

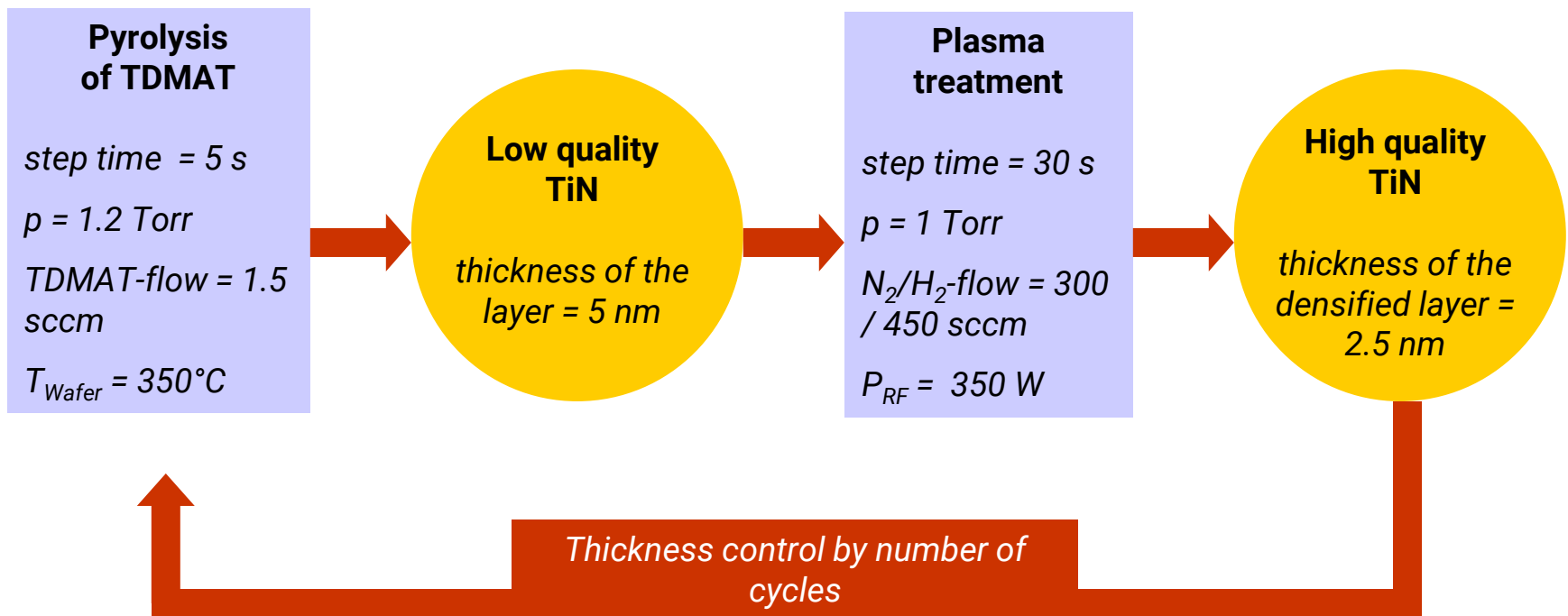
Q3 Please name the two steps in an MOCVD TiN deposition process using TDMAT precursor!

- 1) Pyrolysis of the TDMAT precursor
- 2) Plasma treatment (N₂/H₂)

CVD of Copper diffusion barriers: **TiN by MOCVD from TDMAT**

Multistep process for high quality TiN

Method was introduced by
M. Danek and coworkers (Applied Materials), 1995



Q4 What is the purpose of plasma post-treatment of MOCVD deposited TiN diffusion barrier films?

- Film densification
- Lower resistivity (higher density, lower contamination level, lower oxygen uptake during air exposure)
- Amorphous → nanocrystalline film (nanocrystals embedded in an amorphous matrix)
- Decrease the contamination content in the film (C, O)
- Improvement in diffusion barrier properties

CVD of Copper diffusion barriers: **TiN by MOCVD from TDMAT - Film properties**

	without plasma treatment	multi step process with plasma treatment
Spec. el. resistivity	$\approx 8000 \mu\Omega\text{cm}$	$170 \mu\Omega\text{cm}$
Stability of resistivity if exposed to air	increase $\approx 200\%$	increase $< 2\%$
Density (bulk value = 5.2 g/cm^3)	2.2 g/cm^3	4.8 g/cm^3
Film stress (all compressive)	- 300 MPa (as dep.) - 500 MPa (after air exp.)	- 1400 MPa (as dep.), no change after air exp.
Microstructure	amorphous like	polycrystalline
Impurities	$\approx 25 \text{ at.}\% \text{ C}$, $\approx 25 \text{ at.}\% \text{ O}$ if exposed to air	6 at.% C, 5 at.% O if exposed to air
Barrier stability against copper diffusion (electrically tested with pn-diodes)	fails already at 350°C	stable up to 450°C

Q5 Please define the term “epitaxy” as a special type of CVD process!

