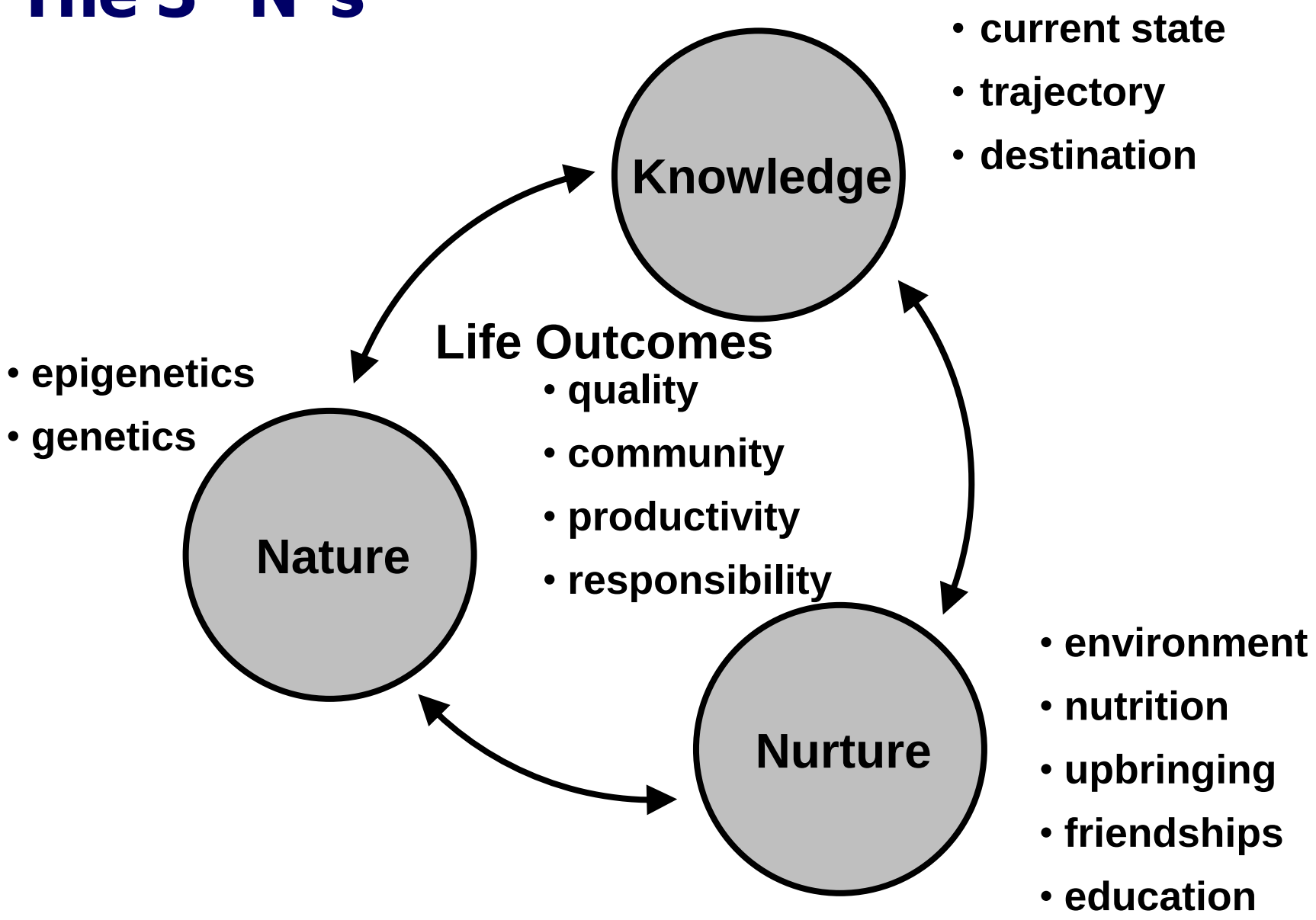
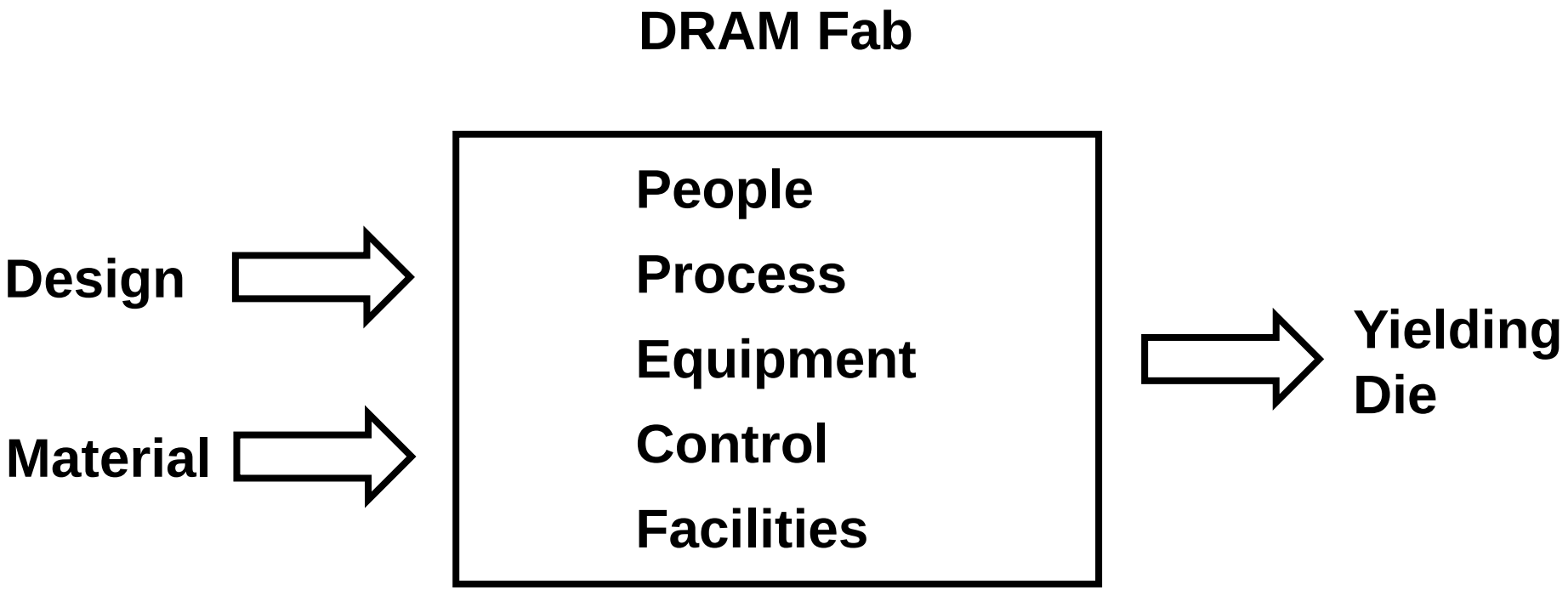
Toward Advanced Applications with Biointerface Technologies

Peter J. Gilgunn, PhD

The 3 "N"s

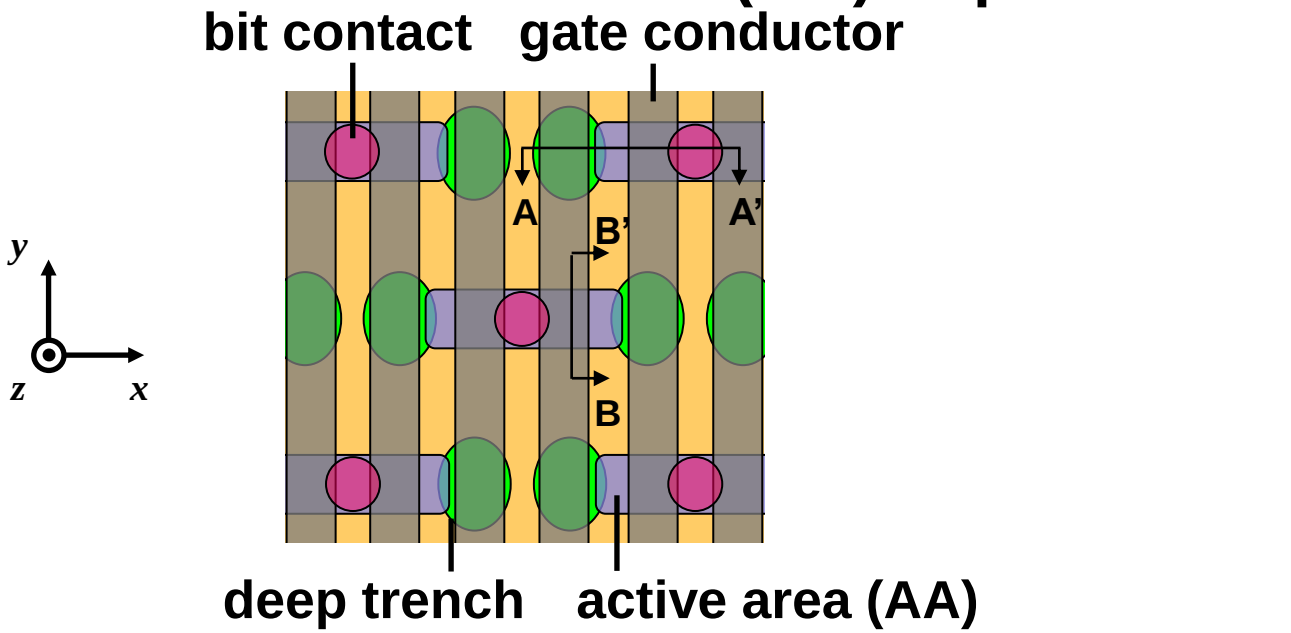


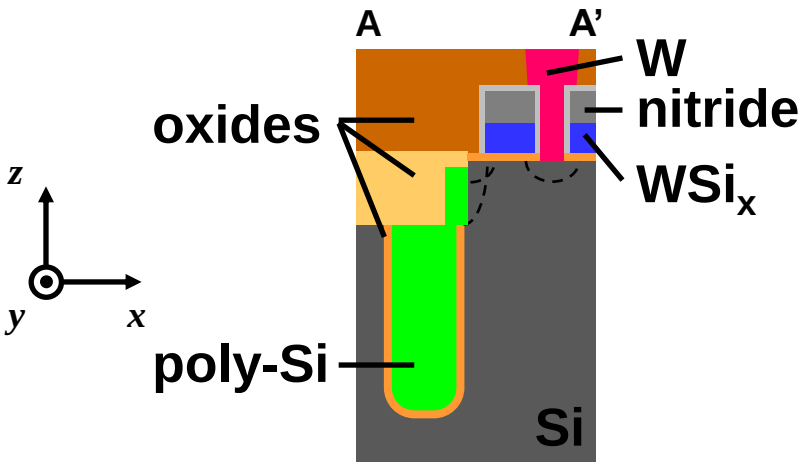
Process and Equipment Control

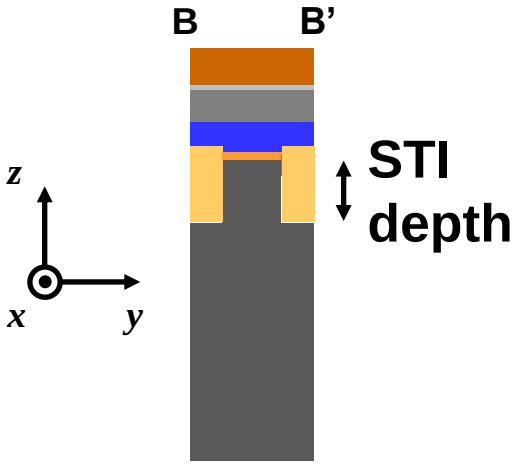


Process and Equipment Control

Shallow Trench Isolation (STI) Depth

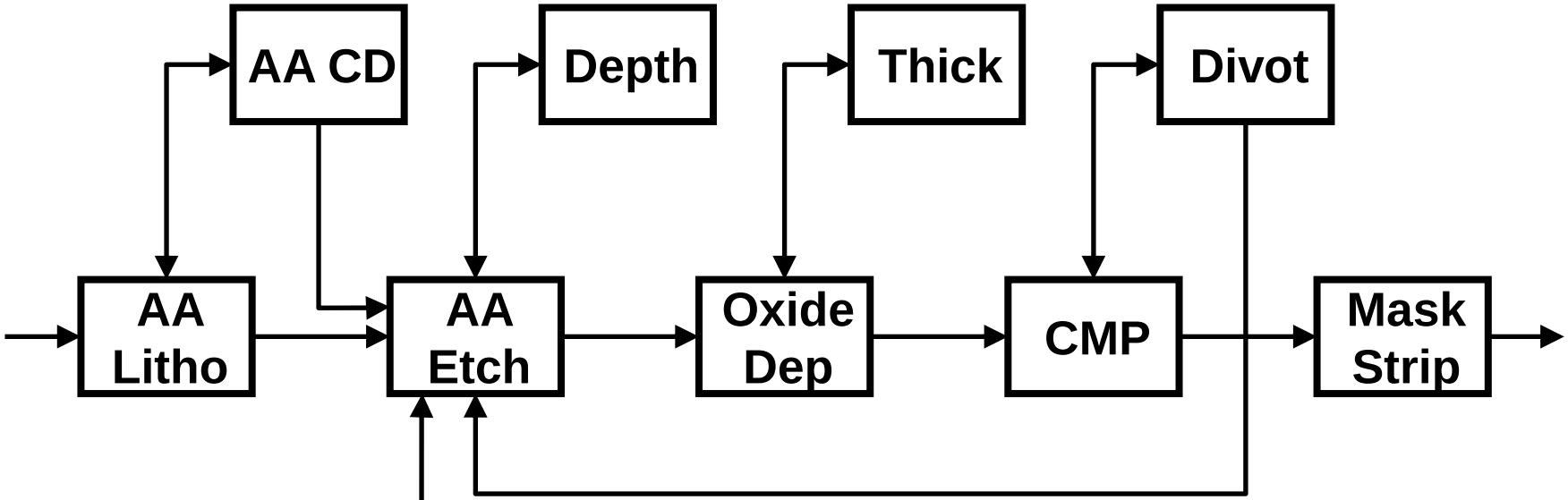






Process and Equipment Control

Shallow Trench Isolation (STI) Depth



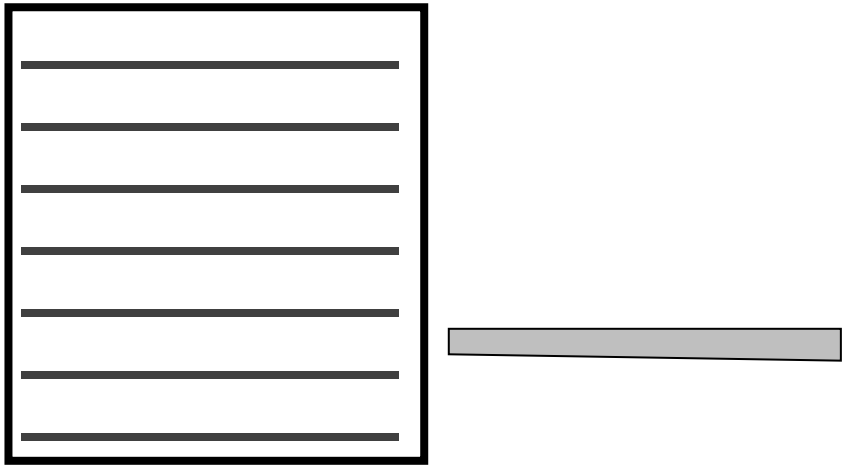
- Electrical Test
- Wafer Yield
- Die Yield

Gilgunn et al., Sematech AEC/APC XV, Colorado Springs, 2003

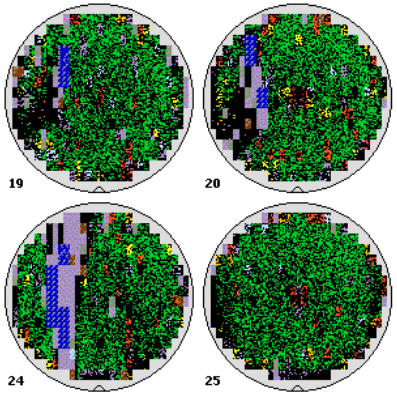
Acoustic Detection of Circuit Damage

- 11,000 wafers per week through each unit process
- If 3 chambers → ~ 525 wafers per day per chamber
- Undetected equipment faults rack up huge losses fast

Wafer Cassette



Robotic Contact Causes Scratches …

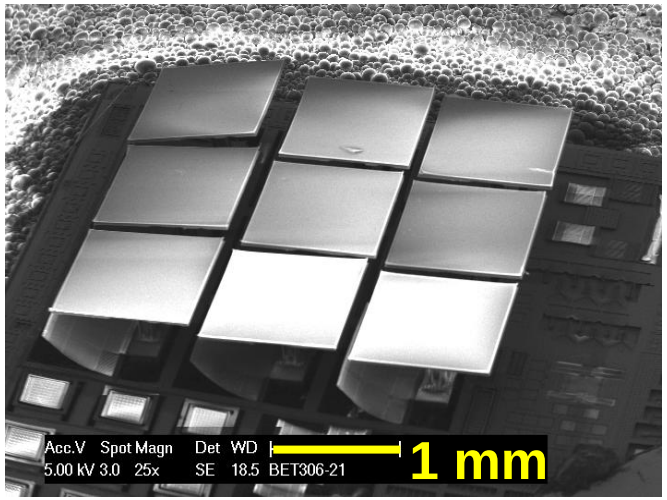


and Scratching Makes Noise

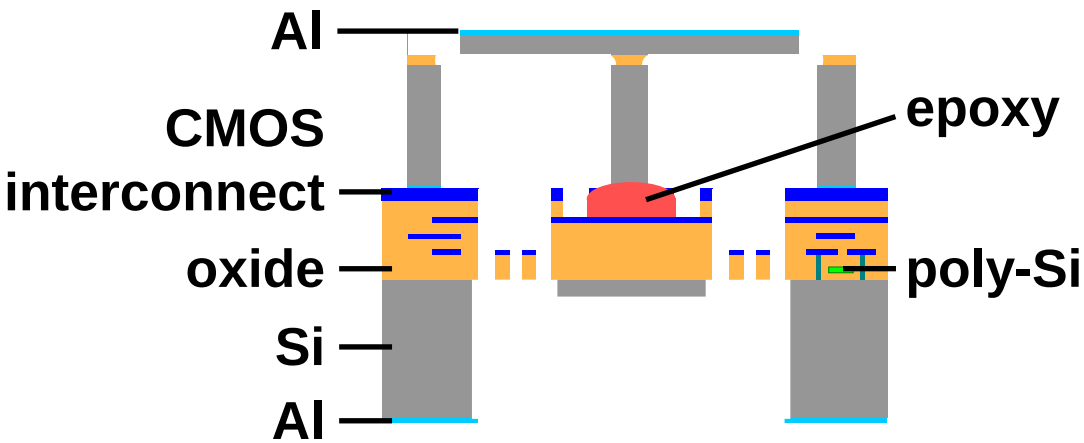
Gilgunn, US Patent No. 6,957,581, Ass. Infineon Technologies, Richmond, VA, Oct. 2005

Electrothermal Micromirrors

1 mm Pitch, 3 x 3 Array



SOI-CMOS-MEMS

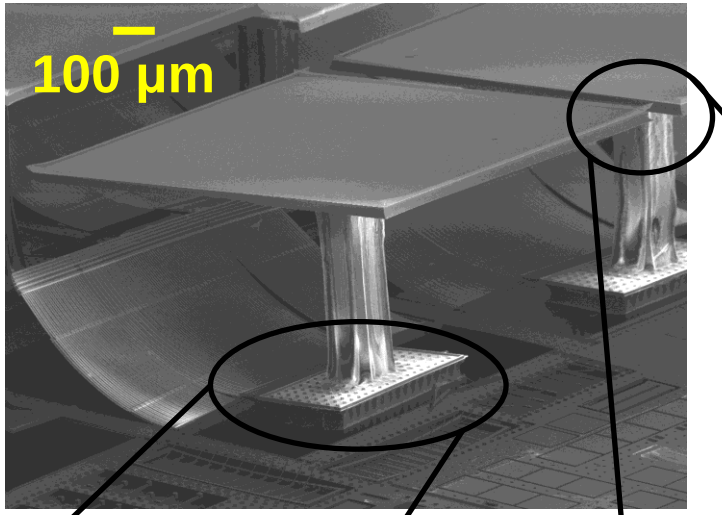


- Optical communications, ranging, imaging, scanning

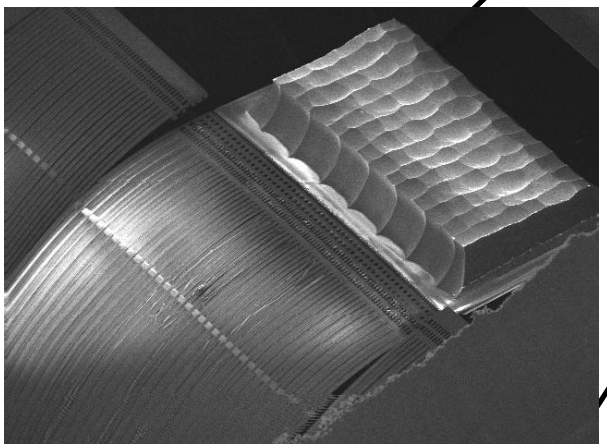
Gilgunn and Fedder in *Hilton Head 2008*

Electrothermal Micromirrors

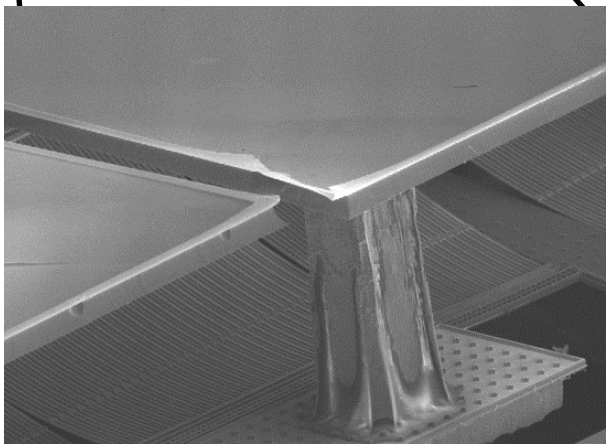
Single Pixel



ARDEM



Etch Heating



Aspect Ratio Dependent Etch Modulation

- Etchrate varies with feature aspect ratio (depth/opening)
- Apply as design tool for 3D structure with single mask

post 31 min Bosch DRIE

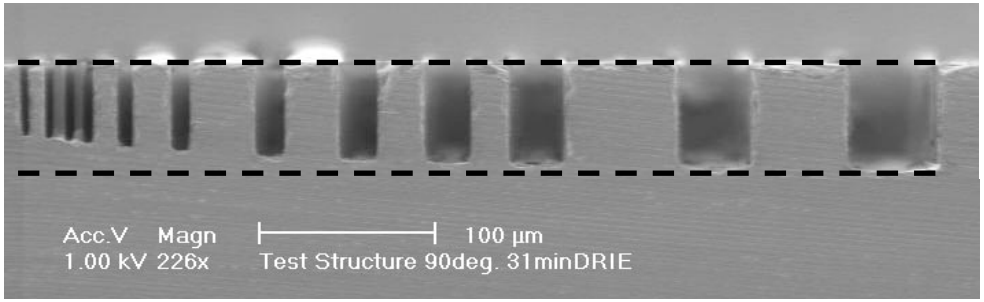
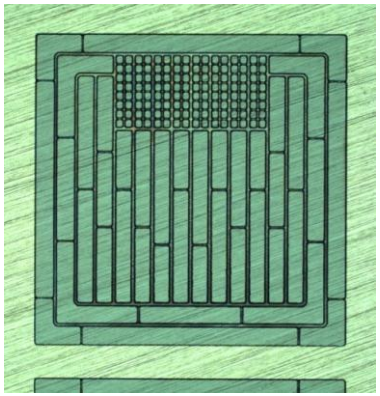
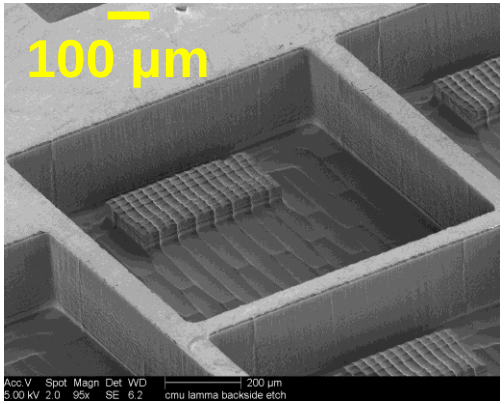


image courtesy of Dr. J. F. Alfaro

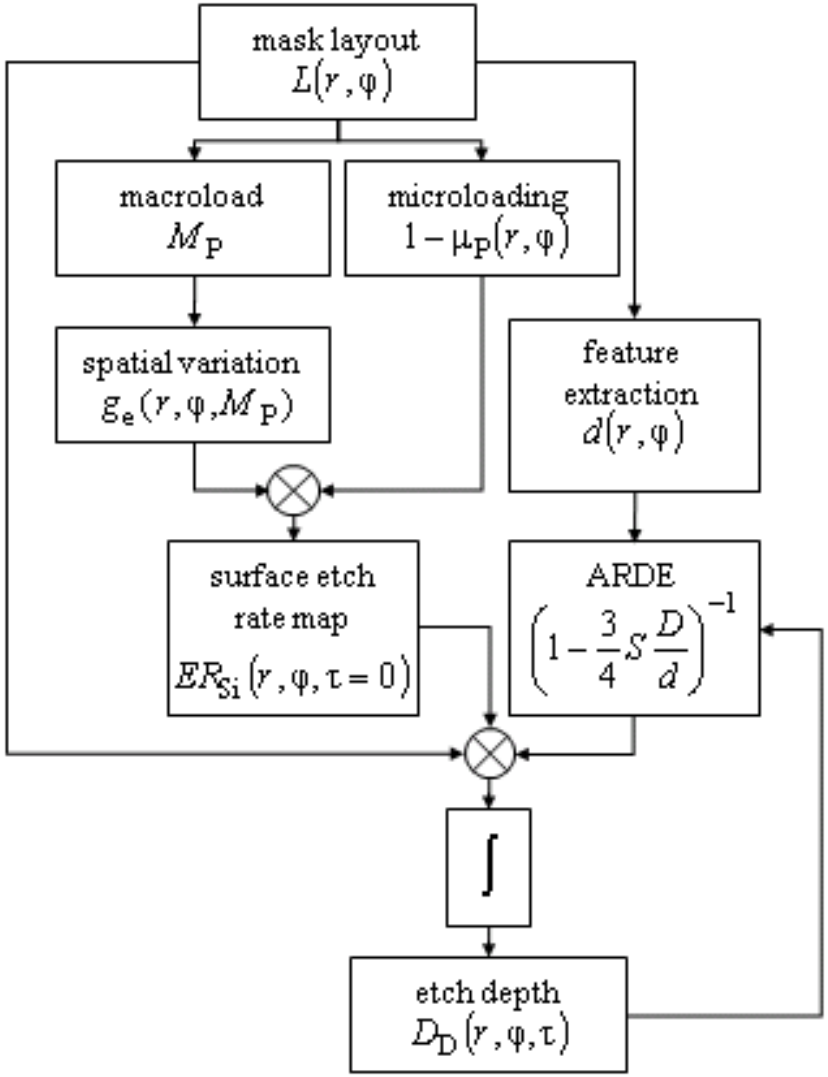




- Conceptual precursors
  - Uniformity control - Kiihamaki et al., *Sens. Act. A*, 2000
  - Feature generation - Chou and Najafi, in *MEMS 2002*

ARDEM Model

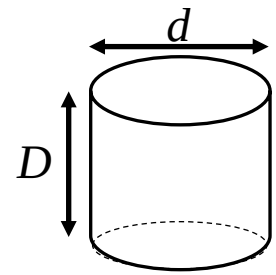
- **ARDE – feature conductance**
  - Coburn and Winters, *Appl. Phys. Lett.*, 1989
- **Macroloading – area load**
  - Mogab, *J. Electrochem Soc.*, 1977
- **Microloading – local variation**
  - Hill et al., in *Hilton Head 2004*
- **Spatial variation – equipment**
  - Taylor et al., *J. Electrochem. Soc.*, 2006



ARDE

- **Coburn and Winters model, *Appl. Phys. Lett.* , 1989**

$$ER(D/d) = \frac{ER(0)}{1 - S\left(\frac{1}{K} - 1\right)}$$



$$A_0 = \frac{\pi d^2}{4}$$

$$H_0 = \pi d$$

- ***D*** **= depth**
- ***S*** **= reaction probability**
- ***K*** **= vacuum conductance correction factor**
- ***d*** **= characteristic dimension**

$$\frac{1}{K} - 1 = \frac{3}{16} A_0 \int_0^D \frac{H(z)}{A(z)^2} \mathrm{d}z \quad \Rightarrow \quad d_c = \frac{4D}{A_0}\left(\int_0^D \frac{H(z)}{A(z)^2} \mathrm{d}z\right)^{-1} = \frac{4A_0}{H_0}$$

- **characteristic dimension d_c - basis for ARDEM mask**

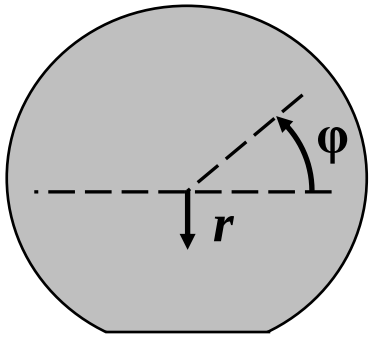
Dushman c. 1930 and *Scientific Foundations of Vacuum Technique,* 1962

ARDEM Test Structures

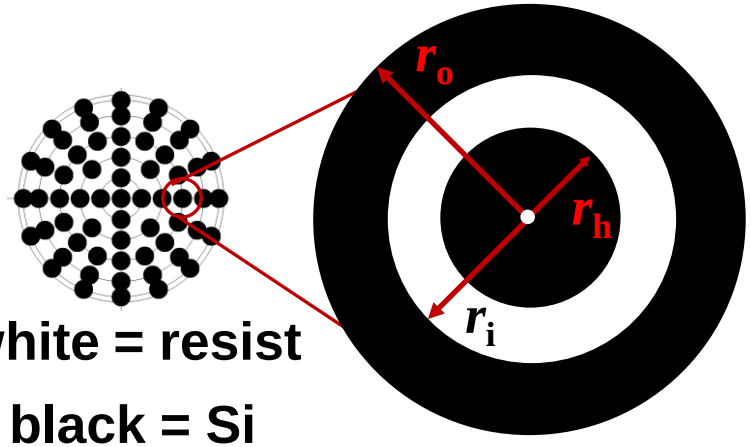
- **Surface etchrate modeling**
  - **Empirical macroloading and spatial variation**

$$g_{\mathrm{e}} = f\left(r, \varphi, M_{\mathrm{p}}\right)$$

Wafer Plan View



Donut Test Structure Pattern



white = resist

black = Si

ARDEM Test Structures

- **Surface etchrate modeling**
  - **Semi-empirical microloading**

$$\mu_{\mathrm{P}}(r,\varphi) = W(r,\varphi) \otimes L(r,\varphi) \qquad W(r,\varphi) = \frac{a}{r}$$

