General Electric Seminar

SAND2009-4967C

August 11, 2009

Testing of Pt- and Ru–coated, thermally actuated μrelays in an ultra-high purity environment

Maarten P. de Boer

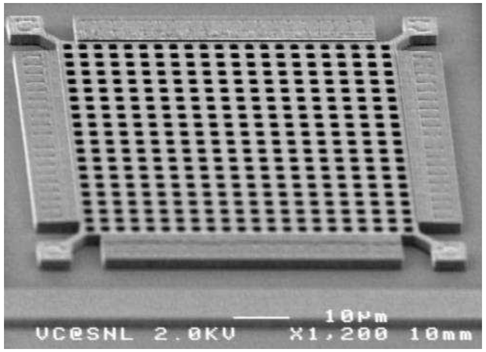
Sandia National Laboratories, Albuquerque, NM

MEMS Technologies Dept.

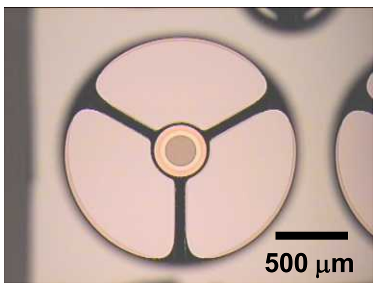
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

MEMS have many real-world applications - examples devices at Sandia

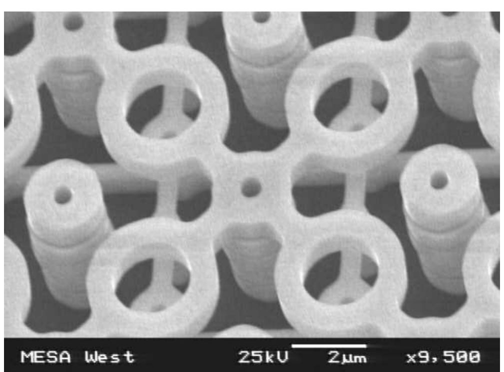
rf–resonators



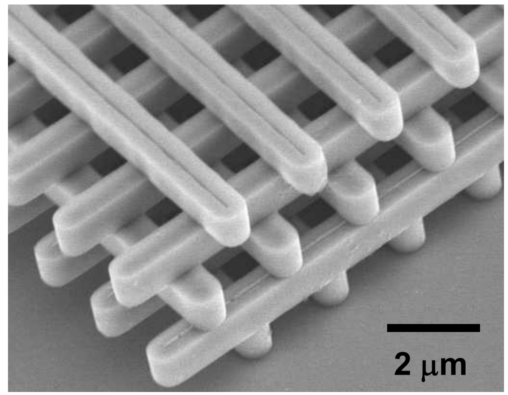
Microphones

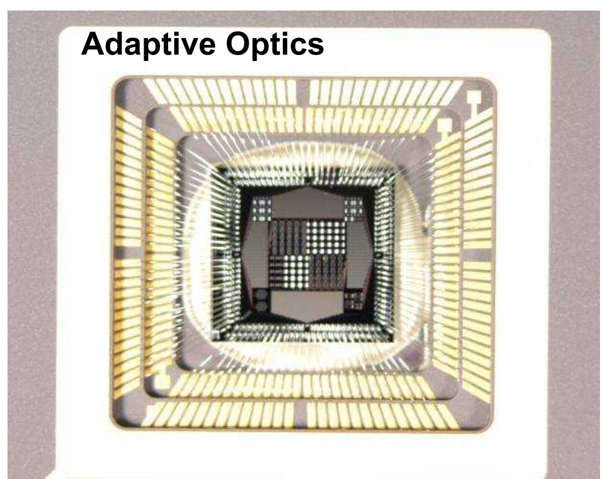


Ion Traps

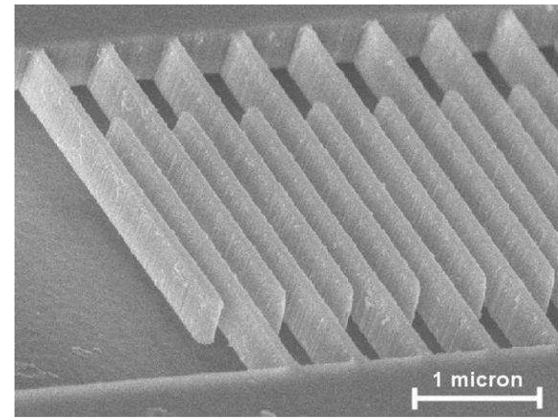


Photonic lattices
Metamaterials
Acoustic Bandgap Structures

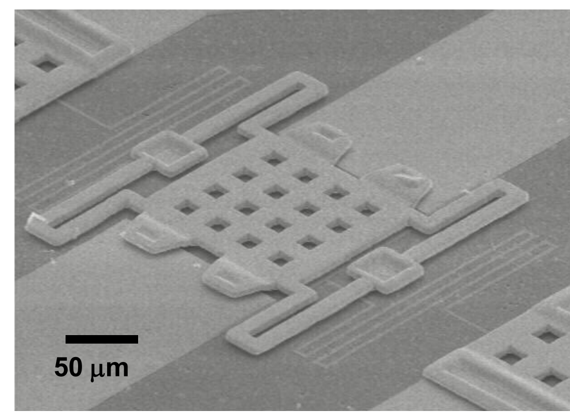




high-sensitivity accelerometers
(~fm/Hz$^{1/2}$)



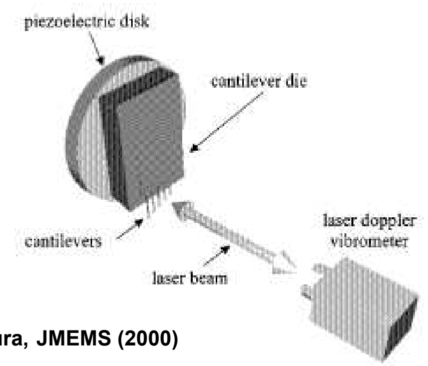
RF-MEMS ohmic switches



Surfaces can dominate response of μscale structures

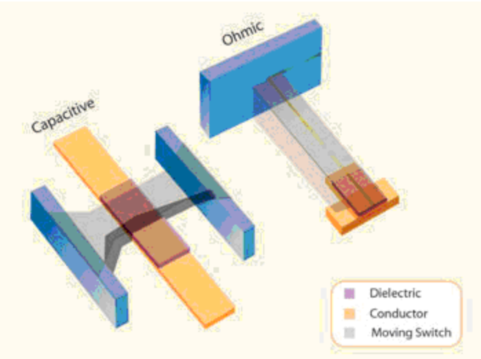
Damping - Acceleration Sensors

$$\frac{1}{Q} = \sum_i \frac{1}{Q_i} = \frac{1}{Q_{clamping}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{volume}} + \frac{1}{Q_{surface}} + \ldots$$



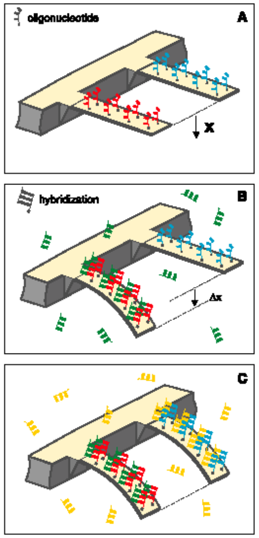
Yasamura, JMEMS (2000)

Contact impedance electrical / optical μswitches μscale / nanoscale



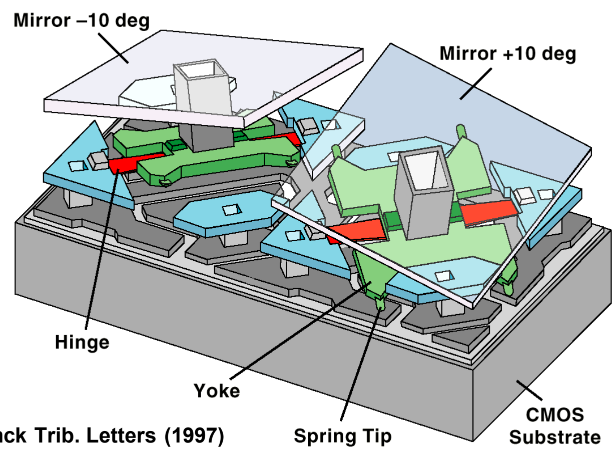
Brown, Mech. Eng. (2003)

Adsorption - cantilever sensors for μgas chromatographs



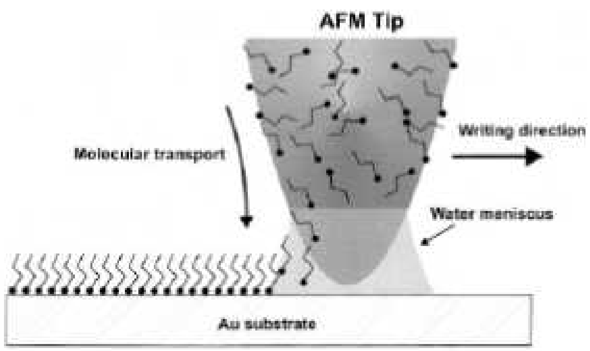
Fritz, Science (2000)

Adhesion
Display technologies:
Accelerometers:



Henck Trib. Letters (1997)

Nanolithography



Piner Science (1999)

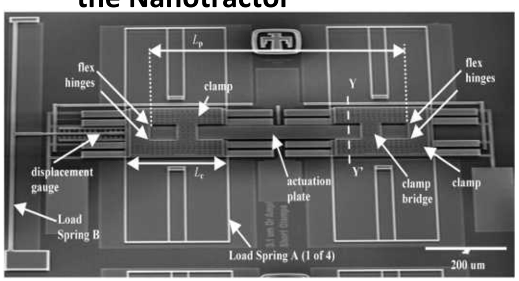
Nano- and Micro-Mechanics

Design, fabricate, test, and analyze structures to understand their mechanical properties at the micro and nanoscales

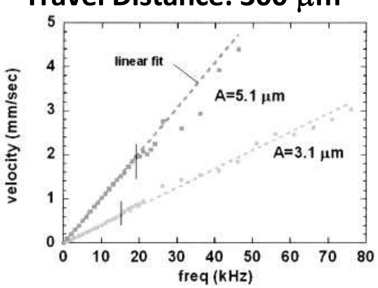
Actuators

Inspiration: Nature's inchworm

Microscale implementation: the Nanotractor



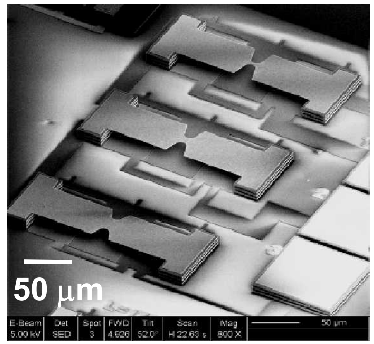
Velocity: 5 mm/sec, Force: 1 mN
Travel Distance: 300 μm



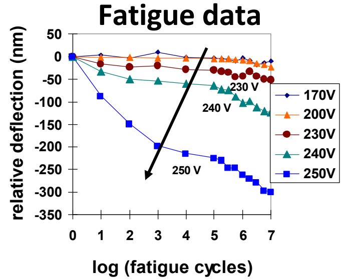
(de Boer et al., JMEMS, 2004)

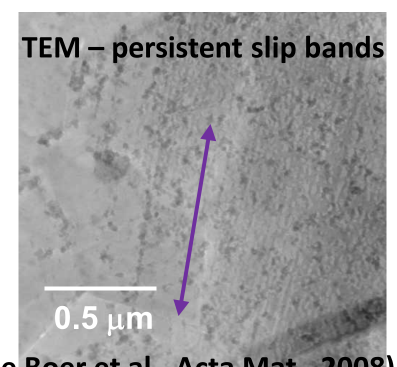
On-chip fatigue testing of free-standing Al thin film alloy

Aluminum notch structures are actuated electostatically and measured by interferometry



Fatigue data

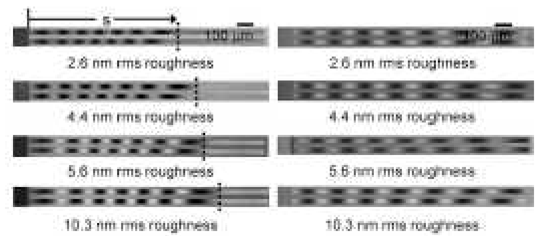




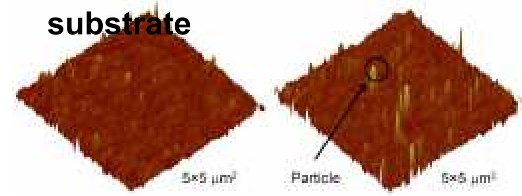
(de Boer et al., Acta Mat., 2008)

Microscale adhesion mechanisms

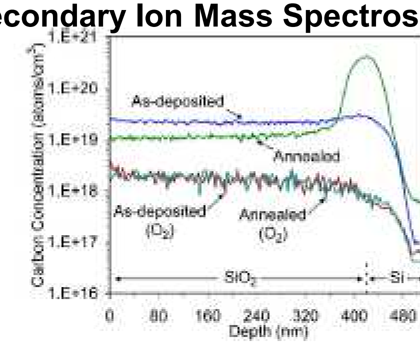
μCantilever beam interferograms: Adhesion does (left) does not (right) correlate with surface roughness



Particles can form on the substrate



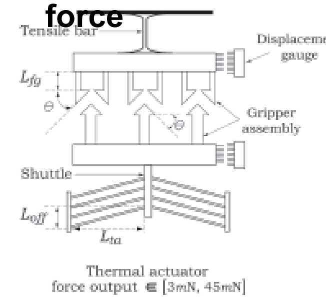
SiC particles grow at Si interface due to residual C in oxide (Secondary Ion Mass Spectroscopy)



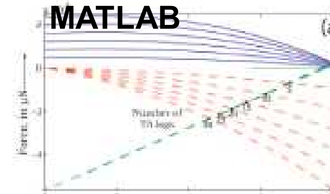
(DelRio, de Boer., JAP, 2006)

On-chip polysilicon strength testing

Device Concept: Use cool-down of thermal actuator to develop large force



Design Analysis: ANSYS & MATLAB



Parts are currently being fabricated at Sandia National Labs

(Hazra & de Boer, Work in Progress)

Collaborators for today's talk (SNL, Albuquerque)

- **David Czaplewski (testing) (now at ANL)**
- **Mike Baker (switch design)**
- **Steve Wolfley and Gary Patrizi (metal deposition)**
- **Lu Fang (packaging)**
- **Dave Tallant (Raman), Tony Ohlhausen (Auger) and Paul Kotula (TEM)**
- **Robert Anderson, Mike Shaw and many others (SUMMiT V^{TM} process staff)**

Outline

- **Brief Introduction**
- **Switch design and processing**
- **Packaging**
- **Testing and Results**
- **Analytical test results**

  SEM, TEM, Auger, XPS, Raman, Interferometry
- **Next steps**

Introduction and Motivation

- Sandia is interested in μswitches for national security applications

- Reliability of switches is of critical concern:
  - role and source of C contamination?
  - material transfer?
  - effect of μswitch design and operation?
  - effect of hot switching versus cold switching?