- Deposition of single crystalline film
- ... on single crystalline substrate

Q6 What is the difference between “homoepitaxy” and “heteroepitaxy”?

Homoepitaxy: film and substrate are same material

Heteroepitaxy: film and substrate are different materials

Epitaxy is the growth of single crystalline films upon the surface of a single crystal substrate.

Homoepitaxy

identical

chemical composition of substrate and deposited film

Heteroepitaxy

different

Examples:

*Si/Si
SiGe*

*Ge/Si
Si/Al₂O₃ (Silicon on Sapphire)
GaAlAs/GaAs (HEMT, HFET)*

Applications: *Bipolar:* - Definition of transistor regions by vertical doping
- SiGe structures heterojunction bipolar transistors (HBT)

CMOS: - Minimization of the vertical "latch-up" effect (switching of a parasitic p-n-p-n thyristor) by deposition of lightly doped epi-Si on heavily doped substrates
- Formation of strained Si on SiGe for higher electron mobility

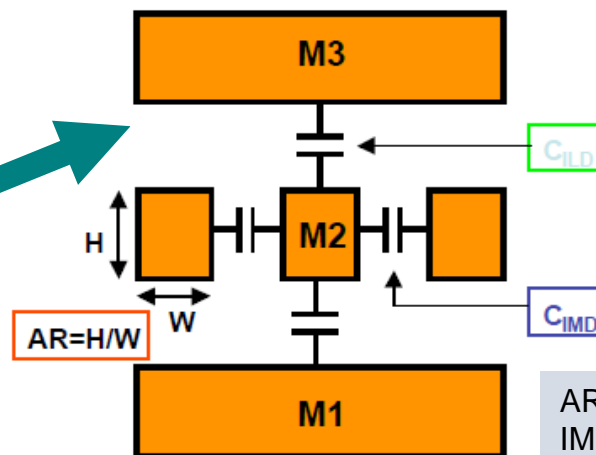
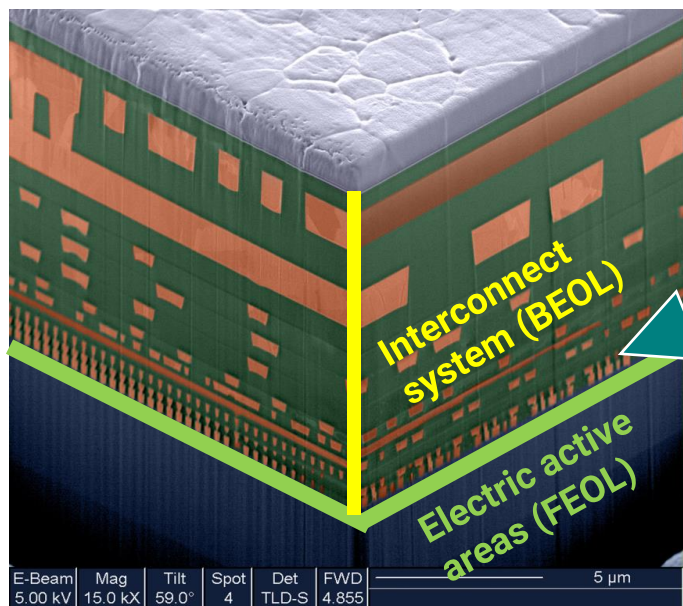
Techniques: - **Vapor-phase epitaxy** (VPE, similar to CVD, dominating in Si processing)
special case: Molecular Beam Epitaxy (MBE)
- Liquid-phase epitaxy (LPE, III-V compounds)
- Solid-phase epitaxy (SPE, annealing of amorphous layers)

Q7 What is the motivation to use low-k dielectrics instead of conventional silicon dioxide as insulator/dielectric in on-chip interconnect systems?

