}{\Gamma_i(\omega_R)} \qquad \Gamma(\omega t) = 1 + \frac{4iK_1(-i\sqrt{i\mathrm{Re}})}{\sqrt{i\mathrm{Re}}\,K_o(-i\sqrt{i\mathrm{Re}})} \qquad \mathrm{Re} = \frac{\rho\omega R^2}{\mu}$$

- **The JPL RF group (Larry Epp and Dan Hoppe) is working with NGC:**
  - **To determine approximate solutions to wave equation**
  - **To develop circuit models and techniques for efficient matching to the NT resonators**
  - **To design RF waveguide structures for coupling to NT devices** ***(see next page)***

Leads to Wave Equation for a nanotube "wheat field":

$$\omega = \sqrt{\frac{k}{M} + \frac{q^2}{\pi\varepsilon_o d^3 M}\left[1 - Cos\,(sd)\right]} \underset{sd<<1}{=} \sqrt{\frac{k}{M} + \frac{q^2 s^2}{2\pi\varepsilon_o d M}}$$

spring constant; charge; wave number; mechanical resonance of single nanotube; stiffening and coupling due to electrostatic forces; mass; separation between nanotubes

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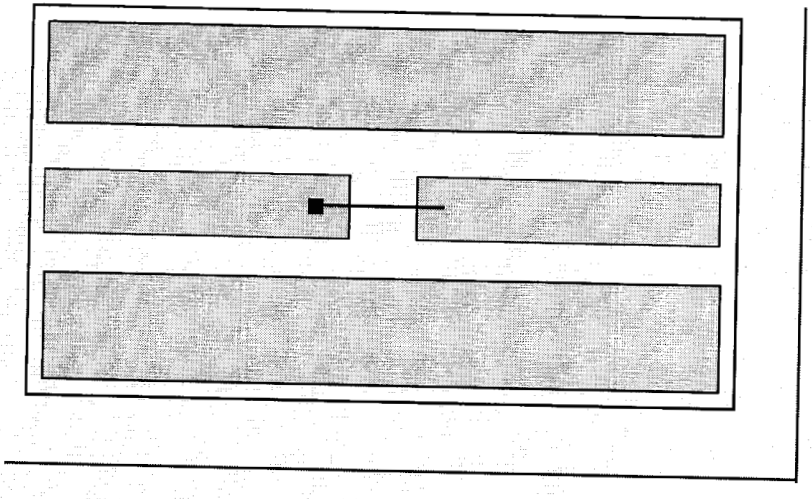
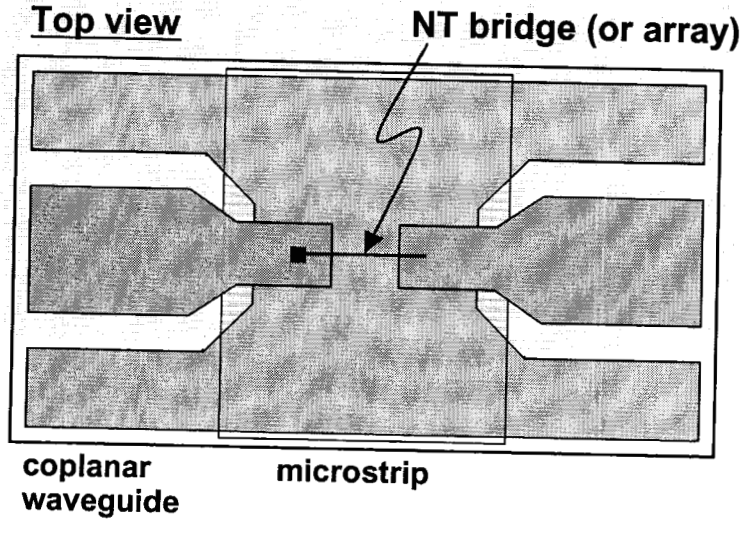
NT resonator RF designs

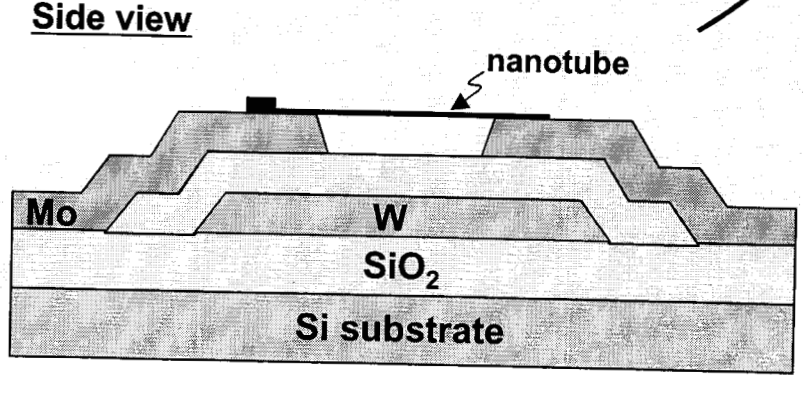
a) Coplanar waveguide *(lateral or vertical NT)*



- CPW-to-µstrip provides efficient coupling to both suspended NT bridges and vertical NT arrays
- Relatively simple fabrication for lateral NT devices
- Vertical array process under development

b) Coplanar waveguide to microstrip transition





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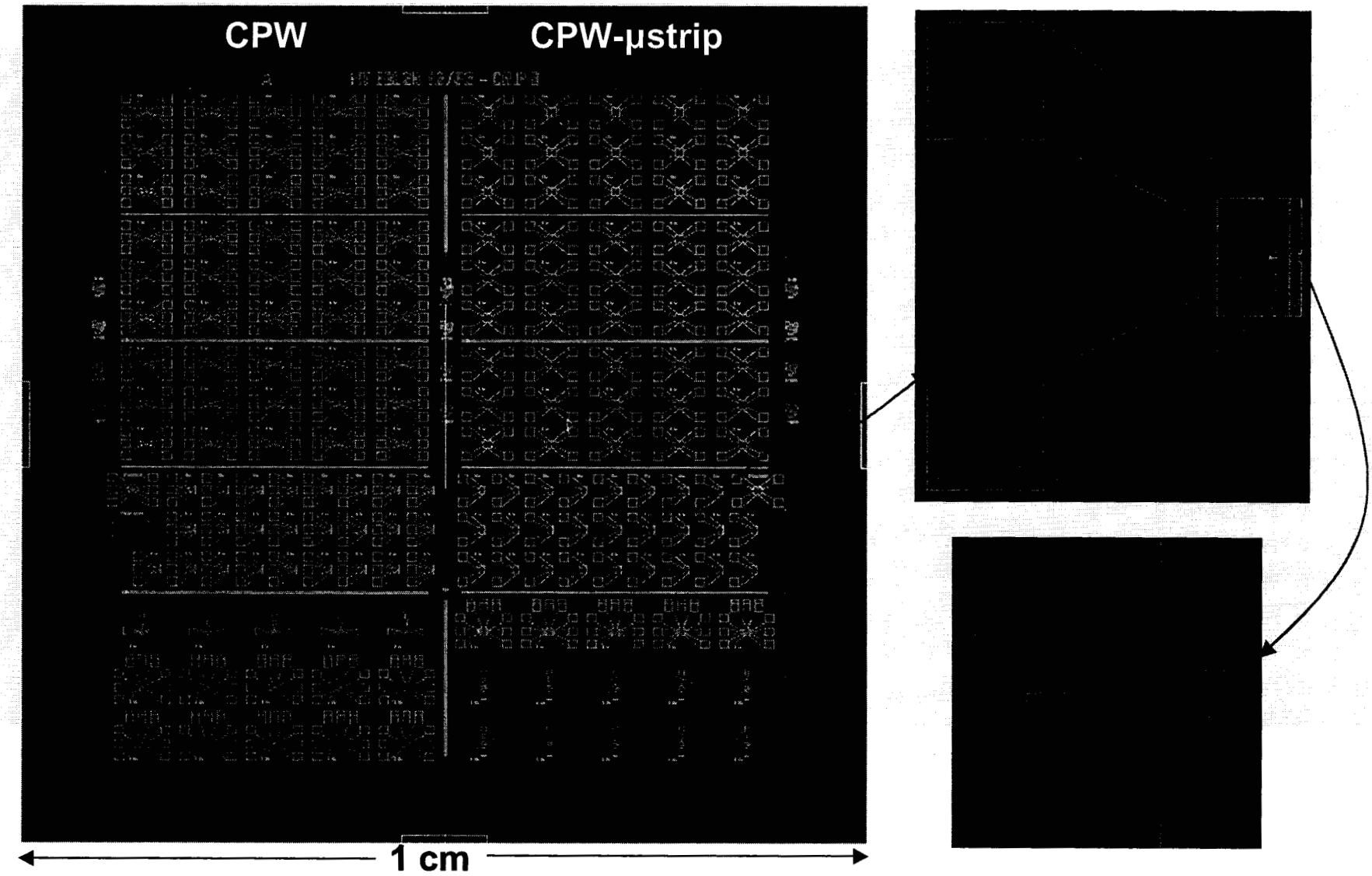
Layout for 1 cm RF chip

- Combination of photomasks and direct-write ebeam patterning



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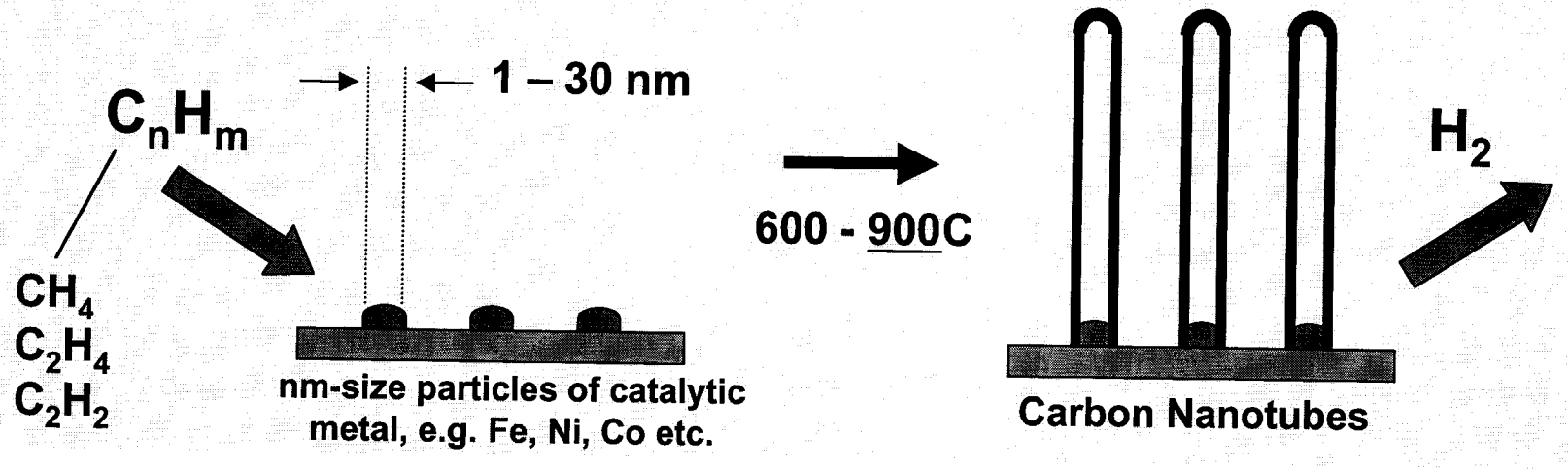
Controlled Carbon Nanotube Growth

We need:

"Perfectly" crystalline nanotubes	⟷	High ν and small Δν, reduced environ. effects
Uniform diameters, lengths	⟷	Narrow Δν
Directed Growth	⟷	Device integration

Chemical Vapor Deposition (CVD) of carbon nanotubes:



Important: size and position of catalytic particles determine size and position of resulting CNT

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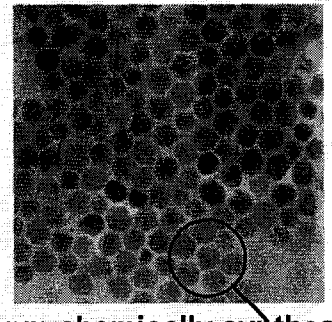
Catalyst Engineering

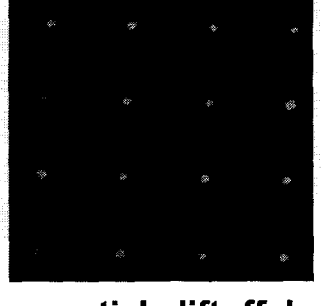
Controlled production and placement of nanoscale metal particles

1) Chemically synthesized Fe nanoparticles

- Synthesis: $Fe(CO)_5$ in octyl ether and oleic acid - 300C



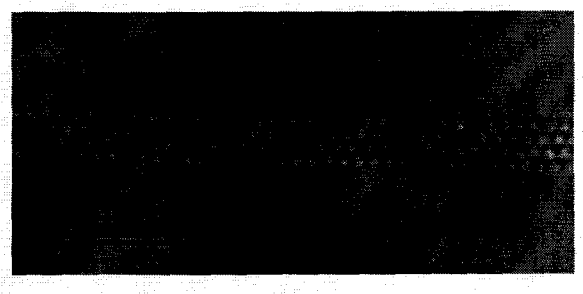
15 nm chemically synthesized Fe_2O_3 nanoparticles (5, 10nm also produced)



Nanoparticle liftoff by e-beam lithography: Fe_2O_3 NP in 50 nm diameter dots

2) Electron-beam lithography

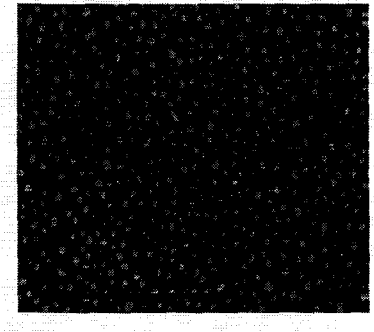
- JEOL JBX-9300FS, ~15 nm resolution
- Need features near e-beam resolution limit
- Customized catalyst patterns possible ---> novel signal processing applications



AFM image of 50 nm diameter Fe catalyst dots patterned by ebeam liftoff (8nm thick)

3) Block copolymers

- PMMA-PS block copolymers
- Self-ordering in spin-on film: inexpensive
- Patterns transferred to metal catalyst films by liftoff
- Arbitrary patterns not possible

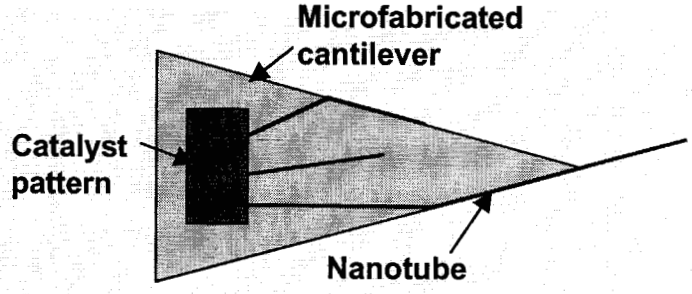


Mo dots on Si by BCP liftoff, 10-30 nm diameter

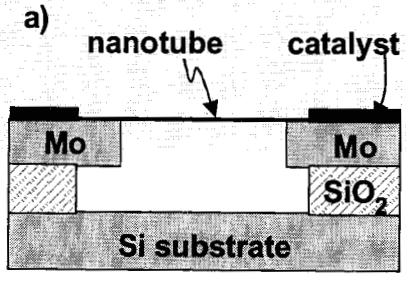
- **Carbon nanotubes grow from these catalysts but yield is typically low --> acceptable for lateral NT devices** *(nanopore template process gives high yield for vertical tubes)*

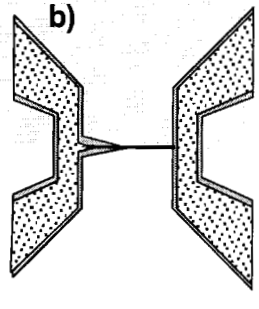
Directed nanotubes - structure aligned growth

Control of in-plane alignment:



- Nanotubes grow along surfaces due to van der Waals attraction
- The tubes protrude from sharp points because the bending energy exceeds the van der Waals binding energy

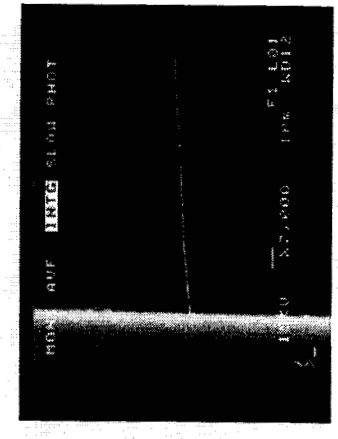




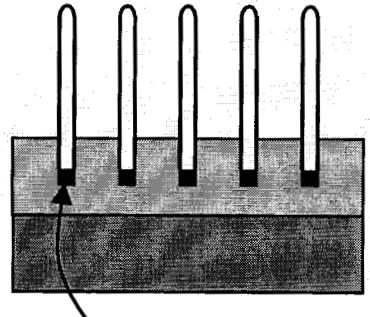
Control of vertical alignment:

Methane CVD at 900C:

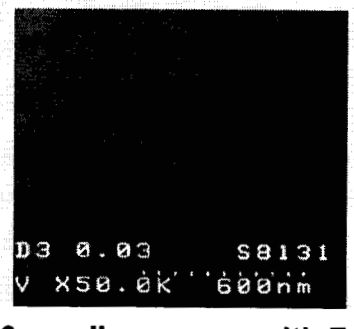
- Promising initial results on sub-nm catalysts
- Straight (low defect density) free-standing isolated nanotubes



- Investigating pore-aligned growth to force vertical alignment



catalyst recessed in pore



30 nm diam. pores with Fe catalyst by e-beam lith.

- Alumina nanopore process…

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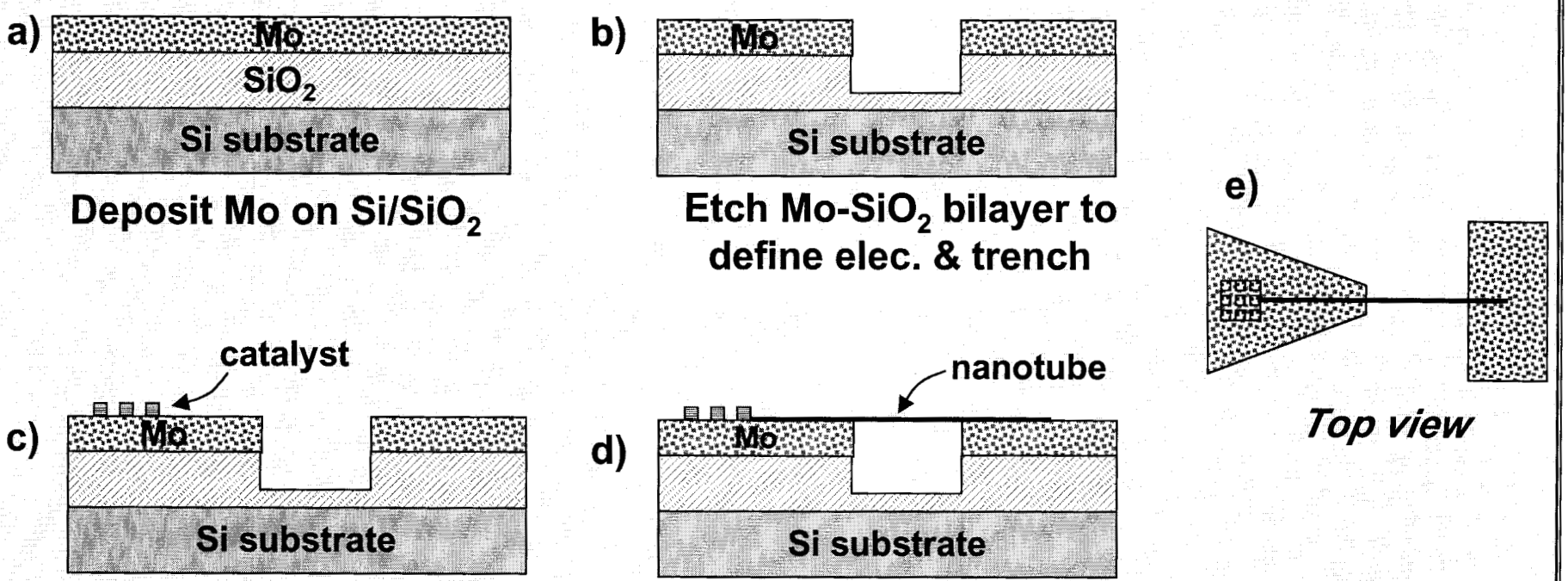
Lateral Nanotube Process - Mo electrodes

Process for growth of suspended CNT bridges with integrated molybdenum electrodes

- **Minimizes nanotube processing after growth**
- **Mo electrodes provide high quality electrical contacts**



Related to H. Dai process, APL 81, 913 (7/29/02)

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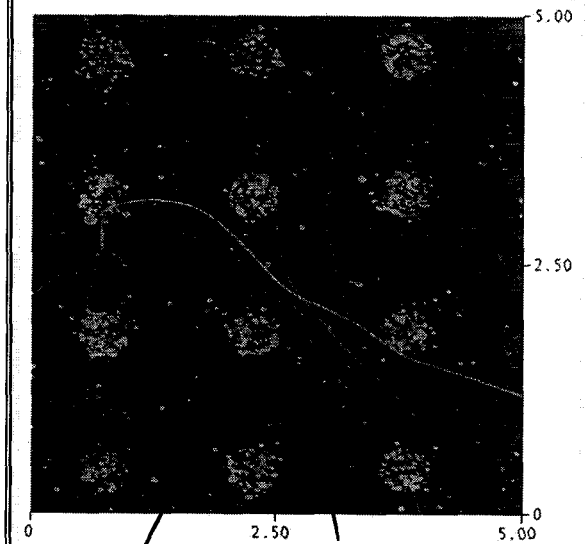
Lateral nanotube device processing

- ***Essential processing steps are under control:***

Fe nanoparticle liftoff and nanotube growth

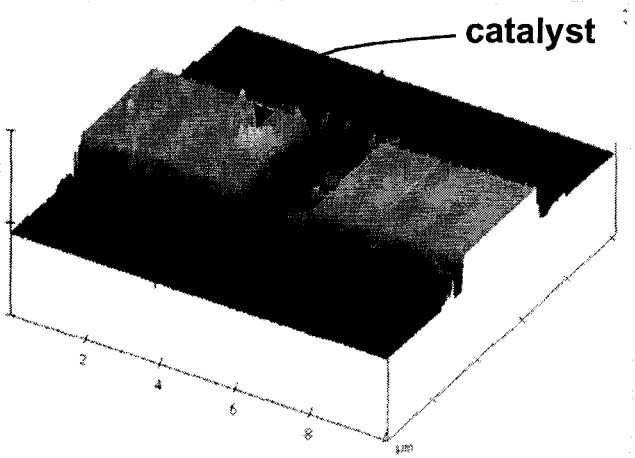


nanotubes

patterned nanoparticles

- Barrier layer essential on Mo
- Annealing and growth gases affect yield

Patterned catalyst on patterned Mo electrode



- E-beam direct write liftoff processing
- Liftoff of Fe nanoparticles and alumina-supported catalysts demonstrated

CNT suspended bridge

CNT bridge over 100nm wide trench - CH_4 @ 900 C with Fe nanoparticle catalyst

Calculated resonant freq. ~ 10GHz

- ***Now producing and testing lateral nanotubes with integrated electrodes***

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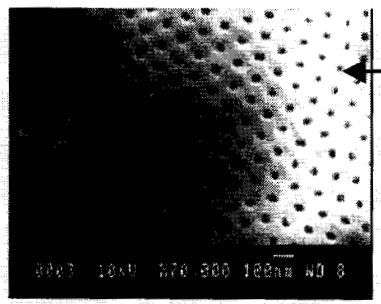
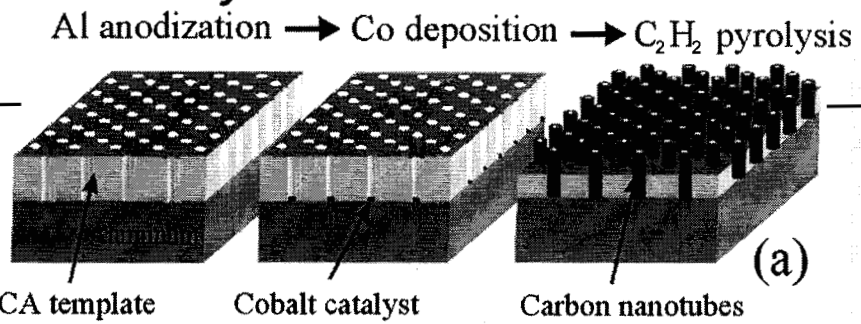
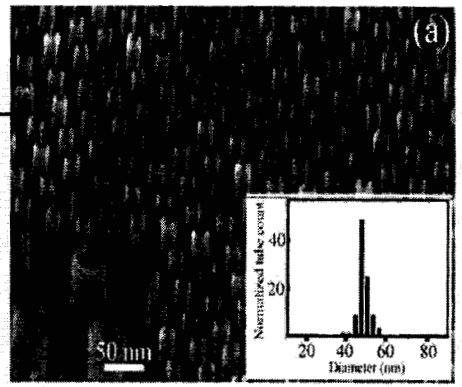
Alumina Nanopore Process for Uniform Vertical Nanotube Arrays

Prof. Jimmy Xu, Brown University:



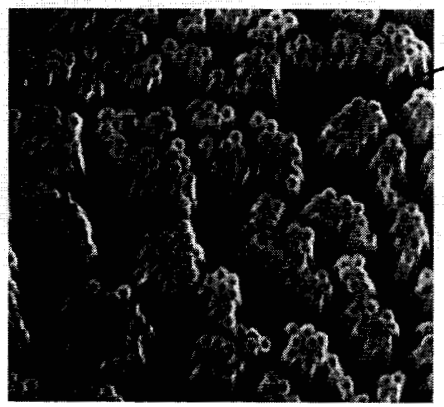




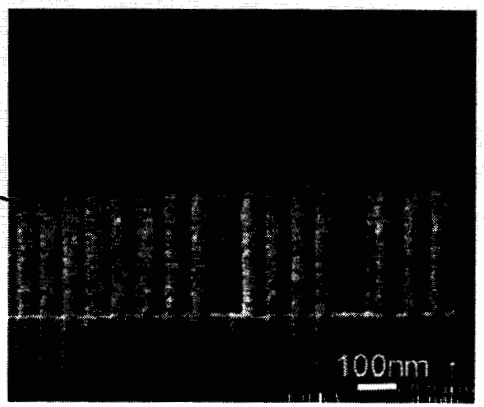
Free-standing Al foil process

- **Anodized Al forms ordered pores - template for CNT array**
- ***Nanotubes are uniform in diameter, length, and spacing***

Baseline process under control



- **Wet etch for removing alumina can lead to tube sticking (chromic+phosphoric)**
- **Improved process with dispersants in etch greatly reduces sticking**
- **Free-standing tubes up to 800nm long with 20:1 aspect ratios are now possible (~ 2.7GHz f_0)**



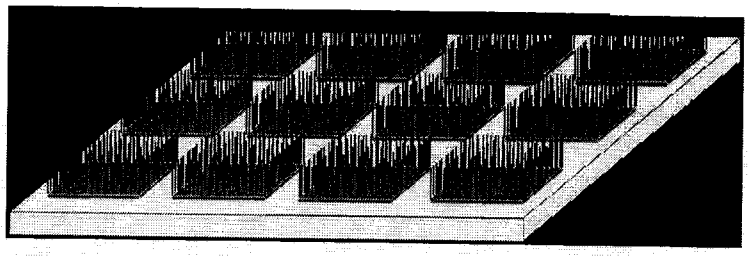
(with 25nm Au/Pt coating)

Carbon nanotube array device processing

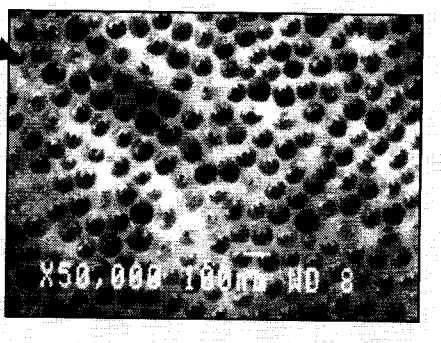
JPL

Aluminum nanopore process on Si:

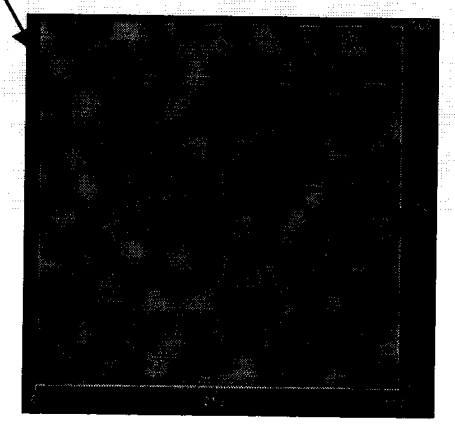
- Requires deposition of high purity, very smooth Al films on Si
- Al film typically much thinner than Al foil in standard process (~3μm *vs* >15μm)
  - Self-ordering of pores more difficult
  - Investigating ebeam-patterned pore nucleation sites
- Buried electrodes may be needed:
  - Must be compatible with high temp. NT growth and with AlO_x etching
  - Investigating tungsten electrodes
- Patterning of arrays and array electrodes
  - Array patterning - pre-pattern Al, window anodization
  - Electrode patterning after NT growth



Want patterned arrays on Si with electrodes and controlled array properties



Pore array with NTs produced in anodized Al on silicon wafer

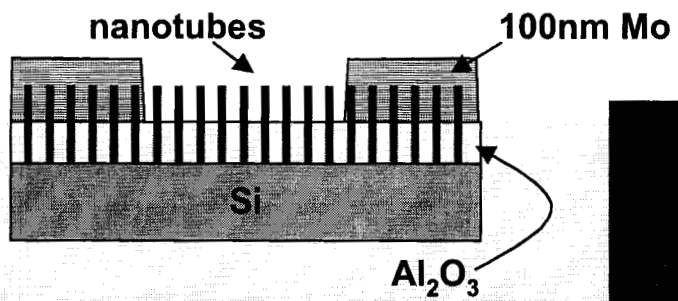


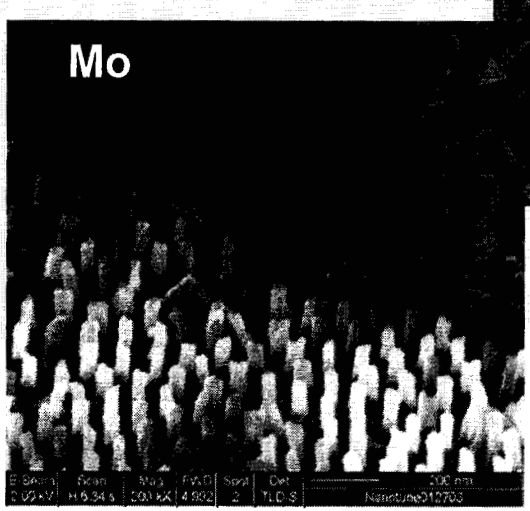
E-beam patterned hole array in PMMA on Al for etching of anodization nucleation sites - 20nm dots on 60nm centers

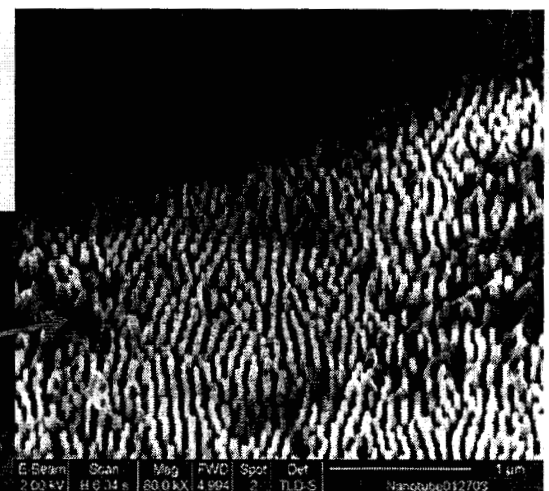
Patterning of RF electrodes on NT arrays

