SWCNT NanoCompass for High Spatial Resolution Magnetometry

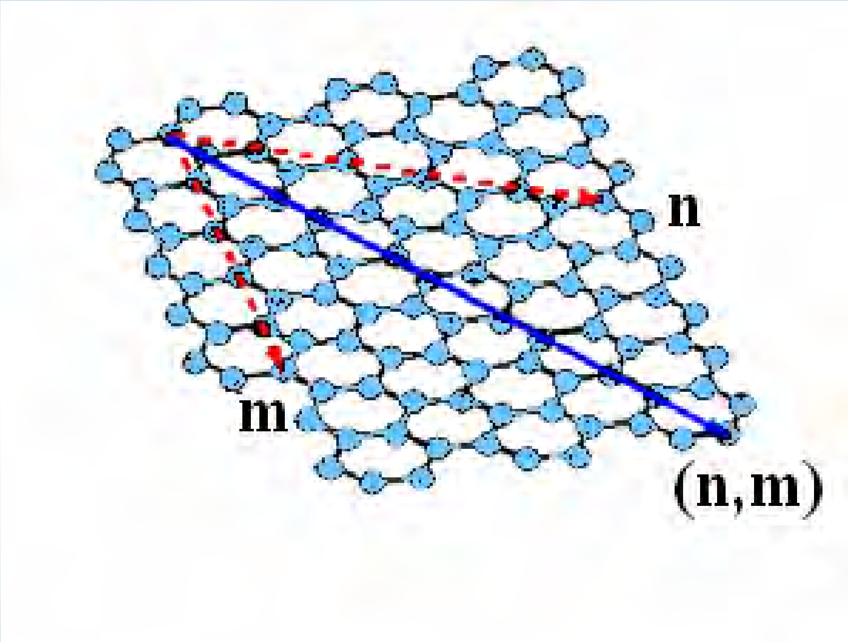
Outline

Carbon Nanotube-based Magnetometer

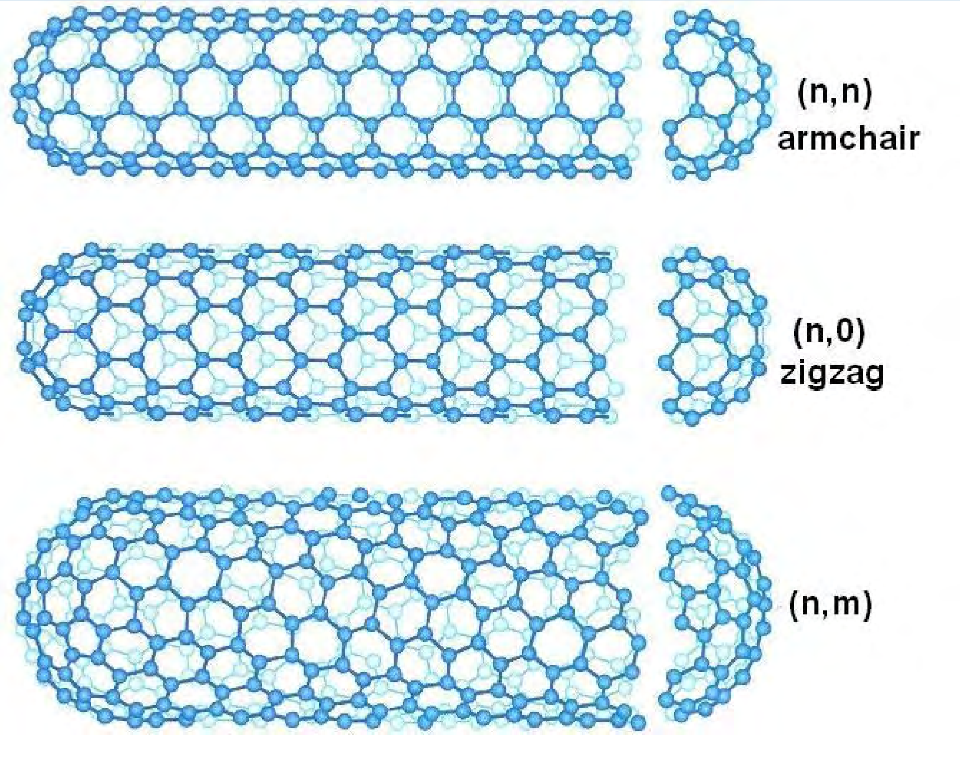
- Background: Carbon Nanotubes
- Electromechanical Properties of SWCNTs
- Magnetometer design and fabrication
  - $Fe(NO_3)_3$ catalyst
  - Thin film Fe catalyst
- Measurements:
  - Magnetoresistance
  - Temperature Dependence
- Conclusions and Future Work

Carbon Nanotubes

- Characterized by chirality, diameter



Courtesy Fuhrer Group, Univ Maryland, College Park



Courtesy Smalley Group, Rice Univ.

Metallic SWCNT:

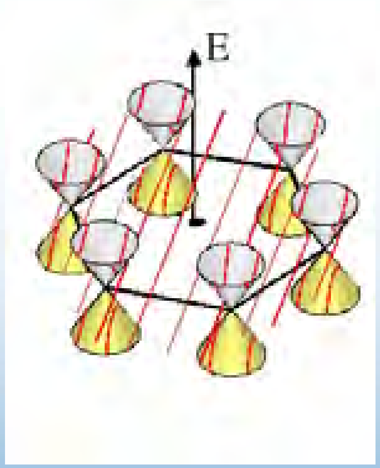
$n - m = 3 \times \text{integer}$

Electronic Properties: CNTs

- Metallic or Semiconducting

Radial Boundary Conditions

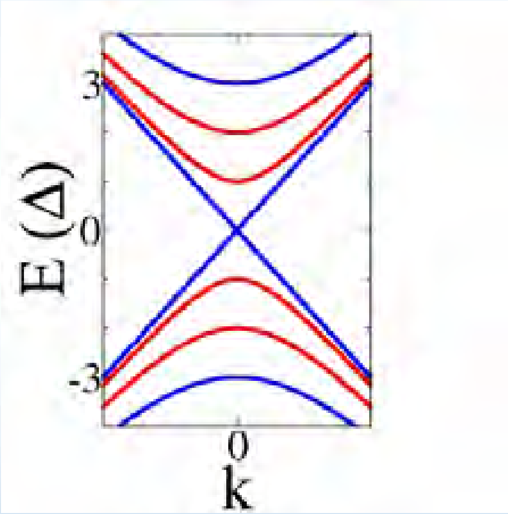
→ Wavevector quantization



Discrete Bands

❖ Metallic

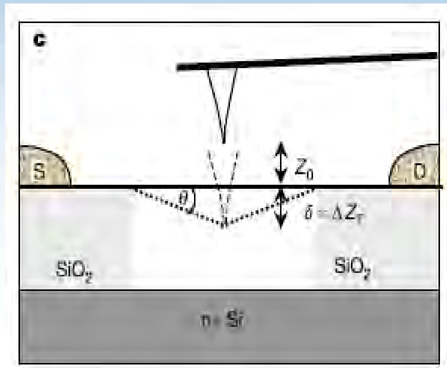
❖ Semiconducting

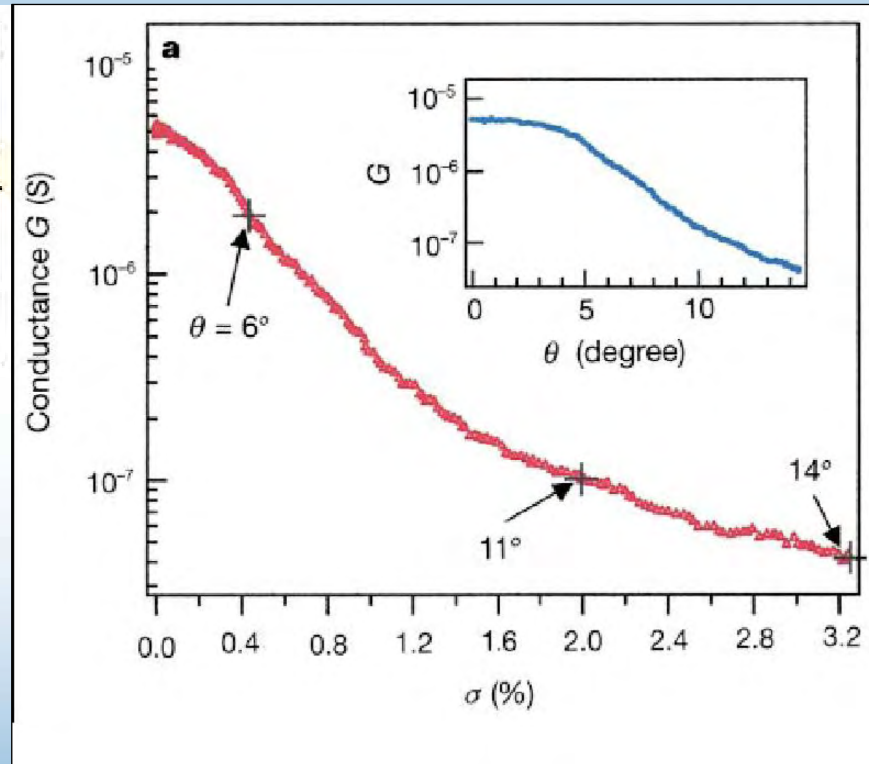


- Difficult to control → trend towards CNT network devices

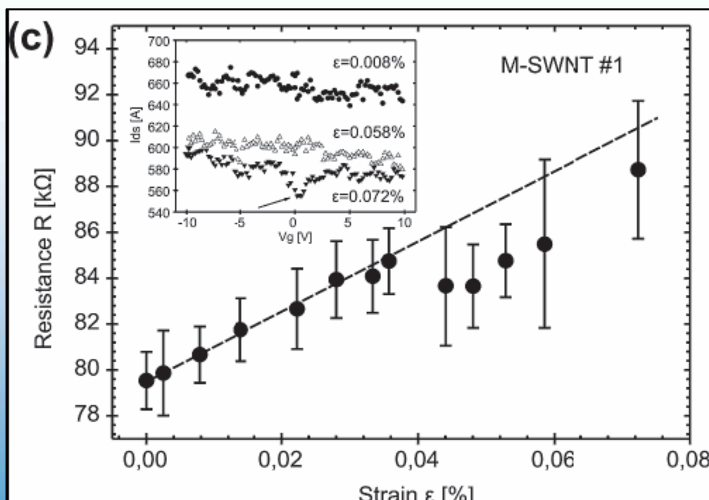
CNT Strain Sensor

- Modulation of conductance by mechanical deformation





Tombler *et al.*, *Nature* **405**, 769 (2000).



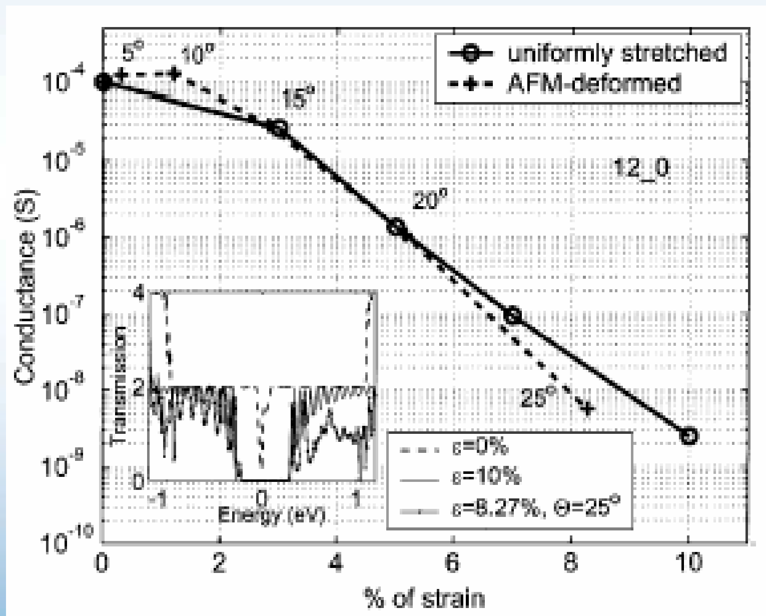
C. Stampfer *et al.*, *Nano Lett.* **6**, 233 (2006).

CNT versus Silicon

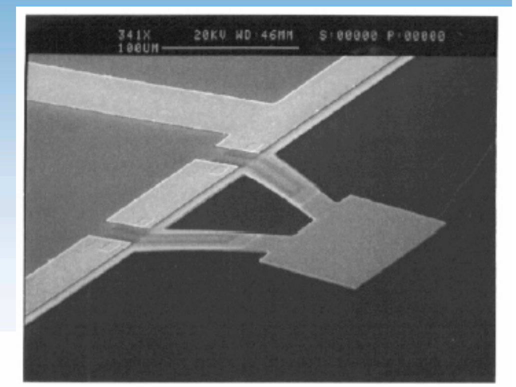
CNTs

$\Delta \sim 4$ *orders of magnitude*

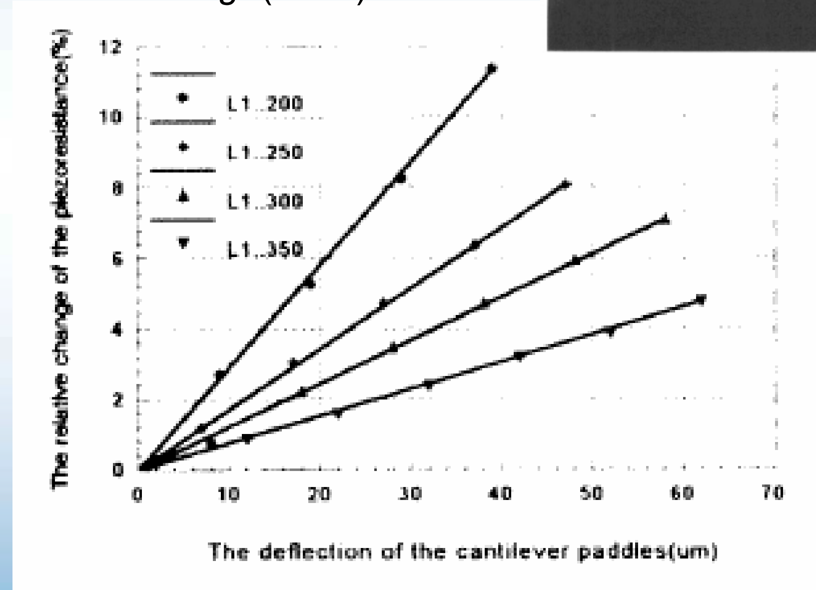
for $\theta \sim 25^o$



Maiti *et al.*, *PRL* (2002)



Y. Su *et al.*, *J. Micromech. Microeng.* (1996)



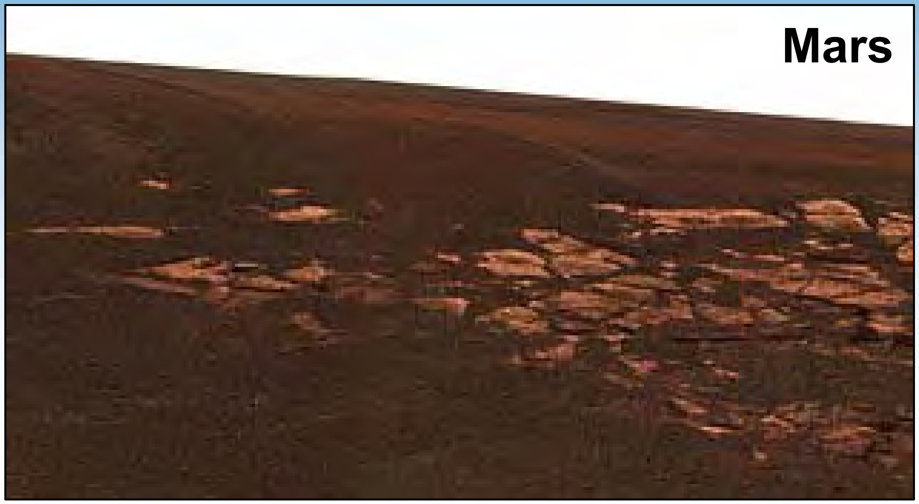
Silicon piezoresistors

$\Delta \sim 12\%$ for $\theta \sim 30^o$

Technological Motivation

Applications:

- Magnetospheric Science
- Spacecraft Orientation
- Planetary Geomagnetism



Fluxgate Magnetometer:

- High sensitivity (nTesla)
- Low noise

but

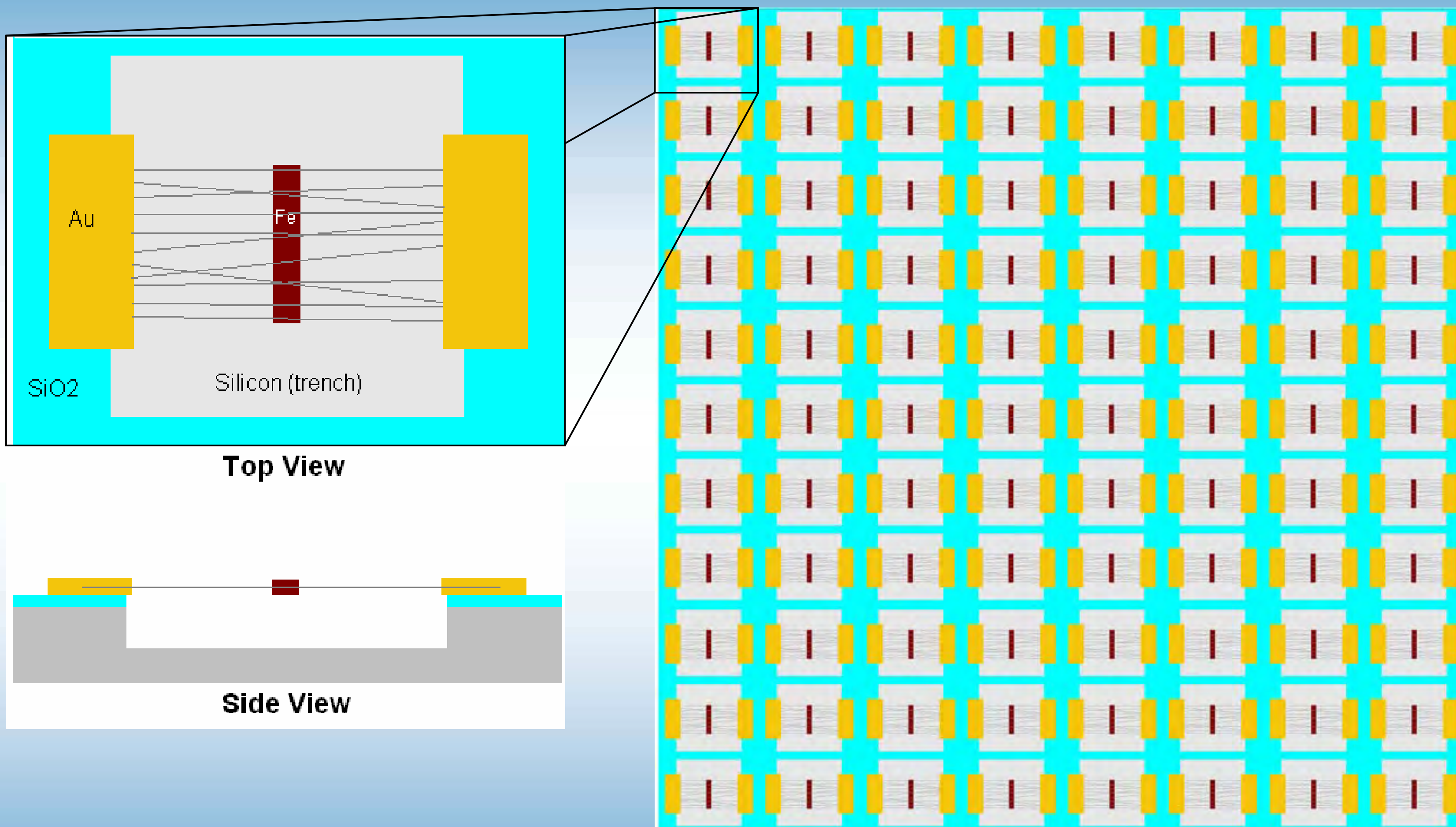
- cm-scale resolution
- Limited materials supply

