Nanopackaging:

Nanotechnologies & Electronics Packaging

Part D ECAs, Simulation, & Nanoelectronics Packaging

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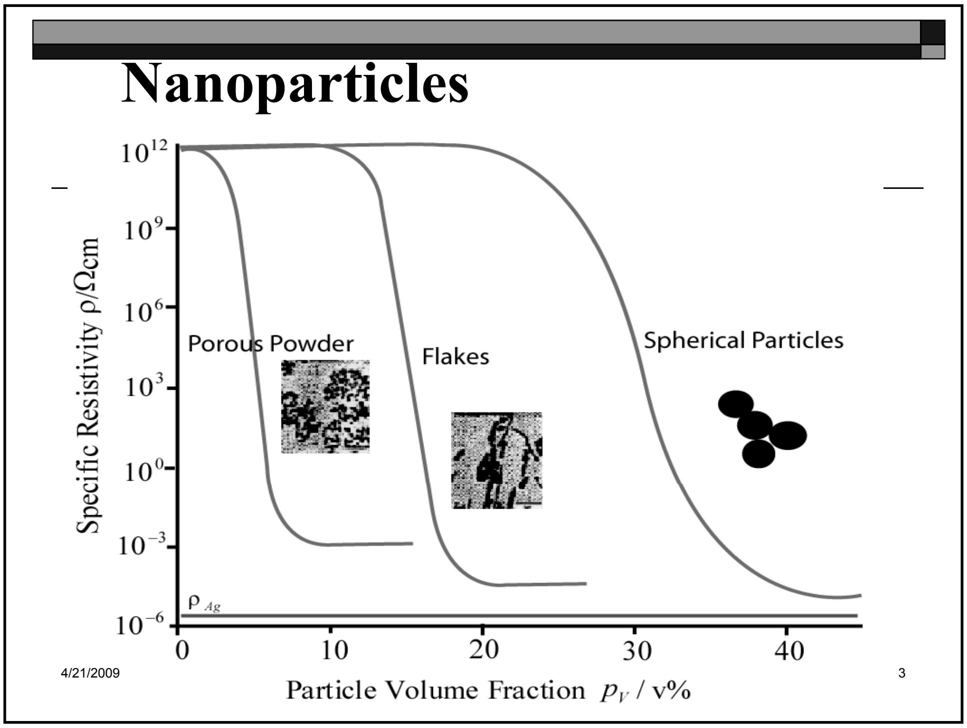
Nanotechnologies in ECAs

- ☐ ECA/ICA/ACA/ACP/ACF/NCA !!!!
- ☐ ICAs
    - Nanoparticles
    - Sintering
    - Surface treatments
- ☐ ACAs, NCAs, & miscellaneous
- ☐ CNTs
- ☐ Microvias



Nanoparticles

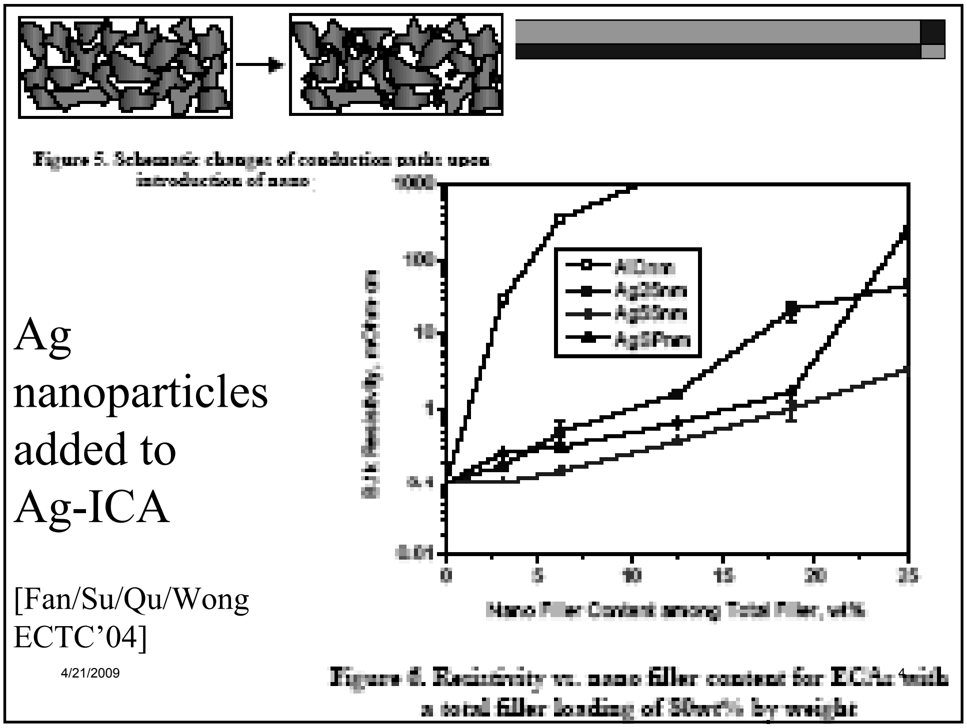
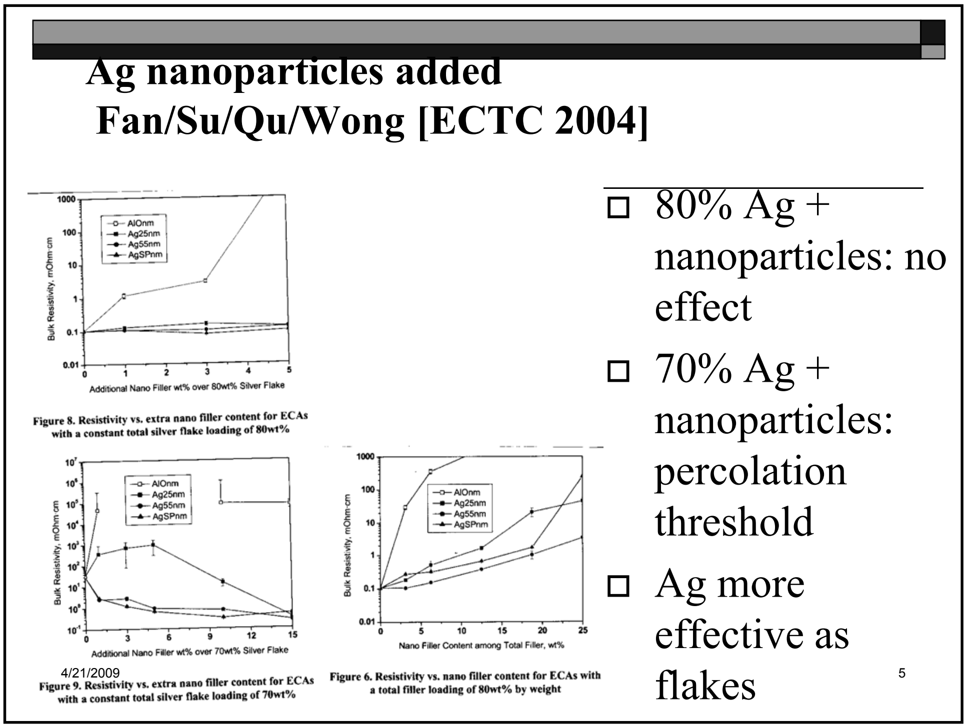


Figure 5. Schematic changes of conduction paths upon introduction of nano

Ag nanoparticles added to Ag-ICA

[Fan/Su/Qu/Wong ECTC'04]

Figure 6. Resistivity vs. nano filler content for ECAs with a total filler loading of 80wt% by weight



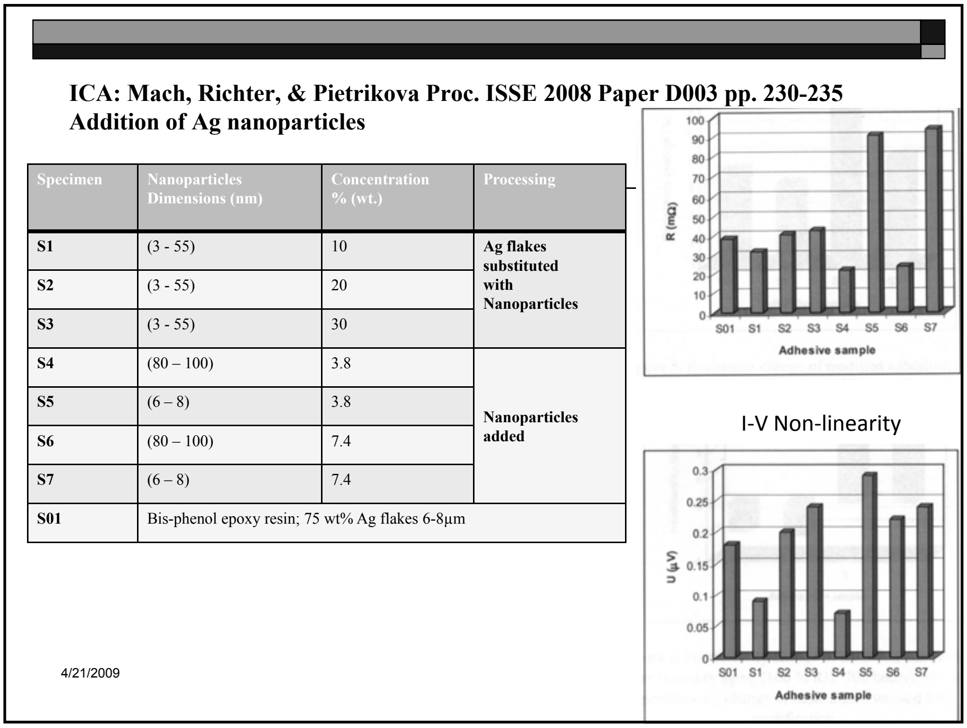
Ag nanoparticles added
Fan/Su/Qu/Wong [ECTC 2004]

Figure 8. Resistivity vs. extra nano filler content for ECAs with a constant total silver flake loading of 80wt%

Figure 9. Resistivity vs. extra nano filler content for ECAs with a constant total silver flake loading of 70wt%

Figure 6. Resistivity vs. nano filler content for ECAs with a total filler loading of 80wt% by weight

- ☐ 80% Ag + nanoparticles: no effect
- ☐ 70% Ag + nanoparticles: percolation threshold
- ☐ Ag more effective as flakes



ICA: Mach, Richter, & Pietrikova Proc. ISSE 2008 Paper D003 pp. 230-235
Addition of Ag nanoparticles

Specimen	Nanoparticles Dimensions (nm)	Concentration % (wt.)	Processing
S1	(3 - 55)	10	**Ag flakes substituted with Nanoparticles**
S2	(3 - 55)	20	
S3	(3 - 55)	30	
S4	(80 – 100)	3.8	**Nanoparticles added**
S5	(6 – 8)	3.8	
S6	(80 – 100)	7.4	
S7	(6 – 8)	7.4	
S01	Bis-phenol epoxy resin; 75 wt% Ag flakes 6-8μm		

I-V Non-linearity

Nanoparticle inclusion in ep AgNO

[Wong et al, ECTC'06]

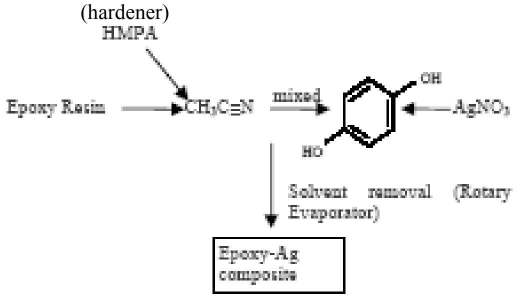


Fig. 4 Schematic illustration of the preparation of the *in-situ* conductive adhesives

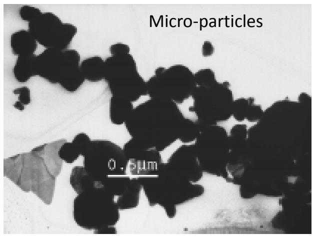


Fig. 9 Silver particles *in-situ* formed in cycloalophatic epoxy matrix.

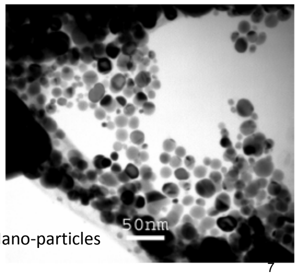


Fig. 10 Silver nanoparticles *in-situ* formed in the cycloalophatic epoxy matrix in the presence of HMPA

Nanoparticle Sintering

[Wong et al, ECTC'06]

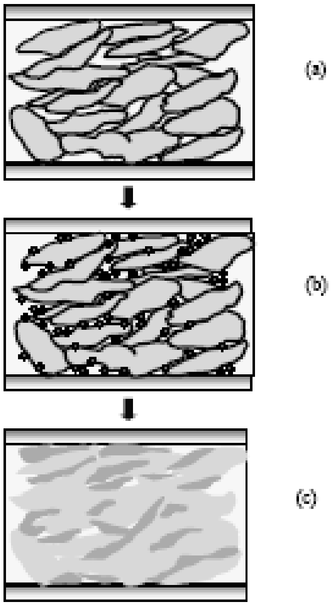
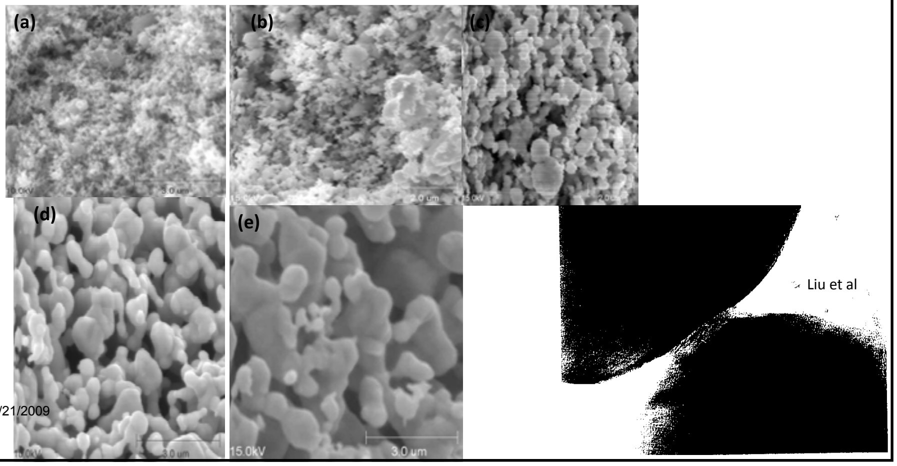


Figure 1. Schematic of particles and flakes between the metal and pads. (a) is conductive adhesives with silver flakes as fillers; (b) is conductive adhesives with both flakes and nanoparticles as fillers; (c) is conductive adhesives with sintered particles among flakes as fillers.

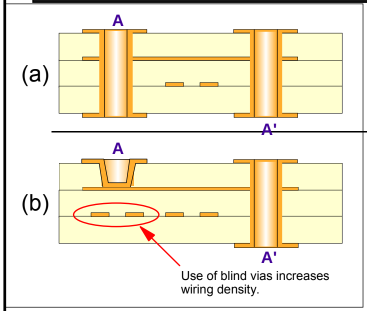
Isotropic Conductive Adhesives (ICAs)

20nm-sized Ag particles annealed at different temperatures for 30 minutes:
(a) room temperature (no annealing); (b) annealed at 100°C; (c) annealed at 150°C; (d) annealed at 200°C and (e)annealed at 250°C.
(Markers: (a) 3μm (b) 2μm (c) 2μm (d) 3μm (e) 3μm)

Lu et al



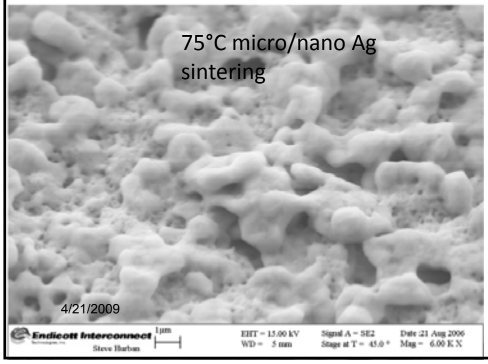
Liu et al



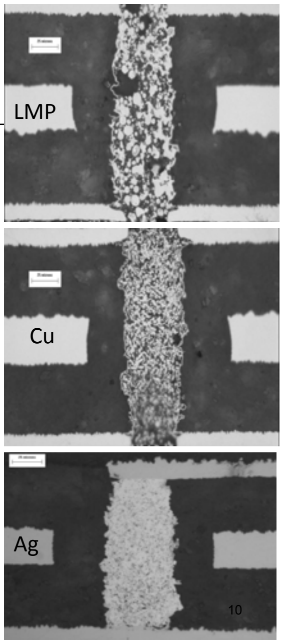
Use of blind vias increases wiring density.

Das & Egitto

ICA Microvia Fill (PWB)

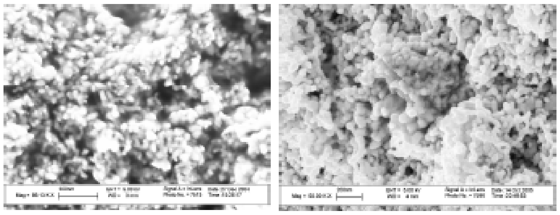


75°C micro/nano Ag sintering



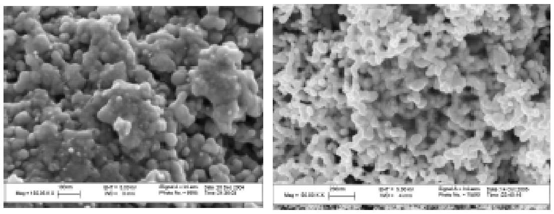
Nano-particle sintering

[[illegible] et al. ECTC'04 & '06]



(a) No annealing of diacid treated silve

(c) Annealing at 100 °C for 30 mins of untreated silver



(b) Annealing at 150 °C for 30 mins of diacid treated silver

(d) Annealing at 100 °C for 30 mins of diacid treated silver

Figure 4. Comparison of the morphologies of silver nanoparticles without treatment and treated by diacids before and after annealing at 100°C and 150°C for 30 mins.

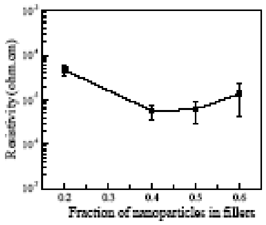
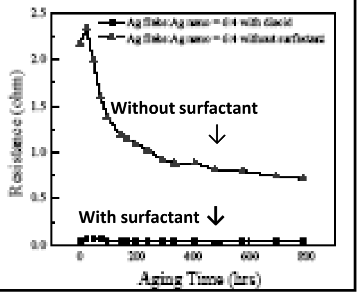


Figure 5. The bulk resistivity of the isotropic conductive adhesives with 5wt% diacids as surfactants

Surfactants: 5% diacids



Without surfactant ↓

With surfactant ↓

Stearic acid can be removed/replaced by short-chain dicarboxylic acids, with strong affinity for Ag surface (e.g. malonic acid) Li/Moon/Li/Wong ECTC 2004]

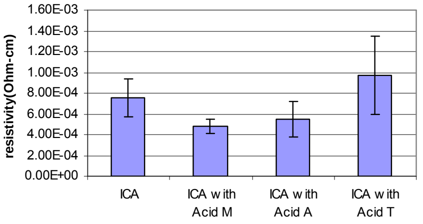


Figure. 5 Effects of different dicarboxylic acids on the conductivity of ICA

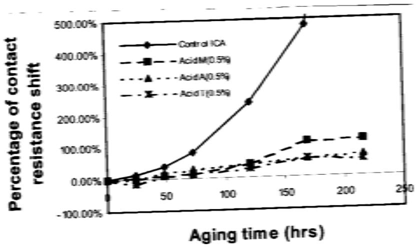
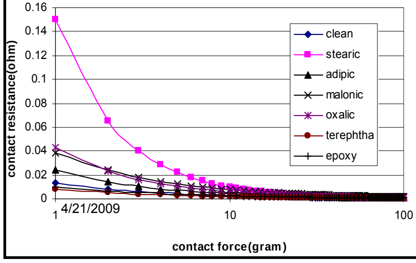
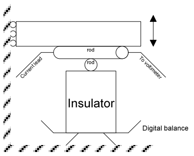


Figure. 6 Contact Resistance Shifts of ECAs with and without dicarboxylic acids



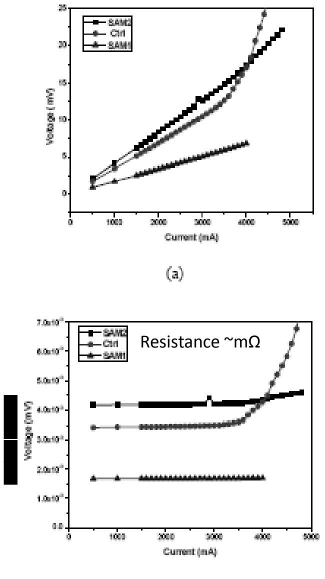


Experimental resistances with short-chain acids

[Qu – APM'05]

Anisotropic Conductive Adhesive (ACA) Enhancement

(Rongwei Zhang et al ECTC'08)



[redacted]

(a)

(b)

Figure 8 (a) I-V curve of ACA filled with Ag particles (Ctrl), SAM1-treated Ag particles and SAM2-treated Ag particles; (b) Corresponding I-R curves.

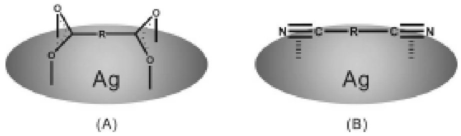


Figure 5 Alignments of SAM1 and SAM2 on a submicron-sized Ag particle surface.

SAM-1:
- "Molecular wires"
- Oxide reduction
  - Lower resistance
  - Higher max current

10-20 nm nano-Ag fillers for NCAs

($AgNO_3$ added to polymer) [Li/Moon/Wong ECTC'06]

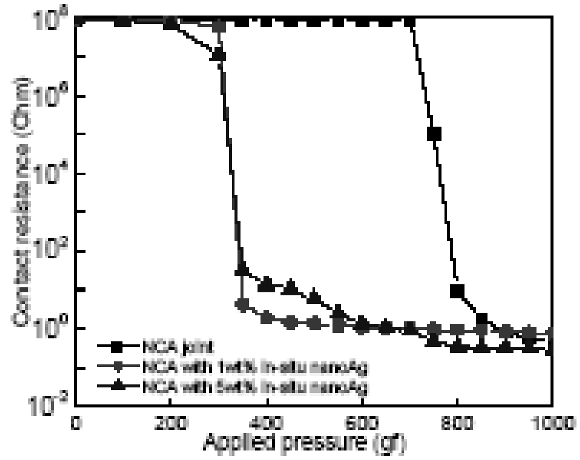


Fig. 12 Influence of pressure on the contact resistance of NCA joints with and without *in-situ* formed nano-Ag fillers.

CNT-PP (petroleum pitch) composite (C mesophase) fillers for conductive pastes

[Bondar et al, ECTC’05]

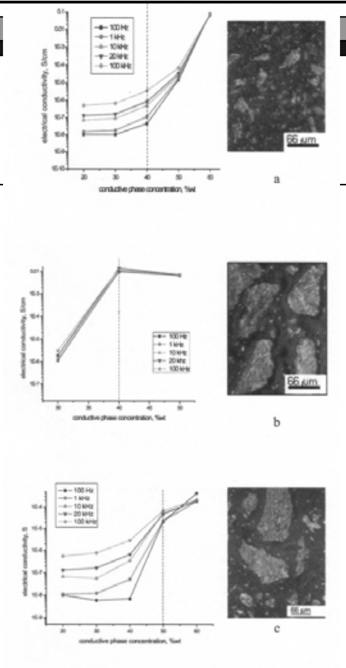


Fig. 2. Electrical conductivity and microstructural aspect of epoxy matrix composites function of the filler concentration and type: a)PP 900; b) PP/0.5SWNT 900; c) PP/1.5MWNT 900

Ag nanowire ACF (Au seed, Co alignment)

[Lin et al, ECTC’05]

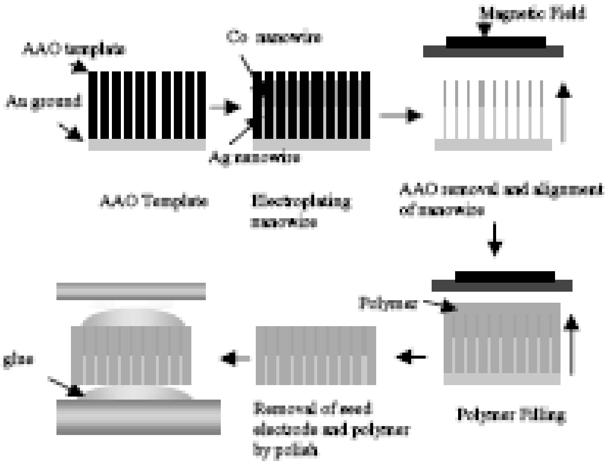
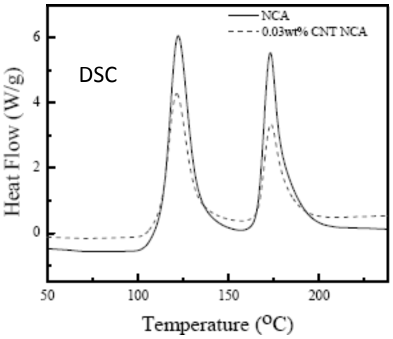


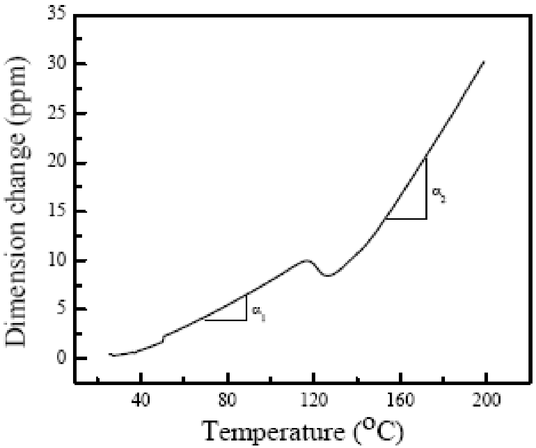
Fig. 1 Process Flow of Nanowire Conductive Film

Addition of CNTs to NCAs: 0.03 wt% CNTs increases electrical and thermal conductivities c. 20%

NCAs/NCFs	CTE ppm/°C (α_1)	CTE ppm/°C (α_2)
No CNTs	71.55	197.2
0.02 wt% CNTs	62.3	179.8
0.03 wt% CNTs	60.9	177.8



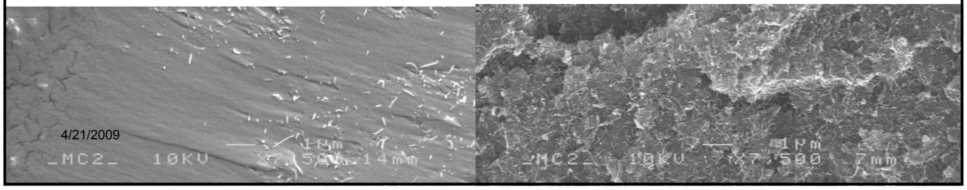
Jiang, Min, Moon, & Wong, Proc. ECTC 2008 pp. 1385-1389



Zhang, Jiang, Liu, & Inoue ICEPT/HDP 2008 E3-04 Effects of CNT & Ag powder addition

Sample	AF2 epoxy % matrix	3-10µm % Ag flakes	0.5-1µm % Ag powder	Vol % CNT	Resistivity µΩ.cm
AgF201	60.762	38.238	1	0	45
AgF202	60.762	37.238	2	0	39
AgF203	60.762	36.238	3	0	40
AgF204	60.762	35.238	4	0	39
AgF205	60.762	34.238	5	0	48
AgF206	60.762	39.238	0	0	52
3F201	60.762	38.138	1	0.1	34
3F202	60.762	37.938	1	0.3	36
3F203	60.762	37.738	1	0.5	29

CNT dispersion in epoxy: (a) CNTs untreated (b) CNTs treated H_2SO_4/HNO_3 16hrs 50°C



Interface effects on the conductivity of CNT composites [Yan et al, Nanotechnology 2007]

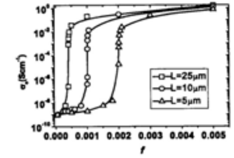


Figure 3. The dependence of the effective conductivities on CNT length L with different volume fraction f.

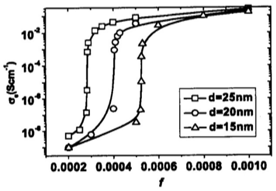


Figure 4. The dependence of the effective conductivities on CNT diameter d with different volume fraction f, with $\sigma_m = 10^{-9}$ S cm^{-1}, $\sigma_s = 1.85$ S cm^{-1}, $\sigma_c = 1850$ S cm^{-1}, $L = 2.5 \times 10^4$ nm, $t = 2.5$ nm.

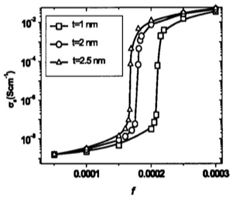


Figure 6. Effect of the thickness of the interface on the electrical conductivity of CNT composites. In the calculation, $\sigma_m = 1 \times 10^{-9}$ S cm^{-1}, $\sigma_c = 1850$ S cm^{-1}, $\sigma_s = 1.85$ S cm^{-1}, $d = 10$ nm and $L = 25$ μm.

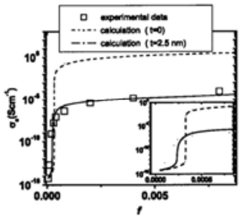


Figure 8. Comparison between the experimental results [10] of electrical conductivity of CNT-epoxy composites and the values calculated by the model. $L = 25\,000$ nm, and $d = 13$ nm. $\sigma_m = 5 \times 10^{-15}$ S cm^{-1}, $\sigma_c = 1850$ S cm^{-1}, $\sigma_s = 1.85 \times 10^{-5}$ S cm^{-1}. Inset: effect of the interfacial layer on the electrical conductivity of CNT composite around the threshold.

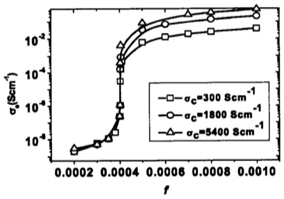


Figure 5. The dependence of the effective conductivities on CNT conductivity with different volume fractions f, with $\sigma_m = 10^{-9}$ S cm^{-1}, $\sigma_s = 1.85$ S cm^{-1}, $L = 2.5 \times 10^4$ nm, $d = 20$ nm, $t = 2.5$ nm.

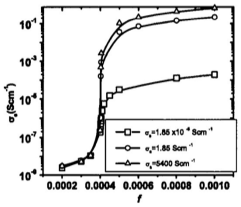


Figure 7. Effect of the electrical conductivity of the interface on the electrical conductivity of CNT composites. In the calculation, $\sigma_m = 2.5 \times 10^{-9}$ S cm^{-1}, $\sigma_c = 1850$ S cm^{-1}, $L = 25\,000$ nm, and $d = 20$ nm.

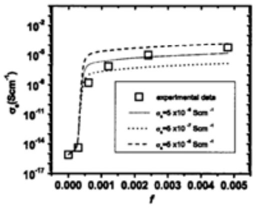
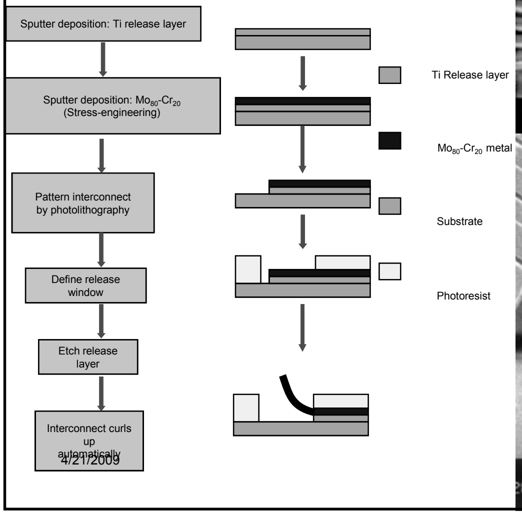


Figure 9. Comparison between the experimental results [22] of electrical conductivity of CNT-epoxy resin composites and the values calculated by the model. $\sigma_m = 7.9 \times 10^{-15}$ S cm^{-1}, $\sigma_c = 1850$ S cm^{-1}, $L = 16 \times 10^3$ nm, $d = 35$ nm, $t = 2.5$ nm.

