Engineered Carbon Nanotube Materials for High-Q Nanomechanical REsonators

Dan Choi, Brian Hunt, Mike Bronikowski, Larry Epp, Michael Hoenk, Dan Hoppe, Bob Kowalczyk, Eric Wong

Jet Propulsion Laboratory

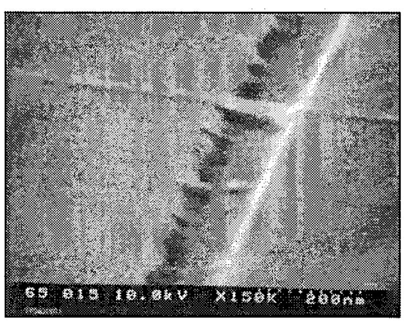
Jimmy Xu

Brown University

Douglas Adam, Rob Young

Northrop Grumman

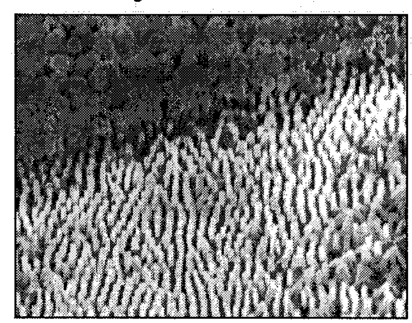
suspended nanotube



NT03

Seoul, Korea, 7/11/03

NT array with electrode

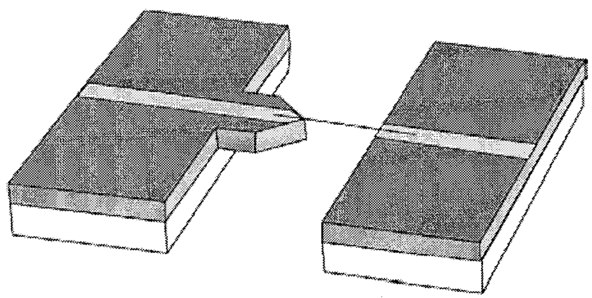


Goals / Approach

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

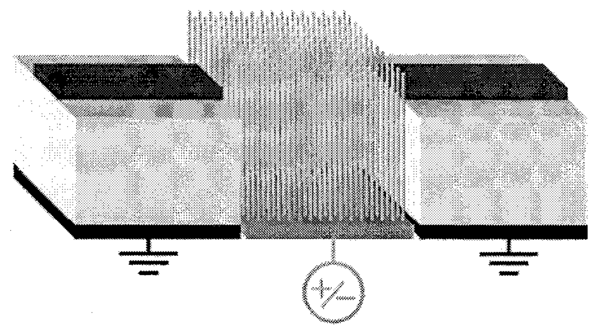
A single horizontal nanotube device for narrow-band detection:

Tunable Nanotube Resonator

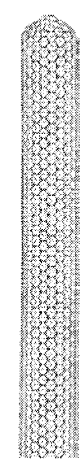


A vertical nanotube array device for high-Q RF power signal processing:

Nanotube Array RF Filter

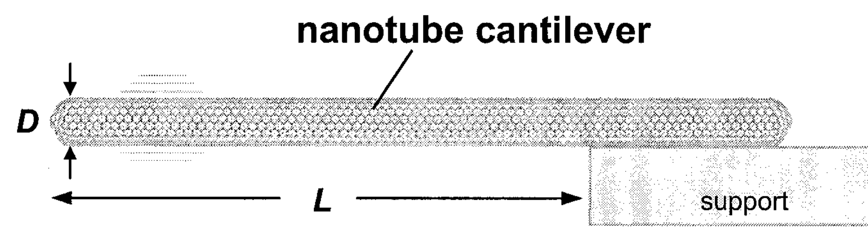


- Parallel efforts to develop both <u>*in-plane*</u> single nanotube resonators as well as <u>*vertical array*</u> power devices
- Basic fabrication approach:
  - Use carbon nanotubes due to excellent mechanical, thermal, and electrical properties
  - *Grow nanotubes in situ with integrated electrodes*



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…**

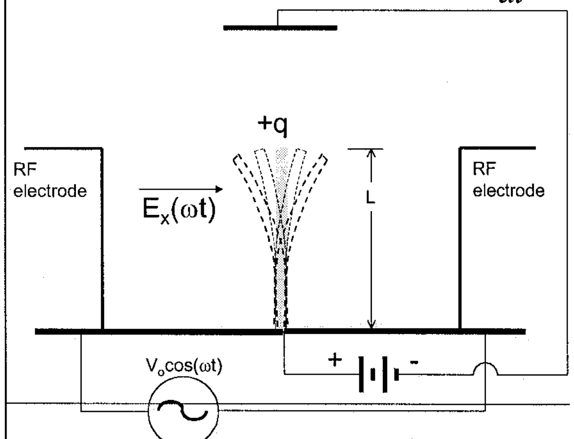
NT resonator modeling - Highlights

- **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 Òwheat stalkÓnanotube.

NewtonÕs 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":

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

mechanical resonance of single nanotube

stiffening and coupling due to electrostatic forces

spring constant

charge

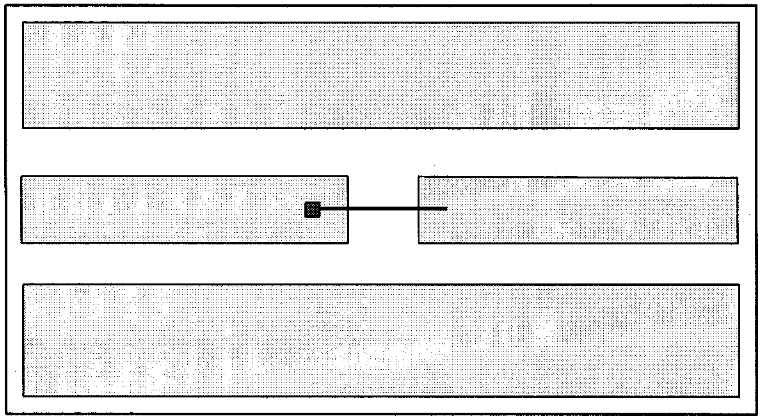
wave number

mass

separation between nanotubes

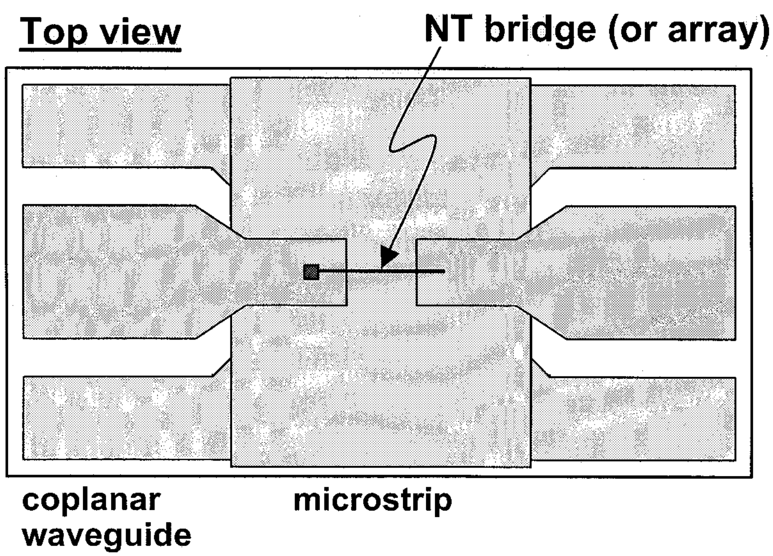
NT resonator RF designs

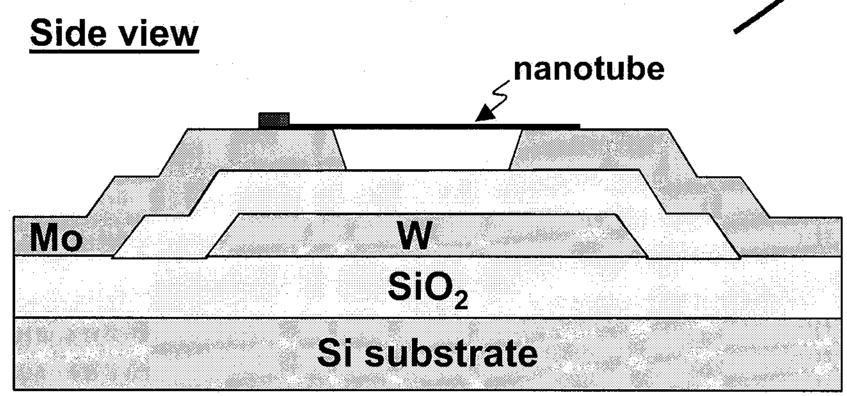
a) Coplanar waveguide *(lateral or vertical NT)*



- 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



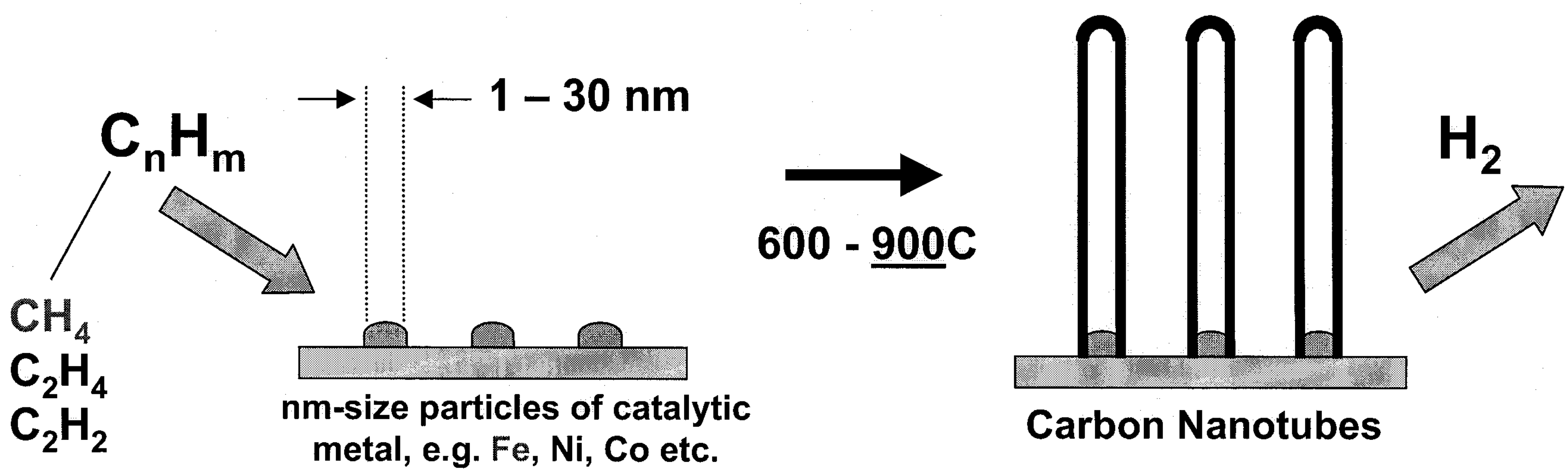


Controlled Carbon Nanotube Growth

<u>We need:</u>

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

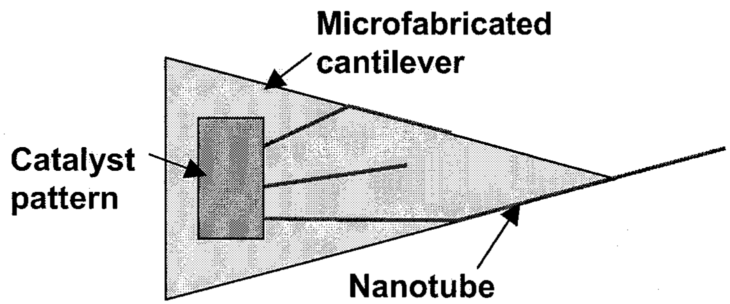
Chemical Vapor Deposition (CVD) of carbon nanotubes:



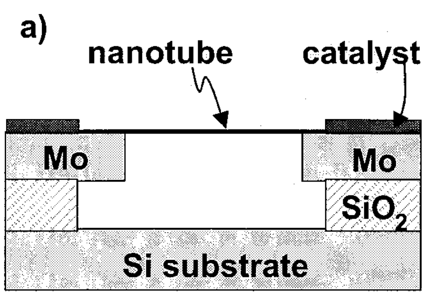
<u>Important</u>: size and position of catalytic particles determine size and position of resulting CNT

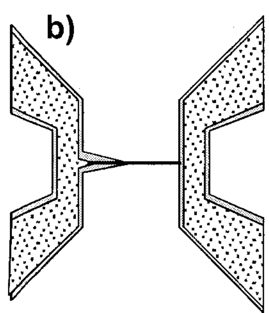
Directed nanotubes - structure aligned growth

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

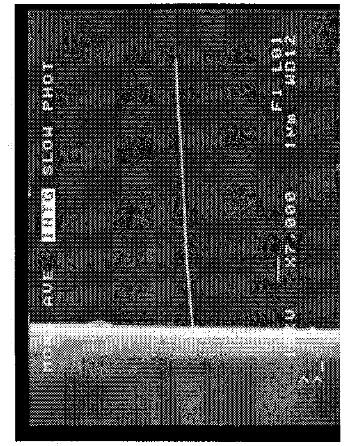




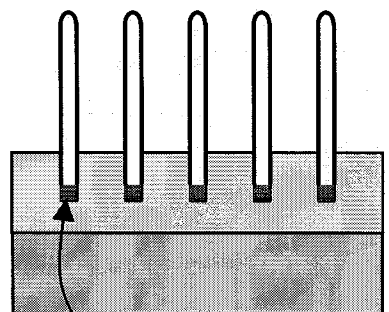
Control of vertical alignment:

Methane CVD at 900C:

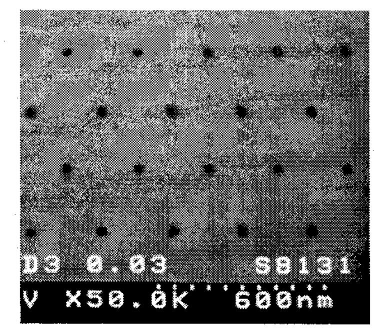
- Promising initial results on sub-nm catalysts
- Straight (low defect density) free-standing isolated nanotubes



- Investigating pore-aligned growth to force vertical alignment



catalyst recessed in pore



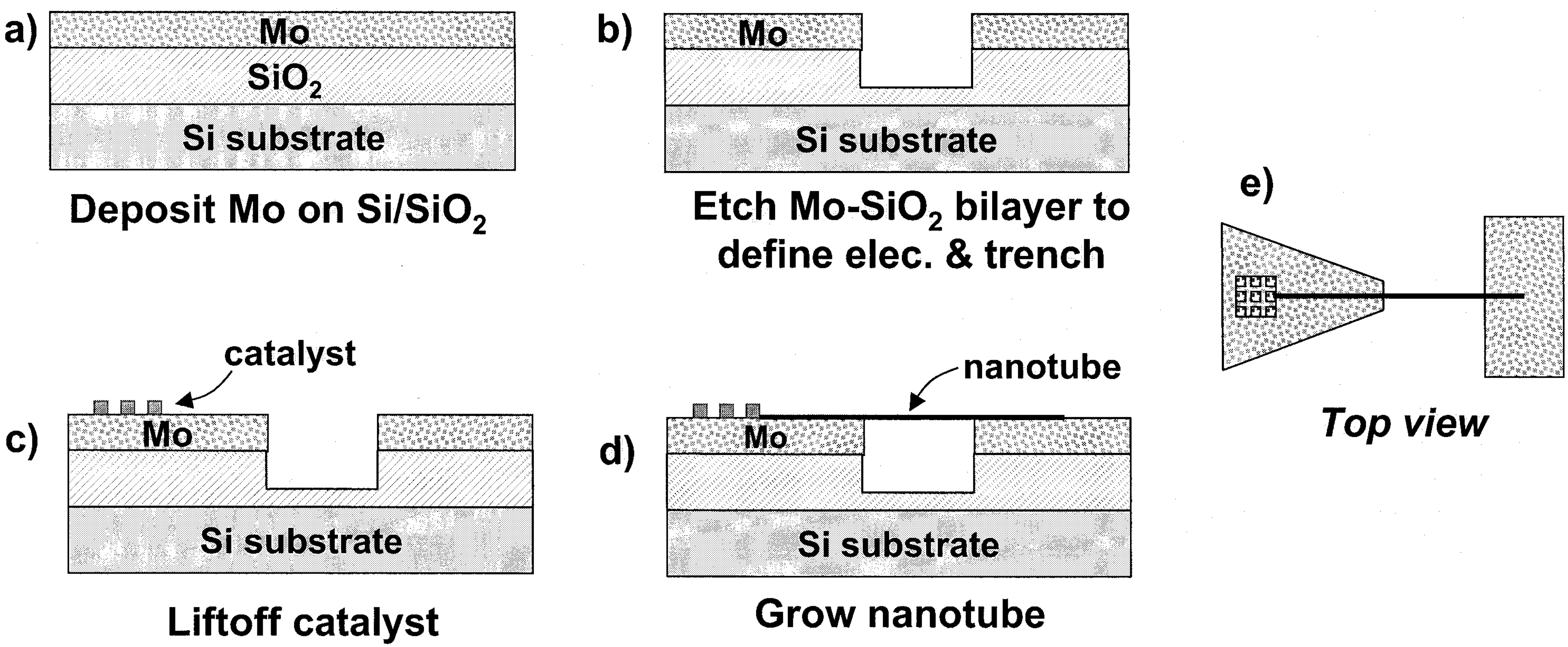
30 nm diam. pores with Fe catalyst by e-beam lith.

- Alumina nanopore process…

Lateral Nanotube Process - Mo electrodes

Process for growth of suspended CNT bridges with integrated molybdenum electrodes

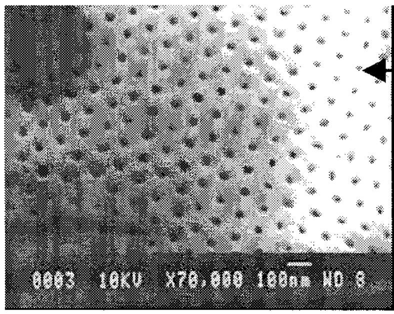
- Minimizes nanotube processing after growth
- Mo electrodes provide high quality electrical contacts

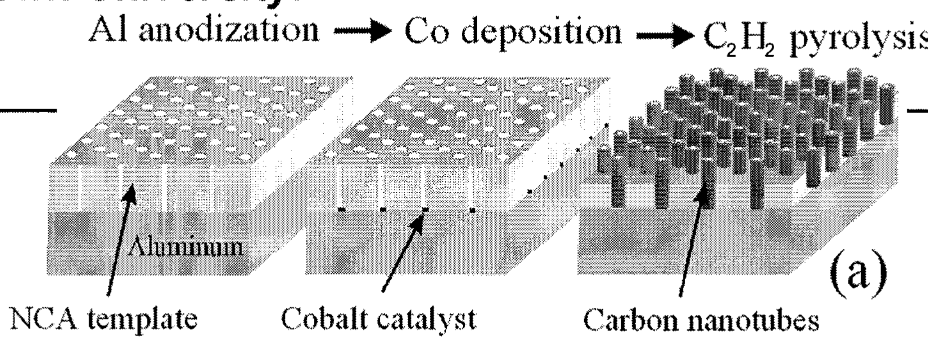


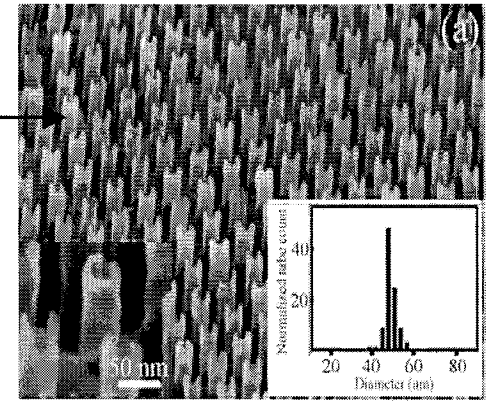
Related to H. Dai process, APL 81, 913 (7/29/02)

