SPUTTER HEATING IN IONIZED METAL PHYSICAL VAPOR DEPOSITION[+]

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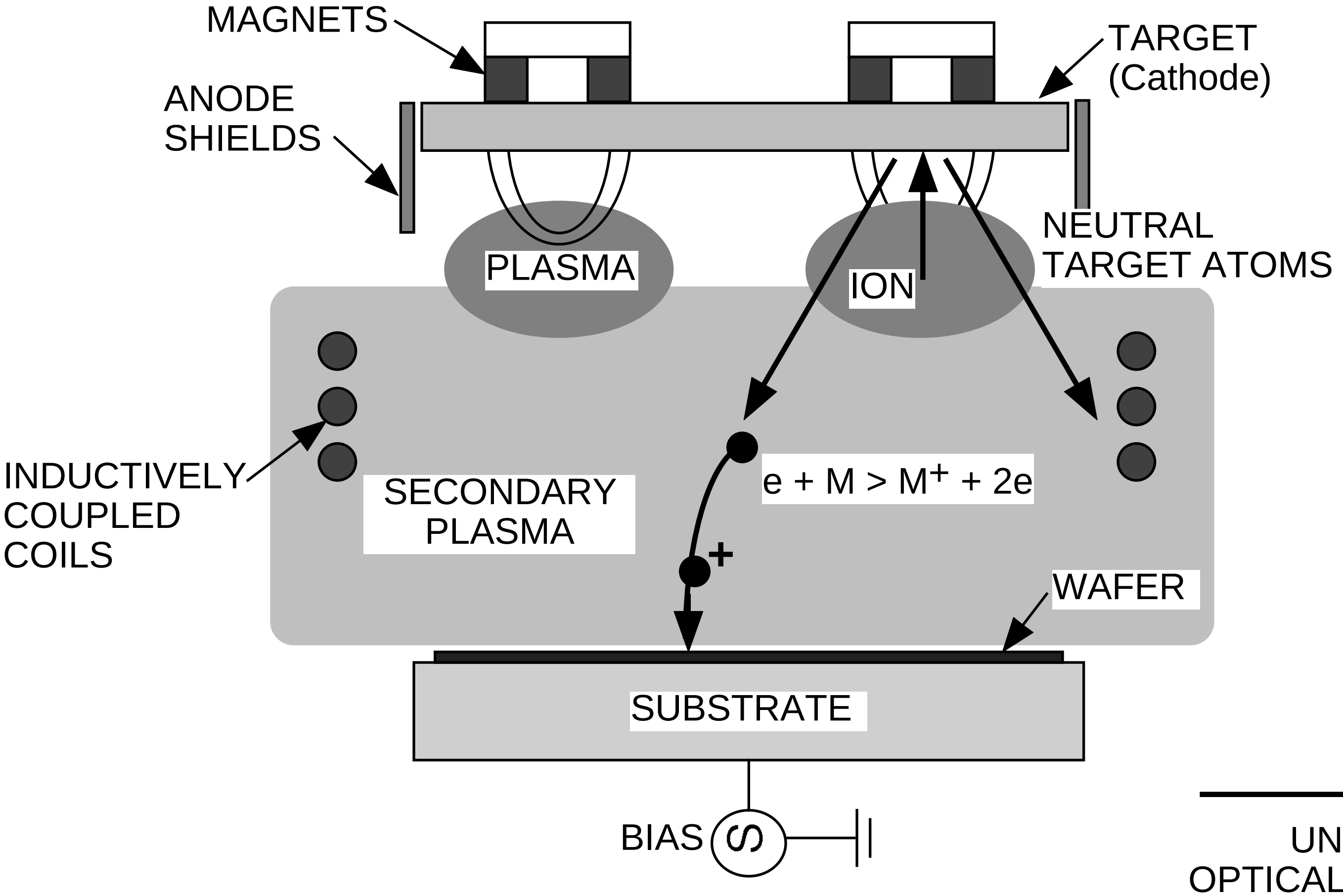
AGENDA

- Introduction to IMPVD
- Description of sputter model
- Overview of Hybrid Plasma Equipment Model
- Validation of sputter model
- Results and discussions:
    - Al target, with and without sputter heating
    - Comparison between Al and Cu target, with sputter heating
- Summary

IONIZED METAL PHYSICAL VAPOR DEPOSITION (IMPVD)

- Ionized Metal PVD (IMPVD) is being developed to fill deep vias and trenches for interconnect, and for deposition of seed layers and diffusion barriers.

- In IMPVD, a second plasma source is used to ionize a large fraction of the the sputtered metal atoms prior to reaching the substrate.



- Typical Conditions:
  - 10-30 mTorr Ar buffer
  - 100s V bias on target
  - 100s W - a few kW ICP
  - 10s V bias on substrate

SPUTTER GAS HEATING IN IMPVD

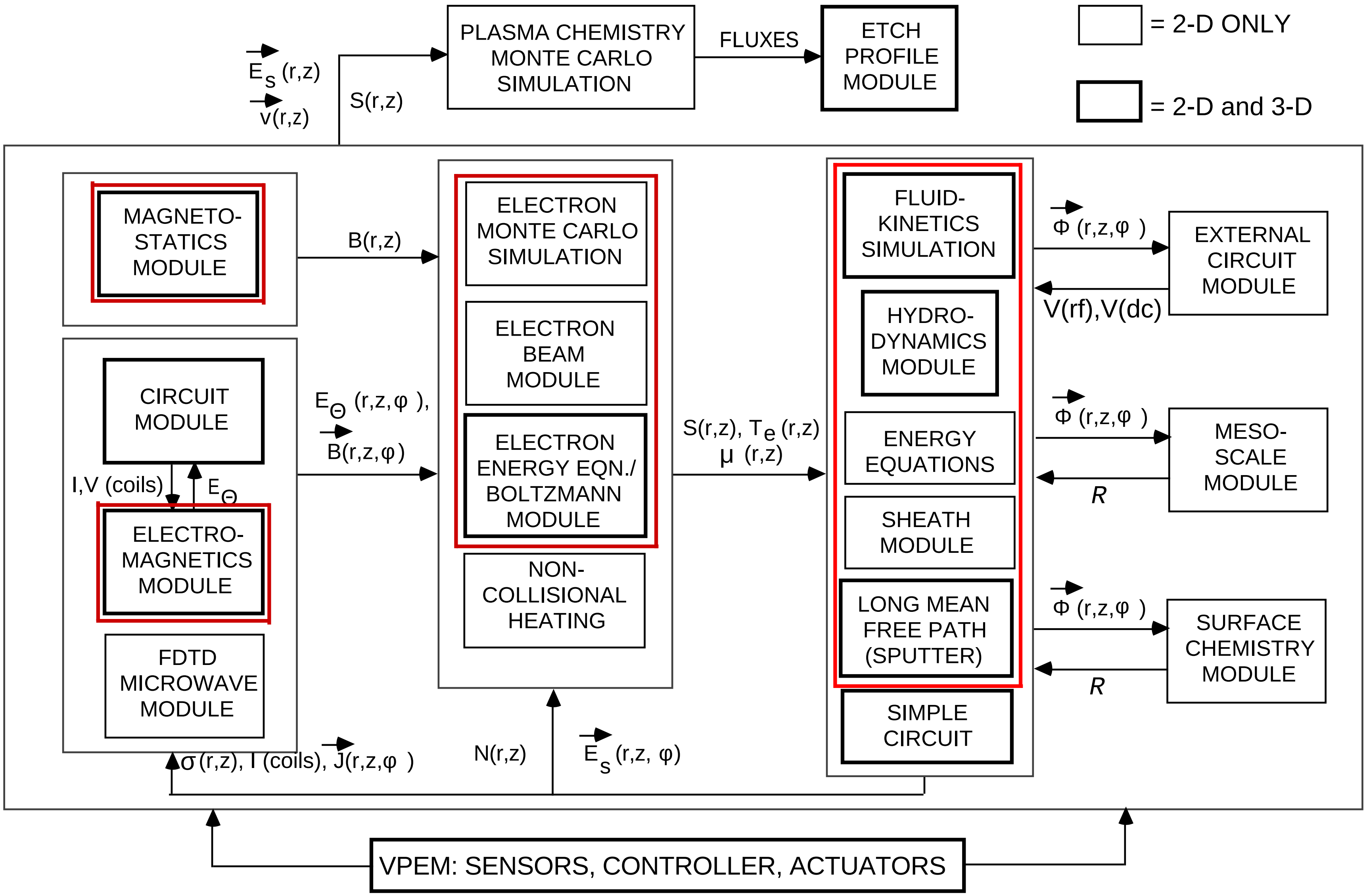
- An important process in IMPVD reactors is gas heating due to momentum and energy transfer from sputtered metal atoms to background gas atoms.

- The degree of gas heating is dependent on the magnetron power, ICP power, and sputter yield.

- This gas heating affects the background gas density, ion flux to the target, and subsequently the sputtered atom flux and the depositing metal flux.

- To investigate the effects of sputter heating, we incorporated a sputter algorithm into a Hybrid Plasma Equipment Model (HPEM).

SCHEMATIC OF 2-D/3-D HYBRID PLASMA EQUIPMENT MODEL



$\vec{E}_s(r,z)$
$\vec{v}(r,z)$
S(r,z)

PLASMA CHEMISTRY MONTE CARLO SIMULATION

FLUXES

ETCH PROFILE MODULE

☐ = 2-D ONLY
☐ = 2-D and 3-D

MAGNETO-STATICS MODULE

B(r,z)

CIRCUIT MODULE

I,V (coils)

E_Θ

ELECTRO-MAGNETICS MODULE

FDTD MICROWAVE MODULE

$E_\Theta(r,z,\varphi)$, $\vec{B}(r,z,\varphi)$

ELECTRON MONTE CARLO SIMULATION

ELECTRON BEAM MODULE

ELECTRON ENERGY EQN./ BOLTZMANN MODULE

NON-COLLISIONAL HEATING

S(r,z), $T_e(r,z)$
μ (r,z)

FLUID-KINETICS SIMULATION

HYDRO-DYNAMICS MODULE

ENERGY EQUATIONS

SHEATH MODULE

LONG MEAN FREE PATH (SPUTTER)

SIMPLE CIRCUIT

$\vec{\Phi}(r,z,\varphi)$

V(rf),V(dc)

EXTERNAL CIRCUIT MODULE

$\vec{\Phi}(r,z,\varphi)$

R

MESO-SCALE MODULE

$\vec{\Phi}(r,z,\varphi)$

R

SURFACE CHEMISTRY MODULE

$\sigma(r,z)$, I (coils), $\vec{J}(r,z,\varphi)$

N(r,z)

$\vec{E}_s(r,z,\varphi)$

VPEM: SENSORS, CONTROLLER, ACTUATORS

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IMPROVEMENT TO SPUTTER ALGORITHMS

- To better model the IMPVD process, the following improvements have been made to the sputter algorithms in the HPEM:
  - Ion energy-dependent yield
  - Ion energy-dependent kinetic energy of the emitted atom
  - