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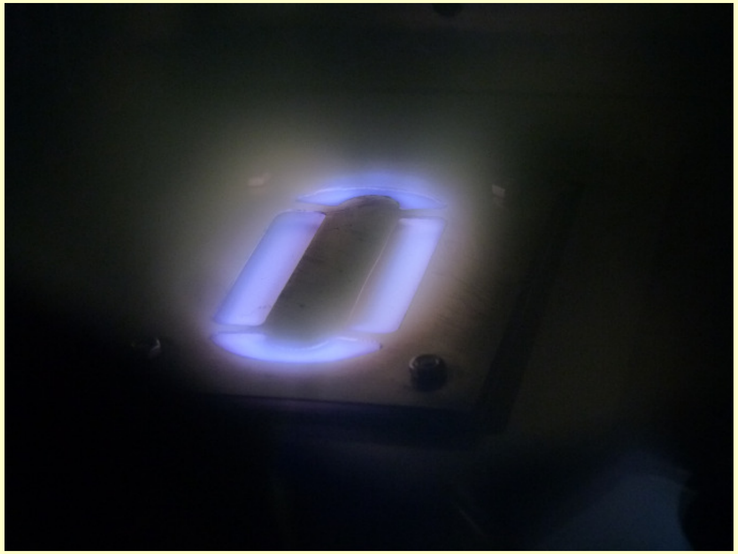
JENION

Magnetron Sputtering with Controlled Primary Ion Energy II: Some simulations and experiments of the corresponding layer growth

11.03.2025



Content:

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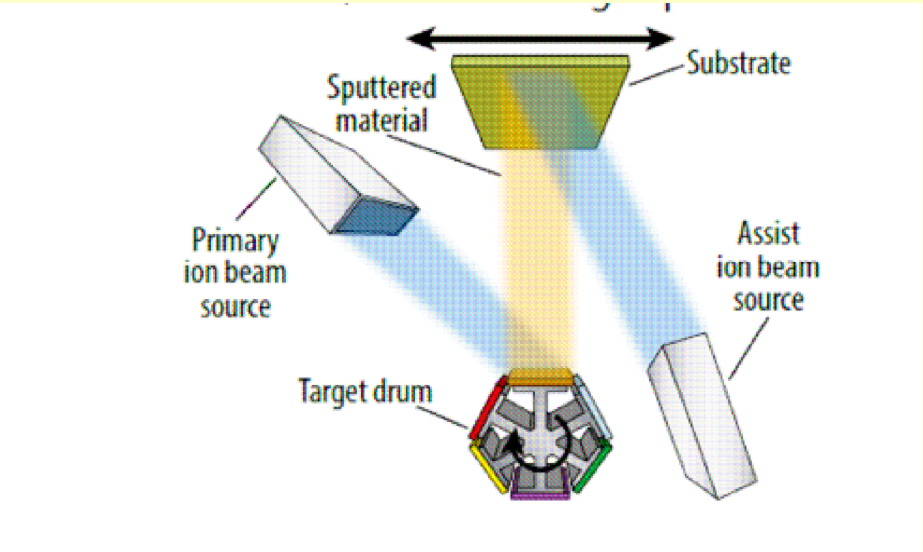
1. Introduction: Magnetron sputtering with controlled primary ion energy – Dual Target Magnetron
2. Primary ion energies in comparison in magnetron sputtering,
3. Particle flux to the substrate at DTM Sputtering
4. Simulated energy distributions and experimental results for:
   - Ar+ → Aluminum,
   - Ar+ → Silicon,
   - Ar+ → Copper.
5. Some estimations: Energy flux to the substrate,
6. Summary, future work ?

Direct Ion Beam Sputtering versus Magnetron Sputtering

Direct Ion Beam Sputtering

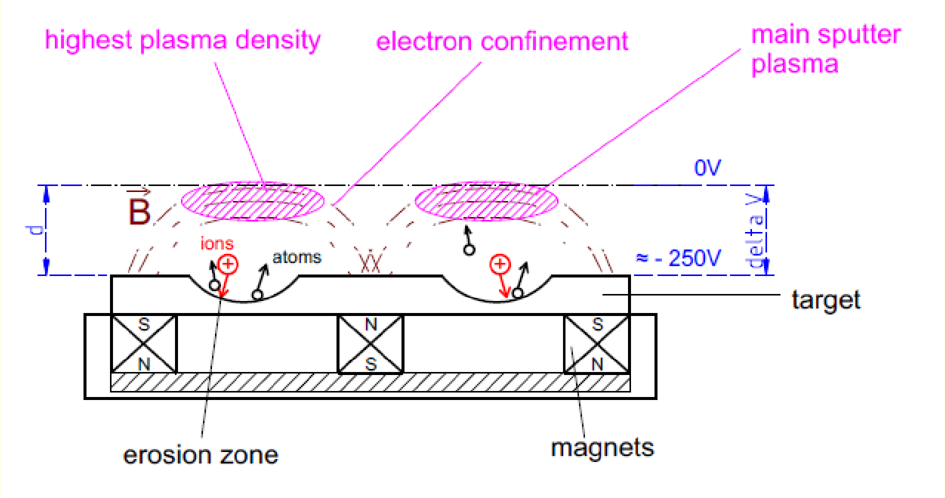


- an ion source generates a broad ion beam (200 – 1000 eV), with Ar^+ or Kr^+,
- ions sputter at target at defined angle,
- sputtered target material is deposited at the substrate,
- limited deposition rates, limited target dimensions,

- **because of variable primary ion energy the energy of sputtered atoms is free controllable in a range of approx. 5 to 20 eV,**

- a lot of publications about that from “IOM & Co workers” in 2005 to now

Magnetron Sputtering

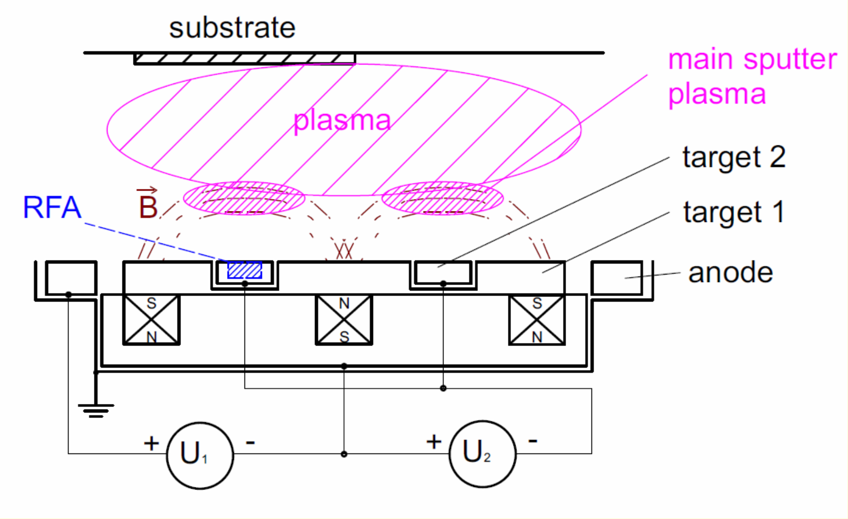


- a special magnetic confined plasma is generated by permanent magnets at a pressure between 10^{-2} to 10^{-3} mbar (magnetron),
- mostly used: argon,
- simple construction,
- high deposition rates, large target dimensions,
- primary ion energy normally 250 to 400 eV,
- maximum primary energy is about 750 eV,