(This figure is in colour only in the electronic version)

Microsprings

(Ma et al)



Sputter deposition: Ti release layer

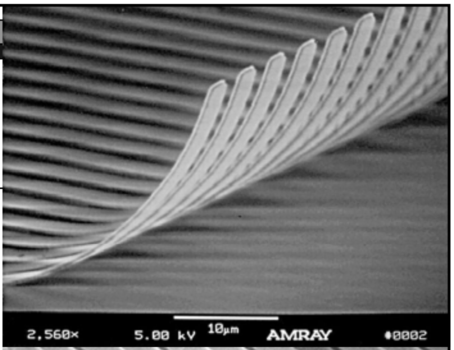
Sputter deposition: Mo_{80}-Cr_{20} (Stress-engineering)

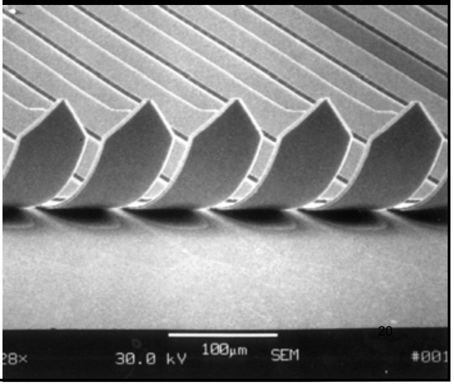
Pattern interconnect by photolithography

Define release window

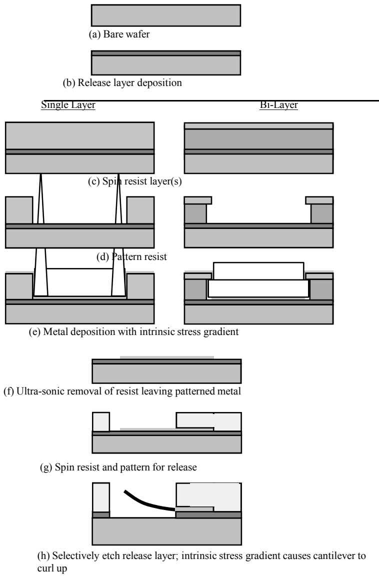
Etch release layer

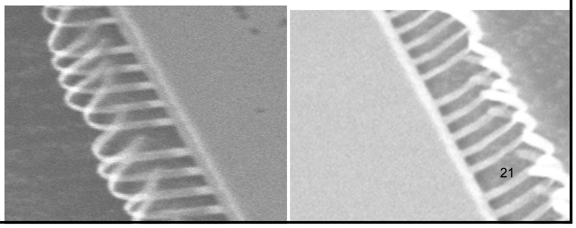
Interconnect curls up automatically





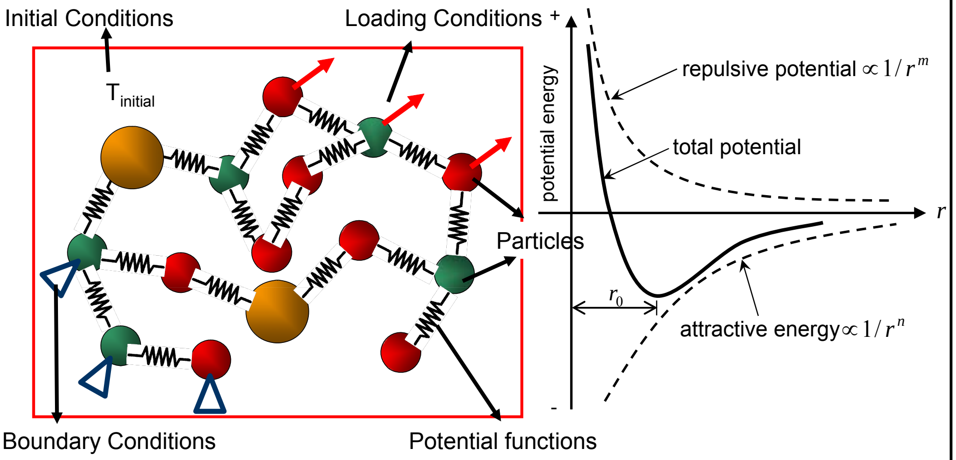
Nanosprings (Ma et al)





Molecular Dynamics

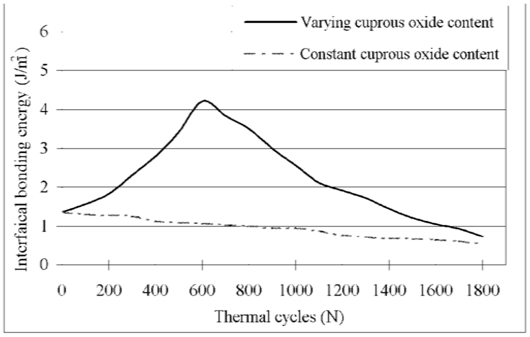
(* van der Sluis et al)



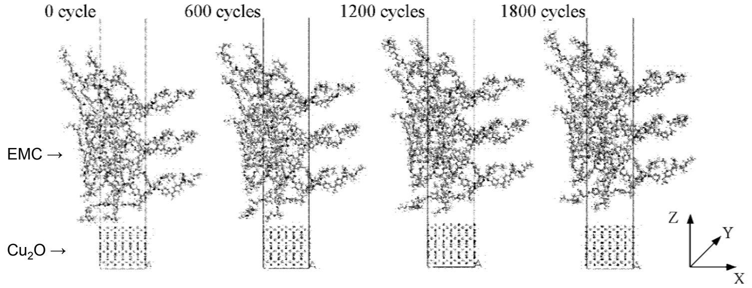
Molecular Dynamics

(* Fan & Yuen)

Modeling of interface H_2O diffusion, CNTs, etc



Adhesion increases with Cu_2O growth, decreases with void development



MD simulation snapshots of the Cu_2O/EMC system, showing void development at the interface

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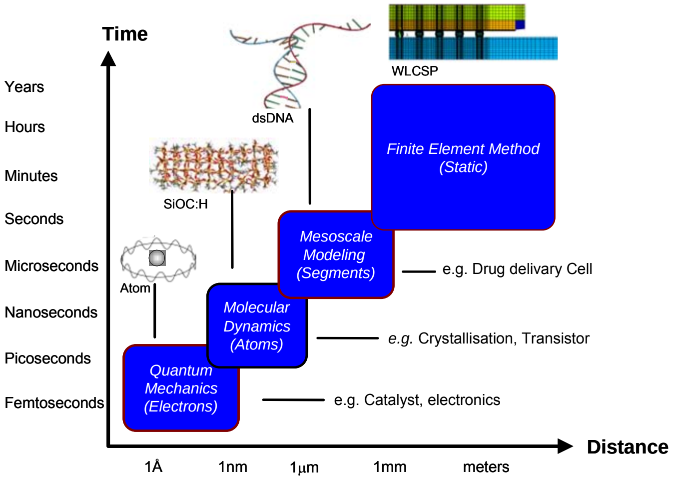
Nanoscale Modeling

(van der Sluis et al)

Molecular Dynamics; interscale interfaces



Time

Years
Hours
Minutes
Seconds
Microseconds
Nanoseconds
Picoseconds
Femtoseconds

Quantum Mechanics (Electrons) — e.g. Catalyst, electronics

Molecular Dynamics (Atoms) — *e.g.* Crystallisation, Transistor

Mesoscale Modeling (Segments) — e.g. Drug delivery Cell

Finite Element Method (Static)

Atom
SiOC:H
dsDNA
WLCSP

Distance

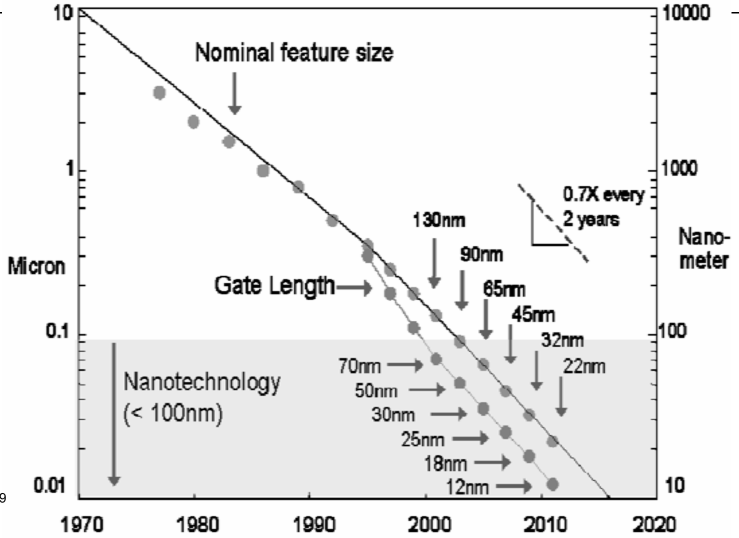
1Å
1nm
1µm
1mm
meters

Need software “interface” packages to transport modeling results between length scales

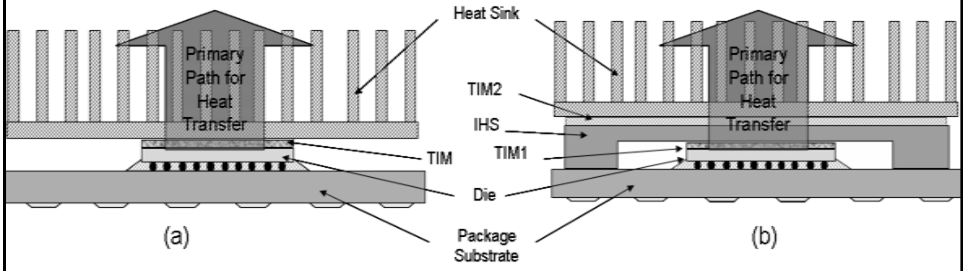
Nanoelectronics Packaging

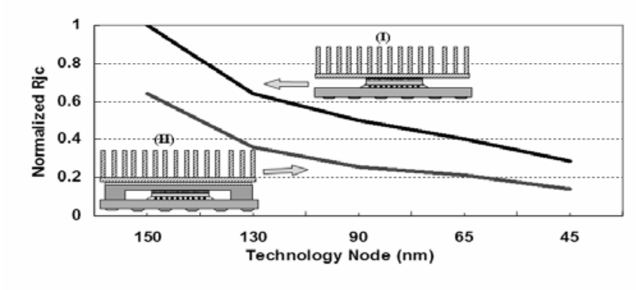
- nm CMOS
- Single electron transistor (SET)
- Discussion: CNTs, molecular, RTDs, spintronics, etc
- Sensors

Nano-CMOS Packaging (Mallik)

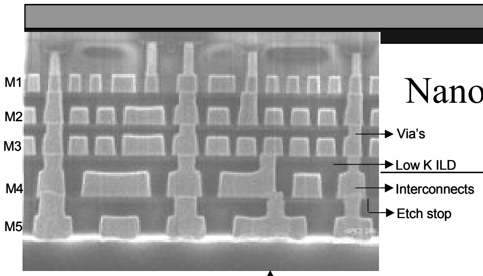


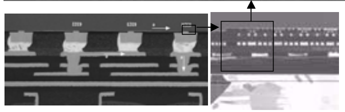
Nano-CMOS Packaging (Mallik)



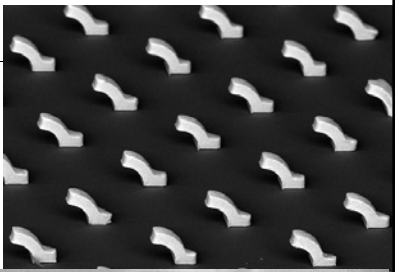


Nano-CMOS Packaging (Mallik)

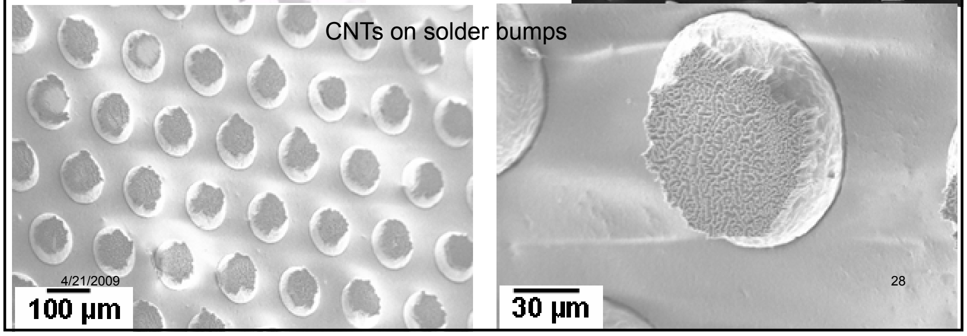




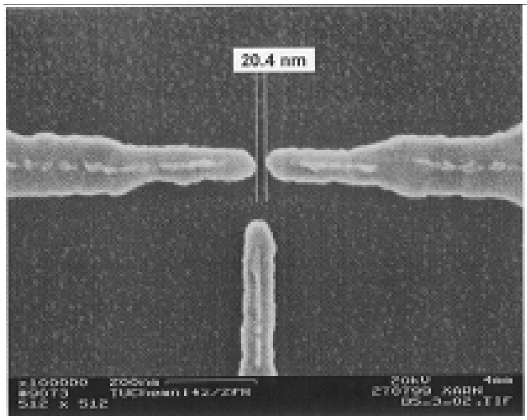
Low k ILD
Porous dielectrics
Brittle material
Stress increasing problem
Compliant interconnect

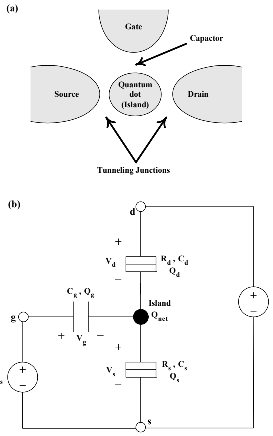


CNTs on solder bumps



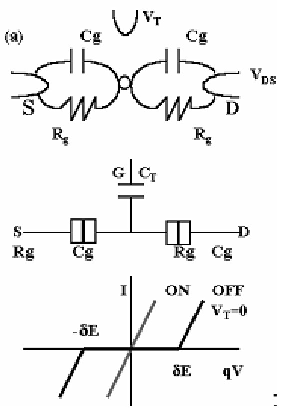
Single electron transistor (SET) as example
Metal nanodot as simple SET example

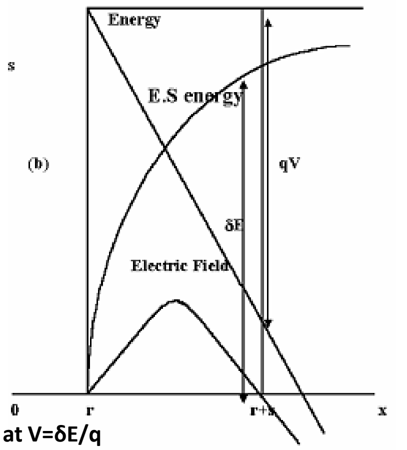




Radehaus et al

Coulomb block & SET: Electric field & temperature





T=0°K: abrupt threshold at V=δE/q

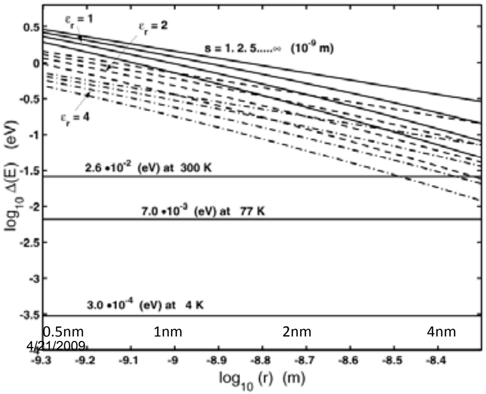
T>0°K: randomly charged exp-δE/kT

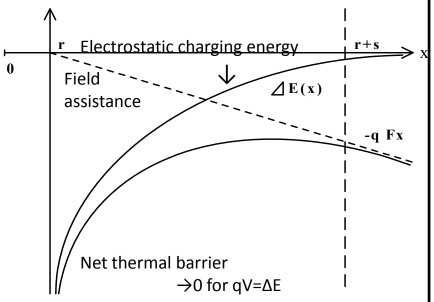
Nanoparticle Charging:

the Coulomb Block (Morris)

