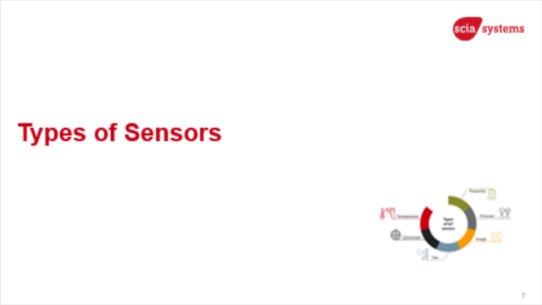
Ion Beam Technology – Enabling an Ever-Evolving Sensor Landscape

2025-04-23, SEMI MSIG Webinar

Agenda

scia Systems – At a Glance

Key facts about the company



Types of Sensors

TMR Sensor Manufacturing

by Ion Beam Milling

Infrared Sensor Manufacturing

by Ion Beam Milling

Piezoelectric Sensor Manufacturing

by Ion Beam Milling

Bio Sensor Manufacturing

by Magnetron Sputtering

Magnetic Thin-Film Head Manufacturing

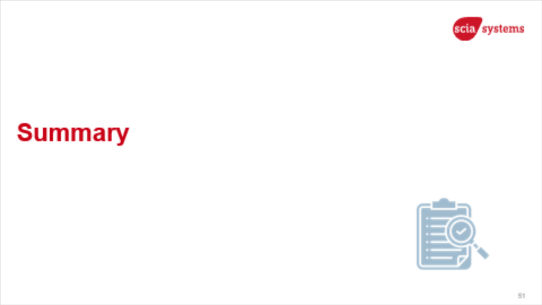
by Ion Beam Trimming

Photonic Integrated Circuits Manufacturing

by Ion Beam Trimming

Micro Bolometer Manufacturing

by Ion Beam Sputter Deposition



Summary

scia Systems – At a Glance

Key facts about the company

scia Systems – At a Glance

scia Systems is a specialist in thin-film process equipment based on advanced ion beam and plasma technologies.

We supply our customers with:

Etching, trimming, coating, and cleaning systems

In-house technology and process development

Global sales and service network

The key components are developed and manufactured by scia Systems itself

Company Figures in Brief

Founded in **2013**
in Chemnitz / Germany

~260
Employees

98.6 Mio. €
Revenue in 2024

17
Sales and service partners worldwide

› 100
Customers in the field of MEMS and optics

› 500
Systems in 24/7 production and R&D

Our Markets

Wafer Processing

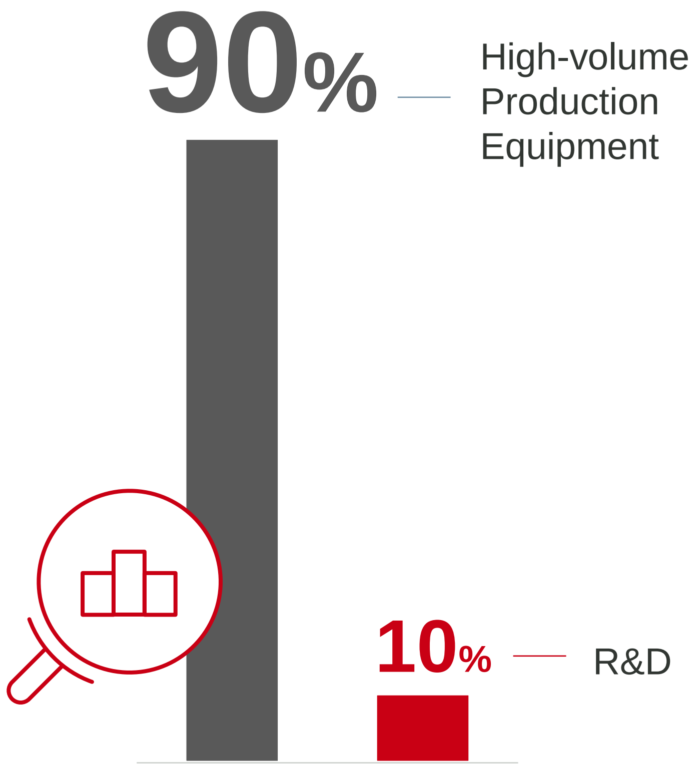
Mobile communication, sensors, magnetic storage, optoelectronics

Optics Manufacturing

Lithography optics, micro- and binary optics, astronomy applications

Customization and Product Development

Diversified (bio)medical applications, R&D



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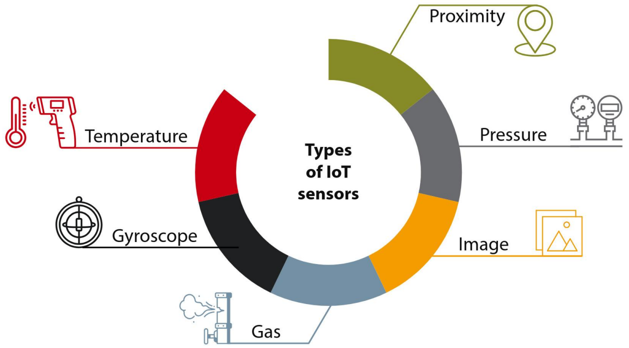

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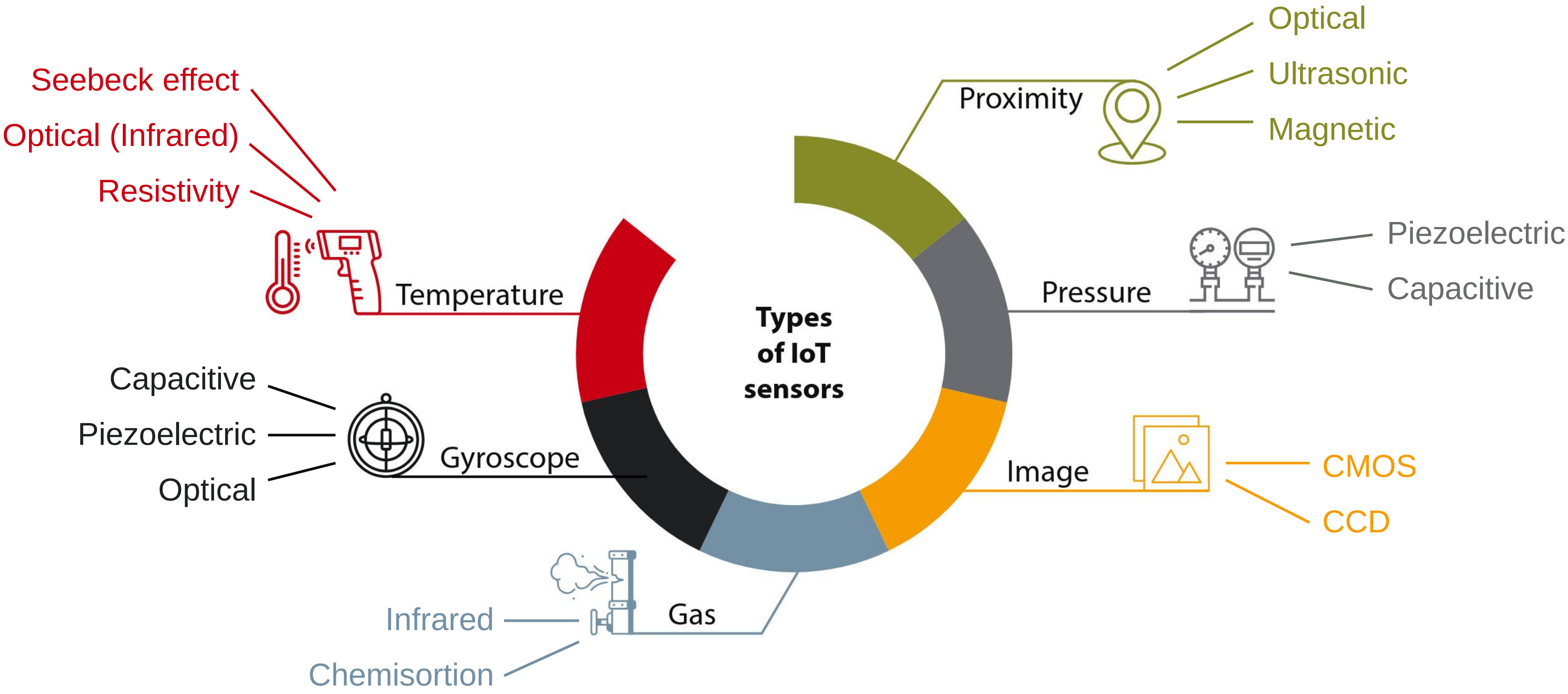


Types of IoT sensors

Temperature
- Seebeck effect
- Optical (Infrared)
- Resistivity

Gyroscope
- Capacitive
- Piezoelectric
- Optical

Gas
- Infrared
- Chemisortion

Image
- CMOS
- CCD

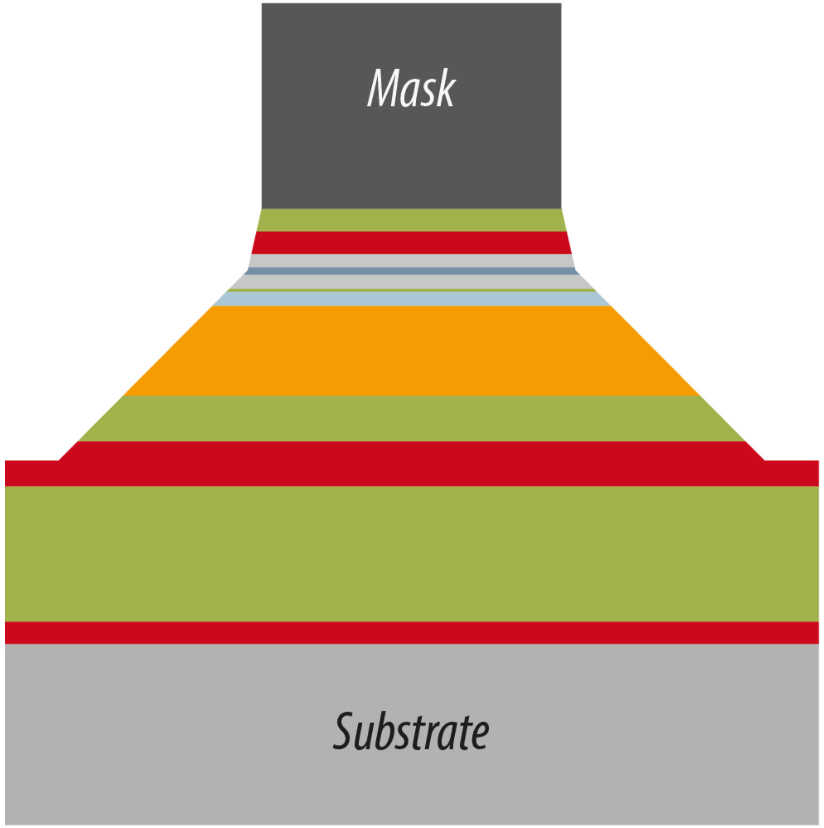
Pressure
- Piezoelectric
- Capacitive

Proximity
- Optical
- Ultrasonic
- Magnetic

What do these Sensors have in Common?

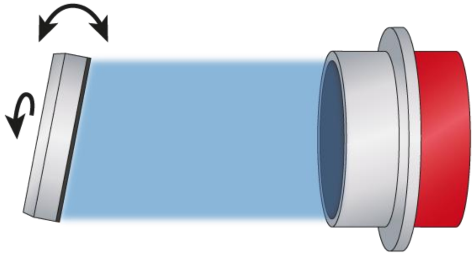
- Complex multilayer structure with film thicknesses between a few hundred nanometers and a few micrometers, consisting of many different materials
  - Optical layers (Si, SiO_2, Si_3N_4, VO_x, LN, LT, BTO, TiO_2)
  - Magnetic layers (CoFe, CoPt, NiFe)
  - Metals (Pt, Au, NiCr, Ta, Ru, Ir)
  - Other (ITO, ZnO, TiN,)
  - Piezoelectric materials (AlN, AlScN, PZT, ZrO_2)
- Those materials need to be deposited and etched

Conventional RIE is not working for many of those elements.



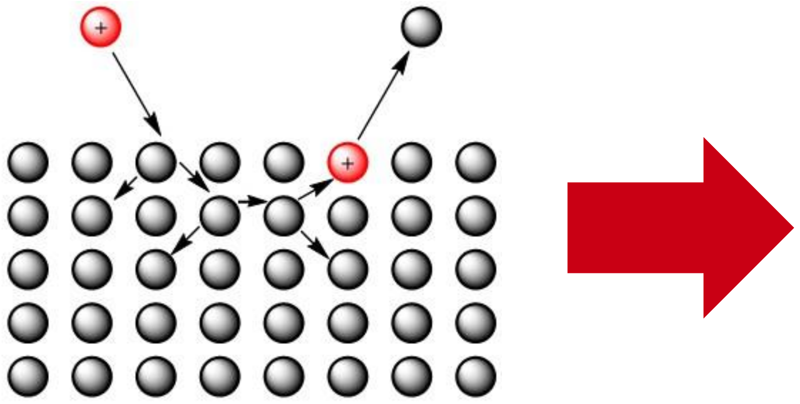
TMR Sensor Manufacturing

by Ion Beam Milling



Ion Beam Milling Principles

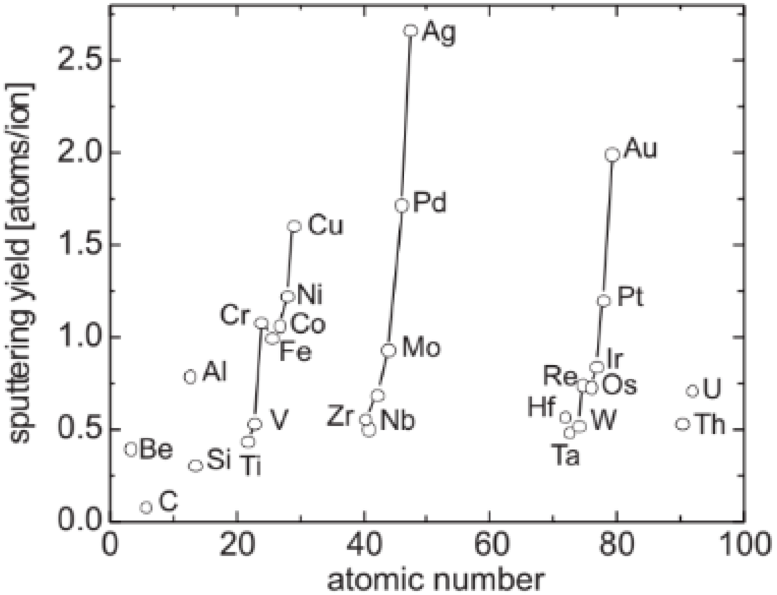
- Atoms of the target material can be ejected by bombardment with high-energy ions
- Momentum exchange between incident ions and atoms of the target material in collision cascades:
  - Material removal with Angstrom accuracy (Ion Beam Etching)
  - Implantation of ions (Ion Implantation)
- Any material with a sufficiently high melting point can be etched
- Low process pressure (10^{-4} mbar) and temperature (< 100°C)