Alumina Nanopore Process for Uniform Vertical Nanotube Arrays

Prof. Jimmy Xu, Brown University:



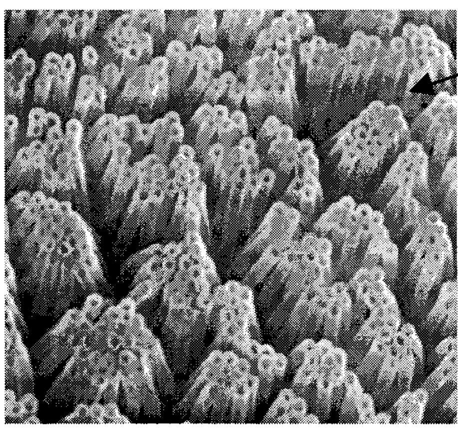




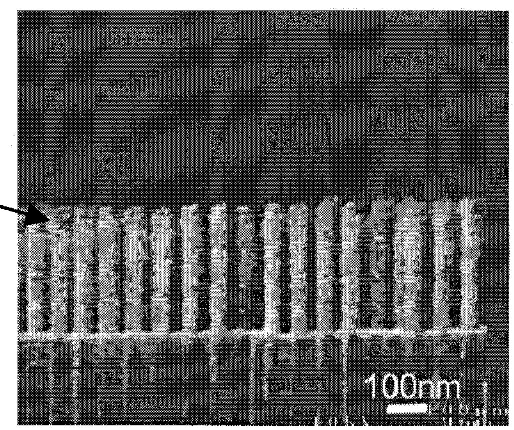
Free-standing Al foil process

- **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)**

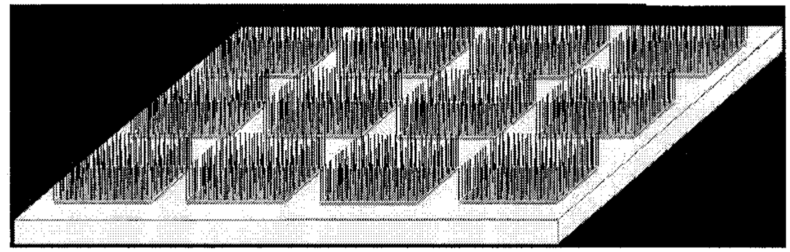


(with 25nm Au/Pt coating)

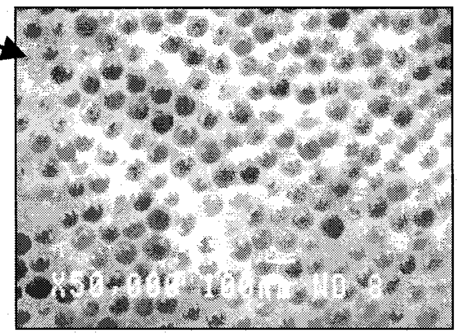
Carbon nanotube array device processing

Aluminum nanopore process on Si:

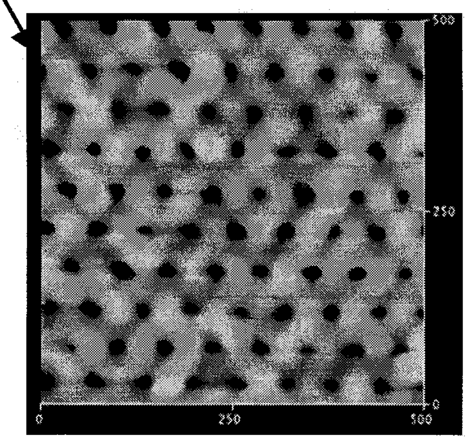
- Requires deposition of high purity, very smooth Al films on Si
- Al film typically much thinner than Al foil in standard process (~3μm *vs* >15μm)
  - Self-ordering of pores more difficult
  - Investigating ebeam-patterned pore nucleation sites
- Buried electrodes may be needed:
  - Must be compatible 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