- **but energy of sputtering ions is determined by the plasma parameters (pressure, power) and not free controllable,**

Principle of the Dual Target Magnetron (DTM)

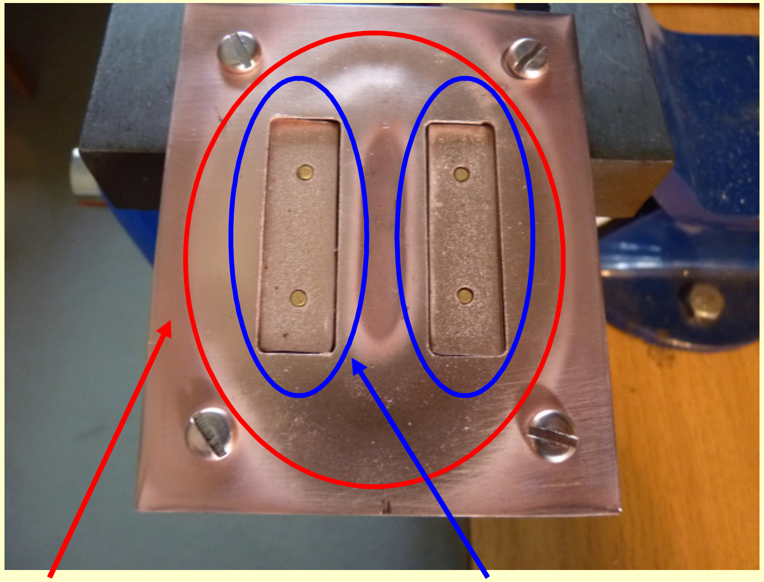
Principle



$P_1 = U_1 * I_1$
"classical" magnetron power, determines deposition speed

$P_2 = U_2 * I_2$
Determines primary ion energy

Targets and sputter areas



Target 1 Keule

Target 2 Keulen

$$W_{ion}(U_1, U_2) = U_1 - U_{anode} + C*U_2$$

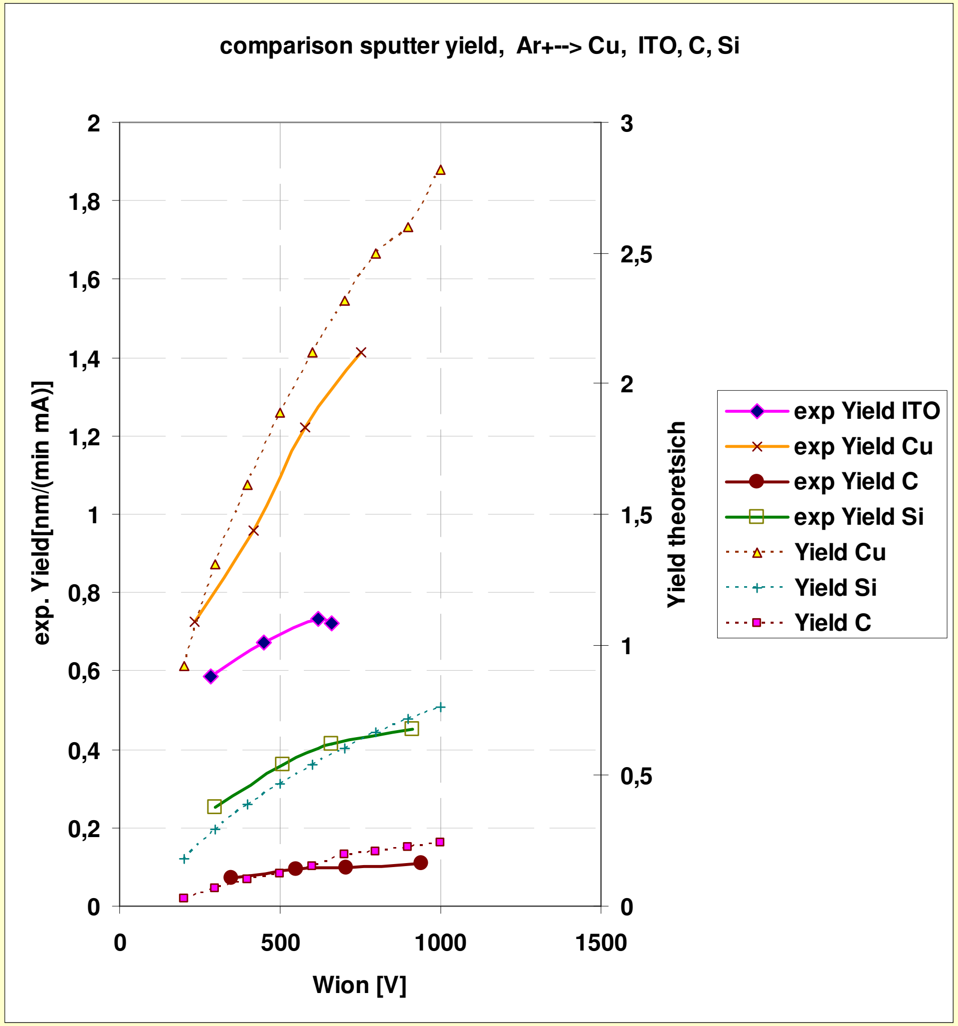
With:

U_1 : Voltage for sputtering (typ. 300 to 400 V),
U_{anode}: Potential of the anode (typ. 25 to 75 V),
U_2: Accelerator voltage target 2,
C : Faktor approx. 0.7 to 0.9

Idea of Dual Target Magnetron (DTM):

- inside of the target (target 1) at place of the erosion zone (highest sputtering) an isolated target area (target 2) is mounted,
- target 2 can be hold at negative potential against target 1 of up to 1.000 V, → additional ion acceleration of primary ions at this place,
- primary ions (Ar+) will be mostly accelerated collision less from the main plasma 5 to 15 mm over target 2,

Primary Ion Energy and Sputter Yield



Comparison of exp. estimated sputter yield (left y-axis) after (1) and theoretical sputter yield values (right y-axis) in dependence from the primary ion energy, DTM at constant plasma (80 W, 1x10^{-2} mbar argon)

Estimation of the behavior of the Sputter Yield at target 2:

- deposition rate **R** measured with quartz monitor (→ deposited mass proportional to deposited atom number),
- current **I_2** is proportional to the number of sputtered ions,

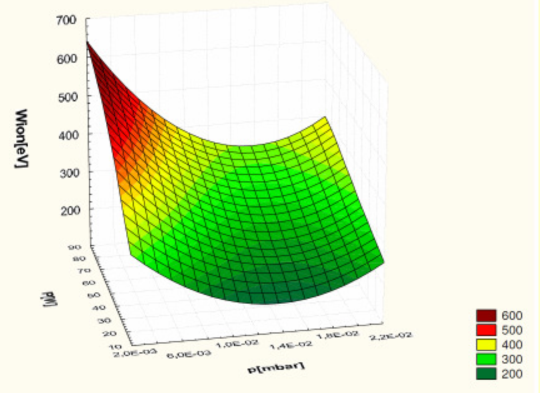
- then the sputter yield is proportional to:

$$\bullet Y_{exp}(Wion) \sim R/I_2 \qquad (1)$$

- the figure shows good agreement between theoretical [1] and experimental sputter yield for four target materials

[1] https://www2.iap.tuwien.ac.at/www/surface/sputteryield

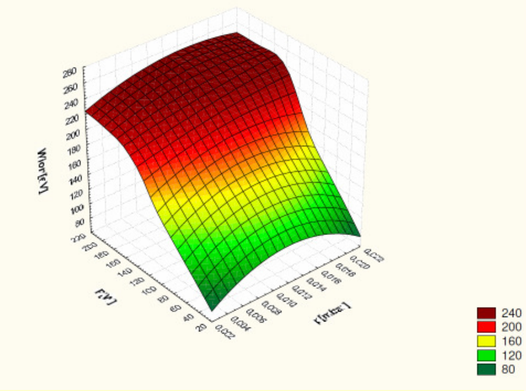
Primary ion energies in comparison in magnetron sputtering



DC-Sputtering [1]

- some increase to low pressure,
- some increase to high power,

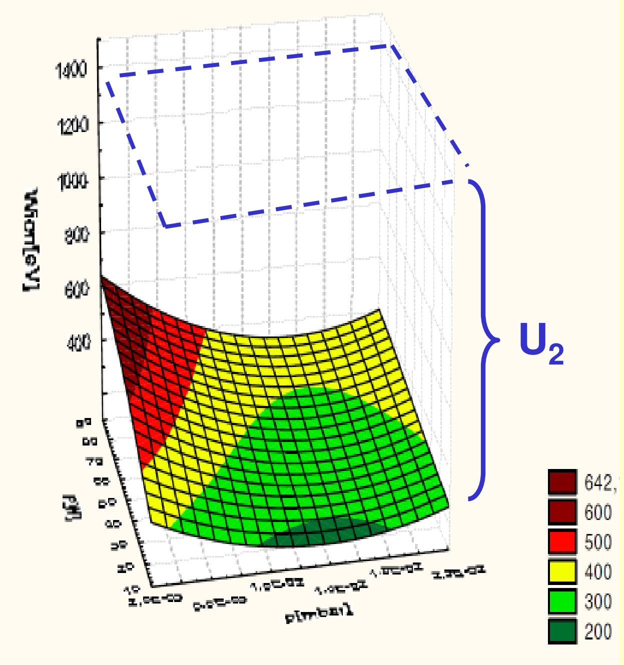
•**Total range: 250 to 600 eV**



RF-Sputtering [1]

- some increase with power,

•**Total range: 250 to 500 eV**



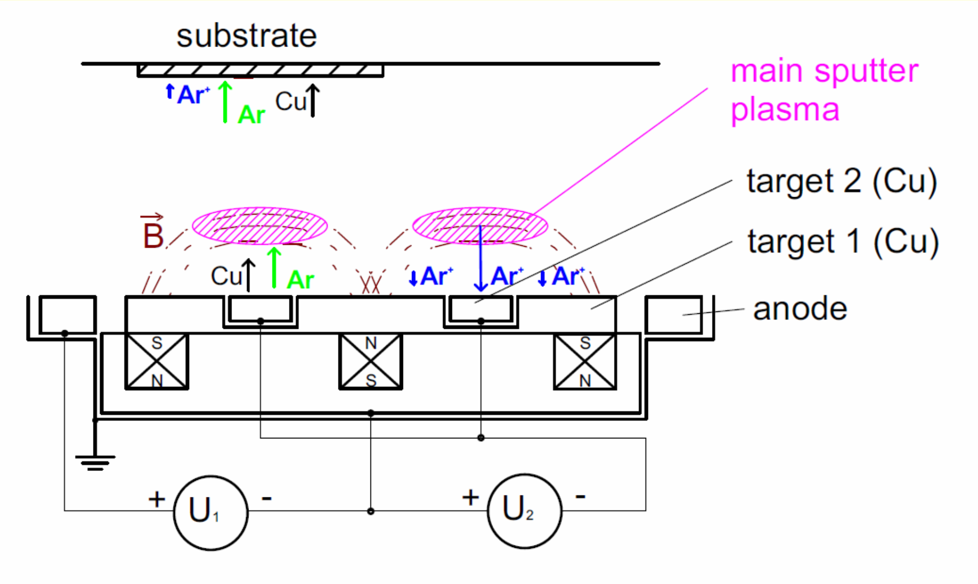
DC-Sputtering DTM [2]

- plasma independent increase by U$_2$

•**Total range: 250 to >1250 eV**

[1], [2]   www.jenion.de/news

DTM Sputtering and layer growth



Question: What are the corresponding energy distributions ?

a) Measurement:

- ions and electrons from the sputter plasma (plasma probes, Retarding Field Analyzer Jenion),
- Ion energy distributions of sputtered and backscattered ions (DIBS > 10 papers from IOM Leipzig with Hiden Analytical)

b) Simulation:

- energy of sputtered target atoms – SRIM [1],
- energy of scattered primary atoms – Tridyn [2]

Processes at the target:

- primary ions with Wion impinge on target,
- target atoms will be sputtered,
- primary ions introduce into the target surface (max. 10 nm),
- primary ions will be reflected as fast neutral atoms or ions,
- on some targets negative ins will be created (e.g. TCO´s) and accelerated by the sputter plasma.

Processes at the gas/plasma:

- consider only low (collision less) pressure (10^{-3} mbar)

Processes at the substrate:

a) Particles from the plasma:

- Argon ions from the plasma sheet,
- Electrons from the plasma sheet (low influence),
- UV-light from the sputter plasma.

b) Particles from the target:

- Sputtered target atoms,
- Fast reflected neutrals,
- Sometimes: fast negative ions