Spherical nanoparticles, radius *r*, separation *s*
Electrostatic charging energy:

$$\Delta E = \frac{q^2}{4\pi\varepsilon r} \rightarrow \frac{q^2}{4\pi\varepsilon}\left[\frac{1}{r} - \frac{1}{r+s}\right]$$





Electrostatic charging energy

Field assistance

Net thermal barrier
→0 for qV=ΔE

Electrostatic activation/charging energy

(usually stated $\delta E = q^2/4\pi\varepsilon r$)

$$\delta E = (q^2/4\pi\varepsilon)(r^{-1} - (r+s)^{-1}) - (2r+s)qF$$

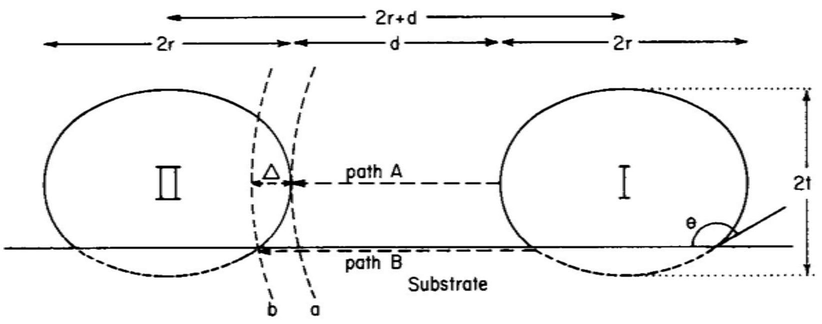
when $F < (q/4\pi\varepsilon)(r+s)^{-2}$

and at high fields

$$\delta E = (q^2/4\pi\varepsilon)r^{-1} + (r/s)(2r+s)qF - (q^2/4\pi\varepsilon s)^{1/2}((2r+s)qF)^{1/2}$$

until $\delta E \rightarrow 0$ when $qV = (1 + s/r)\,\delta E_{V=0}$

The geometry of 2 ellipsoidal nanodots of eccentricity $e = (1-(t/r)^2)^{½}$



δE for oblate spheroids with applied field

- $\delta E = q^2/C$

  $= (q^2/4\pi\varepsilon R)(2/e)[\sin^{-1}e-\sin^{-1}(e(1-p)/(1+p))]/(1-p)-qREa$

  for $E_a<E_{amin} = (q^2/4\pi\varepsilon R)4p(1+p)^{-1}[(1+p)^2-e^2(1-p)^2]^{-½}$, where $p = d/R$, $R = 2r+d$, and
- $\delta E=(q^2/4\pi\varepsilon R)(2/e)[\sin^{-1}e-\sin^{-1}(e(1-p)R/((1-p)R+2x))]/(1-p)$

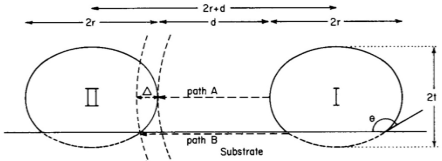
  $-qEax/p$

  for $E_{amin}<E_a<E_{amax}=(q^2/4\pi\varepsilon R)4p(1-p)-2(1-e^2)^{-½}$,

where $x=½Re(1-p)\{[([\{2qp/\pi\varepsilon Ea(1-p)^2R^2e^2\}^2+1]^{½}+1)/^2]^{½}-e^{-1}\}$
- and $\delta E = 0$ at $E_a = E_{amax}$

Mechanical stress effects

- Electron tunneling: σ_0 = const. x exp-4πd$(2m^*\Phi)^{1/2}$
- Gauge factor G=$(2m\Phi)^{1/2}$(4πd/h), if δE constant
- High gauge factor, approx. linear with d at low strain
- δE not constant
- Thermomechanical stress effects



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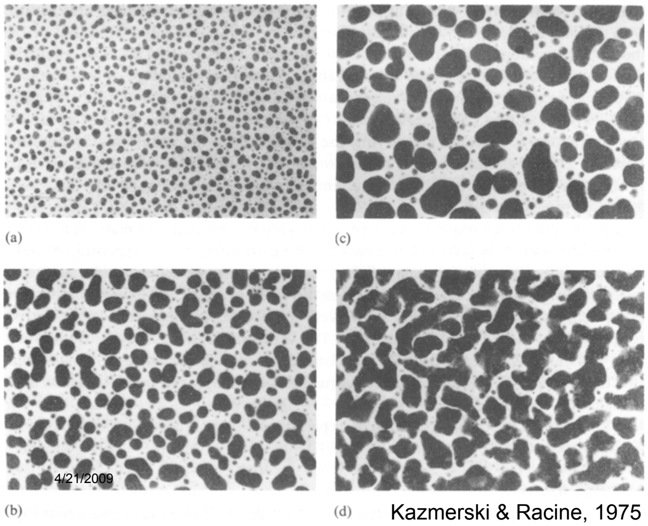
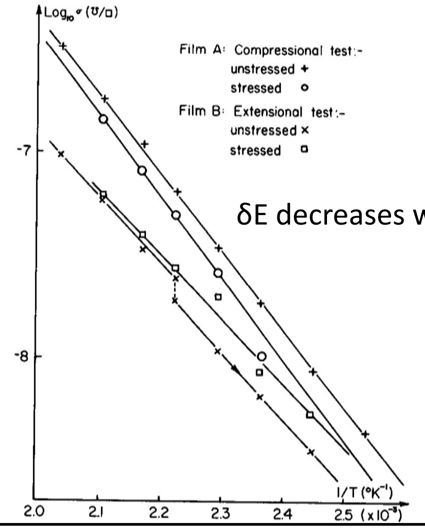
Discontinuous Metal Thin Films (DMTF)



Kazmerski & Racine, 1975

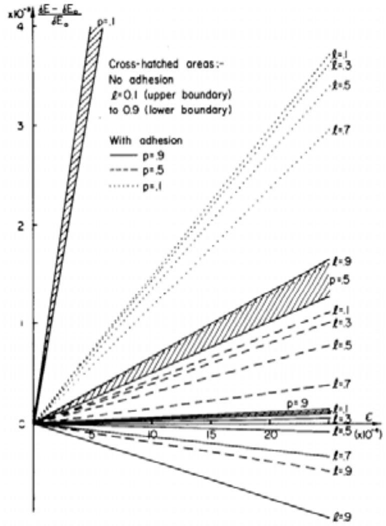
- ☐ Formation
  (e.g. Au/glass)
- ☐ nm islands
  nm gaps
- ☐ Well researched
  1960's-1970's
- ☐ Electron tunneling
  Charging energy
- ☐ Coulomb blockade
  nanodots in series
- ☐ $\sigma = \sigma_0 \exp{-\delta E/kT}$