Lowering parasitic capacitance, to minimize:

- RC delay time
- Power consumption
- Cross-talk

Interconnect Challenges – Shrinking feature sizes



AR = aspect ratio
IMD = intermetal dielectric
ILD = interlevel dielectric
 $\epsilon_r = k$

$$C = \epsilon_0 \epsilon_r \frac{A}{d}$$

RC-Delay

$$\tau \propto RC_{inttot}$$

Power (consumption)

$$P = \alpha C_{inttot} V^2 f \propto C_{inttot}$$

Crosstalk

$$X_{talk} \propto \frac{C_{IMD}}{C_{inttot}} = \frac{1}{1 + \left(\frac{\epsilon_{ILD}}{\epsilon_{IMD}} \right) AR^2}$$

To
minimize/
decrease

Goal: *lower parasitic capacitances in the interconnection system*
by integration of dielectric materials with lower permittivity (k-value)
compared to standard SiO₂ (k=3.9...4.3)

Q8 How can a lower k-value be achieved compared to SiO_2 ?

(two different systematics: 1+2; A+B)

1) lower the material's density

- Introduce porosity via localized pores (0.5 – 2 nm size)
- Increase bond length
- Terminating groups

2) lower the polarizability: no dipoles, low pol. of bonds itself (e.g. Si-F, Si-C)

A) Change bond properties

- Higher bond length (\rightarrow lower density)
- Introduce elements (F) or groups (CH_3) terminating properties – Si-F; Si-C(-H)₃
- low pol. of bonds itself

B) Localized pores – introduce porosity

How to build a low dielectric constant material?

1. Minimize polarizability

- Choose a nonpolar dielectric system: polarity is weak in materials with few polar chemical groups and with symmetry to cancel the dipoles of chemical bonds between dissimilar atoms
- Introduce elements with smaller electronic polarizability, e.g. C, F

Bond	C–C	C–F	C–O	C–H	O–H	C=O	C=C	C≡C	C≡N
Polarizability (Å)	0.53	0.56	0.58	0.65	0.71	1.02	1.64	2.04	2.24

(Source: K.J. Miller et al., Macromolecules, 23, 3855 (1990))

- Minimize the moisture content of the dielectric / design a dielectric with minimum hydrophilicity ($k_{\text{water}} \approx 80 \rightarrow$ only small traces of water need to be absorbed before the low-k dielectric loses its permittivity advantage)

How to build a low dielectric constant k material?

2. Increase the free volume \rightarrow reduce N_j

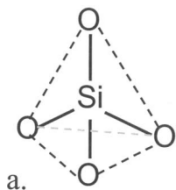
Microscopic level:

\rightarrow increase bonding length, bonding orientation, e.g. partially substitute Si-O (1.5097 Å) by Si-CH₃ (1.857 Å)

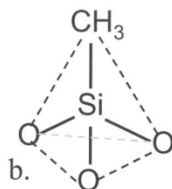
\rightarrow discontinue the network by inserting single bond atoms or groups in the backbone structure: adding F or CH₃ into SiO₂ network

Macroscopic level:

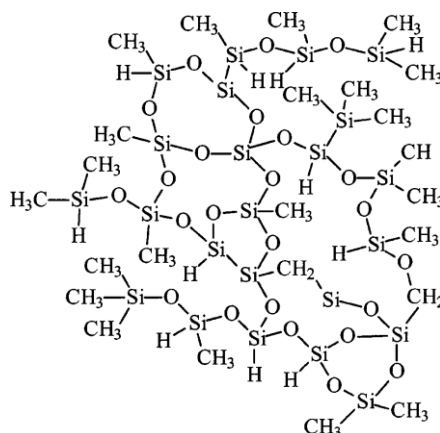
\rightarrow Add porosity ($k_{\text{air}} = 1$): incorporation of a thermally degradable material (porogen) within a host matrix



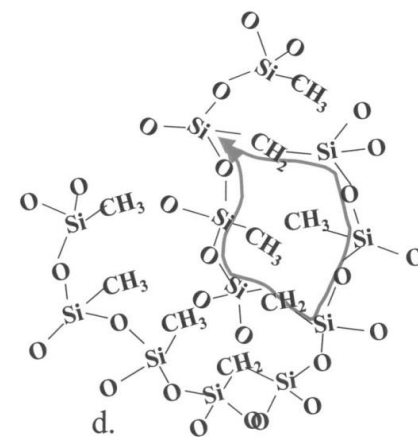
SiO₂
 $k \approx 4.0$



C-doped oxide
 $k \approx 3.0$



Dense SiCOH (Precursor
TMCTS)
 $k \text{ min. } 2.6$

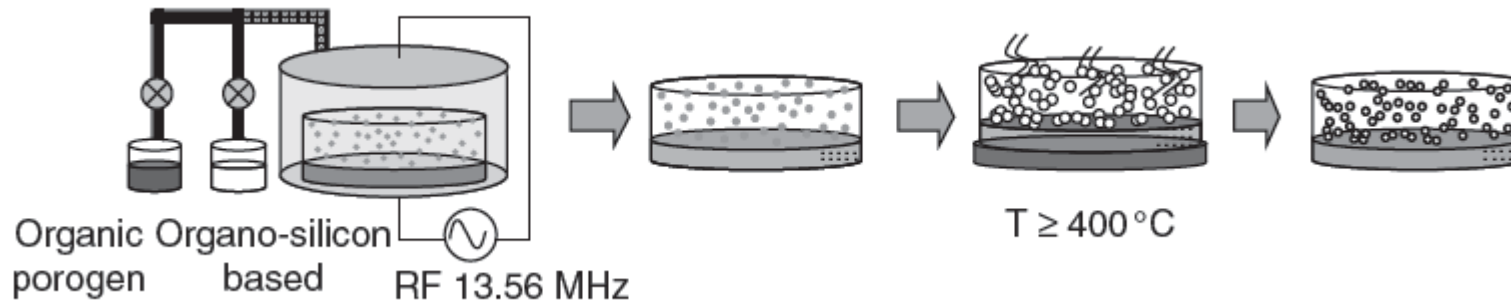


Porous SiCOH
(Precursor TMCTS +
Porogen)
 $k \approx 2.1 - 2.5$

Q9 Which types of processes can be used for low-k dielectric deposition?
Which of those is *most frequently used* in IC production?

- 1) Spin-on process
- 2) *Plasma-enhanced CVD (PECVD)*

Deposition of porous low-k dielectrics by PECVD



PECVD porogen approach: sacrificial process, currently performed in high-volume manufacturing for 32 / 28 nm technology nodes and below

- Deposition from the decomposition of (at least) two precursors in the plasma
 - Pure organic molecule (porogen)
 - Molecule consisting of silicon atoms and organic radicals (matrix precursor)
- Formation of a „hybrid“ film composed of organosilicate-based matrix enclosing organic inclusions

Q10 Which type of post-deposition (curing) processes can be used to form porous low-k dielectrics?

What is the purpose of those curing processes and which film properties are affected?

- 1) Thermal annealing (T)
- 2) Thermal annealing (T) + UV radiation
- 3) Thermal annealing (T) + e-beam
- 4) Thermal annealing (T) + Plasma treatment by using H₂
- 5) Supercritical CO₂ treatment

Purpose/affected properties:

- Removal of porogen (C-organic material)
- Porosity (higher) / density (lower)
- Shrinkage (film thickness reduction, needs to be minimized)
- Permittivity → lower k-value
- Increase of crosslinking in the matrix material → enhance mechanical properties
- Mechanical properties: hardness, Young's/elastic modulus decrease
- Thermal conductivity is lower

Deposition of porous low-k dielectrics by PECVD

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Post-deposition treatment (curing)

-thermal annealing, UV-assisted thermal annealing, e-beam assisted thermal annealing, H₂ plasma, supercritical treatment in CO₂

Purpose:

- *removal of the organic phase, mostly consisting of porogen molecule fragments → Film becomes porous and has ultra low-k properties*
- *Improvement of mechanical properties of matrix network by additional cross-linking*

