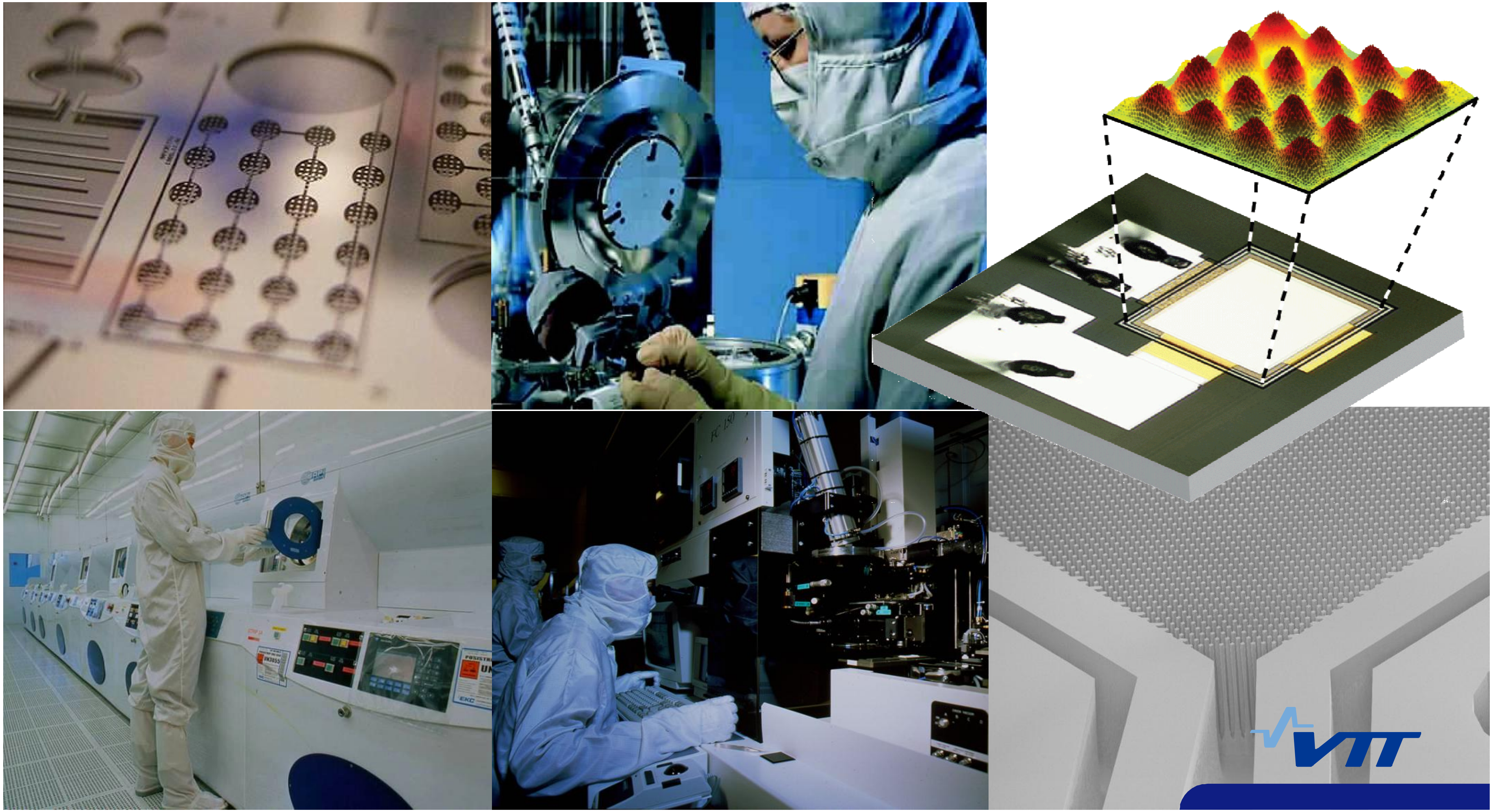
Business from technology

Brief Overview of Microsystems and Nanoelectronics

Seminar Presentation at UC Berkeley
Kai-Erik Elers
VTT Technical Research Centre of Finland

Application Driven Research for Innovation



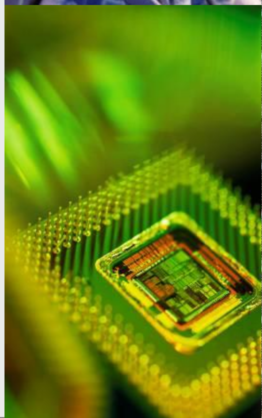
VTT in brief 2010

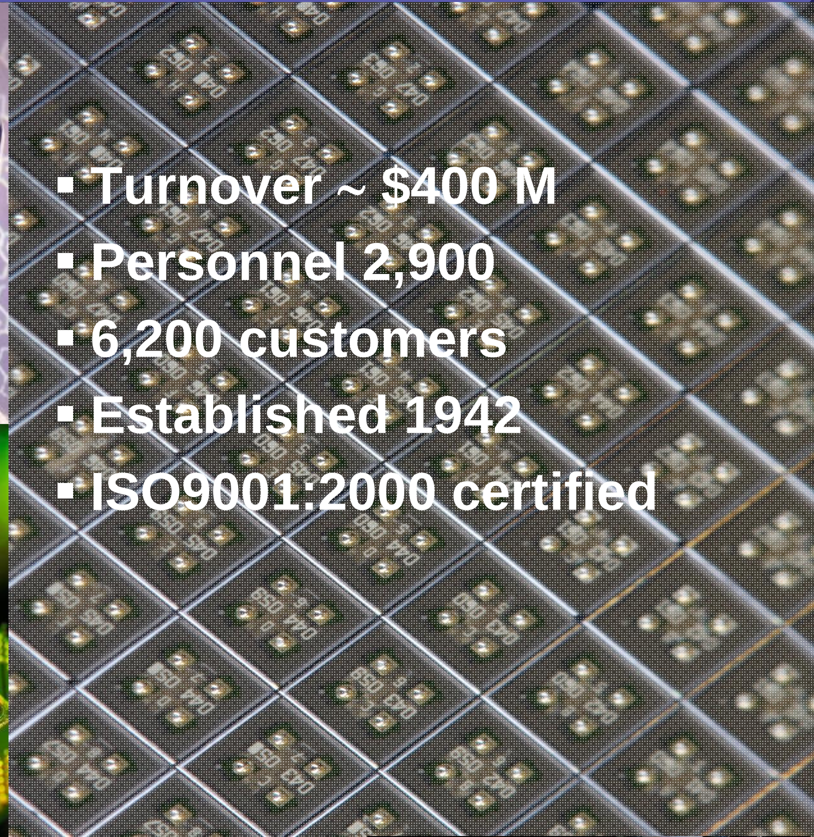
Multidiciplinary R&D organisation

Global presence

Headquartered in Finland

- 4 main domestic sites
  - Espoo, Tampere, Oulu, Jyväskylä
- Brussels, Belgium
- Silicon Valley, US
- St. Petersburg, Russia
- Shanghai, China
- Seoul, South Korea





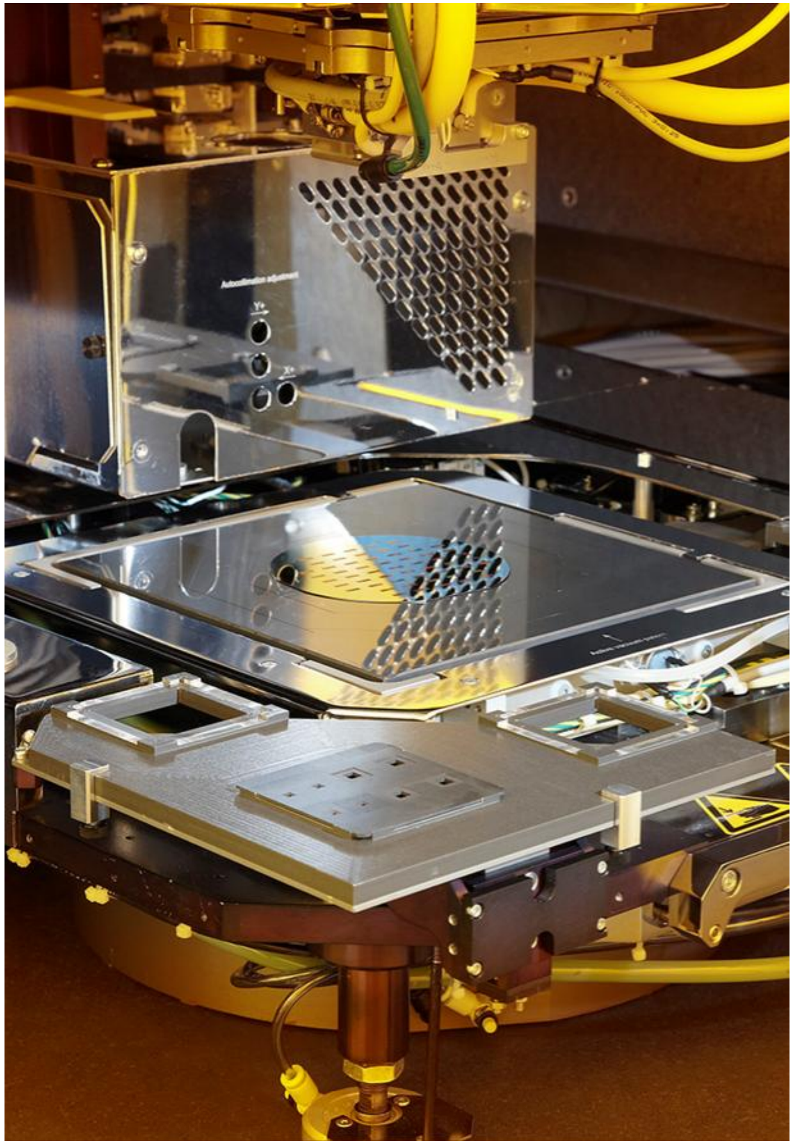
- **Turnover ~ $400 M**
- **Personnel 2,900**
- **6,200 customers**
- **Established 1942**
- **ISO9001:2000 certified**

VTT’s MICRONOVA

Ultraclean Wafer Foundry for Micro and Nanofabricaton

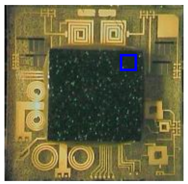
Clean room space: 28,000 ft^2

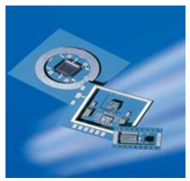
VTT's strategy in silicon technology

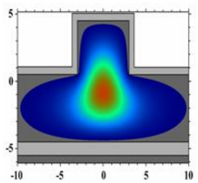


Functional integration on CMOS silicon platform:

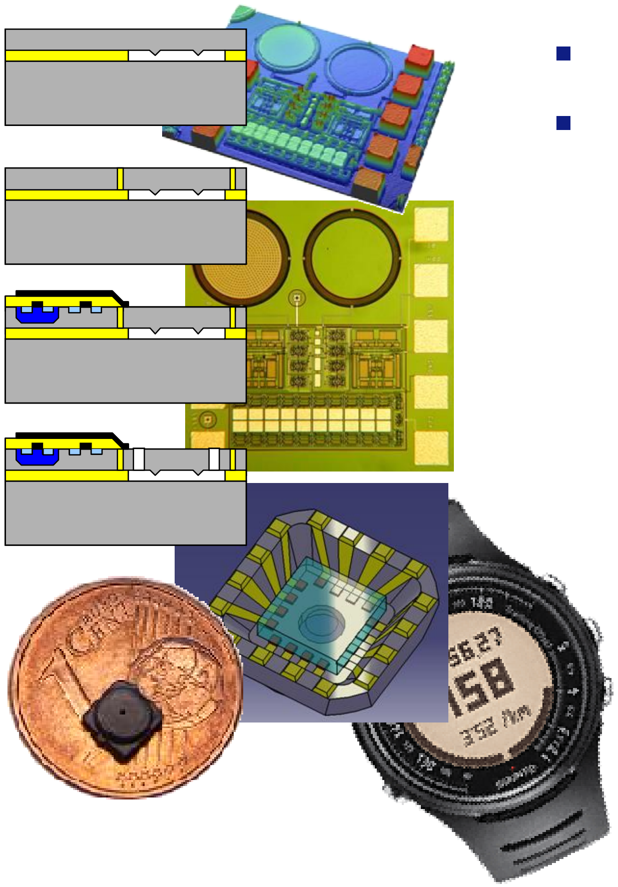
- Integration of MEMS (or NEMS) components for actuators, sensors, gyroscopes, accelerometers etc
- Integration of optoelectronics for control and switching of optical signals
- Integration of bioactive functions for biological sensing and interfacing
- Integration of RF functionality using thin film technologies such as FBAR, ferroelectrics, passive components etc







MEMS Sensors and Transducers



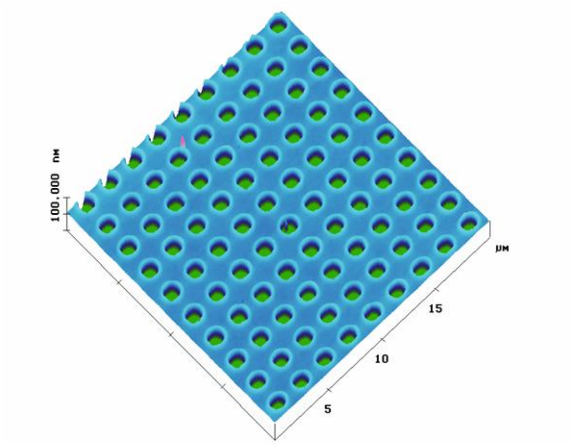
- SOI based technology for CMOS on MEMS
- Surface micromachining
- Thin film MEMS based on amorphous metals
- Applications:
  - Integrated altimeters using CMOS on MEMS technology
  - cMUT ultrasonic transducers
  - Microcompass
  - Microbalance
  - Accelerometers
  - Gyros
  - MEMS microphone

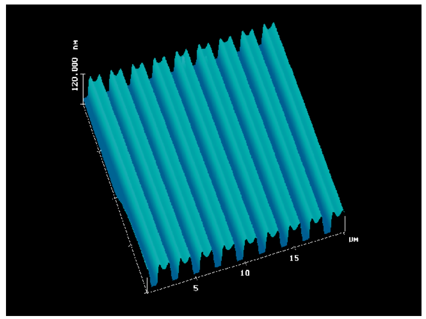
Nanoimprint lithography

NaPa - Emerging Nanopatterning Methods

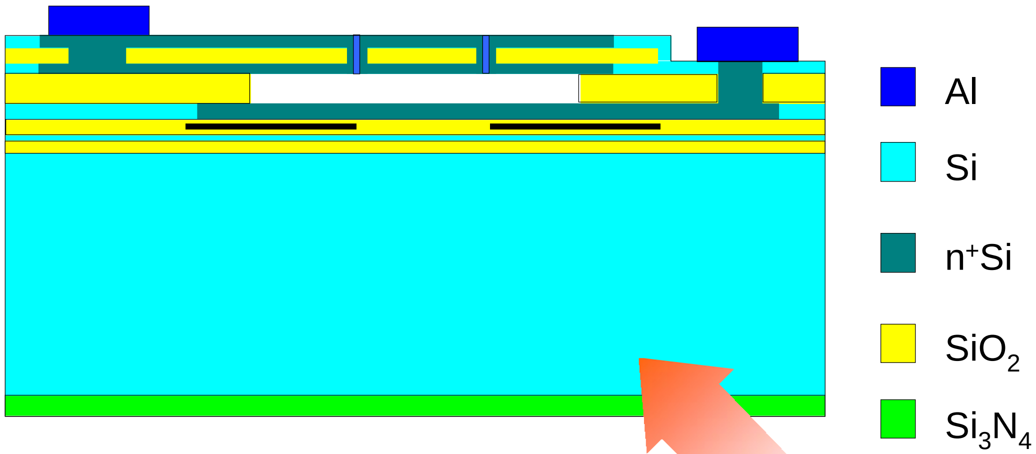
- Integrated project coordinated by VTT for EU 6. framework program
- Nanoimprint lithography development since 1998 in EU funded projects
- Imprints with sub 20 nm accuracy
- Nanopatterning stepper assessment with Süss MicroTec
- Materials development with Microresist Technology

www.phantomsnet.net/NAPA/index.php





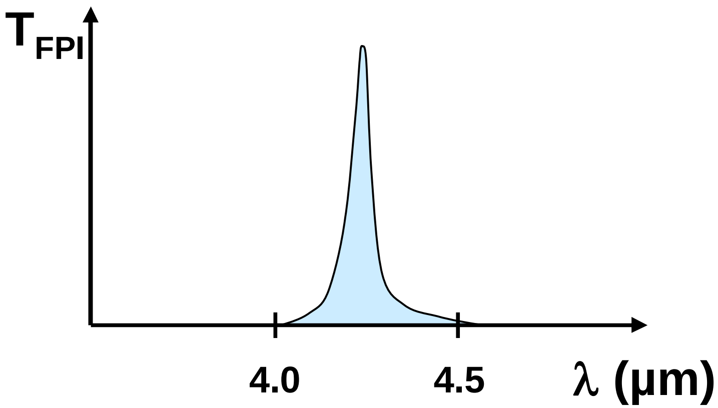
Tunable MEMS Fabry-Perot interferometer for NIR

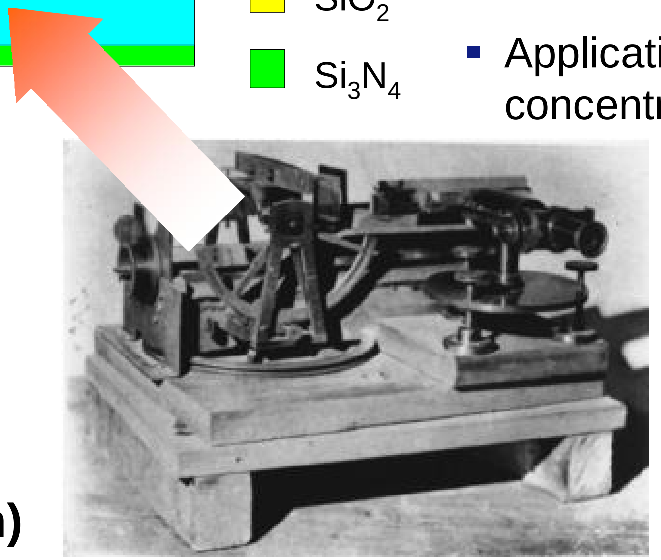


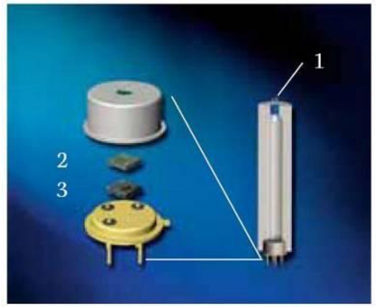
Specifications

Dimensions:	3 x 3 x 0.5 mm^3
3-layer mirror:	Si-SiO_2-Si
Aperture:	0,75 mm (dia)
FWHM:	1,7% wavelength@ 0V
Transmission:	90%

- Applications in monitoring the concentration of CO2 and other gases



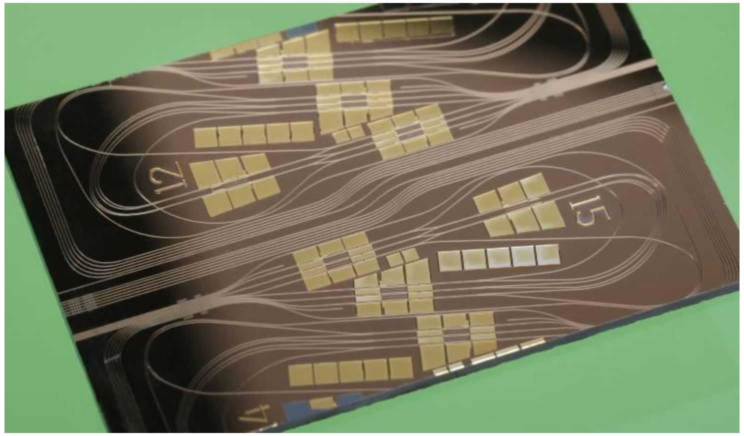


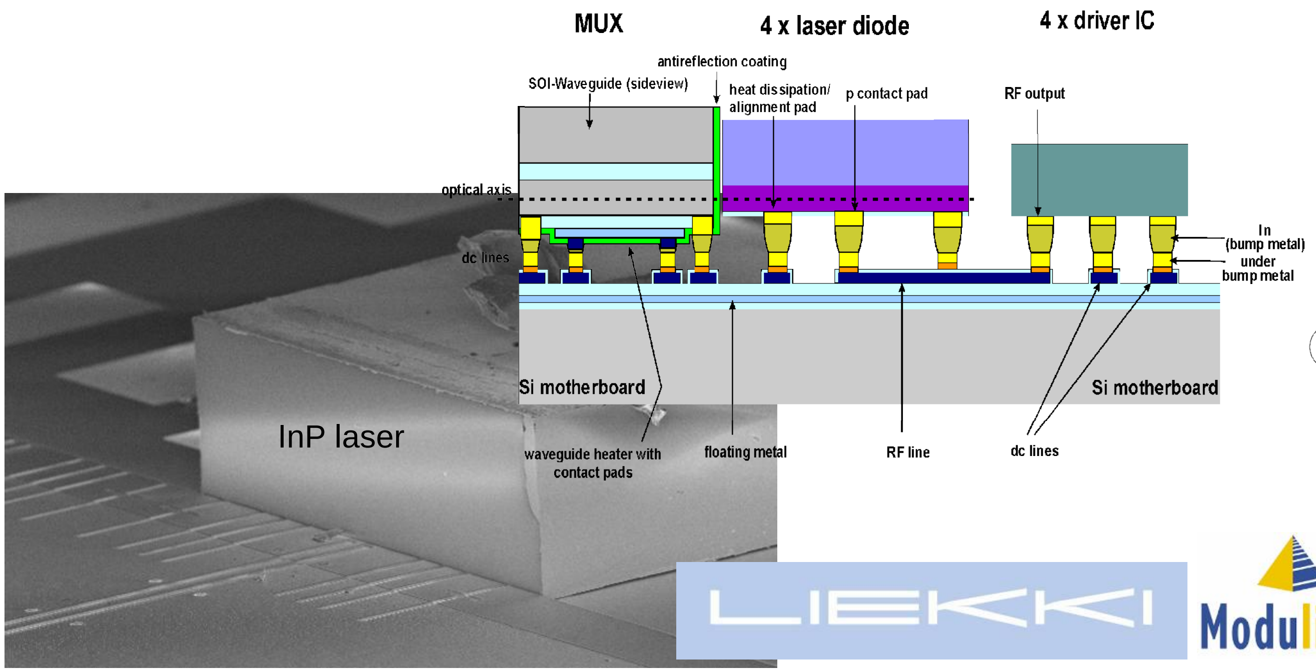


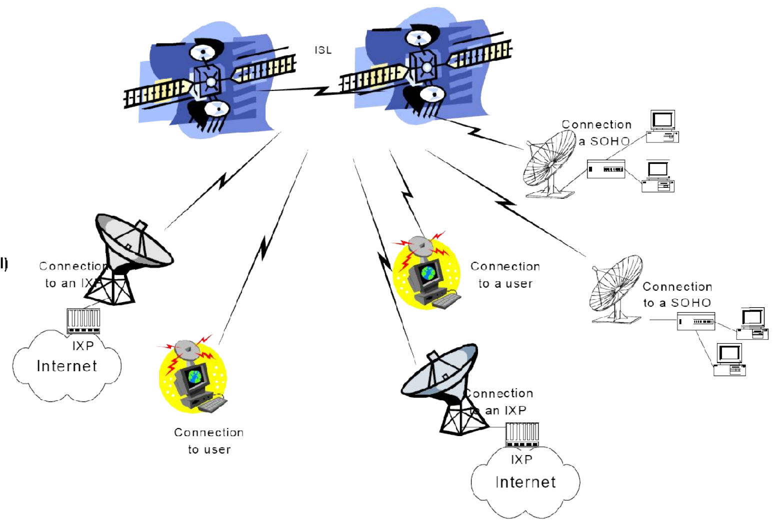
The Vaisala CARBOCAP® Sensor components:
1. Infrared source
2. Tunable FPI filter
3. Infrared detector

Silicon waveguides for photonic circuits

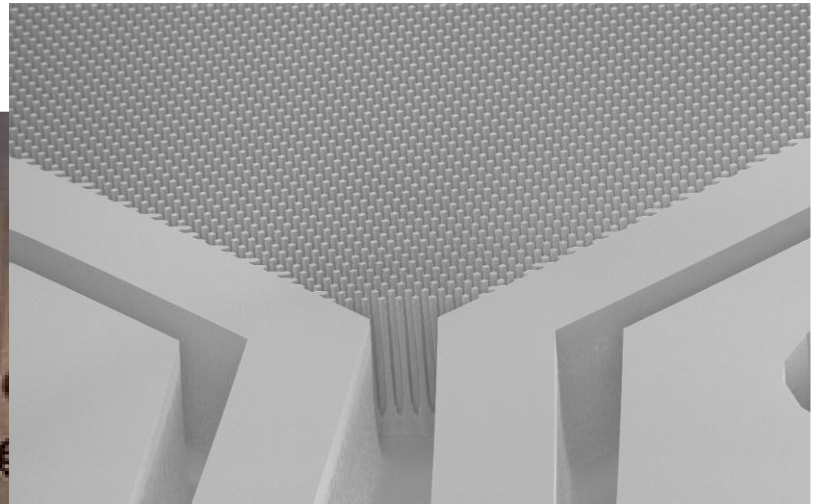
- SOI waveguide components
  - Modulators, switches, filters, adiabatic couplers etc.
  - VTT uses advanced 3D processing methods to realise state-of-the-art components and circuits
  - Lowest losses with 2-10 µm thick SOI (0.1 dB/cm)
  - Smallest footprint with <1 µm thick SOI



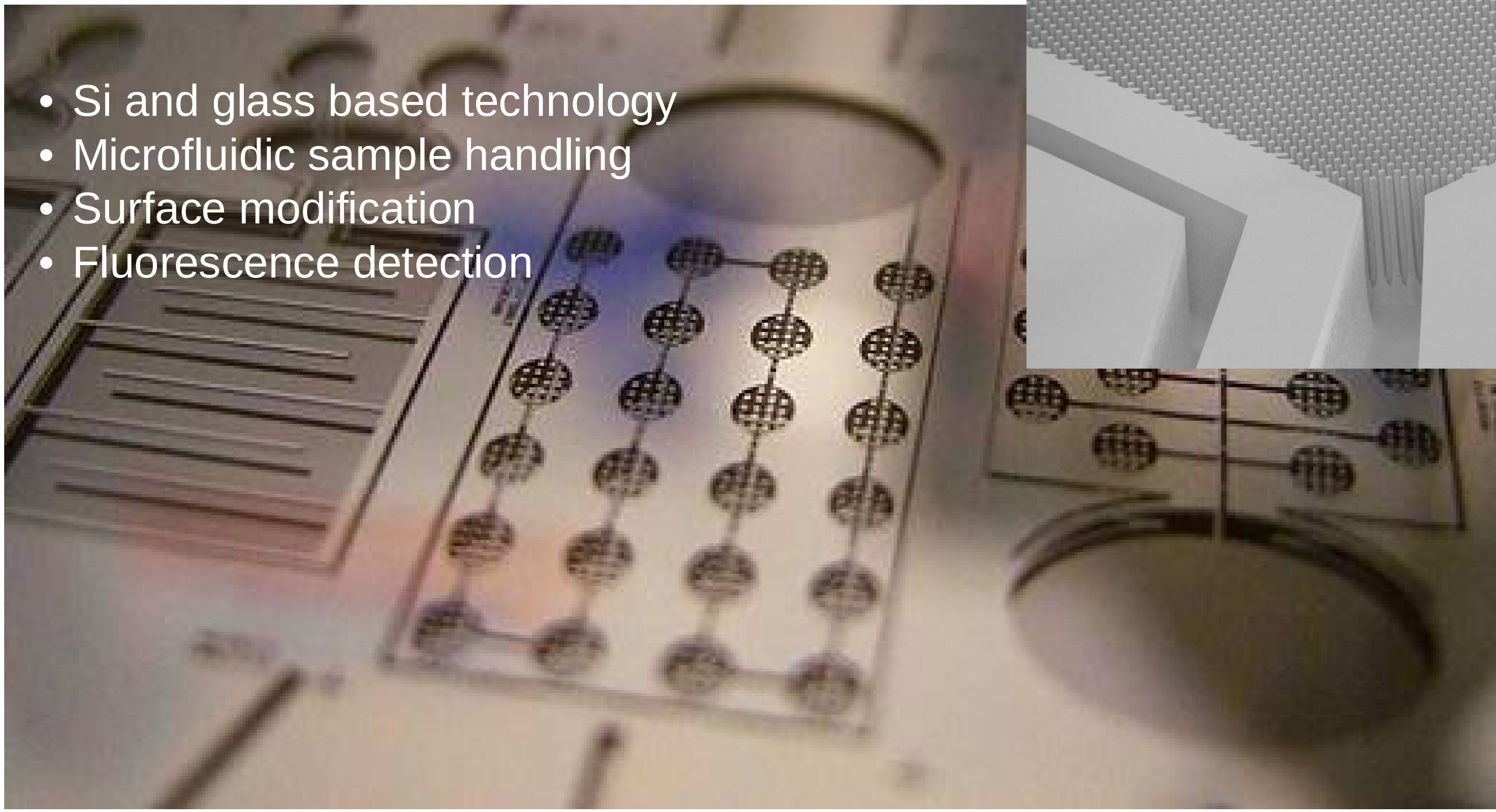




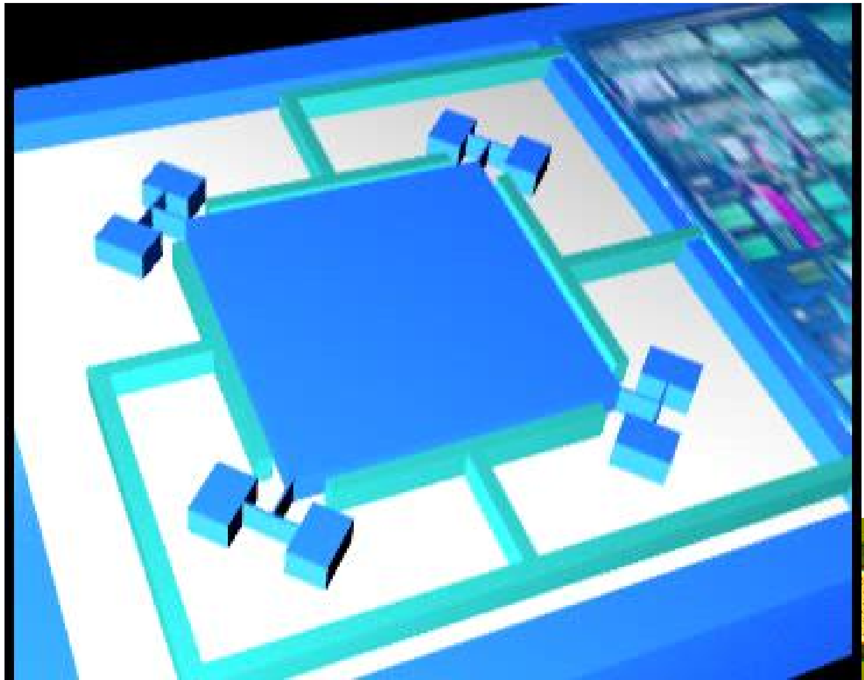
Lab-On-Chip



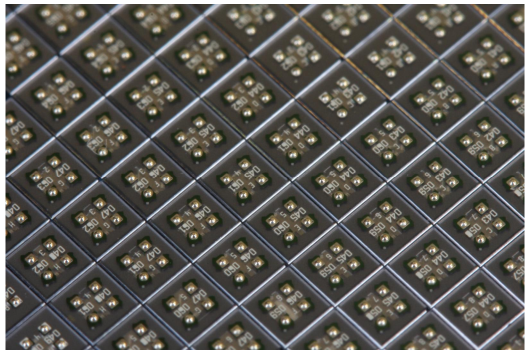
- Si and glass based technology
- Microfluidic sample handling
- Surface modification
- Fluorescence detection

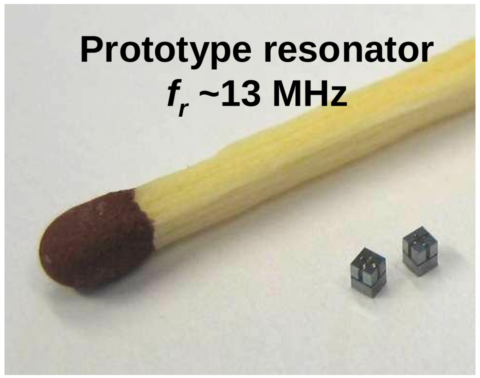


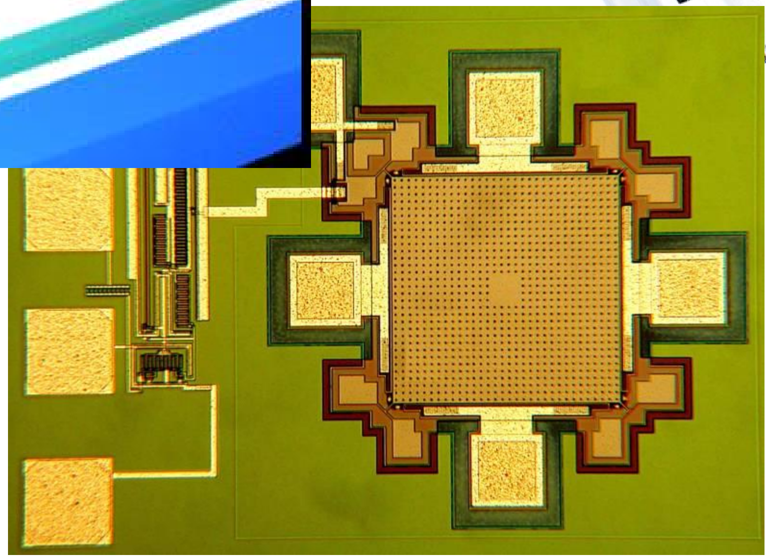
Timing devices – replacing quartz with silicon



WL packaged resonators



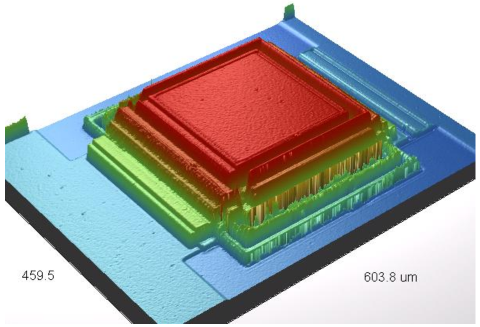


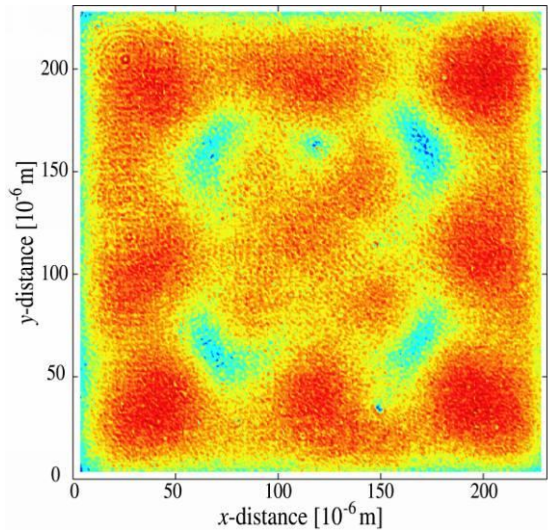


Thin Film Bulk Acoustic Wave Resonators

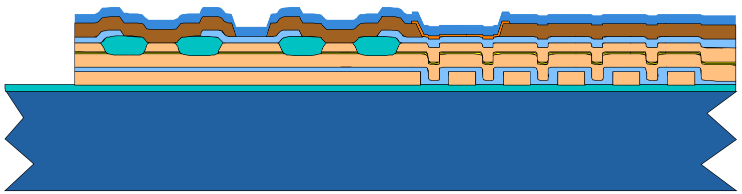
• Extension of the crystal oscillator (eg. Quartz oscillator) principle to the GHz range by thin film technology
• RF filters utilising FBARs have many advantages over SAW and other filter technologies:

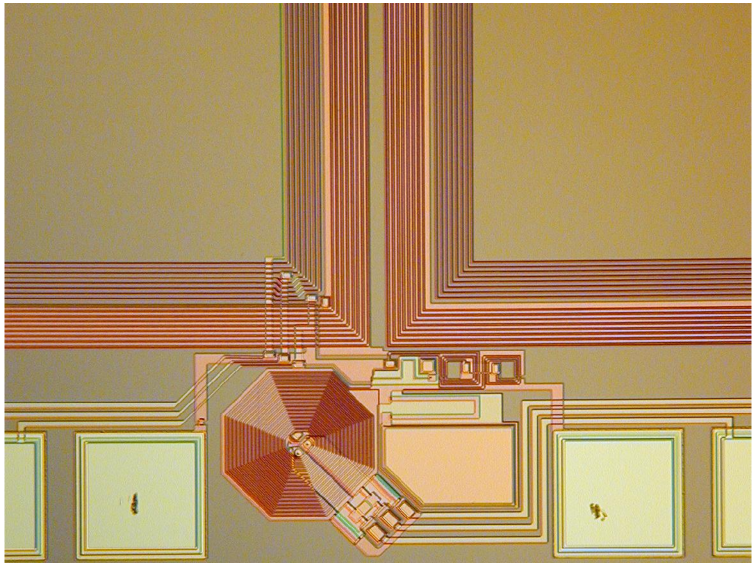
- high Q-values (1000 - 1500 achieved)
- steep passband skirts
- low insertion loss (~1 dB)
- high power handling capability
- applicability to high frequencies 2 … 5 GHz (… 10 - 20 GHz?)
- small size (<< ceramic filter, ~ SAW-filter)
- robust
- low cost manufacturing
- good ESD handling
- ultimately, integration with RF-IC?

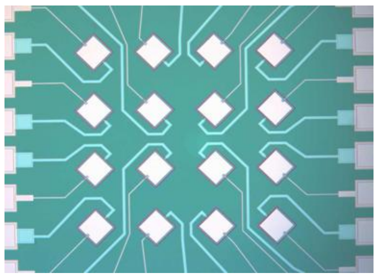


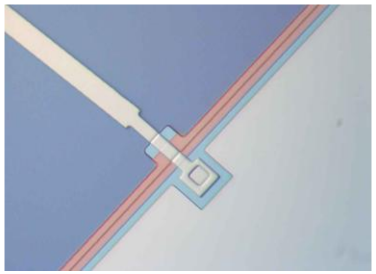


Superconducting Thin Films







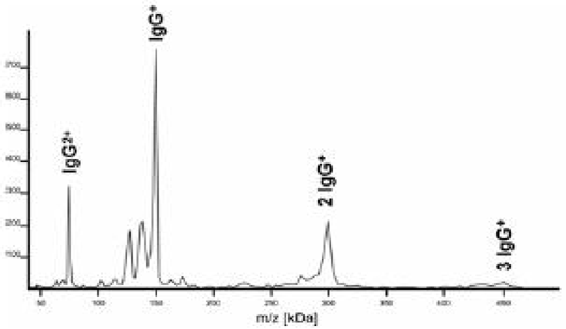


Low temperature superconducting thin films

- Nb on Si
- NbN on Si
- Epitaxial Nb and Ta on sapphire
- Nb/Al/AlOx/Al/Nb Josephson junction technology

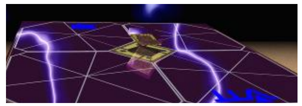
Applications in superconducting devices

- SQUIDs for magnetoencephalography (MEG)
- Josephson voltage standards
- Superconducting tunneling junction (STJ) detectors
- RSFQ circuits
- Superconducting readout for transition edge bolometers



Signal of human IgG, 1:1 mixed with sinapinic acid. The trimer above 450 kDa is clearly visible.

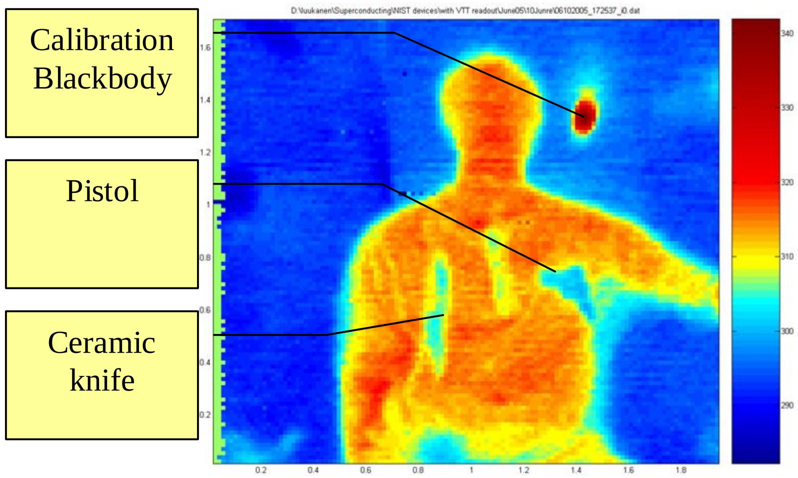
Superconducting sensors for brain research

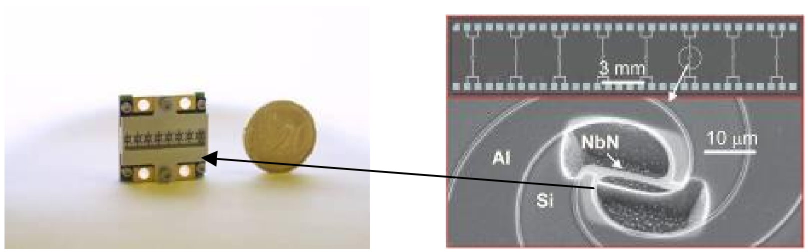


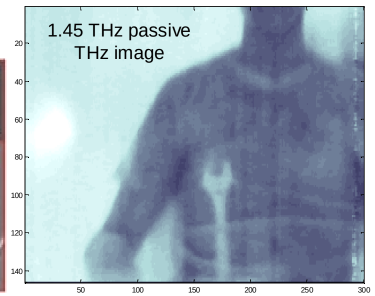
Terahertz imaging sensors

- Integrated, low cost pixels with a room temperature readout (developed by VTT)
- Capability for low-resolution *spectroscopic* imaging
- Best devices show radiometric sensitivity of 0.6 mK/Hz$^{1/2}$ (0.1 - 1 THz)
- In collaboration with NIST, USA
- Operating temperature ~4 K, being transferred to operation within a closed-cycle cryocooler

Passive *indoors* THz image (0.1-1 THz)

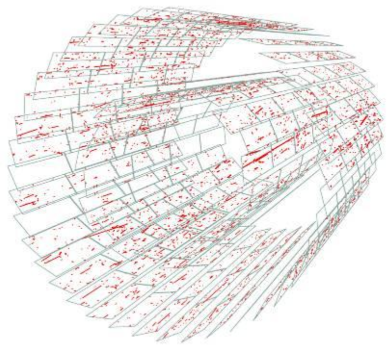




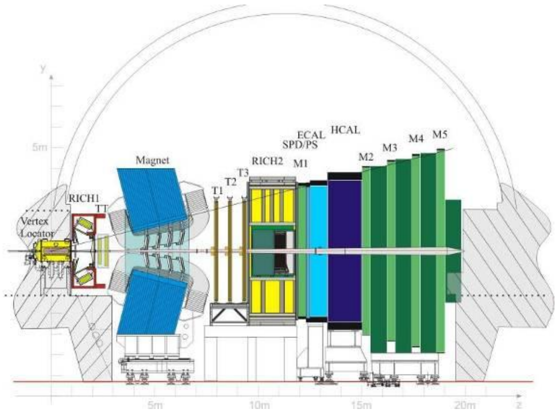


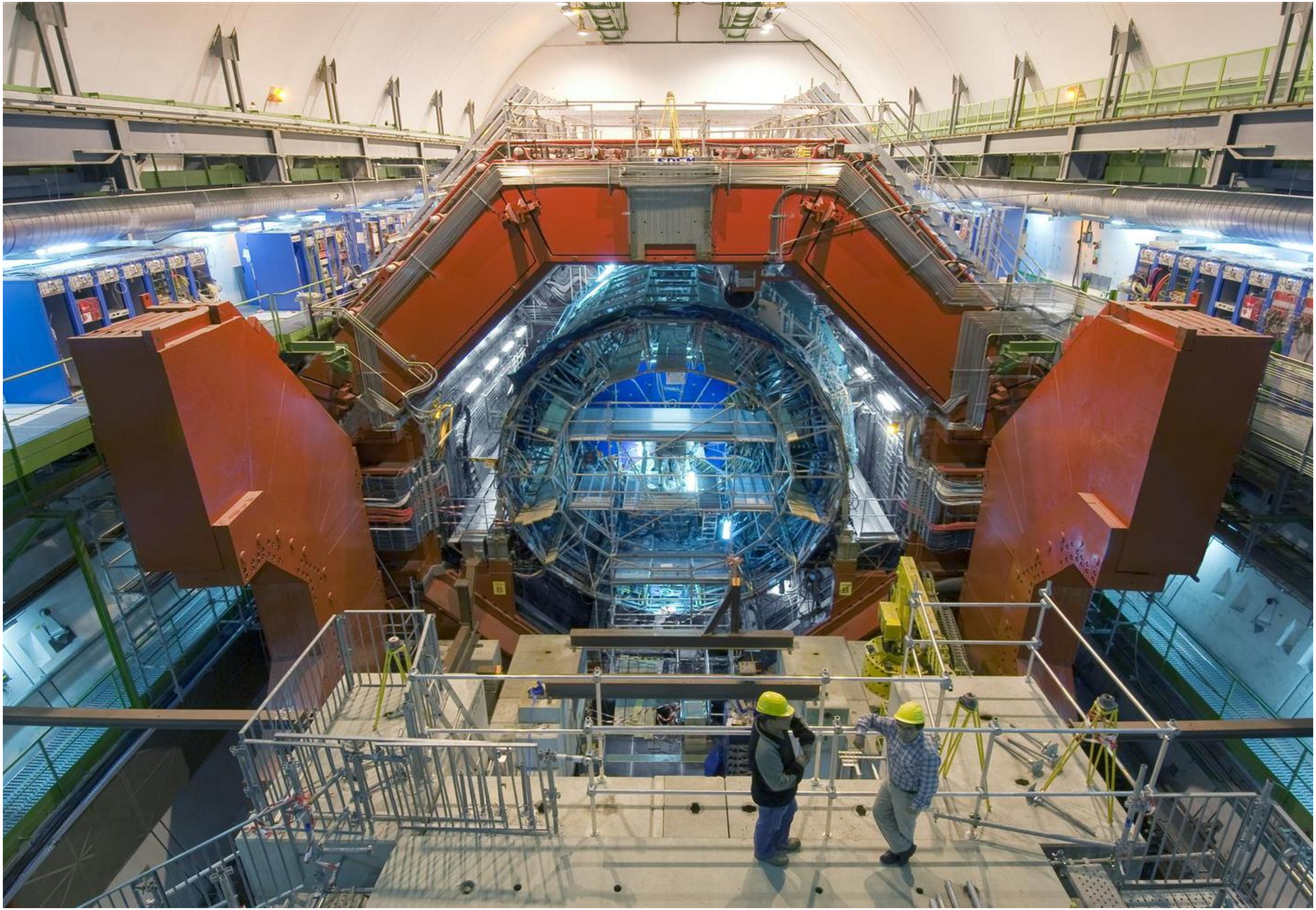
Hybridized pixel detectors

ALICE ITS: 240 5x1 SPD modules (~10 million pixels)



