Adapted particle bombardment during layer growth by pulse magnetron sputtering

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Outline

- **Introduction**
- **Experimental: Hardware for Pulse Magnetron Sputtering**
- **Technology controlling the energetic substrate bombardment**
  - **Pulse mode and pulse parameters**
  - **Reactive process control**
- **Examples of applications for controlling the energetic substrate bombardment**
  - **ITO/Al_2O_3: Low damage sputtering**
  - **AlN: Unipolar/bipolar hybrid pulse mode**
- **Summary**

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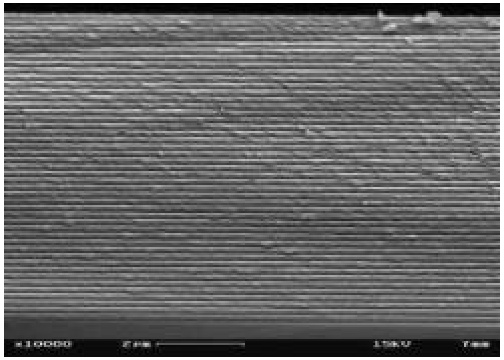
Introduction

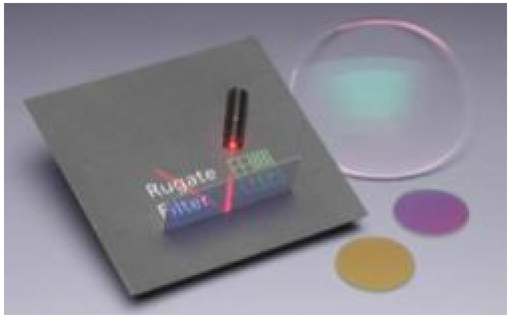
Characteristics of the Reactive Pulse Magnetron Sputter Process

- Excellent **process stability** and **reproducibility**
- Stoichiometric compound layers with very **low absorption** and **high barrier** properties
- Deposition of **dense climatically stable** films by intense energetic substrate bombardment during deposition
- **High deposition rate**
- **Uniform** coating of large substrates

Adjustment of process parameters allows **influencing the energetic substrate bombardment**

  - Key to **control** layer growth and **layer properties**
  - New layer properties for **new applications**





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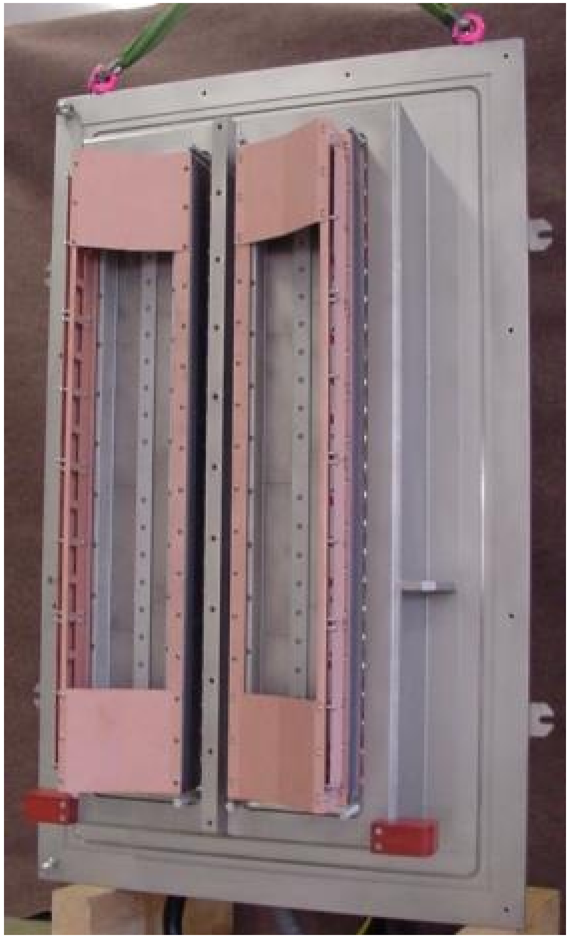
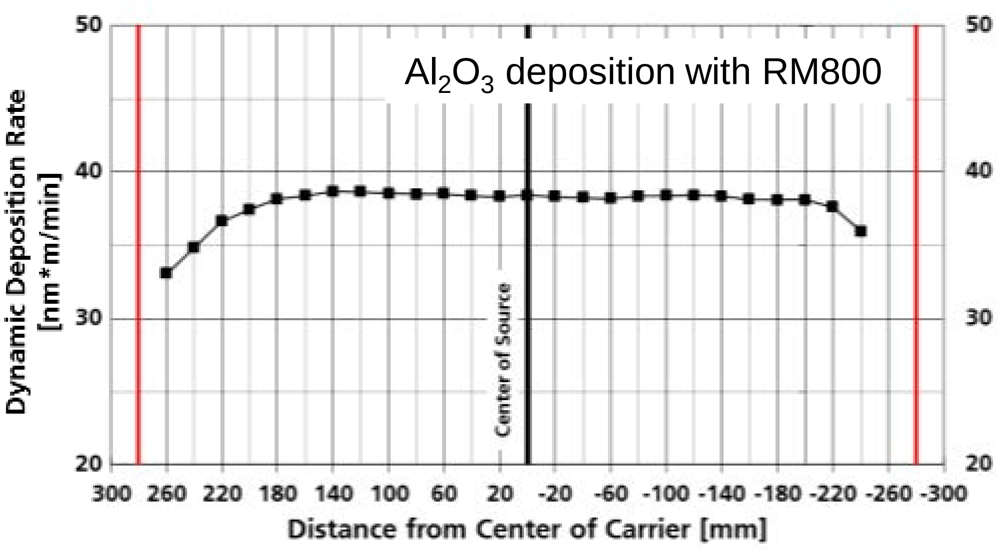
Rectangular Magnetron RM- series

Double Magnetron System (DMS) with Rectangular Magnetrons RM999 for a web coating system

band width: 600mm





- Dynamic coating
- Film thickness uniformity: up to ±0.5% on large area substrates
- Unipolar pulse (Single Magnetron) and bipolar pulse (DMS) operation
- Target length (design ready): up to 1m

Coating System with RM

Process Management Computer

Plasma Control Unit (PCU) for reactive gas control

DC power supply

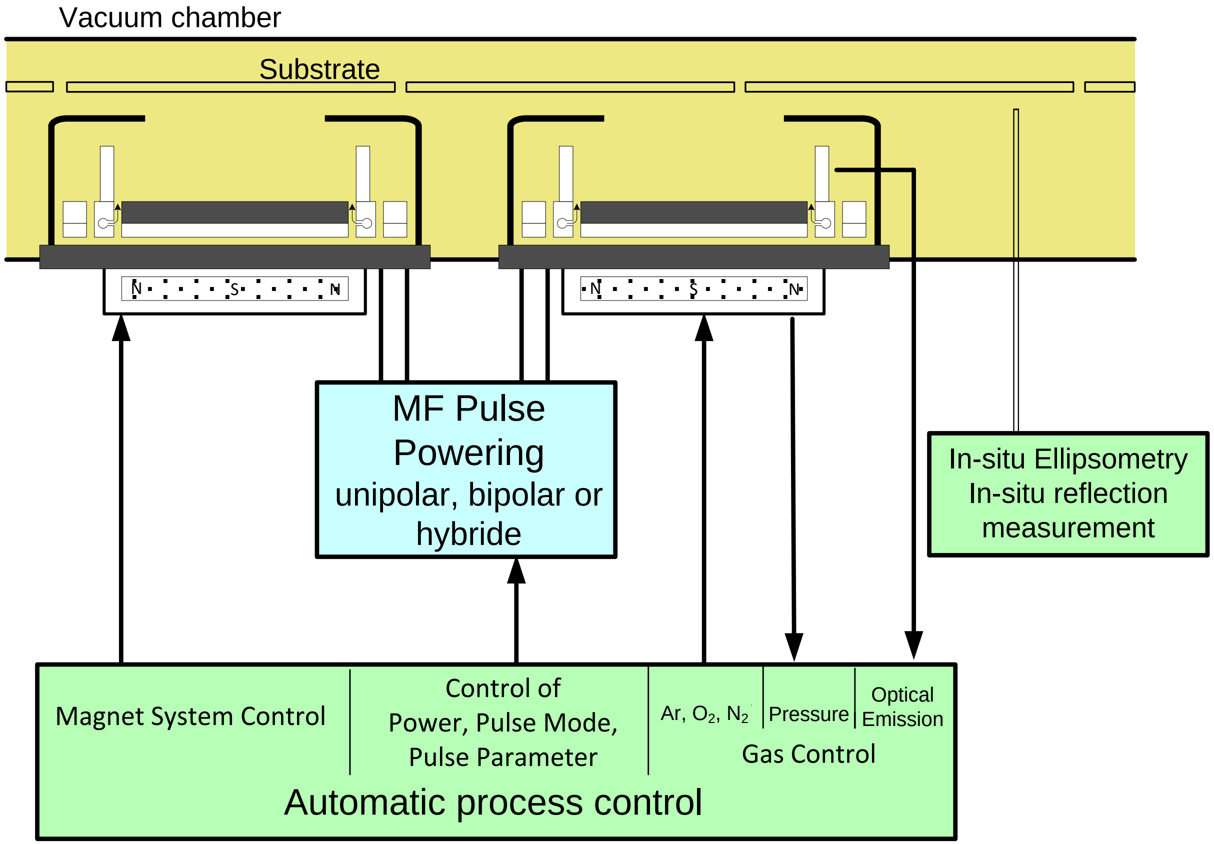
Pulse power supply UBS-C2

DMS with Rectangular Magnetrons RM 999

Reactive Pulse Magnetron Sputtering: Sputter parameters

Deposition parameters influencing energetic substrate bombardment:

- Powering parameters (I, V, P)
- Pulse mode
- Pulse parameters (f, duty cycle)
- Reactive working point
- Magnetic field strength at target surface
- Pressure
- Additional plasma sources (RF bias)



MF Pulse Powering
unipolar, bipolar or hybride

In-situ Ellipsometry
In-situ reflection measurement

Magnet System Control

Control of Power, Pulse Mode, Pulse Parameter

Ar, O_2, N_2

Pressure

Optical Emission

Gas Control

Automatic process control

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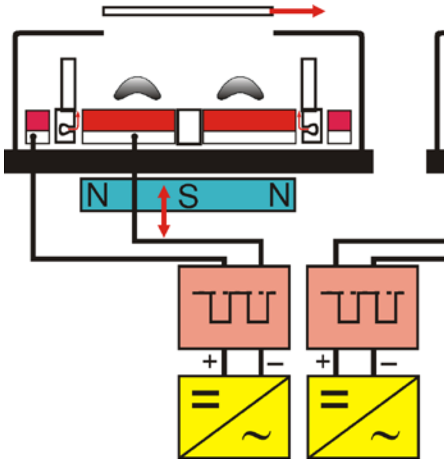
Deposition parameter: Pulse mode of the discharge

Unipolar and bipolar pulse mode operation

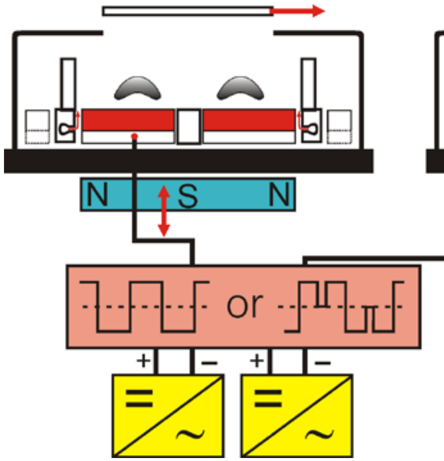
- Unipolar pulse mode:
  Pulsed dc between each of the targets and a separate hidden anode

- Bipolar pulse mode
  (and pulse package mode):
  Voltage with alternating polarity between the two targets of a dual magnetron arrangement



Switching unit UBS-C2
(unipolar pulse mode)

DC power supplies



Switching unit UBS-C2
(bipolar pulse mode or
pulse packet mode n=2)
DC power supplies

Energetic substrate bombardment in unipolar and bipolar pulse mode

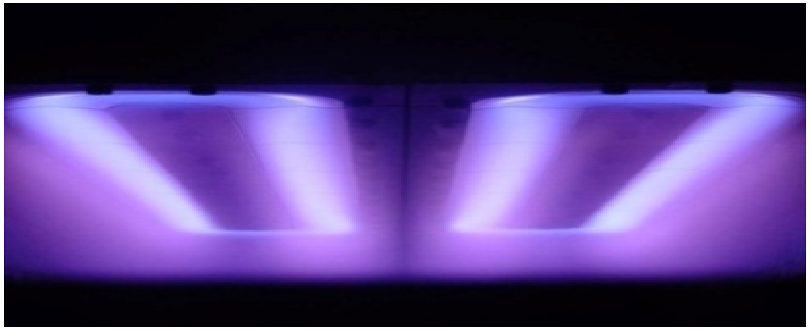
Pulse mode	Plasma density [1/cm³]	Electron temperature [eV]	Thermal substrate load [W/cm²]
Unipolar	$1.8 \cdot 10^{10}$	10	0.15
Bipolar	$11 \cdot 10^{10}$	6	0.75

(Results of Langmuir Probe and temperature measurements, SiO_2 sputtering at 7.5kW)

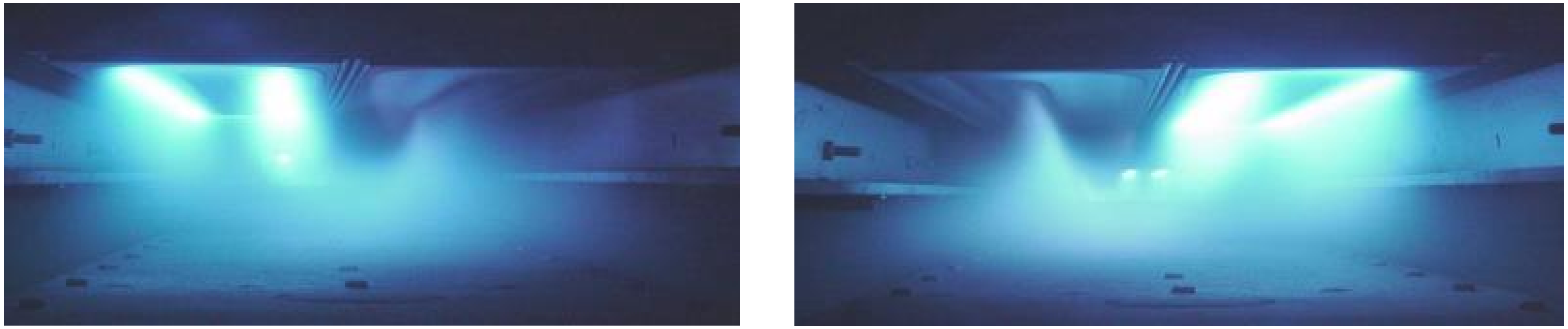
- Unipolar pulse mode: low thermal substrate load
  - Coating of temperature sensitive substrates, e.g. plastic substrates
- Bipolar pulse mode: intense energetic ion bombardment
  - Deposition of very dense films

Pulse Magnetron Sputtering

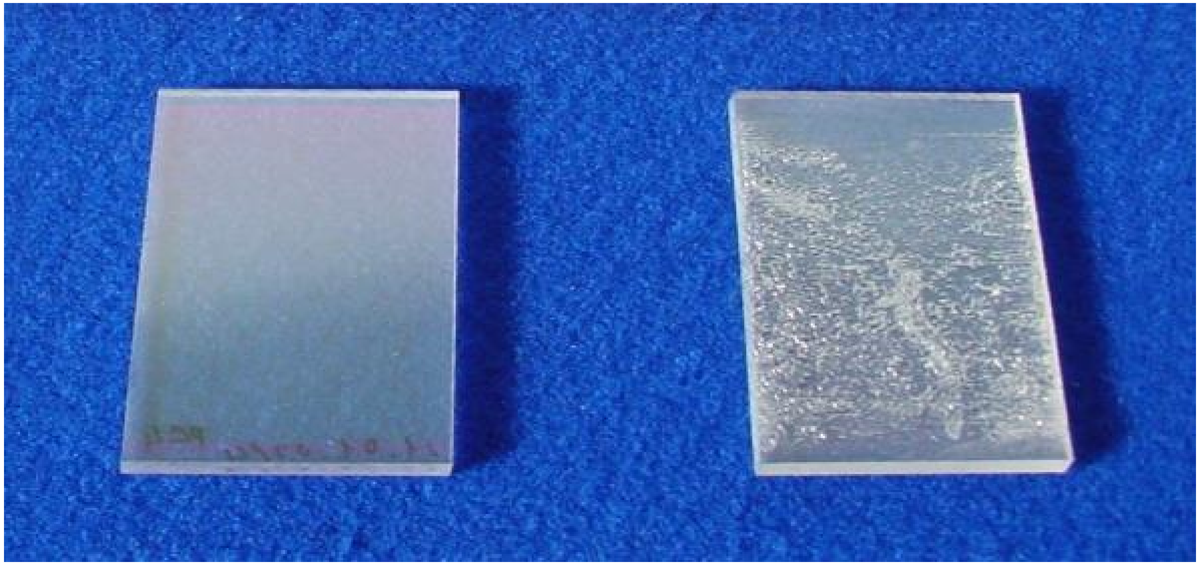
Discharge during the unipolar pulse



Discharge during the two phases of the bipolar pulse



Energetic substrate bombardment in unipolar and bipolar pulse mode



- Substrate: polycarbonate (PC)
- Layer material: TiO_2
- Layer thickness: 500 nm
- Surface overheating in bipolar pulse mode by strong particle bombardment

Unipolar	Bipolar	Pulse mode
duty cycle: 80 %	duty cycle: 45 %	Duty cycle
143 °C	204 °C	Surface temperature

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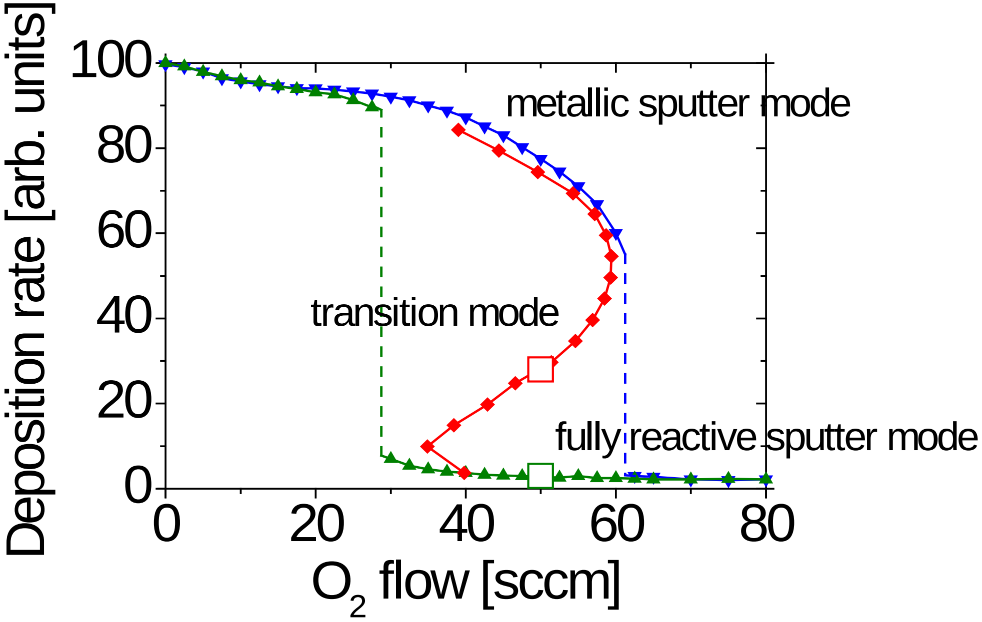
Deposition parameter:
Working point of the reactive sputter process

Inlet of O_2 and N_2 for deposition of compound layers (e.g. Al_2O_3)

- Fully reactive sputter mode:
  very low deposition rate because target is fully covered with compound film
- Transition mode:
  Deposition of stoichiometric compound layers while the target is not covered by a compound film
  - ➢ Fast feedback process control necessary
- Other deposition parameters:
  e.g. gas pressure, temperature, pulse frequency ...



OED (OEI) control:

- Control on optical emission of plasma species

Impedance control:

- Control on the impedance of the plasma

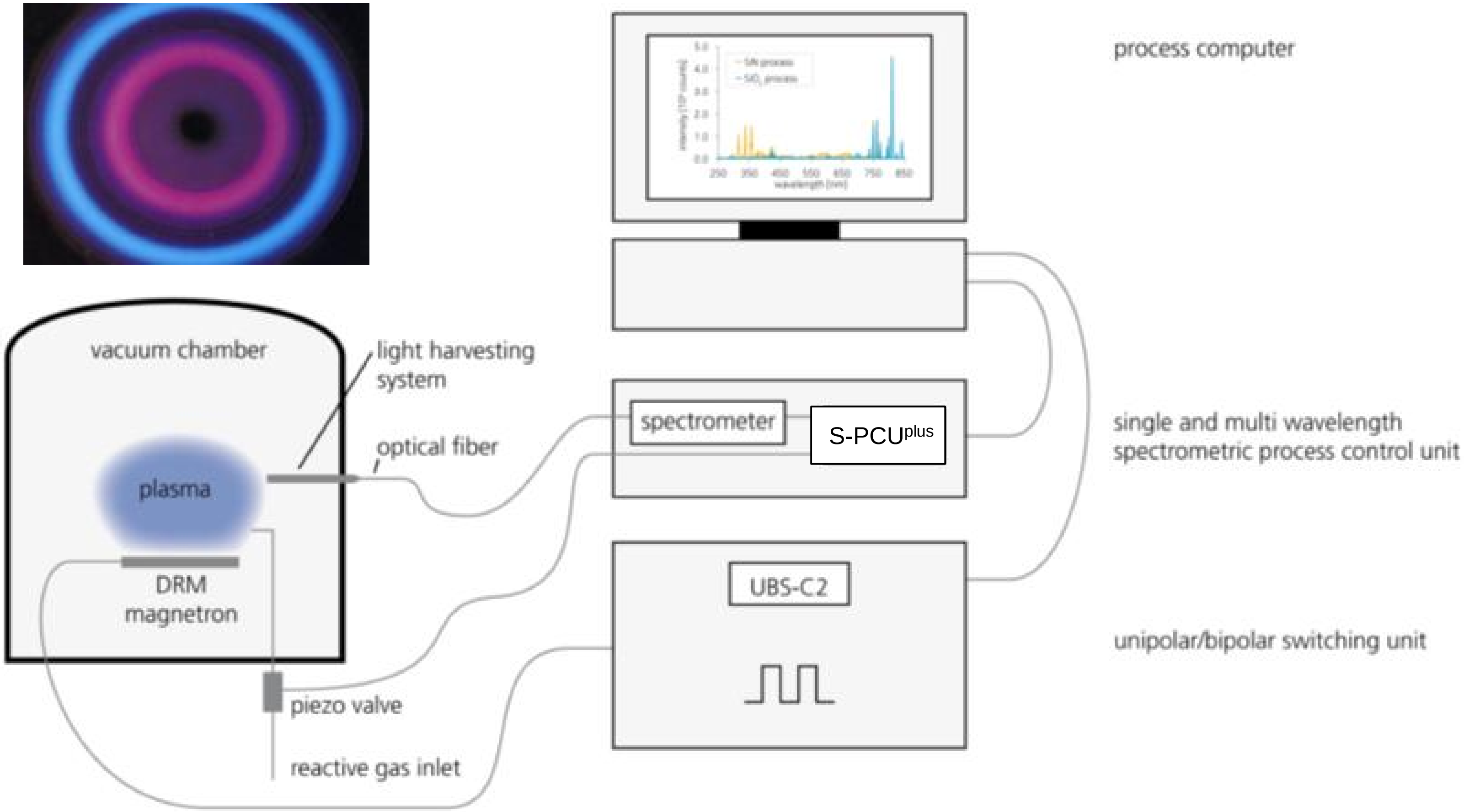
Deposition rates

Type of layer	Deposition rate [nm/s]	Powering
Metals		
Al	20	DC
Cr	15	DC
Cu	25	DC
Alloys		
Ni/ Al	10	DC
Multilayer		
CrNiCo/ Cr	5	DC

Type of layer	Deposition rate [nm/s]	Powering
Compounds		
AlN	3	MF pulse
Al_2O_3	2.5	MF pulse
Si_3N_4	2	MF pulse
SiO_2	4 0.2	MF pulse RF
TiO_2	2	MF pulse
Ta_2O_5	3	MF pulse

Spectrometric process control by S-PCU^{plus}

Universal tool for OES and plasma process control



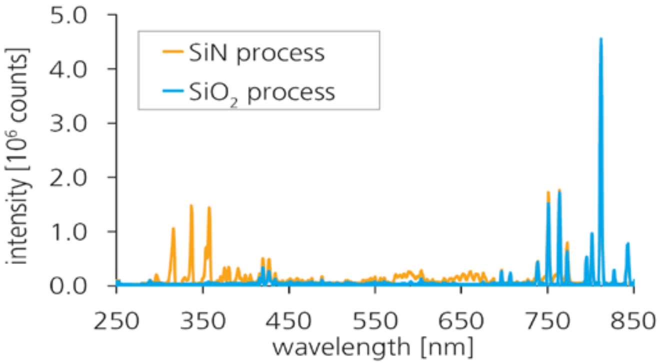
Spectrometric process control by S-PCU^{plus}

Magnetron discharge during gas and power change for gradient layer deposition

SiO_2 deposition

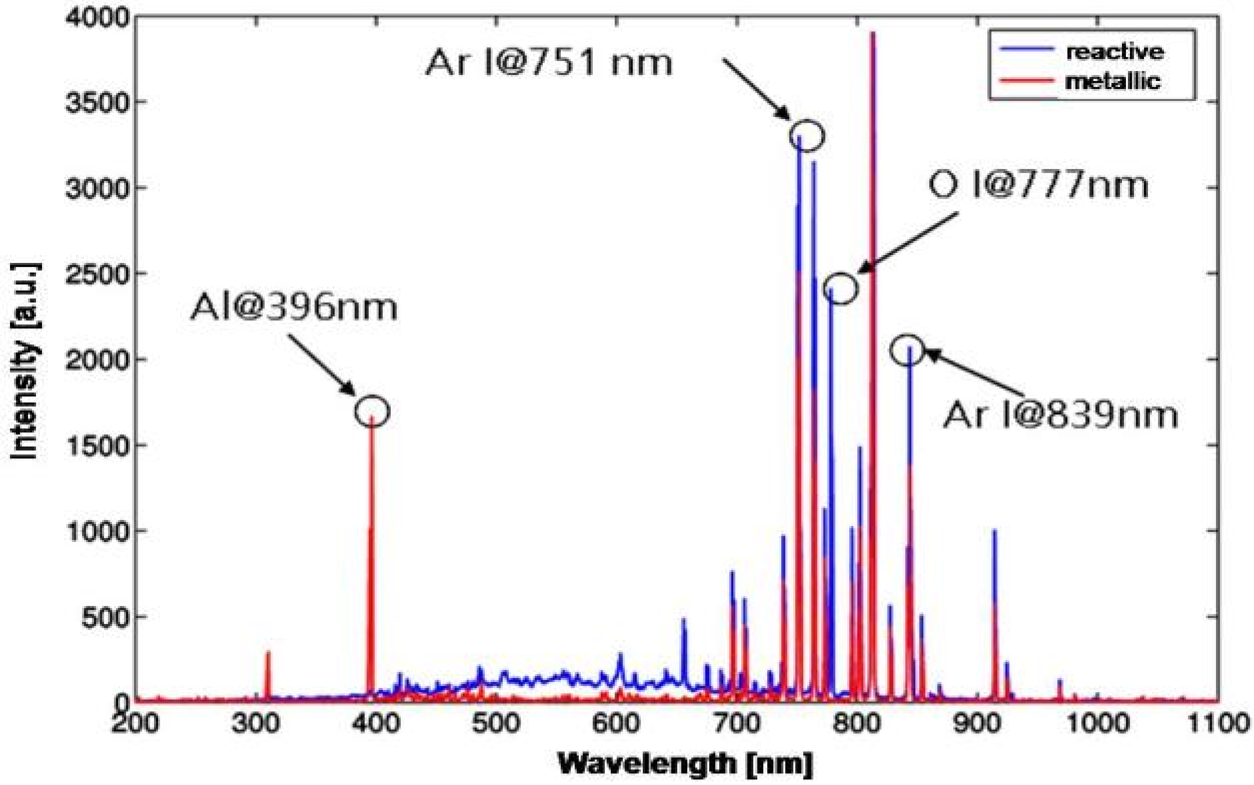
$SiO_2 \longrightarrow Si_3N_4$

Si_3N_4 deposition



Spectrometric process control by S-PCU^{plus}

S-PCU for Al_2O_3 deposition

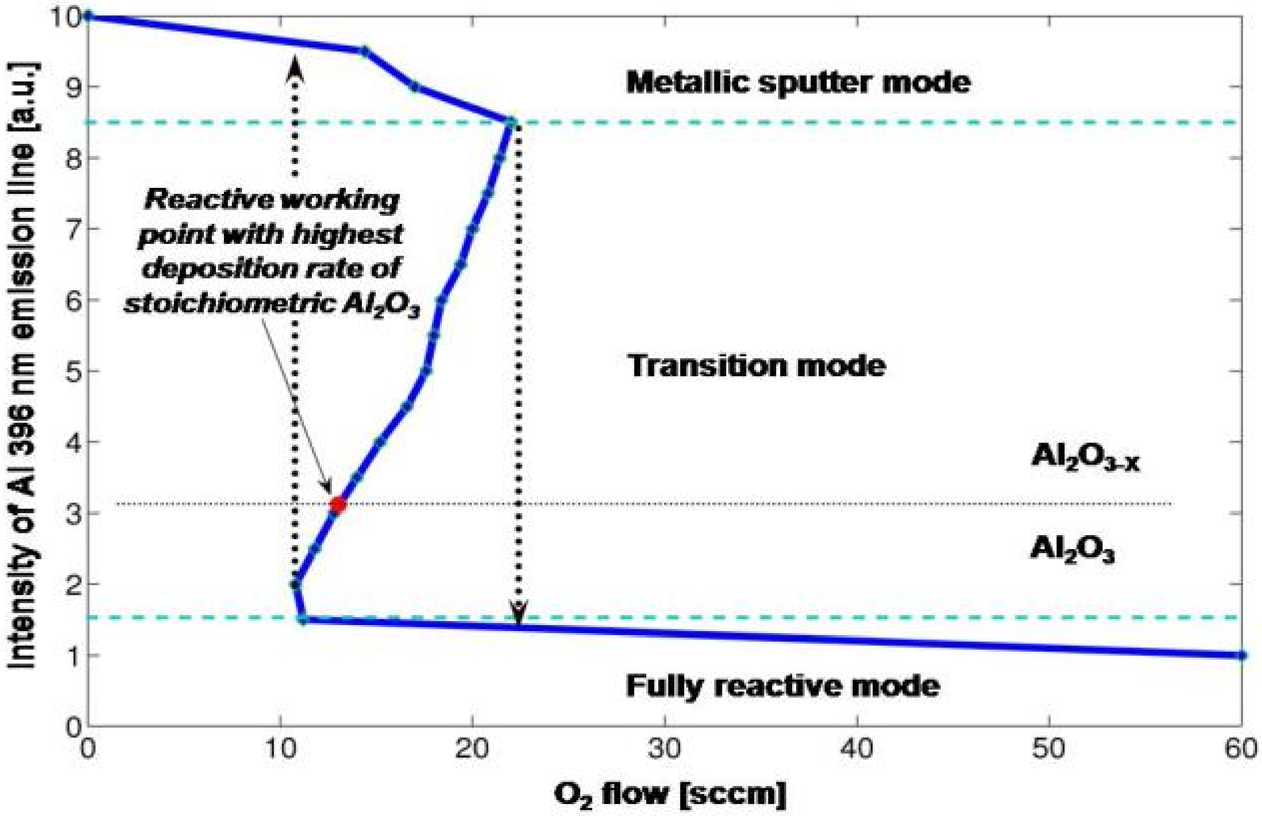


Plasma emission of Al (metallic) and AlO (fully reactive) plasma

- Well defined plasma emission lines for the different plasma species:
  Al, O_2, Ar
- Especially Al and O_2 lines show strong dependency on the reactive working point
  - Can be used for reactive process control
  - **By using ratio of two lines, process drifts can be suppressed**

Spectrometric process control by S-PCU^{plus}

S-PCU for Al_2O_3 deposition

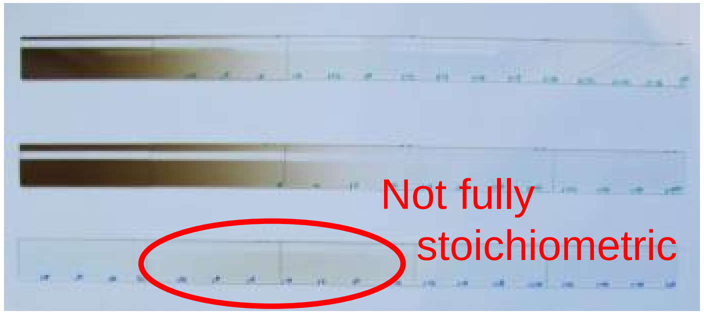


Hysteresis of the AlO sputter process

- Highest deposition rate of stoichiometric Al_2O_3 possible in the transition mode
- Reactive process control: S-PCU using optical emission of the Al 396 nm line

Combined process control for large area deposition e.g. Al_2O_3 deposition with RM800

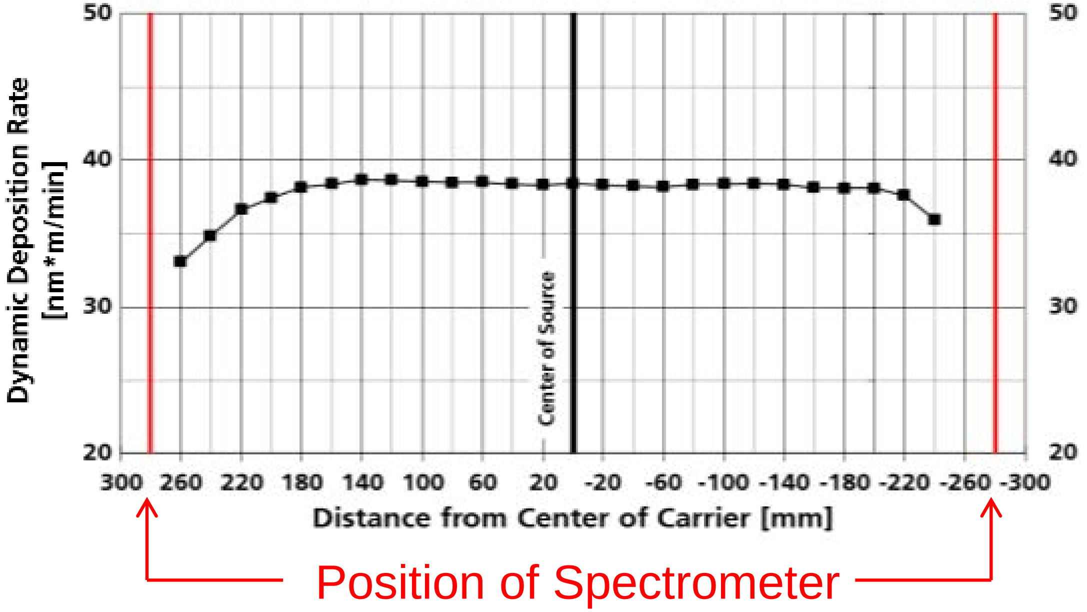
Impedance control



Not fully stoichiometric

Typical depositions of Al_2O_3 and best attempt (bottom) with single channel impedance control

Impedance control + Spectrometric process control



Position of Spectrometer

- Combined process control allows deposition of transparent and stoichiometric Al_2O_3 all over deposition range:
  ± 1% @ 380 mm with deposition rate 38 nm*m/min @ 13 kW (single magnetron)

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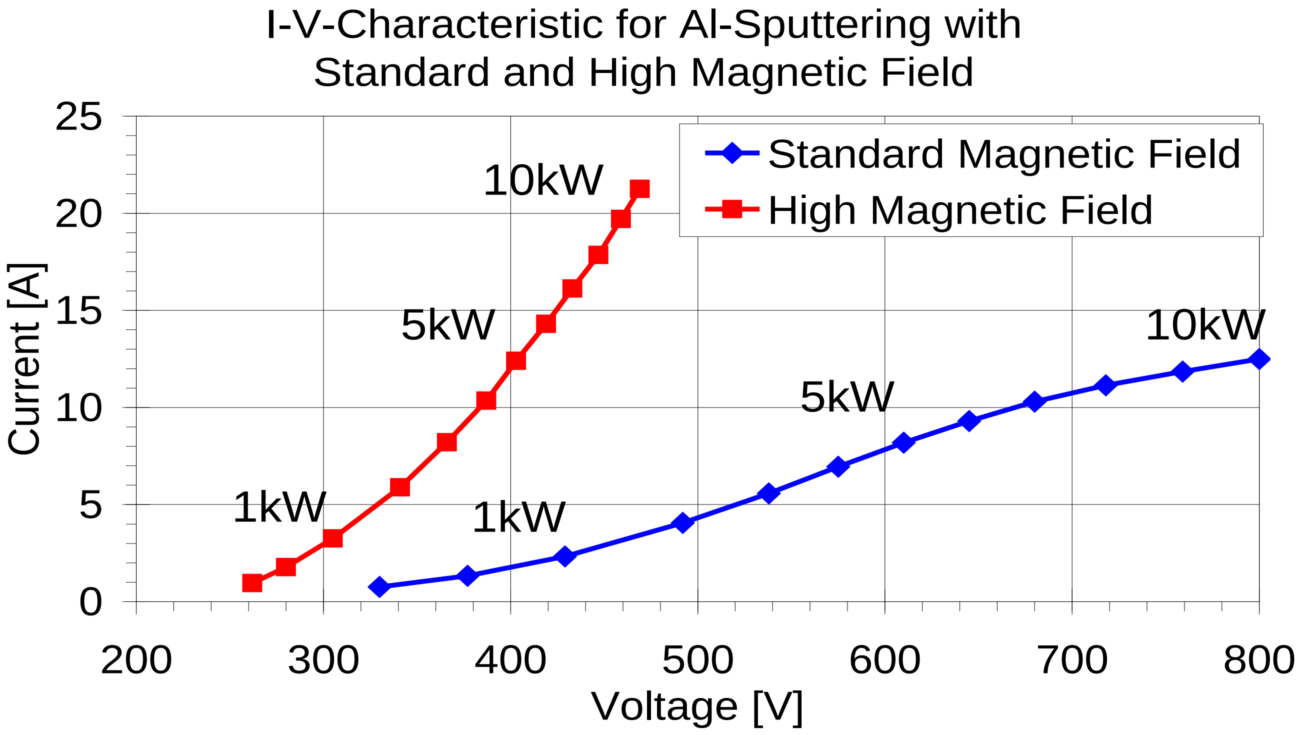
Magnetrons with very strong magnetic field

- RM/DRM cathodes with very strong magnetic field (35 kA/m in comparison to 16 kA/m for standard magnetic field)
- Operation at very low pressures possible ($2 \cdot 10^{-4}$ mbar)
- Lower energy of energetic ions


I-V-Characteristic for Al-Sputtering with Standard and High Magnetic Field

Deposition of ITO films with high magnetic field for low damage and lower resistivity

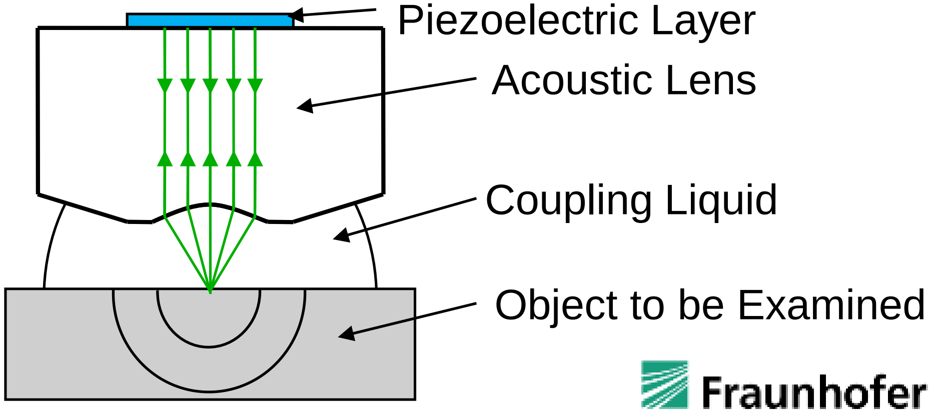
- Lower energy of energetic ions
  - ➢ Reduced damage to sensitive substrates or underlayers
- Higher conductivity of ITO films
- Example: Organic photovoltaic, OLED

Process	**Specific resistivity**	
	$T_{Substrate}$ = 30 °C	**$T_{Substrate}$ = 210 °C**
ITO standard magnetic field	$3.7 \cdot 10^{-4}$ Ωcm	$1.8 \cdot 10^{-4}$ Ωcm
ITO strong magnetic field	$3.0 \cdot 10^{-4}$ Ωcm	$1.5 \cdot 10^{-4}$ Ωcm

Specific resistivity of TCO films on glass substrates

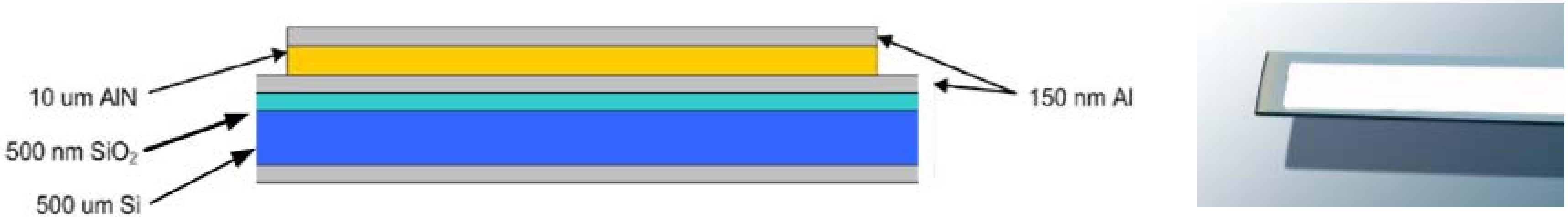
Applications of AlN films

- Ultrasonic devices
- LED
- SAW
- Energy Harvesting



Fraunhofer IKTS

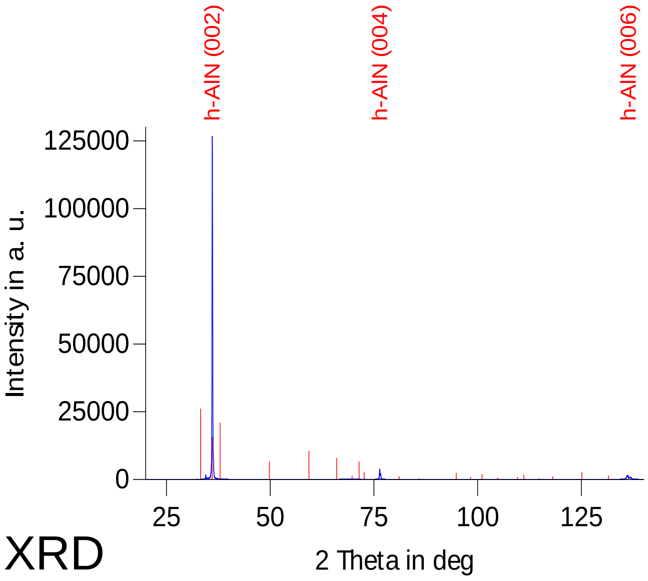
Lens for ultrasonic microscopy



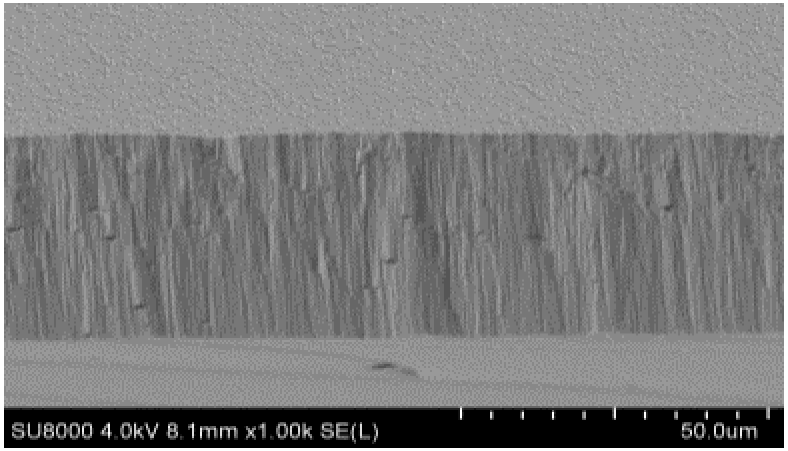
Test setup for evaluation of Energy Harvesting

Properties of sputtered AlN films

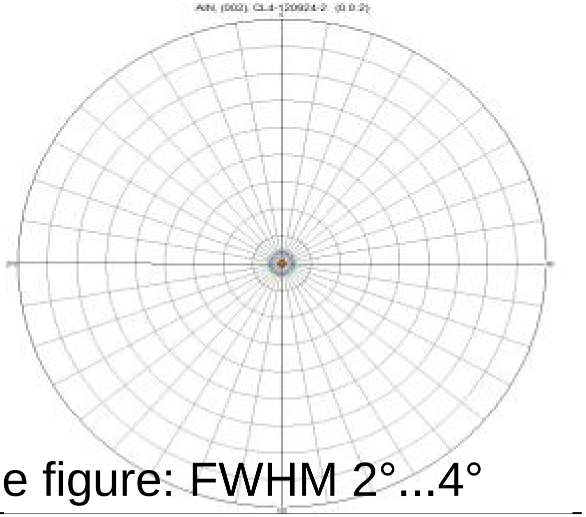
- Strong 001 texture (c-axis orientation of wurtzite structure perpendicular to surface)
- Piezoelectric coefficient d_{33} very high:
  AlN: ~ 7 pC/N AlScN: ~ 30 pC/N
- Deposition rate: ~ 150 nm/min
- Film thickness: up to 50 µm with high d_{33}



XRD



SEM of 50 µm sputtered AlN layer

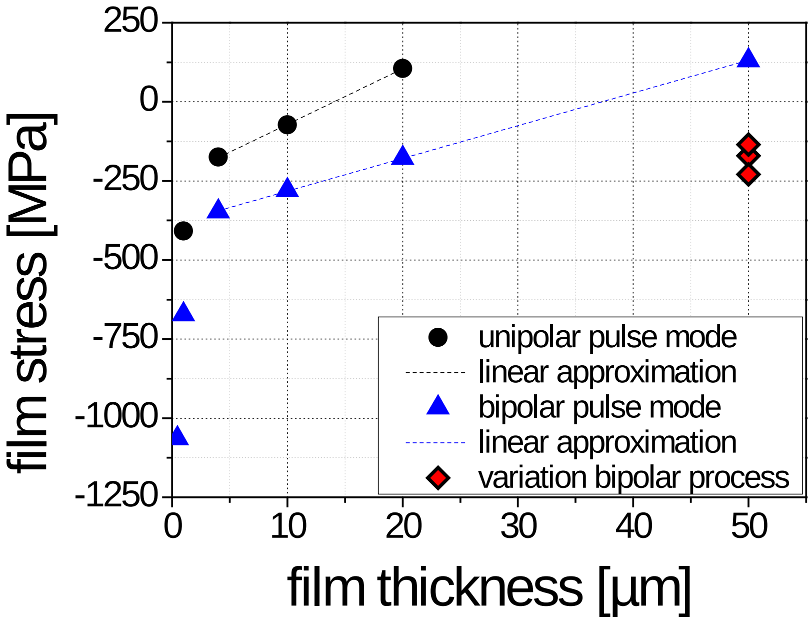


Pole figure: FWHM 2°...4°

Influence of pulse mode on stress of piezoelectric AlN layers

- **In Unipolar and Bipolar pulse mode AlN layers with good crystalline c-axis** orientation could be obtained (d_{33} ~ 7 pC/N)

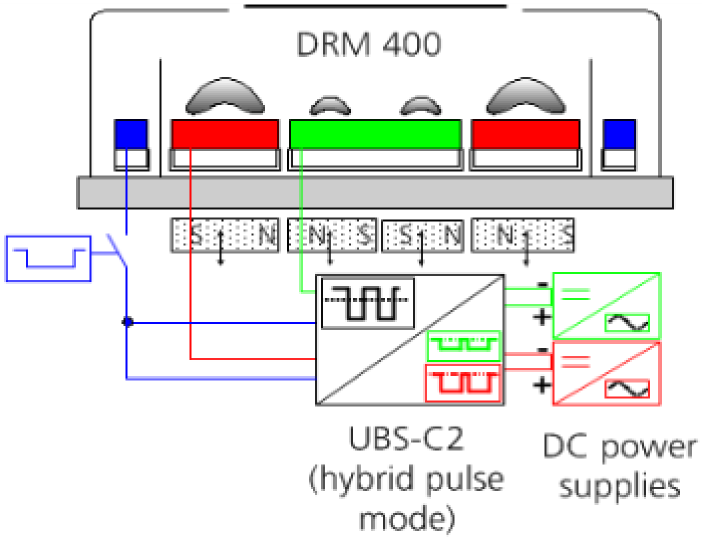
Unipolar pulse mode	Bipolar pulse mode
moderate	strong
bombardment of the growing thin film by high energy particles	



- Bipolar pulse mode:
  higher tendency to compressive stress
- At higher film thickness tendency to tensile stress

New approach for fine adjustment of layer properties: hybrid pulse mode

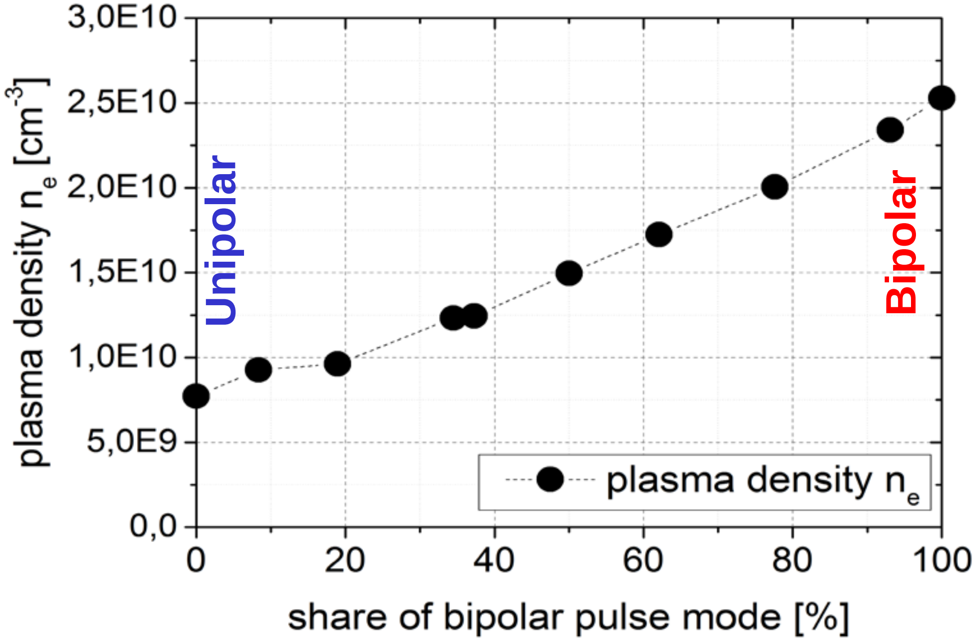
- Idea: switching between unipolar and bipolar mode at frequency 1kHz (1msec)
  - Faster then the time necessary for deposition of a single atomic layer (~ >20msec)
  - Slower then discharge pulse frequency (typically 20…100kHz)
- Hardware solution: electronic switch to switch on/ off anode periodically (Anode pulse unit)
  - ➢ Synchronized with UBS-C2 to switch between unipolar und bipolar pulsing

