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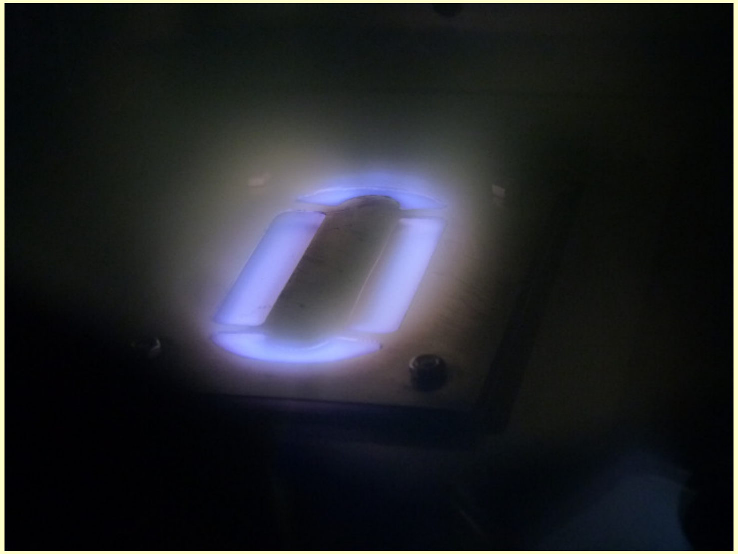
Magnetron Sputtering with Controlled primary Ion Energy – first results, future work ?

12.03..2024



Content:

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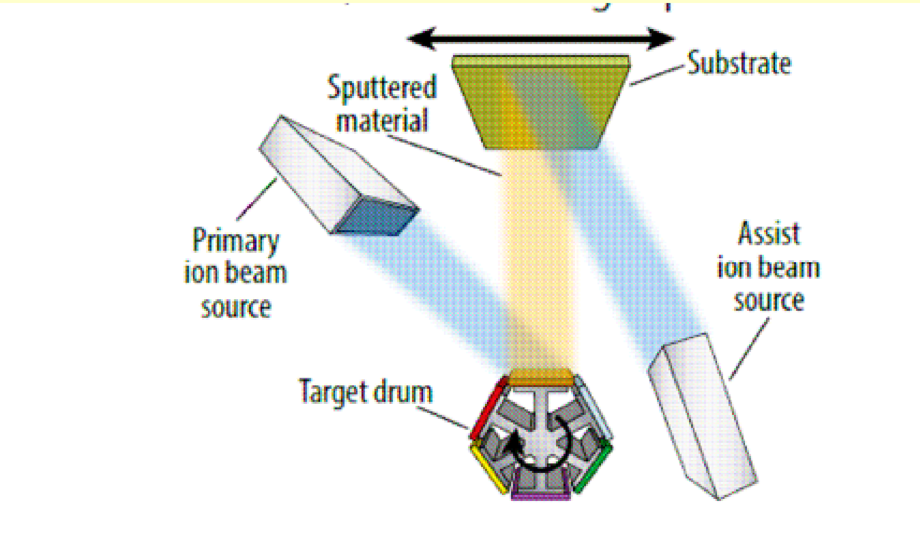
1. Magnetron Sputtering versus Direct Ion Beam Sputtering,
2. Dual Target Magnetron characterization (principle, plasma characterization, sputter yields .....),
3. Some sputtered layers ($Ar^+ \rightarrow Cu$, $Ar^+ \rightarrow Si$),
4. Some estimations: Energy flux to the substrate,
5. Summary, future work ?

Direct Ion Beam Sputtering versus Magnetron Sputtering

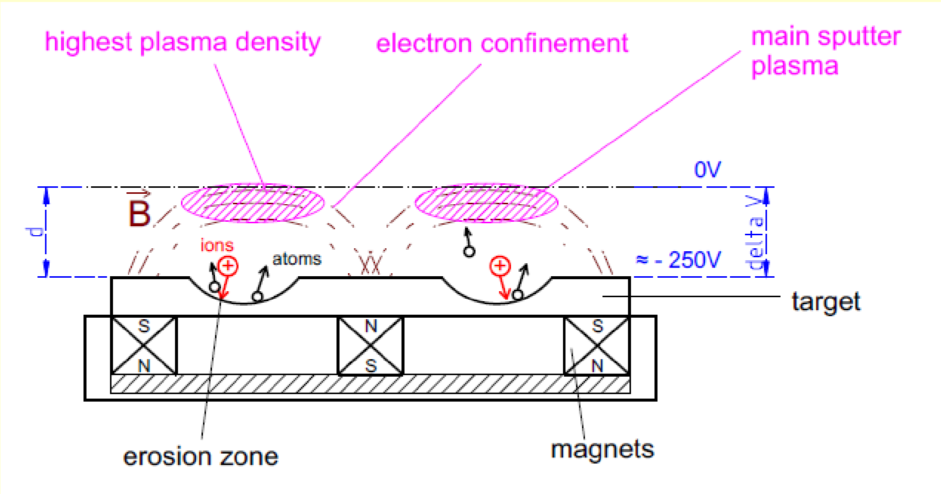
Direct Ion Beam Sputtering



- 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,**

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,**

Direct Ion Beam Sputtering – 50 years of research

1960 – 1980: First sputter research:

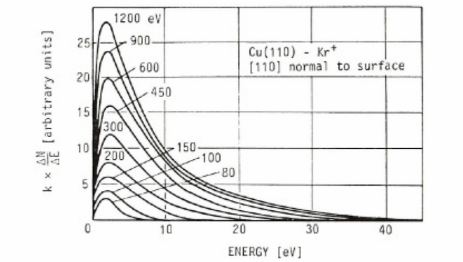
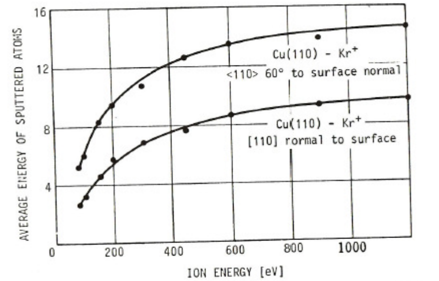


Figure 3.15: Energy distributions of sputtered atoms for various incident ion energy (Stuart, Wehner, 1964 (43)).



.18: Average energy of sputtered atoms (Stuart, Wehner, 1964 (43)).