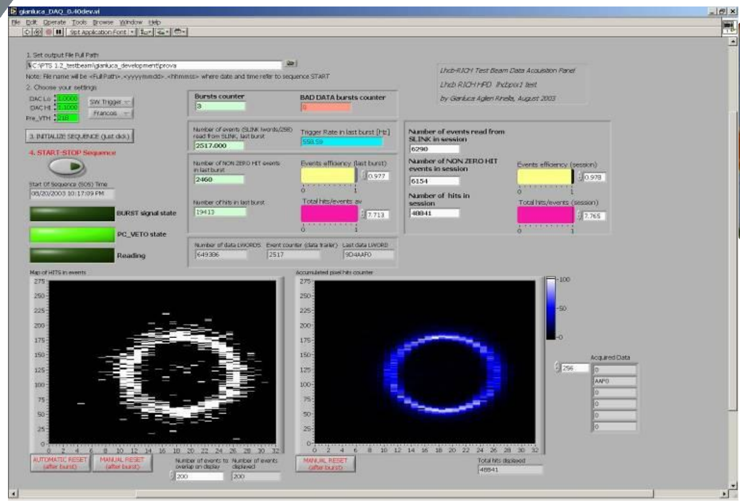
LHCb RICH: 830 single assemblies for HPD anodes

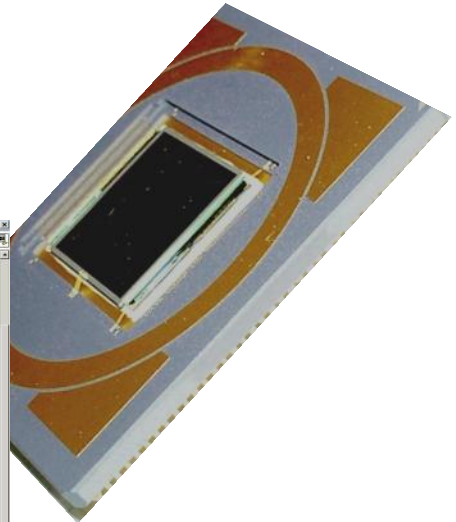


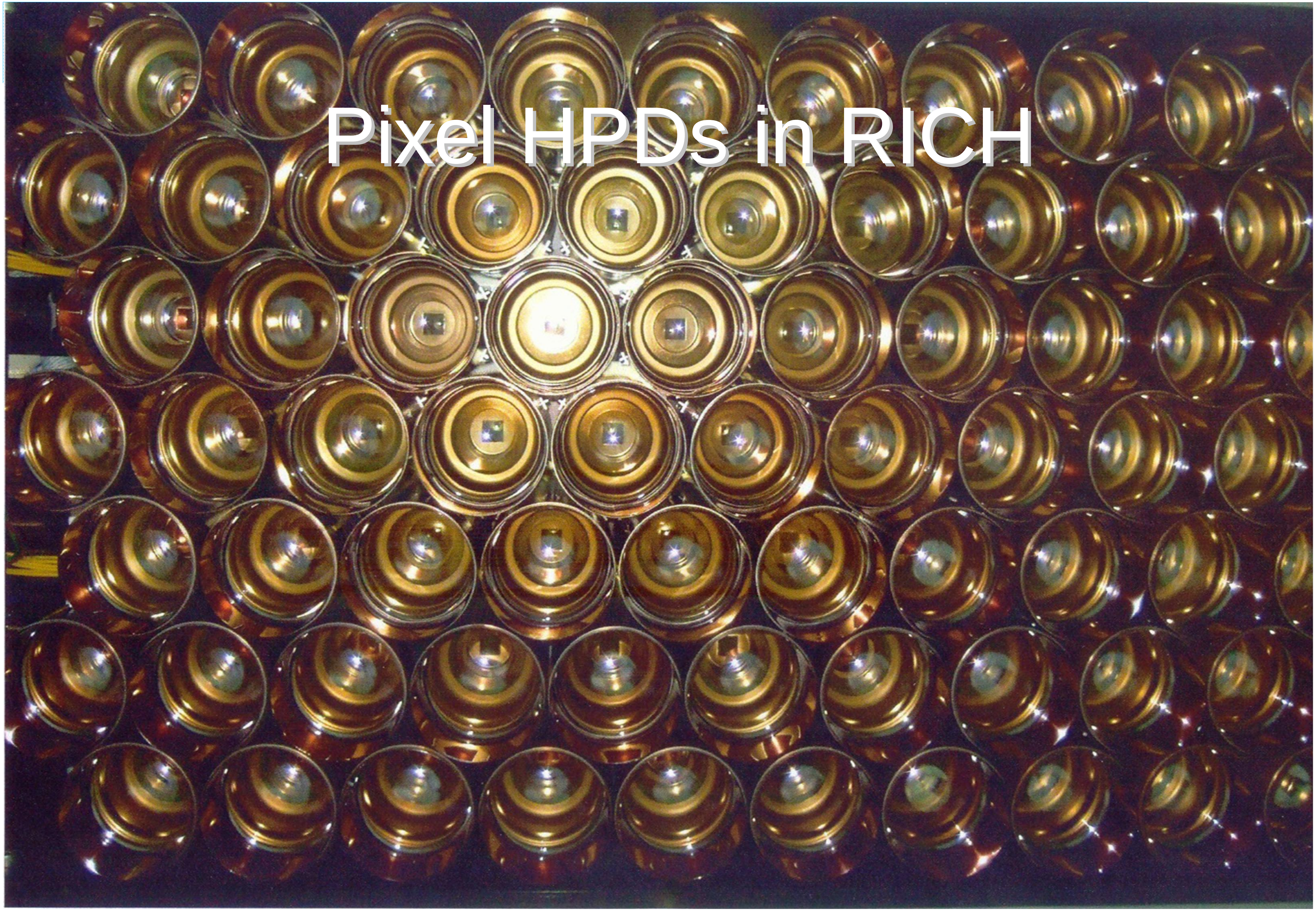


Ring Imaging Cherenkov HPDs

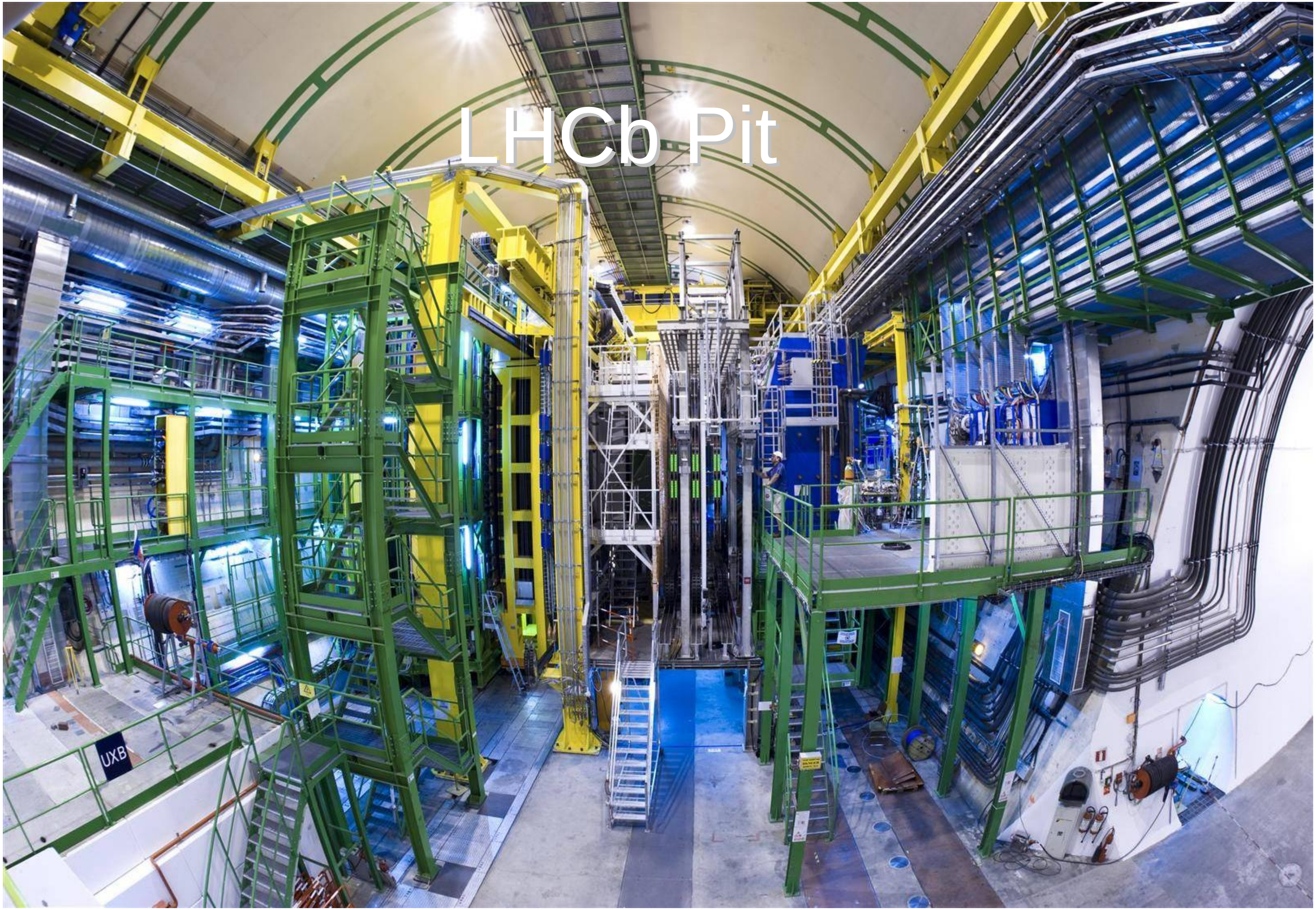
- Hybrid photon detectors for low noise detection of Cherenkov radiation
- Pixel anodes mounted on a ceramic carrier inside a vacuum tube
- New high lead flip chip process developed for tube assembly
- Total of 830 production assemblies were made






Pixel HPDs in RICH

LHCb Pit



Atomic Layer Deposition

Seminar Presentation at UC Berkeley
Kai-Erik Elers
VTT Technical Research Centre of Finland

CONTENTS:

- Background of ALD
- ALD principle and its characteristic features
- Precursors and surface chemistry
- ALD reactors for R&D and hardware design
- ALD materials and their industrial applications

Source Material for the Presentation

Prof. Markku Leskelä   Prof. Mikko Ritala   Dr. Jaakko Niinistö   Dr. Riikka Puurunen

University of Helsinki
Dept. Chem., Inorganic Chemistry Lab.
- precursor synthesis
- process development
- characterization

Technical Research Centre of Finland
- Applied research
- Process integration for ALD
- ALD films in devices

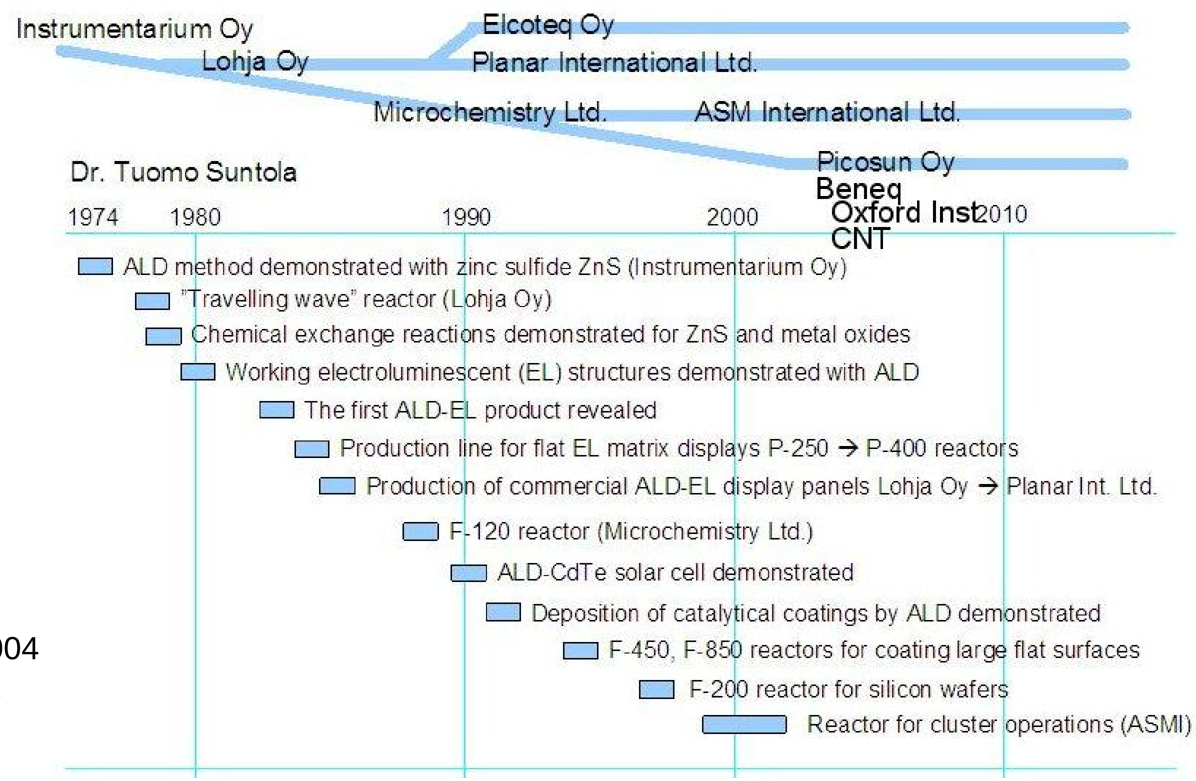
Beneq   Picosun   CambridgeNanoTech Simply ALD

Background of ALD

Atomic Layer Deposition was developed by Dr. T. Suntola and co-workers in Finland to meet the needs of producing improved thin films and structures based thereupon for electroluminescent thin film (TFEL) flat panel displays

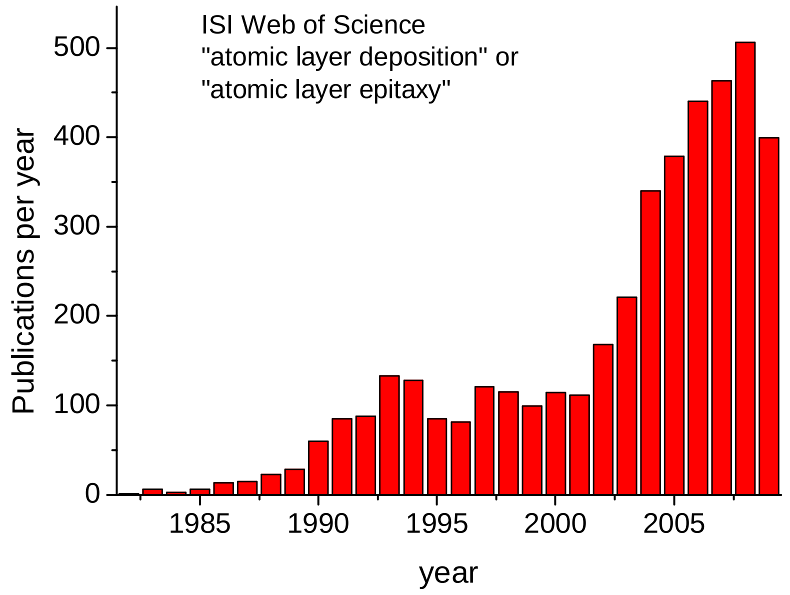
- First Finnish Patent 1974
- First U.S. patent 1977

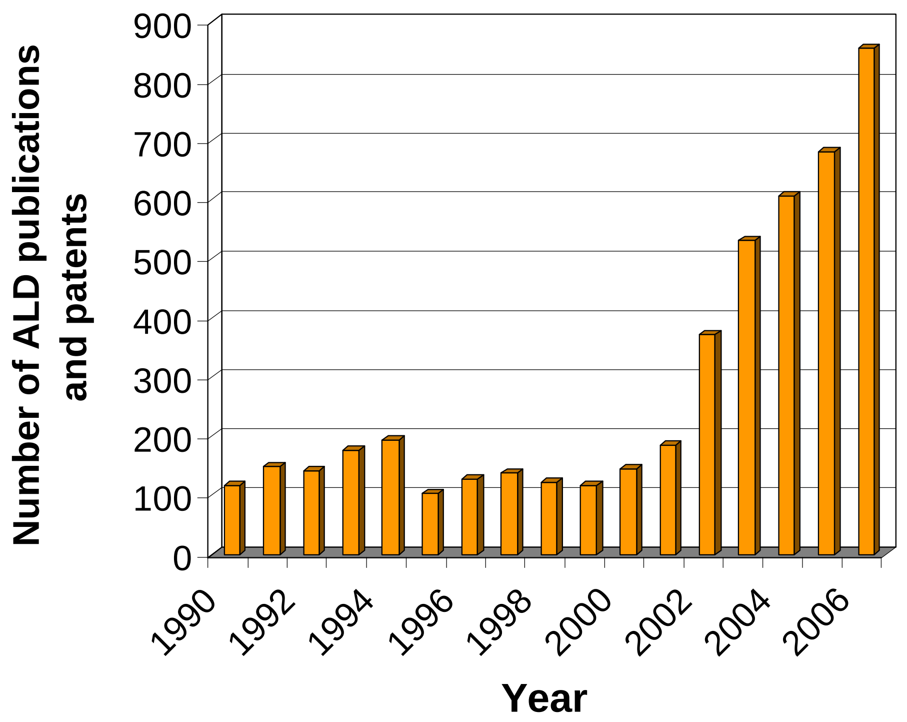
The head of SEMI organization President and CEO Stanley T. Myers (left) presents the European SEMI 2004 award to Dr. Tuomo Suntola (right) at Semicon Europa 2004 exhibition in Munich.

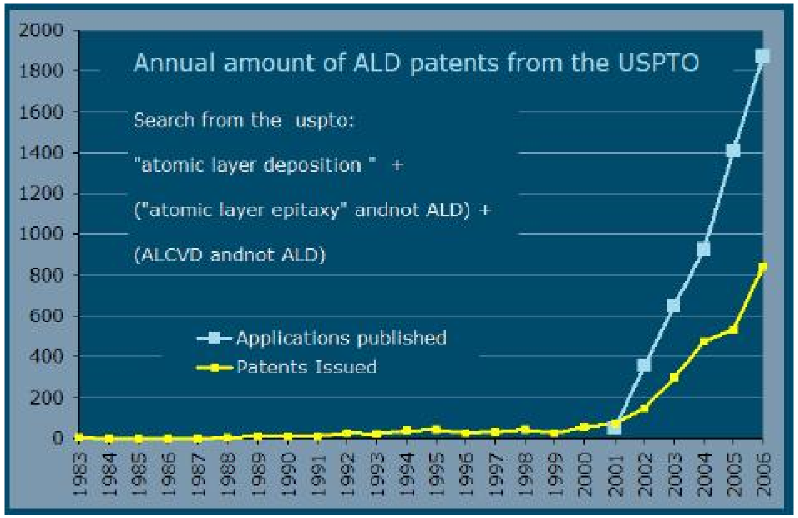


Dr. Suntola worked in VTT in early 70's

Popular ALD



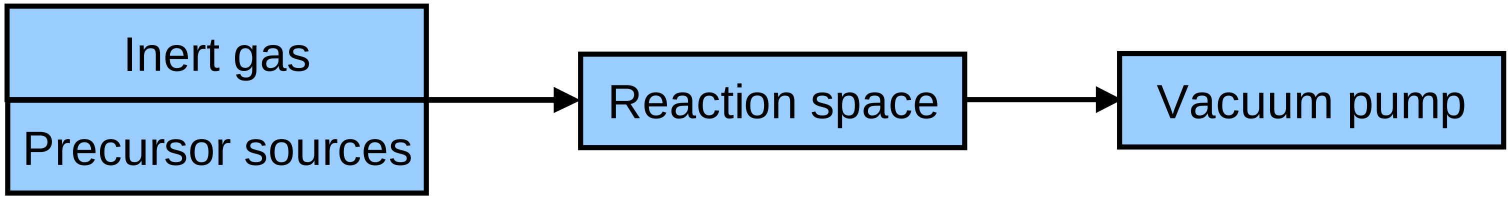


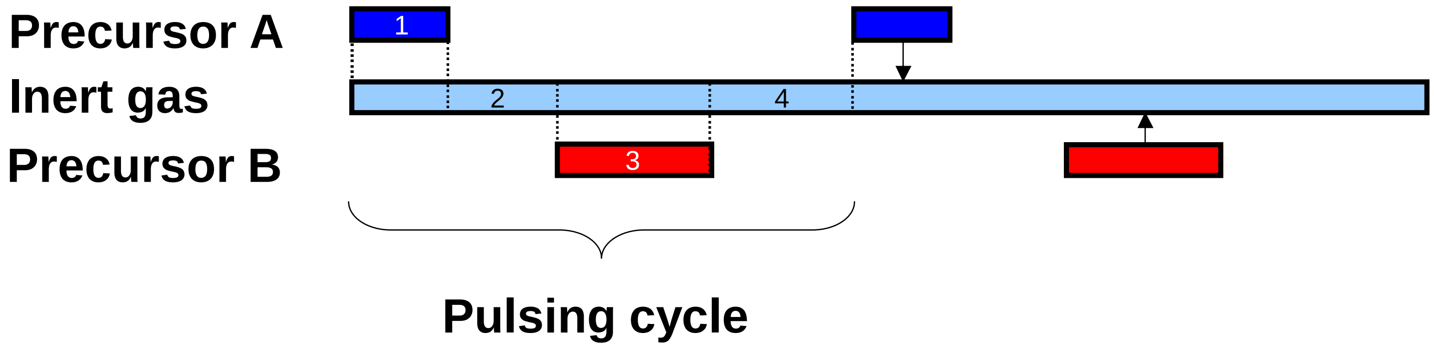


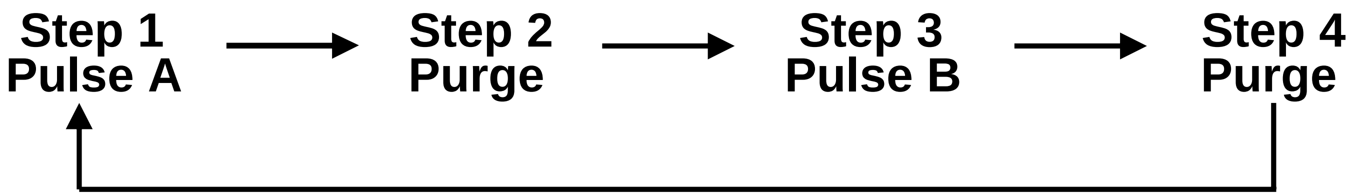
Dramatic increase in number of ALD publications and patents since 2002 (ISI, Scifinder, USPTO)

ALD principle
and
its characteristic features

ALD Cycle

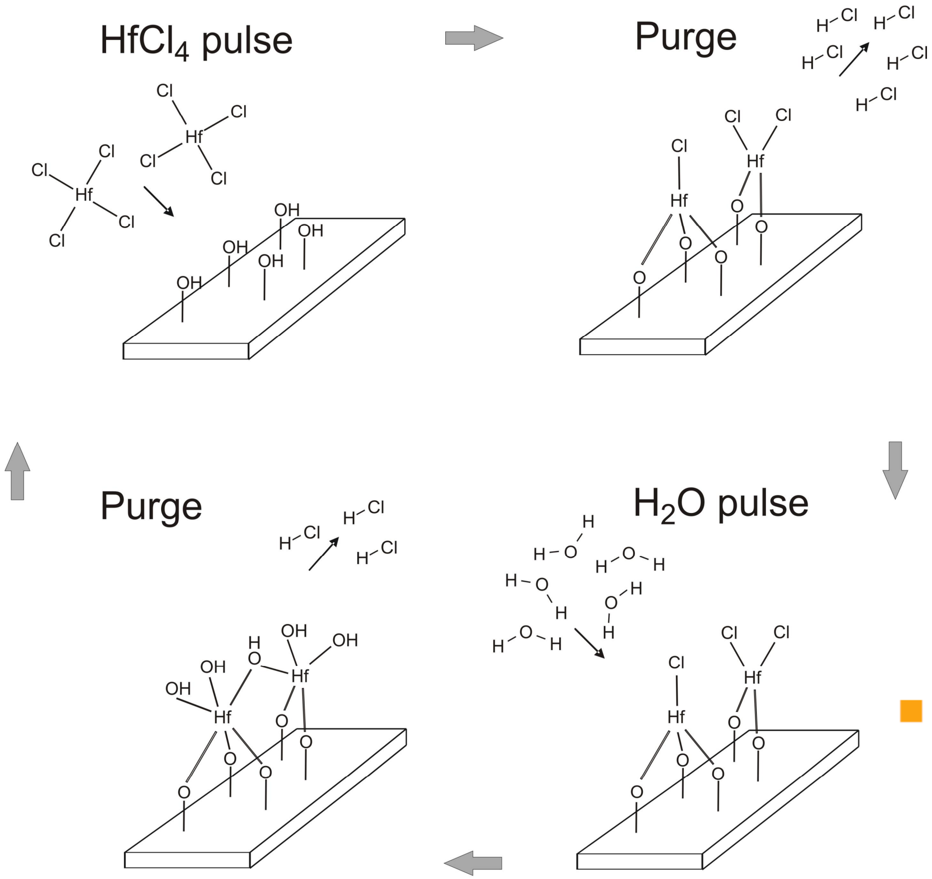

Inert gas
Precursor sources
Reaction space
Vacuum pump

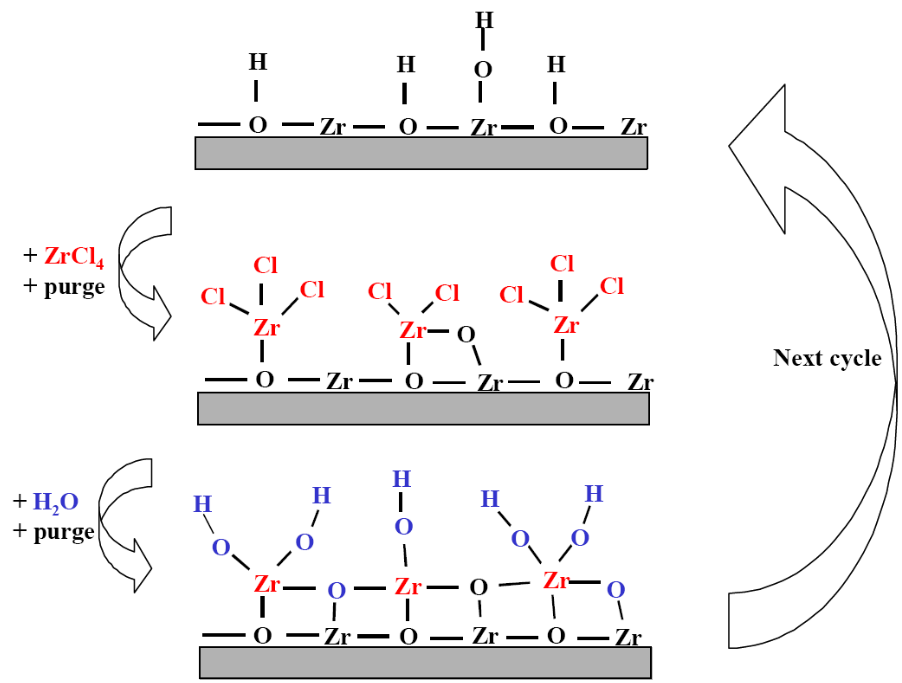

Precursor A
Inert gas
Precursor B
1
2
3
4
Pulsing cycle


Step 1
Pulse A
Step 2
Purge
Step 3
Pulse B
Step 4
Purge

ALD Cycle for HfO_2 and ZrO_2

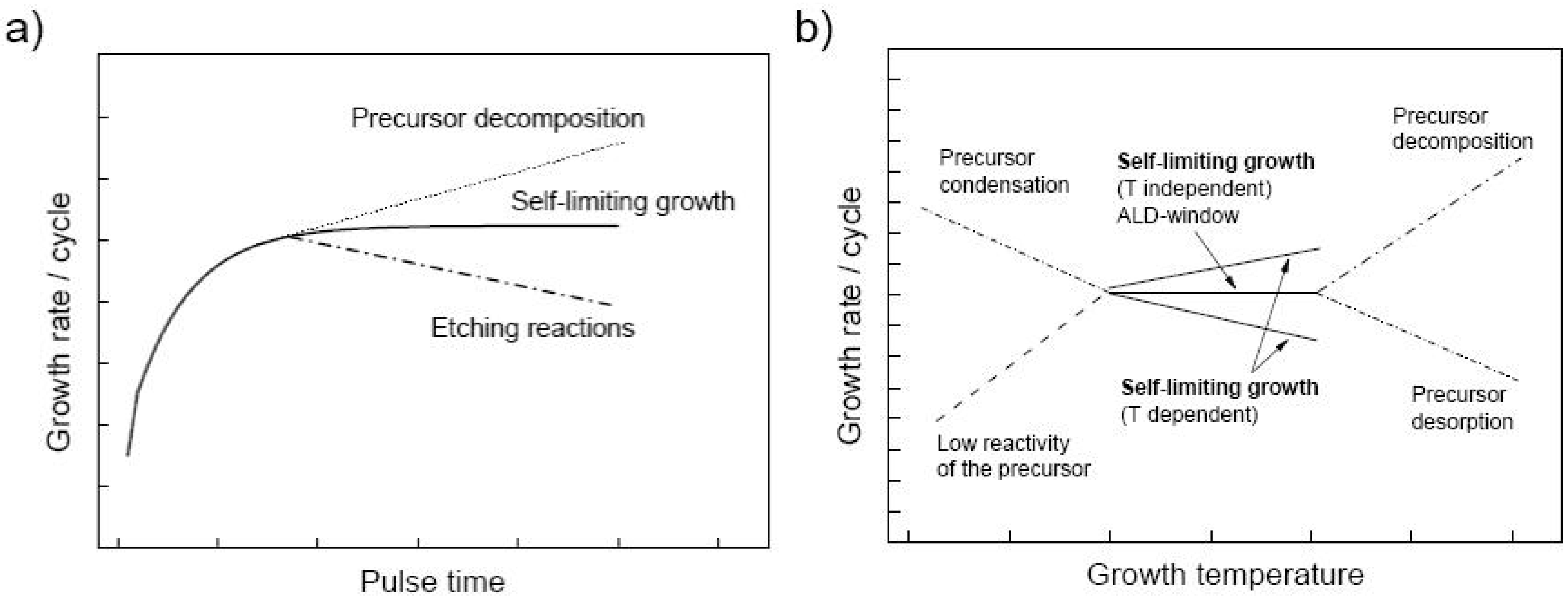
Self-limiting film growth via alternate saturative surface reactions





- for oxides a favourable and quite general ALD reaction mechanism exists
  - -OH groups and coordinatively unsaturated surface ions are efficient reactive sites for the metal precursors

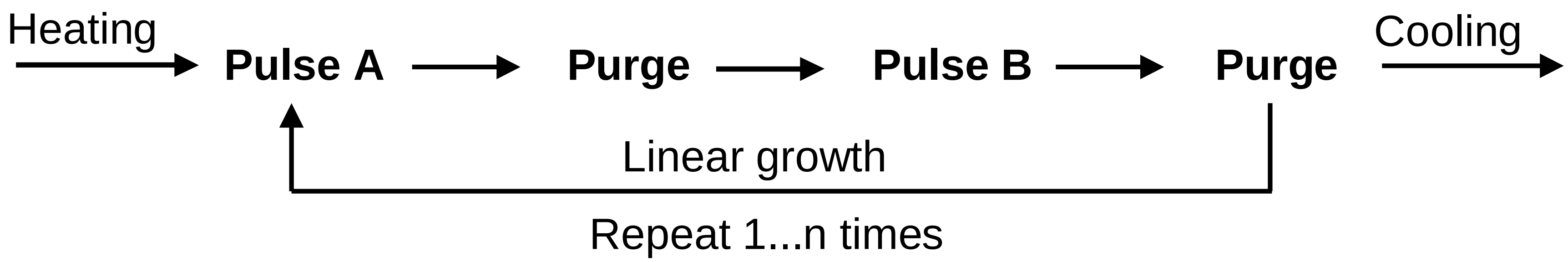
Characteristic ALD Curves

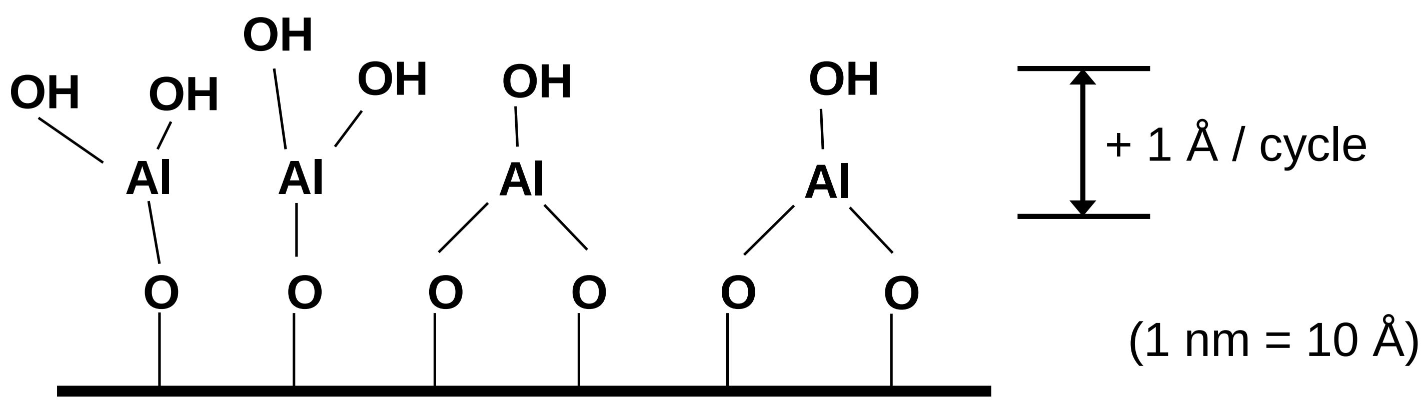


a) The precursor pulse length (dose) has no effect on the growth rate provided that the surface is saturated, i.e. all available surface sites are occupied by adsorbed precursor molecules (Steps 1 and 2)

b) Factors limiting the self-limiting growth at various temperatures

Film Growth by Repeating Cycle

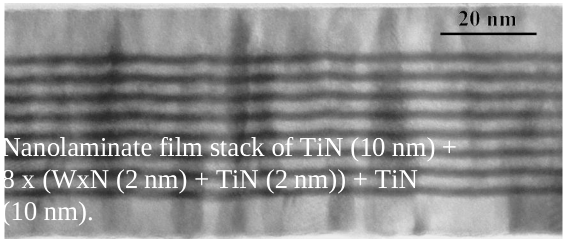




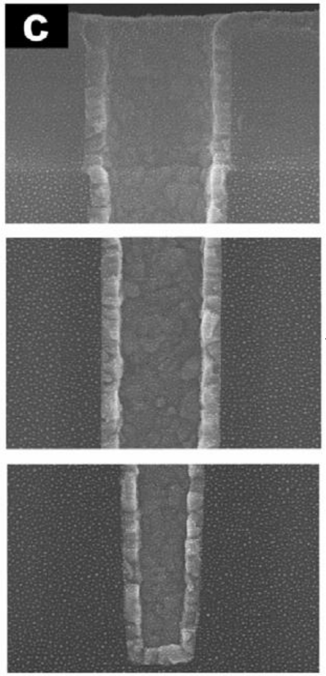
100 cycles → 10 nm **1000 cycles → 100 nm**

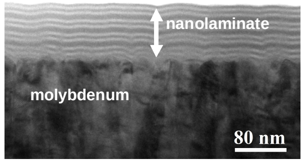
Benefits of ALD

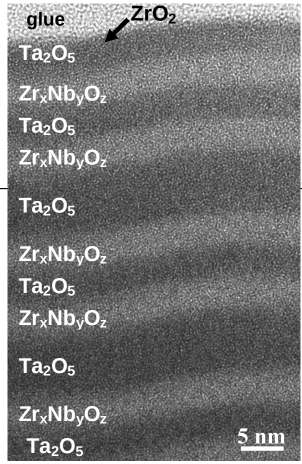
Characteristic feature of an ALD process	Practical advantage
Self-limiting growth process	Precise film thickness control by the number of deposition cycles
	No need to control reactant flux homogeneity
	Excellent uniformity and conformality
	Large-area and batch capability
	Dense, uniform, homogeneous and pinhole-free films
	Atomic level composition control
	Good reproducibility and straightforward scale-up



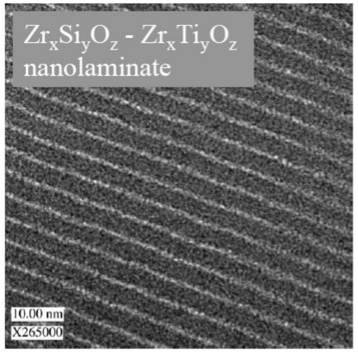
Nanolaminate film stack of TiN (10 nm) + 8 x (WxN (2 nm) + TiN (2 nm)) + TiN (10 nm).

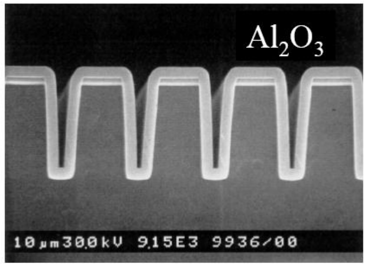




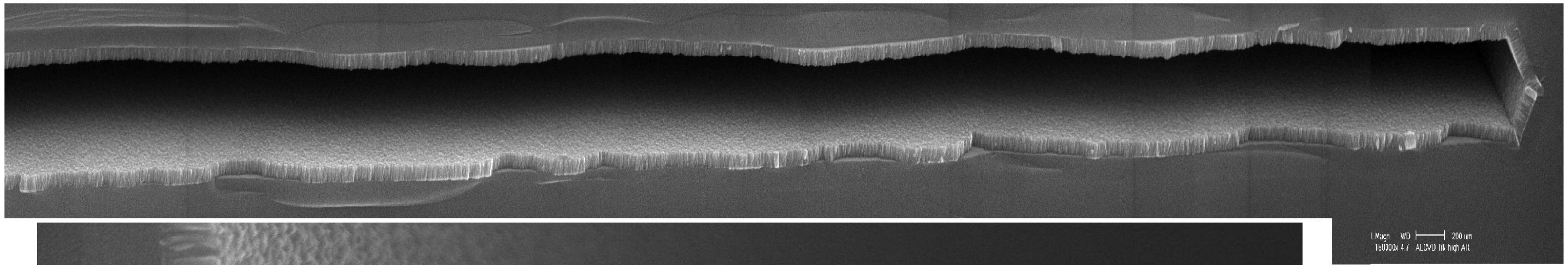


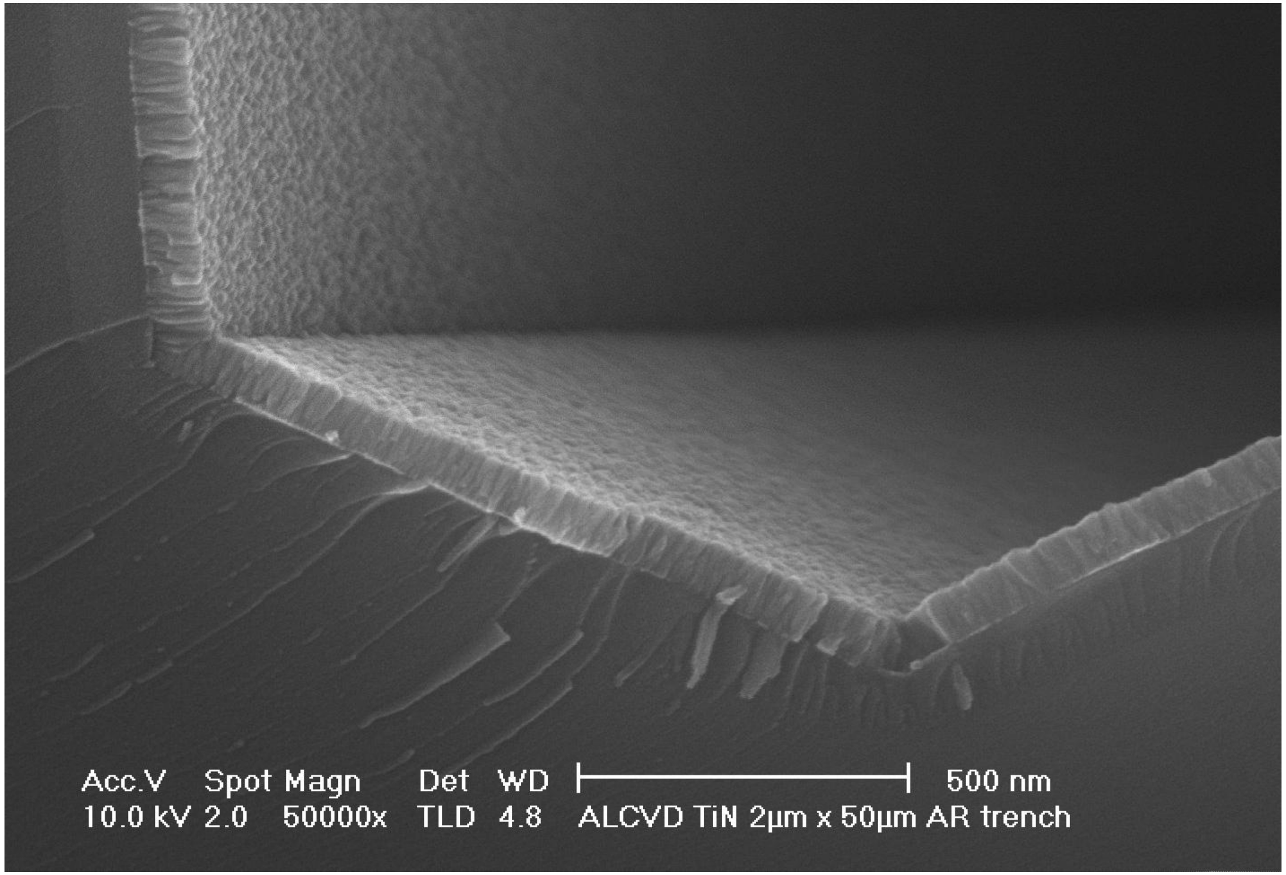
Leskelä *et al.* Mater. Sci. Eng. C 27 (2007) 1504.





Film Conformality



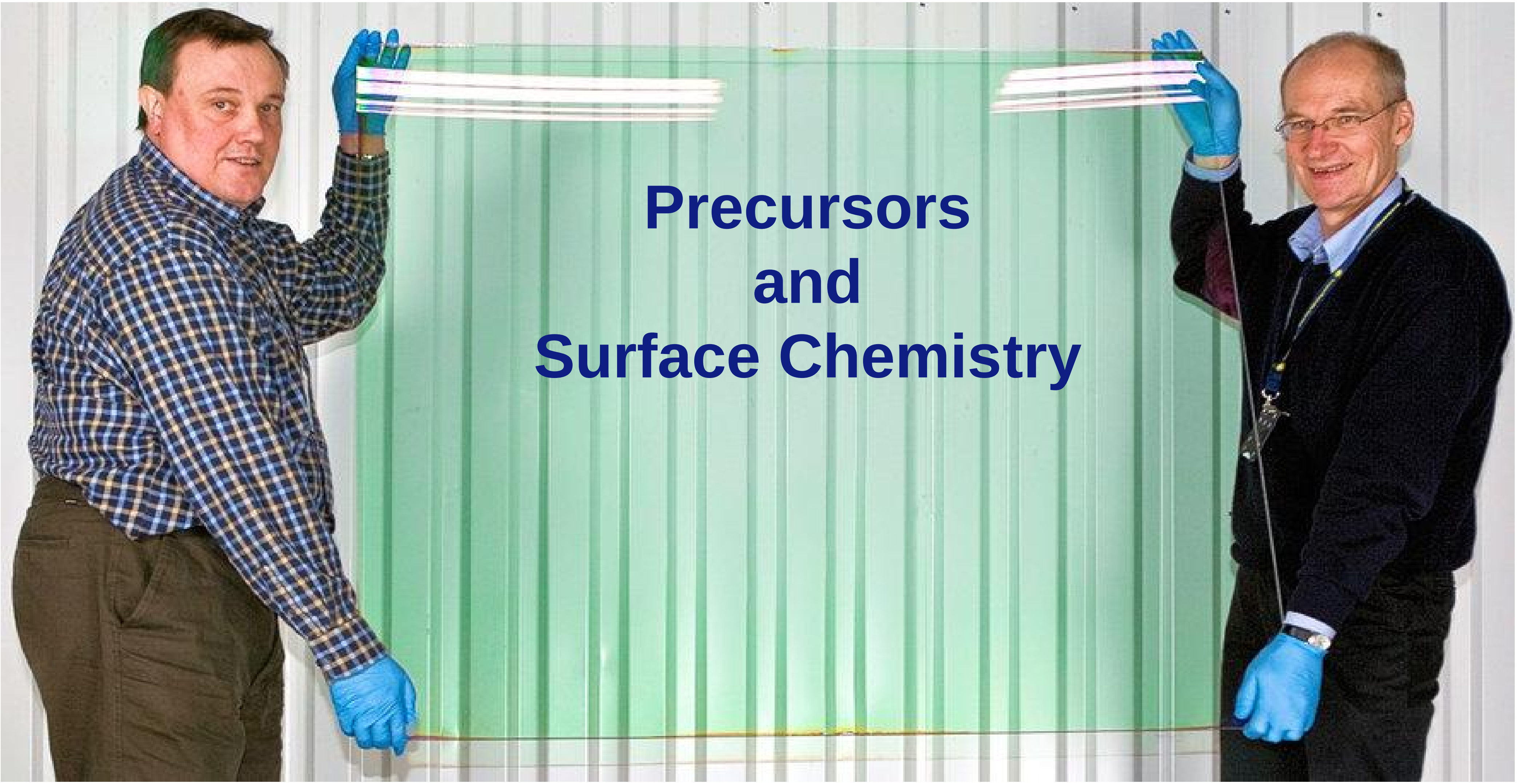


TiN,
AR=80:1

Limitations

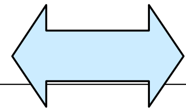
- *Low effective deposition rate*
  - 100 nm/h is quite common value for good ALD processes
- *No existing processes for some materials*
  - Si, Ge, many metals, metal silicides, multicomponent oxide superconductors, ferroelectrics and chalcogenides
- *No knobs to adjust crystal phase of deposited material (excl. temperature)*
- *Deviations from 'ideal ALD growth'*
  - Incubation time, not truly self-limiting growth

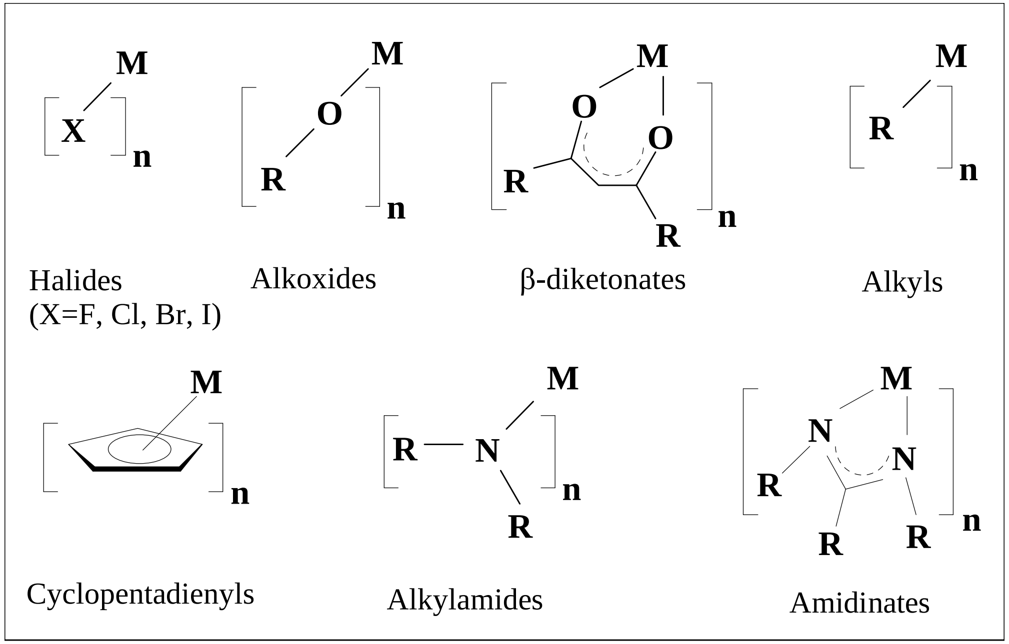
Precursors and Surface Chemistry



Precursor chemistry in ALD

Essential properties	Desirable but not necessary
Volatility	Unreactive volatile byproducts
Fast and complete reactions	Inexpensive
No self-decomposition	Easy to synthesize and handle
No etching of the film or substrate material	Nontoxic and environmentally friendly
No dissolution into the film substrate	
Sufficient purity	

Thermal decomposition  Aggressive reactions



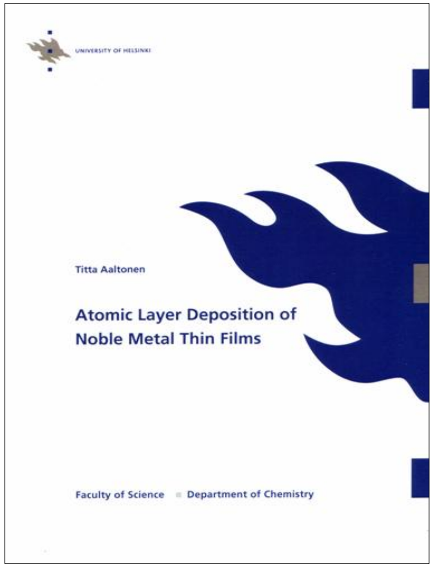
N.B. Mixed-ligand precursors also possible, *e.g.* alkoxide and cyclopentadienyl ligands coordinating to the same metal ion.

Ref. M. Ritala and J. Niinistö, *Atomic Layer Deposition,* in Chemical Vapour Deposition: Precursors and Processes, Eds. Jones, A.C. and Hitchman, M.L., RSC, *in press*.

ALD of noble metals with O_2 based chemistry

- Ru, Pt, Ir, Rh, Pd
  - capable of dissociating O_2 to atomic O
- organometallic and β-diketonate metal precursors

- summarised in PhD thesis of Titta Aaltonen 2005
  ethesis.helsinki.fi/julkaisut/mat/kemia/vk/aaltonen/

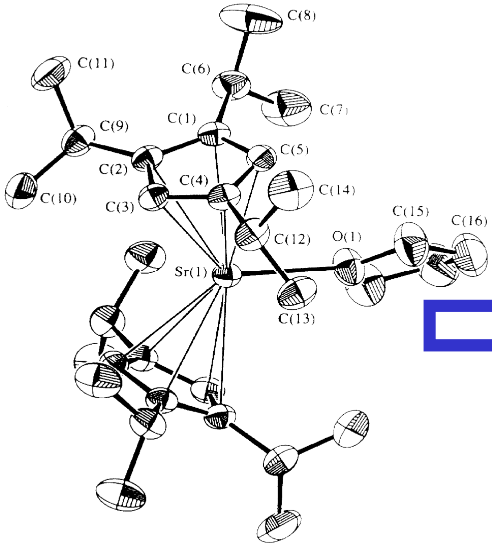


ALD research at University of Helsinki

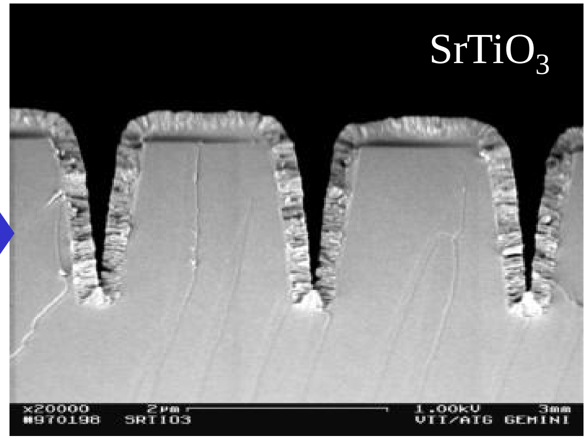
Starting from precursor chemistry, develop new well characterized ALD processes and materials,

and transfer these to the first stages of applied research, in a wide range of application areas.

$$Sr(C_5iPr_3H_2)_2 + H_2O + Ti(OiPr)_4 + H_2O \rightarrow SrTiO_3$$

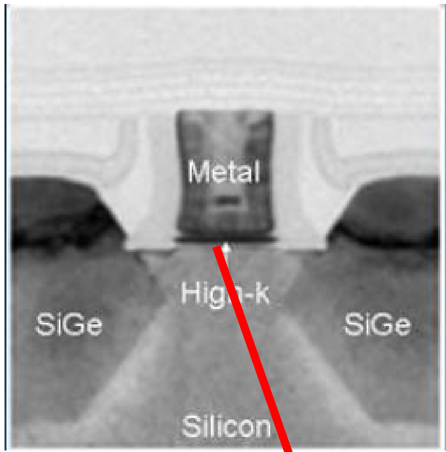


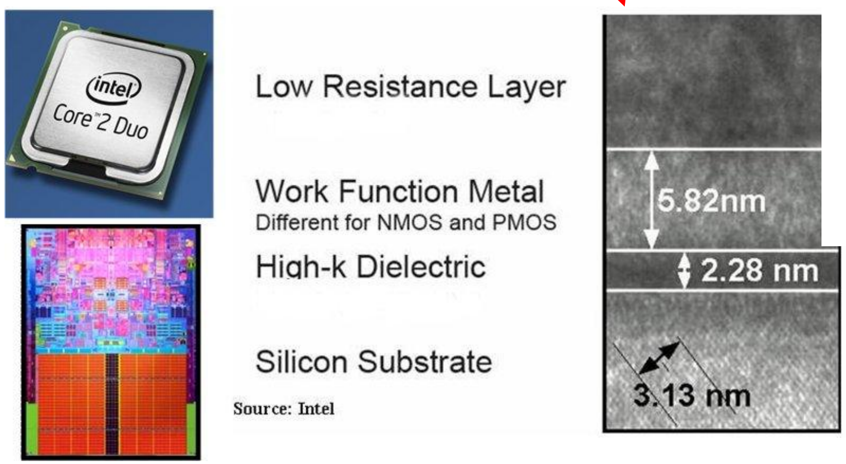
$Sr(C_5{}^iPr_3H_2)_2(THF)$

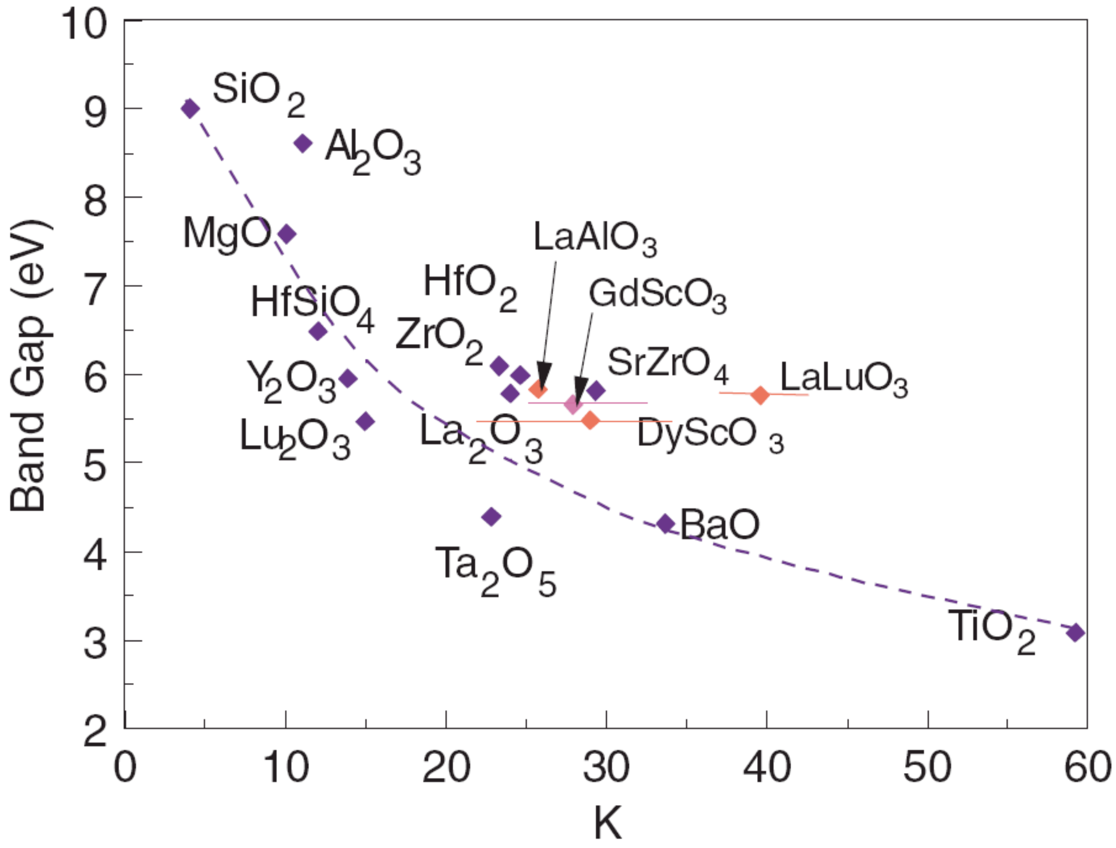


Vehkamäki et al., Electrochem. Solid State Lett. 2 (1999) 504.

High-K Compounds







John Robertson J. Appl. Phys. **104**, 124111 (2008)

Published ALD Precursor for ZrO_2

Precursors		T_{growth}			Impurities (at preferred T_{growth})			
Metal precursor	O source	Range [°C]	Preferred [°C]	Saturation verified at 300°C	C [at-%]	H [at-%]	Other (if detected) [at-%]	Analysis method
Halides								
$ZrCl_4$	H_2O	180–600	300	YES		1.5	Cl: 0.6–0.8	TOF-ERDA
	$H_2O + H_2O_2$	180–600	300	YES		N.R.		
	O_2*	500	500					
ZrI_4	$H_2O + H_2O_2$	230–500	275–325	YES		3-8	I: 0.5–1.2	TOF-ERDA, XPS
Amides								
$Zr(NEtMe)_4$	H_2O	< 250	< 250	NO	< 1	N.R.	N:<0.25	RBS
	O_3	150–350	< 300	NO	1	N.R.		AES
$Zr(NMe_2)_4$	H_2O	< 300	< 300	NO	< 1	N.R.	N: < 0.25	RBS
$Zr(NEt_2)_4$	H_2O	< 350	< 350	NO	< 1	N.R.	N: < 0.25	RBS
	O_2	250	250		3–5	N.R.		AES
$ZrCl_2[N(SiMe_3)_2]_2$	H_2O	150–350	250	NO	N.R.	N.R.	Si: 4	RBS, SIMS
Amidinates								
$Zr(amd)_4$	H_2O	150–350	150–350	YES	N.R.	N.R.		
Alkoxides								
$Zr(O^tBu)_4$	O_2	250	250	NO	6–8	N.R.		AES
	H_2O	150–300	< 250		8	2		TOF-ERDA
	N_2O	150–300	< 250	NO	N.R.	N.R.		
$Zr(dmae)_4$	H_2O	190–340	190–340	NO	5	30	N: < 4	TOF-ERDA
$Zr(O^tBu)_2(dmae)_2$	H_2O	190–340	190–340	NO	1.7-3	8-13	N: 0.3–1.3	TOF-ERDA
$Zr(O^iPr)_2(dmae)_2$	H_2O	190–340	190–340	NO	N.R.	N.R.	N: < 1	TOF-ERDA
β-Diketonates								
$Zr(thd)_4$	O_3	275–500	375	YES	0.2	0.3	F: < 0.1	TOF-ERDA
Cyclopentadienyls								
Cp_2ZrMe_2	H_2O	200–500	350	YES	< 0.1	< 0.1	N.R.	TOF-ERDA
	O_3	250–500	310–365	YES	0.2	0.1	F: 0.1	TOF-ERDA
Cp_2ZrCl_2	O_3	200–500	300	YES	0.5	0.5	Cl: < 0.07	TOF-ERDA
$(CpMe)_2ZrMe_2$	H_2O	300–500	< 400	YES	< 0.5	0.4		ERDA
	O_3	250–450	< 400	YES	< 1	N.R.		RBS
$(CpMe)_2Zr(OMe)Me$	H_2O	300–500	< 400	YES	< 0.5	0.5		ERDA
	O_3	250–500	< 400	YES	< 1	N.R.		RBS
$(CpMe)_2Zr(O^tBu)Me$	H_2O	300–450	< 350	NO	N.D	N.R.		AES
Ansa-metallocenes								
$(Cp_2CMe_2)ZrMe_2$	O_3	200–350	<350	NO	2.8	N.R.		AES[
$(Cp_2CMe_2)ZrMe(OMe)$	O_3	200–350	<350	NO	1.8	N.R.		AES
Mixed alkylamido-cyclopentadienyls								
$CpZr(NMe_2)_3$	O_3	250–400	300	YES	< 1	N.R.		RBS, AES
$(CpMe)_2(NMe_2)_3$	O_3	250–400	300	YES	< 1	N.R.		RBS, AES
$(CpEt)_2(NMe_2)_3$	O_3	250–400	300	YES	< 1	N.R.		RBS, AES

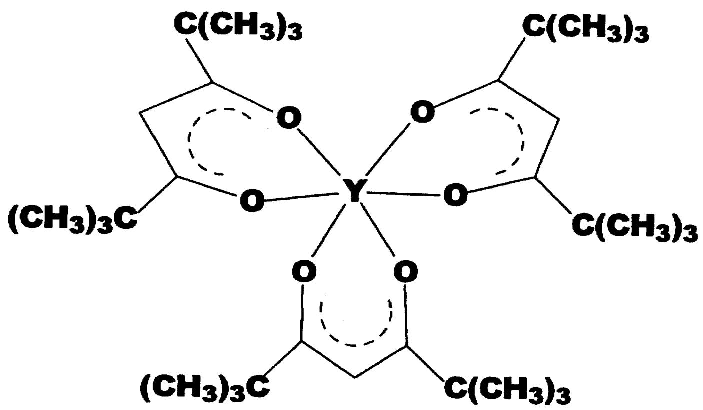
* atmospheric pressure.

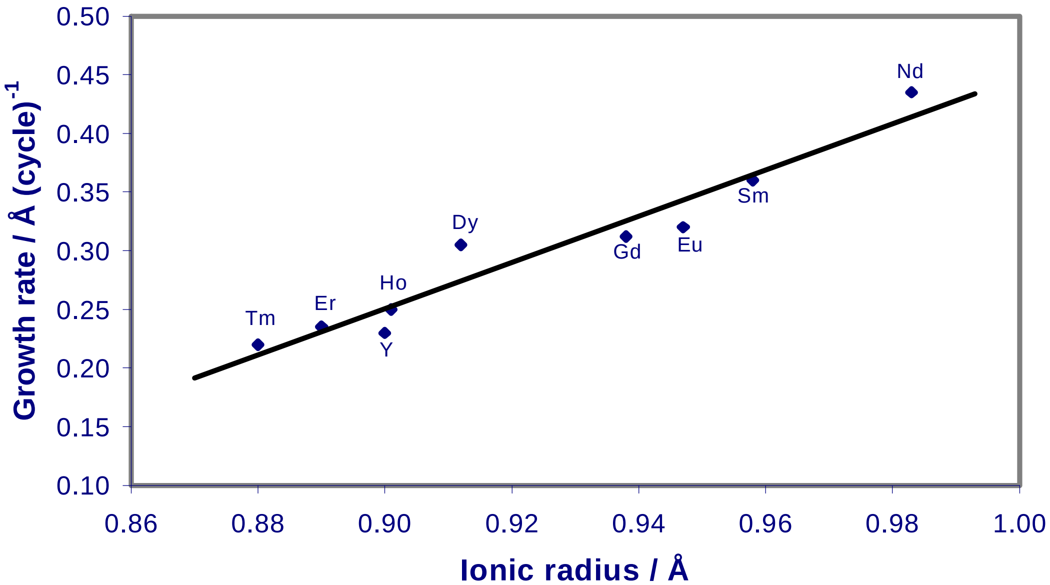
Ref. J. Niinistö *et al. Adv. Eng. Mater.* 2009

	Precursor LnX_3	
alkoxides	$La(OPh)_3$	Not suitable for ALD (thermal decomposition)
	$La(bammp)_3$	
	$La(dmomph)_3$	
	$La(O^tBu)_3$	
	$La(mmp)_3$	
	$La(dmop)_3$	
	$La(thd)_3$	Ozone needed
Cyclopentadienyls	$La(Cp)_3$	Thermal decomposition
	$La(MeCp)_3$	Thermal decomposition
	$La(EtCp)_3$	Partial decomposition
	$La(^iPrCp)_3$	Partial decomposition
	$La(^tBuCp)_3$	N.R.
Others	$La(^iPr\text{-}amd)_3$	Thermal stability?
	$La[N(SiMe_3)_2]_3$	Partial decomposition

ALD of rear earth oxides

- The rare earths have only a few volatile compounds
- Solid β-diketonates, most notably RE(thd)$_3$, can be used in ALD (thd=2,2,6,6-tetramethyl-3,5-heptanedione)
- Ozone is required as an oxygen source
- First ALD RE oxide processes published in some 15 years ago (Growth of Y_2O_3 and CeO_2, Refs. H. Mölsä and L. Niinistö, *Adv. Mater. Opt. Electr.* 1994, MRS 1994)
- Growth rate of RE_2O_3 films mainly depends on the ionic radius:





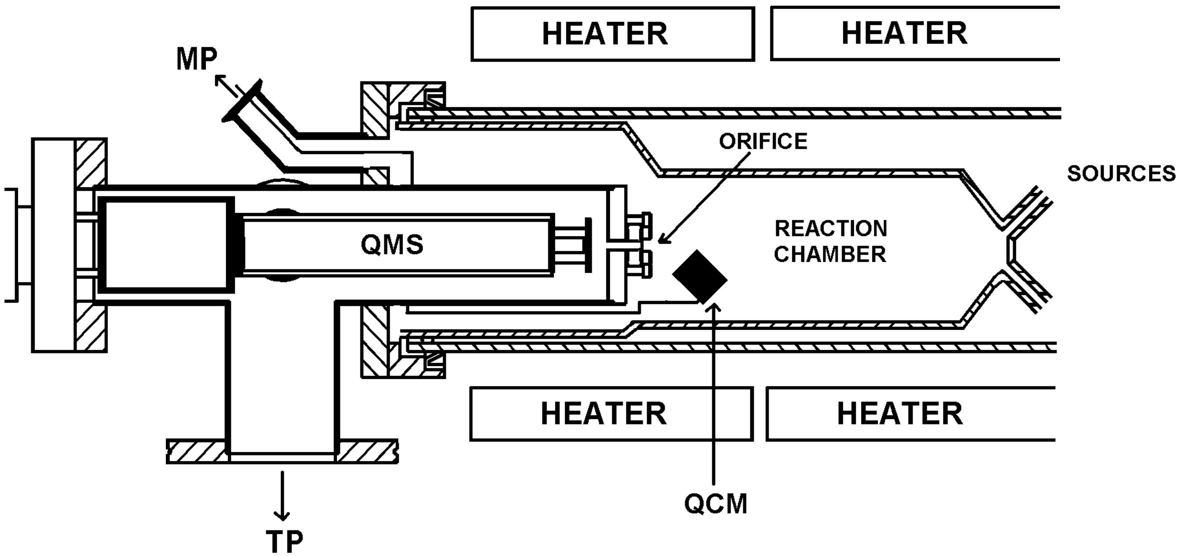
Some Cp based RE precursors tested for ALD

Rare earth	**Ionic (+III) radius, Å**	**Ligand**			
		Cp	**CpMe**	**Cp^{i}Pr**	**$CpMe_4$**
Sc	0.75	**Suitable**			
Er	0.89		**Suitable**		
Y	0.90	**Suitable**	**Suitable**		
Gd	0.94		**Partial dec.**		**Partial dec.**
Pr	0.99	**Not suitable**		**Partial dec.**	**Not suitable**
Ce	1.02		**Not suitable**		
La	1.03	**Not suitable**	**Partial dec.**	**Partial dec.**	**Not suitable**

Surface chemistry and in situ studies

- In situ studies of reactions: Infrared spectroscopy (IRS), mass spectrometry (MS), quartz crystal microbalance (QCM), Fourier transform infrared spectroscopy (FTIR), XPS
- ALD process is often made in analysis equipment $\Rightarrow$ Process performance is compromised (e.g. CVD growth) $\Rightarrow$ conclusion can be misleading
- 1) Analysis equipments can be integrated to the ALD reactors or 2) Sample can be transferred between modules with cluster tool

In situ reaction mechanism studies on ALD processes

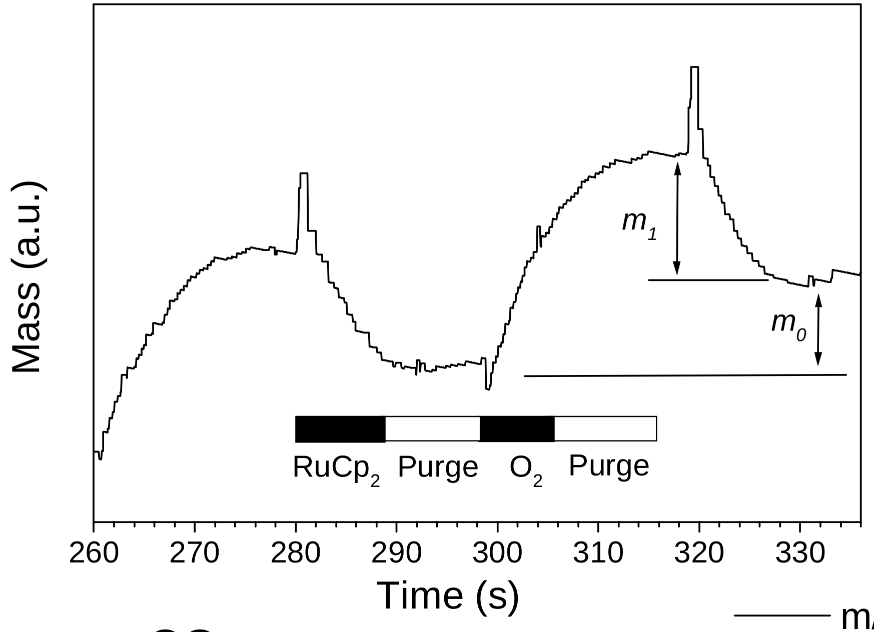


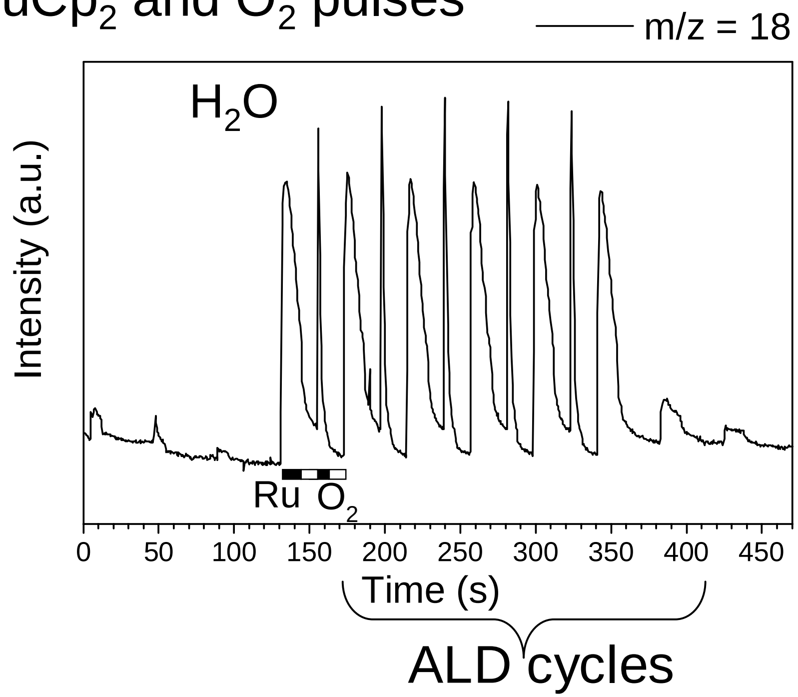
- quadrupole mass spectrometer (QMS) and quartz crystal microbalance (QCM) attached to a flow-type F120 reactor

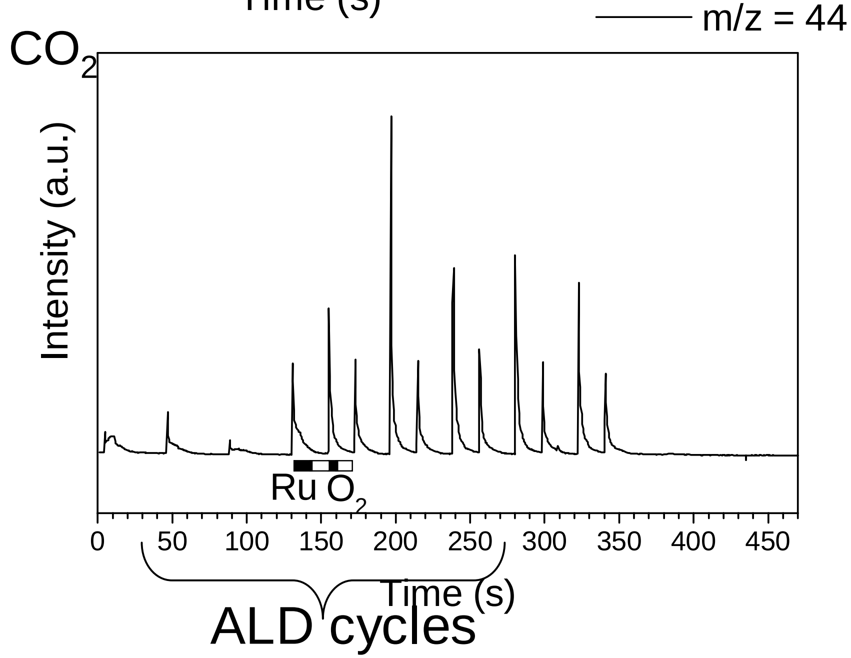
$RuCp_2$ – O_2 process

QCM: *mass decreases during the $RuCp_2$ pulse* and increases during the O_2 pulse!

QMS: H_2O and CO_2 are released during both the $RuCp_2$ and O_2 pulses

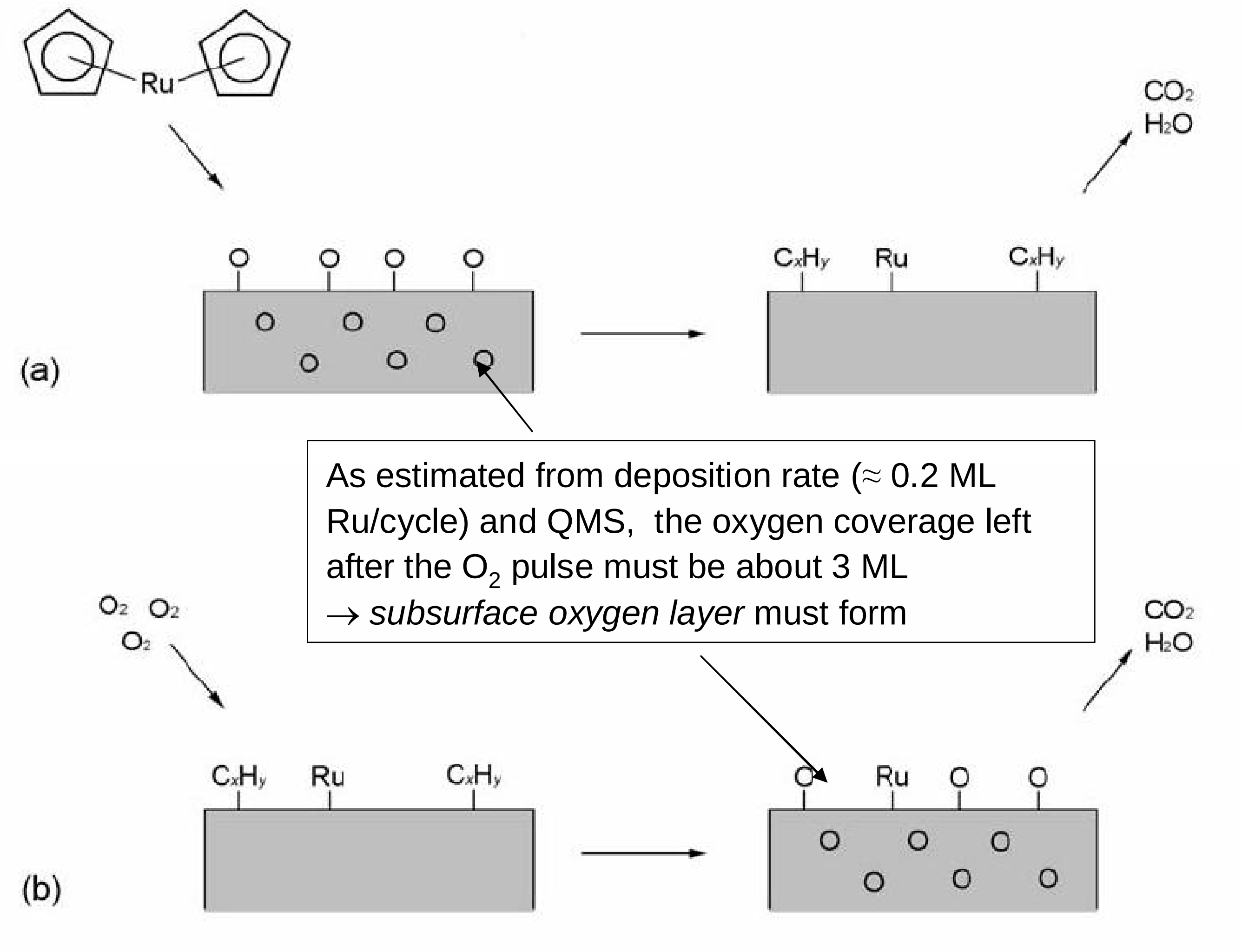






T. Aaltonen, A. Rahtu, M. Ritala, and M. Leskelä, *Electrochem. Solid-State Lett.*, **6** (2003) C130.

Suggested reaction mechanism



As estimated from deposition rate (≈ 0.2 ML Ru/cycle) and QMS, the oxygen coverage left after the O_2 pulse must be about 3 ML
→ *subsurface oxygen layer* must form

TMA/O_3 process

Ozone-based growth of Al_2O_3 from TMA recently studied by George *et al.* with QMS and FTIR

- Reaction mechanism:
- During TMA pulse, CH_4 released
- During O_3 pulse, CH_4, CO_2 and CO released
- Water as a by-product **not seen**

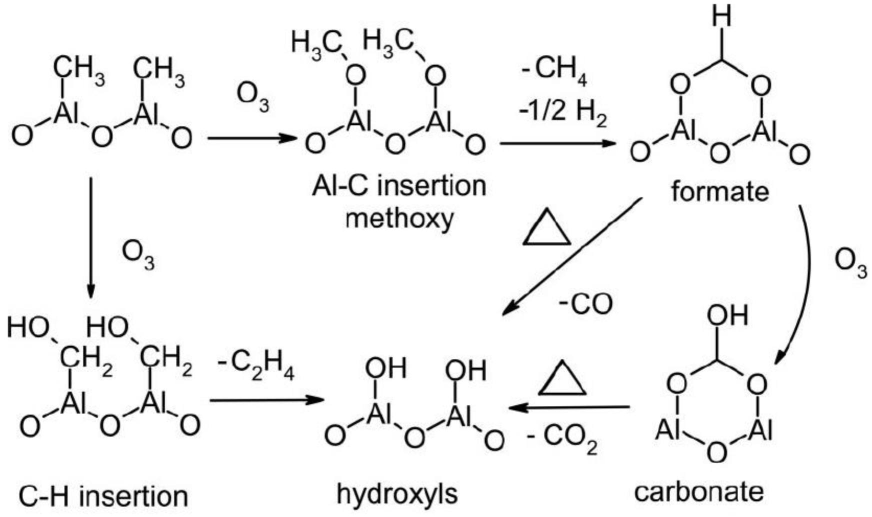


Figure 14. Proposed mechanism for O_3 reaction during Al_2O_3 ALD using TMA and O_3.

J. Phys. Chem. C **XXXX,** *xxx,* 000

Al_2O_3 Atomic Layer Deposition with Trimethylaluminum and Ozone Studied by in Situ Transmission FTIR Spectroscopy and Quadrupole Mass Spectrometry

David N. Goldstein,† Jarod A. McCormick,‡ and Steven M. George*,†,‡

TMA/O_3 process at 280ºC

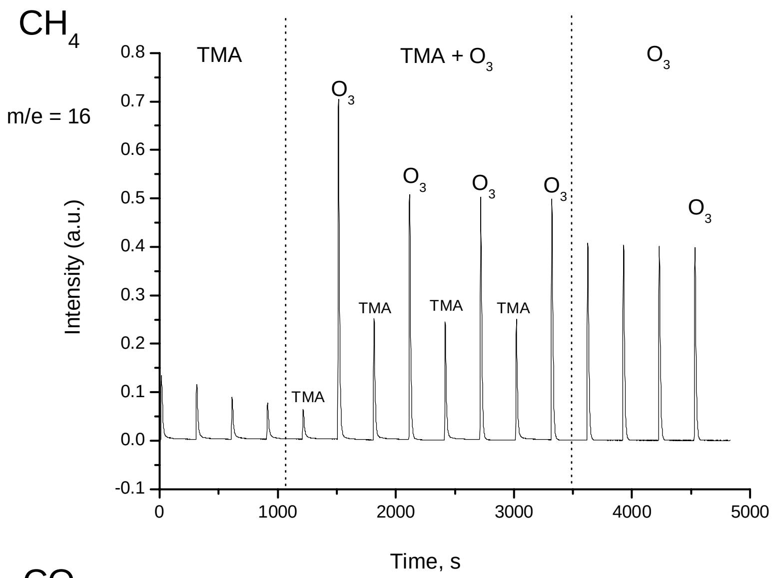
By-products released during the TMA pulse

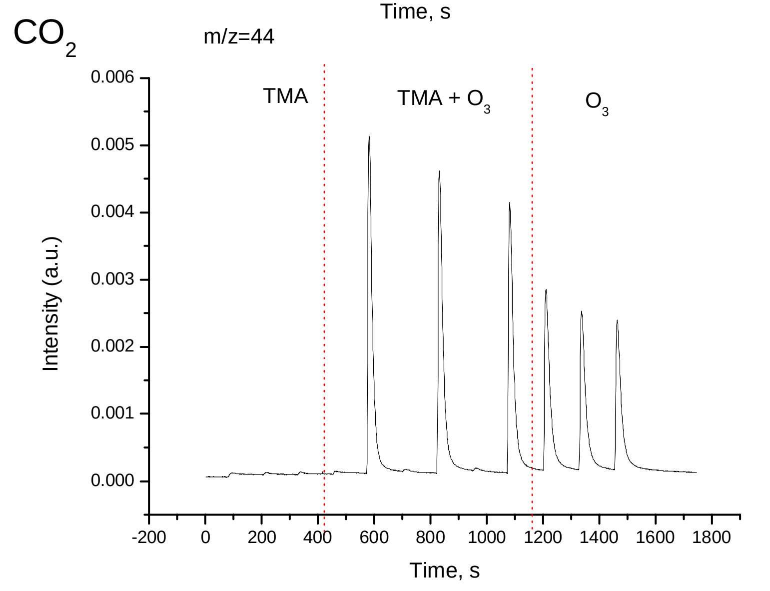
- CH_4

→ TMA chemisorbs to the surface via methyl ligands – as expected

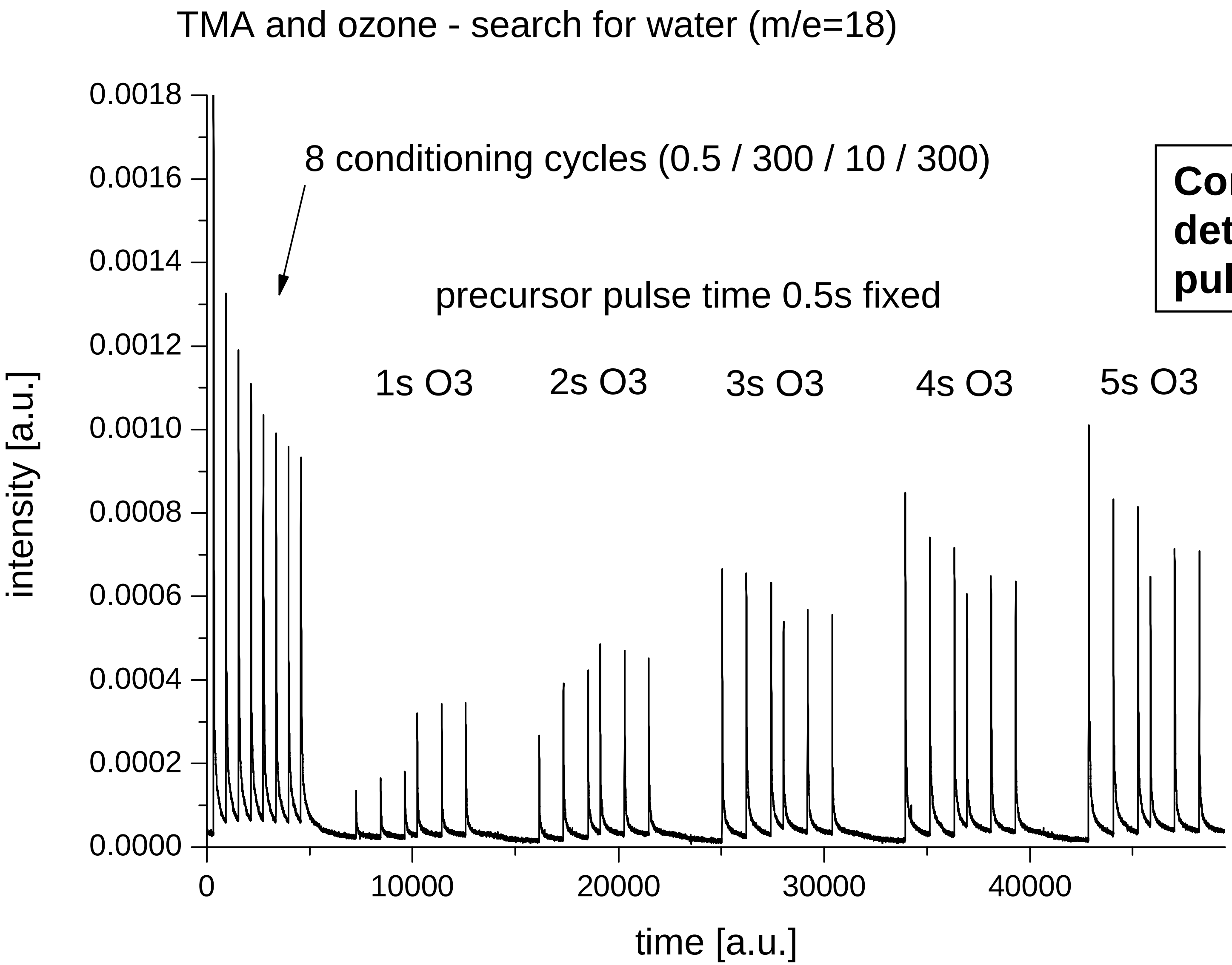
By-products released during the ozone pulse