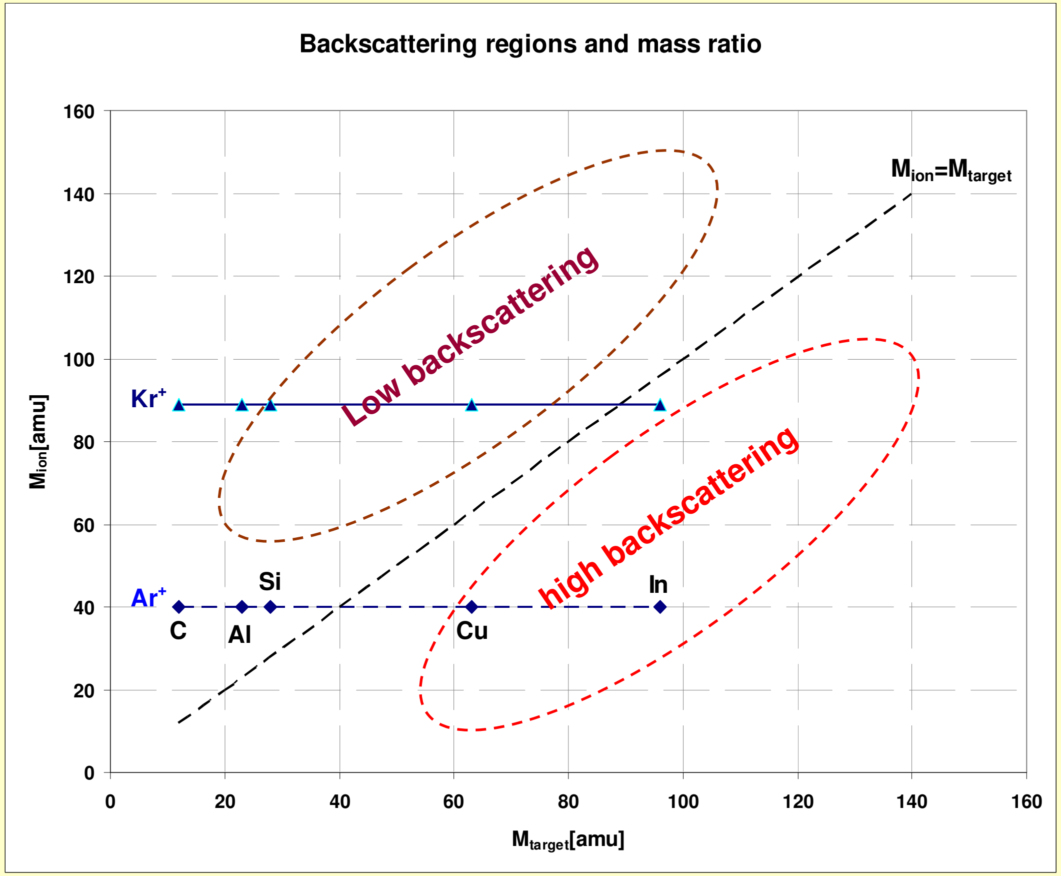
[1] J. Ziegler, SRIM Transport of ions in matter, www.srim.org
[2] W. Moeller, Tridyn, https://hzdr-innovation.de/products/simulationssoftware-tridyn/

Important: the mass ratio M_{ion}/M_{target}

mass ratio (M_{ion}/M_{target}):

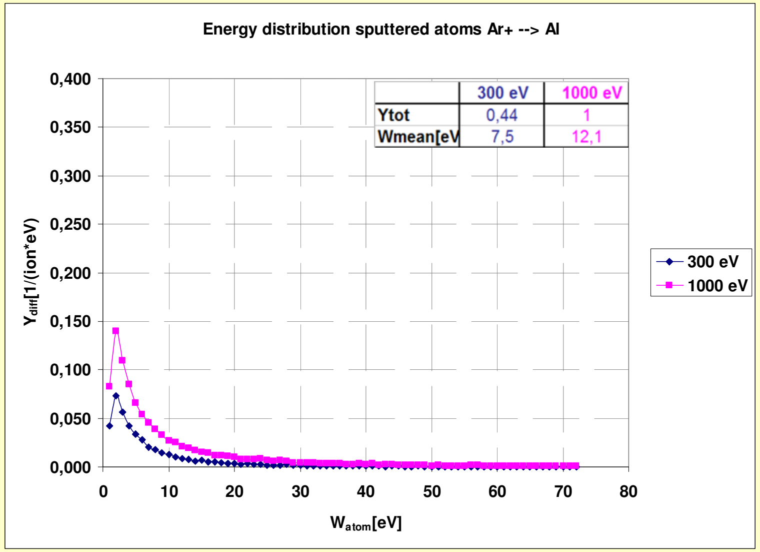
- if M_{target} is lower than M_{ion} both sputtered target atoms and reflected neutral argon atoms have lower energies,

- if M_{target} is higher than M_{ion} both sputtered target atoms have higher and reflected neutral argon atoms may have energies up to the primary ion energy.



Example: DTM Sputtering of Ar^+ → Aluminum

Sputtered atoms

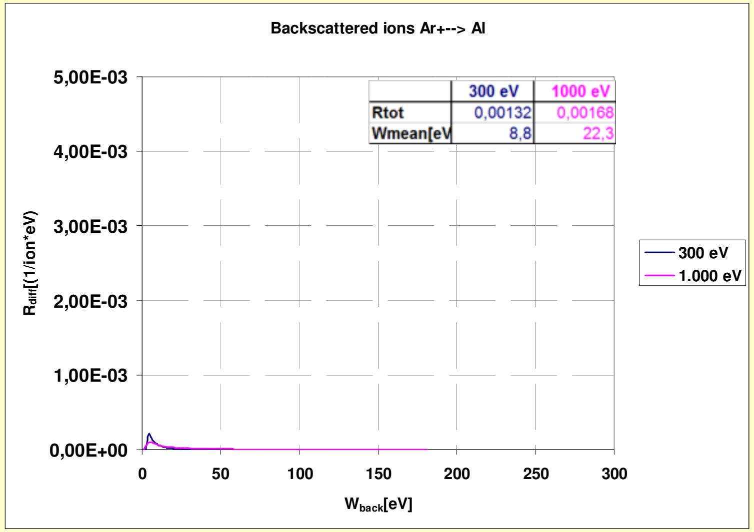


$$\frac{M_{ion}}{M_{tar}} = \frac{40}{23}$$

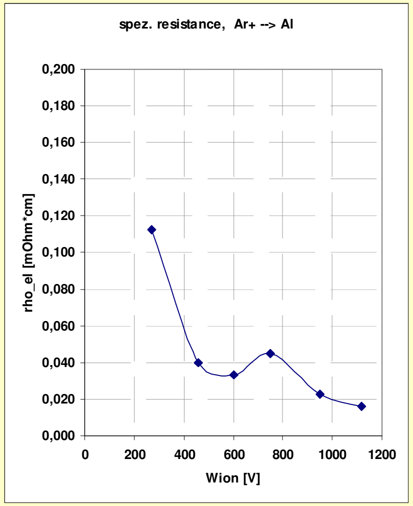
Demonstration experiment with DTM:

- pressure 10^{-2} mbar (→ 2 to 4 collisions target → substrate),
- plasma power 80 W,
- primary ion energy from 350 to 1.100 eV

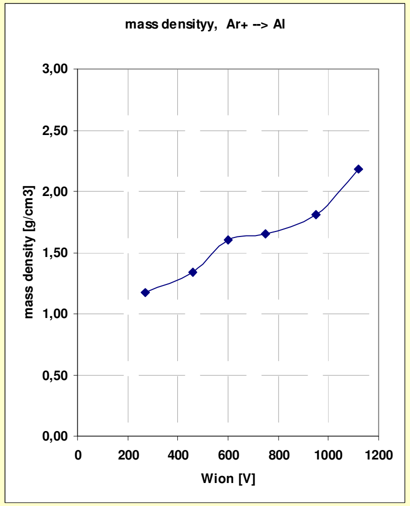
backscattered ions/atoms



specific resistance



mass density

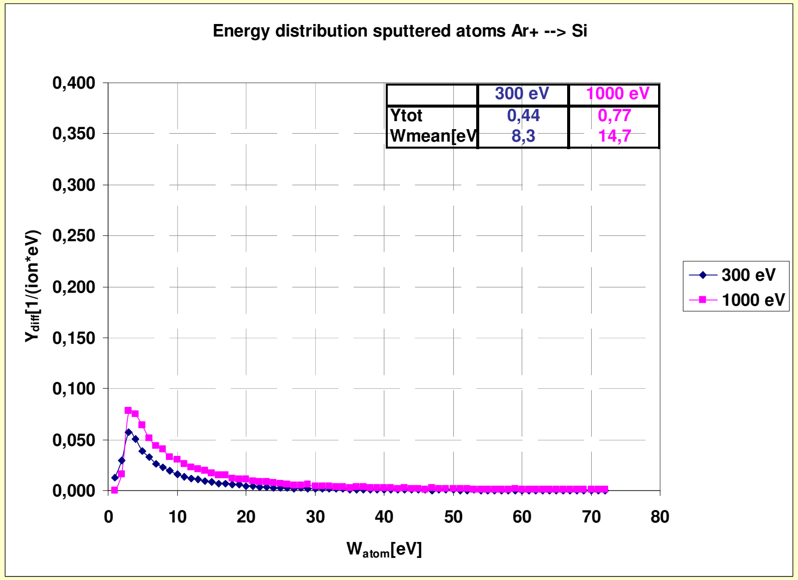


Specific resistance (left) and mass density (right) of aluminum layers in dependence from the primary ion energy sputtered with the DTM

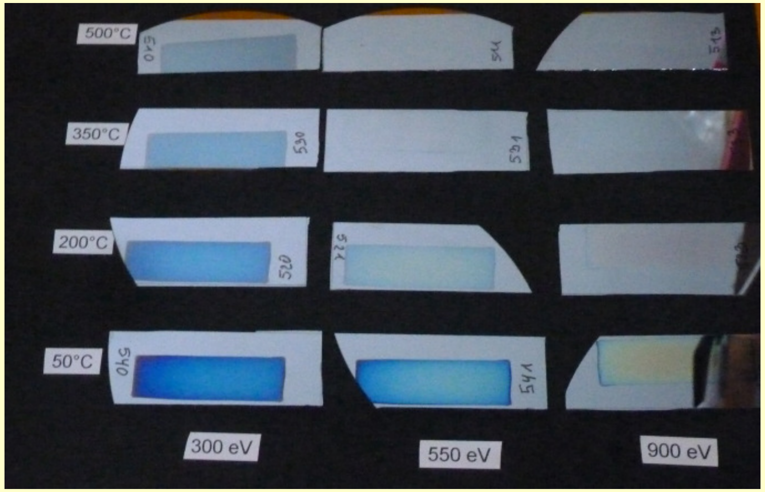
Example: DTM Sputtering of Ar^+ → Silicon

$$\frac{M_{ion}}{M_{tar}} = \frac{40}{23}$$

Sputtered atoms

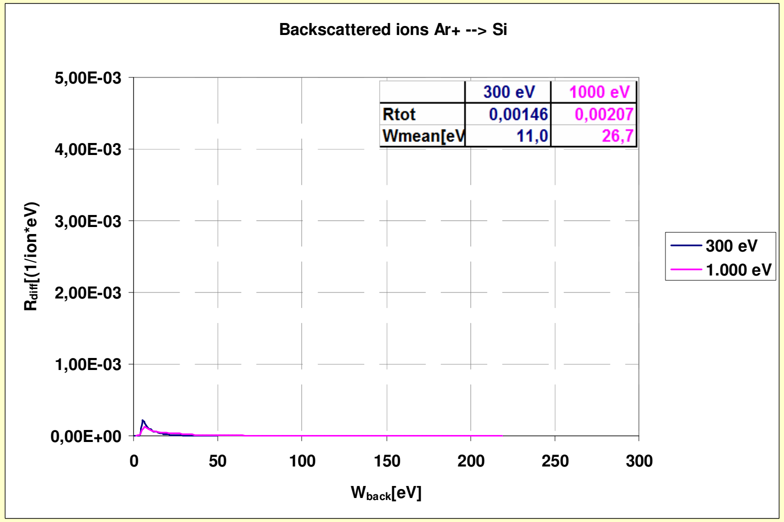


	300 eV	1000 eV
Ytot	0,44	0,77
Wmean[eV	8,3	14,7

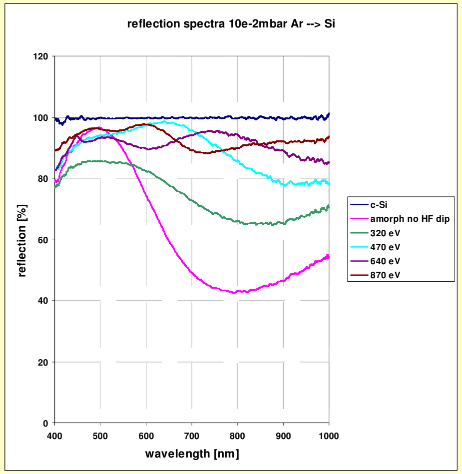


Amorphous or crystalline silicon layers on <100> silicon in dependence from temperature and the primary ion energy sputtered with the DTM

backscattered ions/atoms



	300 eV	1000 eV
Rtot	0,00146	0,00207
Wmean[eV	11,0	26,7



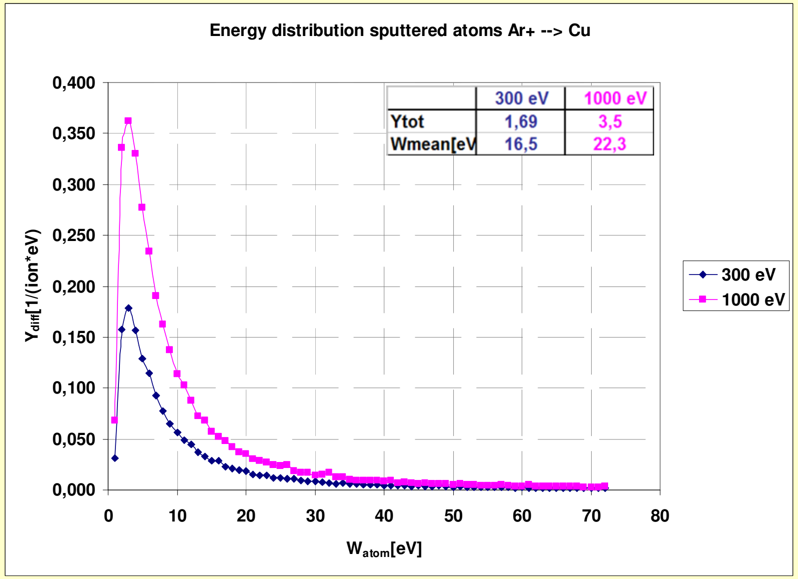
Reflection spectra of the silicon layers on <100> silicon at 350°C in dependence from the primary ion energy sputtered with the DTM