- Our approach:
  - Simple switch with basic elements of more complex designs
  - Different thin film metallurgies to make contact (Pt, Ru)
  - processing, packaging and testing as clean as possible

- Addresses the questions:
  - Can we eliminate C contamination?
  - How low can we get the resistance?

Switch fabrication - SUMMiT V^{TM} process

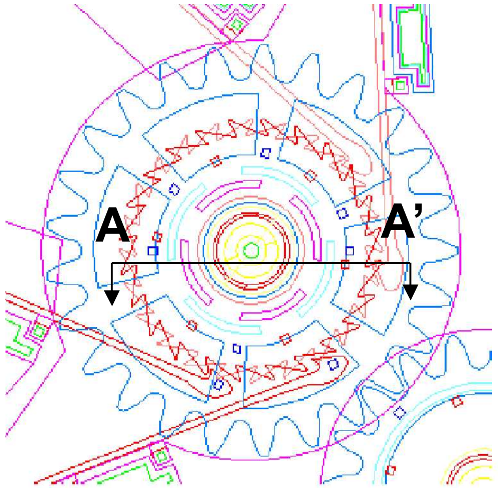
A series of structural and sacrificial layers are deposited

Ground plane layer (Poly 0)
4 structural levels
(Poly 1 - Poly 4)

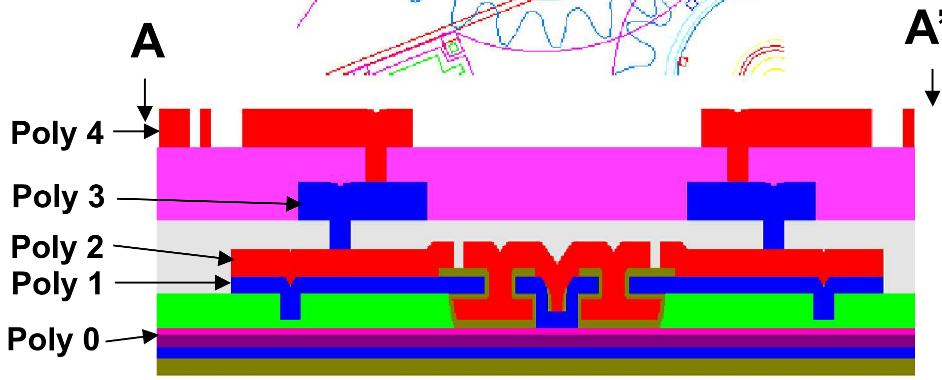
Chemical Mechanical Planarization (CMP)

1 μm design rule

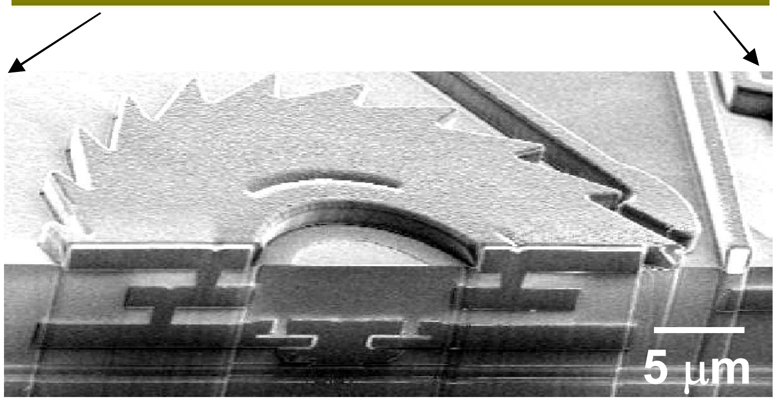
Create freestanding thin film structures by "release" process



Design



Cross-section drawing



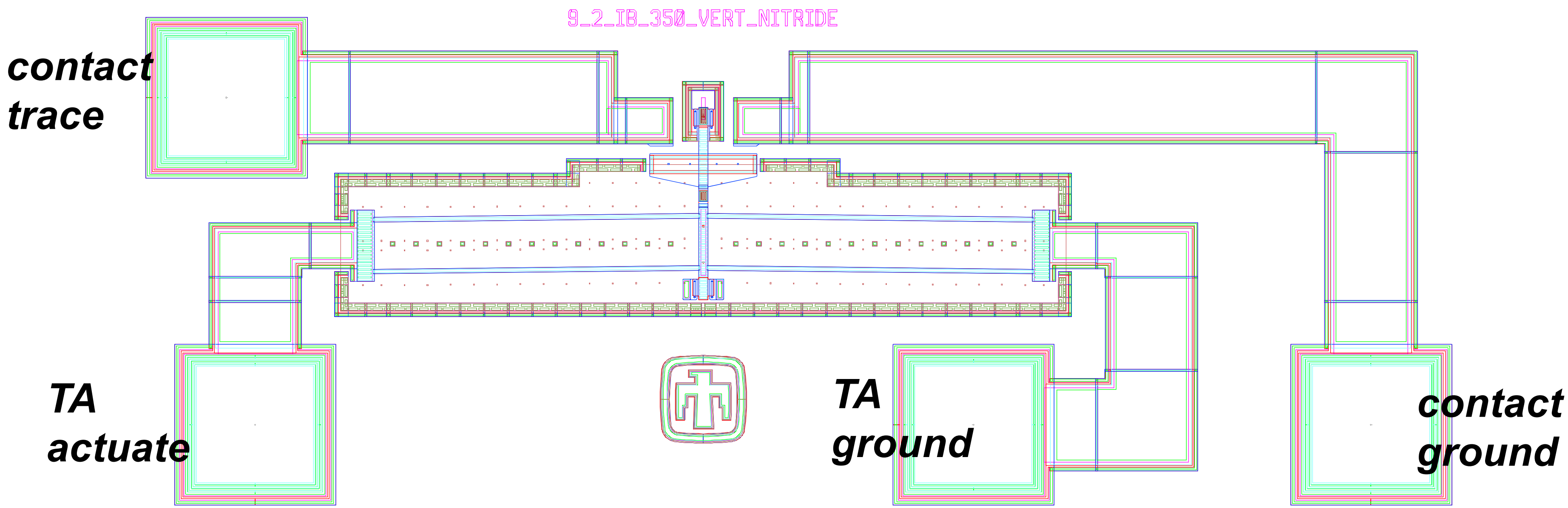
FIB cross-section

Sniegowski & de Boer, Annu. Rev. Mater. Sci. (2000)

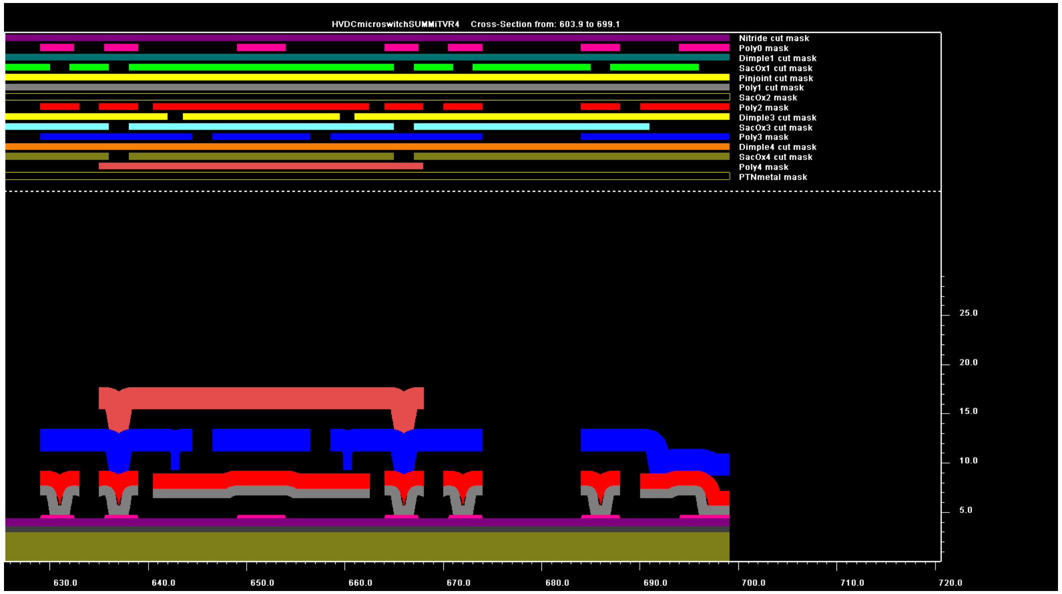
Switch Design

Thermal actuator

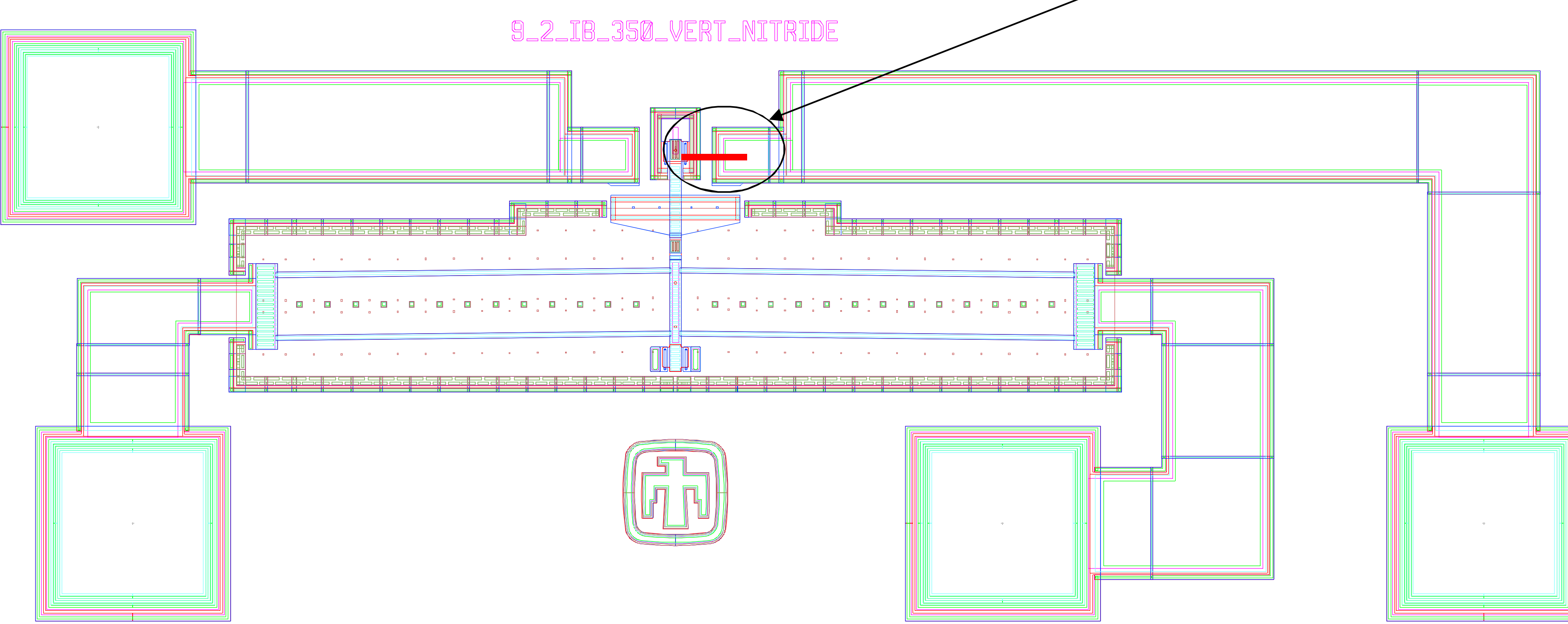
- 250 cycles/s (20 million cycles/day)
- electrically-isolated contact bar shorts out two traces
  contacts are on coated polysilcon sidewalls
- SUMMiT V[TM] process
- self-shadowing design enables variations of post-process contact metallurgies
- contact force ~100 μN
- apparent contact area ~ 50 μm^2



Switch cross-section



Cross-section area

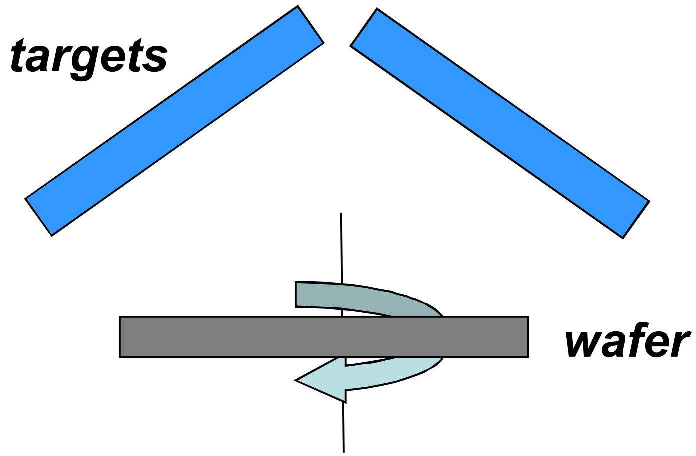


Post-process metal depositions

To be discussed today:

Pt/Ti (4250/500 Å) sputtered in tool
Ru – thermally oxidized (2000 Å)
RuO_2 – reactively sputtered (5000 Å)
RuO_2/Al/Ti – sputtered (5000 Å / 5000 Å / 500 Å)

Why Pt?	*- Harder than Au*
Why Ru?	*- Thermal oxide of Ru, reed relay work (1980s), reduce catalytic activity*
Why RuO_2?	*- Reactively-sputtered RuO, quite conductive*
Why RuO_2/Al?	*- lower contact R*

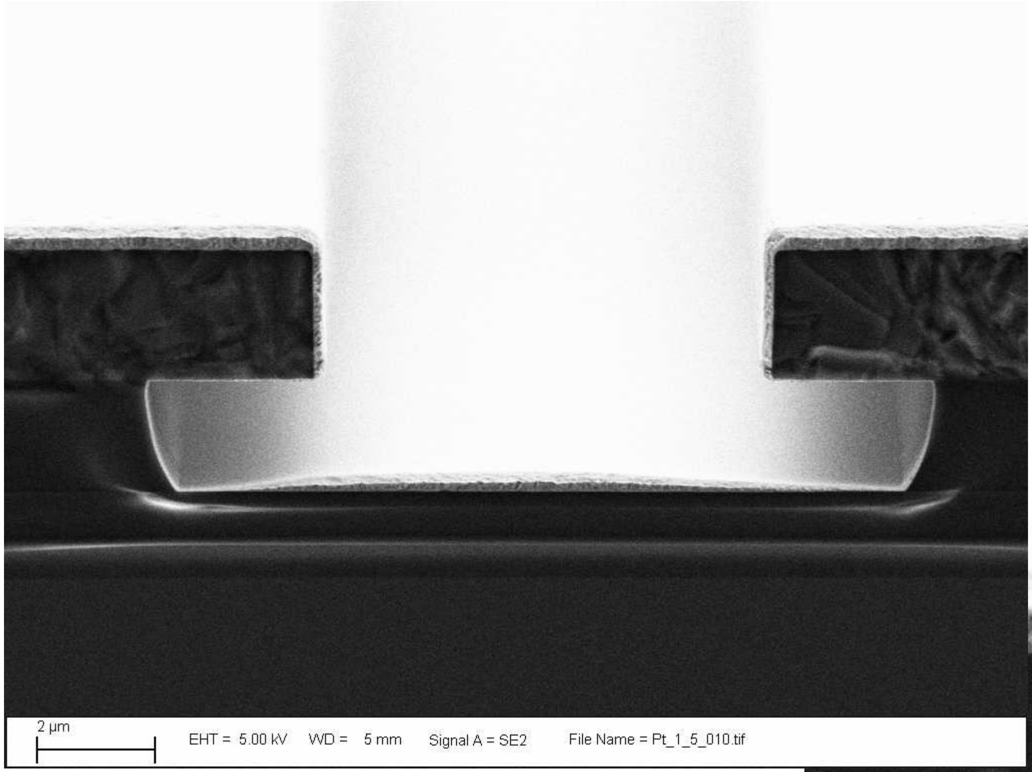


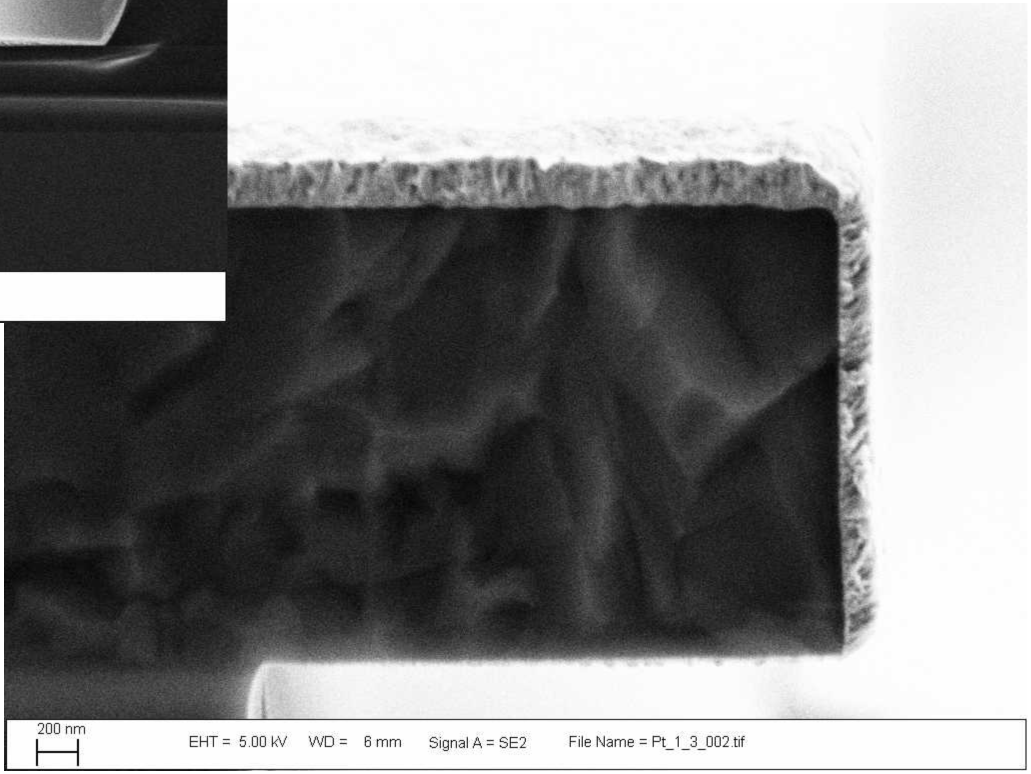
Metallization details

<u>Metal deps</u> are done in Denton Discovery 550 sputter tools. Deposition chamber is arranged with 4 cathodes in a confocal arrangement. The sample holder sets on a rotating stage (samples facing up) and each cathode is focused on the sample stage at roughly a 60 degree angle.

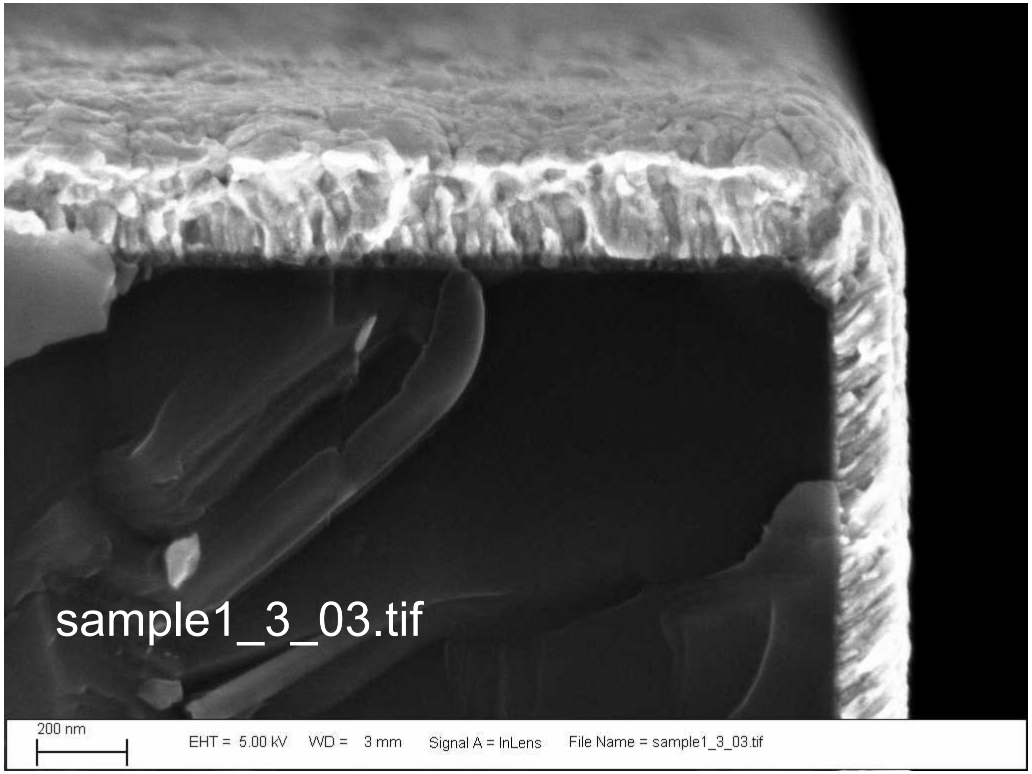
<u>Thermal oxidation</u> is done in a horizontal anneal furnace for 120 minutes at 420 C with an O_2 flow rate of 5 slm. The system is manufactured by MRL industries.

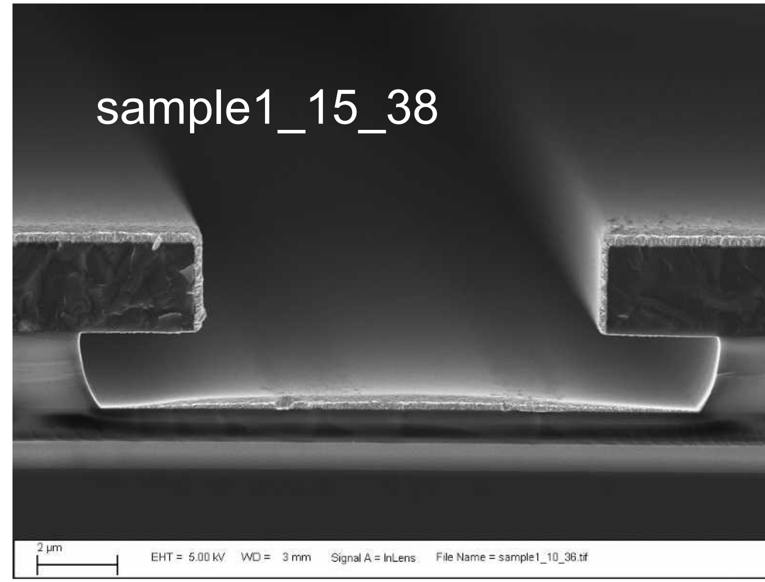
Switch cross-section (Pt film)

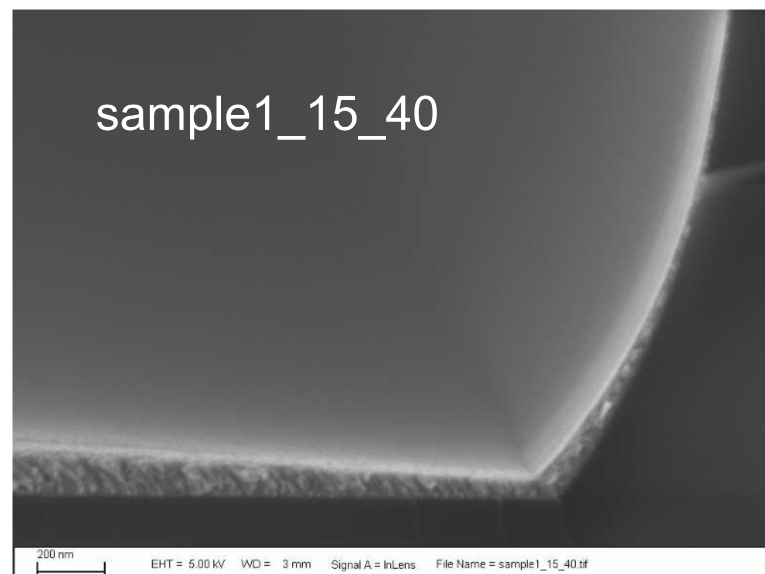




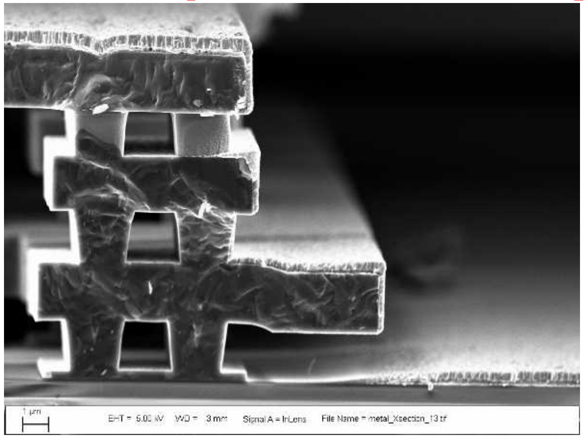
Switch cross-section (Pt film)

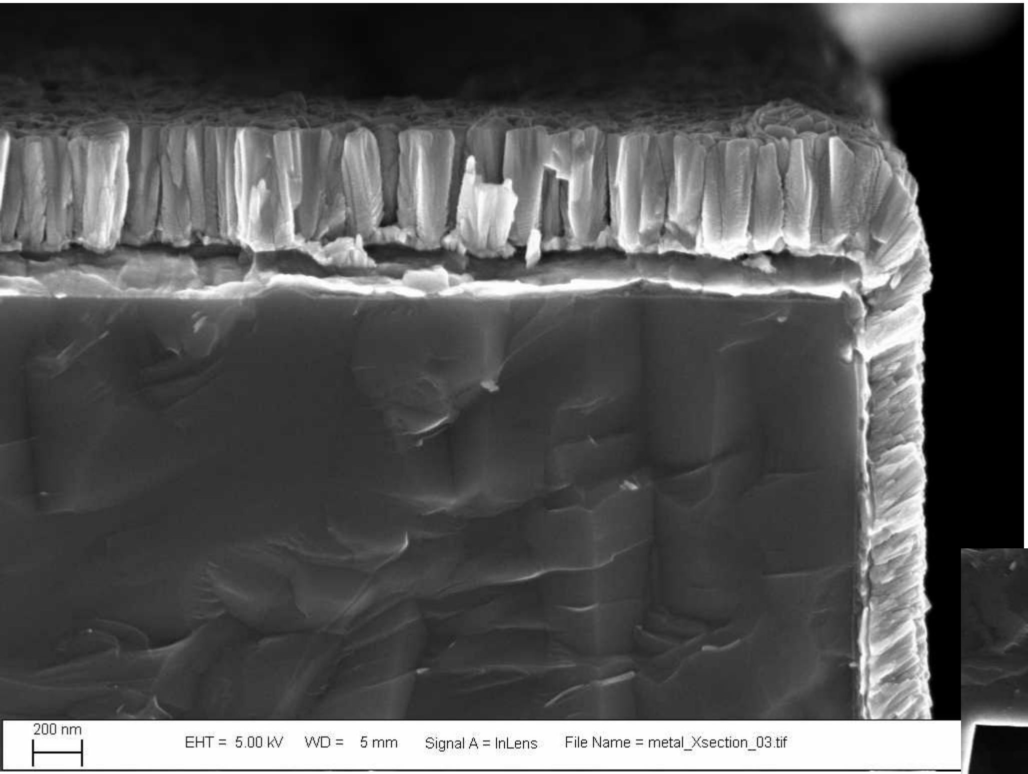


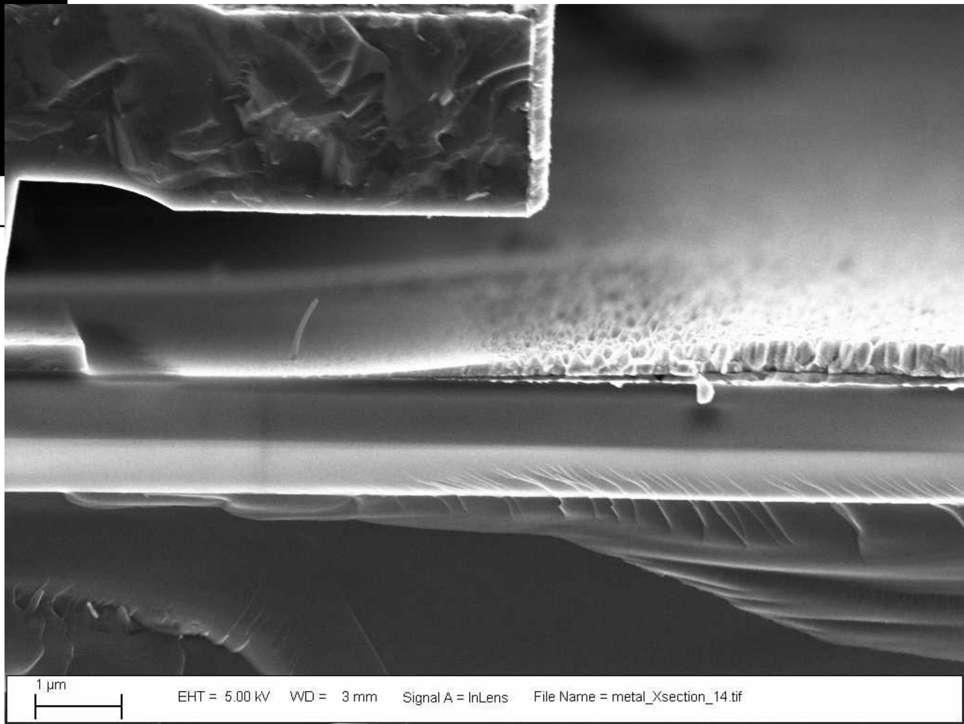




Switch cross-section after processing (Ru O film)

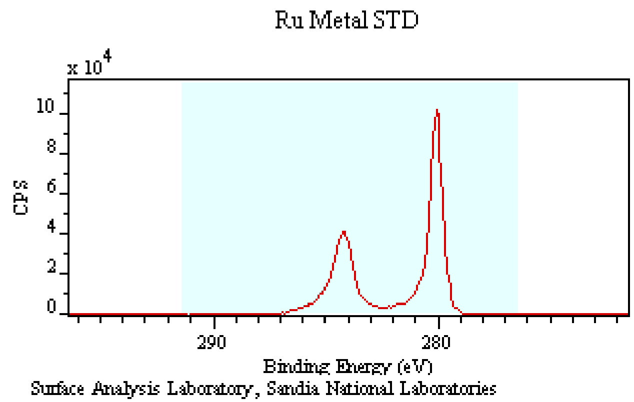




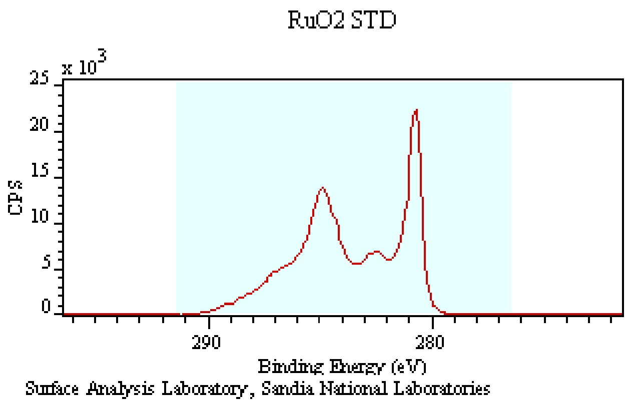


XPS of thermally oxidized Ru films

- Use Ru metal and RuO_2 standard spectra as basis spectra for fit (Ru 3d region).
- This method includes the entire peak structure found in each spectral shape.



Ru Metal Peak Shape Basis



RuO_2Peak Shape Basis

XPS Oxide Thickness Calculation

The Hill equation, commonly used to calculate thin, homogeneous film thickness.

$$t = \lambda \cos\theta \left(1 + \frac{I_O / s_O}{I_S / s_S} \right)$$

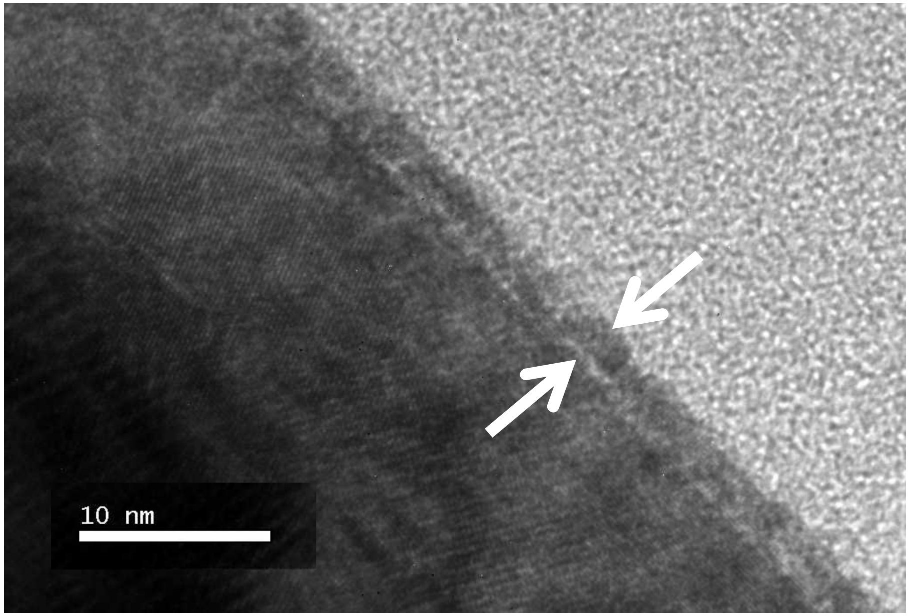
where t = thickness (nm), λ = Effective Attenuation Length, θ = Angle of analysis from surface normal, I = intensity, s = sensitivity, subscripts = oxide or substrate

For XPS analysis of RuO_2 on Ru:
- $\theta = 0$
- Sensitivities (s_O and s_S) are equal (both from Ru 3d transition)
- λ=1.4 nm (from database)

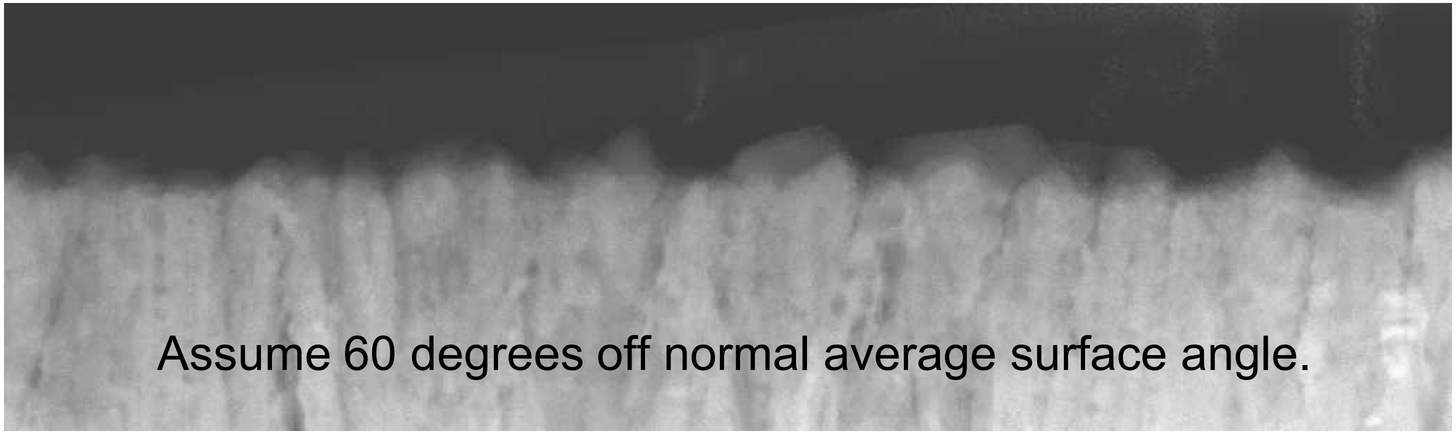
Assumptions in this calculation:
- $\lambda_O = \lambda_s$=1.4 nm (from EAL metal database)
- I_O/I_s comes from raw peak area ratio in new Ru 3d peak fit results.
- Assume full conversion to RuO_2 for oxide in fit
- No significant carbon overlayer
- Homogeneous oxide overlayer

New assumption (per email 5.8.07):
- Sample is faceted (average of 60º from sample normal) – use 0.5x multiplier

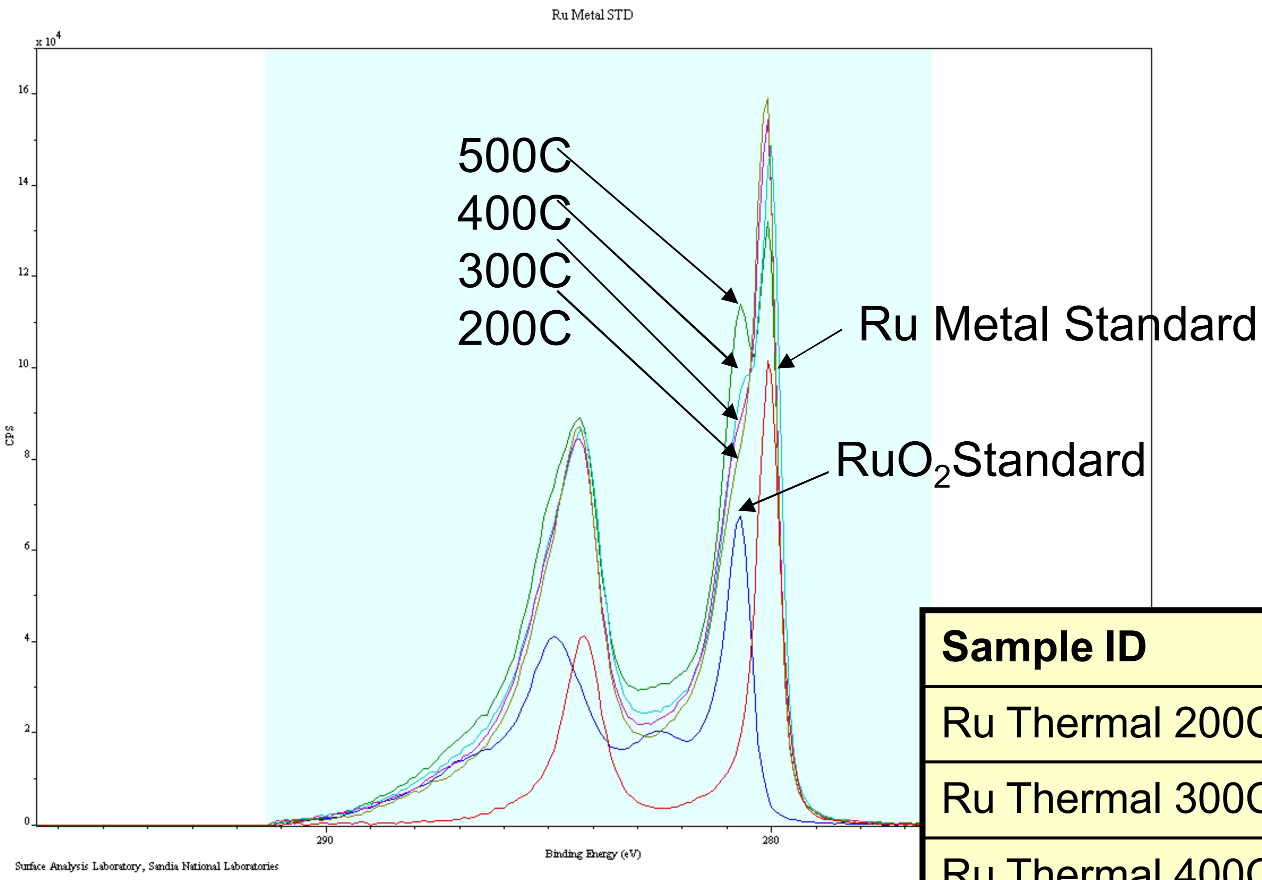
TEM photos of 2 hr sample (420C)



TEM shows an ~3 nm oxide on this surface, which is consistent with XPS results.