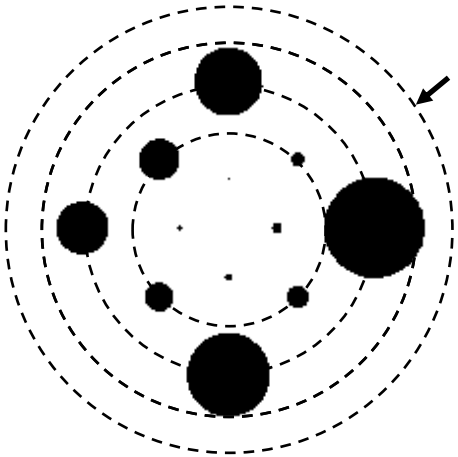
Hill et al., in *Hilton Head 2004*

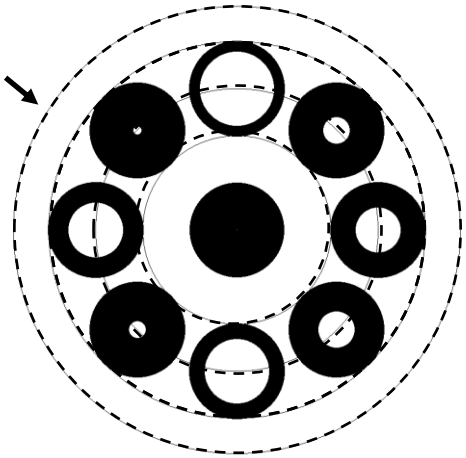
Constant r_{h} = 50 µm

Constant r_{i}
Varying r_{o}

Varying r_{i}
Constant r_{o}

r = 47.5 µm





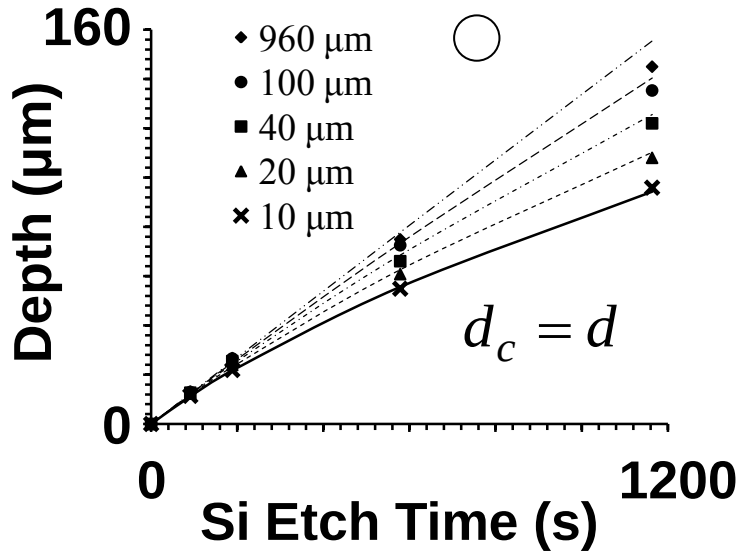
$$\mu_{\mathrm{P,donut}}(0,0) = 2\pi a r_{\mathrm{h}} + 2\pi a (r_{\mathrm{o}} - r_{\mathrm{i}})$$

ARDEM Unified Model

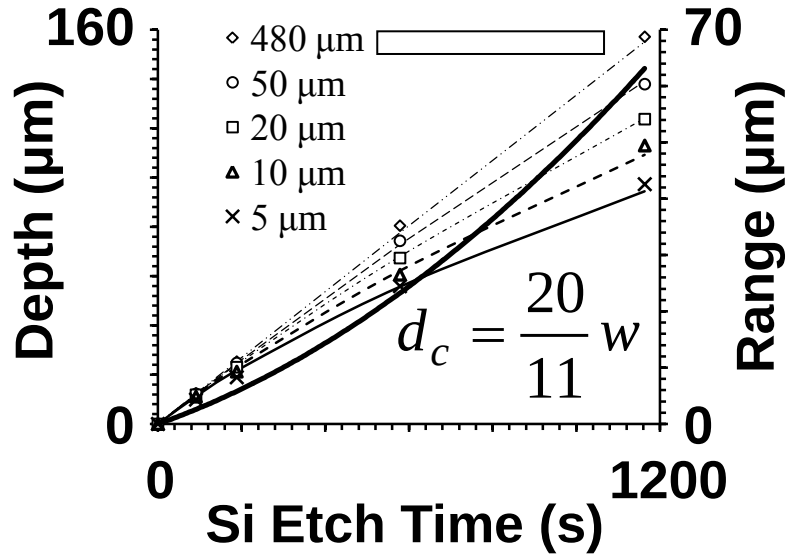
$$ER(r,\varphi) = L(r,\varphi)\cdot g_{\mathrm{e}}(r,\varphi,M_{\mathrm{P}})\cdot\left(1-\mu_{\mathrm{P}}(r,\varphi)\right)\left[1-\frac{3}{4}S\frac{D}{d_c}\right]^{-1}$$

$$D(r,\varphi,\tau) = \left[\frac{8d_c}{3S}g_{\mathrm{e}}\left(1-\mu_{\mathrm{P}}\right)\tau+\left(\frac{4d_c}{3S}+t_{\mathrm{mask}}\right)^2\right]^{0.5}-\left(\frac{4d_c}{3S}+t_{\mathrm{mask}}\right)$$

Hole Measured cf. Model



Trench Measured cf. Model

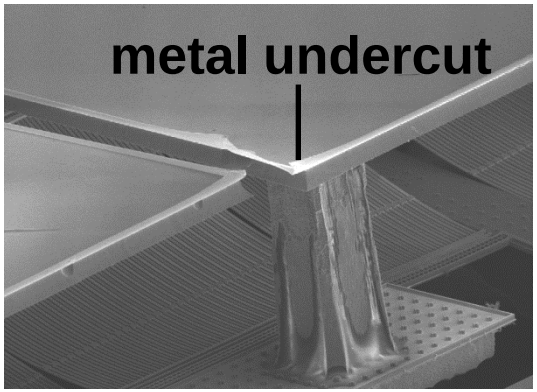


- **LSR fit using S = 0.24**
- **Better than 10% match**

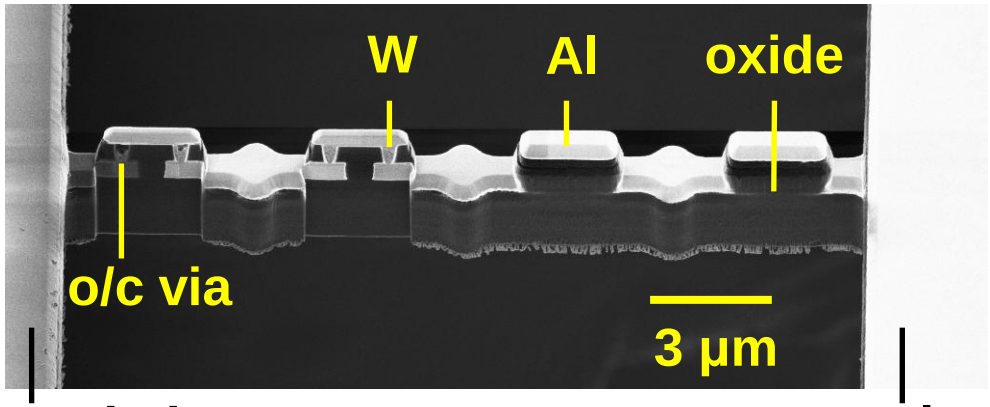
Gilgunn et al., *J. Vac. Sci. A*, *2010*

DRIE Selectivity and Anisotropy Loss

Anisotropy Loss



Selectivity Loss W/Si



suspended plate

anchor

- **DRIE passivation is essentially a condensation process**
- **Temperature drives selectivity loss**

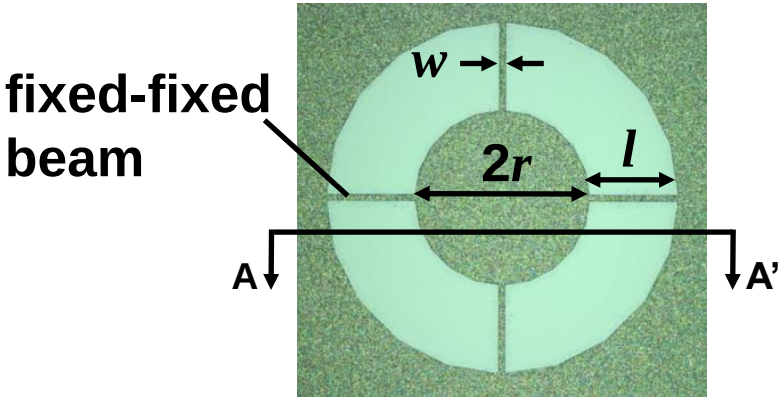
$$S_{\text{Si-TiW}} = \frac{ER_{\text{Si}}}{ER_{\text{TiW}}} = \frac{A_{\text{Si}}}{A_{\text{TiW}}} \exp\left(\frac{E_{\text{A,TiW}} - E_{\text{A,Si}}}{k_{\text{B}} T} \right)$$

As $T \uparrow$ $S_{\text{Si-TiW}} \rightarrow \dfrac{A_{\text{Si}}}{A_{\text{TiW}}}$

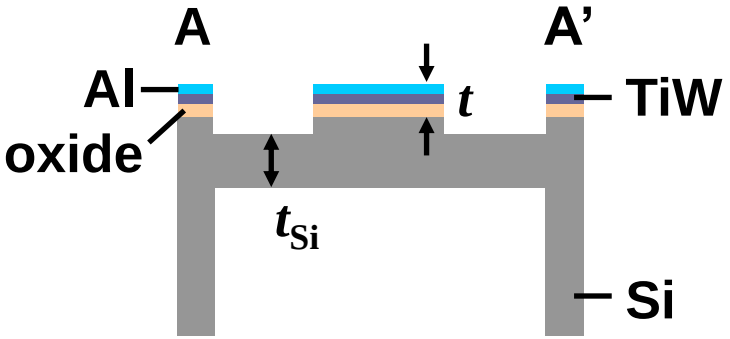
Etch Heating Test Structure

- *In situ* infrared imaging of MEMS release etch

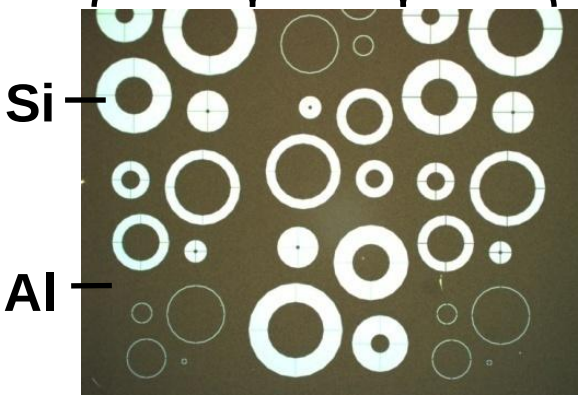
Suspended Disc Test Structure



Cross-section Pre-etch



w = 10 µm, 5 µm, 20 µm



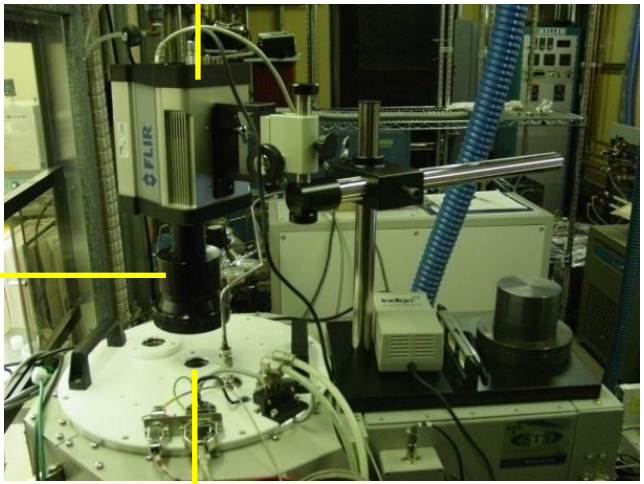
Varying l and r

Etch Heating

- *In situ* infrared imaging of MEMS release etch
- Bosch DRIE, polymer removal and isotropic etch

Hardware Setup

FLIR SC4000

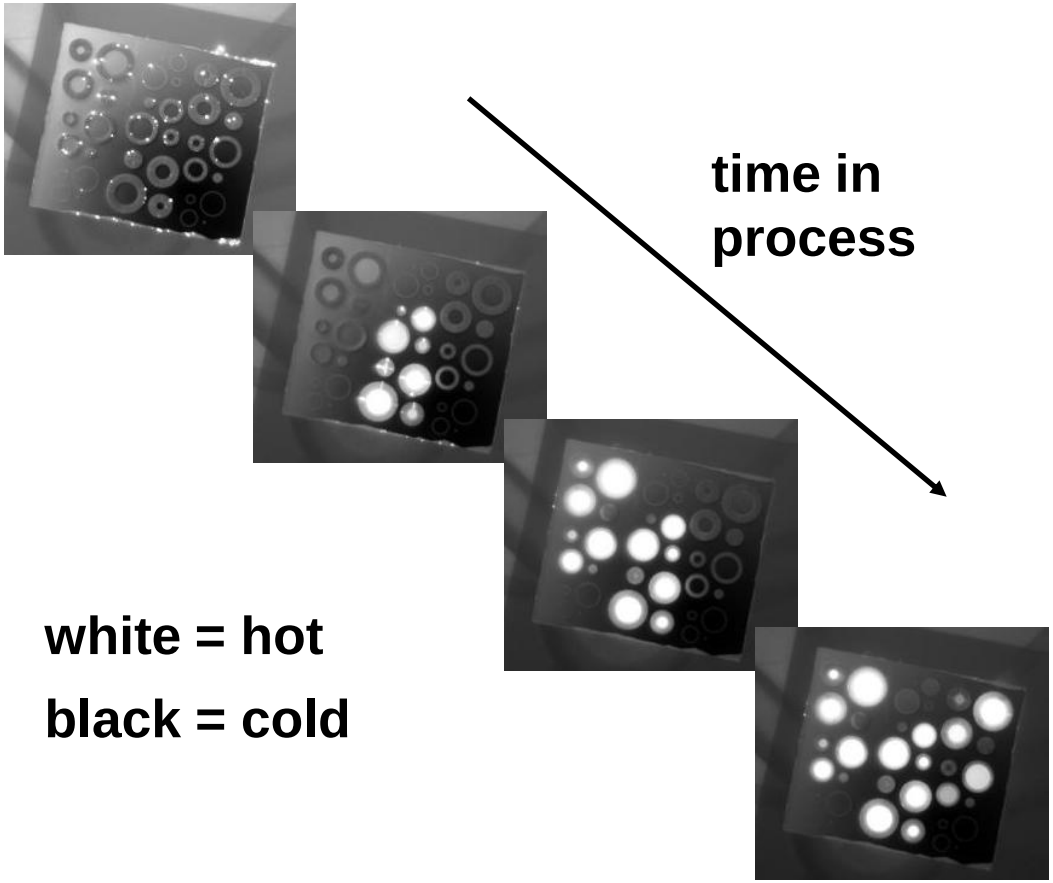


InSb lens

CaF_2 window

show movies

IR Images During Processing



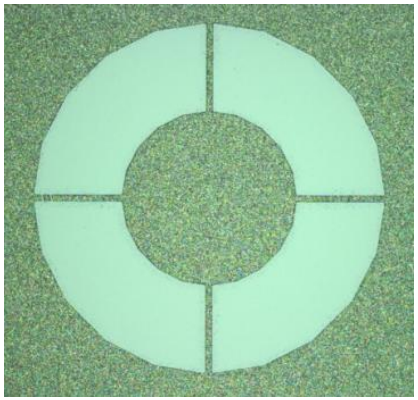
white = hot

black = cold

Etch Heating Temperature Modeling

- **Power balance model**
  - **Cooling – suspension conduction P_c**
    radiation P_r
  - **Heating – exothermic reaction heat P_e**
    ion bombardment P_i

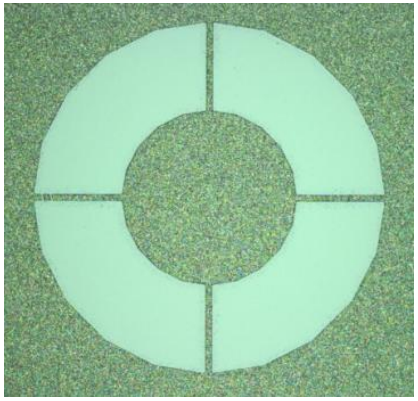
$$P_c + P_r = P_i + P_e$$



- **Find suspended disc temperature T during etching**

Power Balance Terms - Cooling

- **Suspension conduction**



$$P_c + P_\mathrm{r} = P_\mathrm{i} + P_\mathrm{e}$$

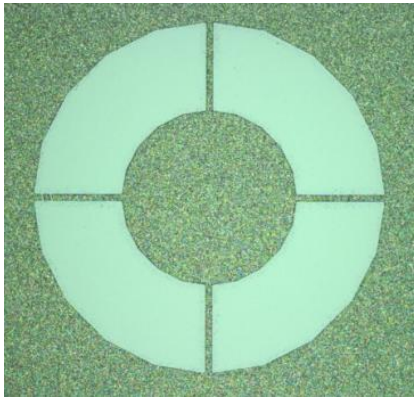
suspension thermal conductivity

$$P_\mathrm{c} = \frac{4\kappa_\mathrm{eff} wt}{l}\left(T - T_\mathrm{anc}\right)$$