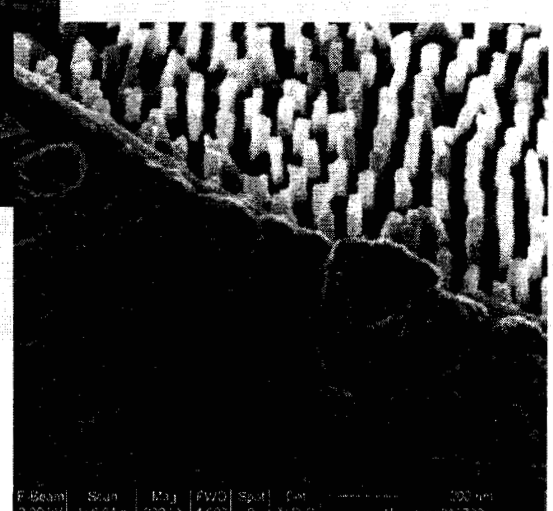
Patterned Mo electrodes

- Liftoff processing on Brown U. NT arrays
- RF-compatible CPW electrodes
- Nanotubes survive processing without de-adhering or tube-to-tube sticking







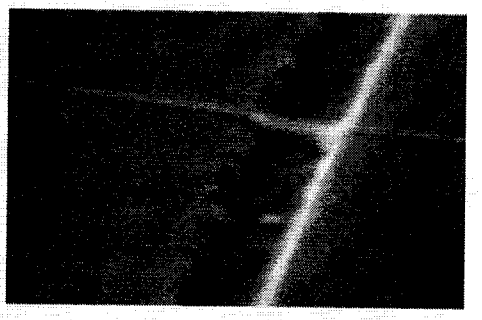


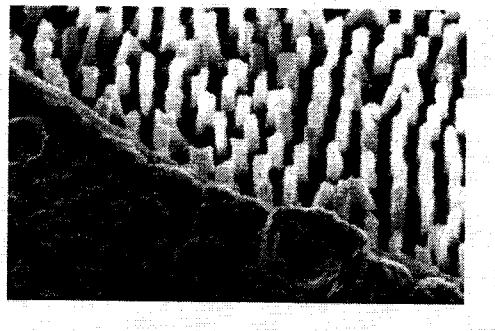
- Electrical measurements show acceptable electrode conductivity and isolation

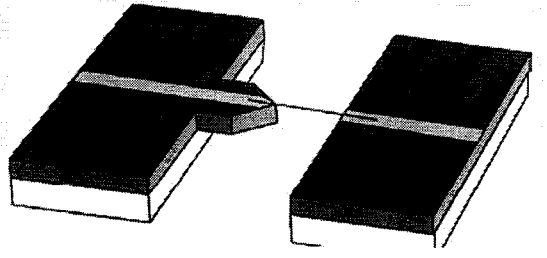
Dan Choi, 1-03

Summary

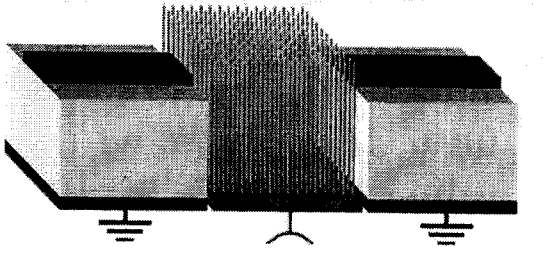
- Developing high-Q mechanical oscillators based on carbon nanotubes
  - Tunable nanotube resonator based on suspended nanotube bridge
  - Narrow band RF filter using CNT array in microstrip waveguide
- Modeling and process development in progress for design and fabrication of in-plane and vertical nanotube devices
- Prototype device structures have been fabricated







Tunable Nanotube Resonator



Nanotube Array RF Filter

Introduction to the research team

- **Jet Propulsion Lab:**
  - Brian Hunt (PI) — Management, device and process design
  - Michael Hoenk
  - Eric Wong
  - Bob Kowalczyk — Lateral nanotube growth/processing
  - Mike Bronikowski
  - Dan Choi — Vertical nanotube growth/processing
  - Larry Epp
  - Dan Hoppe — RF device design, testing, modeling
- **Brown University**
  - Jimmy Xu
  - Baohe Chang, Aijun Yin, Maryam Jouzi — Nanotube vertical array development and device fabrication
- **Northrop Grumman**
  - Douglas Adam
  - Rob Young — RF system design - MEMS-based tunable filters for radar applications, testing, modeling