- CH_4
- CO_2
- CO (fragmentation of the CO_2)
- **H_2O**



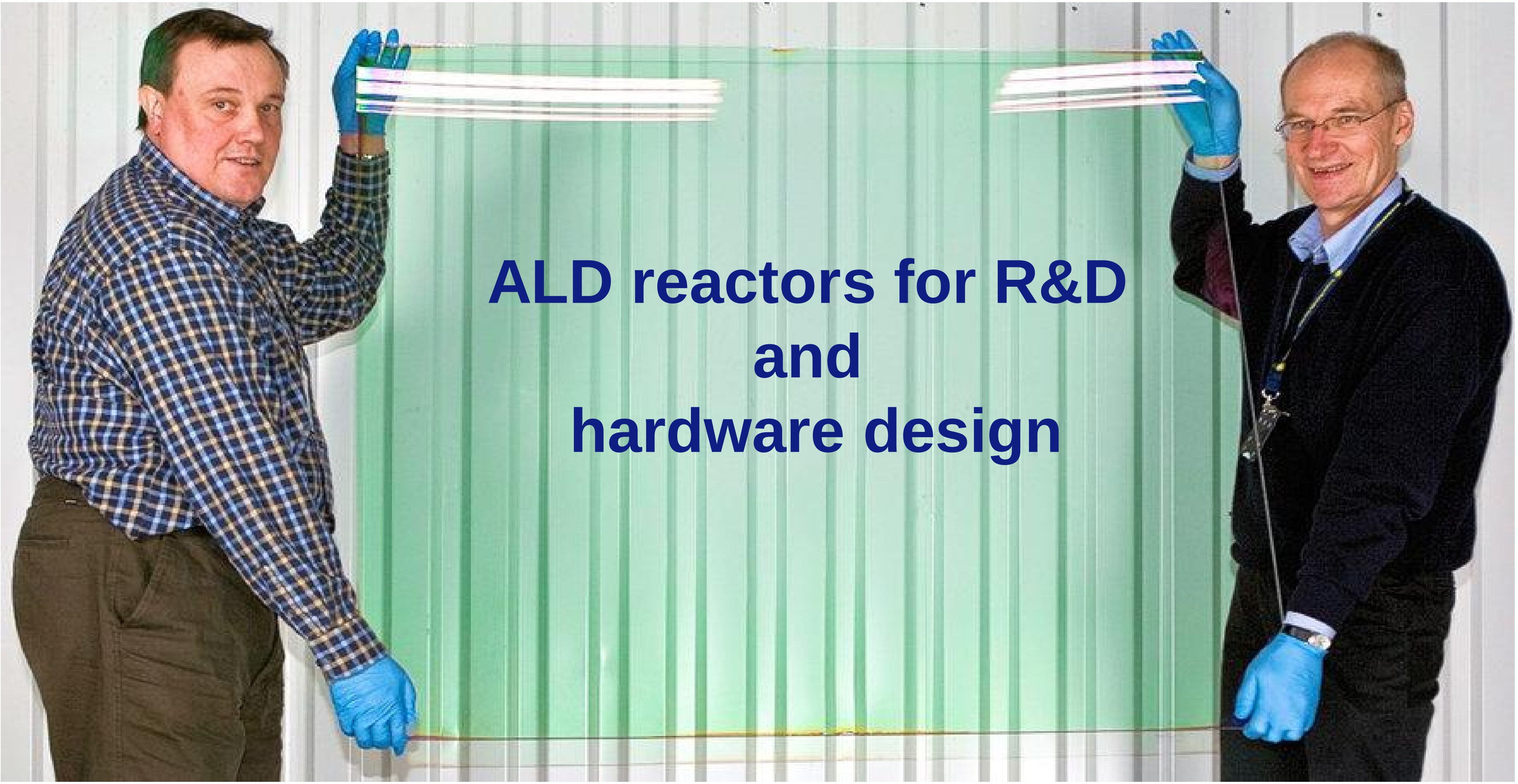


Water formed in TMA/O_3 process

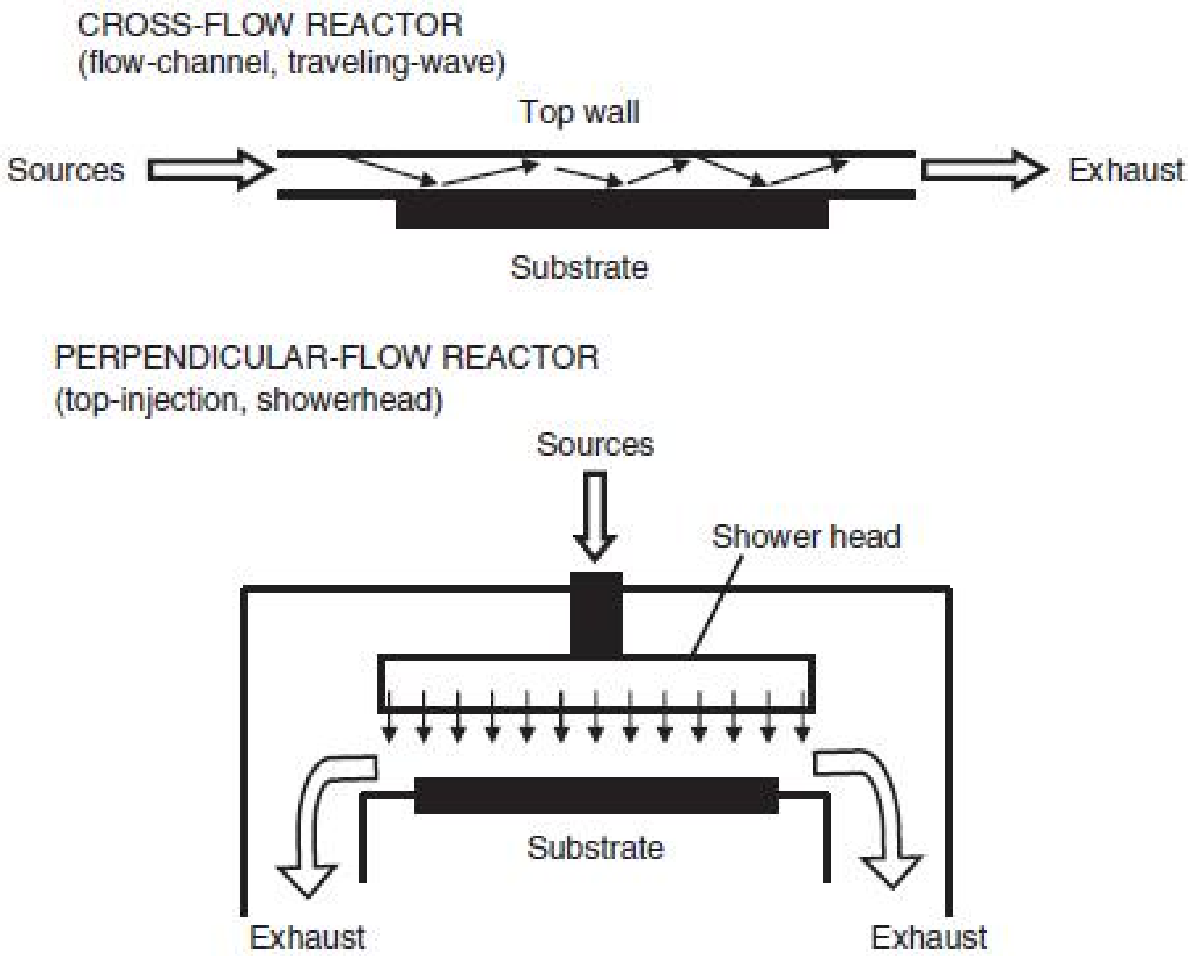


Conclusion: Water is detected during the ozone pulse

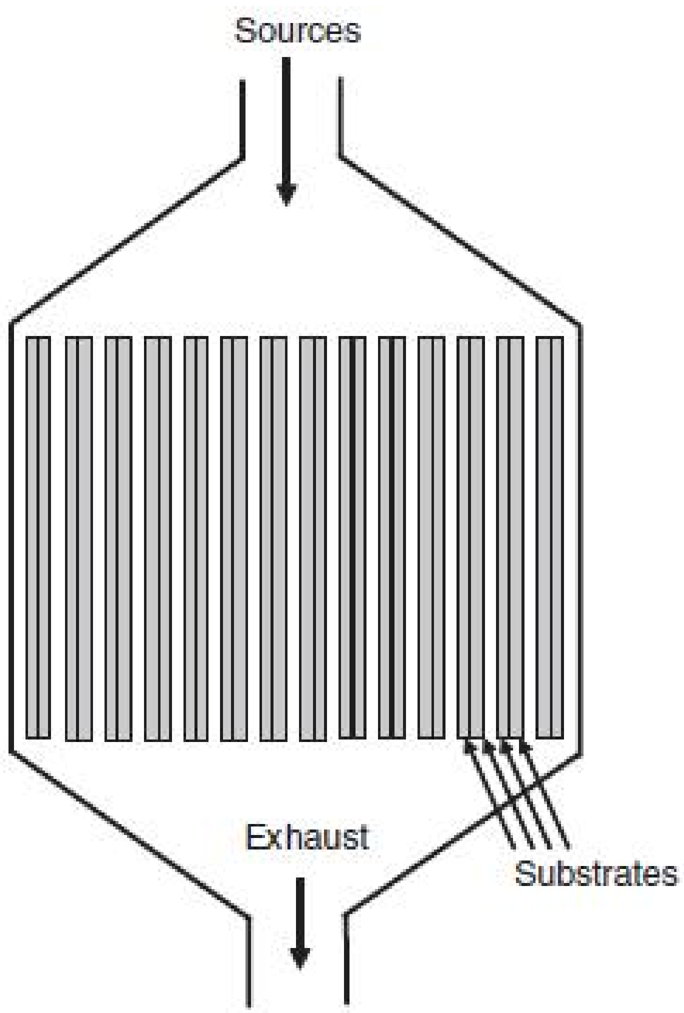
ALD reactors for R&D and hardware design



Perpendicular and cross flow reactors



Batch ALD in cross flow reactor

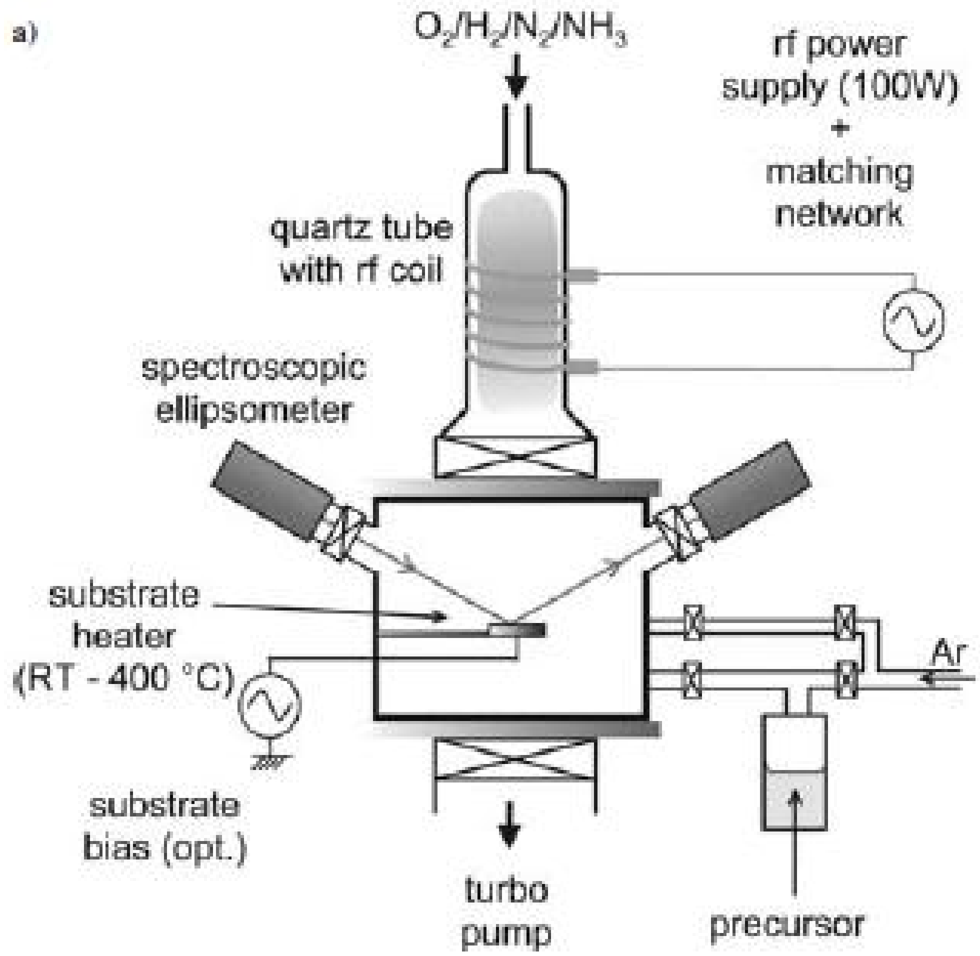


Perpendicular vs. cross flow reactor

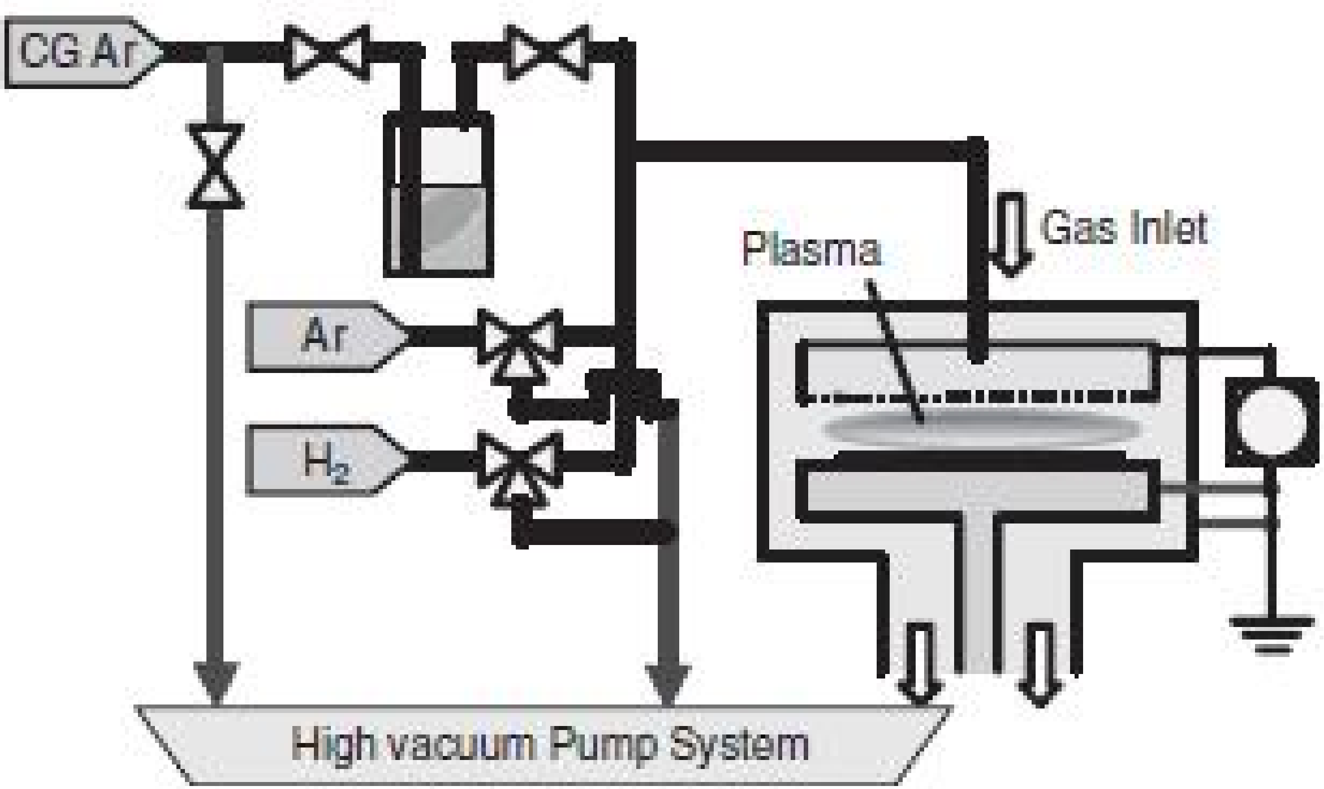
- Perpendicular flow with showerhead or diffuser plate offers better film uniformity than cross flow reactor:
  - Thermally non-stable precursors
  - Secondary reactions of gaseous by-products of the surface reaction
- Flow dynamics can suffer in showerhead reactor making it slower than cross flow reactor
- Cross flow reactor is clearly more feasible to scale up for batch processing

Film uniformity in Atomic Layer Deposition: Elers et al., chemical.vap. Deposition **2006**,12, 13-24

IC RF plasma source in ”remote” plasma ALD



Capacitively coupled direct plasma ALD

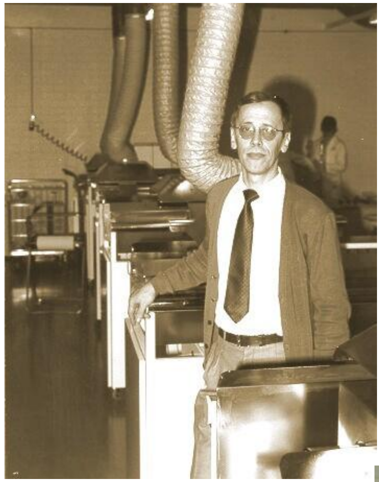


Plasma vs. non-plasma ALD

- There is no clear advantage to use plasma for metal oxide processes (some exceptions found in electrical properties)
- Advantage of plasma can be seen in low temperature reduction processes to make some metals
- Plasma process compromises some characteristic ALD properties: step coverage, surface sensitivity of substrate, bacth capability
- Plasma process includes more novelty: easier to publish
- Equipment and process tehcnology of plasma ALD is not mature yet for production

Generations of ALD Reactors in FINLAND

P400 replaced P250



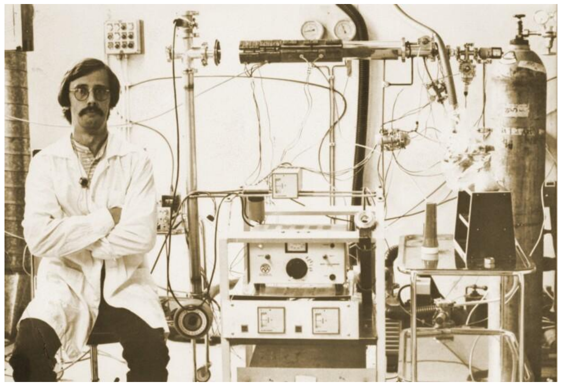
F-150

P200

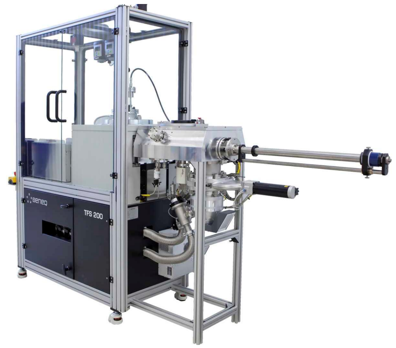
F950

TFS500

P300



Sven Lindfors and his ALD reactor in 1978



TFS 200

Sunale

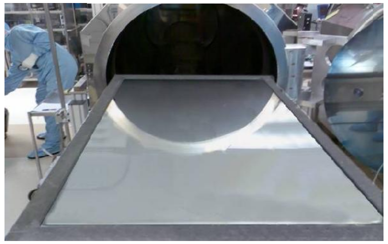
Widests range of ALD tools for industry and research

Also special research versions:
TFS 200R - Rotating version for continuous ALD
TFS 200 With Plasma

TFS 200

TFS 500

P400A / P800



TFS 1200

Beneq is the global leader for industrial ALD applications.

Savannah ALD Research System

Savannah S200

Precursor Cylinders

• **Max. substrate size, 3D objects**

- •100mm, 200mm or 300mm samples. Dome lid accomodates batch processing and 3D objects.

•**Number of liquid, gas and heated sources**

- • Up to 6 precursor ports (all heated lines)
- •Cambridge NanoTech precursor ports are invidually heated and each port accomodates solid, liquid and gas precusors

• **Max. Temp. of heated source:** Up to 200°C

•**Chamber flow dynamics:** Cross flow

•**Films - Oxides**: Al_2O_3, HfO_2, La_2O_3, SiO_2, TiO_2, ZnO, ZrO_2, Ta_2O_5, In_2O_3, SnO_2, ITO, Fe_2O_3, MnO_x, Nb_2O_5. **Nitrides:** WN, Hf_3N_4, Zr_3N_4, AlN, TiN. **Metals:** Ru, Pt, W, Ni, Fe, Co

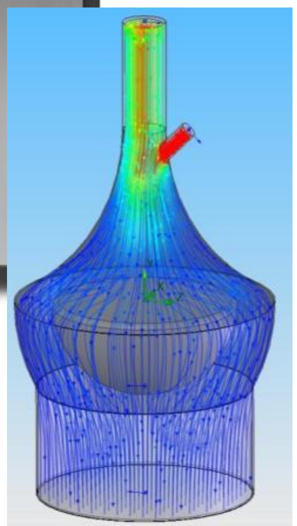
•**PEALD:** N/A

•**Savannah Reactor Features**

- •Two deposition modes
  - •Continuous Mode for rapid film growth
  - •Exposure Mode for high aspect ratio (> 2,000:1)

Fiji Plasma ALD Research System

Fiji F200



Fiji Chamber Design

- **Max. substrate size, 3D objects**
  - •200mm samples, 3D objects that are 50mm high
- **Number of liquid, gas and heated sources**
  - •Up to 6 precursor ports (all heated lines) and up to 6 plasma gases
  - •Cambridge NanoTech precursor ports are invidually heated and each port accomodates solid, liquid and gas precusors
- **Max. Temp. of heated source:** Up to 200°C

•**Chamber flow dynamics:** Perpendicular

•**Films - Oxides**: Al_2O_3, HfO_2, La_2O_3, SiO_2, TiO_2, ZnO, ZrO_2, Ta_2O_5, In_2O_3, SnO_2, ITO, Fe_2O_3, MnO_x, Nb_2O_5. **Nitrides:** WN, Hf_3N_4, Zr_3N_4, AlN, TiN. **Metals:** Ru, Pt, W, Ni, Fe, Co

•**PEALD:** Yes

•**Fiji Reactor Features**

- •Three deposition modes
  - •Plasma Mode
  - •Continuous Mode for rapid film growth
  - •Exposure Mode for high aspect ratio (> 2,000:1)
- •Load-lock and cluster tool capable
- •High temperature capability (up to 1,000°C)

SUNALE™ Atomic Layer Deposition Systems

High quality ALD systems for micro- and nanotechnology applications

Picosun Defines the New Standards for ALD Research and Production

SUNALE™ ALD systems are user-friendly, reliable and productive process tools, which offer unique scalability of results from R&D to production.

SUNALE™ ALD Systems Interest Groups

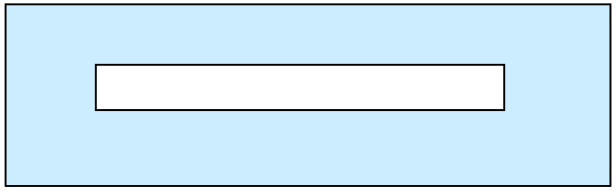
Universities, research institutes and industry.

Oxford Instruments (FlexAL)



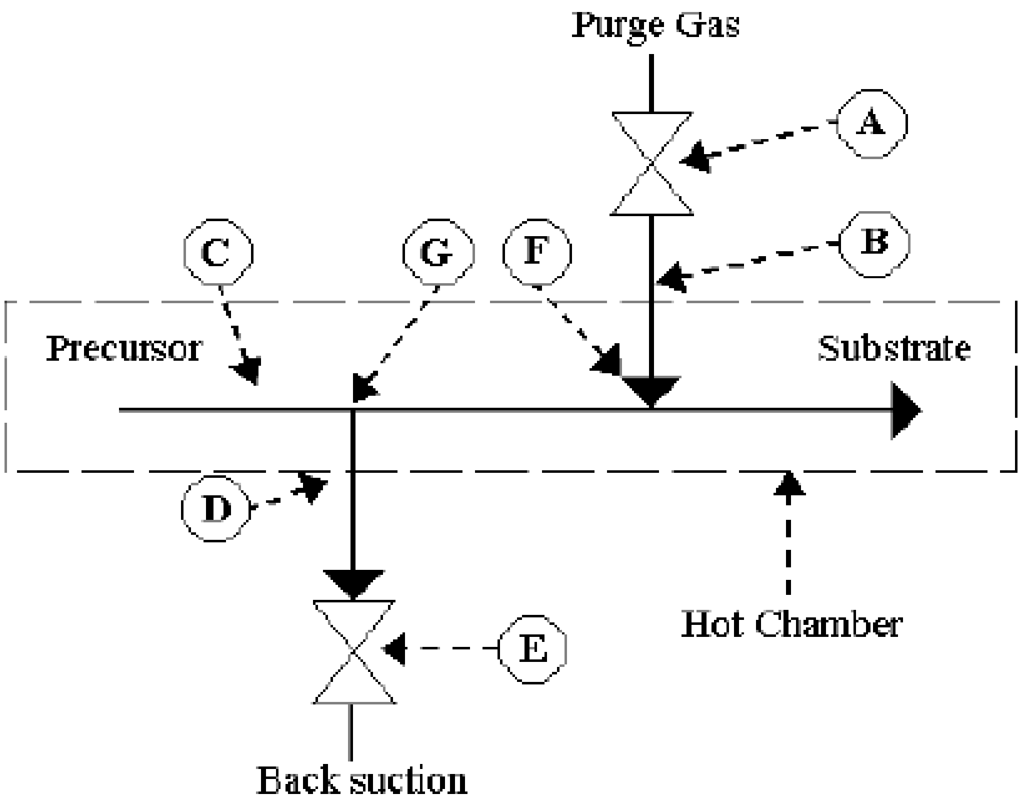

Some important design rules of ALD reactors

- Reaction chamber
  - Hot wall reaction chamber, minimized volume, no dead gas pockets
  - Double wall chamber makes possible easy maintenance ⇒inner and outer chamber isolated from each other
  - Effective gas mixing required for large substrates



- Source delivery lines
  - Reactive precursors have individual source delivery lines from the source to the reaction Chamber
  - Positive temperature gradient from the source to the reaction chamber
    - 1. Heating tapes ⇒ 2. heating jackets ⇒ 3. body mounted heating ⇒ 4. oven
      - 1/2: Cold spots nearly impossible to avoid
  - Pulsing valves must be as close possible to the reaction chamber
    - Minimized purging volume
    - Degassing of ”sticky” precursors like water
  - No dead gas pockets

Inert gas valving

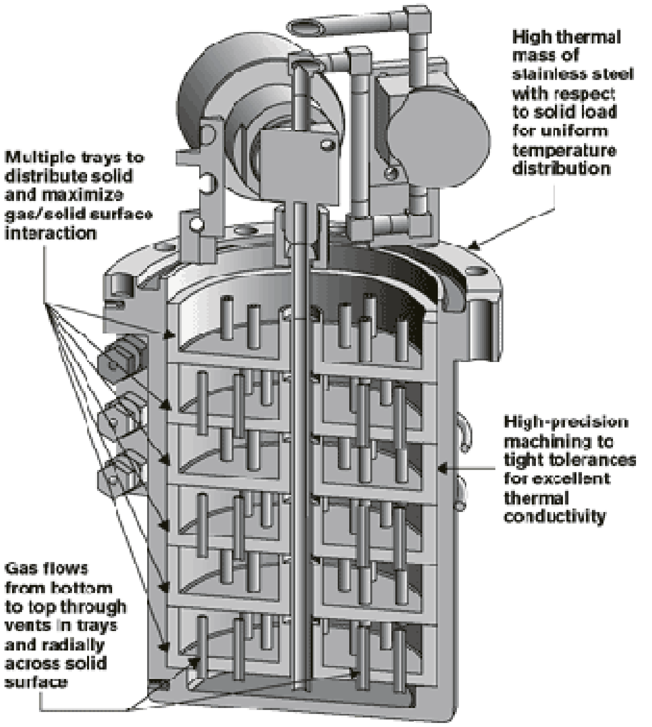


Some important design rules of ALD reactors

- Sources
  - Grain size of powder and powder distribution in the source vessel impact to dosing
  - High viscous liquids may form a film on the surface and thus, require mixing
  - Pressure transducer helps to indentify empty source vessel and adjust high enough temperature
  - Heating requirements are the same as for the source delivery lines
  - For high pressure gas source: the volume between the last flow restriction and pulsing valve must be minimized

  ⇒ It causes high pressure dose

Cross-Section of Solid-Source Vaporizer



ALD Materials and their Industrial Applications

Materials deposited by ALD

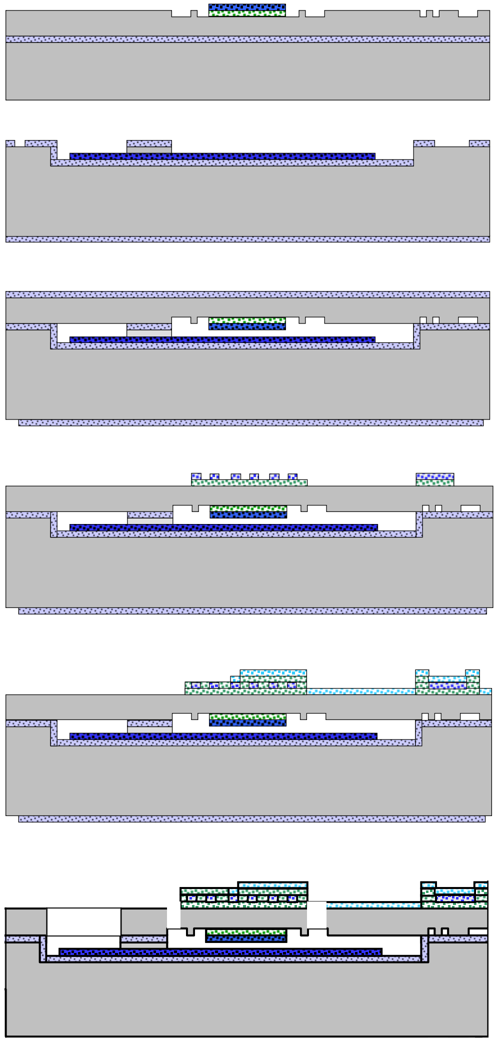
Oxides	
Dielectric	Al_2O_3, TiO_2, ZrO_2, HfO_2, Ta_2O_5, Nb_2O_5, Sc_2O_3, Y_2O_3, MgO, B_2O_3, SiO_2, GeO_2, La_2O_3, CeO_2, PrO_x, Nd_2O_3, Sm_2O_3, EuO_x, Gd_2O_3, Dy_2O_3, Ho_2O_3, Er_2O_3, Tm_2O_3, Yb_2O_3, Lu_2O_3, $SrTiO_3$, $BaTiO_3$, $PbTiO_3$, $PbZrO_3$, Bi_xTi_yO, Bi_xSi_yO, $SrTa_2O_6$, $SrBi_2Ta_2O_9$, $YScO_3$, $LaAlO_3$, $NdAlO_3$, $GdScO_3$, $LaScO_3$, $LaLuO_3$, $Er_3Ga_5O_{13}$
Conductors/ Semiconductors	In_2O_3, In_2O_3:Sn, In_2O_3:F, In_2O_3:Zr, SnO_2, SnO_2:Sb, ZnO, ZnO:Al, ZnO:B, ZnO:Ga, RuO_2, RhO_2, IrO_2, Ga_2O_3, V_2O_5, WO_3, W_2O_3, NiO, FeO_x, CrO_x, CoO_x, MnO_x
Other ternaries	$LaCoO_3$, $LaNiO_3$, $LaMnO_3$, $La_{1-x}Ca_xMnO_3$
Nitrides	
Semiconductors/Dielectric	BN, AlN, GaN, InN, SiN_x, Ta_3N_5, Cu_3N, Zr_3N_4, Hf_3N_4
Metallic	TiN, Ti-Si-N, Ti-Al-N, TaN, NbN, MoN, WN_x, WN_xCy
II-VI compounds	ZnS, ZnSe, ZnTe, CaS, SrS, BaS, CdS, CdTe, MnTe, HgTe,
II-VI based TFEL phosphors	ZnS:M (M = Mn, Tb, Tm), CaS:M (M = Eu, Ce, Tb, Pb), SrS:M (M = Ce, Tb, Pb)
III-V compounds	GaAs, AlAs, AlP, InP, GaP, InAs
Fluorides	CaF_2, SrF_2, MgF_2, LaF_3, ZnF_2
Elements	Ru, Pt, Ir, Pd, Rh, Ag, W, Cu, Co, Fe, Ni, Mo, Ta, Ti, Al, Si, Ge
Others	La_2S_3, PbS, In_2S_3, Cu_xS, $CuGaS_2$, Y_2O_2S, WS_2, TiS_2, SiC, TiC_x, TaC_x, WC_x, $Ca_x(PO_4)_y$, $CaCO_3$

Potential use of ALD in MEMS

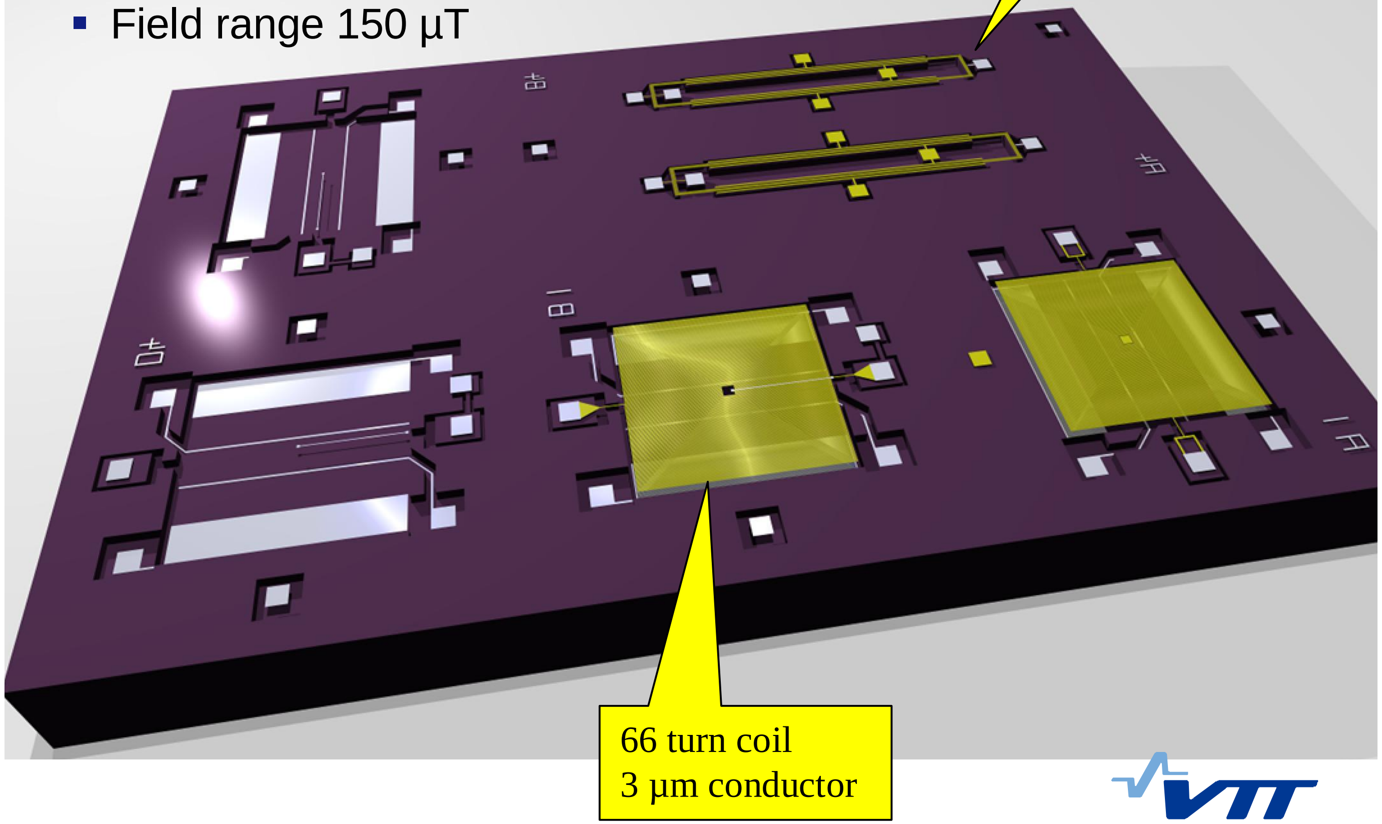
- Electrically insulating conformal layers at low temperatures
- Etch masks, etch stop layers
- Conductive seed layers for plating
- Thermally conductive conformal layers
- Hydrophobic layers → decrease of stiction
- Hermetic coatings
- Biocompatible coatings
- Closing of nanoscale pores
- Optical layers (reflective, anti-reflective, black absorbers)
- Layers reducing frictional wear
- Diffusion barrier
- Passivation
- …

First reports of ALD in MEMS year 2002 → developing area

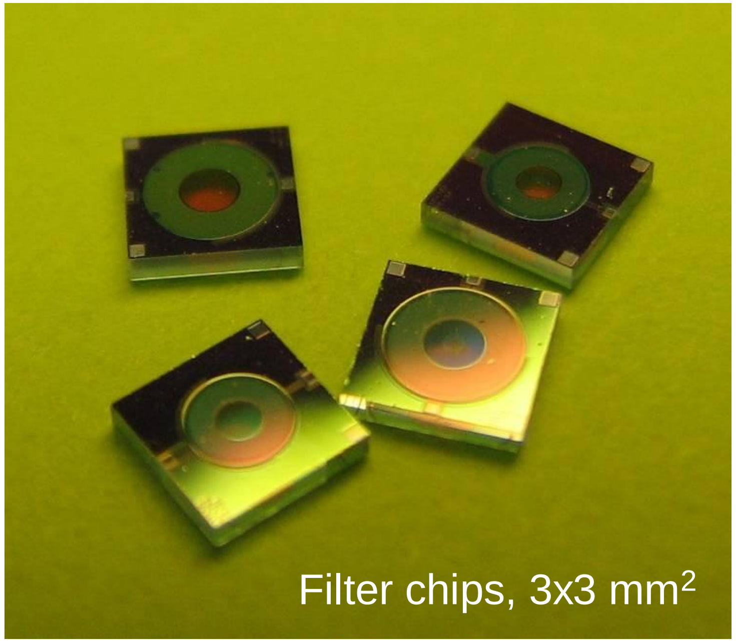
MEMS Magnetometer



- Based on Lorentz force: Multi-turn coil processed on a SOI resonator
- Measured resolution 7 nT/rtHz
- Angular resolution 4 deg/rtHz
- Field range 150 µT

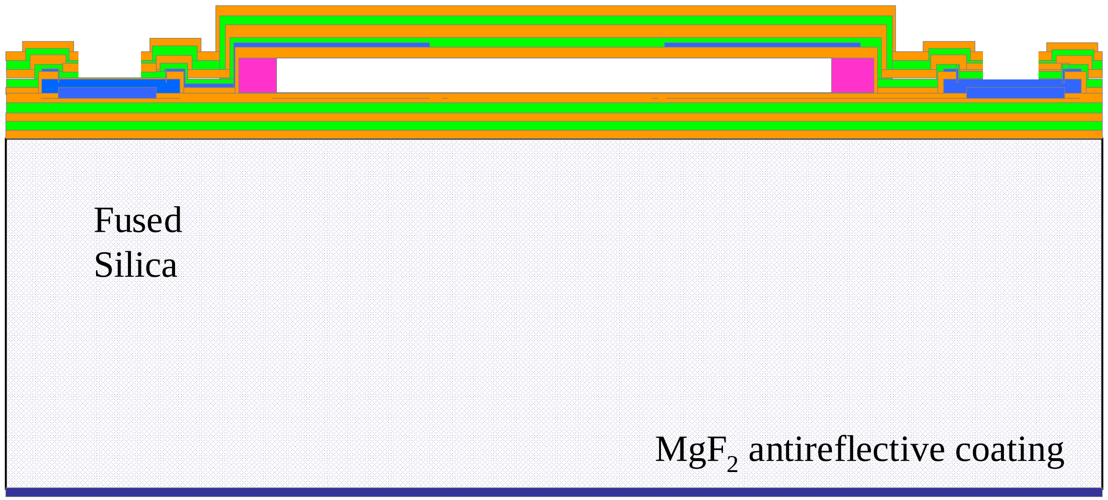


Tunable UV/VIS/IR band-pass filters



Filter chips, 3x3 mm^2

- Potential use in fuel quality monitoring in automotive applications



Key parameters

Wavelength range:	**350 … 5000 nm**
Orders:	**1st up to the 6th order FPIs**
Dielectric mirror materials:	**Si_3N_4, SiO_2, Si, Al_2O_3 or TiO_2**
Sacrificial layer material:	**Polymer or oxide**
Aperture size:	**1 - 3 mm dia.**

Visible FPI process flow
→ → VTT Monolithic Spectrometer

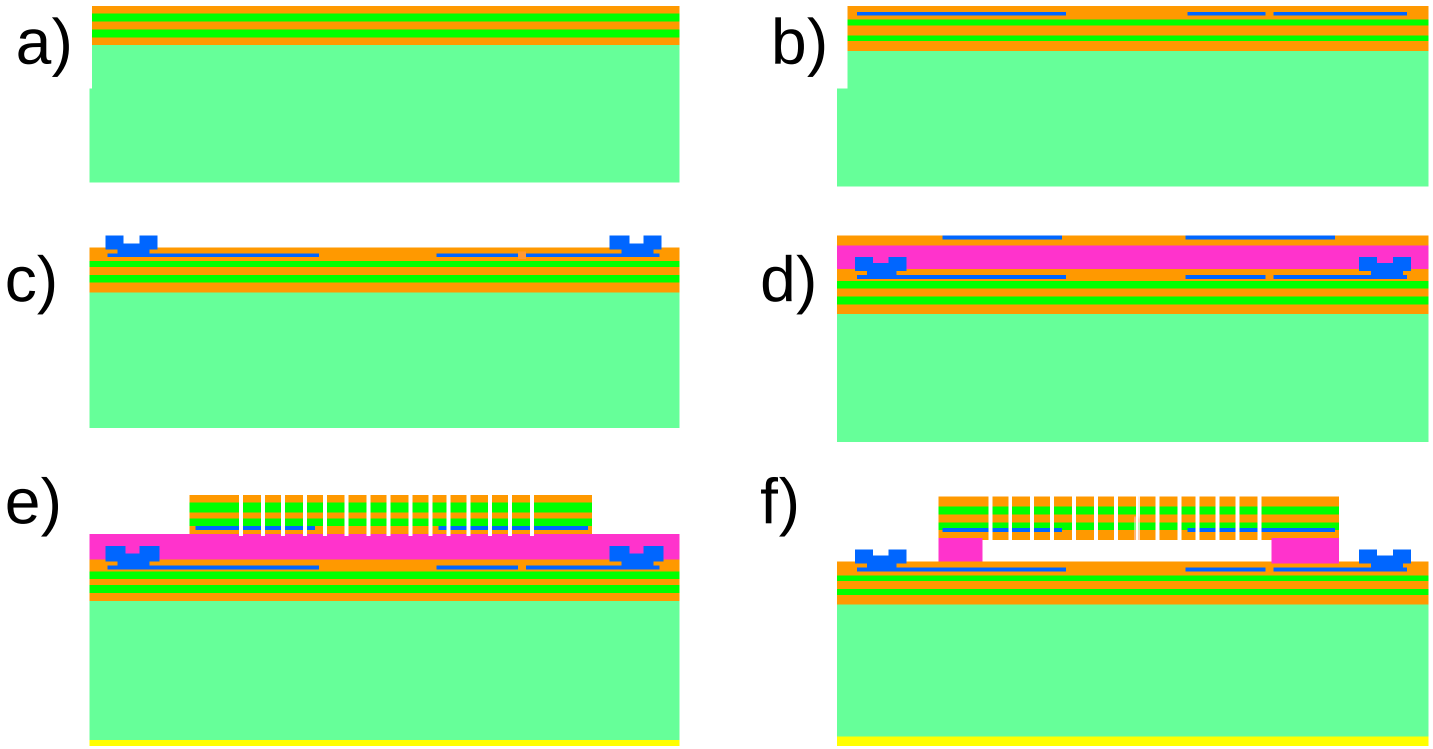
a) bottom mirror (Al_2O_3 and TiO_2)

b-c) bottom electrodes

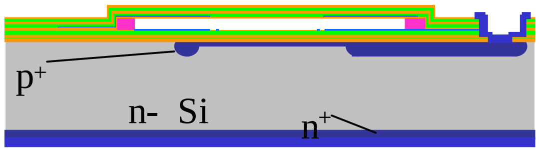
d) sacrificial polymer layer and top electrodes

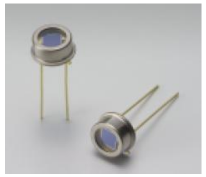
e) top mirror and patterning

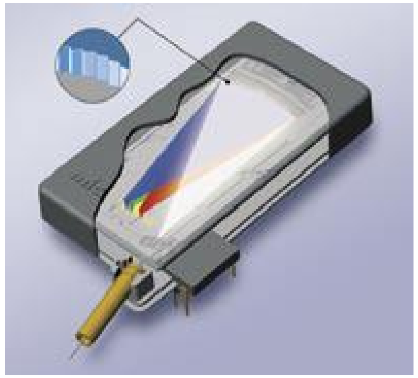
f) release in O_2-plasma

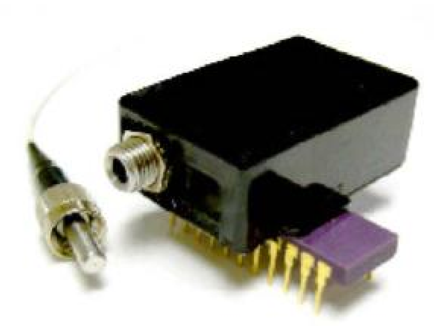


VTT Monolithic spectrometer compared to state-of-the-art









CP20 Compact Spectrometer System

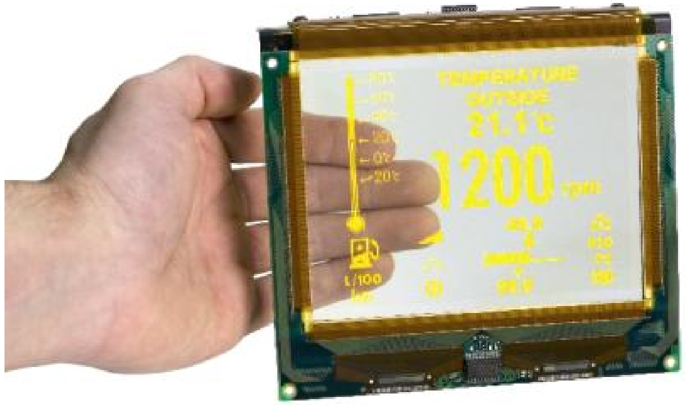
	VTT monolithic spectrometer	Boehringer Ingelheim microParts GmbH Micro-spectrometer	Horiba Jobin-Yvon Micro-spectrometer
Dimensions	TO-5, diam.=9.2 mm, Height 4.2 mm	54 mm x 32 mm x 9.5 mm	34.5 mm x 13.5 mm x 9.5 mm
Spectral range	(220)350 – 1100 nm	350 – 850 nm	380 – 760 nm
Spectral resolution @ FWHM	2 – 7 nm	< 10 nm	< 5 nm
Minimum Transmission at full spectral range	> 70 %	> 30 %	> 30 %
Relative manufacturing cost	1.0	4.0	8.0

EL display production since 1983

- Planar has delivered in total over 3.000.000 million displays by 2009
    - Denso in Japan started EL production in late 90’s

Helsinki-Vantaa airport information boards were delivered in 1983

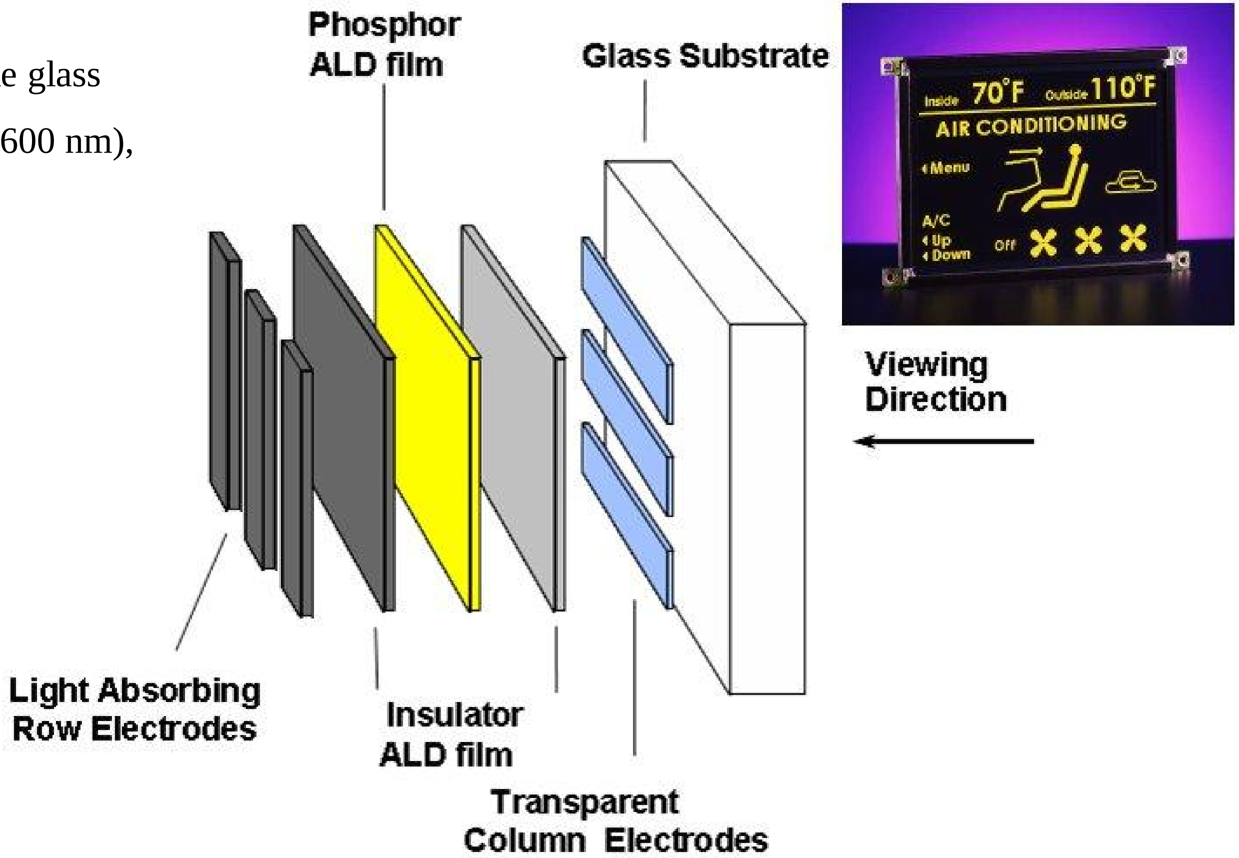
Transparent displays



PLANAR

Atomic Layer Epitaxy (ALE) until mid 90's

1. Al_2O_3 (200 nm) ion barrier for soda lime glass
2. DSD: Al_2O_3/TiO_2) (200 nm), ZnS:Mn (600 nm), Al_2O_2/TiO_2 (200 nm)
3. Al_2O_3 (200 nm) passivation



Industrial applications

- Thin film electroluminescent displays (TFELs)
  - Al_2O_3,TiO_2, ZnS:Mn
- Magnetic heads in hard disks
  - Al_2O_3
- High-k insulator for DRAM and gate oxide of CMOS
  - HfO_2, $HfSi_xO_y$, Hf_xAl_yO, ZrO_2-Al_2O_3
- Protective coating for jewellery (Kalevala Koru and Lapponia jewellery)
  - Al_2O_3
- Optical application (filters)
  - Al_2O_3, Ta_2O_5, TiO_2
- New areas
  - Solar cells, fuel cells, batteries
  - OLED passivation
  - IC applications (MIM capacitor, phase change, flash, memories)

VTT creates business from technology