Affected film properties

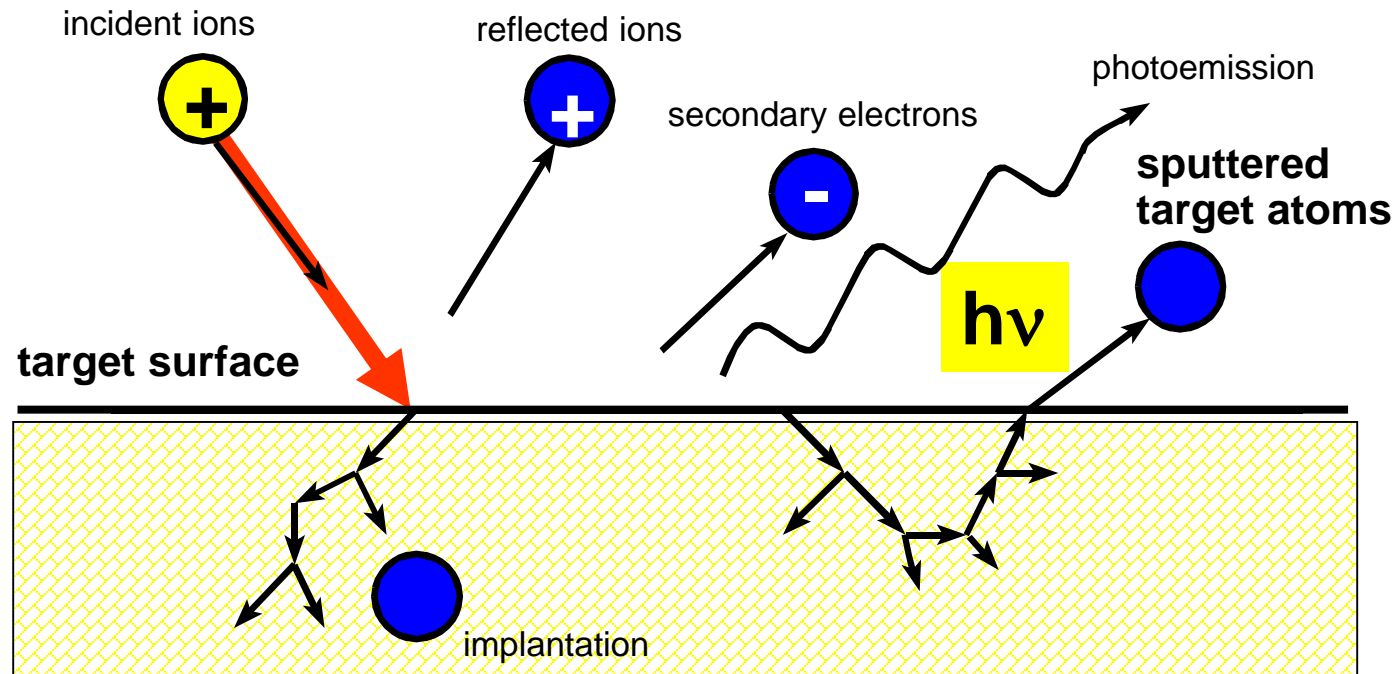
- *porosity/density*
- *mechanical stability (hardness, Elastic modulus)*
- *Thermal conductivity*

-...

Q11 What are the basic steps/mechanism of sputtering? (elementary processes)

- 1) Collision cascade in the solid → leads to the sputtering
- 2) implantation of Ar
- 3) reflected ion
- 4) secondary electron emission
- 5) photoemission