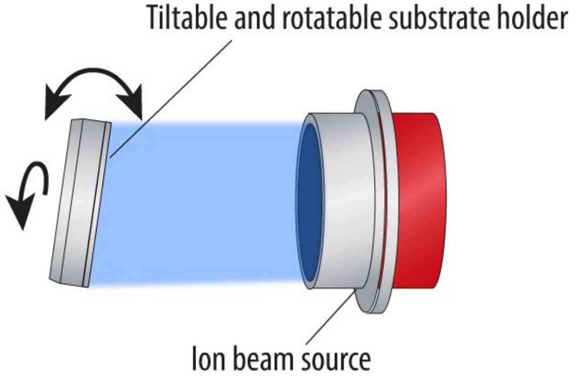
Process with resolution on atomic scale

Basic Principle – Ion Beam Etching (IBE)

- Generation of an ion beam by a broad ion beam source
- Atoms of material are ejected by bombardment with high-energy ions
- Any material with a sufficiently high melting point can be etched
- **Ion Beam Milling (IBM)** / Ion Beam Etching (IBE)
  by (mostly) noble gases, resulting in a physical sputter process
- **Reactive Ion Beam Etching (RIBE)**
  Where reactive gas is directly supplied to the ion beam source
  and combined physical and chemical process
- **Chemically Assisted Ion Beam Etching (CAIBE)**
  The reactive gas is injected as background gas, and reactions are driven
  by ions activating absorbed reactive gas species



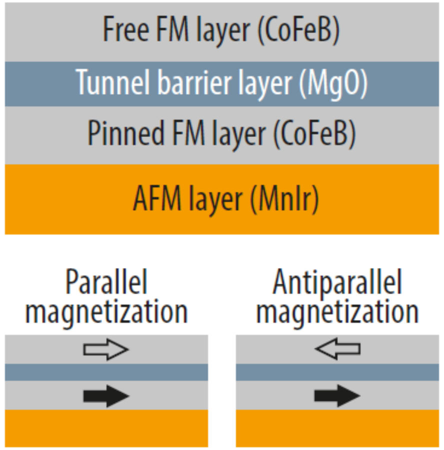
Periodic dependency of the sputter yield



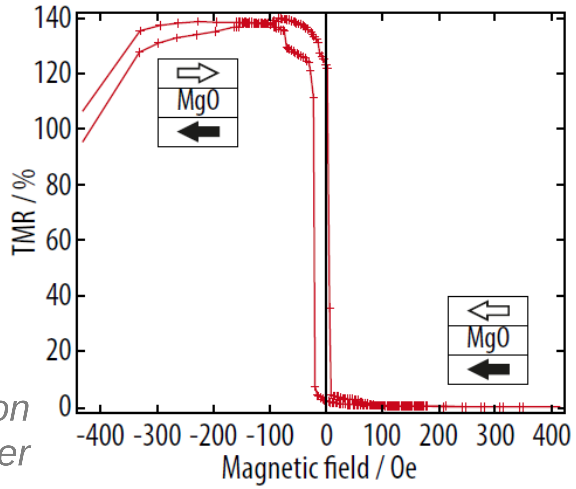
Process arrangement of scia Mill 200

TMR Sensors

- The tunnel-magneto-resistance effect (TMR) is used as a high-precision sensor for magnetic fields
- The main component of the TMR sensor is the magnetic tunnel junctions (MTJ)
- Insulating layer between soft magnetic ferromagnetic layer (free layer) and hard ferromagnetic layer (pinned layer
- Free layer changes easily magnetization direction depending on an external magnetic field, which changes the tunnel probability of electrons/resistivity of the insulating layer



Magnetic tunnel junction based on CoFeB/MgO/CoFeB

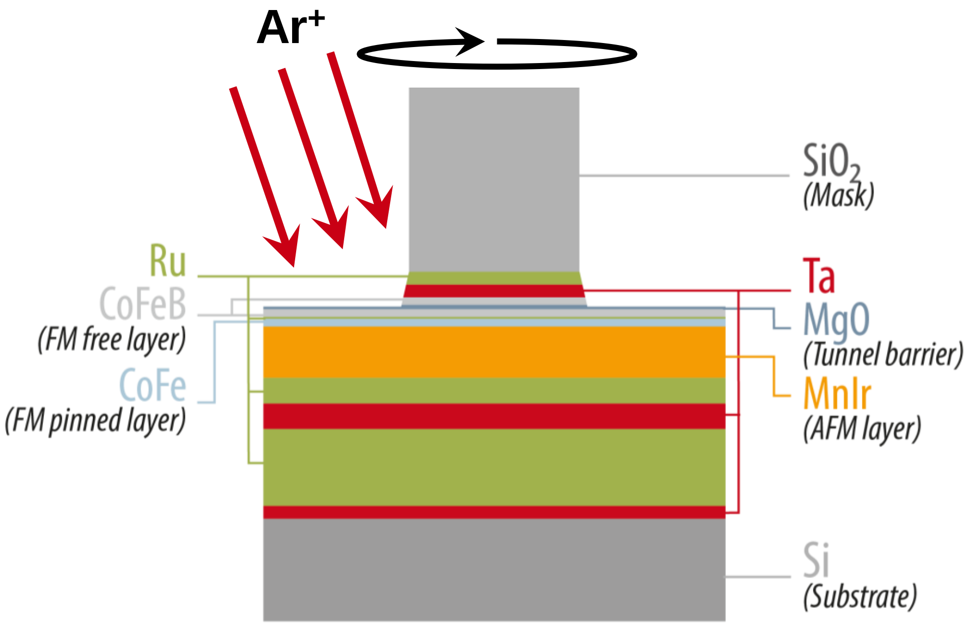


TMR value depending on magnetization of free layer

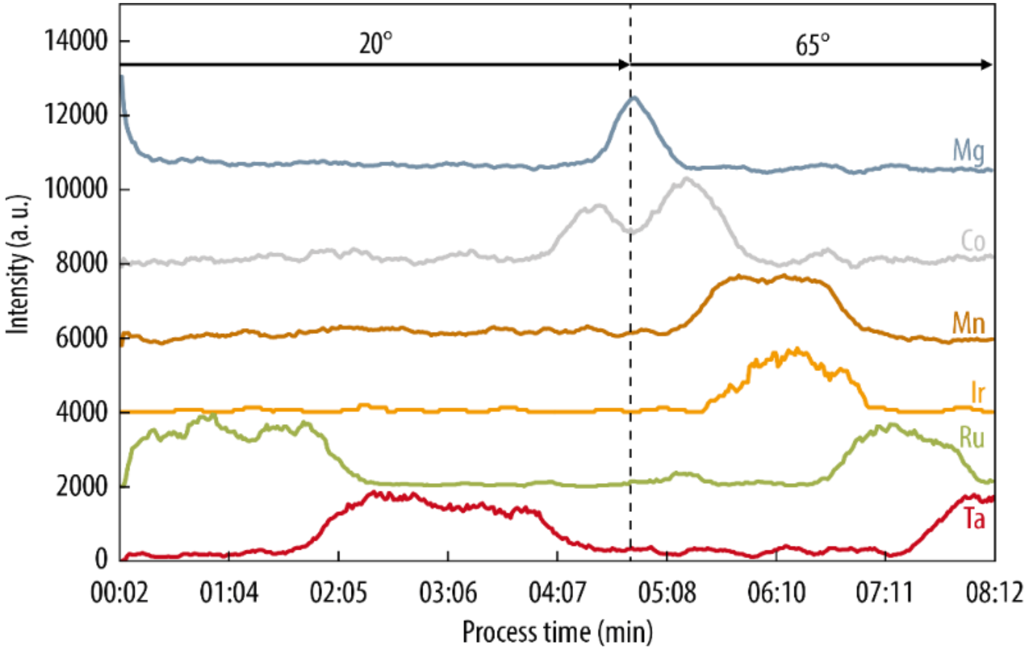
Application - Magneto-Resistance Sensors

- Structuring of Tunnel Magneto Resistance (TMR) stack
- Substrate with a 2 cm x 2 cm size consisting of several layers (Ta, Ru, MnIr, CoFe, Mg)
  - Full process step control by SIMS and OES end point analysis
  - Milling at 20° until tunnel barrier, afterwards milling at 65° until bottom contact

1st step with 20°



Corresponding SIMS-Detection



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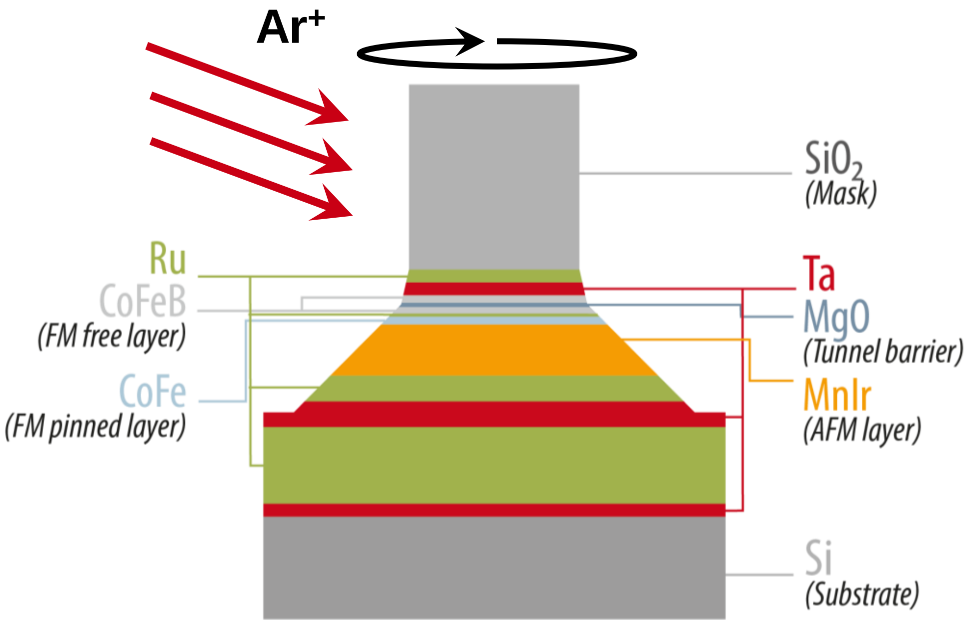
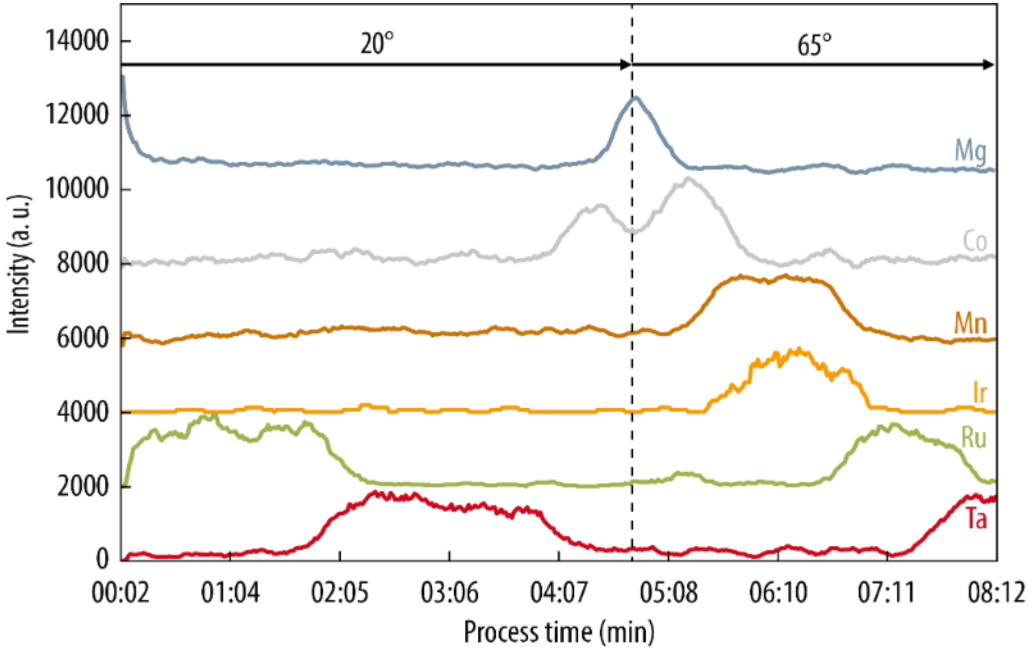
2nd step with 65°



Corresponding SIMS-Detection



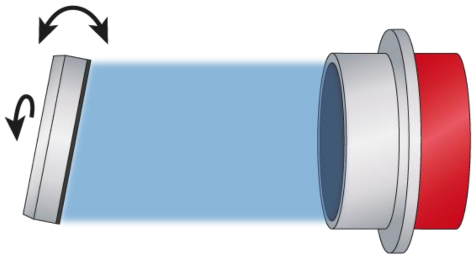
Related Systems - scia Mill 200

- 350 mm on ion beam source for processing of up to 200 mm wafer
- Substrate holder
  - E-chuck for processing of wafers with PR
  - Rotation
  - Tilting
- Process control with
  - SIMS end point detection or
  - optical emission spectroscopy
- Throughput-optimized production systems in variable cluster layouts
- Flexible tool for R&D and small-scale production with single substrate load lock

scia Mill 200 in cluster layout with 3 process chambers

Infrared Sensor Manufacturing

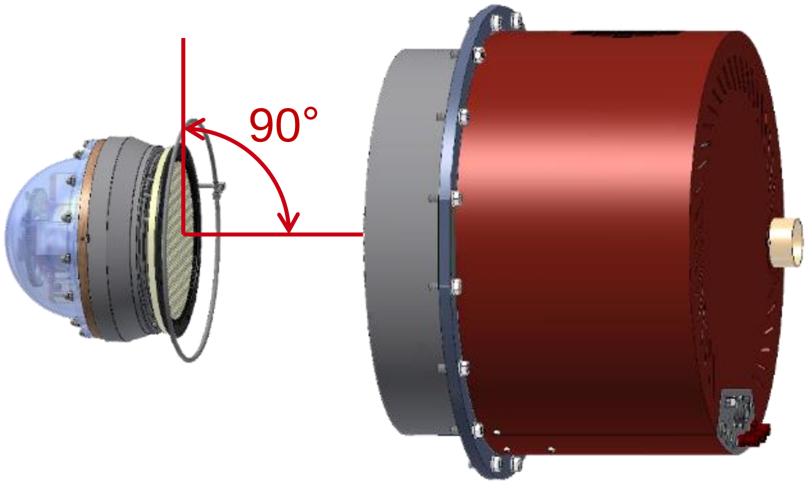
by Ion Beam Milling



Etching of defined Sidewall Angle

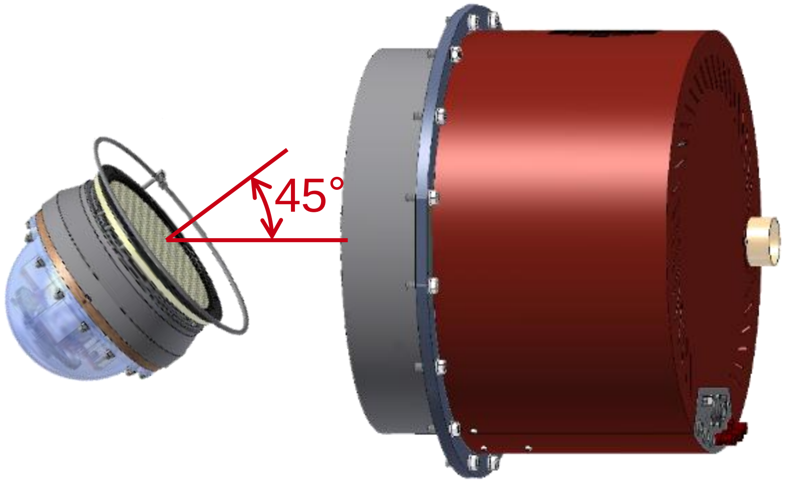
Perpendicular Ion Incidence Angle

- Tilt axis in wafer plane
- End point detection by OES or SIMS



Oblique Ion Incidence Angle

- Any tilt angle from 90° to 0° adjustable
- In-situ tilt movement by recipe
- Gas ring tilts with substrate plane



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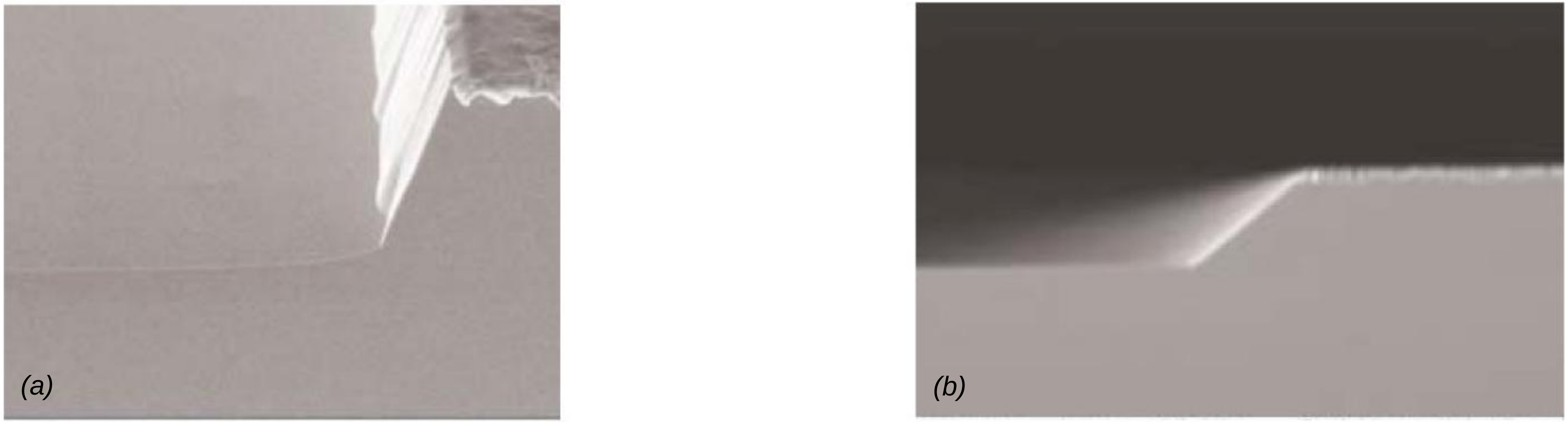
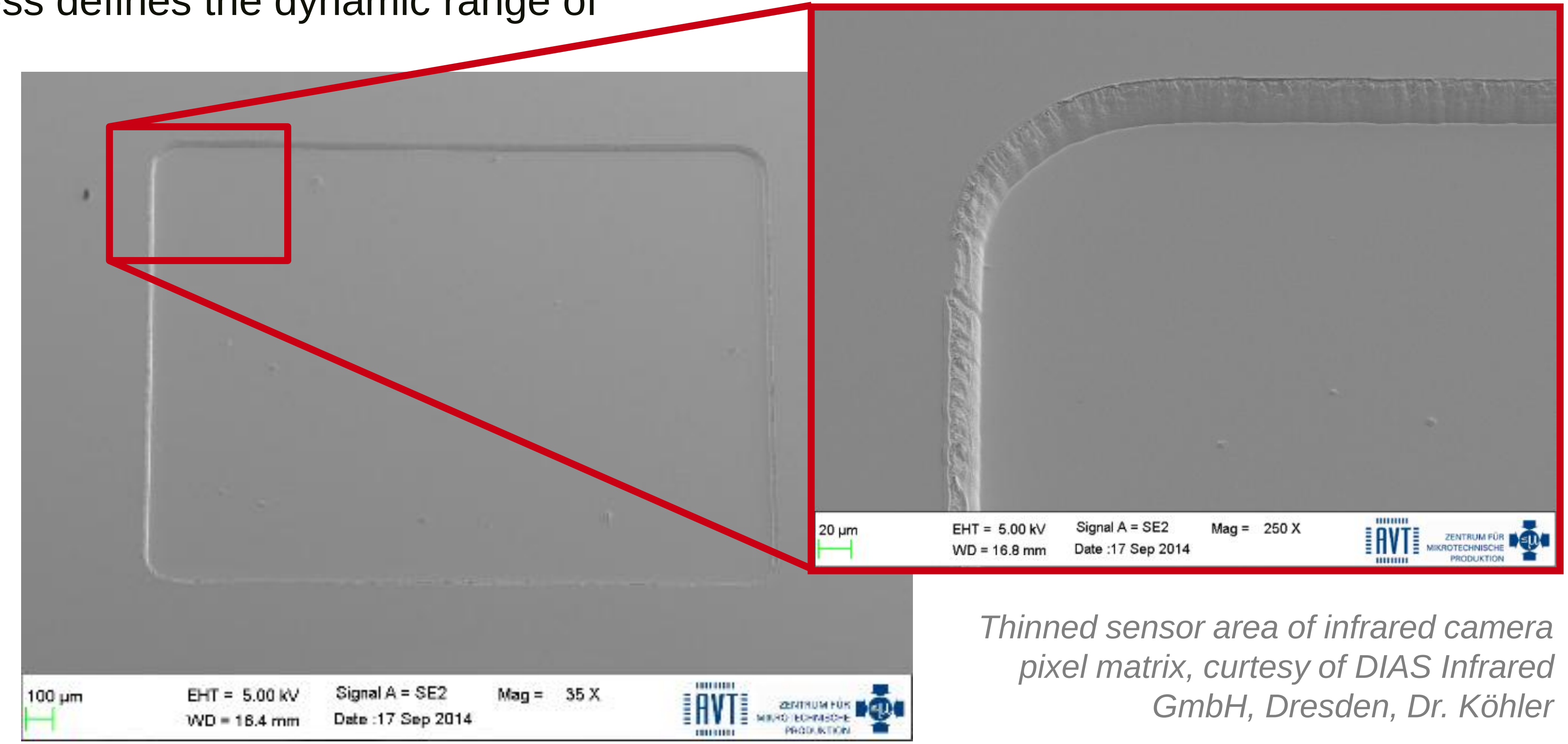


Ion beam etching of an arbitrary film with different beam angles: (a) normal incidence (steep sidewall angle), (b) away from normal incidence (shallow sidewall angle); from: Master Thesis “Integration of CoFeB/MgO-based Magnetic Tunnel Junction on Silicon”, S. Pandharpure

Wafer Thinning for IR Camera Sensors

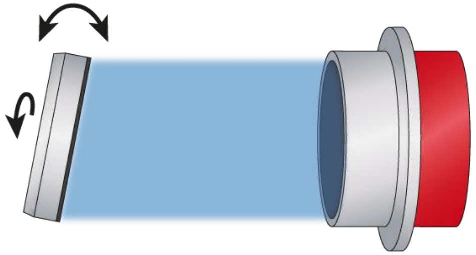
- Backside thinning of $LiTaO_3$ from 25 µm to 5 µm on the scia Mill 150
- Shallow structure sidewall angle for proper metal contact overlap
- Uniformity of recess thickness defines the dynamic range of the infrared sensor array



Thinned sensor area of infrared camera pixel matrix, curtesy of DIAS Infrared GmbH, Dresden, Dr. Köhler

Piezoelectric Sensor Manufacturing

by Ion Beam Milling



Piezoelectric Sensors

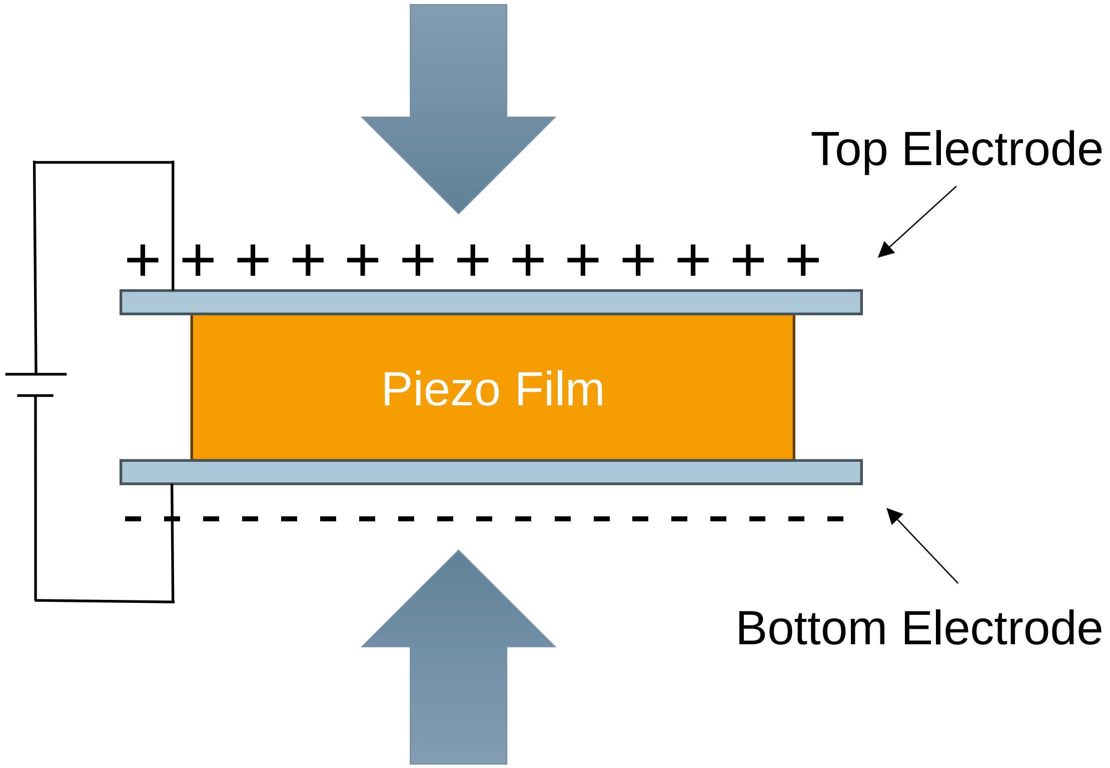
Principle

- Thin piezoelectric layers convert a mechanical force into electrical signals
- Applications:
  - Pressure Sensors
  - Accelerometers
  - Ultrasonic transducers
  - Microphones

Materials with a “high” piezo-electric coefficient

- PZT
- AlScN
- Difficult to etch with RIE → **IBM needed**

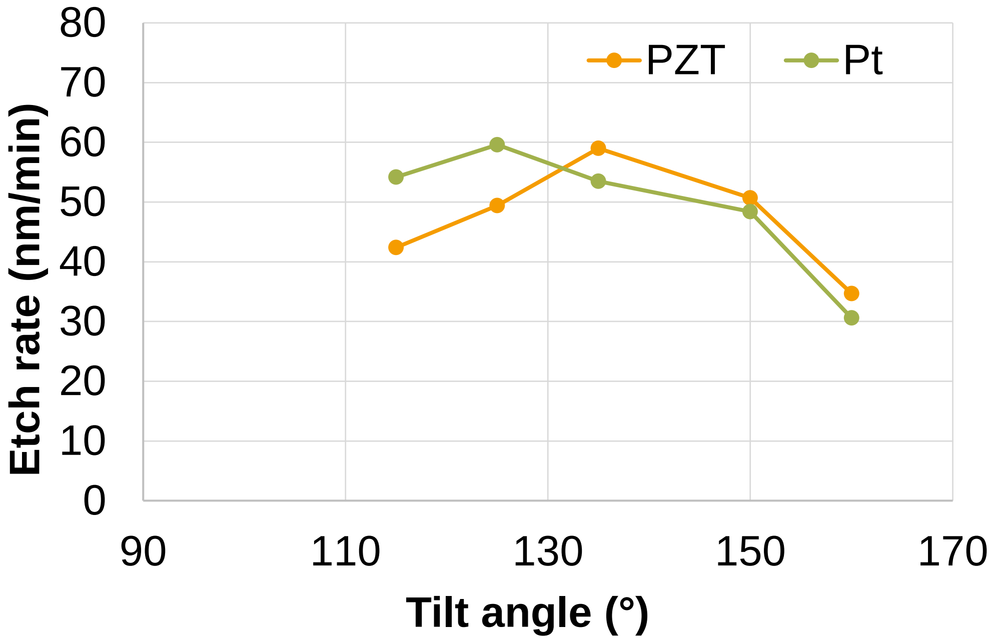
Compression induces electrical field

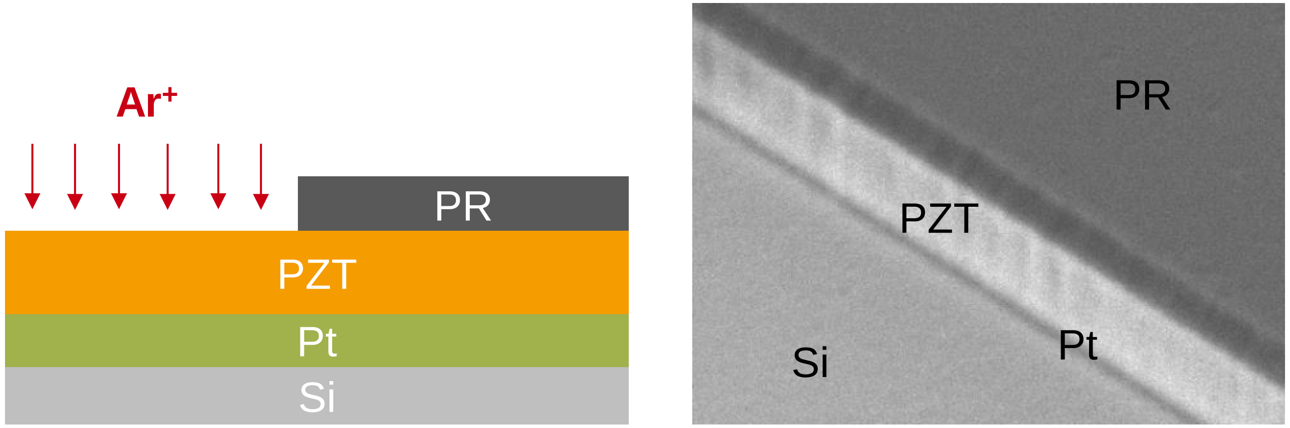


Principle of sensor using piezo electric materials

Etching of PZT

- Etching of Lead-Zirconium-Titanate (PZT)
- Inert etching allows etching of metal electrodes as well
- Ion incidence angle allows selectivity control and higher etch rates

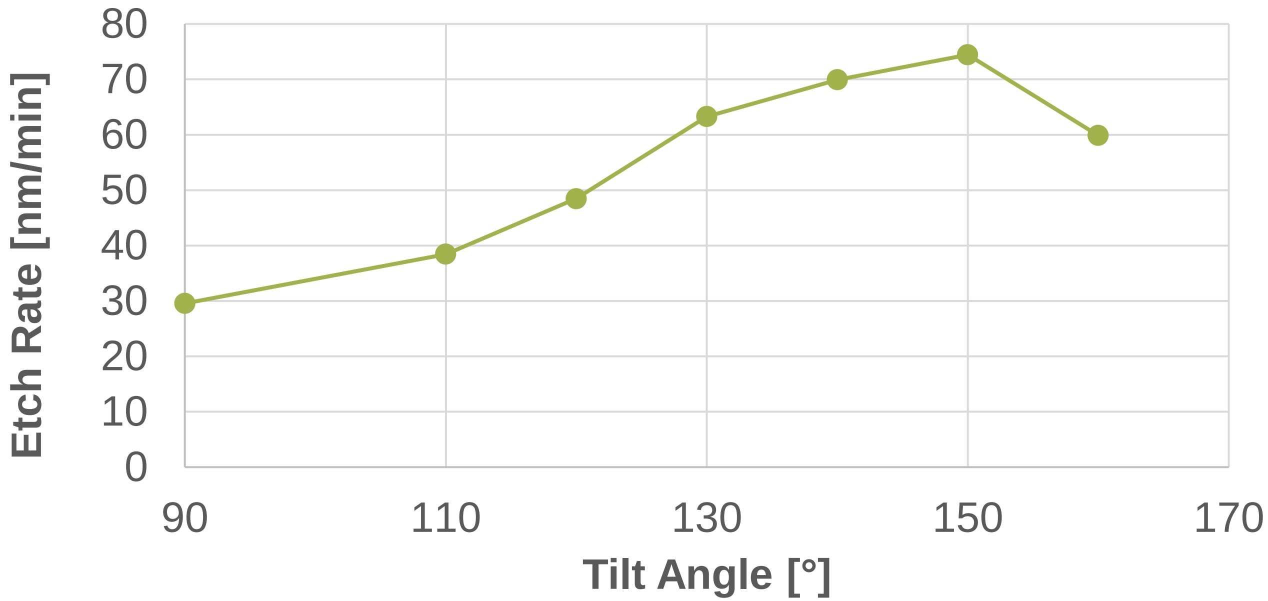


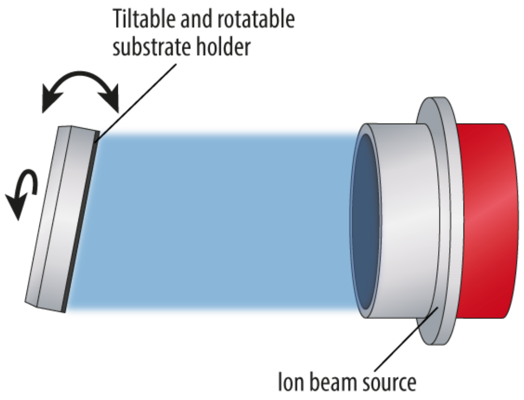


Layer stack and SEM picture after PZT etching

Etching of AlScN

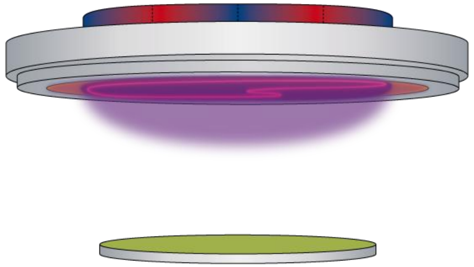
- Etching of AlScN, incl. high concentration up to with 40 % Sc
- Inert etching allows etching of metal electrodes as well
- Ion incidence angle allows higher etch rates





Bio Sensor Manufacturing

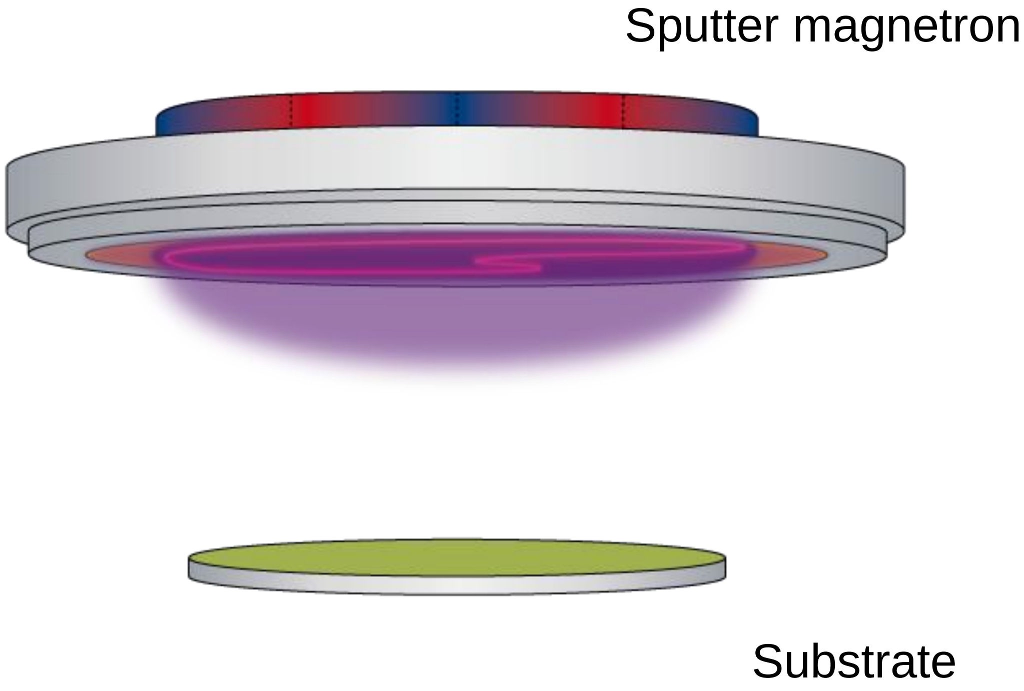
by Magnetron Sputtering



Magnetron Sputter Deposition

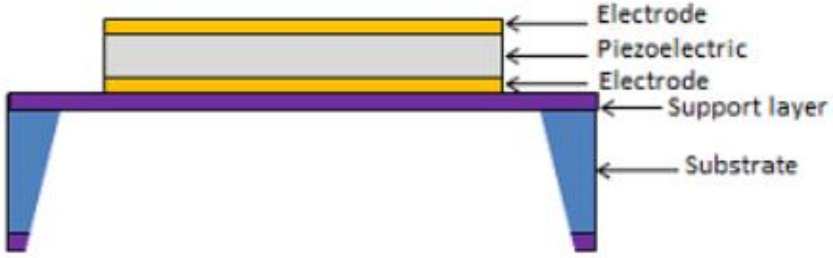
- High voltage and magnetic fields create a plasma in front of a target
- Ions bombard the target and sputter atoms from the target, which are deposited on the substrate

- Substrate motion/rotation improves uniformity
- Substrate heating and bias influence layer properties

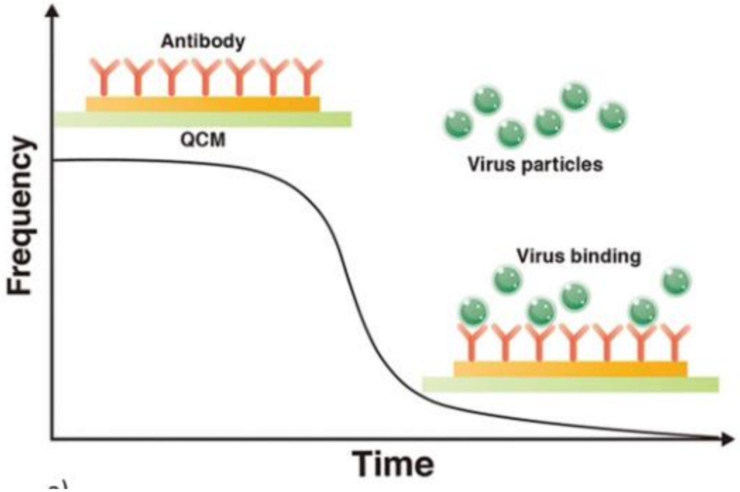


Sensing Principle of BAW Devices

- BAW devices react extremely sensitively to mass load change
- A change in resonant frequency can be easily detected
- Activation of the device by specific bioreceptors
- Limit of detection of 10 pg/ml cf. COVID-19 PCR tests

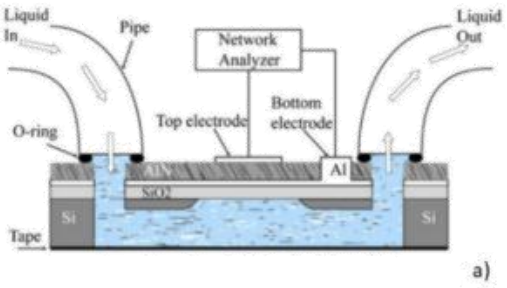


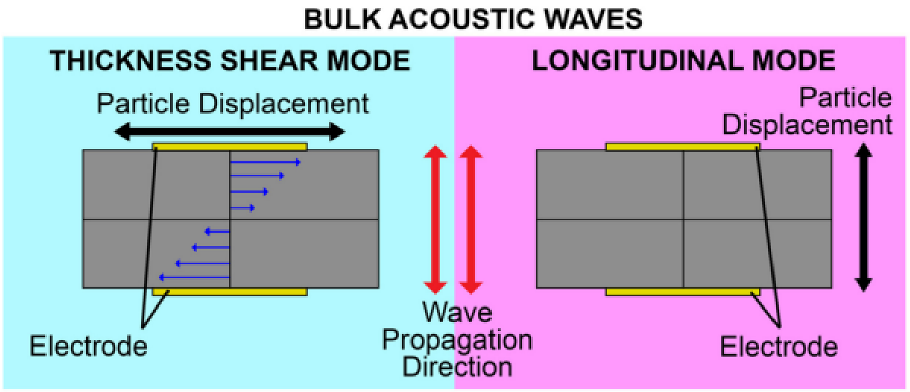
Thin Film Bulk Acoustic Wave Resonator (FBAR)

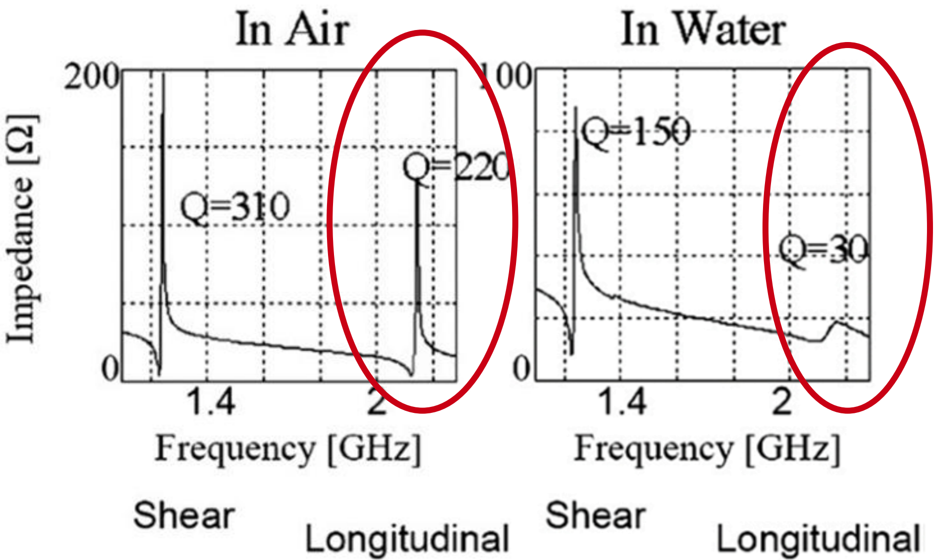


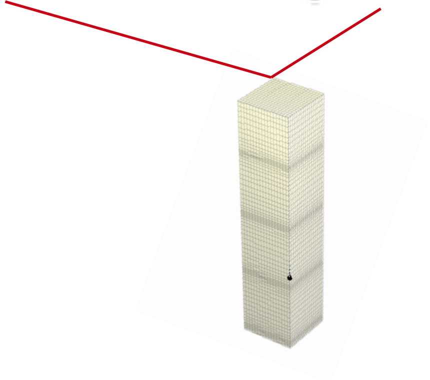
Resonator Modes in Liquids

- **Longitudinal mode** in liquid solvents is strongly damped, due to the higher viscosity of the liquids vs. air









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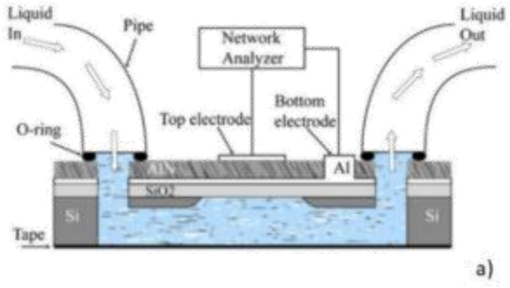
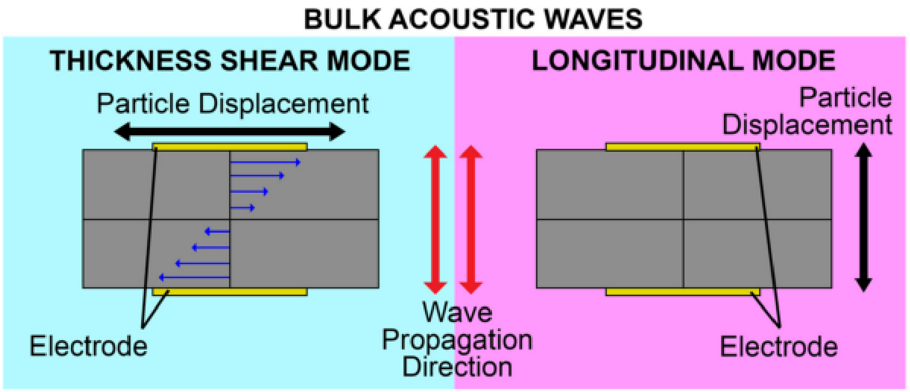
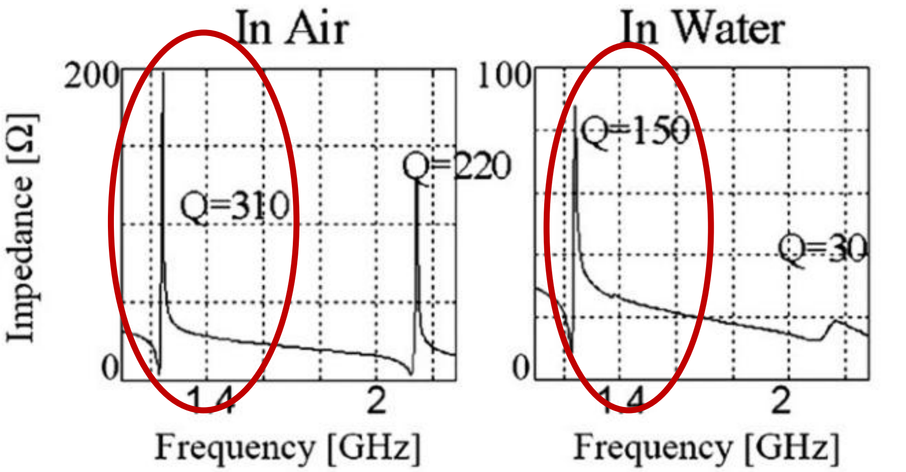
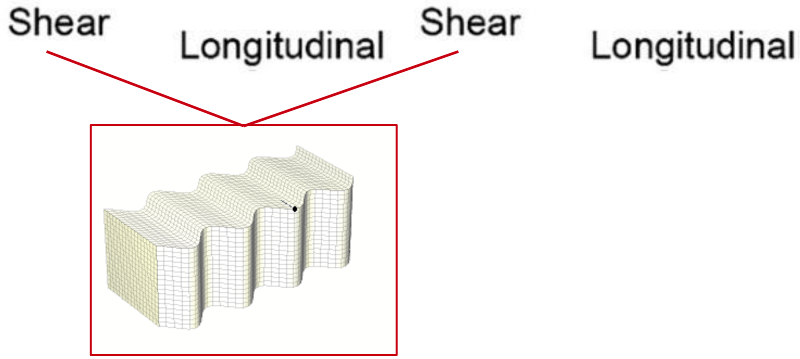


- Less damping of **shear mode** in liquids







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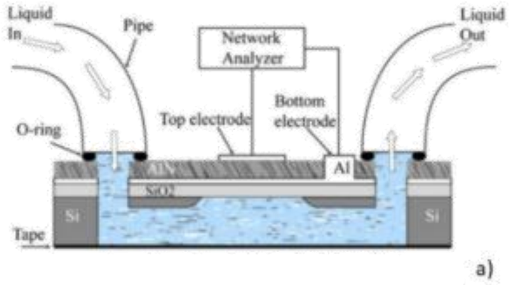
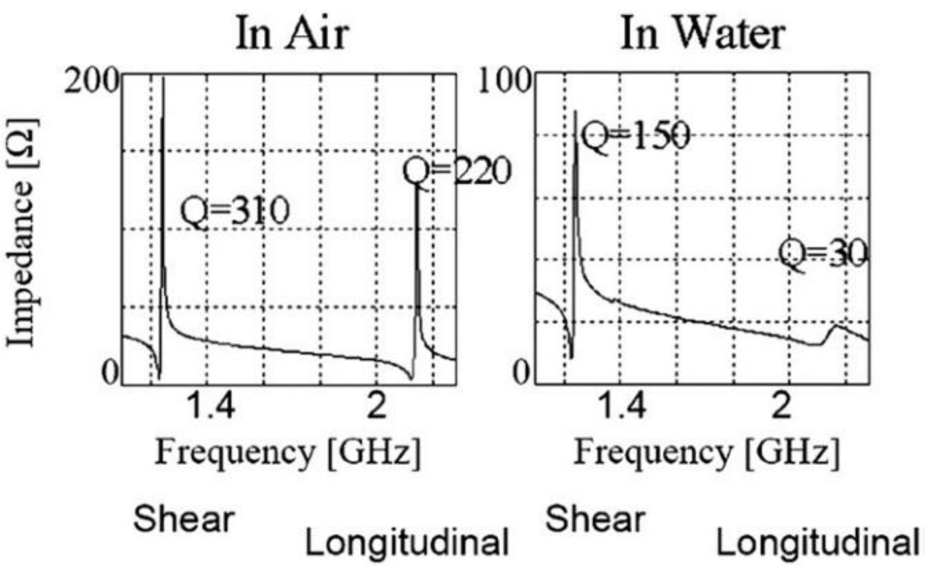
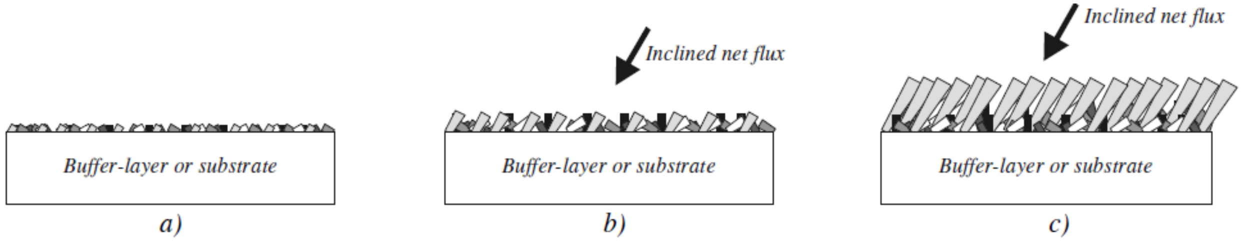


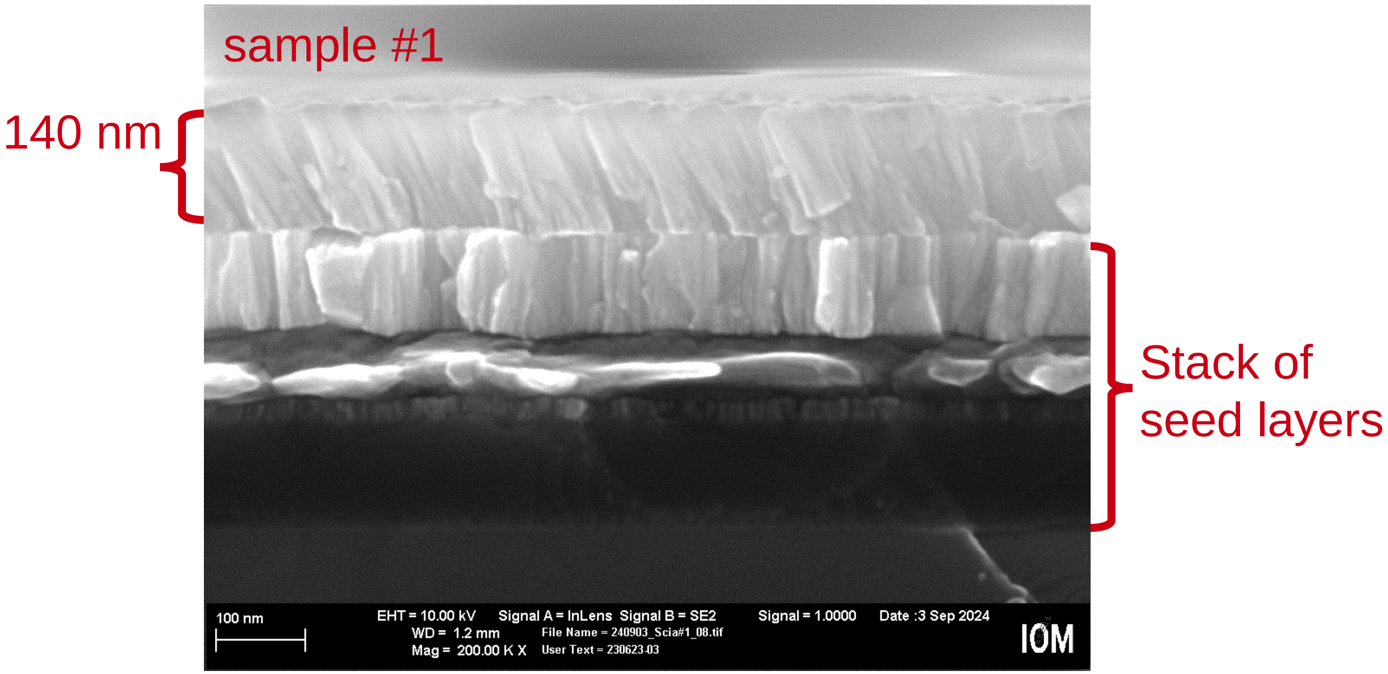
- Less damping of **shear mode** in liquids
- Tilted c-axis AlN used for shear mode excitation



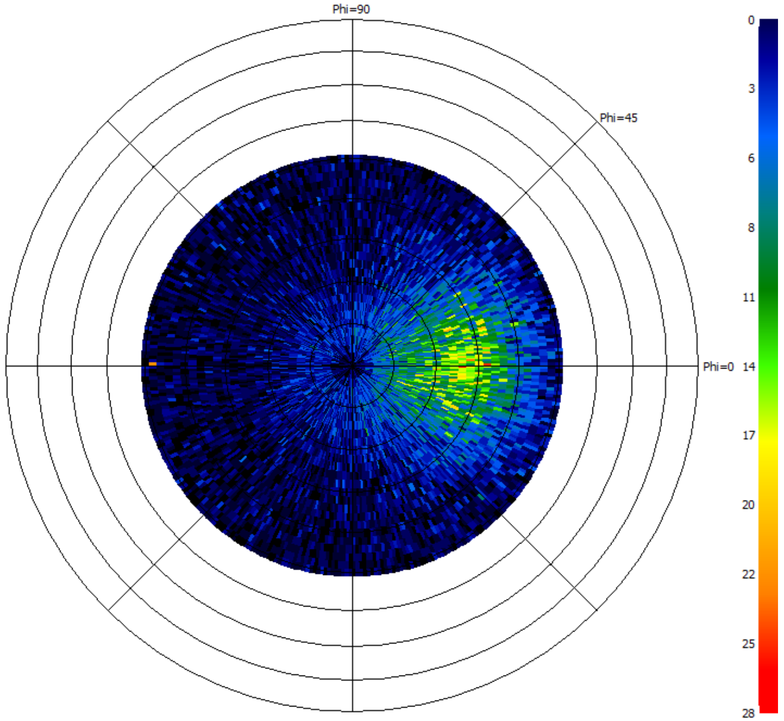


Application - Shear Mode Layers

- 140 nm off-axis AlN → ~ 30° tilt angle of c-axis
- Underlying seed stack of different layers



SEM of deposited AlN



XRD pole figure for off-axis AlN(002)