Power Balance Terms - Cooling

- **Radiation**

$$P_c + P_\mathrm{r} = P_\mathrm{i} + P_\mathrm{e}$$

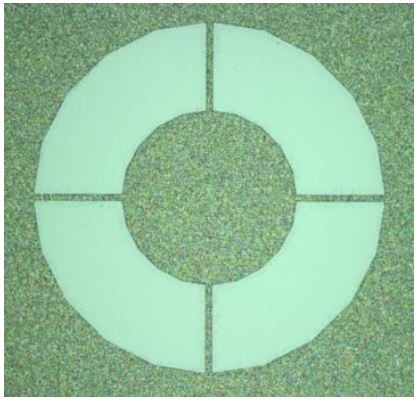


$$P_\mathrm{r} = \underbrace{2\pi r\left(r + t_\mathrm{Si}\right)}_{\text{radiating area}} \overset{\text{emissivity}}{\varepsilon}\sigma\left(T^4 - T_0^4\right)$$

Power Balance Terms - Heating

- **Ion bombardment**

$$P_c + P_\mathrm{r} = P_\mathrm{i} + P_\mathrm{e}$$



$$P_\mathrm{i} = \underbrace{\pi r^2}_{\text{surface area}} \overbrace{q c_\mathrm{i} V_\mathrm{b} \left(q T_\mathrm{q}\right)^{0.5} \sum_j \frac{y_{\mathrm{i},j}}{m_{\mathrm{i},j}^{0.5}}}^{\text{ion borne power flux}}$$

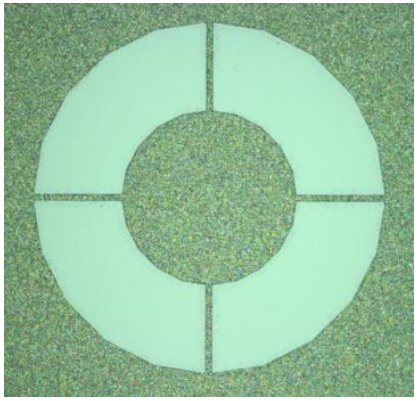
species weighting

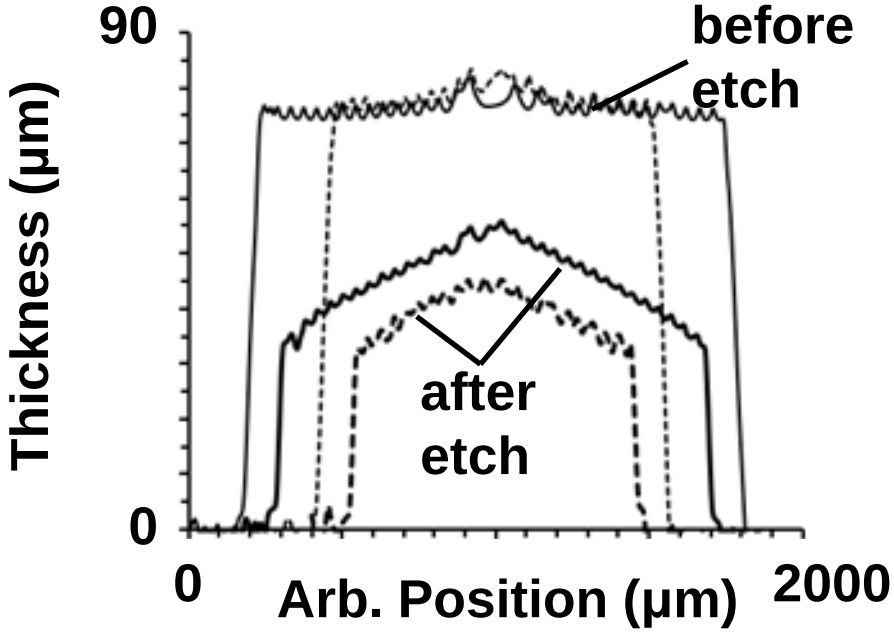
Lieberman and Lichtenberg, *Principles of Plasma Discharges and Materials Processing, 2nd* ed., 2005

Power Balance Terms - Heating

- **Exothermic reaction heat**

$$P_c + P_r = P_i + P_e$$



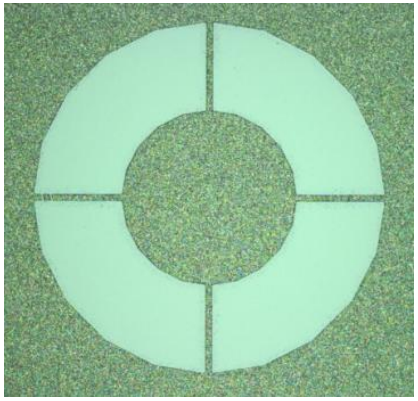


Etch rate varies along underside of the suspended structure

Power Balance Terms - Heating

- **Exothermic reaction heat**

$$P_c + P_\mathrm{r} = P_\mathrm{i} + P_\mathrm{e}$$



Arrhenius etch rate relation

F plasma concentration

etching area

$$P_\mathrm{e} = \int \upsilon A_\mathrm{Si} T^{0.5} \exp\left(-\frac{E_{A,Si}}{k_\mathrm{B} T}\right) c_\mathrm{Si}\, c_\mathrm{F}\, \Delta H_\mathrm{SiF_x}\, \mathrm{d}A_\mathrm{e}$$

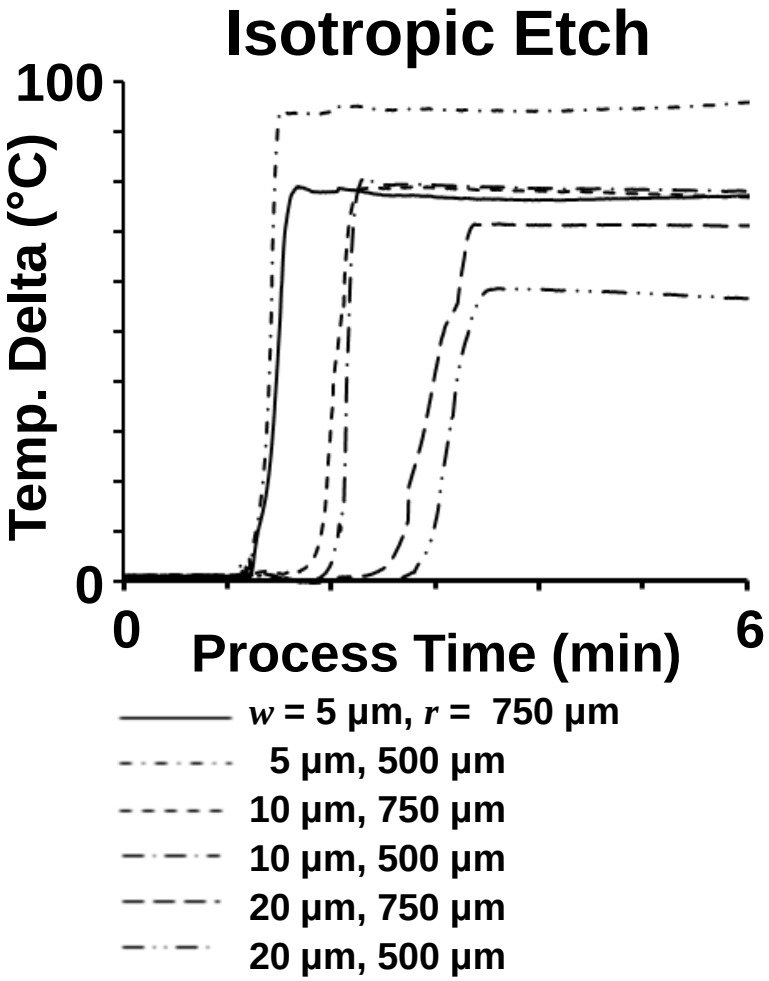
fraction of heat absorbed by etching structure

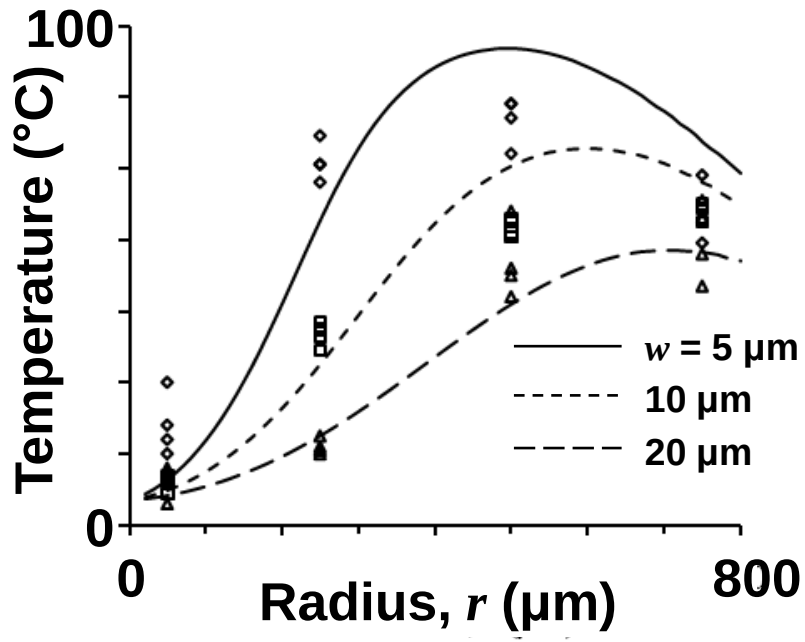
Si atomic concentration

reaction heat

Etch Heating Model

- Release etch thermometric data extracted and modeled



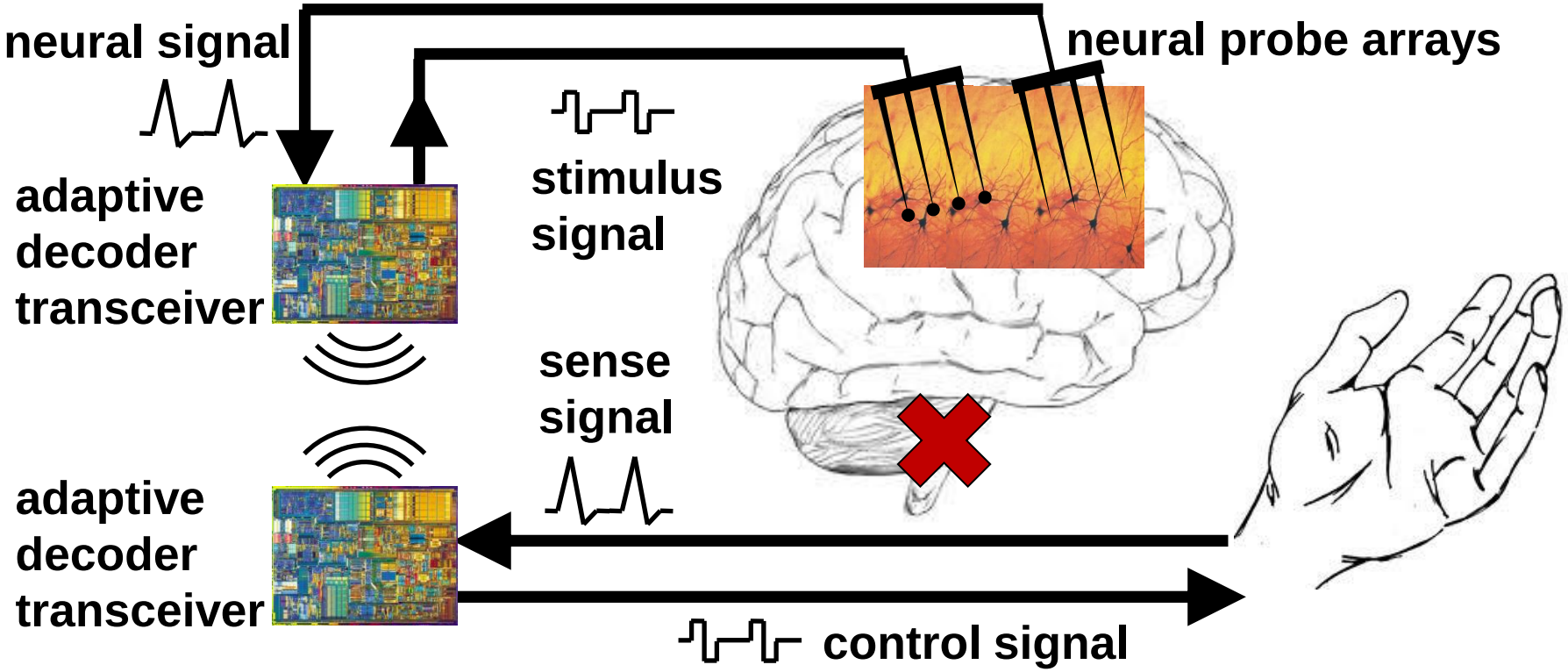


- lines = model
- qualitative match to data
- best fit for υ = 25%

Gilgunn and Fedder, *J. Micromech. Microeng.*, 2010

Brain Machine Interface (BMI)

- Bypass damage to biological signal channels – in/out
  - Stroke – 700k per year
  - Spinal cord injuries – 12k – 20k per year in US
  - Amyotrophic lateral sclerosis – 3k – 6k per year



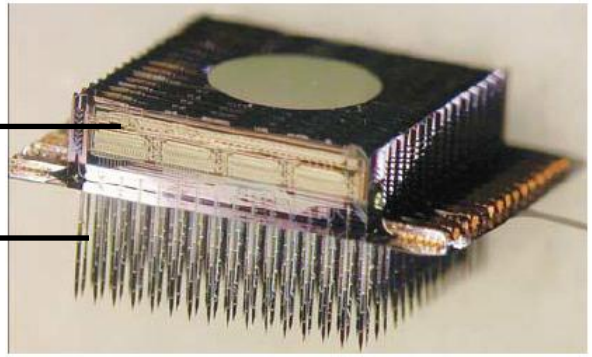
Adapted from Yu, Carnegie Mellon and Nicolelis, Duke

State-of-the-Art Neural Probes

128 Channel Michigan Array (Si)

ICs

probes

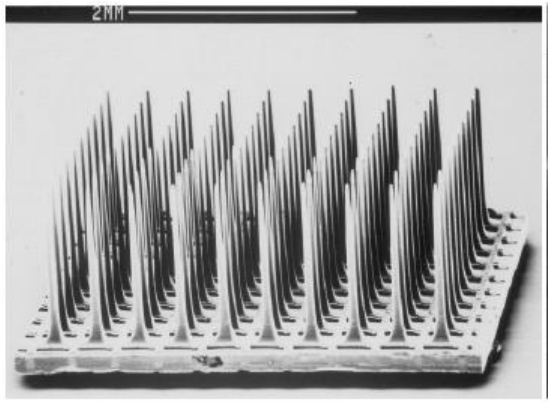


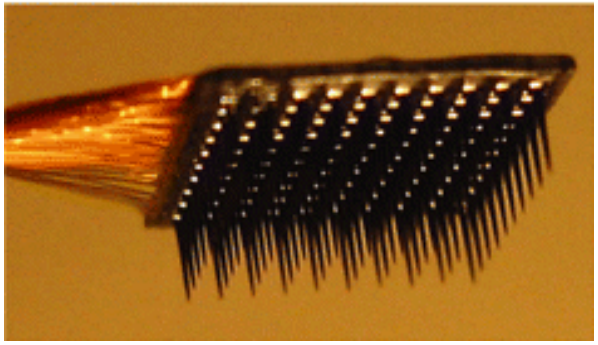
since 1969

Wise et al., in *Proc. IEEE*, 2004

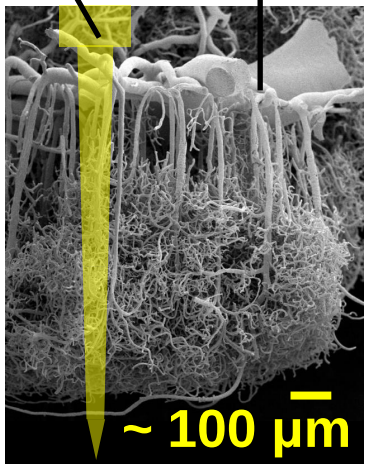
100 Channel Utah Array (Si)

since 1991





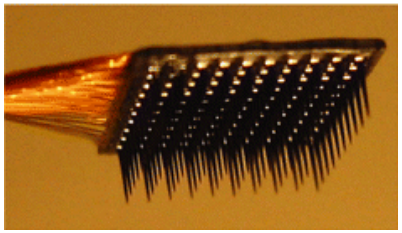
shank vasculature



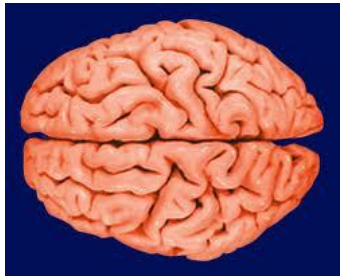
Rousche and Normann, *J. Neurosci. Meth.*, 1998

State-of-the-Art Neural Probes

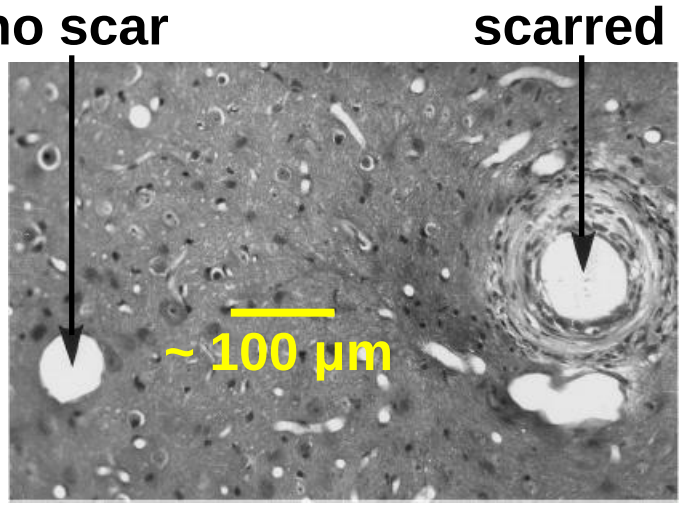
- Utah Array Signal Degradation
  - Relative motion
  - Compliance mismatch
  - Mechanical damage
  - Inflammation
  - Expulsion from brain
  - Cable failure



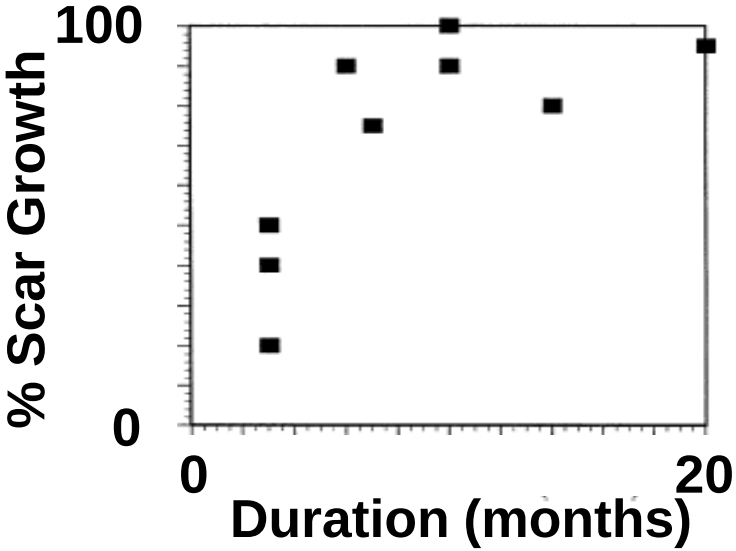
modulus ~100 GPa



modulus ~10's kPa



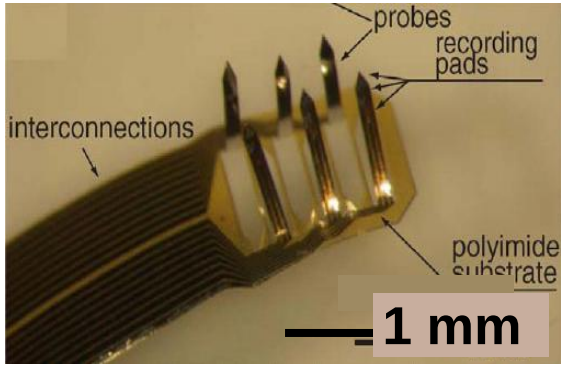
post-implant histology



Rousche and Normann, *J. Neurosci. Meth.*, 1998

New Directions in Probe Research

Polyimide Probes

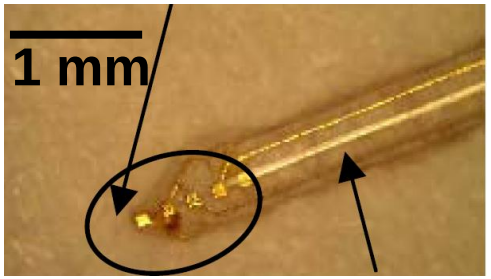


Takeuchi et al., (U.Tokyo)
J.Micromech Microeng., 2004

Parylene Probes

Insertion depth control

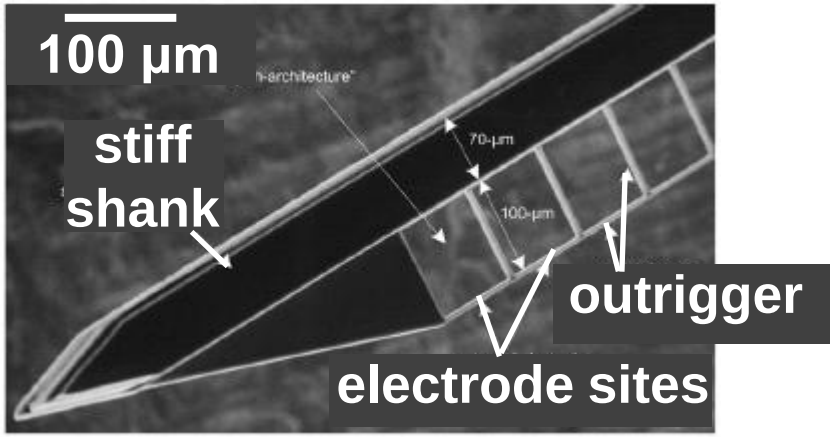
Wester et al. (GaTech)
J. Neural Eng., 2009



neural growth factor in PLGA spheres

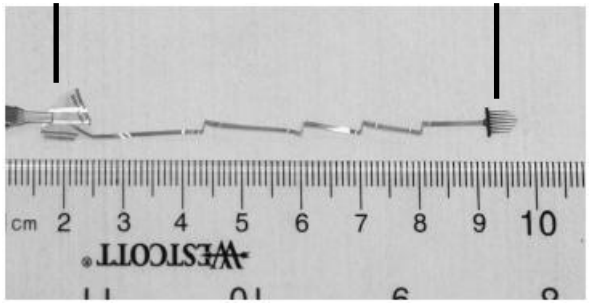
Kato et al., (U.Tokyo) in
IEEE EMBS 2006

Lattice Probes



Seymour and Kipke (U. Mich) *Biomaterials*, 2007

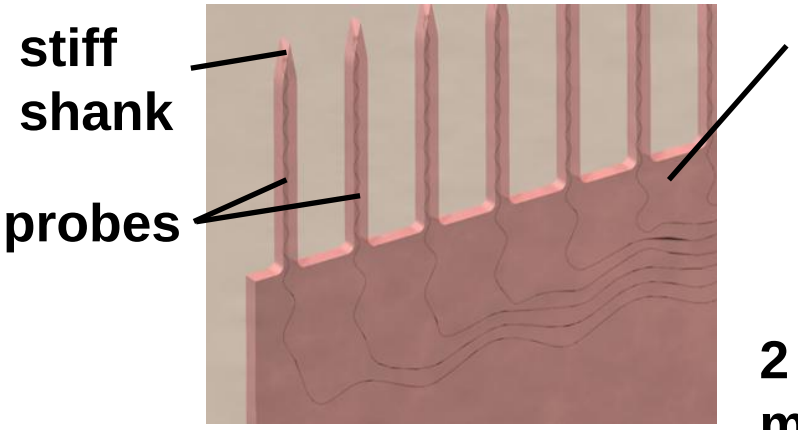
Integrated Parylene Cabling

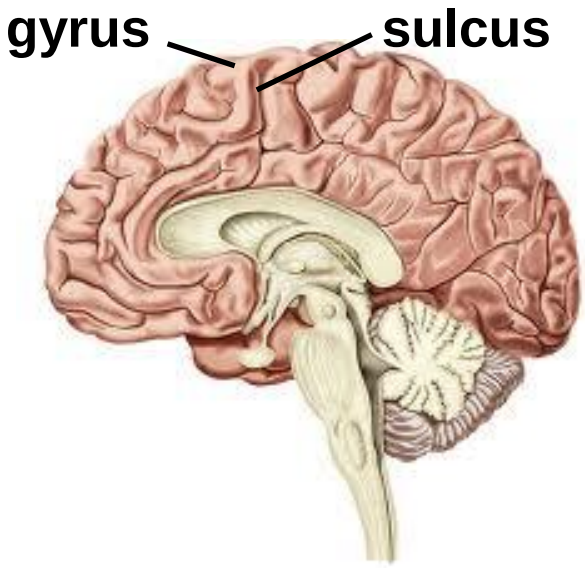


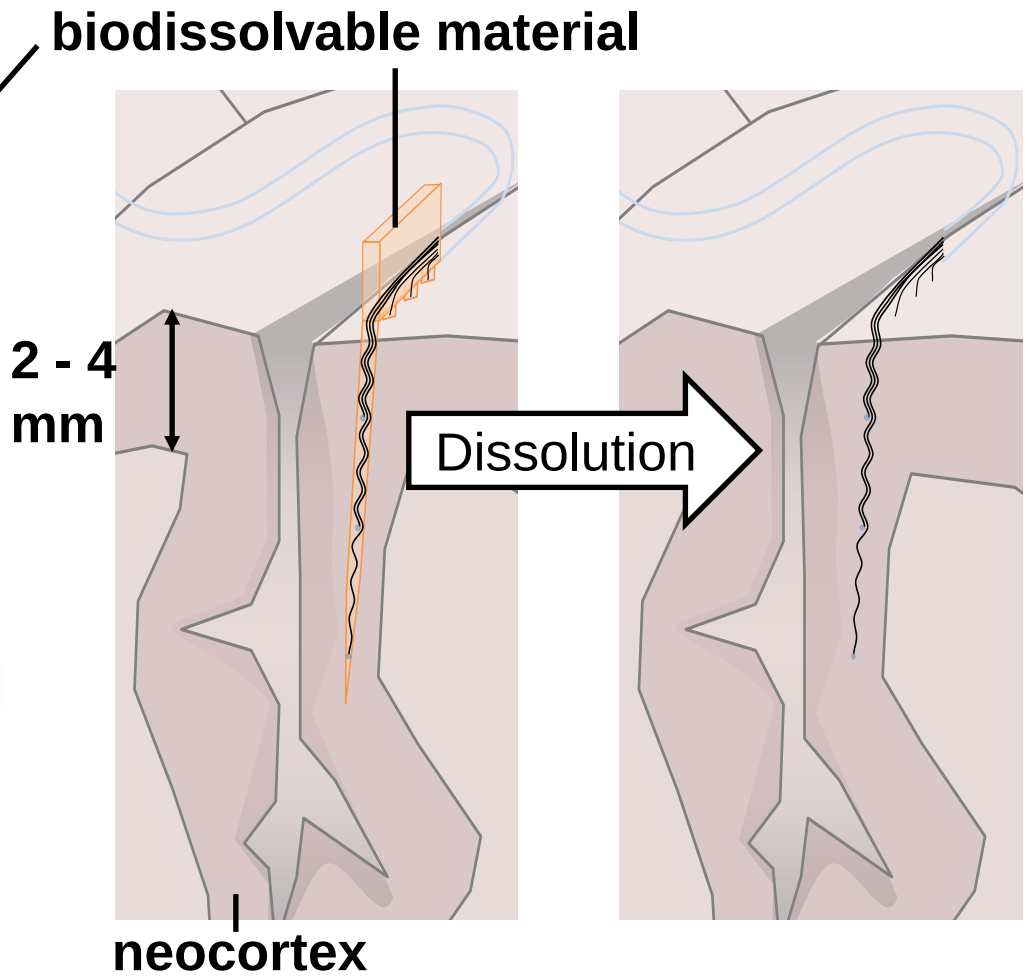
Huang et al., (CalTech) in *IEEE NEMS* 2008

Ultra-Compliant Neural Probes

- Compliance match probe to brain tissue < 0.3Nm^{-1}
- Reduce probe size to cellular scale < 20 µm







Ultra-Compliant Neural Probes

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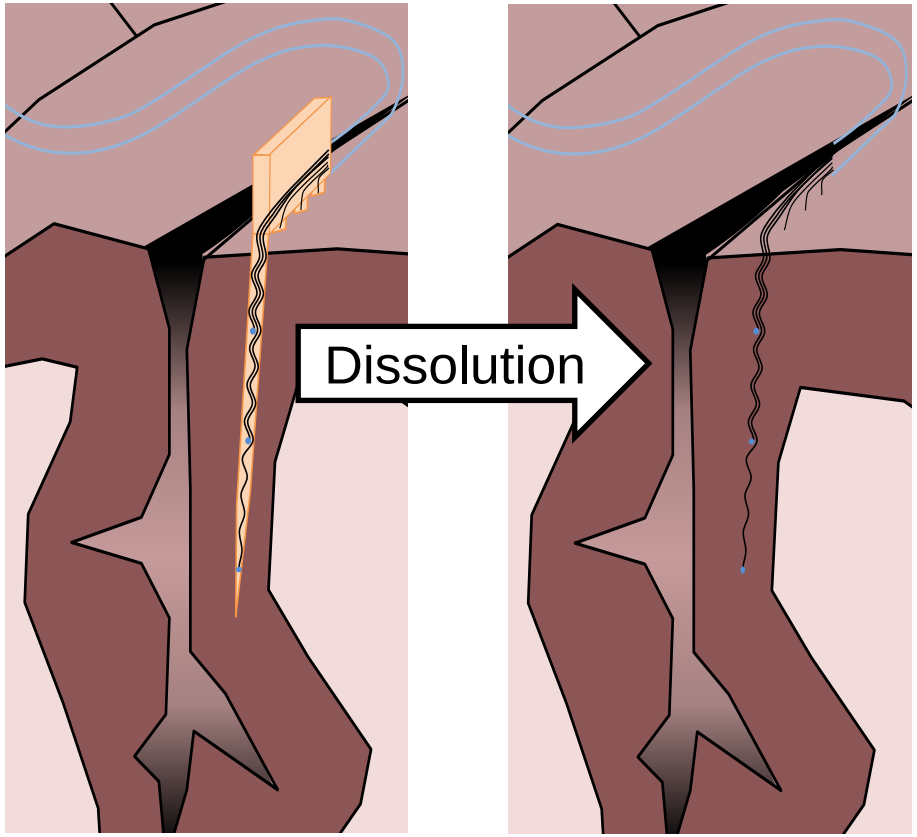
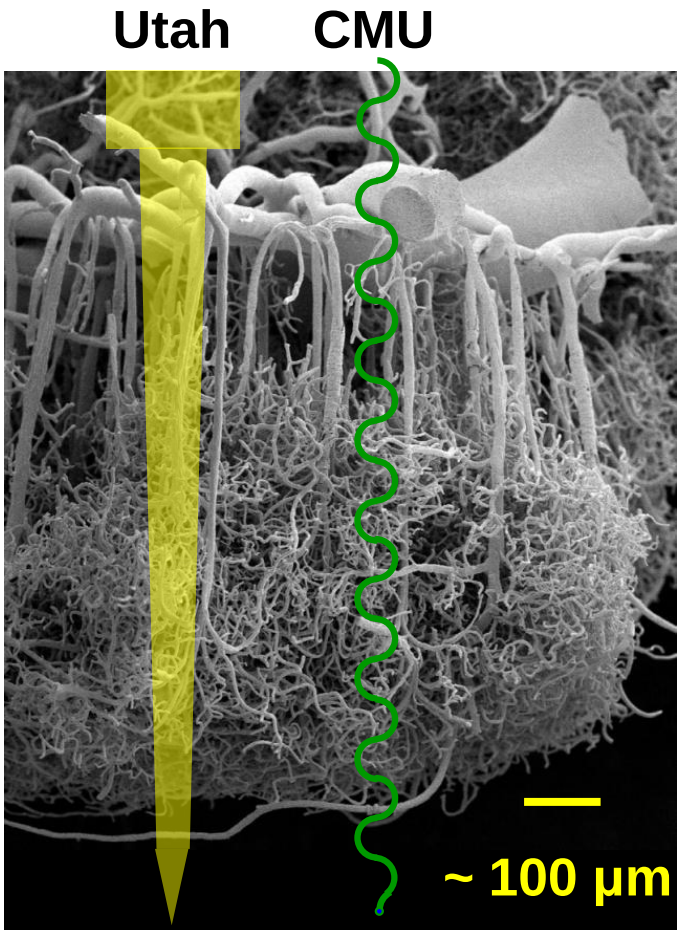
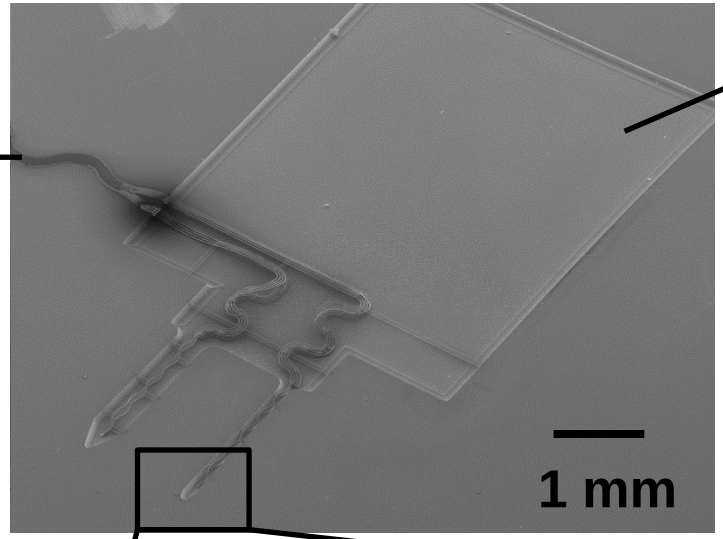
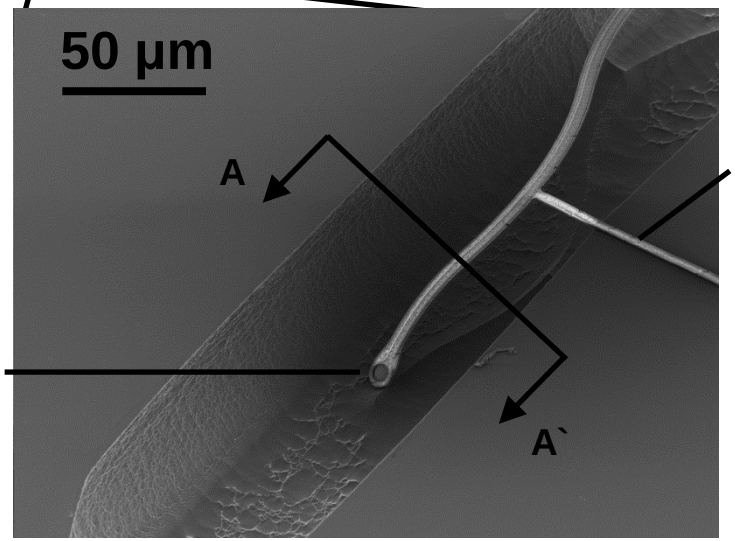