- First measurements of sputter yields and energy of sputtered atoms,
- fundamental formulas (Thompson etc.)

1980 – 2000: Monte Carlo Simulations (TRIM – Transport of Ions in Matter):

- detailed step by step simulation of the collisions for ion implantation,
- sputtering simulation as a "by product", → TRIM.SP is more correct,
- but simulation for all ion and Target masses available,

2000 – 2020: Detailed fundamental research (IOM Leipzig):

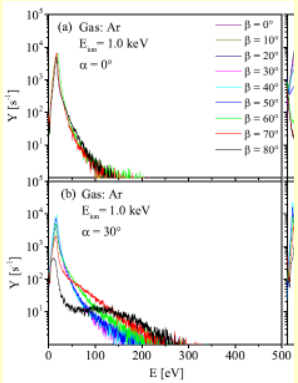
Tutorial: The Systematics of Ion Beam Sputtering for Deposition of Thin Films with Tailored Properties

Carsten Bundesmann* and Horst Neumann
Leibniz Institute of Surface Engineering (IOM), Ion Source Development and Application Group, Permoserstraße 15, 04318 Leipzig, Germany

There is an increasing demand for thin films with tailored properties, which requires the use and control of adequate deposition techniques. Ion beam sputter deposition (IBSD) is a physical vapor deposition (PVD) technique that is capable to fulfill the technological challenges. In contrast

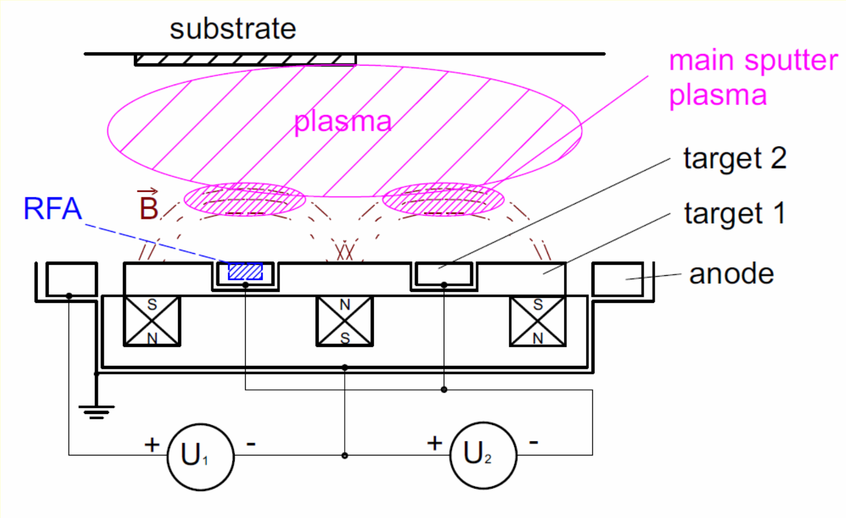
C. Bundesmann and H. Neumann, J. Appl. Phys. 124, 231102 (2018),

C. Bundesmann, R. Feder, T. Lautenschläger, H. Neumann,
Energy Distribution of Secondary Particles in Ion Beam Deposition Process of Ag: Experime Calculation and Simulation
Contrib. Plasma Phys. 55 (2015) 737-746



Principle of the Dual Target Magnetron (DTM)

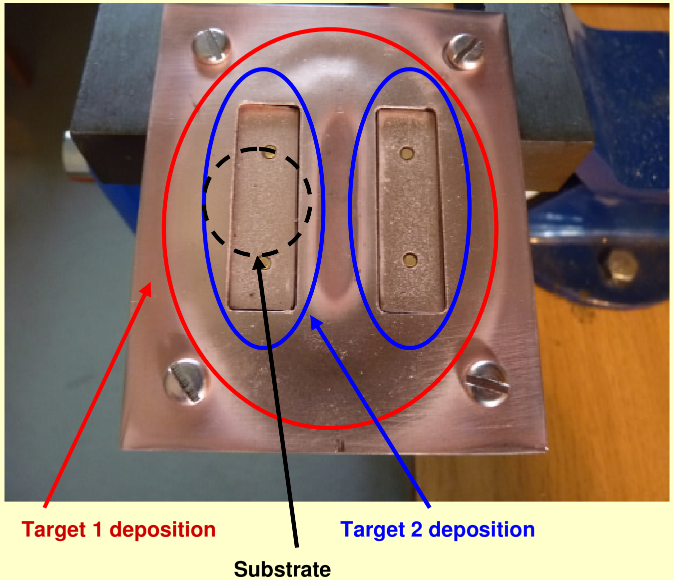
Principle



P1 = U1 * I1
"classical" magnetron power, determines deposition speed

P2 = U2 * I2
Determines primary ion energy

Targets and sputter areas



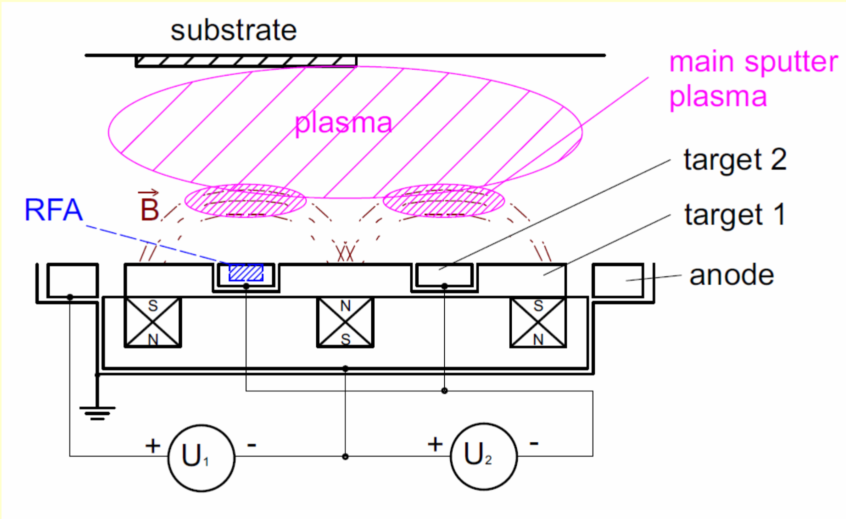
Idea of Dual Target Magnetron (DTM):

• 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 collisionless from the main plasma 5 to 15 mm over target 2,

Primary ion energy at Target 2 measured with Retarding Field Analyzer



Wion(U1, U2) = U1-Uanode + C*U2

With:

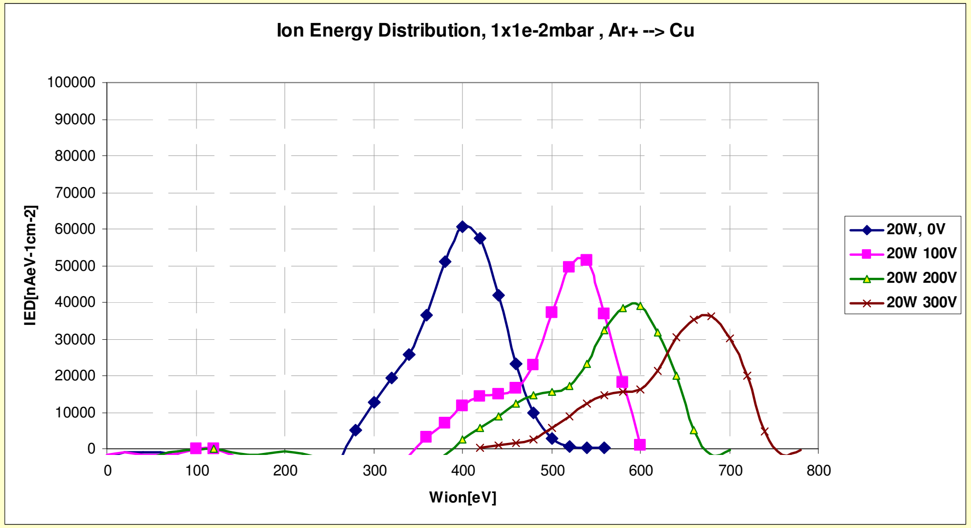
U1 : Voltage for sputtering (typ. 300 to 400 V),

Uanode: Potential of the anode (typ. 25 to 75 V),

U2: Accelerator voltage target 2,

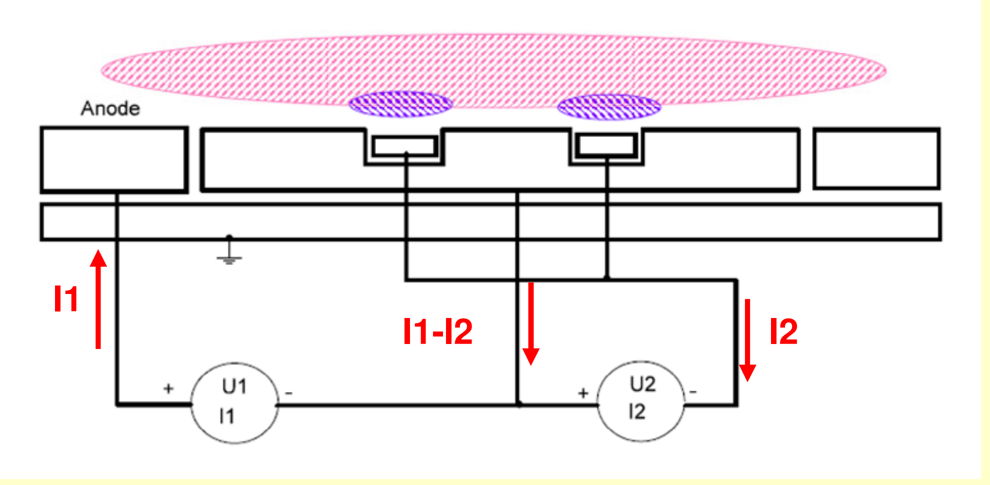
C : Faktor approx. 0.7 to 0.9

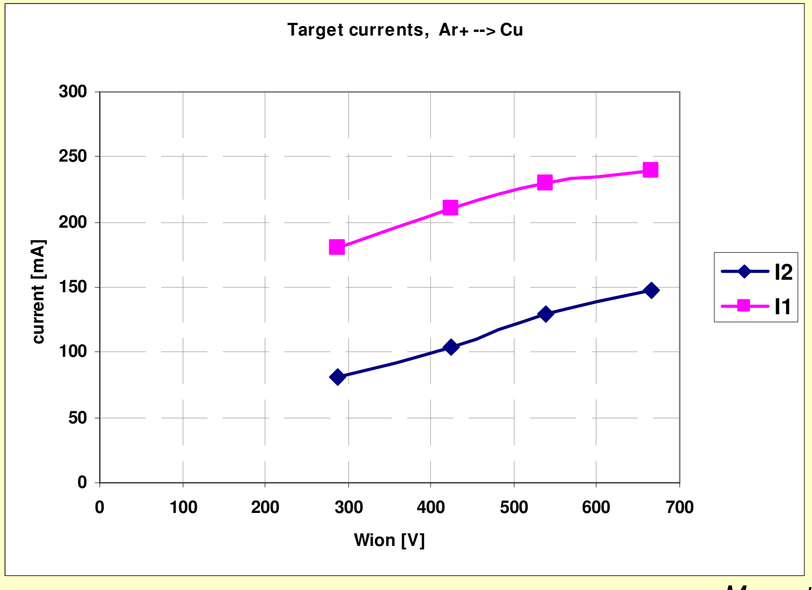
Ion Energy Distribution at target 2



Some characteristic properties of the DTM (Ar+ → Cu)

Currents at the DTM



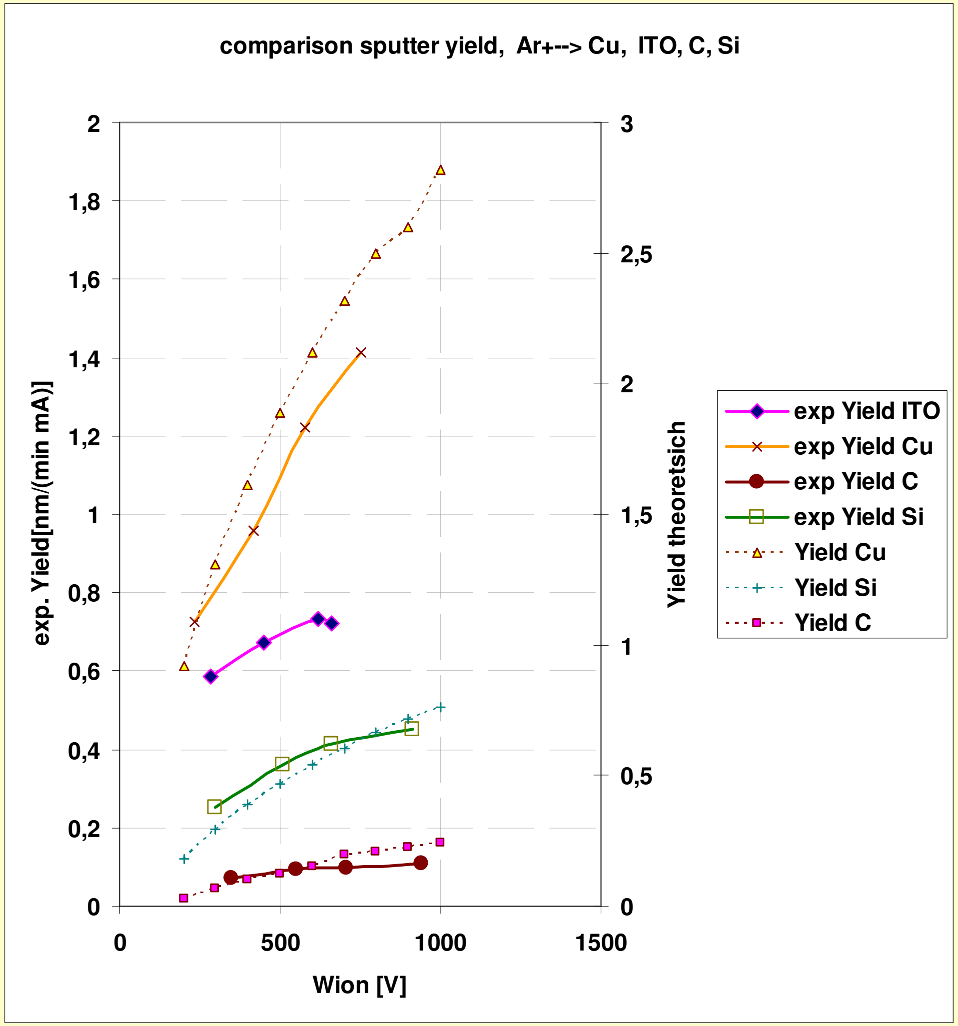


Remarks:

- typ. Parameters:
  - 10^{-2} mbar argon,
  - P1 = 80 W,
  - copper target.

- approx. 50% of the total current sputters at target 2,

Primary Ion Energy and Sputter Yield



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

- substrate is located over target 2,
- deposition rate **R** measured with quarz monitor (→ deposited mass proportional to deposited atom number),
- current $\mathbf{I_2}$ is proportional to the number of sputtered ions,

- then the sputter yield is proportional to:

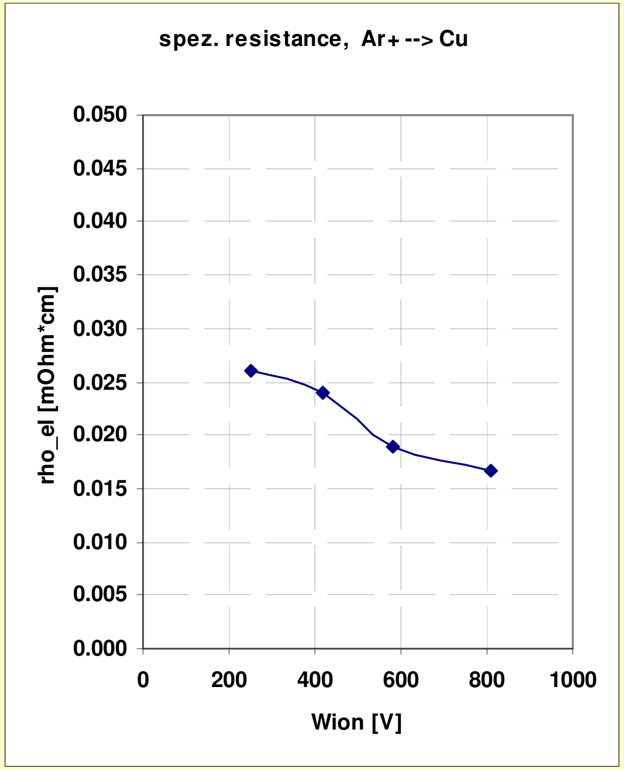
$$\bullet Y_{exp}(Wion) \sim R/I_2$$

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

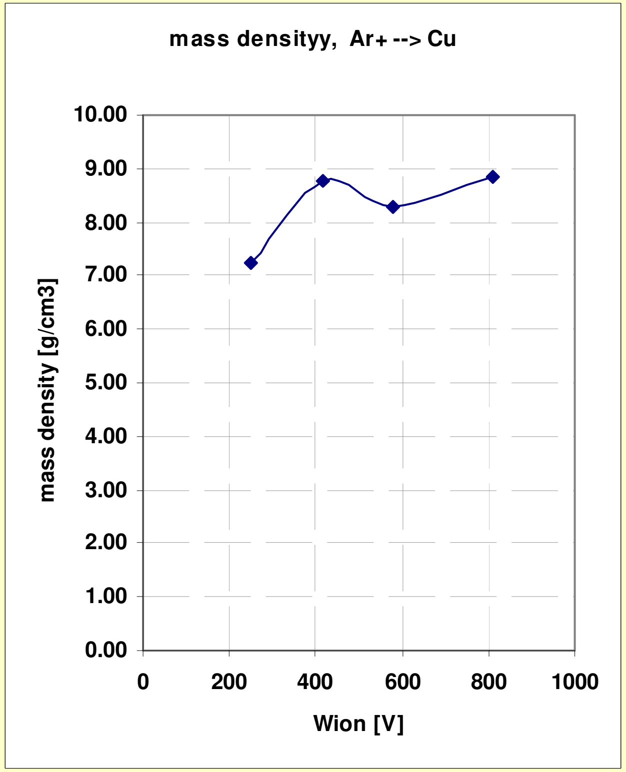
[1] https://www2.iap.tuwien.ac.at/www/surface/sputteryield

Example: Sputtered Copper layers

Electrical conductivity (Wion)



Mass density (Wion)

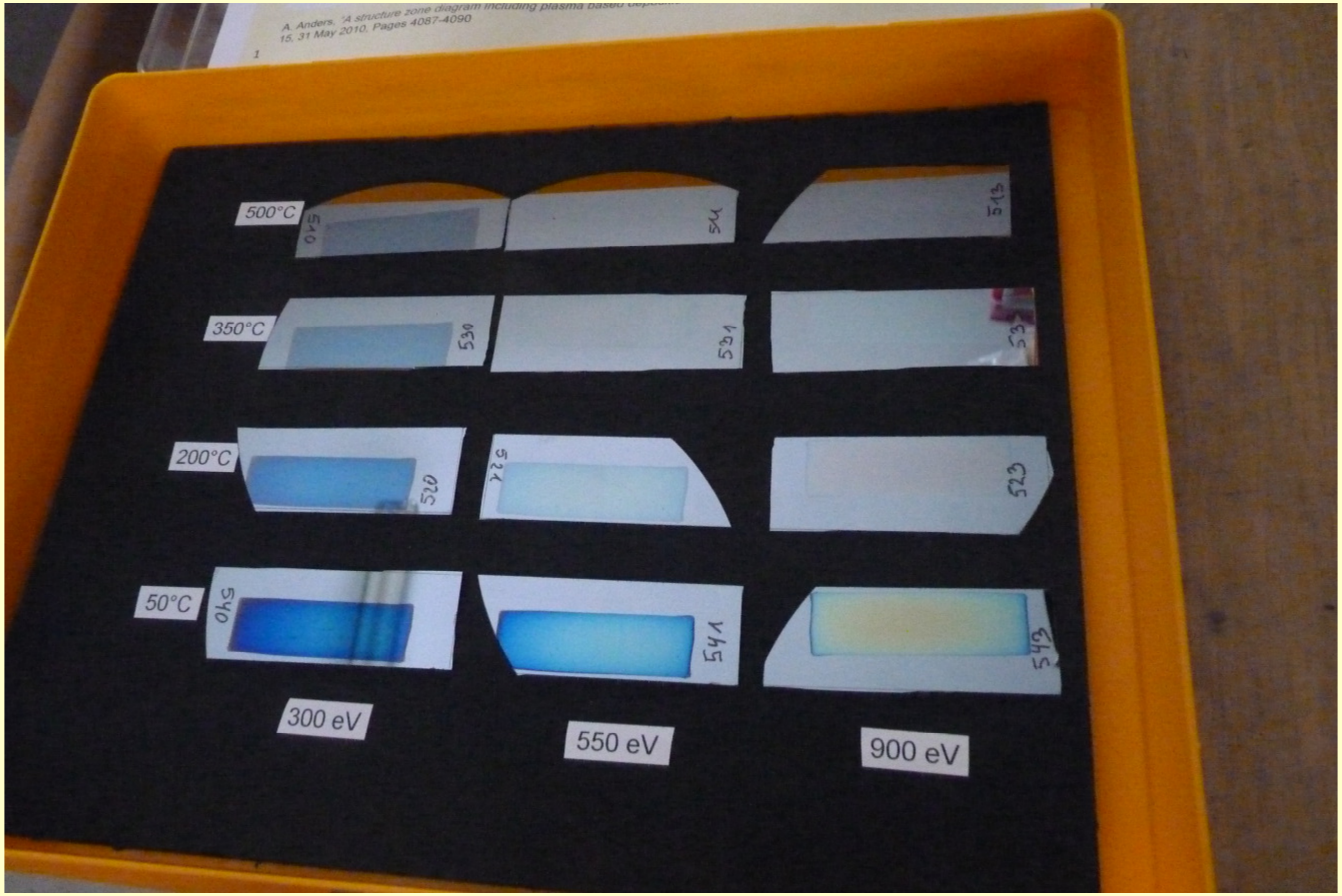


Typical parameters:

- 10^{-2} mbar argon, P1 = 80 W,
- Cu-layer thickness approx. 200 nm,
- Specific resistance measured by four point probe (seems ok),
- mass density from quartz microbalance and layer thickness byTalystep (Tayler&Hobson 1962) ← only rough estimation of mass density,

Example: Sputtered Silicon layers on crystalline silicon

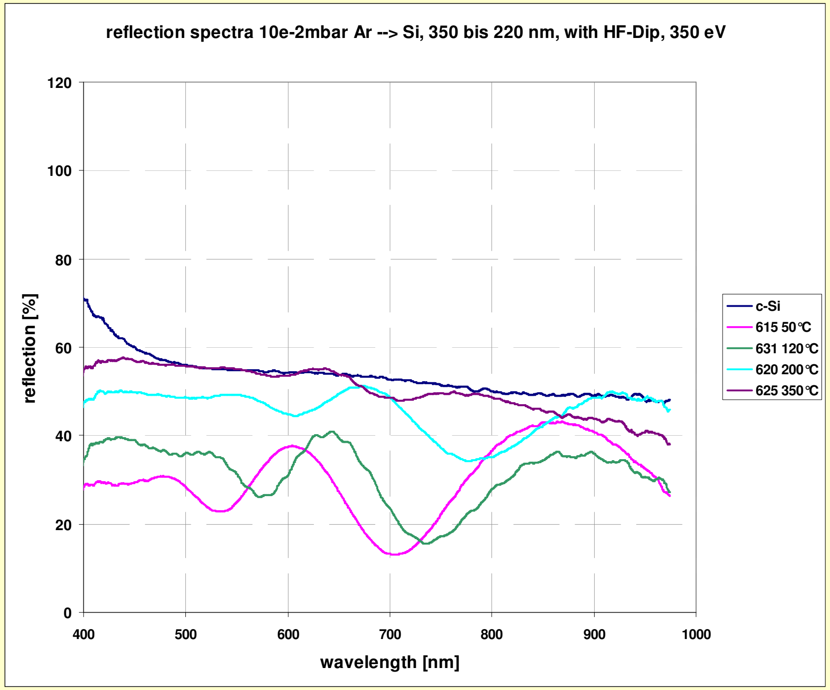
Approx. 50 nm silicon layers on silicon (temperature, primary ion energy)



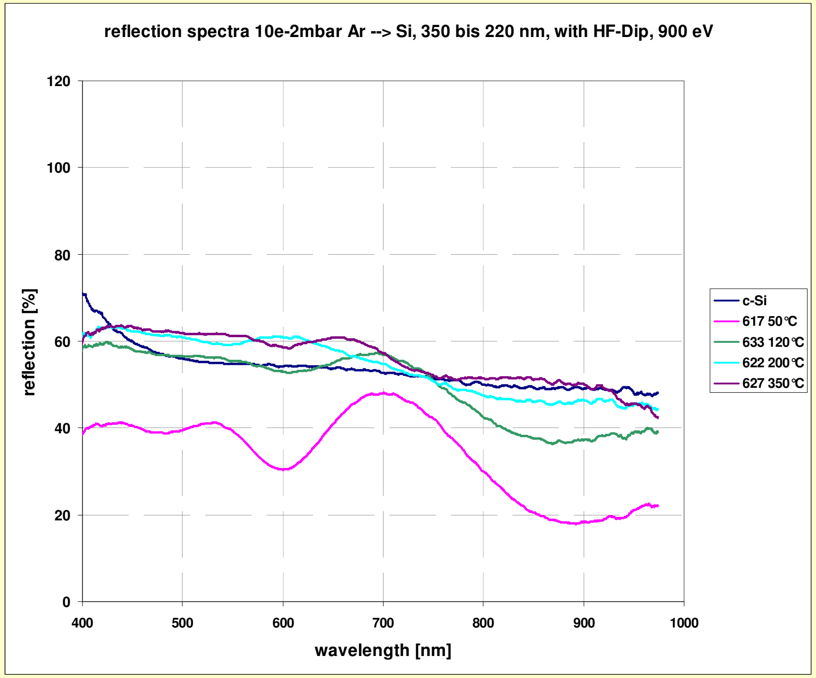
- conductive silicon target: 10^{20} cm^{-3} phosphorous doped silicon
- primary ion energy was varied from 300 to 900 eV**,**
- substrate temperature from 50℃ to 500 ℃,
- constant deposition time of 3 min → layer thickness from 40 nm (300 eV) to 70 nm (900 eV),
- substrate with HF-dip (5 min, 5% HF),

Example: Reflection spectra fo sputtered Silicon layers

Temperature dependence for 350 eV primary ion energy



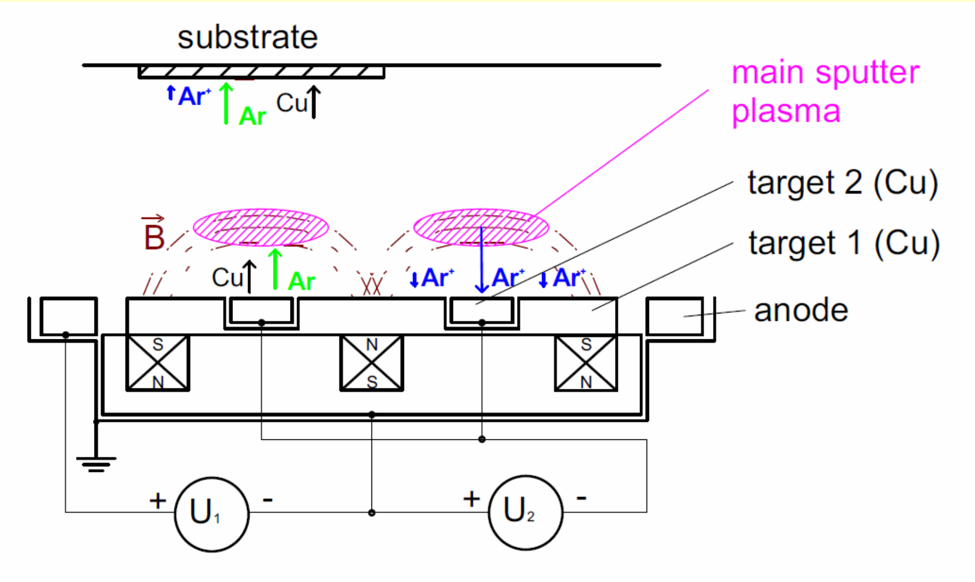
Temperature dependence for 900 eV primary ion energy



Remarks:

- layer thickness around 250 nm, temperature between 50℃ and 350℃,
- **amorphous silicon:** strong absorption between 400 and 750 nm (band gap), then refractive index 2.8 … 3.2,
- **crystalline silicon:** week absorption, refractive index 3.8

DTM Sputtering and layer growth



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,
- on some targets negative ins will be created (e.g. TCO´s) and accelerated by the sputter plasma.

Processes at the substrate:

a) Particle from the plasma:

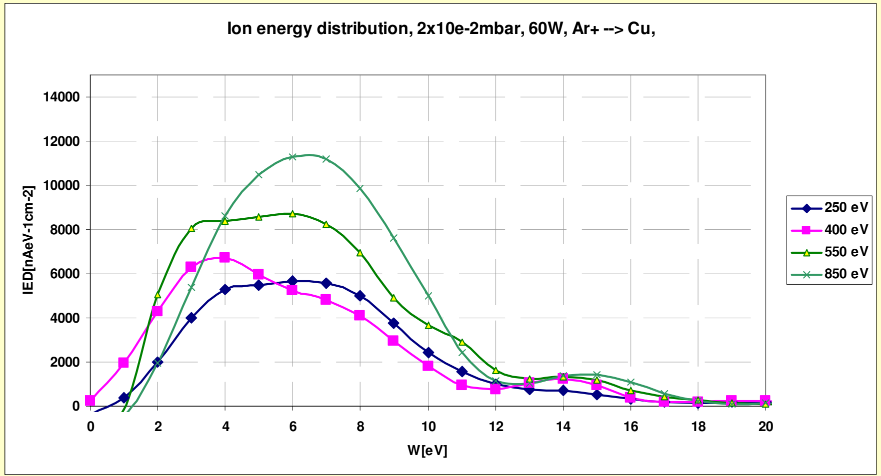
- Argon ions from the plasma sheet,
- Electrons from the plasma sheet (low influence),
- UV-light from the sputter plasma.

b) Particle from the plasma:

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

Plasmasheet analysis at substrate

Ion energy distribution at substrate for diff. primary ion energies (300 eV to 900 eV)



Remarks:
• measured with PlasmaMon from Jenion [2] at 50 mm distance from target (substrate place)

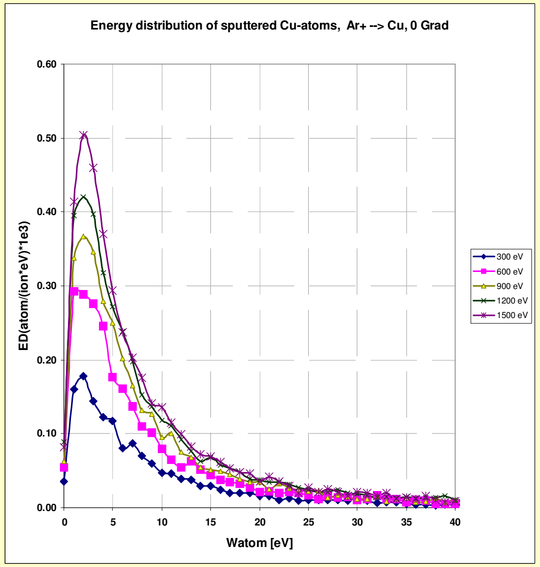
Plasma sheet probe:
• small increase in ion current density with Wion,
•ion current density : 120 – 180 $uAcm^{-2}$,

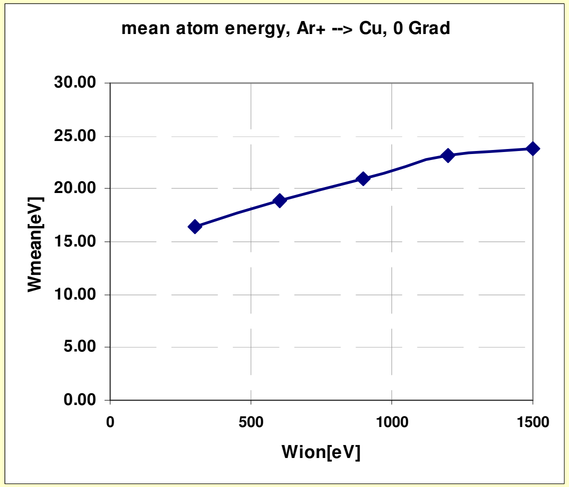
Retarding Field Analyzer:
• only small influence,
• mean ion energy in the range of 5 – 8 eV

[2] http://www.jenion.de/Plasma-Analysis/

Simulation of the energy of sputtered atoms (SRIM 2013)

a) Sputtering Ar+ → Cu:

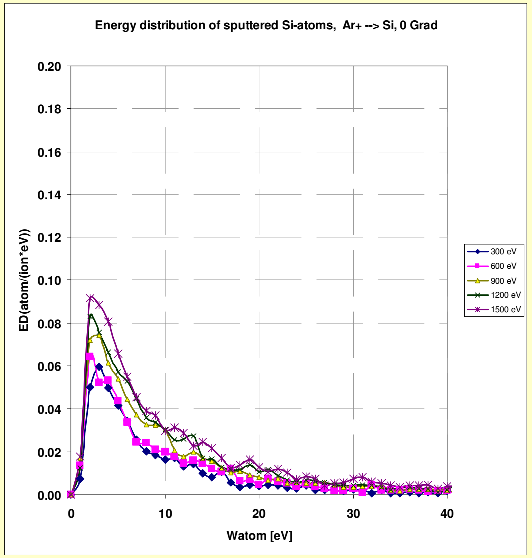


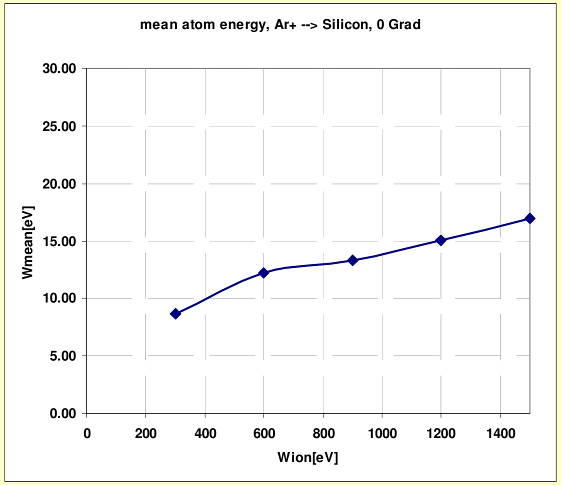


DTM - Cu-atom mean energy:
- 300 eV: 16 eV,
- ….
- 900 eV: 21 eV,

Energy gain: 5 eV

b) Sputtering Ar+ → Si:



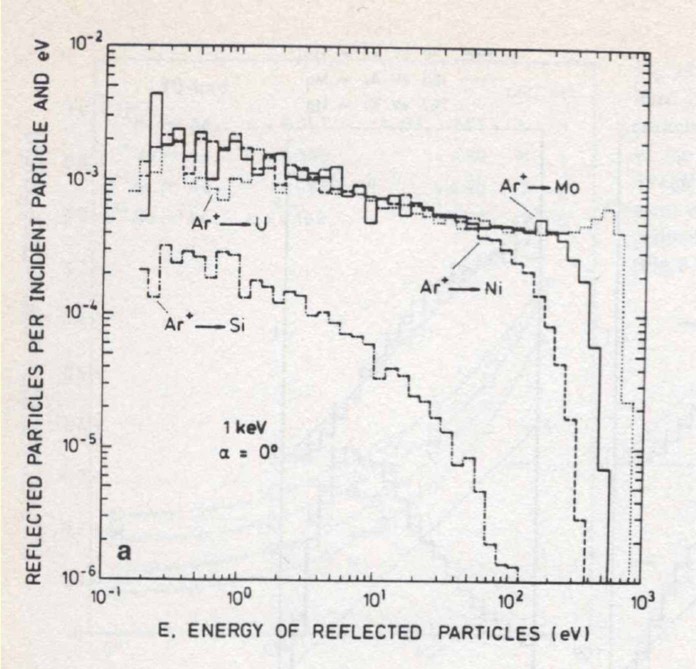


DTM - Si-atom mean energy:
- 300 eV: 9 eV,
- ….
- 900 eV: 15 eV,

Energy gain: 6 eV

Energy of reflected neutrals and negative ions

Energy distribution of reflected argon @ 1000 eV {3]:



Reflected neutrals (argon):

- data taken from [3], Monte Carlo Simulation TRIM.SP,

Estimations:

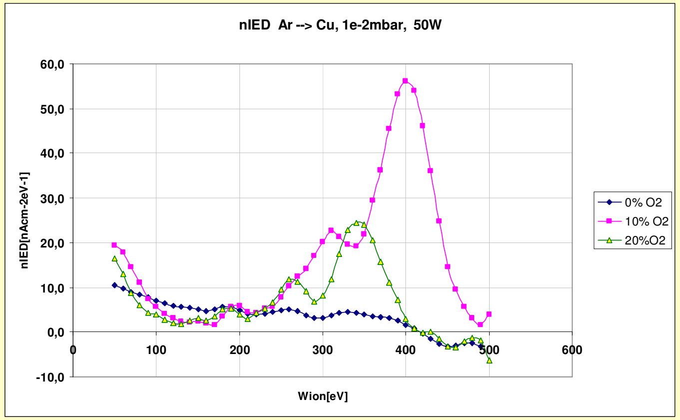
a) Ar+ → Cu:

- Target atoms are heavier than argon,
- mean reflection coefficient approx. 20%,
- mean argon energy approx. 30 to 50% of Wion

b) Ar+ → Si:

- Target atoms are lighter than argon,
- mean reflection coefficient approx. 5%,
- mean argon energy approx. 5% of Wion

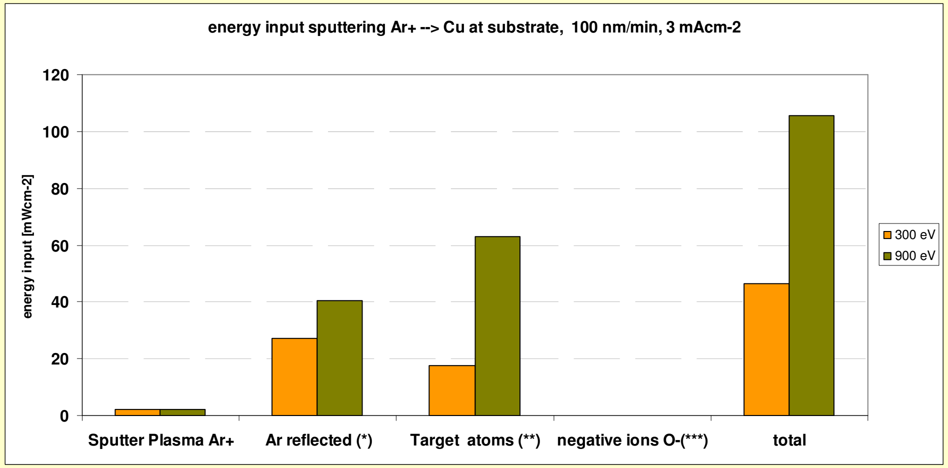
Negative Ion Energy distribution (RFA, PlasmaMon)



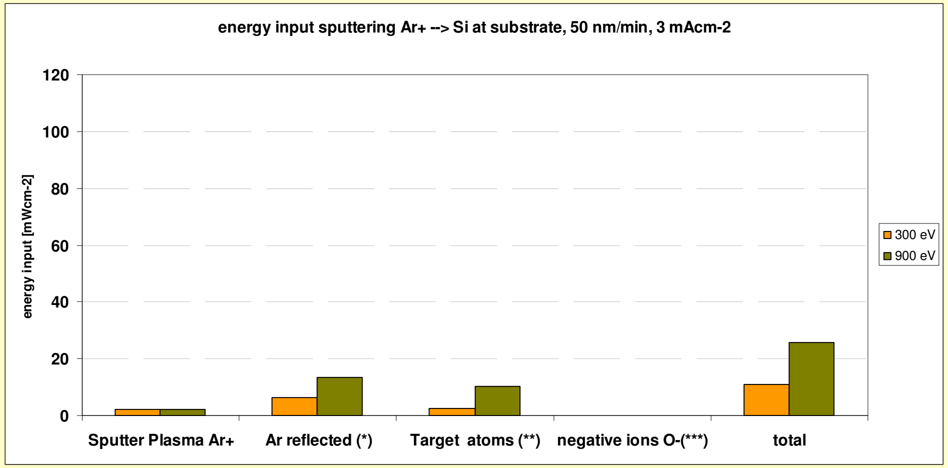
[3] W. Eckstein, Computer Simulations of Ion-Solid Interactions, Springer Series in Material Science 10, 1991, 162

Estimated total energy flux at the substrate

Energy flux Ar+ → Cu, 300 eV against 900 eV



Energy flux Ar+ → Si, 300 eV against 900 eV



Parameters sputter deposition:
- 10^{-2} mbar Argon, substrate distance 50 mm, → low gas diffraction,
- sputter power 60W, → primary ion current density 3 – 5 $mAcm^{-2}$,
- deposition speed Cu: 50 – 125 nm/min,
- deposition speed Si: 25 – 75 nm/min,

Data taken from:
- **sputter plasma:** plasma probe measurement + RFA,
- **reflected argon:** Data from TRIM.SP Simulation [2],
- **sputtered target atoms:** SRIM simulation,
- **negative ions**: no negative ions,

Remarks:
- effect of mass ratio at sputtering is good visible (argon mass/target atom mass),
- **Ar(M=40) → Cu(M=52),** heavy target atom,
- **Ar(M=40) → Si(M=28),** light target atom,

Some conclusions:
- **yellow bars:** energy flux at conventional sputtering,
- **green bars:** DTM sputtering at 900 eV,
- DTM sputtering has increased energy flux to the substrate coming both from reflected neutrals and from target atom energy

Summary and future work ?

Summary:

- a DC sputter magnetron (DTM) for operation with controlled primary ion energy has been developed,
- With an Retarding Field Analyzer integrated into the target, the control of the primary ion energy could be demonstrated at a range of 300 to 900 eV,
- Rough estimations of the resulting sputter yield show the same effect,
- For sputtering of copper an silicon with argon some change in layer growth is observed,
- Estimations of the energy flux to the substrate show that increased primary ion energy is coupled with increased energy flux, arising from increased sputter atom energy and from increased neutral argon energy.

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.SP…)
- More investigations of the total energy flux at the substrate.

Maybe the working principle of the DTM is not **"IBAD"** (Ion Beam assisted Deposition)
but **"NBAD"** (Neutral Beam Assisted Deposition).

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Thank You!