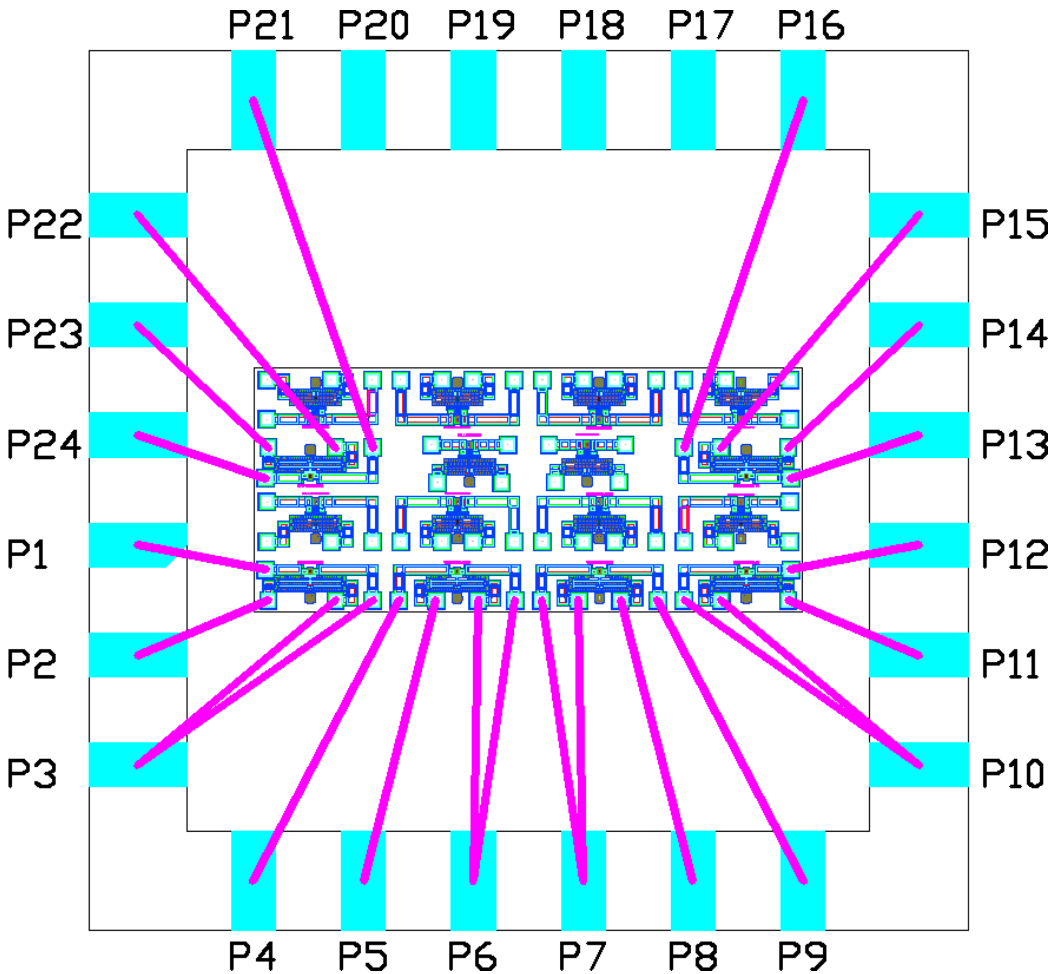


Overlay of all Spectra (Ru 3d)



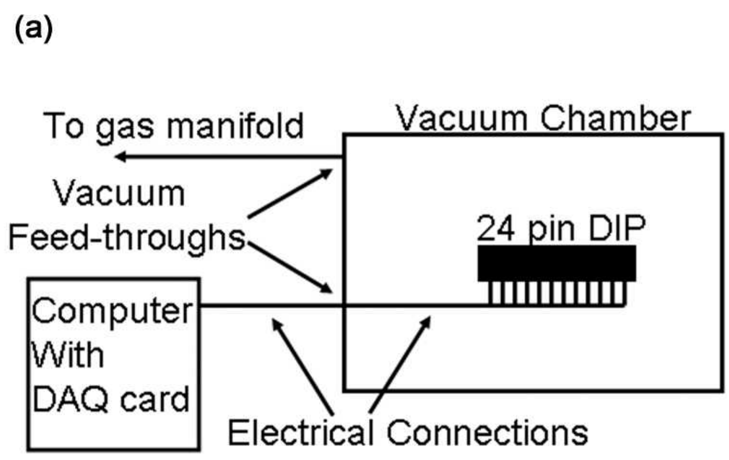
Sample ID	Oxide Thickness
Ru Thermal 200C	0.14 nm
Ru Thermal 300C	0.16 nm
Ru Thermal 400C	0.19 nm
Ru Thermal 500C	0.25 nm

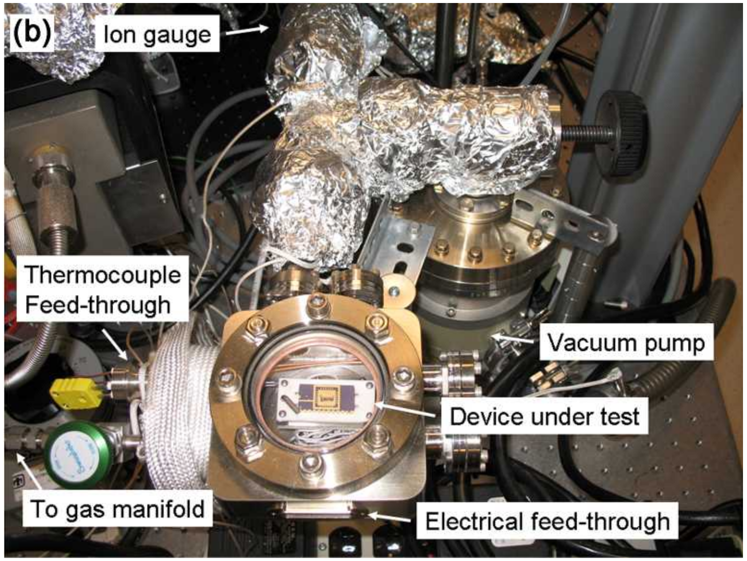
Packaging process



- **24 pin ceramic dip, package 6 devices at a time**
- **Pb/Sn solder to minimize outgassing**
- **Al bond wires**
- **No lid**

Test Apparatus





Sample prep:

Insert parts into ceramic dip
UHV bakeout at 200 C,
$<1 \cdot 10^{-9}$ Torr base pressure
Refill chamber with UHP gas
Begin test

Test:

6 devices/package
Cold switch
Measure voltage divider between
500 Ω series resistor and switch
Check that switch opens
1st 100 cycles – every cycle
Logarithmic increments thereafter
($20 \cdot 10^6$ cycles/day)

Contact Resistance (R_c) calculations

$R_s = \rho/t$ (Ω /□)

$R = 15$ □'s*R_s+2*R_c (neglecting contact resistance of bond)

For Pt ρ =0.15*10^{-6} Ω *m, for 3K Pt, Rs=(0.15*10^{-6}/0.3*10^{-6})=0.5 Ω / □

expect R=7.5 + 2*Rc Ω

For RuO_2 ρ =2*10^{-6} Ω *m, for 5K RuO_2, Rs=(150*10^{-6}/0.5*10^{-6})=4 Ω / □
expect R=60 + 2*R_c Ω

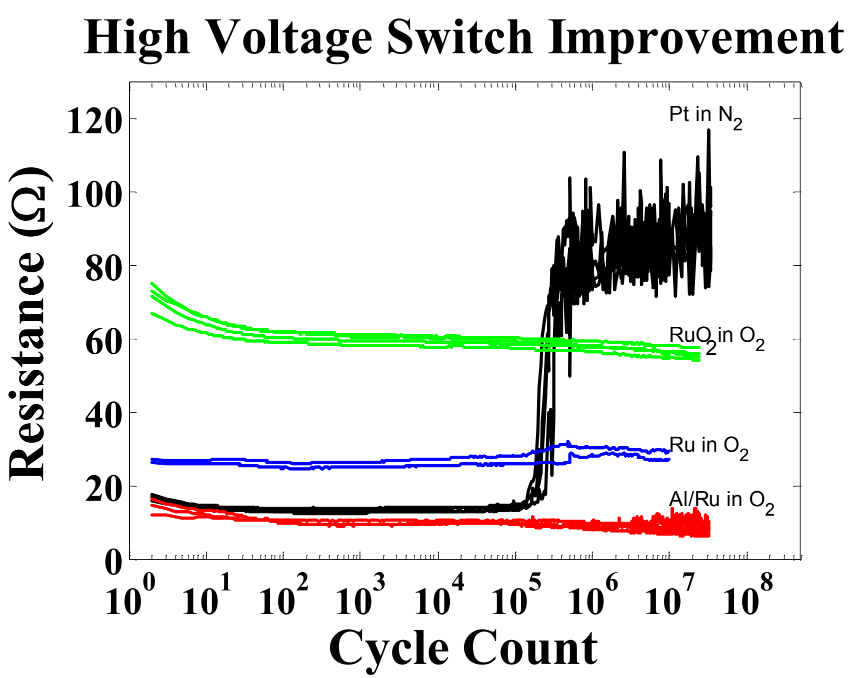
For RuO_2/Al, Rs~0.05 Ω / □
expect R = 0.75 + 2*Rc Ω

For Ru, ρ =0.1*10^{-6} Ω *m, for 2K Ru, Rs=(0.1*10^{-6}/0.2*10^{-6})=0.5 Ω / □
expect R=7.5 + 2*Rc Ω

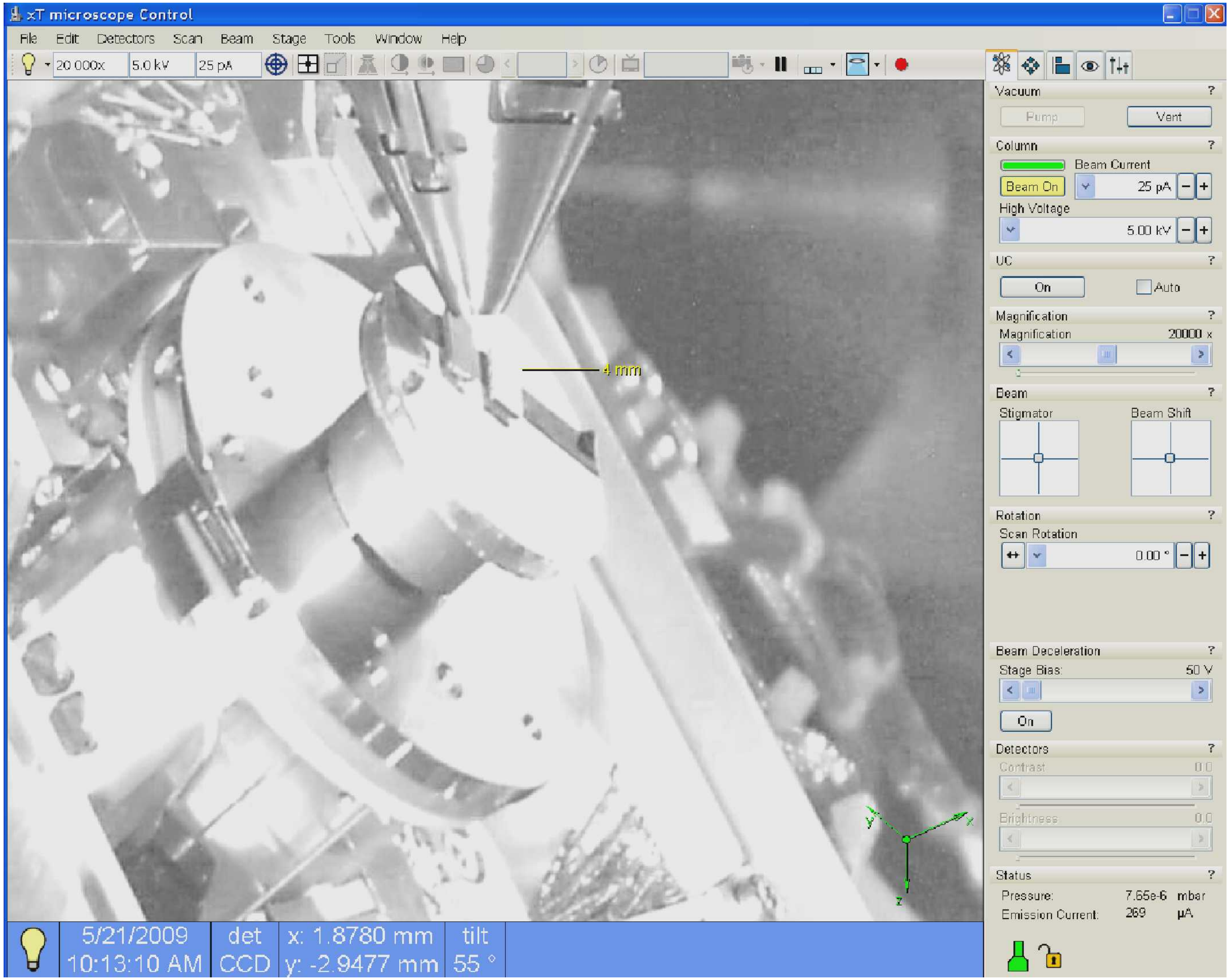
Test Summary

R=15 □'s*Rs+2*Rc

Film stack	R_{series} (Ω)	R_c (Ω) (inferred) (1st cycle)
Pt	7.5	3
Ru	7.5	7.5
RuO_2	60	5
Ru/Al	0.75	7.5