Demonstration experiment with DTM:

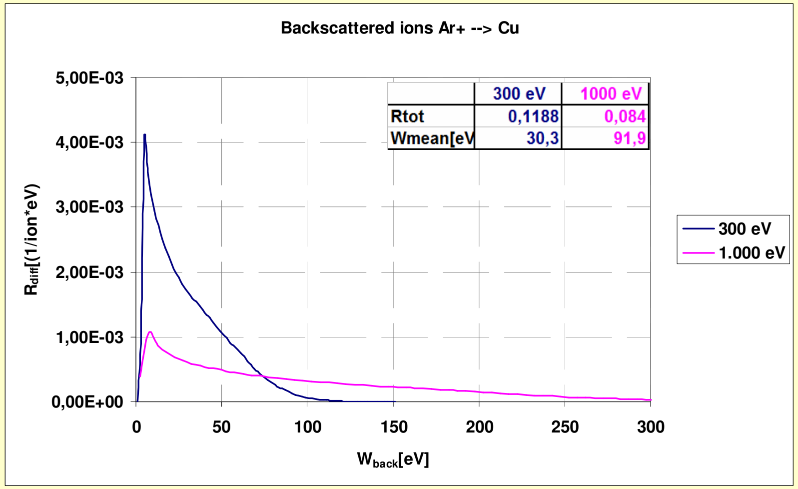
- pressure 10^{-2} mbar (→ 2 to 4 collisions target → substrate),
- plasma power 80 W,
- primary ion energy from 300 to 870 eV,
- substrate temperature from 50°C to 500 °C

Example: DTM Sputtering of Ar$^+$ → Copper

Sputtered atoms



backscattered ions/atoms

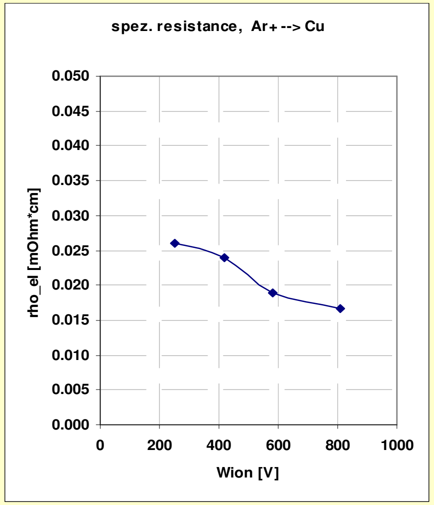


$$\frac{M_{ion}}{M_{tar}} = \frac{40}{63}$$

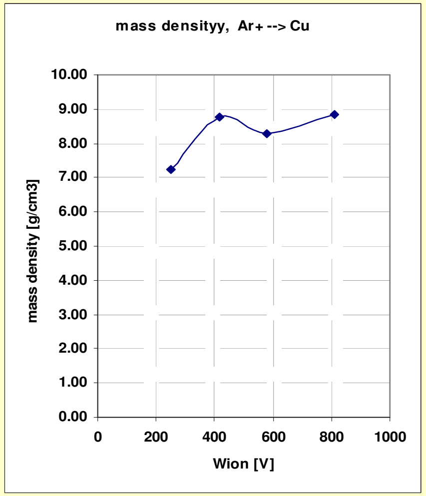
Demonstration experiment with DTM:

- pressure 10^{-2} mbar (→ 2 to 4 collisions target → substrate),
- plasma power 80 W,
- primary ion energy from 250 to 800 eV

specific resistance

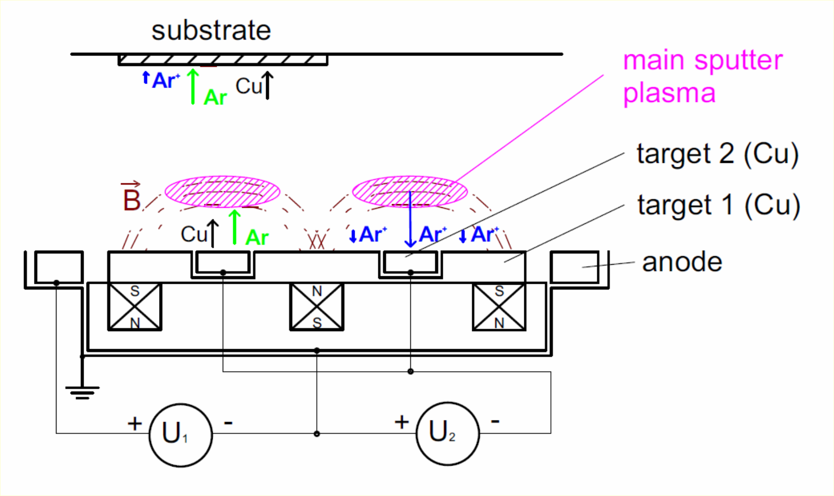


mass density



Specific resistance (left) and mass density (right) of cupper layers in dependence from the primary ion energy sputtered with the DTM

Estimation of the energy flux to the substrate



Direct sputter plasma at substrate:

$$dE/dA_{plasma} = j_{sub}/e * E_{submean} \quad (1)$$

Backscattered neutrals (argon):

$$dE/dA_{back} = j_{prim}/e *FV*R_{tot}* E_{backmean} \quad (2)$$

Sputtered target atoms:

$$dE/dA_{tar} = j_{prim}/e * FV*Y_{tot}*E_{tarmean} \quad (3)$$

Total energy flux:

$$dE/dA_{tot} = dE/dA_{plasma} + dE/dA_{back} + dE/dA_{tar} \quad (4)$$

With:

j_{sub} – ion current density at substrate (100 uAcm^{-2}),

$E_{submean}$ – mean energy from argon ions at substrate (25 eV),

J_{prim} – primary ion current density at target (3 mAcm^{-2}),

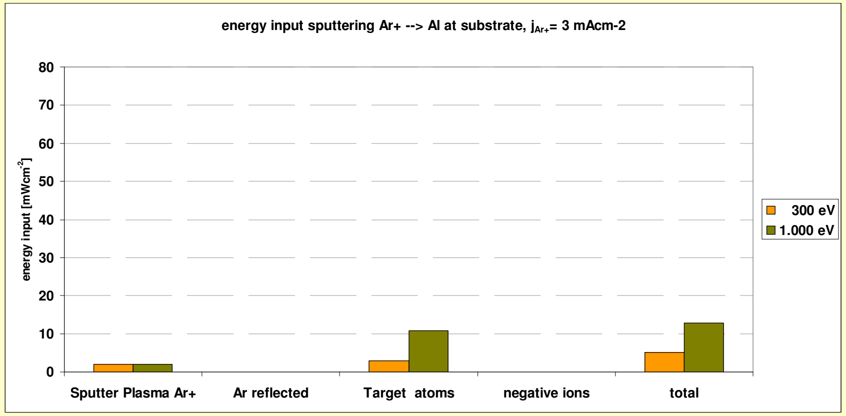
FV – area factor (0,3),

R_{tot} – total reflection coefficient of backscattered argon (from Tridyn),

$E_{backmean}$ – mean energy of backscattered argon from Tridyn)
Y_{tot} – totaler sputter yield, (from SRIM),