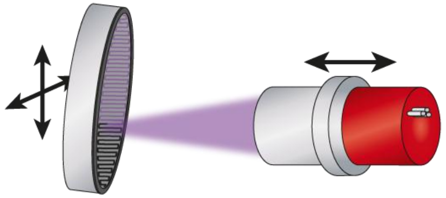
Our Solution - scia Magna 200

- scia Magna 200 Inline with wafer handling robot and EFEM
- Automatic processing of a wafer cassette with 25 wafers
  - Includes wafer alignment, flipping, and loading into the carrier
  - Pre-cleaning
  - Magnetron sputter sources
  - In-site thickness measurement

scia Magna 200 Inline with load lock

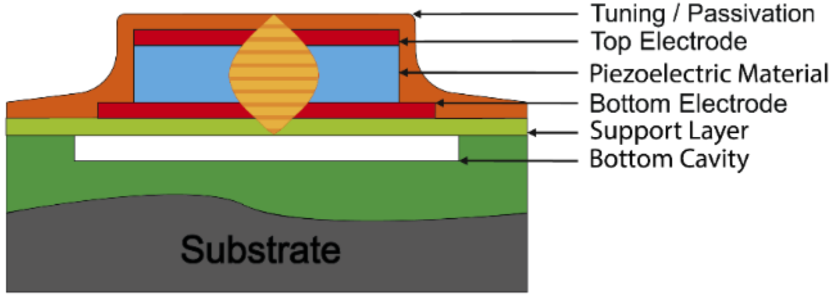
Magnetic Thin-Film Head Manufacturing

by Ion Beam Trimming

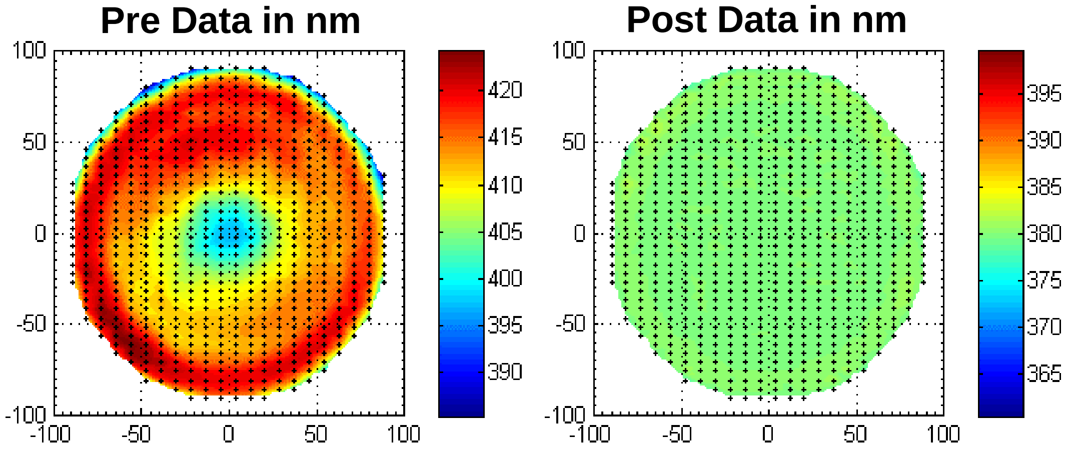


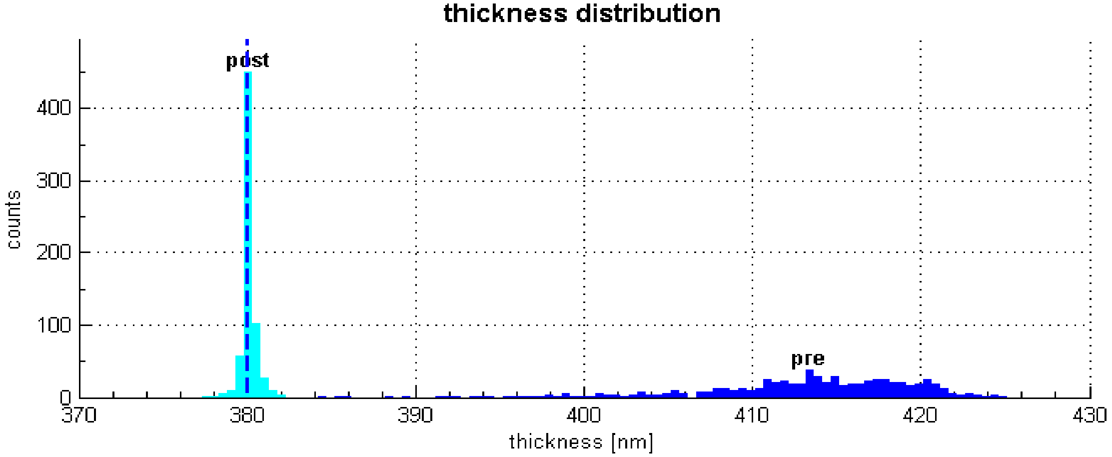
Application - Si_3N_4 Passivation Trimming for BAW

- To keep filter dimensions small, piezo-electric materials like Aluminum Nitride (AlN) are used to convert electromagnetic to acoustic waves
- Bulk Acoustic Wave (BAW) resonators are designed to run a vertical wave in a $\lambda/2$ thickness
- Trimming of mass load layer/passivation to adjust device to target frequency



Film Bulk Acoustic Resonator (FBAR)



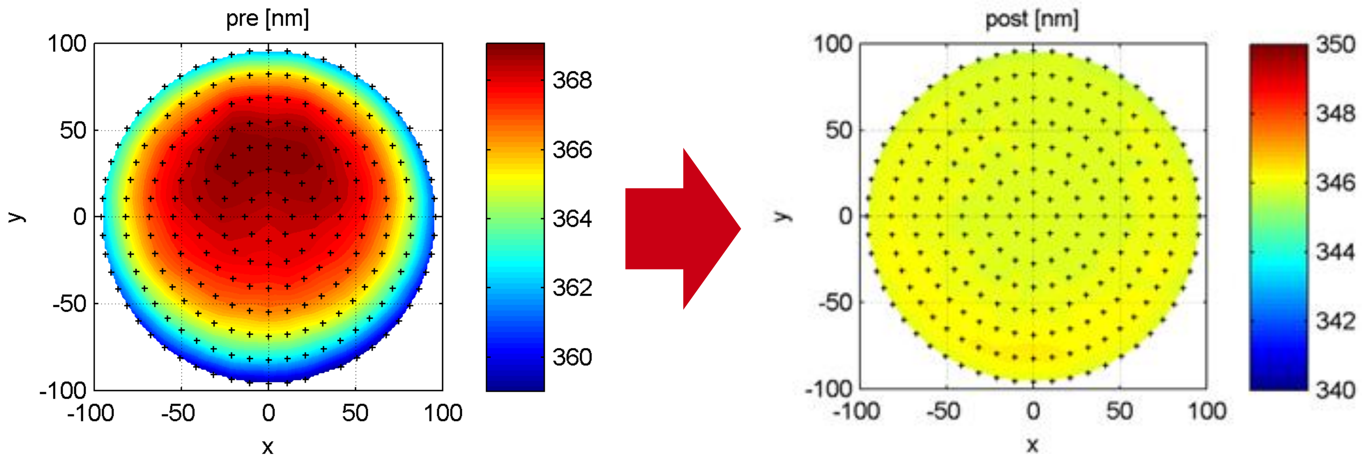


Standard Deviation	pre: 6.60 nm	post: 0.45 nm	factor 14.6 improvement
Average Thickness	pre: 413.2 nm	post: 380.1 nm	

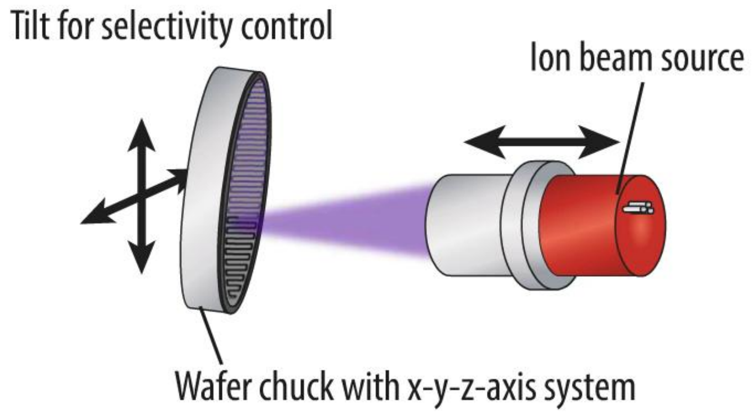
Pre and post thickness data for Si_3N_4 layer with factor 14.6 improvement

Basic Principle - Ion Beam Trimming (IBT)

- Localized dimensional (mostly thickness) correction by focused broad ion beam
- Contactless high vacuum process with depth resolution close to single-atom layers
- Removal controlled by the local dwell time of the ion beam at certain wafer positions
- Dwell time adjustment handled by pre-calculated velocity map in raster scan pattern
- Better thickness uniformity leads for many applications to higher yield



Thickness data before (3.0 nm RMS) and after (0.13 nm RMS) ion beam trimming



Principle of ion beam trimming by scia Trim 200

No Restrictions on Processed Materials

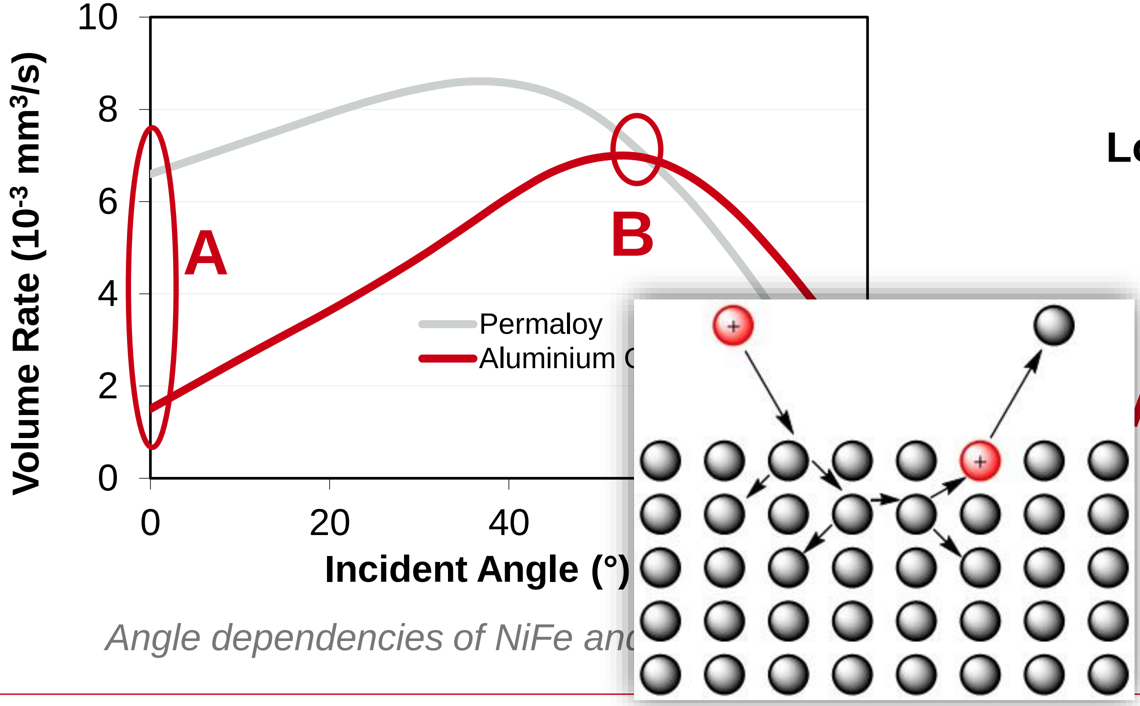
- All solid materials might be trimmed by ion beams independent of their chemical properties
- Materials processed in production

BAW: AlN, Mo, W, SiO_2, Si_3N_4
SAW: Al, Cu, SiO_2, Si_3N_4, Quartz, $LiTaO_3$, $LiNbO_3$
TFH: Ru, NiFe, CoNiFe, Al_2O_3
MEMS: Ta, W, Ru, Si, SiCr, SiO_2
Wafers: Si, SiC, $LiTaO_3$, $LiNbO_3$
Optics: Glasses, Quartz, SiC, WC, Si, Ge, Si_3N_4, $LiTaO_3$, $LiNbO_3$

TFH heads for writing and reading magnetic discs

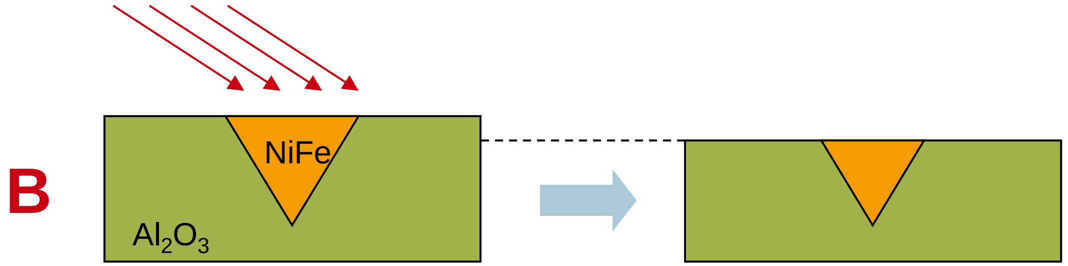
Localized Pole Trimming for TFH

- Yield gain of Thin Film Head (TFH) by shaping the magnetic pole cross section
- The ion incident angle utilized in pole trimming for
  - Selectivity adjustment between materials
  - Rate enhancement

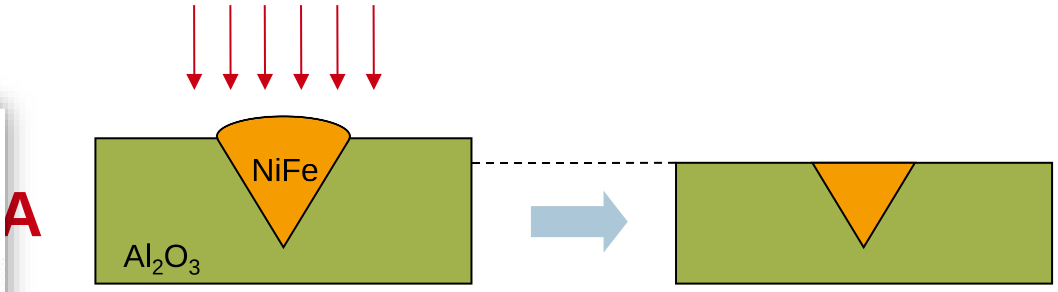


Angle dependencies of NiFe an

Localized pole trimming with 1:1 selectivity



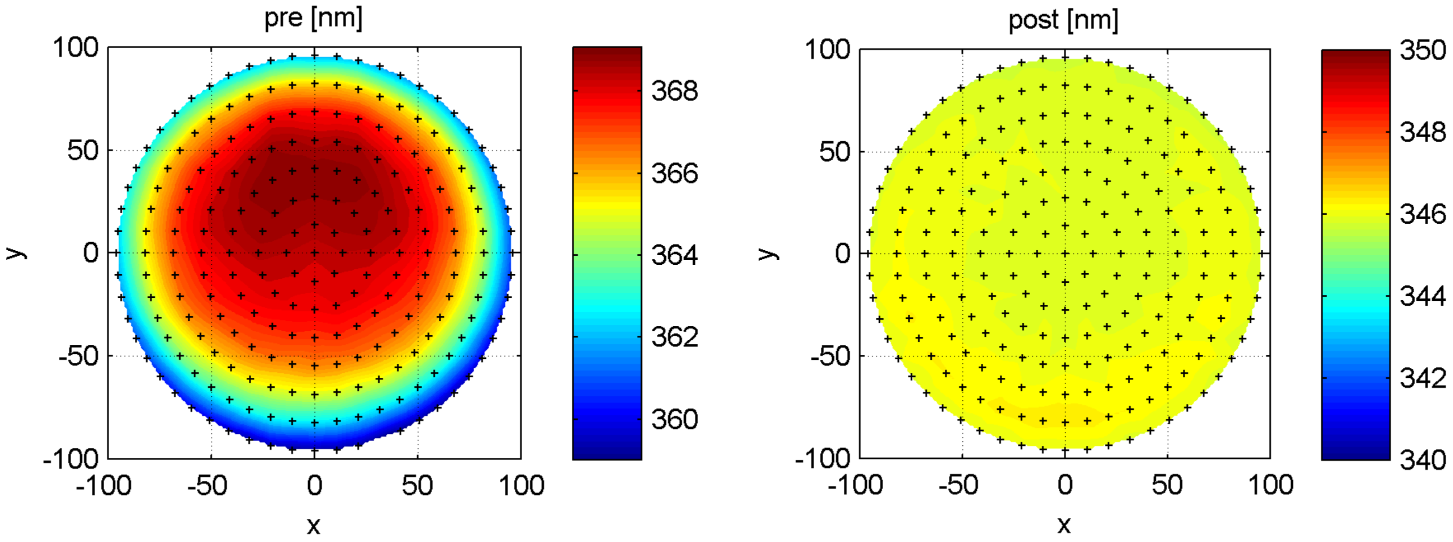
Localized step height reduction with 3:1 selectivity



Selectivity adjustment between NiFe and Al_2O_3 utilizing defined ion incident angles

Trimming of Al_2O_3 for TFH Application

- Typical average removal of 10 … 100 nm with process times of 15 … 30 min
- Improvement of film uniformity by a factor of 10 … 30



Pre and post thickness data for Al_2O_3 layer

Standard Deviation	pre: 3.0 nm	post: 0.13 nm	factor 21 improvement
Average Thickness	pre: 365.3 nm	post: 345.0 nm	

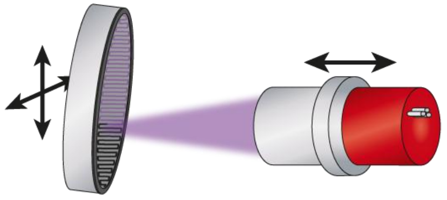
Related Systems - scia Trim 200

- Fully automatic processing of any film and wafer materials
- Throughput optimized design with up to two process chambers and single or double cassette load lock
- Film thickness correction down to 0.1…0.5 nm RMS at typical process times of a few minutes
- Significant yield improvement
- No edge exclusion with electrostatic chuck
- Sub-nanometer removal

scia Trim 200 with Brooks MX 400 robot and cassette load lock

Photonic Integrated Circuits Manufacturing

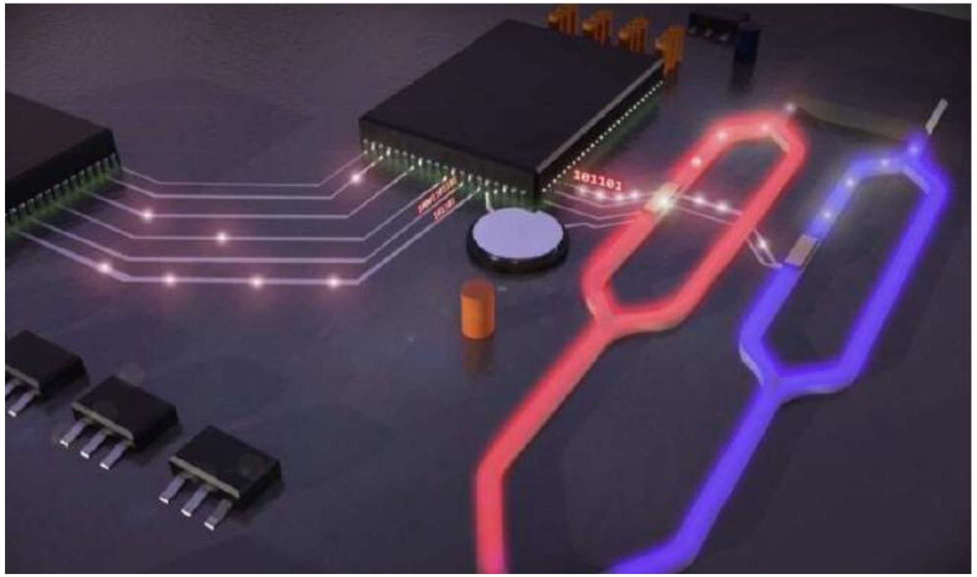
by Ion Beam Trimming



PIC Sensors

- Photonic Integrated Circuits (PICs) are specialized chips that integrate optical components, like lasers, modulators, and detectors, onto a single substrate, enabling the manipulation, generation, transmission, and detection of light within a compact footprint.
- Sensor types
  - Bio chips
  - Automotive Lidar
  - Environmental sensing
  - Optical gyroscope

image source: George Washington University

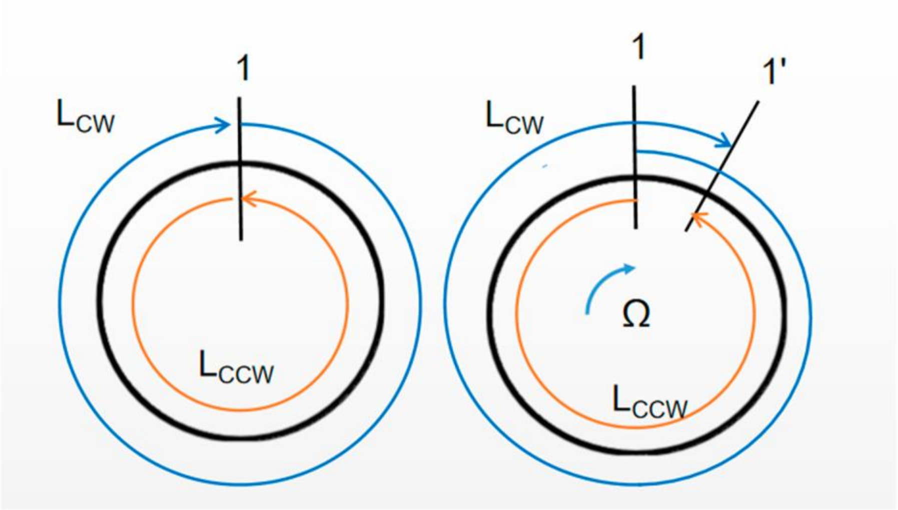


Silicon chip (grey), electrical data (white) travels through a Mach-Zehnder interferometer.

Optical Gyroskope

- Light travels in opposite directions in ring resonator
- Rotation causes phase shift between two signals
- Phase shift is measured and related to angular velocity (Sagnac Effect)
- High precision of 0.001 °/s

- Extremely high uniformity of waveguide thickness required to ensure
  - No phase shift due to changing effective refractive index
  - Low dispersion
  - Single mode operation



Schematics of the Sagnac effect. The left panel: the situation of zero rotation rate. The right panel: the resonator under Ω rotation rate. Difference between clockwise (CW) and counterclockwise (CCW) optical paths caused by the Sagnac effect.
*Source: Photonics 2020, 7(4), 96; https://doi.org/10.3390/photonics7040096**;** Zuo Feng;*

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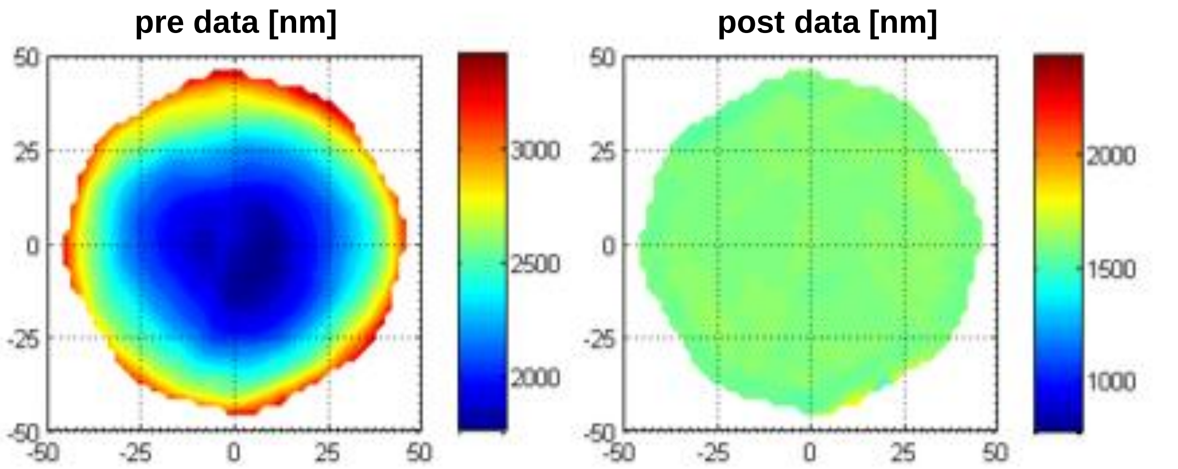
Waveguide Trimming for PICs

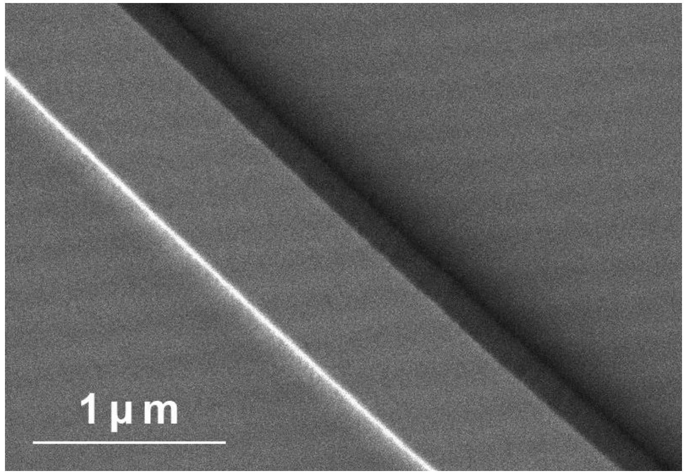
- Precise adjustment of waveguide structures
- < 0.5 % thickness uniformity possible
- No increase in optical losses
- POI wafers (LN or LT on Silicon), Si_3N_4, SiO_2, Si, and other materials possible


pre data [nm]

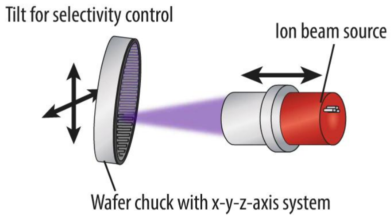
post data [nm]

Pre and post thickness distribution of $LiTaO_3$-Structure

RMS	*Pre:*	*439 nm*	→	*Post:*	*35 nm*
Thickness	*Pre:*	*2 455 nm*	→	*Post:*	*1 600 nm*



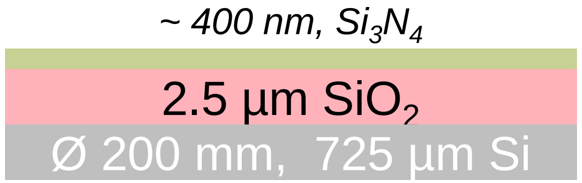
Waveguide structures with adjusted thickness by ion beam trimming and patterned by ion beam etching, in $LiNbO_3$



Principle of ion beam trimming by scia Trim 200

SiN Trimming for Waveguides

- Trimming of **SiN layer** before waveguide patterning



~ 400 nm, Si_3N_4

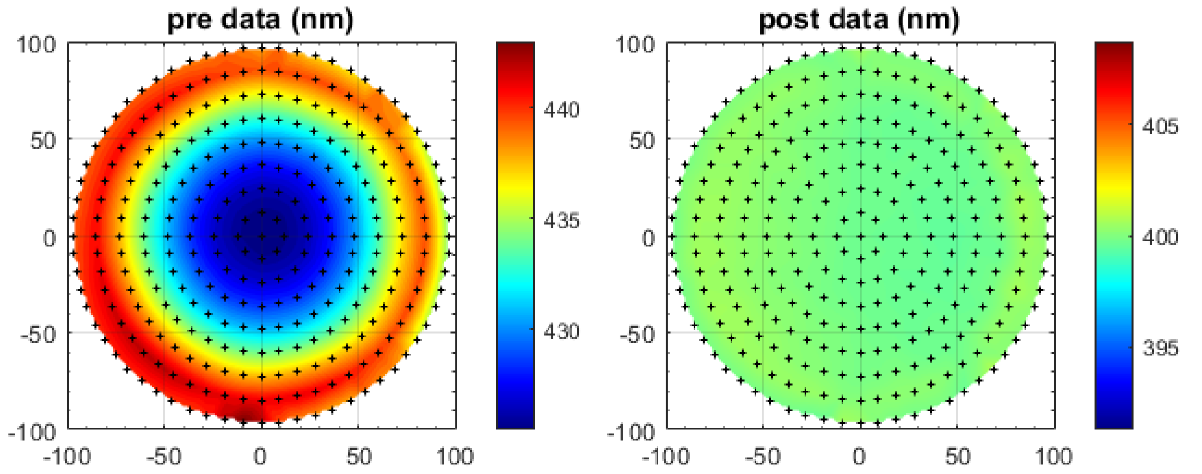
2.5 µm SiO_2

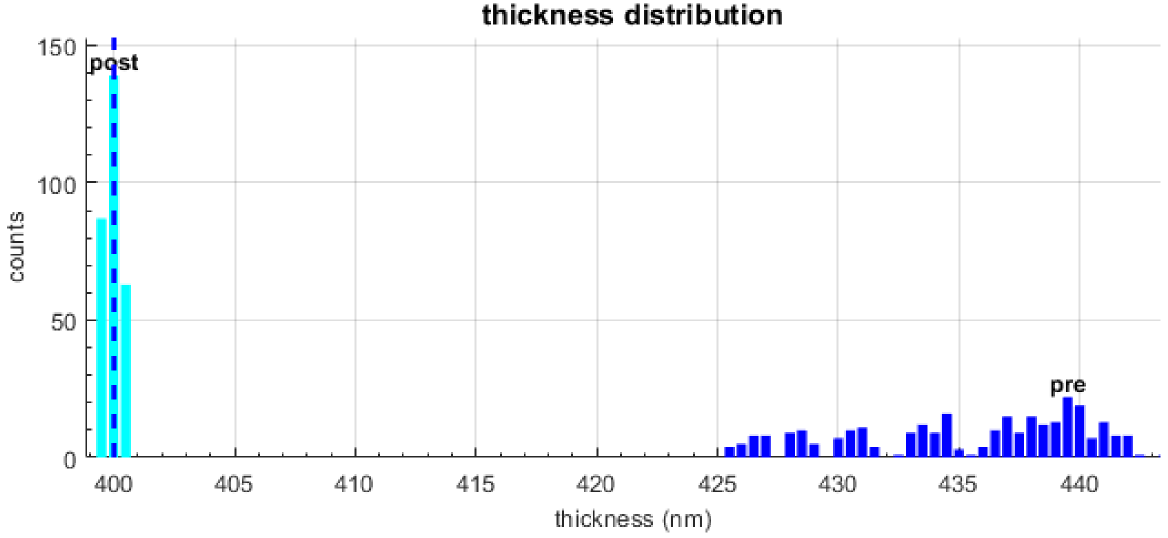
Ø 200 mm, 725 µm Si

Pre and post properties of SiN layer

Standard deviation	*Pre:*	*4.80 nm →*	*Post:*	***0.30 nm***
Thickness	*Pre:*	*435 nm →*	*Post:*	*400 nm*
RMS roughness	*Pre:*	*0.3 nm →*	*Post:*	*0.3 nm*
Refractive index	*Pre:*	*2.023 →*	*Post:*	*2.023*