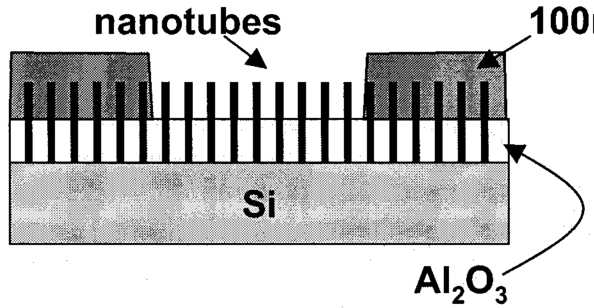


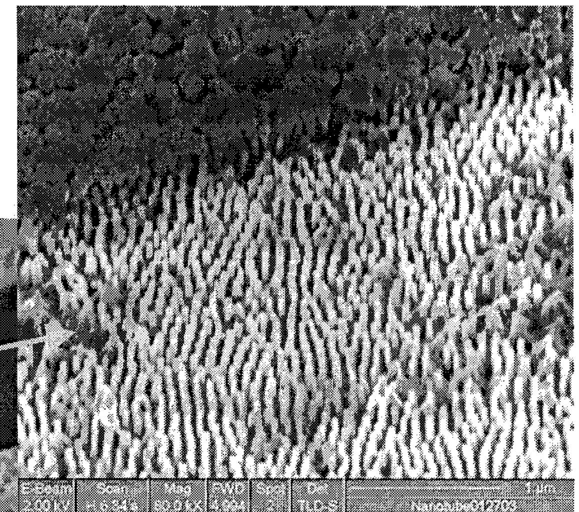
E-beam patterned hole array in PMMA on Al for etching of anodization nucleation sites - 20nm dots on 60nm centers

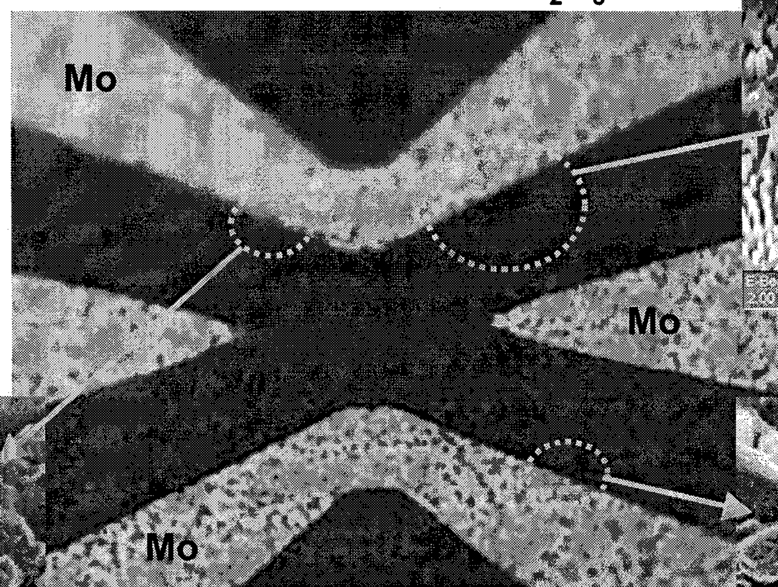
Patterning of RF electrodes on NT arrays

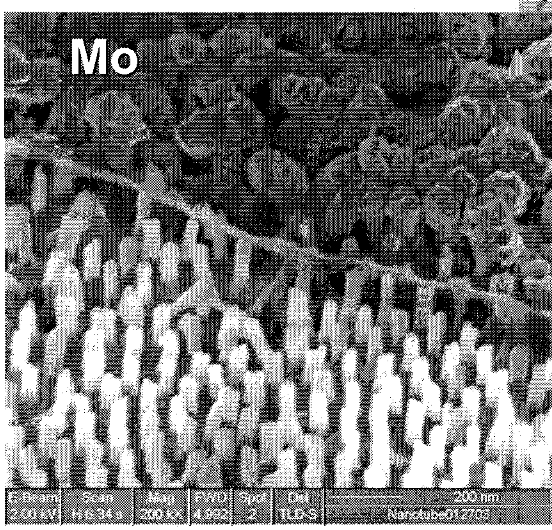
Patterned Mo electrodes

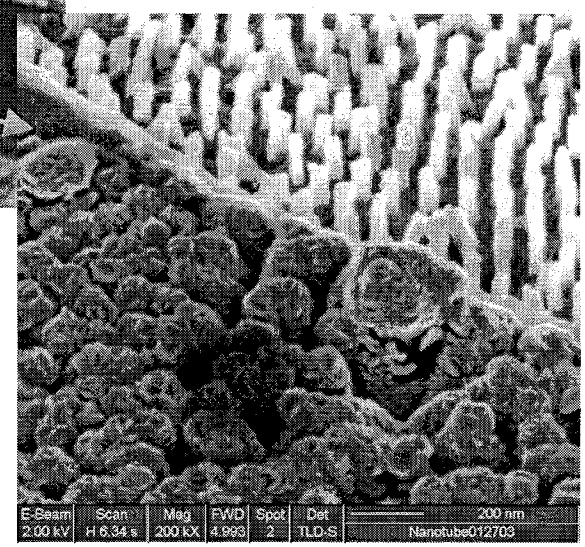
- Liftoff processing on Brown U. NT arrays
- RF-compatible CPW electrodes
- Nanotubes survive processing without de-adhering or tube-to-tube sticking









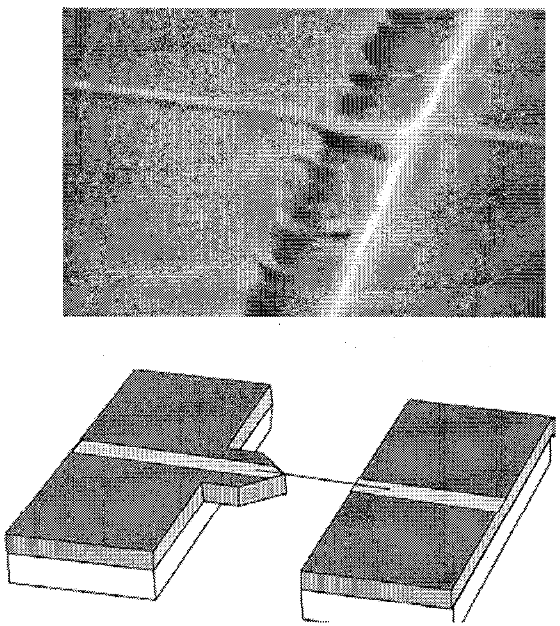


- Electrical measurements show acceptable electrode conductivity and isolation

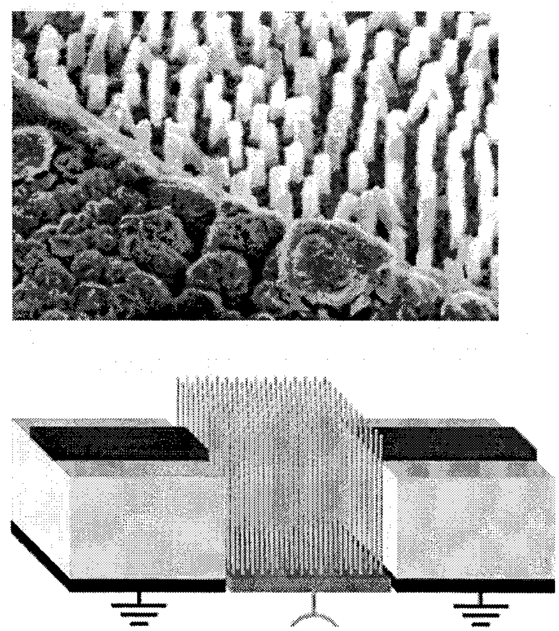
Dan Choi, 1-03

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