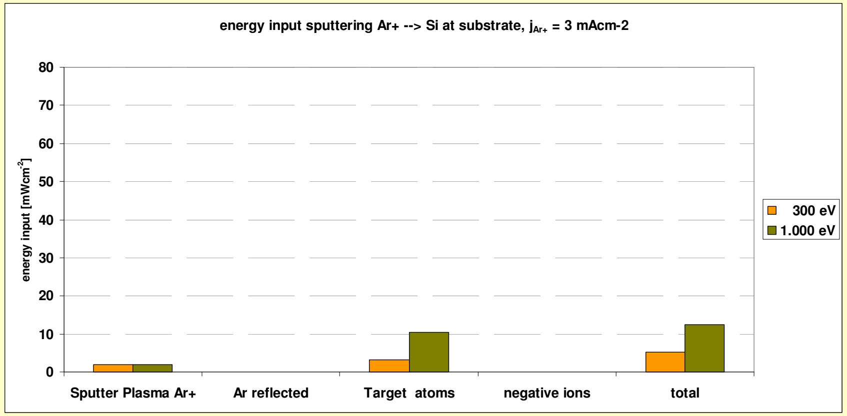
$E_{tarmean}$ – mean energy of sputtered target atoms (from SRIM),

Summary: Energy flux to the substrate



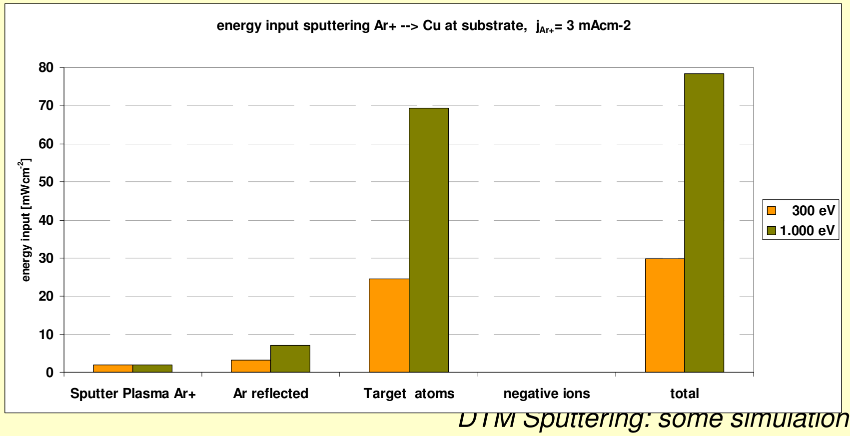
Sputtering Ar+ → Aluminum:

- direct plasma energy flux normal,
- neglect able energy flux from backscattered argon,
- energy flux determined by energy of target atoms,
- at 1.000 eV primary ion energy nearly 3 times total energy flux



Sputtering Ar+ → Silicon:

- direct plasma energy flux normal,
- neglect able energy flux from backscattered argon,
- energy flux determined by energy of target atoms,
- at 1.000 eV primary ion energy nearly 3 times total energy flux



Sputtering Ar+ → Copper:

- direct plasma energy flux normal,
- small energy flux from backscattered argon,
- energy flux determined by energy of target atoms,
- at 1.000 eV primary ion energy nearly 3 times total energy flux,

Summary and future work ?

Dual Target Magnetron (DTM) status:

- Since 2020 several constructions of DTM´s had been tested by Jenion and are applicable for research projects (planar linear DTM´s),
- The working principle of the DTM is now clear and demonstrated,
- Round, coaxial DTM´s are only small tested but seem make able,
- Concepts for rotational magnetrons can be developed on basis of the linear DTM´s but request solving of several technical issues (cooling, electrical insulation, high power, etc.),

Status layer deposition with the DTM:

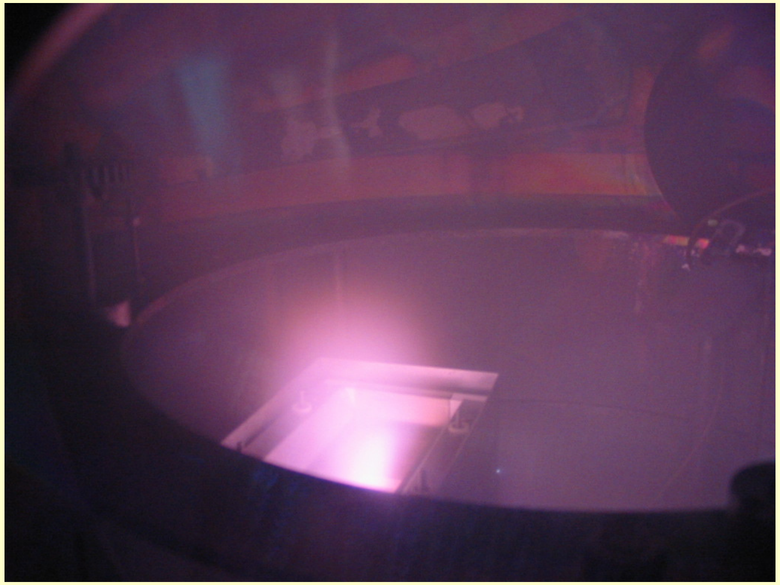
- Although Direct Ion Beam Sputtering (DIBS) is an acknowledged deposition method since more then 30 years, not very much results exist on corresponding layer growth,
- Since 2023 we have a interesting discussion with sputter experts about the influence of the controlled primary ion energy to the corresponding layer growth in DTM sputtering,
- Like shown here, the deposition effect can be simulated and experimental demonstrated,
- More professional research should be done on this,

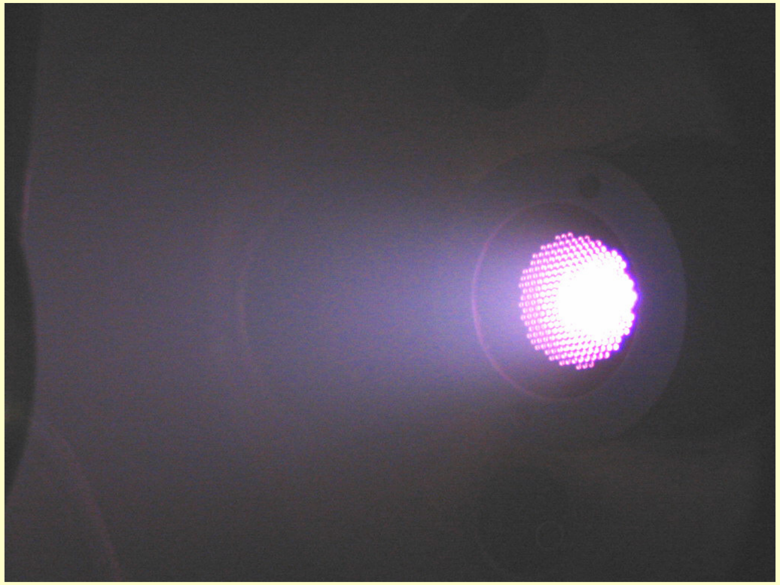
Future work:

- Optimization of details of the Dual Target Magnetron,
- DTM for RF-sputtering,
- More investigations of layer properties, deposited with the DTM,
- More Monte Carlo Simulation of the sputter effect (100 to 2000 eV, SRIM, Tridyn)
- More investigations of the total energy flux at the substrate.