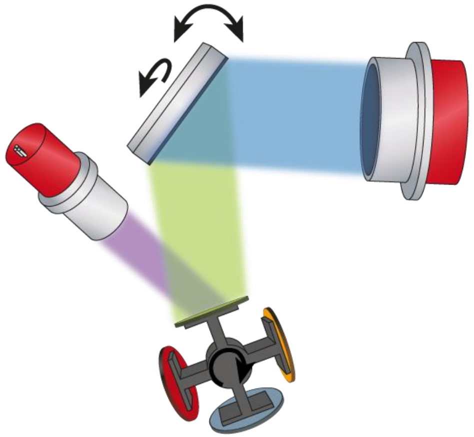
- **Improvement** of **SiN thickness** standard deviation by a factor of **~ 16**
- **No change** in **roughness** or **refractive index**





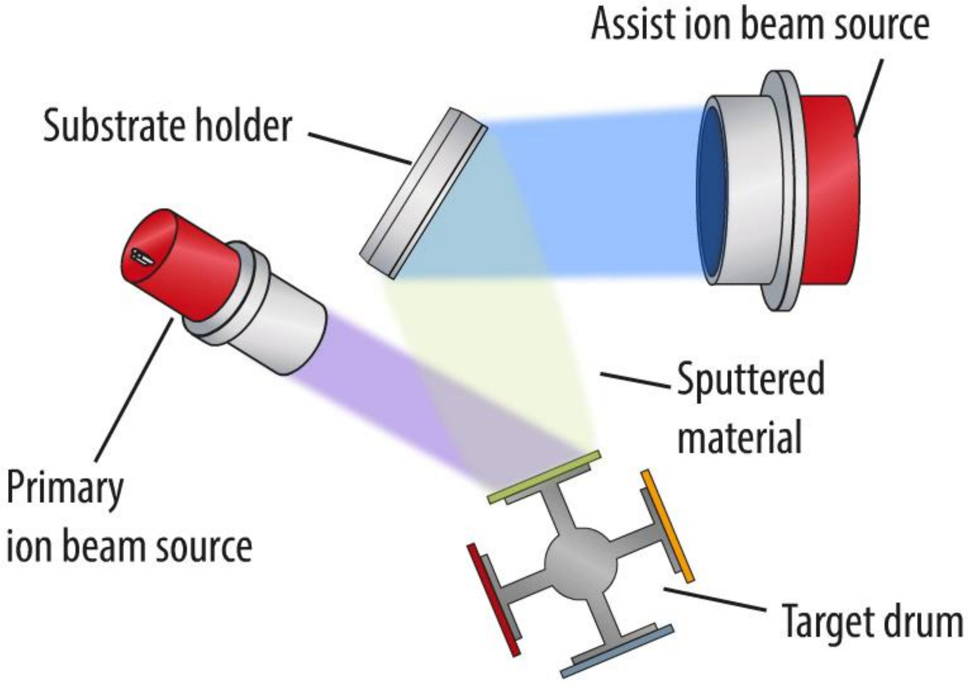
Micro Bolometer Manufacturing

by Ion Beam Sputter Deposition



Basic Principle - Dual Ion Beam Sputtering (DIBS)

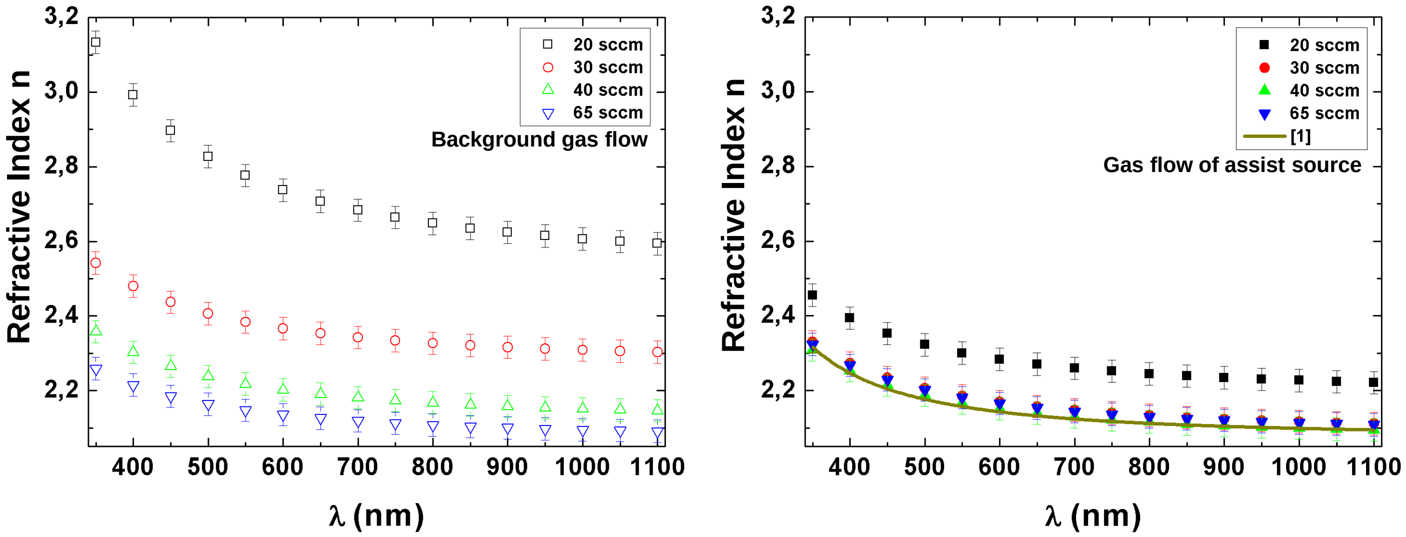
- Ion beam energies are exactly adjustable with a small energetic distribution
- Material is sputtered from a target and condensates at the substrate surface as a growing film
- Kinetic energies of sputtered particles (neutral target atoms) in the range of several 10 eV (10 x higher than magnetron sputtering or evaporation)
- High surface mobility of condensing particles led to smooth and defect-free films
- Additional densification and modification (e.g., oxidation) by an ion beam source



Principle of dual ion beam sputtering by scia Coat 200

Reactive Ion Beam Sputtering

- Reactive gas as background or by an assist source (excitation by plasma or beam operation)
- Deposition of oxides or nitrides directly from metal target (higher rate)
- Optical parameters can be adjusted by reactive gas flow
- Good control of the stoichiometry of growing films
- High purity of deposited films



Refractive indices of Ta2O5 over wavelength for different oxygen gas flows a) in background and b) of assist ion beam source

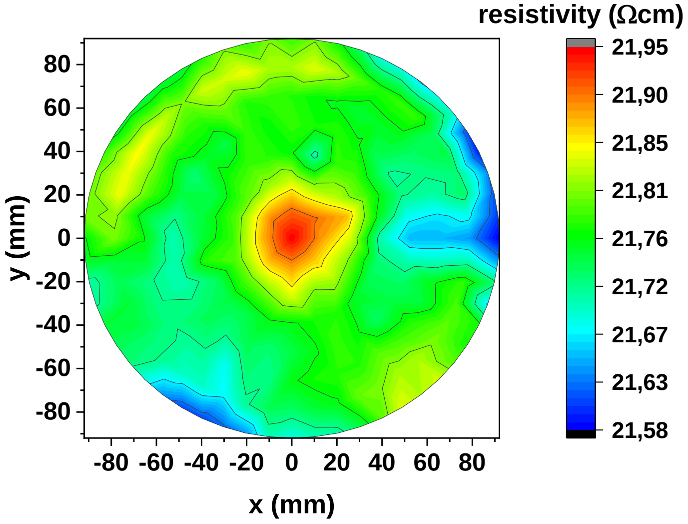
VOx Coatings

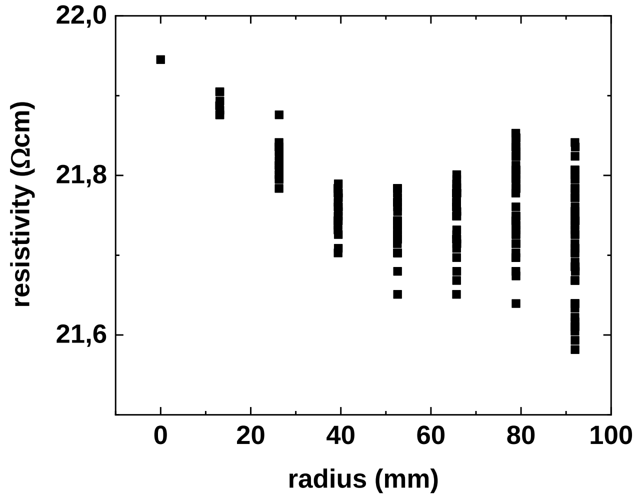
- VOx has a very high temperature coefficient of resistivity (TCR)
- Used as an infrared sensor
- Application
  - CPD (Child Presence detector) to detect left children in a car (danger due to heat)
  - In different countries, new regulations are being discussed to make it mandatory
  - Infrared sensors/cameras
- Control of material stoichiometry is significant to achieve high TCR
- Ion Beam Sputter Deposition with scia Coat 200

Application - Deposition of Metal Oxide (VO_{2-X}) films

- Deposition of vanadium oxide films on a 200 mm wafer with high oxygen flow
- Thickness detected using optical monitor or quartz balance, in situ
- Resistivity via four-probe measurement
- Target resistivity: **5 Ωcm / 20 Ωcm**

Thickness	Rate (A/s)	R□ (kΩ)	Resistivity (Ω·cm)	Resistivity Uniformity
~157 nm on SiO_2/Si	1.05	61.7	4.4	1.0% (σ/mean)
~102 nm on SiO_2/Si	0.78	471.6	21.8	0.3% (σ/mean)





- Resistivity and thickness shows good uniformity of resistivity and thickness (further optimization possible)
- Broad range of resistivity can be achieved by exact control of gas flow and parameters of ion beam source

Related Systems – scia Coat 200

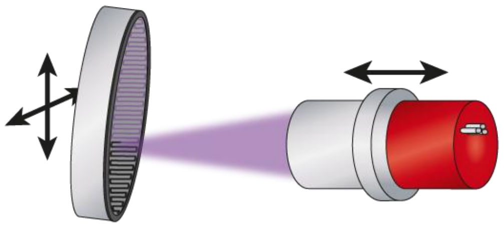
- Sputter ion beam source RF120-e:
  - RF source with 120 mm diameter
  - Focusing grid-system
- Etching ion beam source RF350-e with a diameter of 350 mm
- Target holder with 5 targets, water-cooled
- Substrate holder:
  - Substrate diameter up to 200 mm
  - Rotation: 1 … 20 rpm
  - Tilting: 0 … 170°
  - Helium backside thermal contact
- Single wafer load lock, as well as single chamber and cluster arrangement with cassette handling

scia Coat 200 with cassette handling

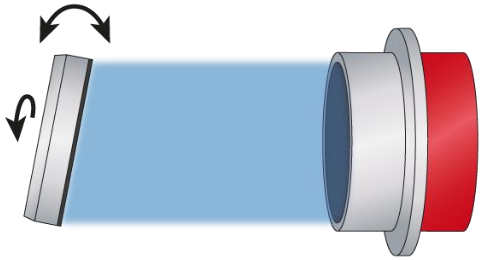
Summary

Summary

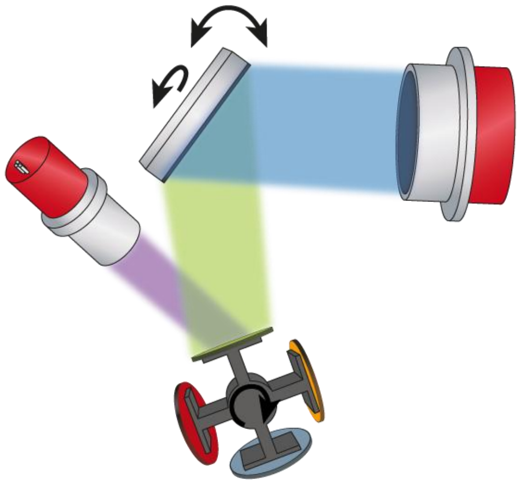
- Ion Beam Trimming, Ion Beam Milling, and Ion Beam Sputter Deposition offer unique capabilities
- Etching and deposition of a large variety of different materials, besides conventional Si and SiO_2
- Tuning film properties like thickness, density, or stoichiometry allows optimization of sensor performance
- All processes are available for volume production
- scia Systems’ demo lab helps our customers to develop processes for next-generation sensors



Ion Beam Trimming



Ion Beam Etching



Ion Beam Sputter Deposition

Thank you!

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