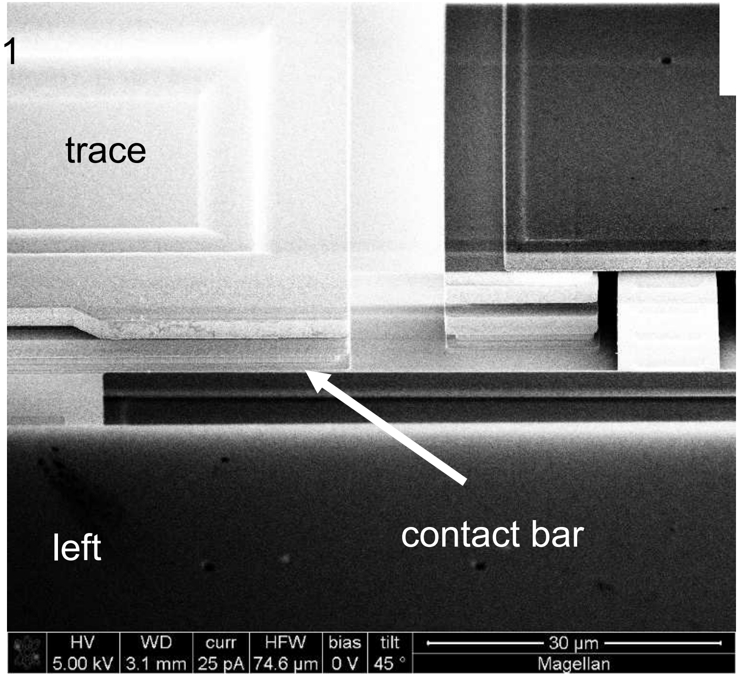


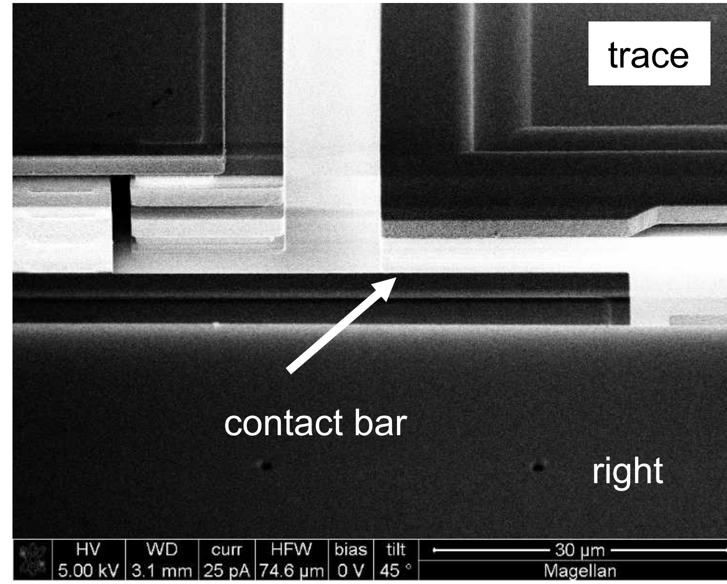
SEM results – tilted views (45)

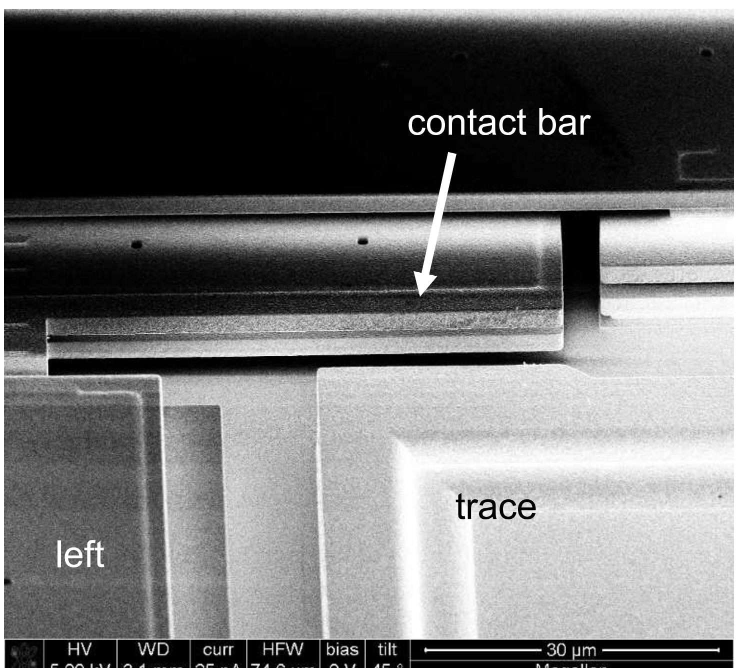


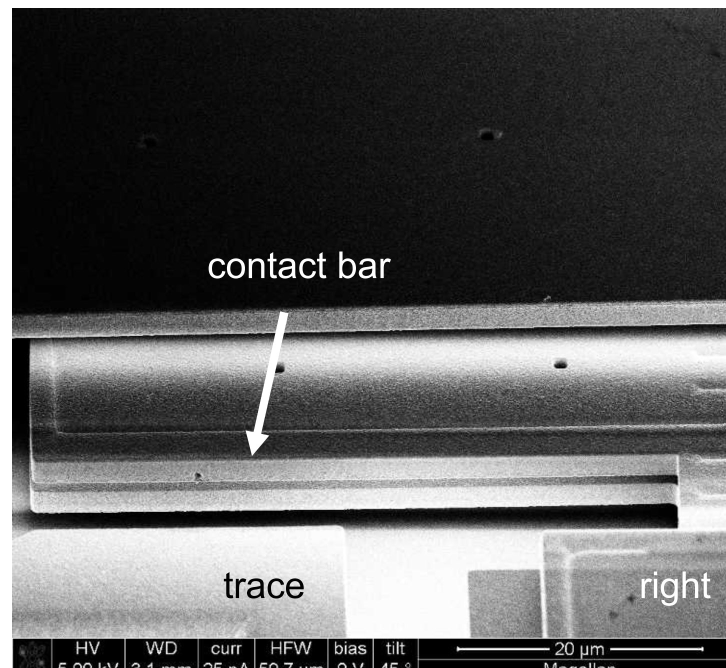
Pt_chp_01

SEM results – Pt switches



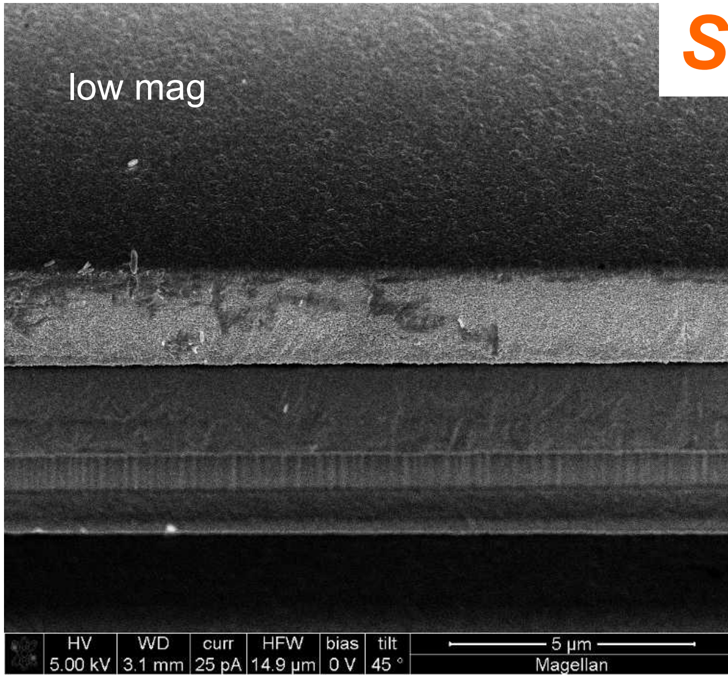


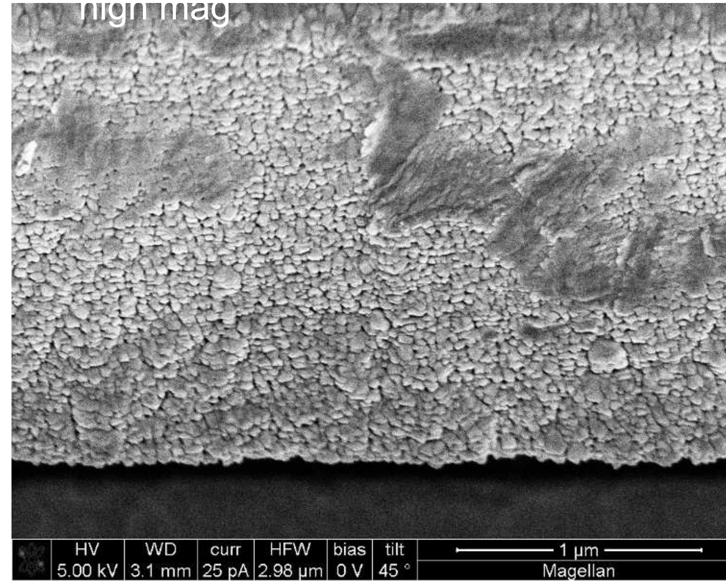




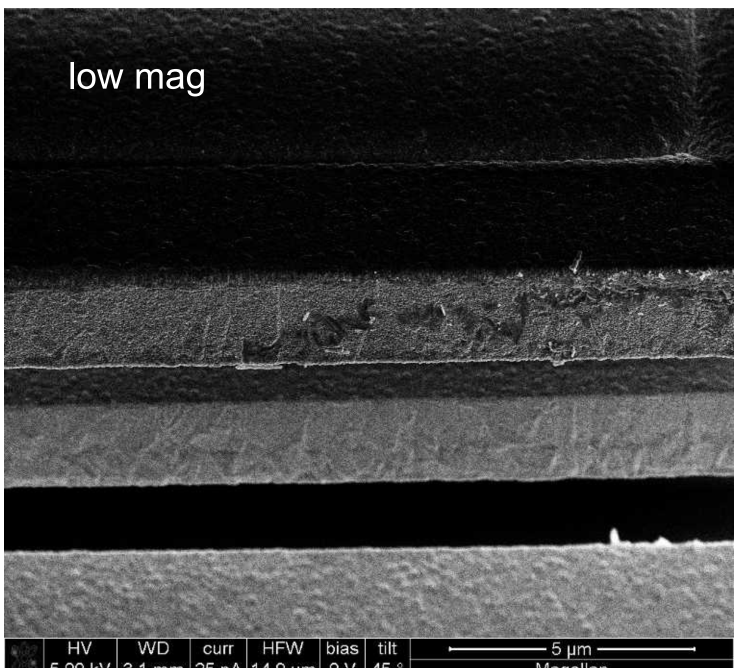
SEM results – Pt switches

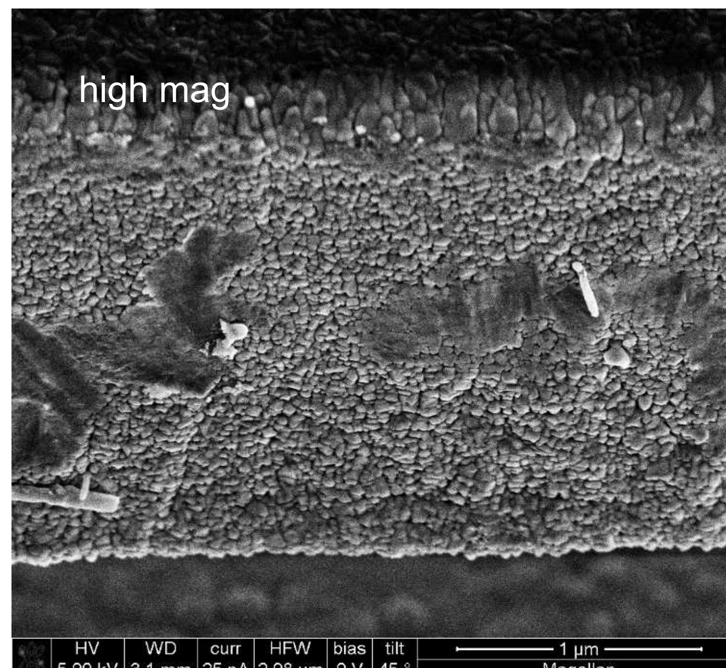
left side
facing trace





facing
contact bar

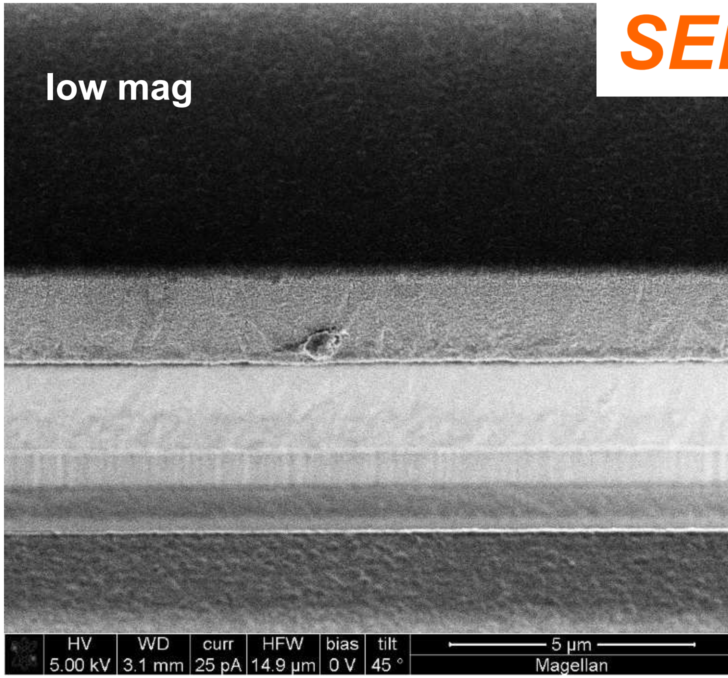


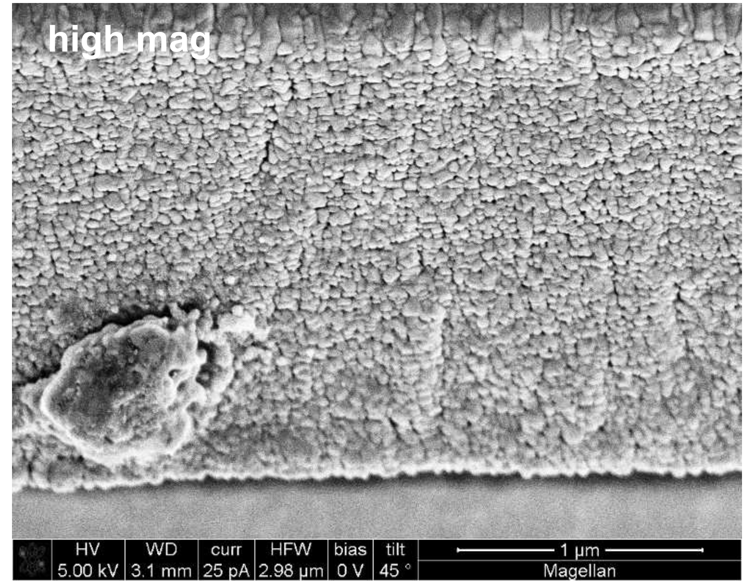


Pt_chp_01

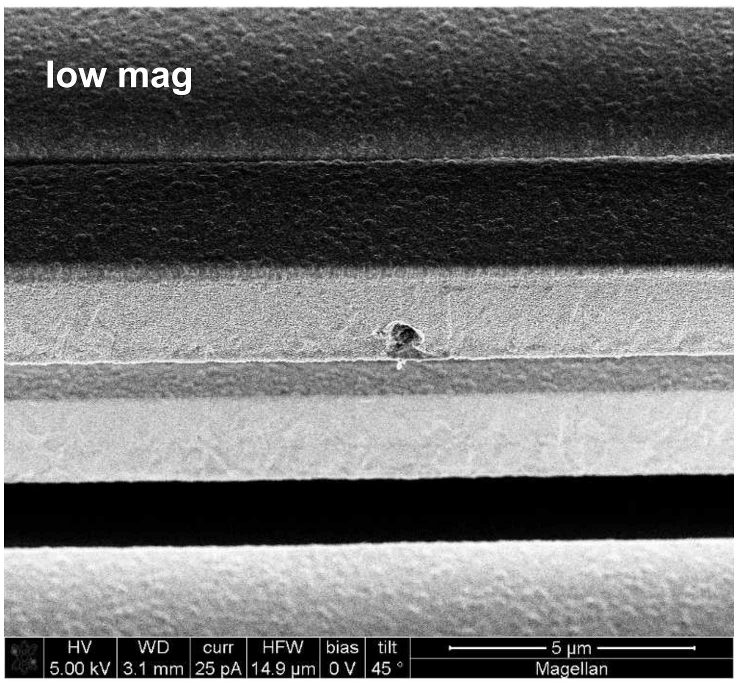
SEM results – Pt switches

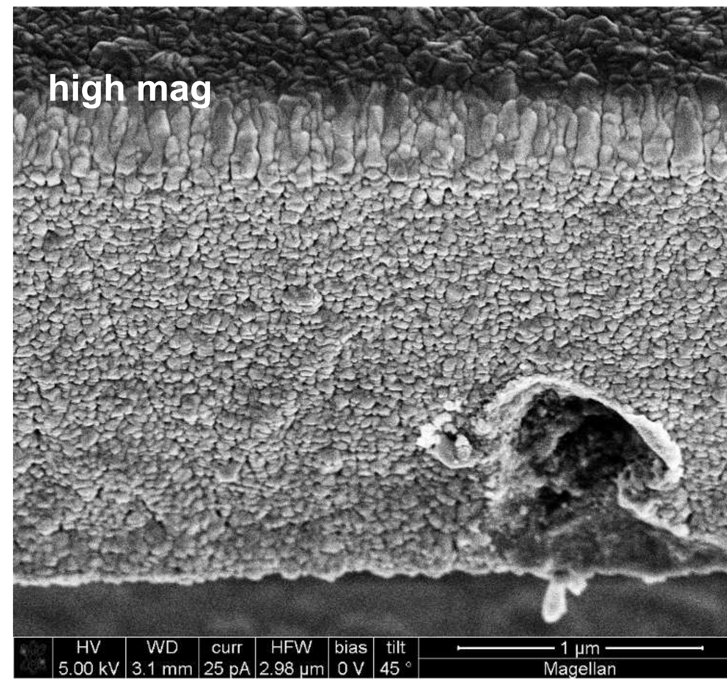
right side
facing trace





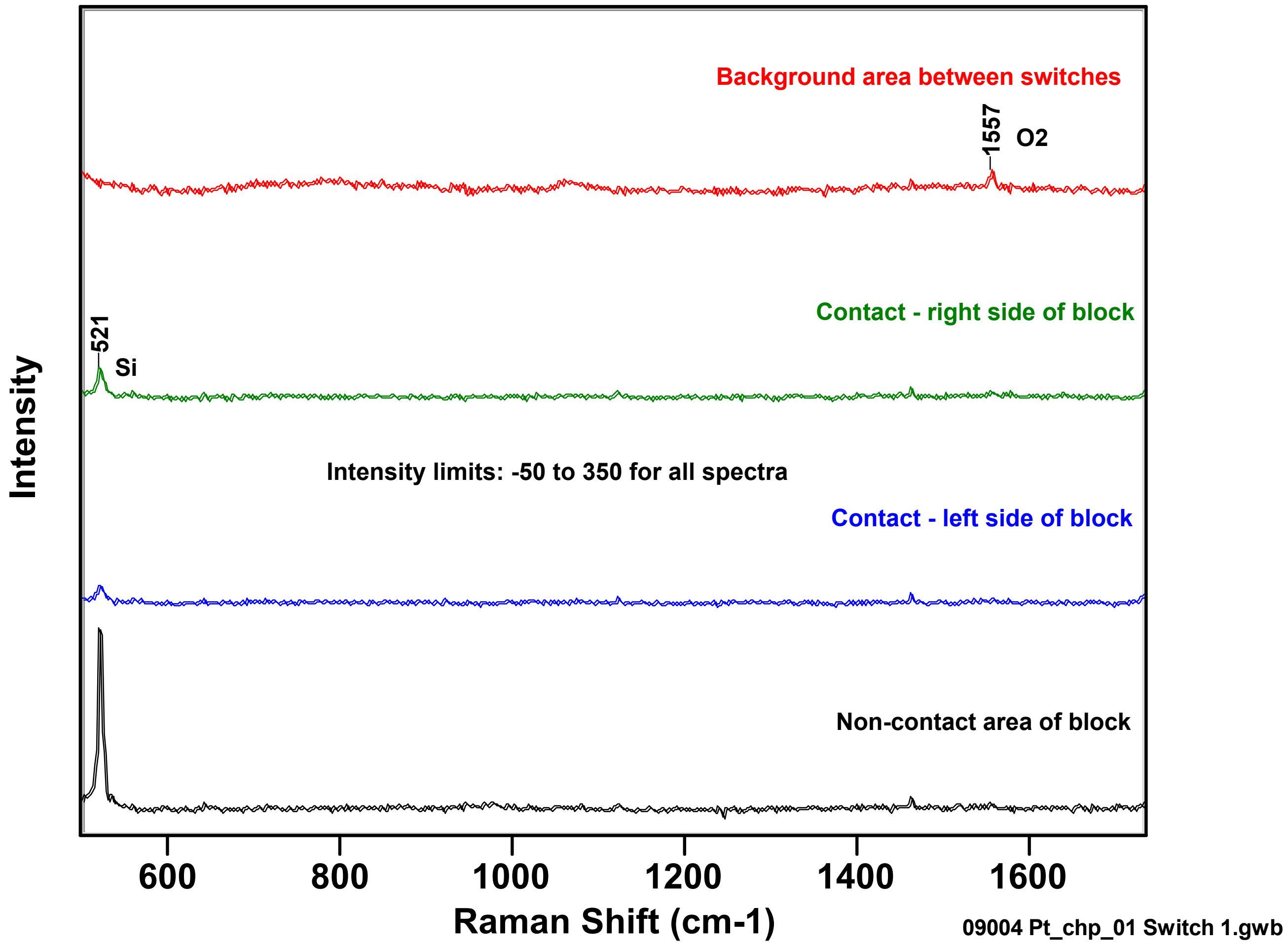
facing
contact bar





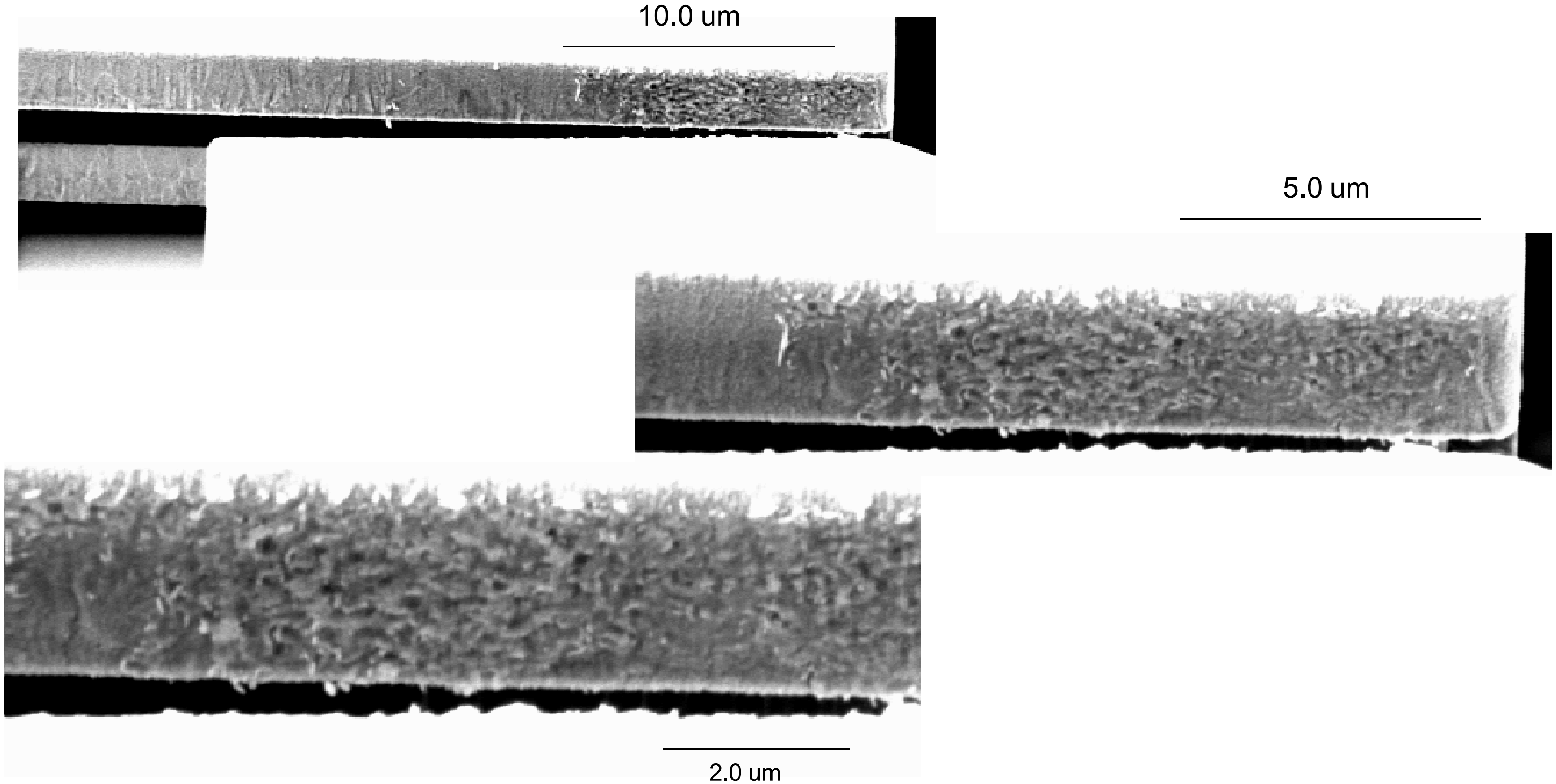
Pt_chp_01

Raman results – Pt switches



no detectable C, some silicon…

Auger results – Pt switches



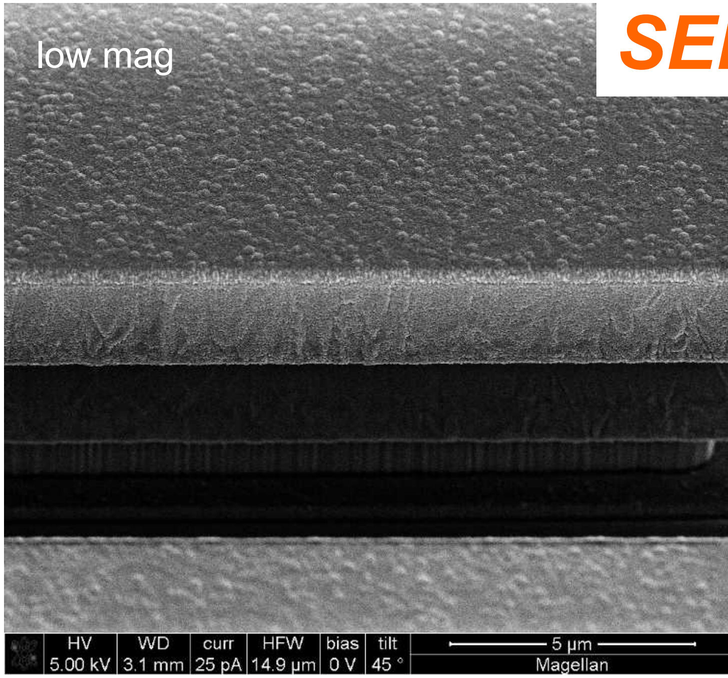
Pt_chp_01 Switch #2

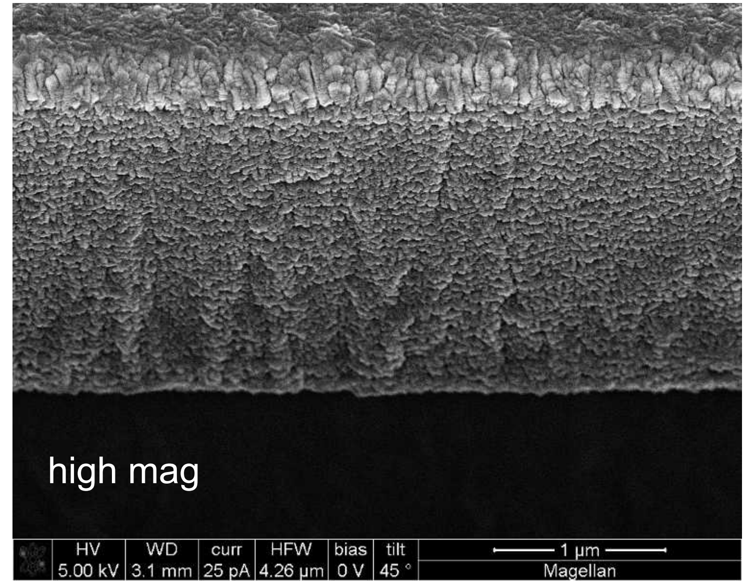
Concentration At. %

	real contact area		nominal contact		non-contact
Area / file	1-14	2-16	3-17	4-15	5-18
C	34	28	46	28	38
Pt	47	59	43	57	53
O	9	5	2	5	4
N	6	8	5	6	6
Si	4	0	4	4	0

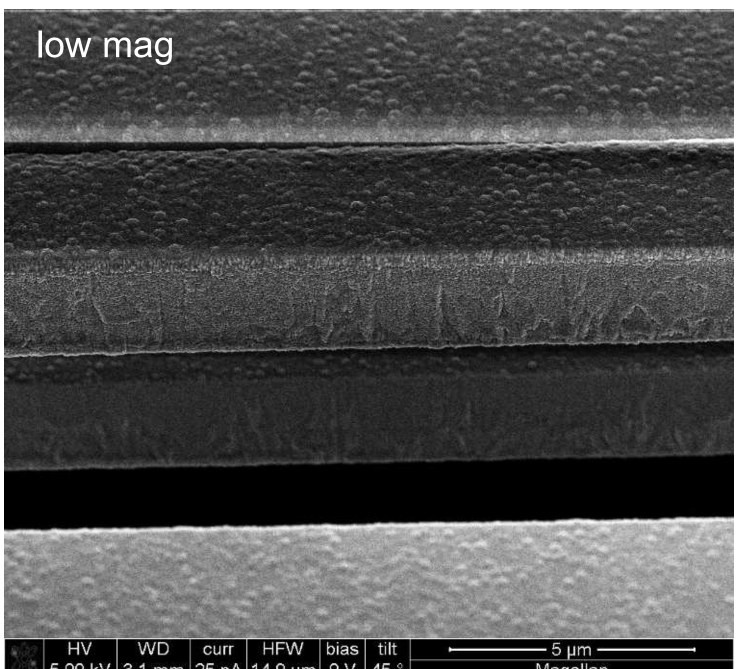
SEM results – Ru switches

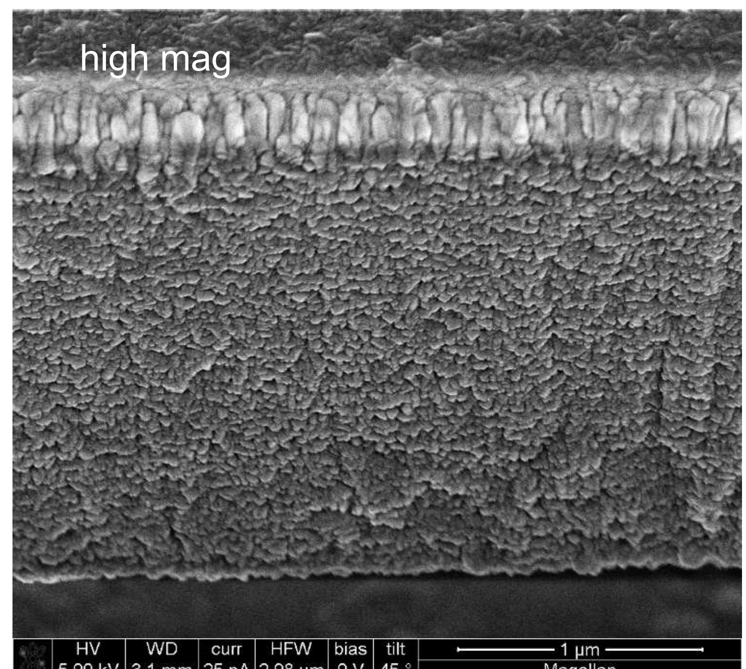
left side
facing trace





facing
contact bar