DMTF strain effects: experimental

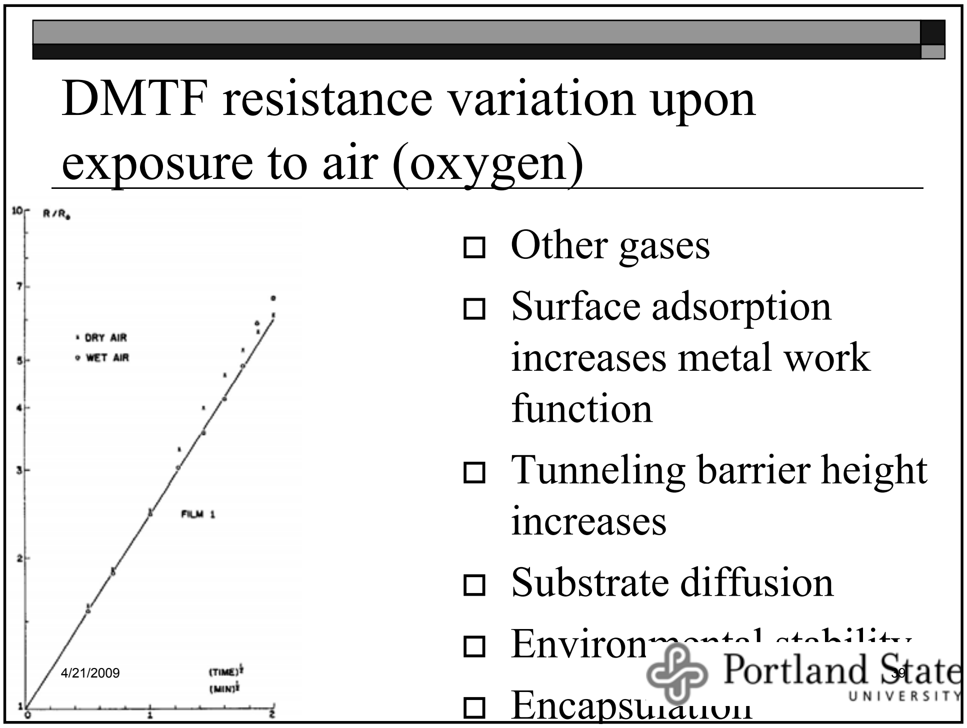


δE decreases with +ve strain

DMTF strain effects:
theoretical δE variation

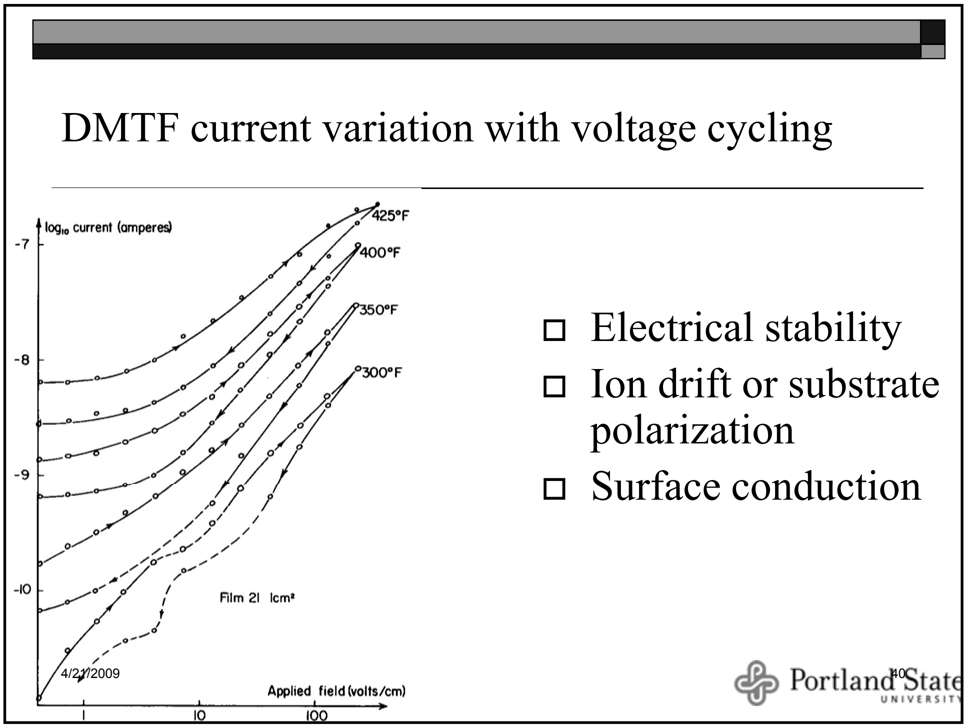


δE decreases with positive strain for island-substrate adhesion and high eccentricity



DMTF resistance variation upon exposure to air (oxygen)

- ☐ Other gases
- ☐ Surface adsorption increases metal work function
- ☐ Tunneling barrier height increases
- ☐ Substrate diffusion
- ☐ Environmental stability
- ☐ Encapsulation

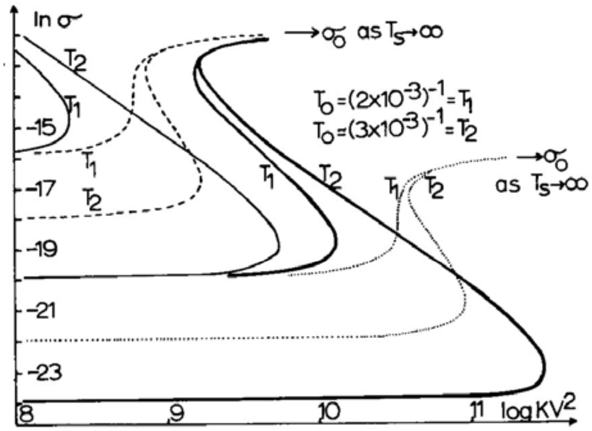


DMTF current variation with voltage cycling

- ☐ Electrical stability
- ☐ Ion drift or substrate polarization
- ☐ Surface conduction

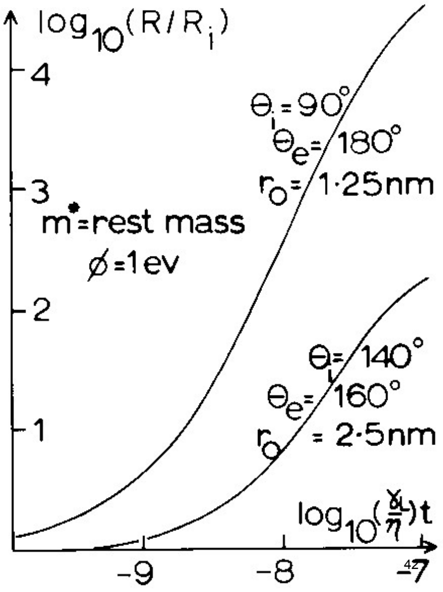
Thermal Stability: DMTF switching

- NDR inherent in all negative TCR materials
- Thermal runaway
- Other switching mechanisms
- N-type & S-type

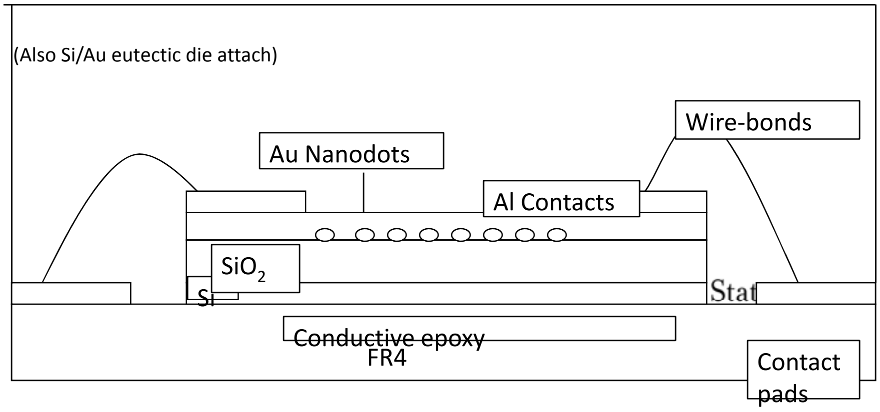


Structural Stability

- Coalescence
- DMTF R(t) model
  - adatom collection
  - surface self-diffusion

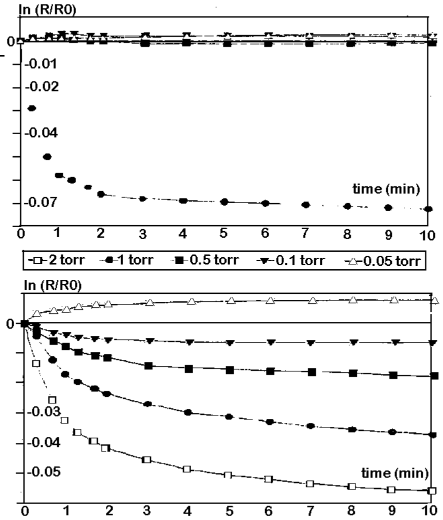


Schematic of reliability test sample



Embedded Package Reliability Sensors

- ☐ DMTF strain sensor
  - See back
- ☐ H_2 Sensor for corrosion
- ☐ Discontinuous Pd film
  - Work function increases → resistance increases
  - Islands swell → gaps narrow → resistance decreases



Summary

- ☐ Nanopackaging materials (electrical, mechanical, thermal):
  - Nanoparticle applications
  - Carbon nanotube (CNT) applications
  - ECAs
  - Nanowires, nanospring contacts
  - Modeling: Molecular Dynamics to Effective Medium
- ☐ Nanoelectronics
- ☐ Health & environment: CNTs in the body, nano-Ag toxicity to bacteria
- ☐ "Nanopackaging: Nanotechnologies in Electronics Packaging," J.E. Morris (editor) Springer (August 2008)

Nanoelectronics & Packaging Lab

Portland State UNIVERSITY