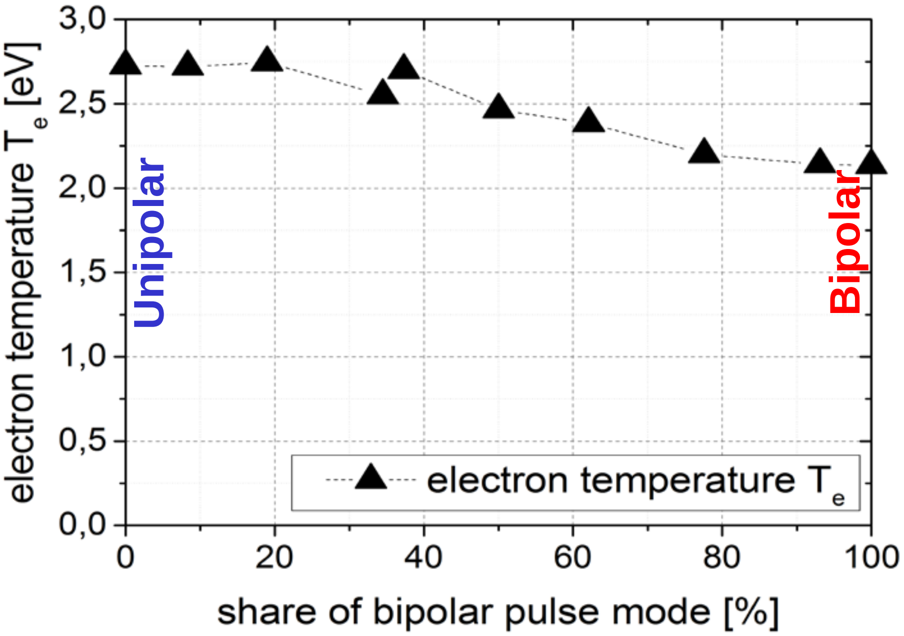


Unipolar pulse mode	Hybrid pulse mode	Bipolar pulse mode
moderate	intermediate	strong
bombardment of the growing thin film by high energy particles		

Plasma Characterization of hybrid pulse mode

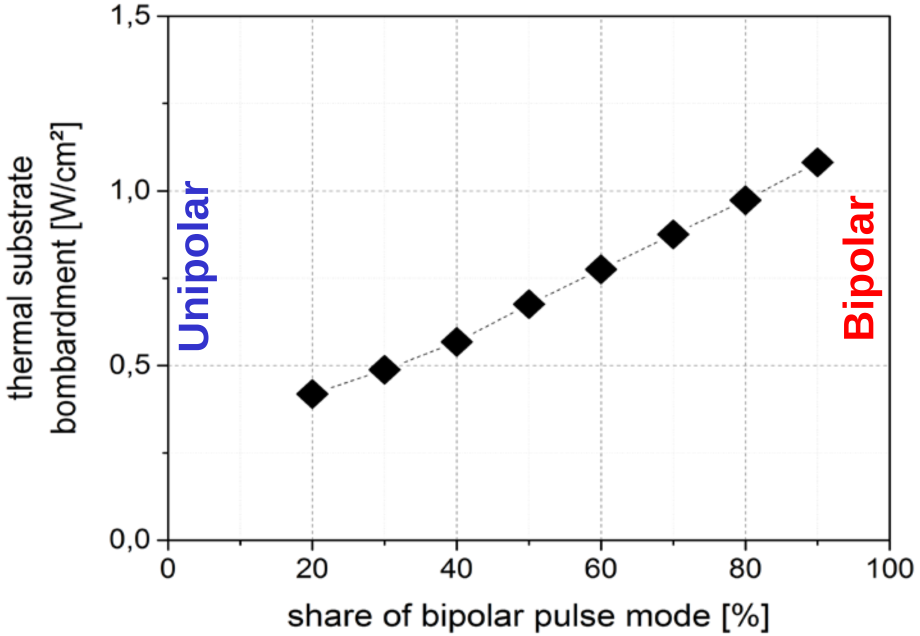
- Results of Double Langmuir probe measurements in substrate vicinity (according to method of Sonin; process: Si 2.5 kW, 0.4 Pa):
  - Plasma density rises linearly with share of bipolar mode (> factor 3)
  - Electron temperature slightly decreases (to 80%)

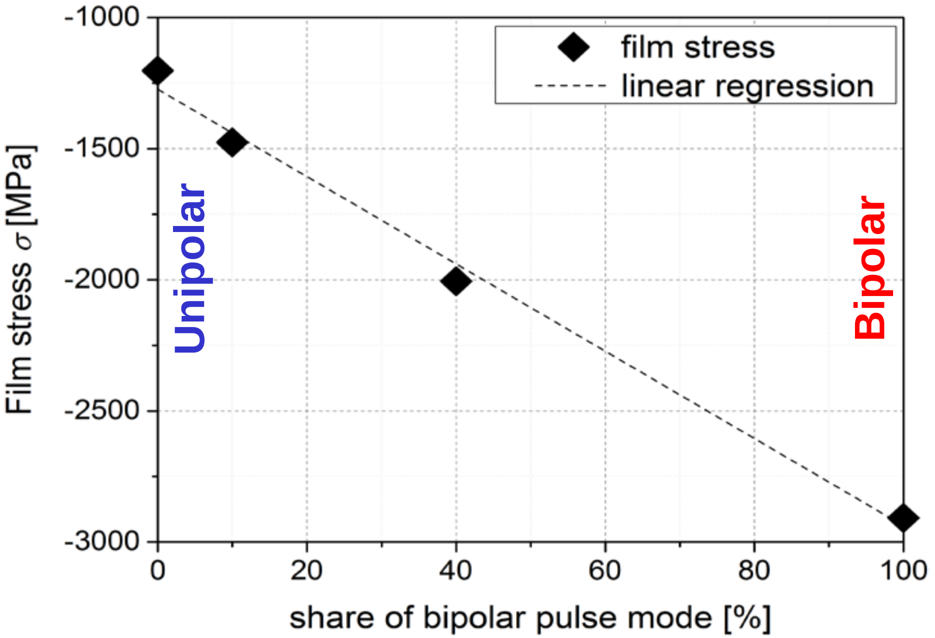




Thermal substrate load and stress of AlN layers deposited with Hybrid pulse mode

- higher share of bipolar pulse mode:
  - Increased substrate bombardment
  - Higher compressive film stress
    - ➢ Fine adjustment of layer properties possible





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- Reactive Pulse Magnetron Sputtering allows precise control of the deposition process.
- There are a number of parameters influencing the plasma density during deposition and hence the energetic substrate bombardment.
- By changing the Pulse mode and Pulse parameters of the Pulse Magnetron Sputter process, the plasma properties can be changed significantly.

Unipolar pulse mode	**Hybrid pulse mode**	**Bipolar pulse mode**
moderate	intermediate	strong
bombardment of the growing thin film by high energy particles		

- The energetic substrate bombardment is the key to control layer growth and layer properties.

Thank you for your attention !

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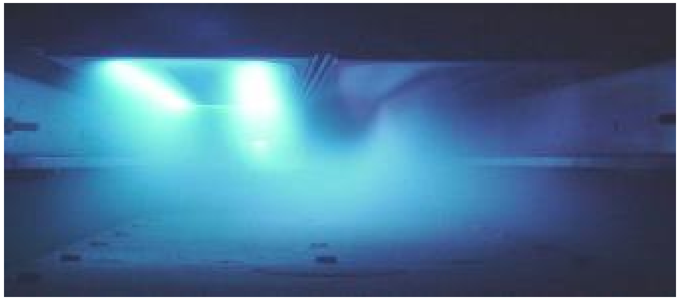

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EFRE

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