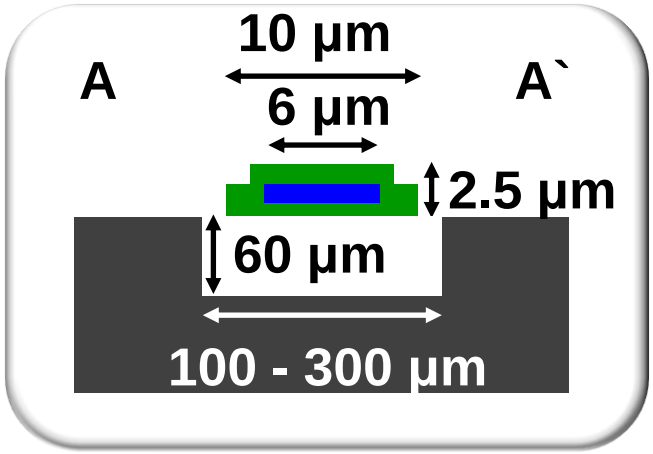
Ultra-Compliant Neural Probes

- Probe formation





Electrode Fabrication



Color Legend

Px* Pt

Si CMC*

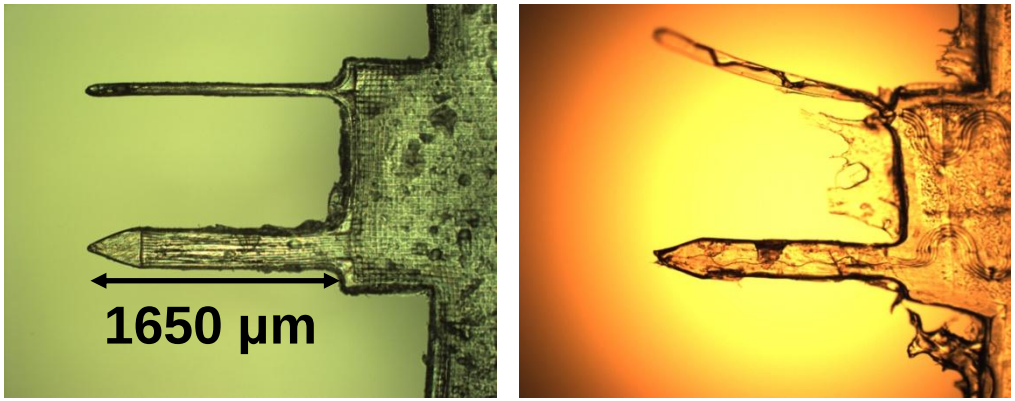
* Px = Parylene

CMC = Carboxy Methylcellulose

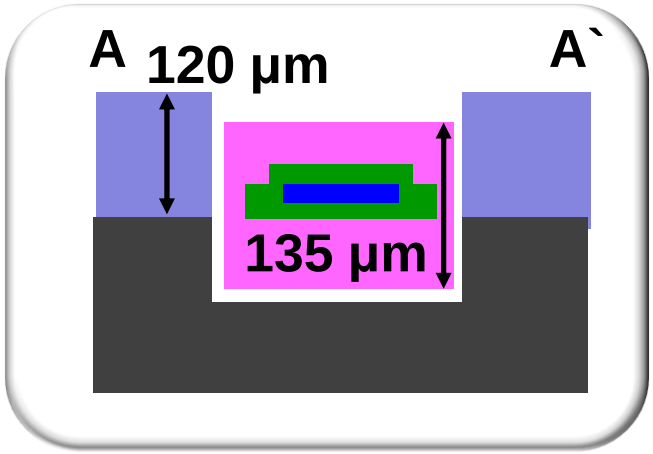
Ultra-Compliant Neural Probes

- **Biodissolvable delivery vehicle formation**

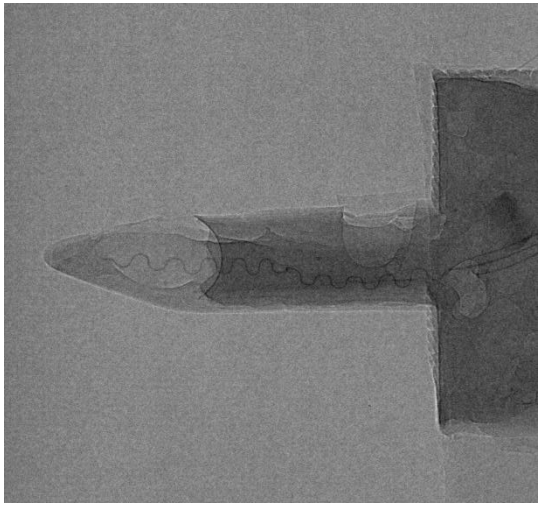
Optical Image Dual Shank



CMC Needle Molding



µCT Image Single Shank



Gilgunn et al., *MEMS 2012*

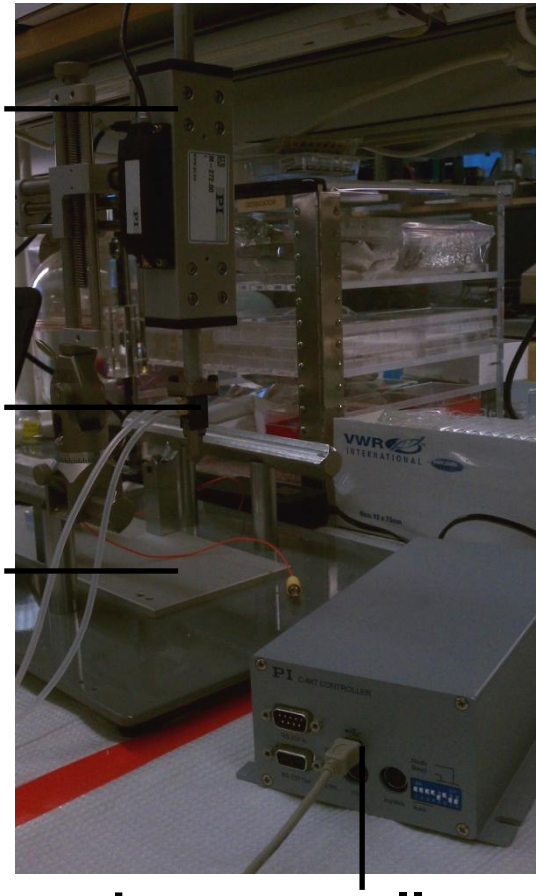
Color Legend

- Px
- Pt
- Si
- PVS*
- CMC

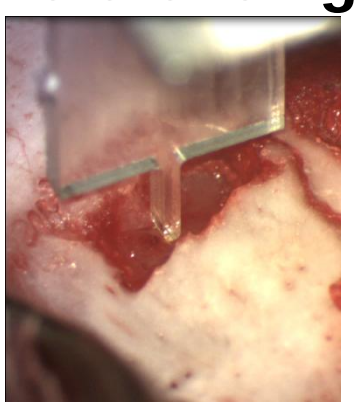
* PVS = Polyvinylsiloxane

Ultra-Compliant Probe Insertion

- **Piezoelectric ultrasonic insertion tool**
  - Speed to penetrate brain surface before CMC gelation
  - Accurate targeting of implantation site and depth (10 µm)

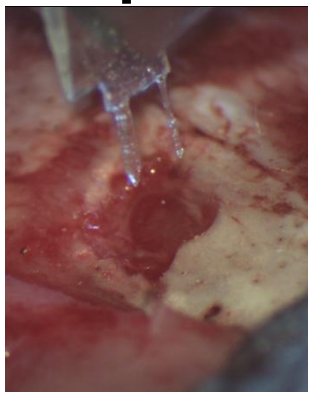


Referencing

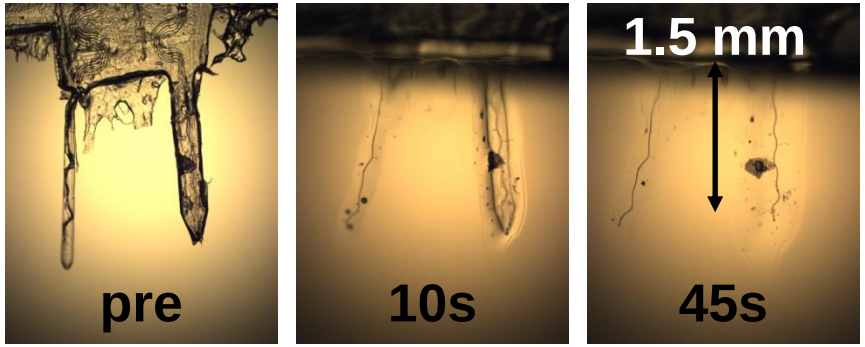


show movie

Implant



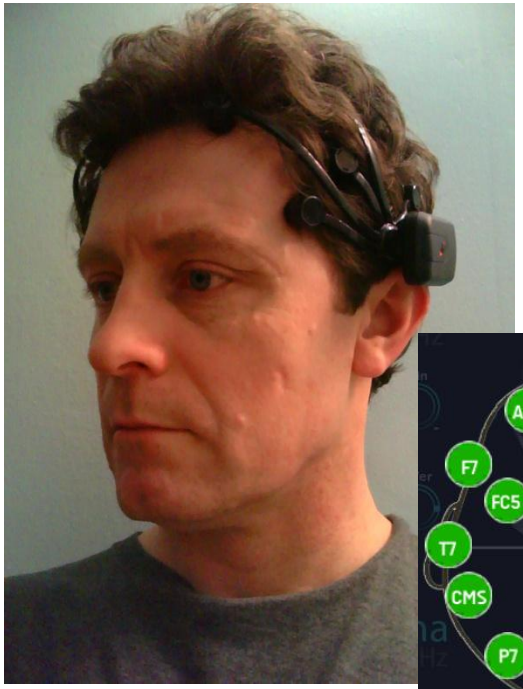
Agar Gel Dissolution Test

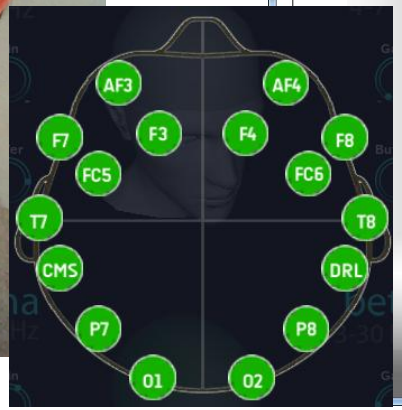


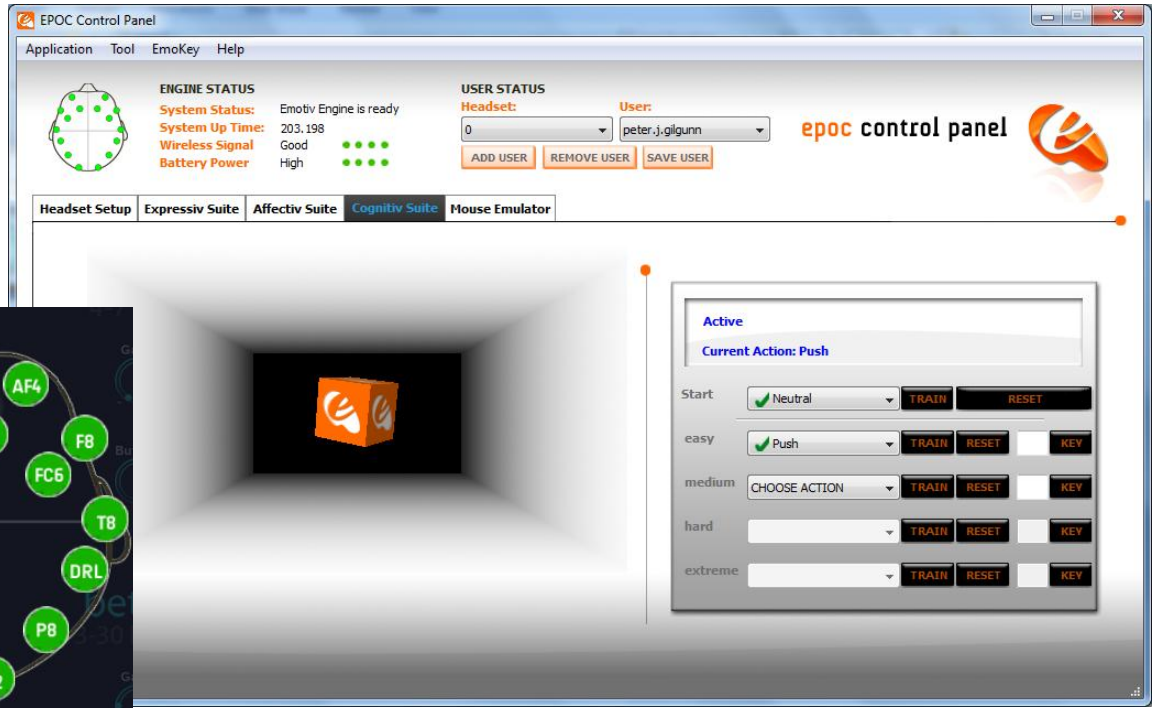
Gilgunn, Özdoğanlar et al., CMU Invention Disclosure, 2012

Free Behavior EEG

- **Emotiv Epoc EEG headset**
  - Research edition – 14 channels (2 emg), 2 axis gyro
  - 128 samples/s/channel
  - Bluetooth wireless for untethered activity
  - 10-20 system of electrode placement
- **Identify synchronous pattern dynamics in free behavior**