Elementary processes of sputtering



Interaction of ions with the surface

reflection secondary electrons

lattice defects radiation damages

change of stoichiometry

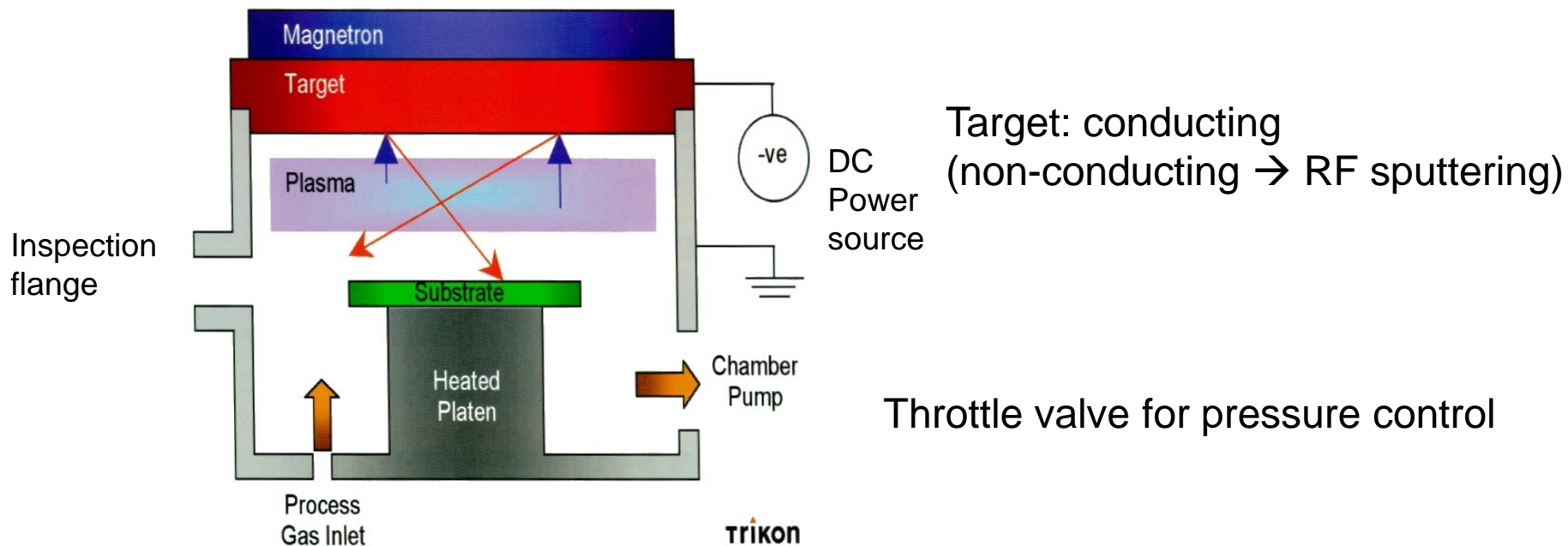
ion implantation

Sputtering:

Generation of a collision cascade

*It differs, if the last collision hits an atom in the bulk or at the surface of the target.
Only in the latter case an emission takes place - efficiency 5% to 25 %!*

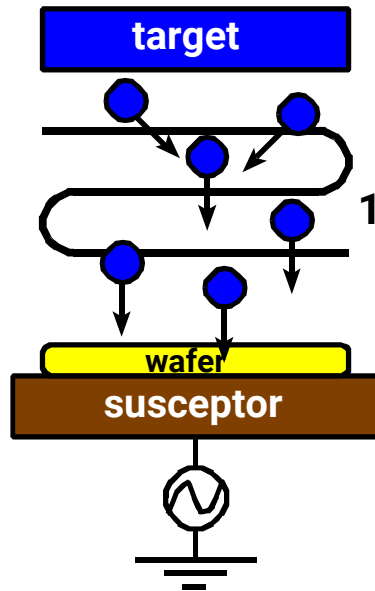
Q12 Please draw a cross-section of a DC magnetron sputtering chamber and name the different parts!



Q13 Which advanced sputtering techniques are possible to improve sidewall coverage in via/trench features?

- 1) Collimated sputtering
- 2) long throw sputtering
- 3) ionized metal deposition

Thin Film Deposition: Sputtering – advanced techniques

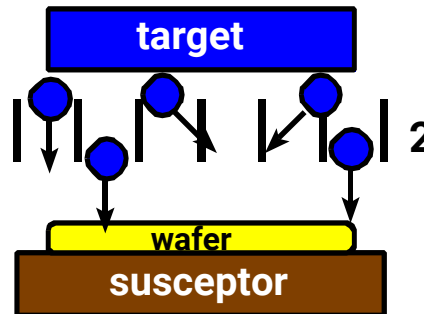


1 water-cooled RF-electrode 1,985 MHz

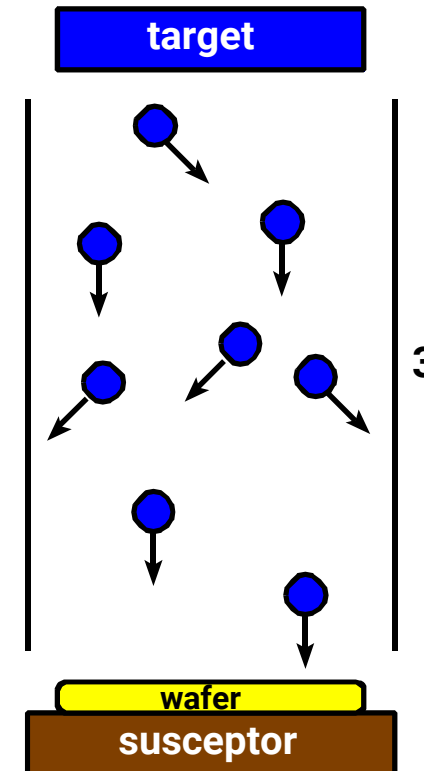
2 collimator

3 chamber wall

ionized metal deposition



collimated sputtering



long throw sputtering

Modern principles to coat contact and via holes with a high aspect ratio
(e.g. TiN, TaN or WN barriers for the copper metallization)

Only target particles with a small angle to the substrate normal reach the surface !