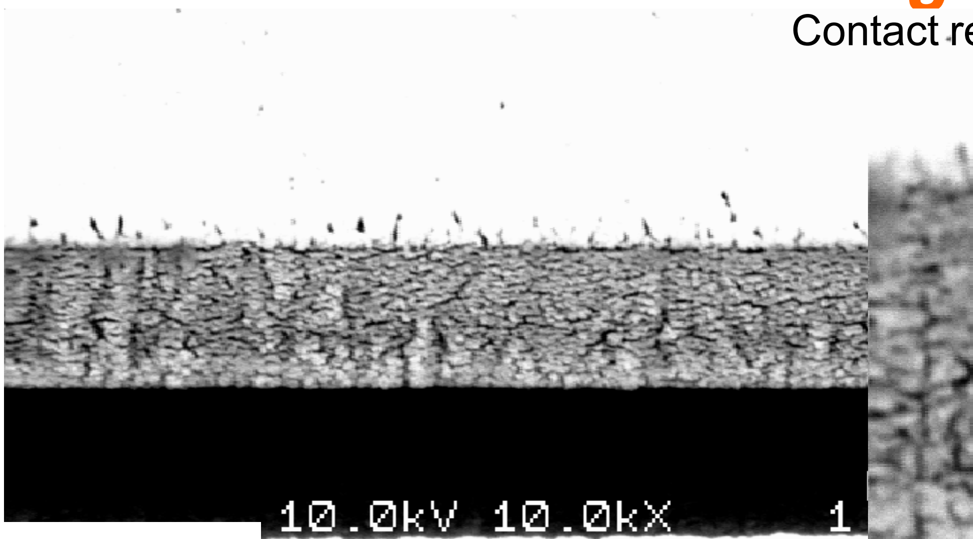
1RuO_1
switch 1

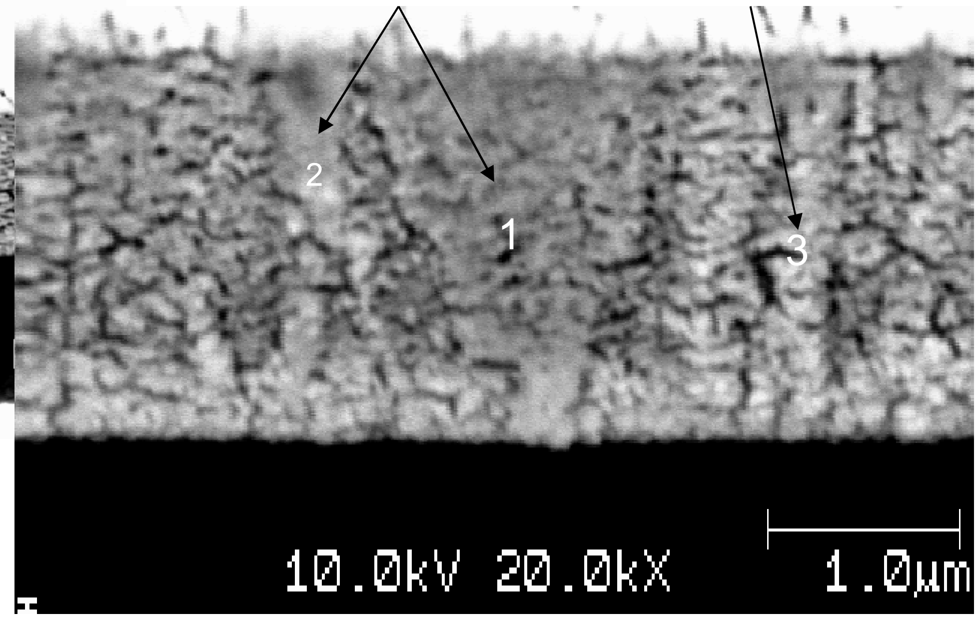
Auger results – Ru switches

2RuO_2 switch 4

Contact region

top surface (5)





Ru277/Ru235	
Theoretical	2.65
1	2.58
2	2.49
3	2.59
4	2.80
5	2.70

Concentration At. %

	1	2	3	4	5
	real contact ?	real contact?	nominal contact	non contact	top surface
Area / file	1-124+2	2- 125+1	3-126	1-139+3	1-140
Ru	74	78	79	58	66
O	17	22	15	10	5
Si	0	0	0	6	8
N	0	0	0	4	3
C	9	0	6	22	18

Next step – introduce contaminant to find threshold level

Organic Deposits on Precious Metal Contacts

By H. W. HERMANCE and T. F. EGAN

(Manuscript received December 12, 1957)

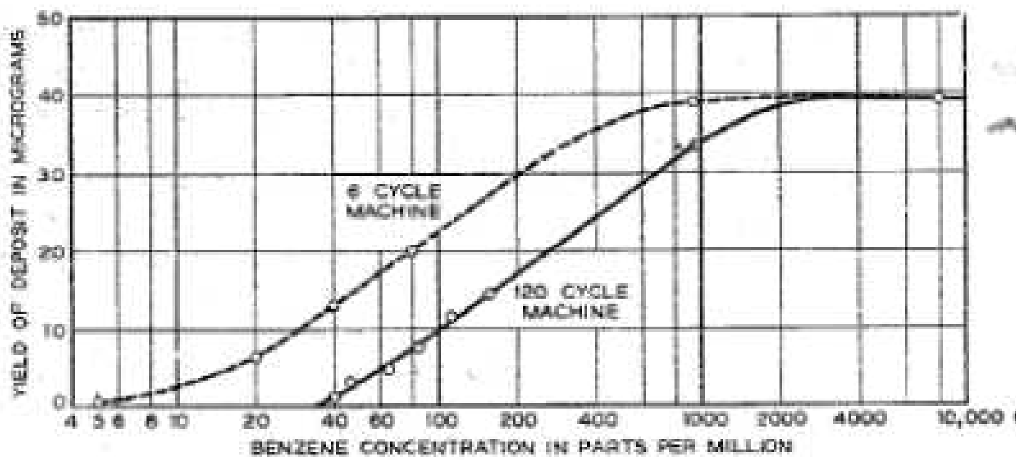
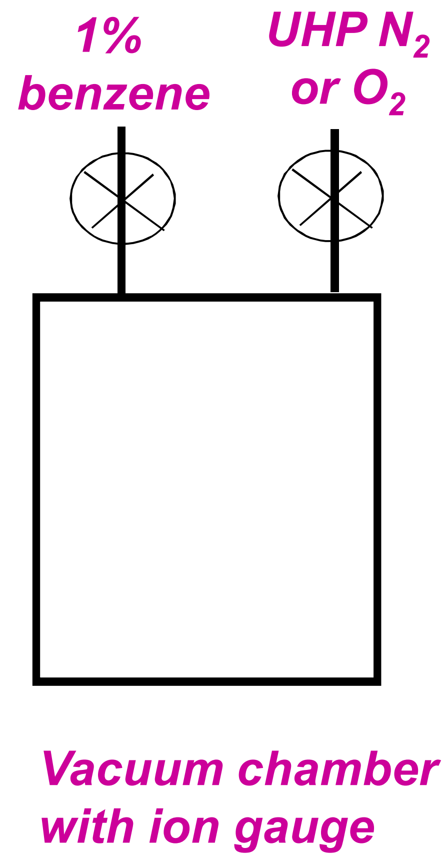


Fig. 12 — Yield of benzene deposit as a function of vapor concentration and wipe frequency.



Summary

- **Resistance of Pt switches increases with cycling**
- **Material transfer resulting in *reduced* contact area appears to be the reason (not C contamination!)**
- **Demonstrated stable, low resistance Ru and RuO_2 contact metallurgies**
- **Corresponding SEM indicates very little damage to contact areas (harder material)**
- **Believe we have a clean process, packaging and test. Now we need to determine threshold levels for C contamination.**