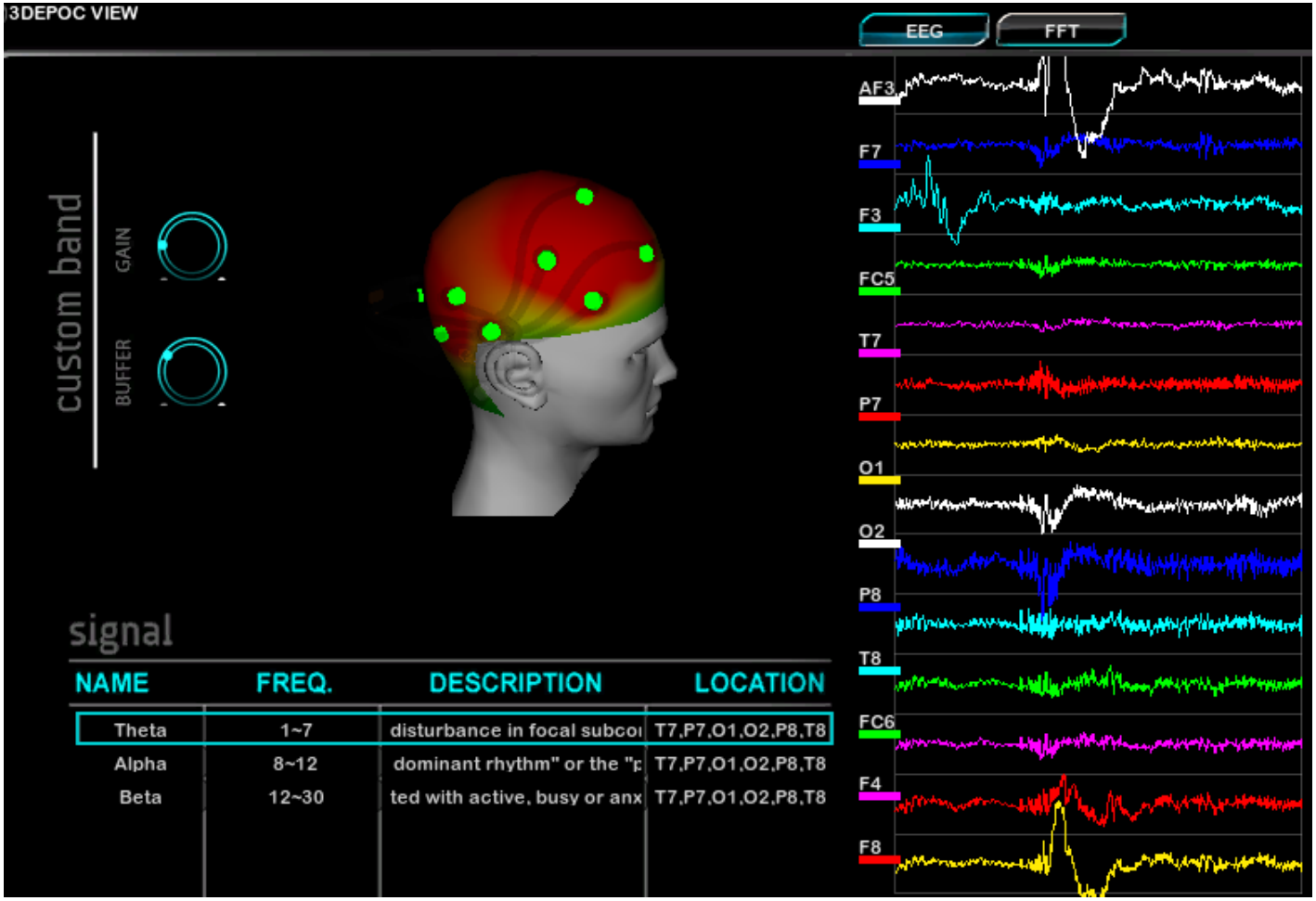




Vision | Past Research | **Present** | Future | Vision Redux

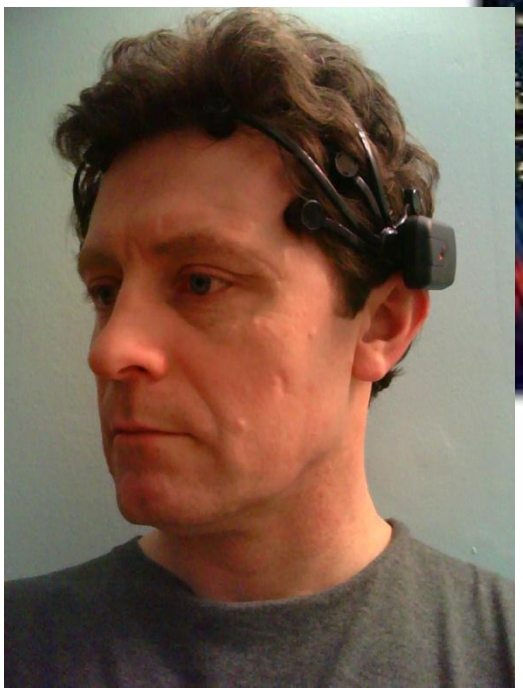
Free Behavior EEG

- **Tracking EEG response for various mundane activities**
  - **Eg. eating, reading, breathing**



Biointegration of Technology

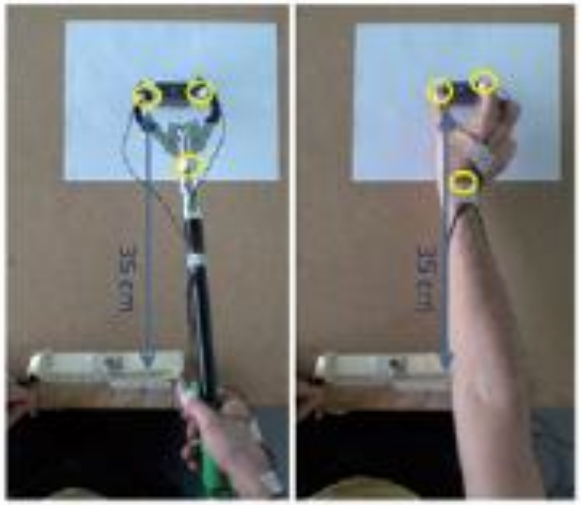
- **Tools (effectors)**
  - achieve goals
  - realize intentions
- **Technology**
  - enhance functionality
  - extend capability
- **Biointegration**
  - intimate
  - naturalistic
  - intuitive
  - coordinated
  - metabolically light
  - cognitively light
  - physically light



Biointegration of Technology

- "Self" model absorbs tools
- Updates body schema to reflect new morphology

IR markers for tracking



Tool - test

Pre-task

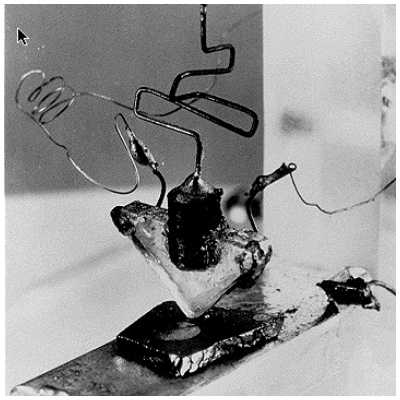
Post-task

Weight - control

- Monkeys - Iriki et al. "Coding of modified body schema during tool use in macaque post-central neurones" *Neuroreport*, 1996
- Humans - Cardinali et al., "Tool-use induces morphological updating of the body schema," *Curr. Bio.*, 2009

The Analogy Slide

The first solid state transistor



is to

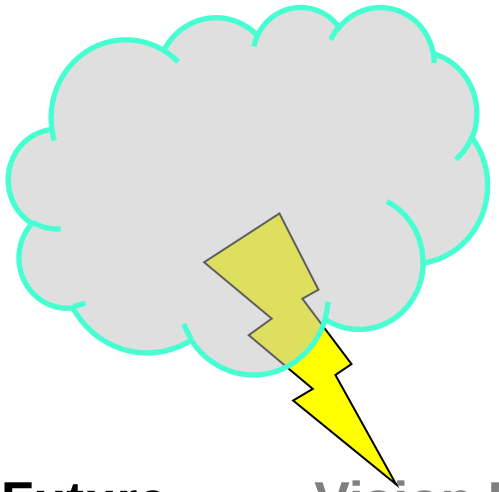
Siri on iPhone4

Ultracompliant neural probes

as

are to

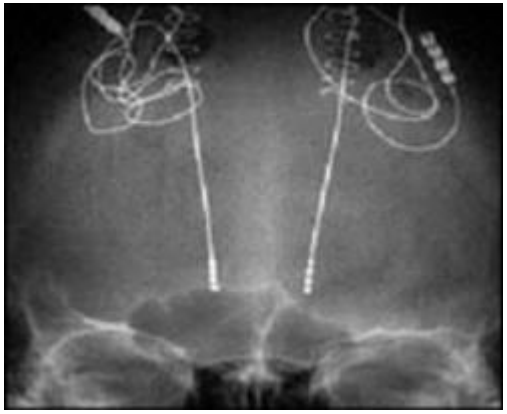
Biointegrated technologies



Vision | Past Research | Present | **Future** | Vision Redux

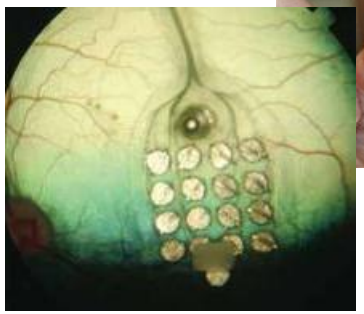
Biointerfaces

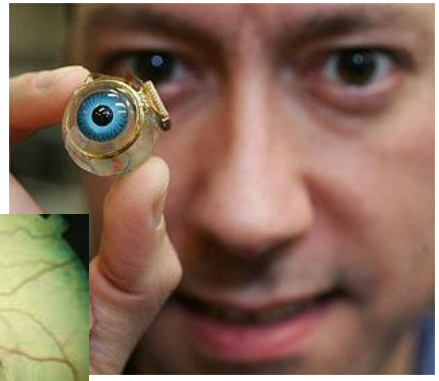
Macroelectrodes 100's µm → **Microelectrodes 10's µm**



Deep brain stimulation

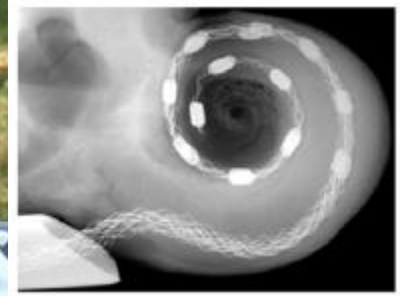
Retinal implants





Tetraplegic mobility

1 — 10 — Electrode Count — 100 — 1000



Cochlear implants

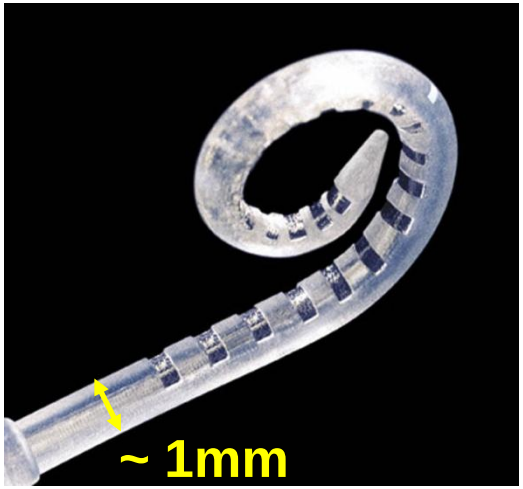
Prosthetic limbs

Vision | **Past Research** | **Present** | **Future** | **Vision Redux**

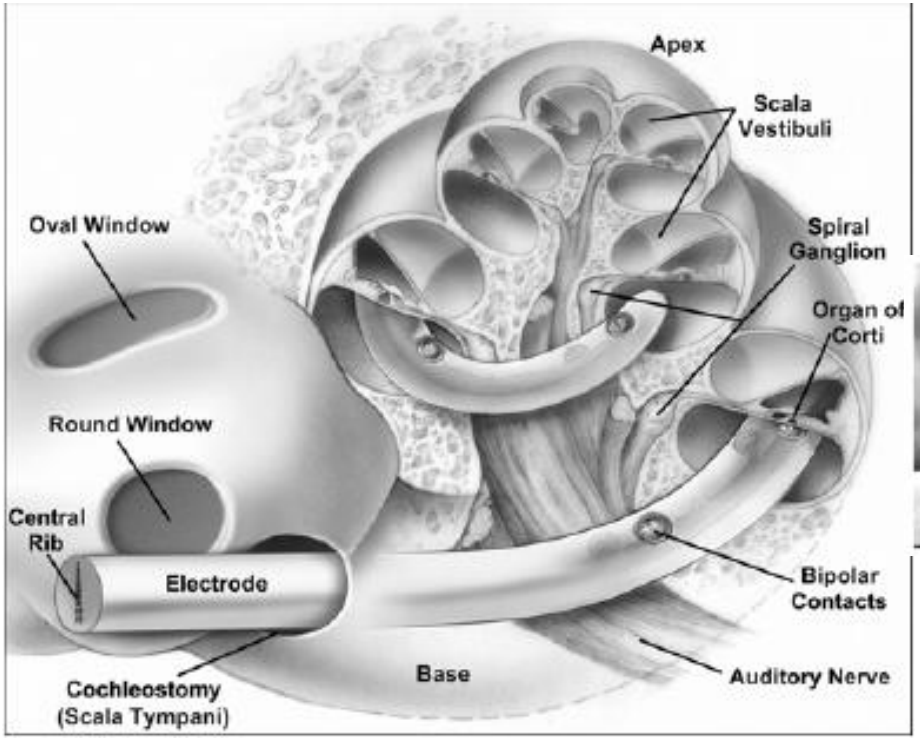
Conventional Cochlear Implant

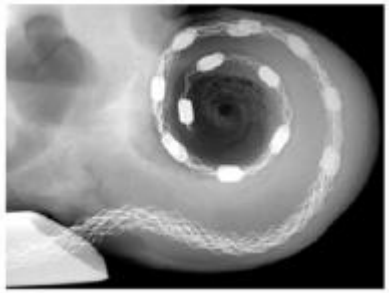
- 220,000 implanted worldwide ($60k per person)
- 16 – 22 electrodes (0.25 mm x 1 mm) manually assembled
- 300 – 3000 Hz – speech recognition only
- Recovery time ~ months, calibration and adjustments

22 channel electrode



Cochlear Ltd.



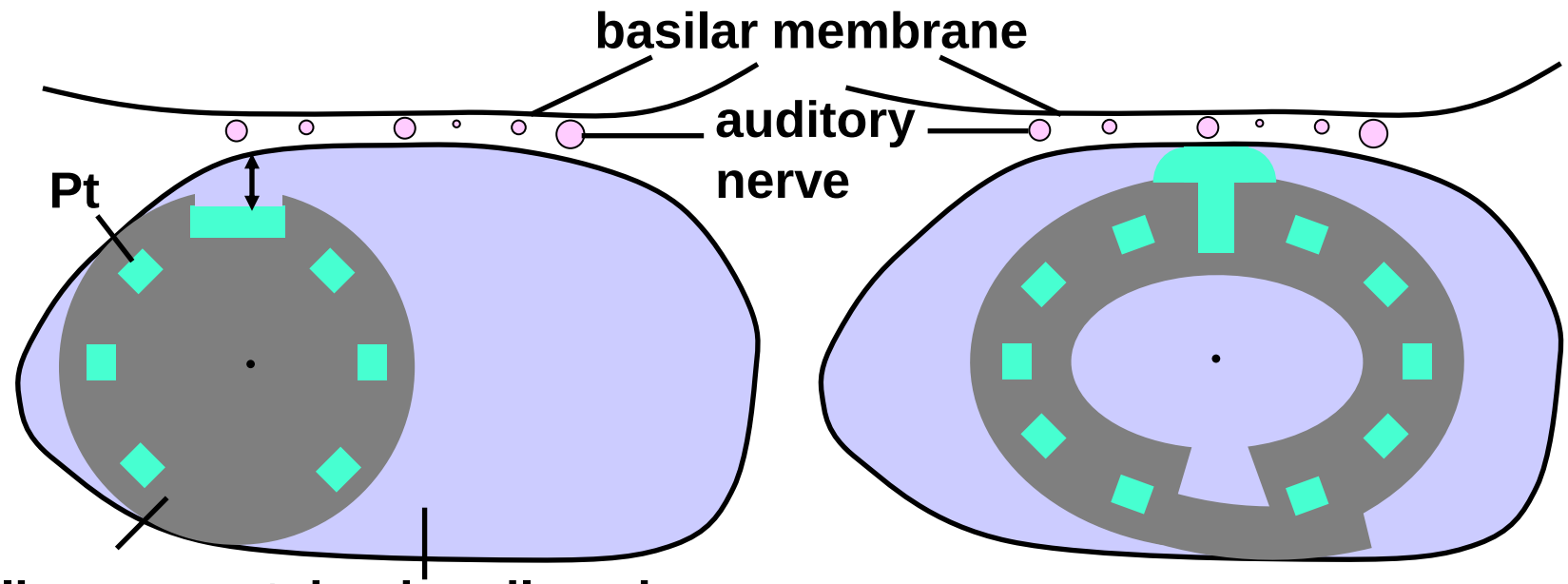


Wilson and Dorman, *J. Rehab. Res. Dev.*, 2008

Microfabricated Cochlear Implant

- Batch fabricated < 50 µm sq. microelectrodes (> 100)
- Collapsed insertion, inflated conformation

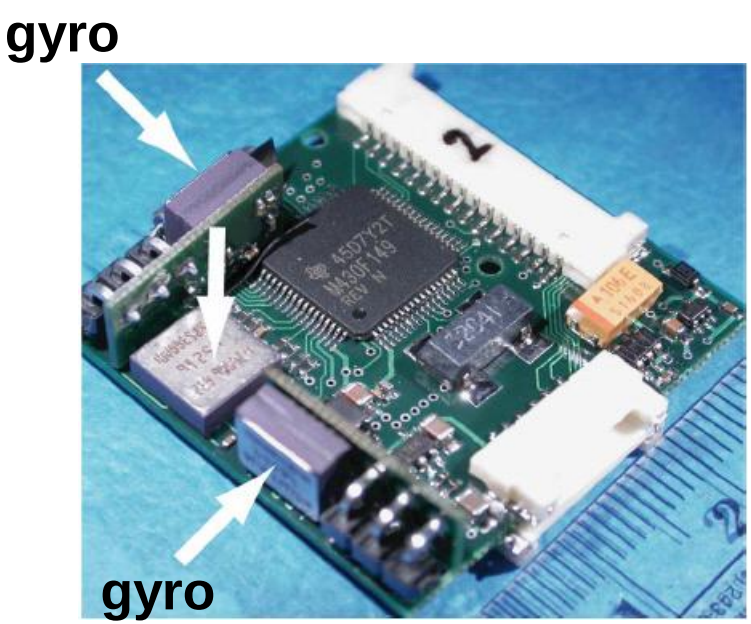
Conventional Implant Transverse Cross-section | **Balloon Implant Transverse Cross-section**



Gilgunn, Karagozler and Cosetti, CMU Invention Disclosure, 2012

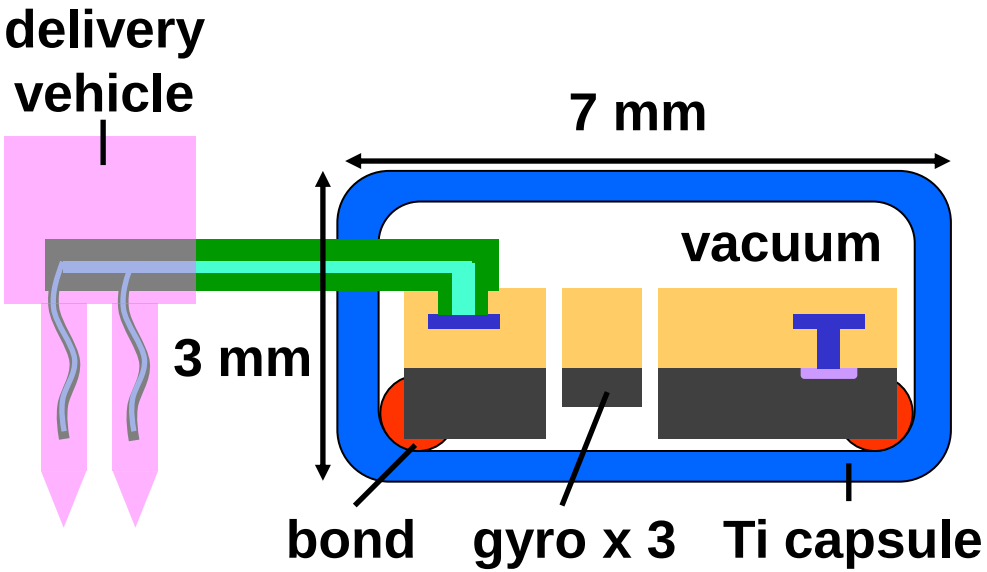
Vestibular Implants

- 1/3 of adults 65 and over fall each year
- Della Santina, Johns Hopkins
  - 30 mm per side
  - 100 mW in continuous operation
  - 75 um Pt/Ir microwire electrodes



Della Santina et al., *IEEE Trans. Biomed. Eng.*, 2007

Compliant probes integrated with CMOS-MEMS gyros

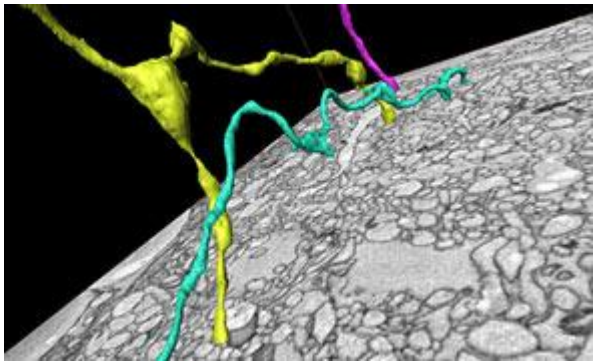


Human Machine Collaboration

- Humans for recognition speed
- Machines for memory and computational speed
- C3 Vision – cortically coupled computer system
  - Rapid satellite image classification
- Connectomics
  - Identification of neural circuitry
- Gaming
  - Starcraft <200 actions per minute

C3 Vision, Columbia

Starcraft



Connectomics

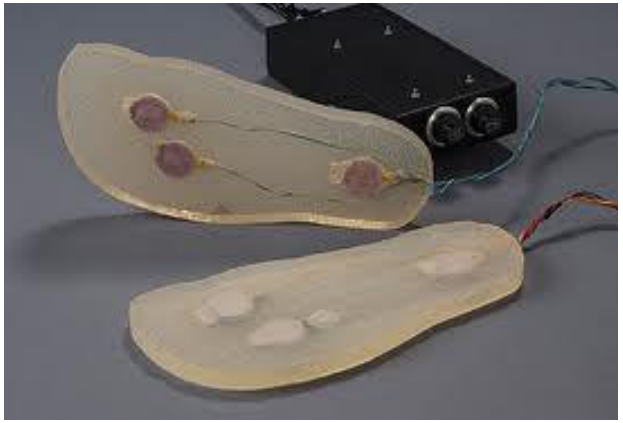
Cognitive and Sensory Enhancement

- **Medical treatment**
  - Alzheimers memory supplement
  - Mental health equilibration
- **New senses for critical tasks**
  - 360 vision for first responders
  - Stress sensing for law enforcement

Prosthetic vision interface

www.superflux.in

Noise-enhanced Balance

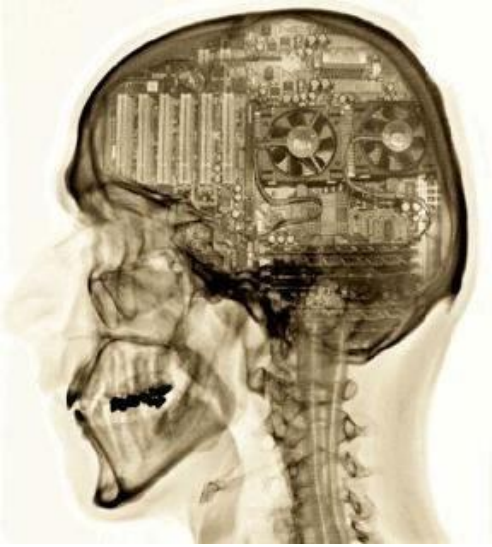


Collins Lab, Boston U.

Haptic Radar

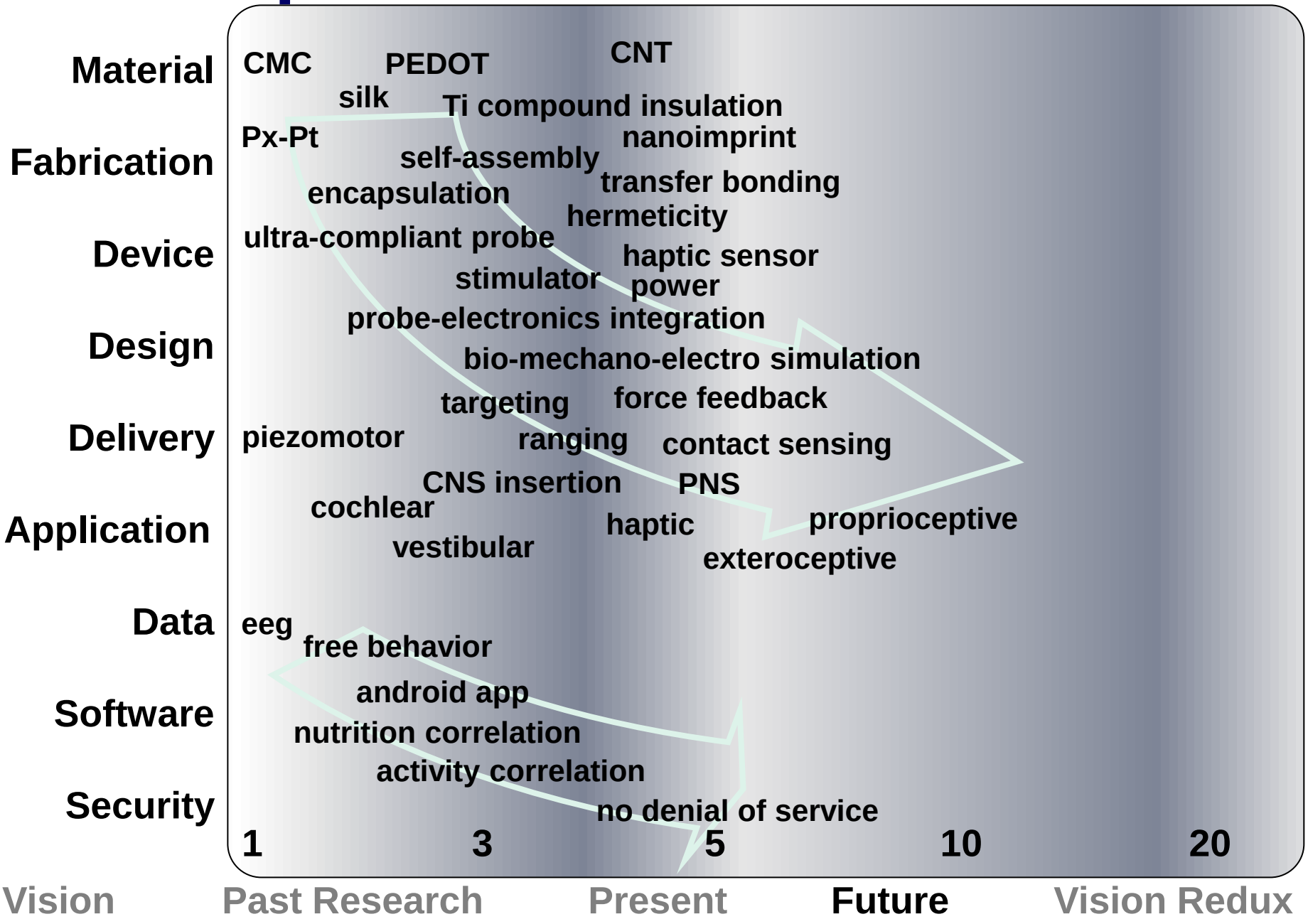
Oku Lab, U. Tokyo

Cognitive Implants

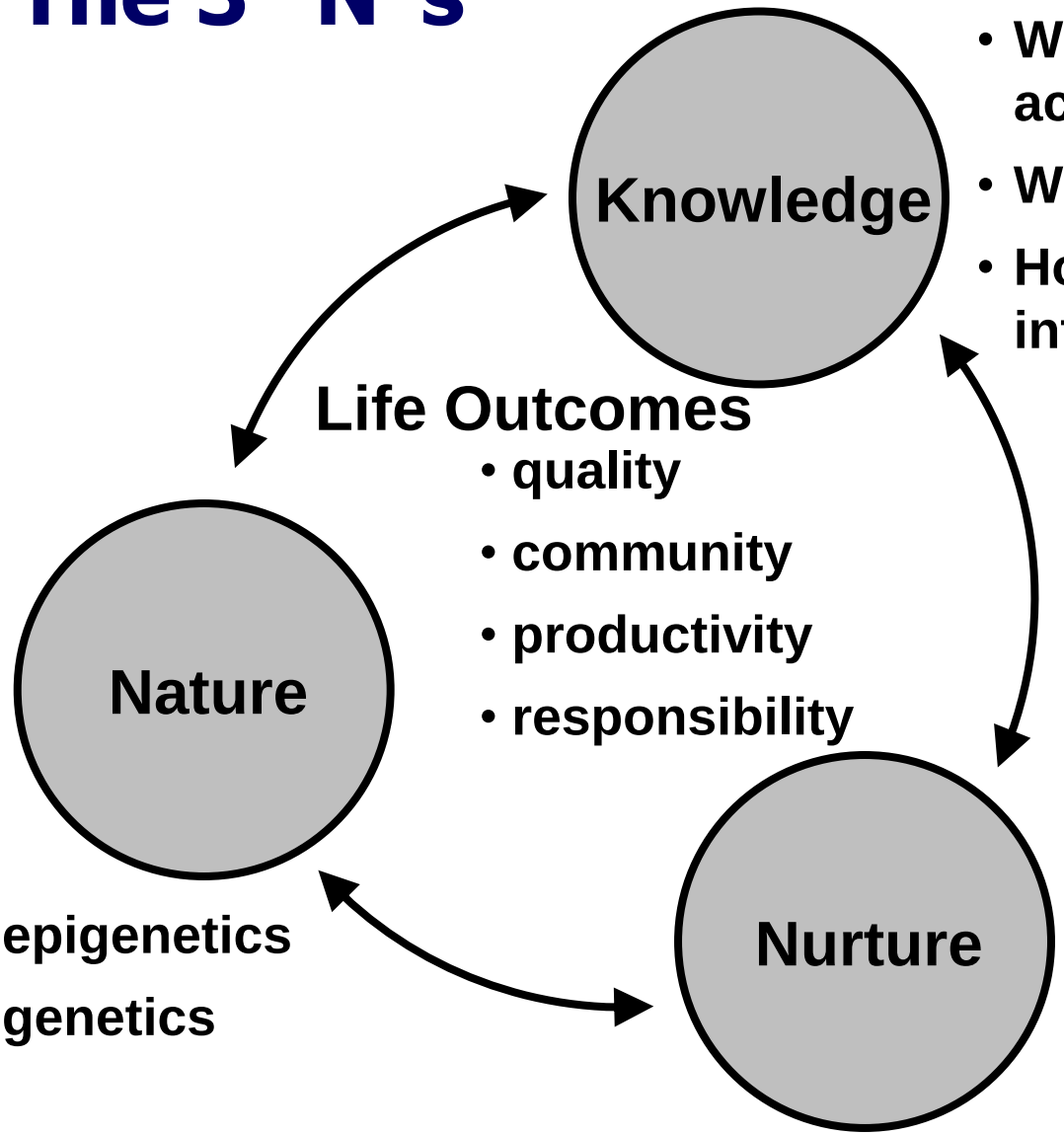


Berger, Bio Eng Lab USC

Roadmap



The 3 "N"s



- What needs to be known to achieve positive life outcomes?
- What can be known?
- How should the knowledge be integrated?

Life Outcomes

- quality
- community
- productivity
- responsibility

- epigenetics
- genetics

- environment
- nutrition
- upbringing
- friendships
- education

Acknowledgements

- **Collaborators**
  - MEMS Fabrication — Gary Fedder, J. Fernando Alfaro
  - Neural Probe — Gary Fedder; CMU MechE: Burak Özdoğanlar, Rakesh Khilwani; U Pitt: Doug Weber, X. Tracy Cui, Takashi (TK) Kozai, Geza Erdos
  - Free Behavior EEG — any interested parties?
  - Cochlear Implant — M. Emre Karagozler, NYUMC: Maura Cosetti
- **Technical Support**
  - Probe Implantation — U Pitt: Xia Li, Kasey Catt, Noah Snyder
  - Fabrication — CMU: Chris Bowman, Suresh Santhanam, Carsen Kline
  - Imaging — CMU: Marc DeGraef, Jason Wolf
- **Funding**
  - MEMS Fabrication — The Boeing Company
  - Neural Probe — DARPA
  - Cochlear Implant — tbd
  - Vestibular Implant — tbd

Toward Advanced Applications with Biointerface Technologies

Thank you

Questions?