M. H. Acuna, *Rev. Sci. Inst.* **73**, 3717 (2002)

Projected Specifications

	NanoCompass (estimated)	*UCLA fluxgate (ST5)*
Max Op Temp	~450°C	100°C
Sensor Dimensions	10^{-5} cm x 10^{-5} cm on Si (scalable)	4 cm x 4 cm x 6 cm
Sensor [Array] Mass	1 g	75 g
Sensor Op Power	10^{-3} - 10^{-2} mW	50 mW

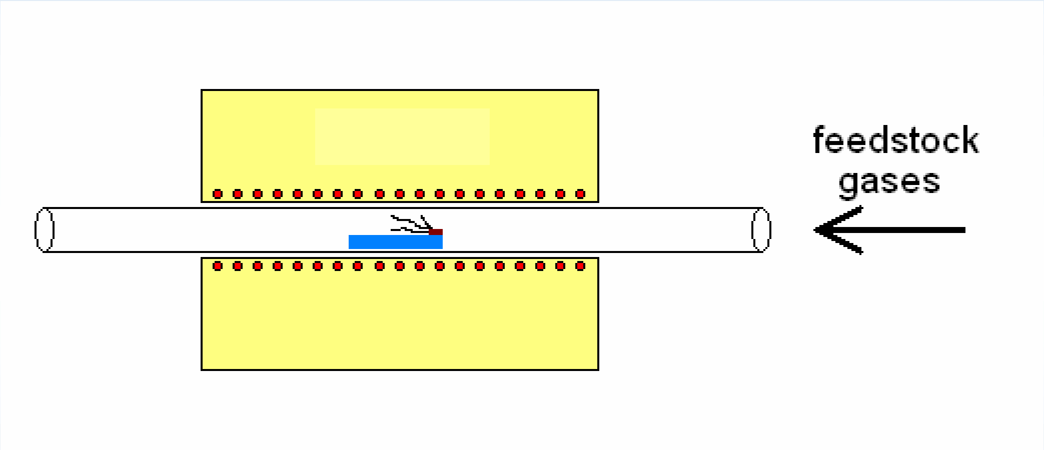
NanoCompass Design



- Single-Walled Carbon Nanotubes
- Au Electrodes
- Ferromagnetic Needle
  - Mech coupled to SWCNTs
  - Deflected in Magnetic Field

Vapor-Liquid-Solid Growth

- Feedstock gas → liquid alloy → solid nanostructure



SWCNTs:

- Catalyst = $Fe(NO_3)_3$:IPA
- Feedstock = CH_4 and C_2H_4
- T_G = 850°C

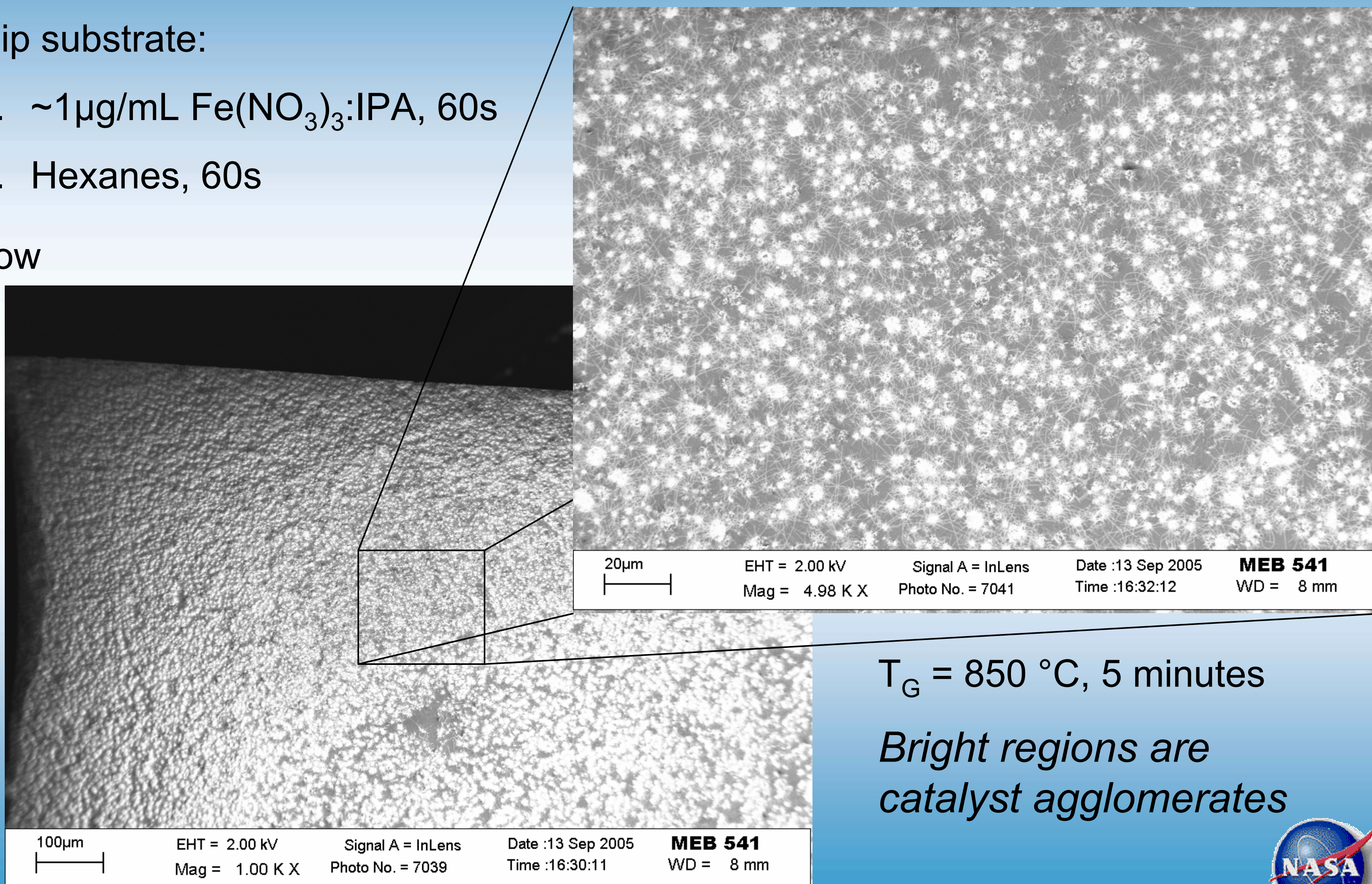
- Catalyst = thin film Fe
- Feedstock = CH_4 and C_2H_4
- T_G = 950°C

$Fe(NO_3)_3$ Catalyst

Dip substrate:

1. ~1µg/mL $Fe(NO_3)_3$:IPA, 60s
2. Hexanes, 60s

flow

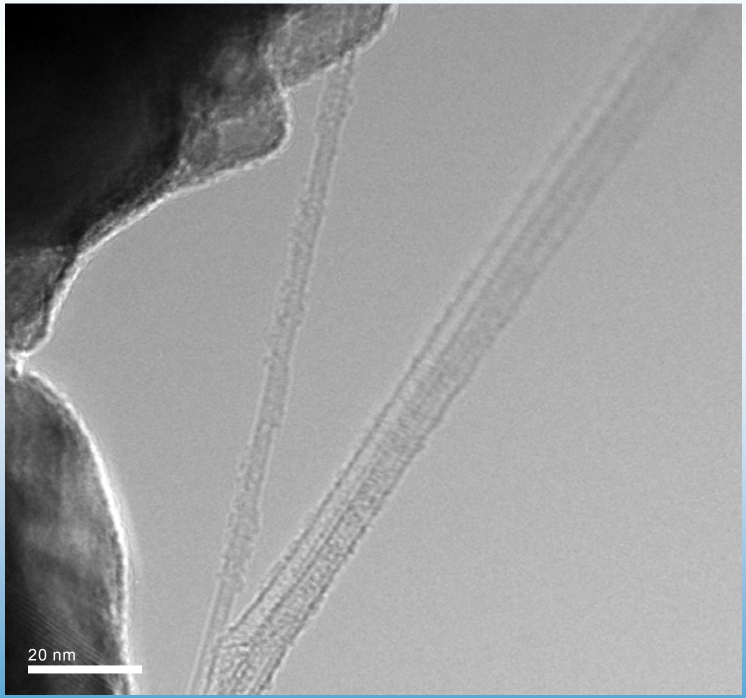


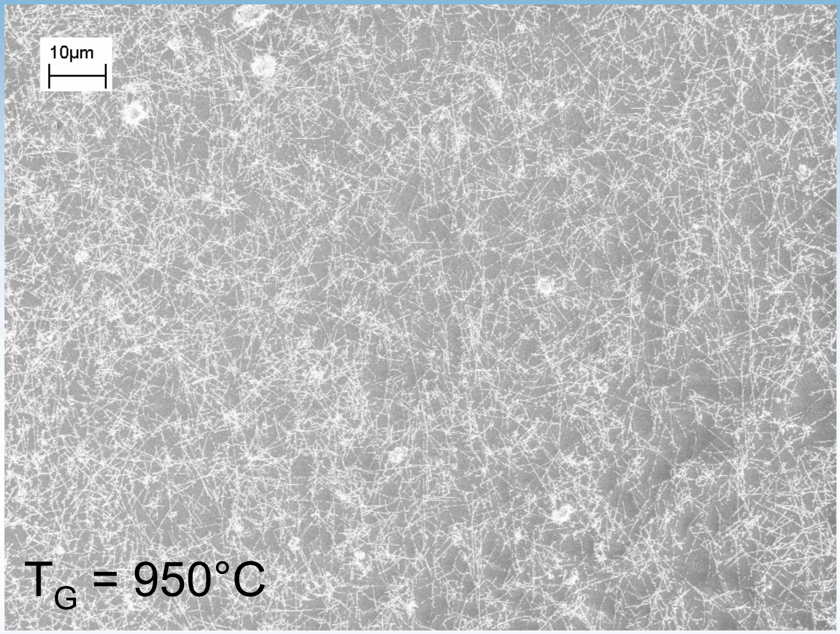
T_G = 850 °C, 5 minutes

Bright regions are catalyst agglomerates

Thin Film Fe Catalyst

- High density
- Improved cleanliness

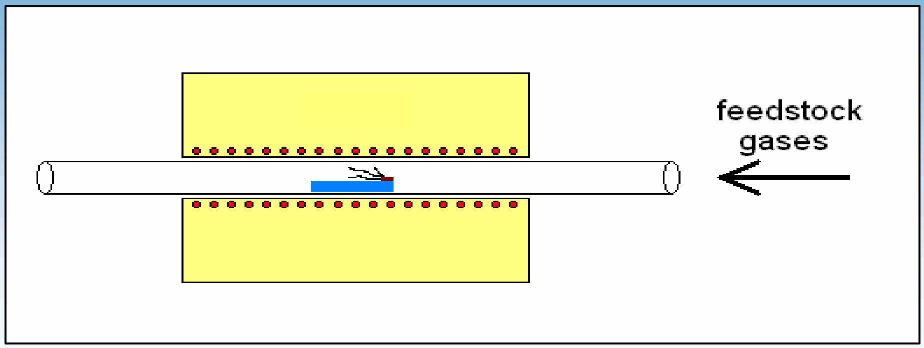


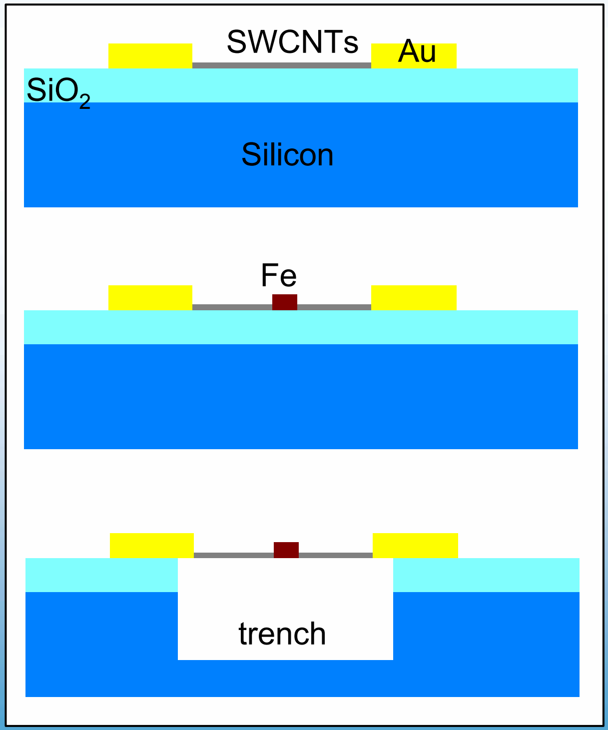


TEM studies show

- –SWCNTs
- –MWCNTs
- –bundles

NanoCompass Fabrication





Step 1: Grow SWCNTs by catalyst-assisted VLS growth

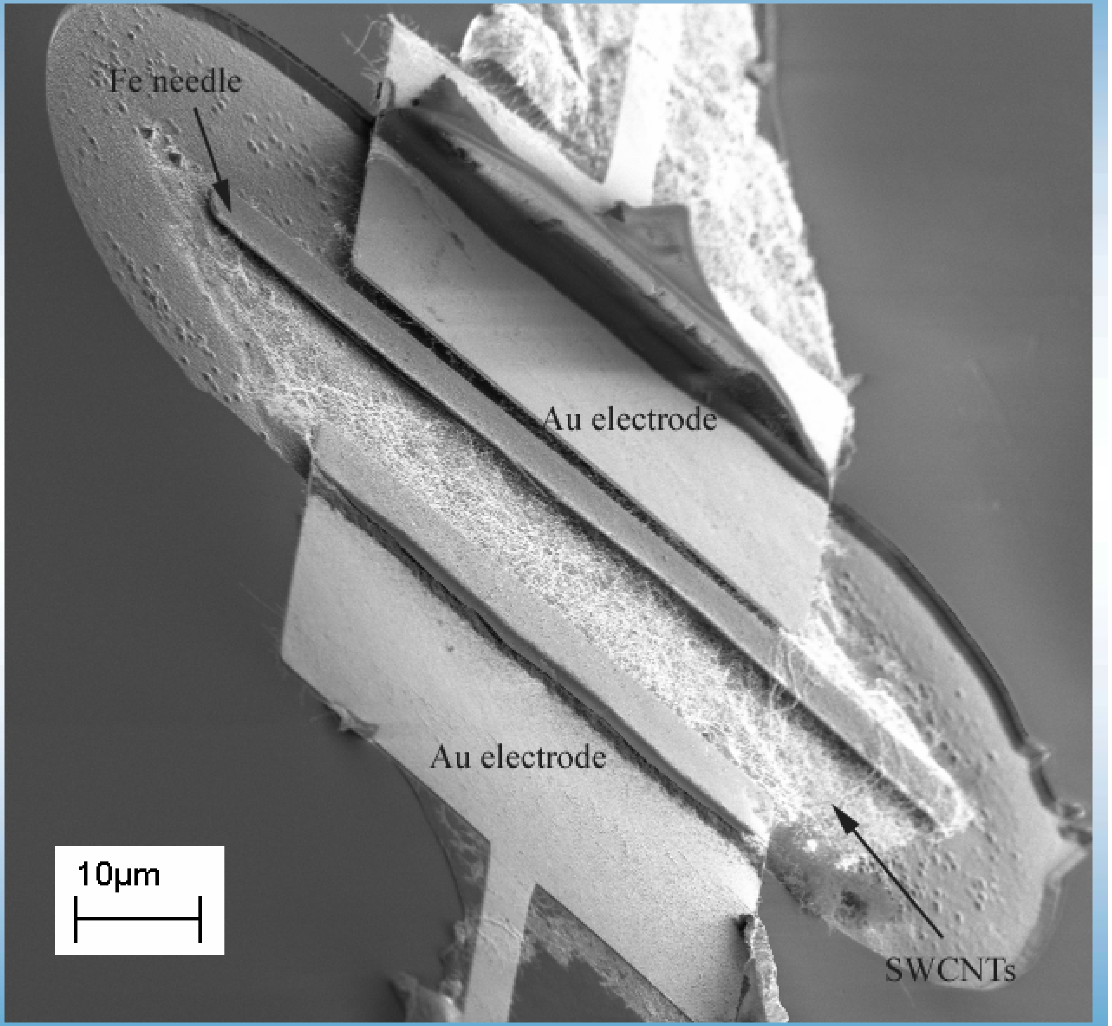
Step 2: Pattern/deposit Au electrodes

Step 3: Pattern/deposit Cr/Fe/Cr needle

Step 4: Pattern/etch trench in SiO_2/Si to release

NanoCompass Fabrication (to step 4)

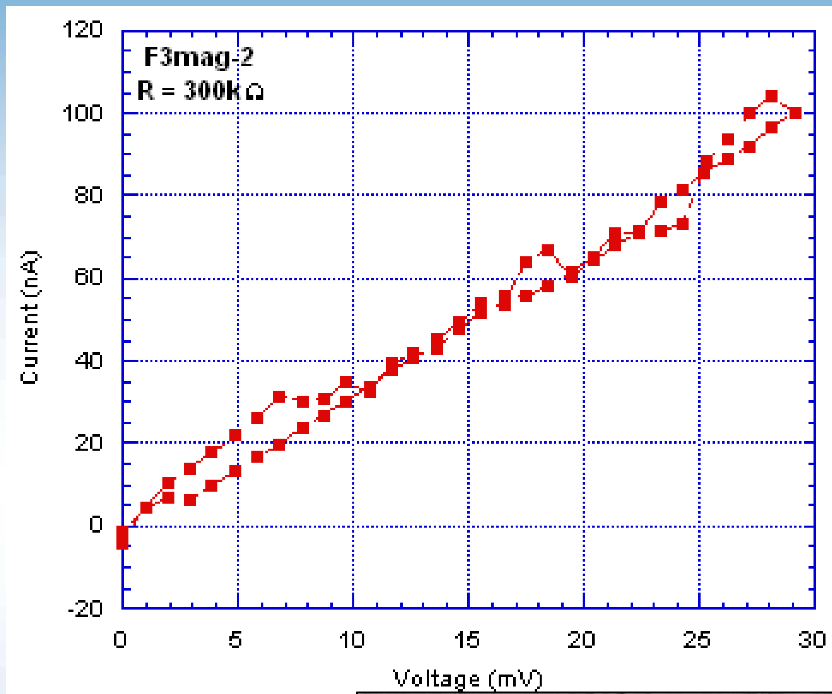
Materials can be robust to fabrication process



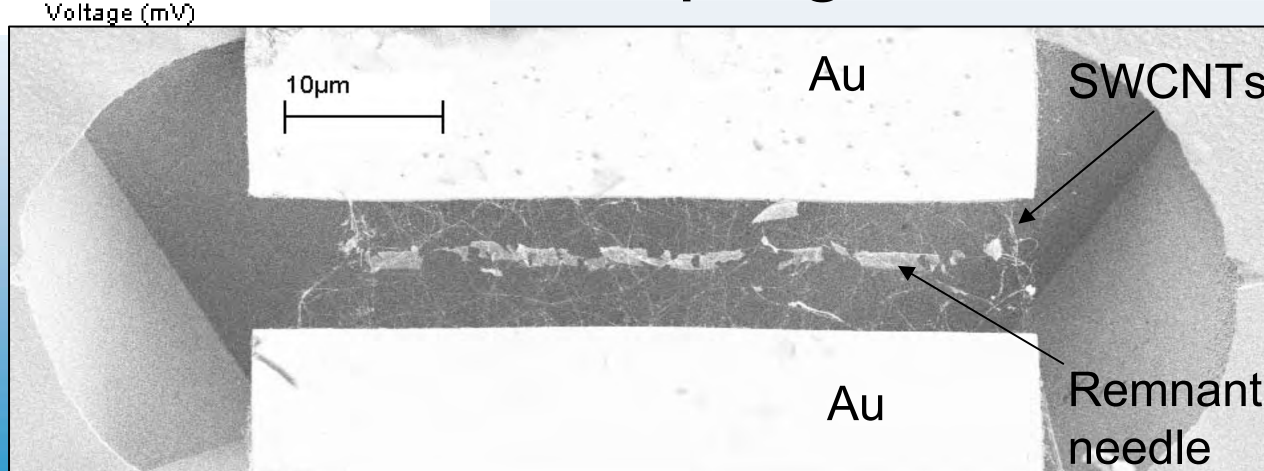
<u>Next steps:</u>

- Reduce electrode spacing
- Reduce needle width
- Increase trench depth

Future Work: Variability in Processing

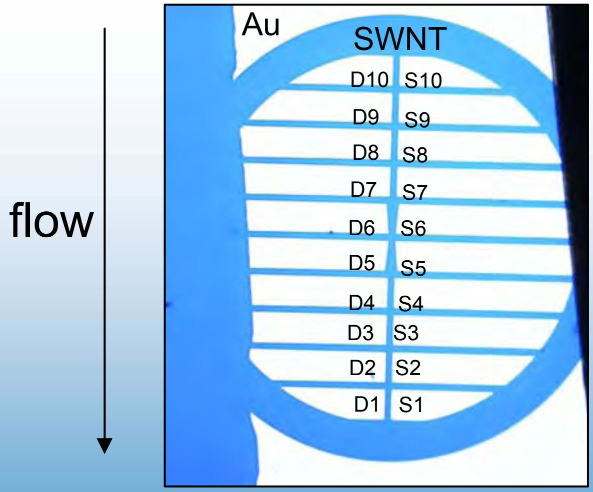


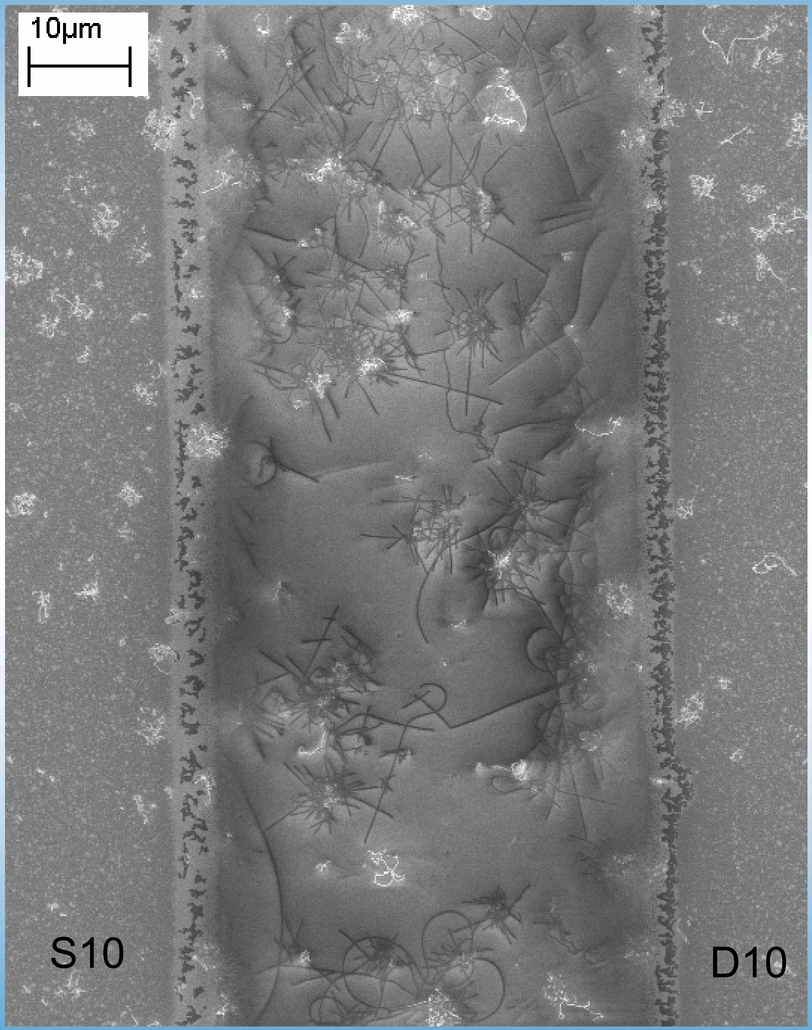
- SWCNT device electrically intact
- During magnetic field testing, continuity lost
- Next prototype in progress



Precursor Device – Bound to Substrate

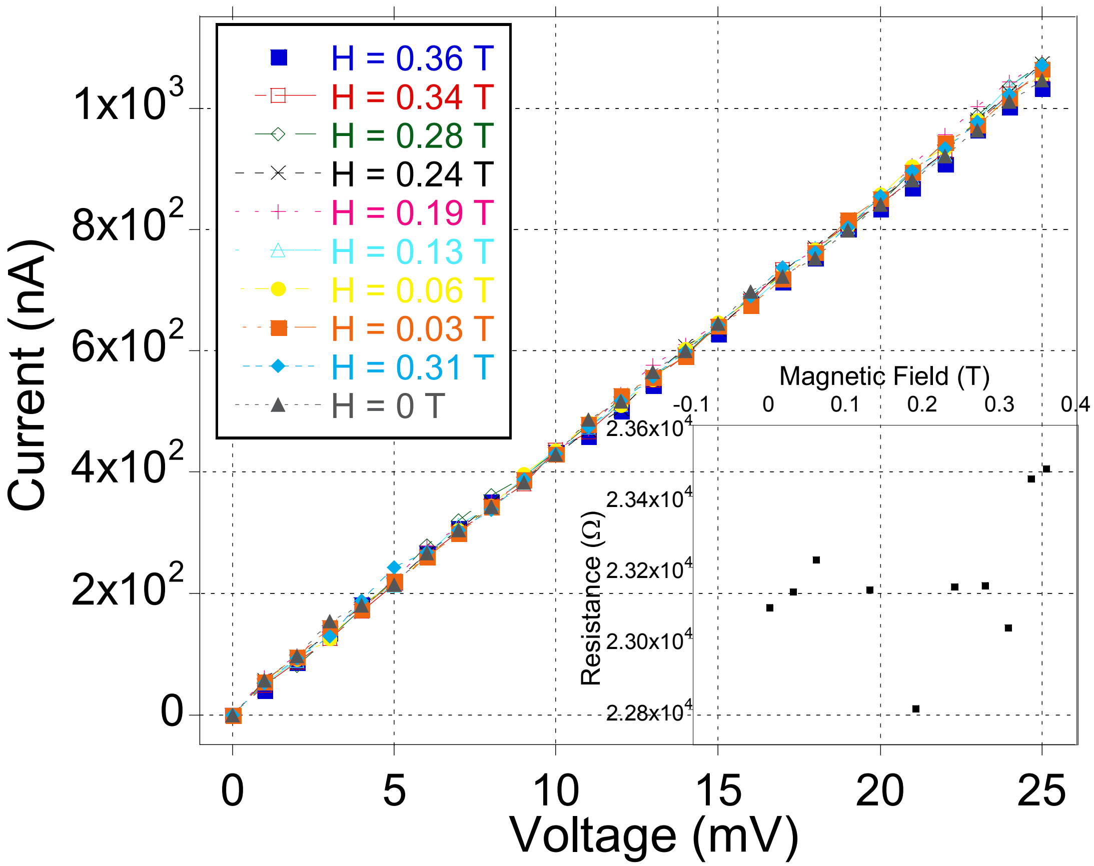
- Catalyst = $Fe(NO_3)_3$
- T_G = 850°C
- Cr/Au electrodes



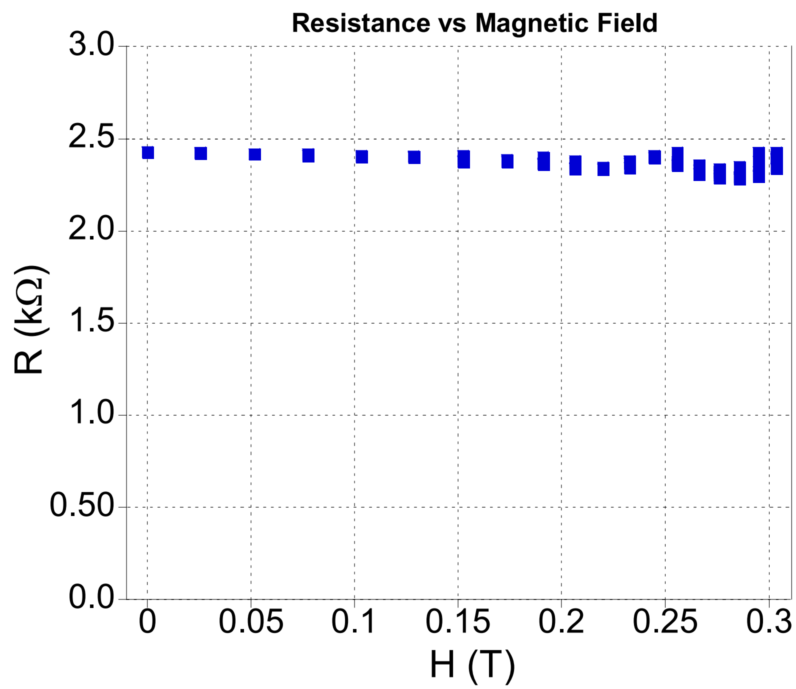


Magnetic Field Measurements

- Catalyst = $Fe(NO_3)_3$



- Catalyst = thin film Fe

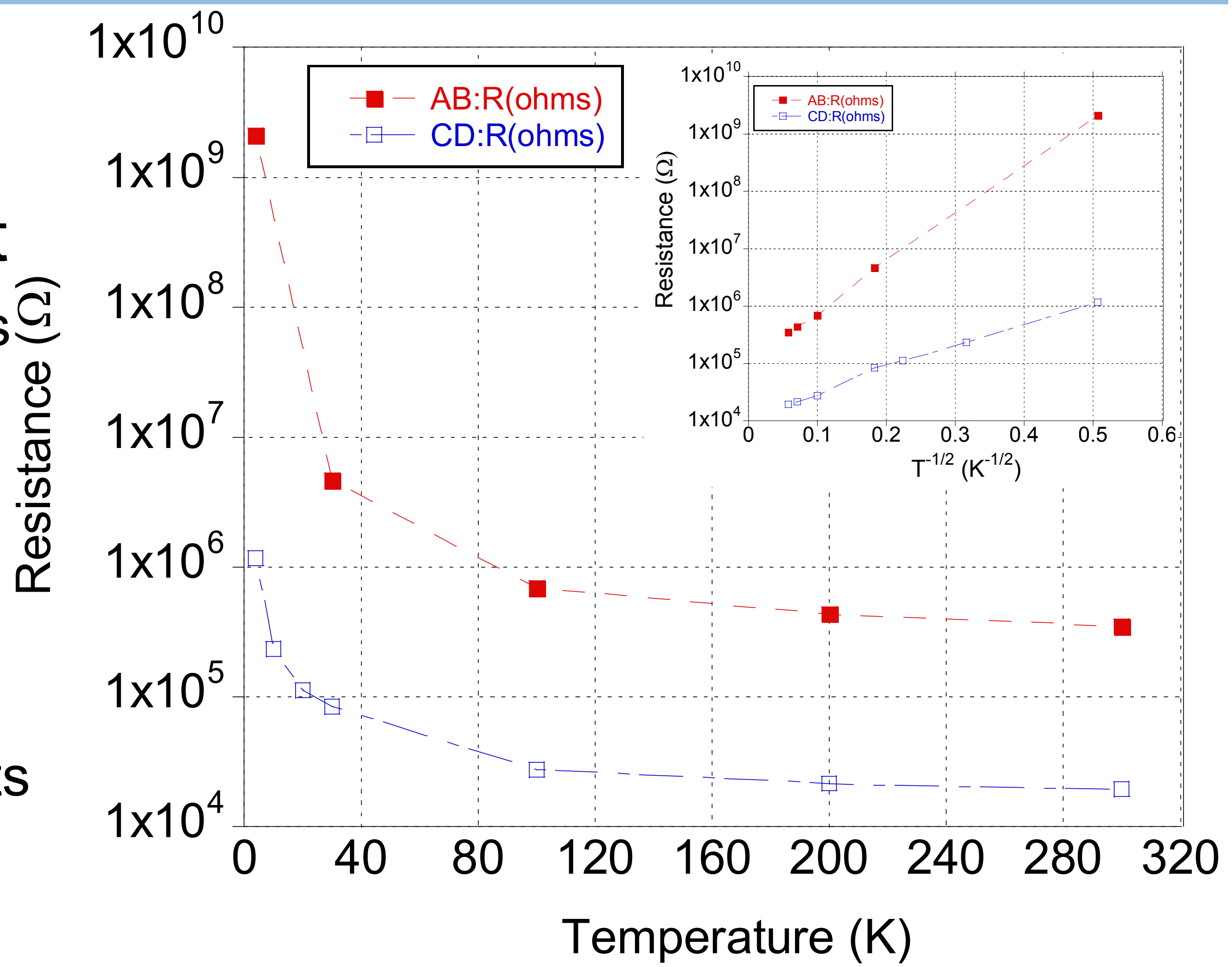


- SWCNT resistance insensitive to low magnetic field
  - Fe catalyst oxidized, well spaced
- Magnetometer operation :
  - Strain mechanism will dominate

Temperature Dependence

- Strong low-T dependence
- Barrier(s) present
  - Tube-tube junctions
  - Electrodes
- Stable operation

  T > 100 K
  - Minimal thermal control requirements



Conclusions and Future Work

- Magnetoresistance, temperature dependence of precursor SWCNT device
  - No inherent magnetoresistive response for base material
    - Strain mechanism will dominate during operation
  - Operating temperature range T > 100 K
    - Minimal thermal control requirements for most targets of interest
- Magnetometer prototype fabrication complete
  - Materials are compatible with processing
  - Next prototype under development