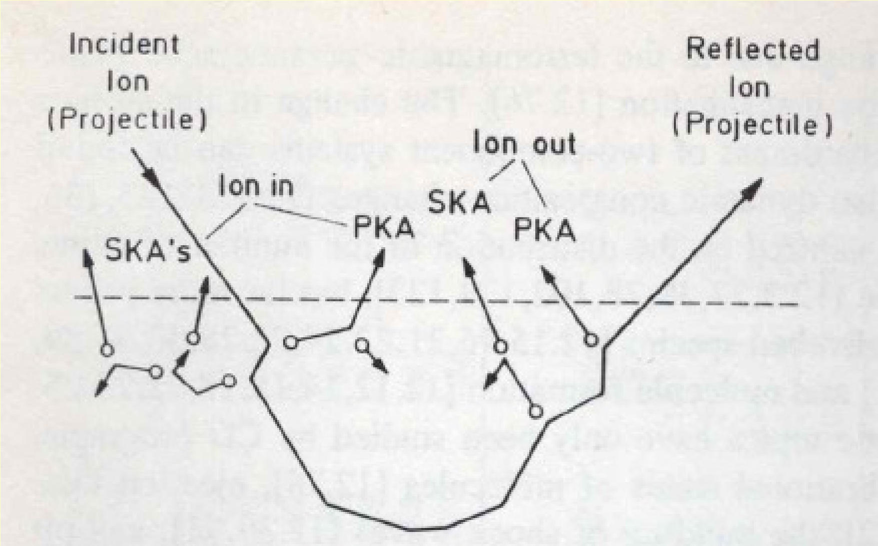
Acknowledgement to Prof. W. Moeller - Helmholtz Zentrum Dresden for the Tridyn Simulations

Thank You!





Monte-Carlo-Simulation mit SRIM & Tridyn



Basic processes at the target surface while sputtering considered in Monte Carlo Simulations like TRIM or Tridyn [1]

TRIM (Transport of Ions in Matter):
- developed for simulation of ion implantation in the 1990-s,
- simulates in principle also sputtered atoms and backscattered ions

Incident ion:
- incomimg ion with energy W_{ion},

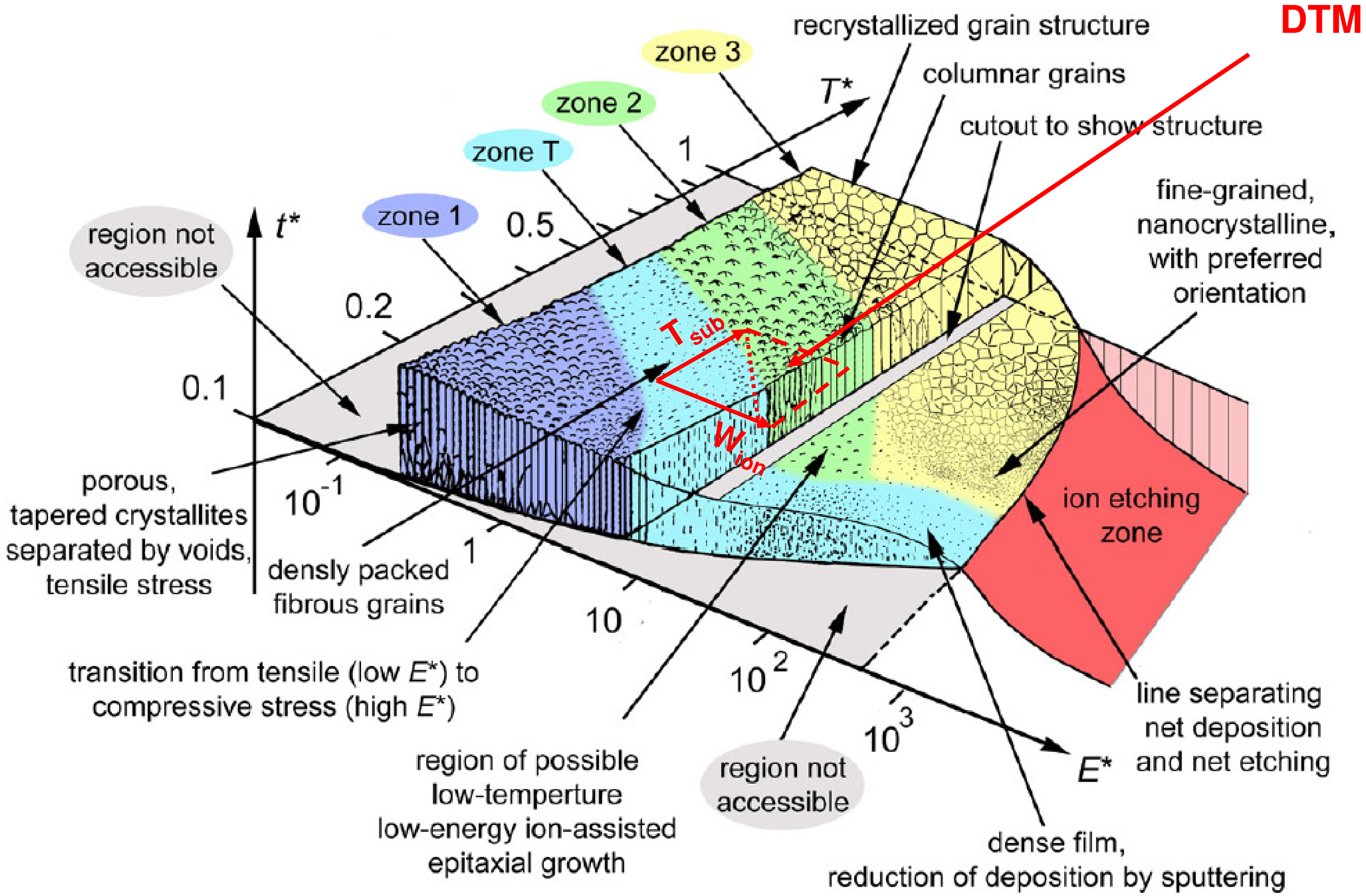
PKA – primäry nock on atom:
- target atom direct sputtered from primarily ion

SKA – secondary nock on atom:
- target atom sputtered indirect from primarly ion (may be by impact cascade)

TRIM und SRIM: do only simulate the PKA at the first monolayer
→ Sputtered target atoms are more or less ok, backscattered ions with bigger derivations

TRIM.SP und TRIDYN: do simulate PKA and SKA ?
→ Both sputtered atoms and backscattered ions ok

[1] W. Eckstein, Computer Simulations of Ion-Solid Interactions, Springer Series in Material Science 10, 1991, 178



A. Anders, *"A structure zone diagram including plasma based deposition and etching"*, Thin Solid Films, Volume 518, Issue 15, 31 May 2010, Pages 4087-4090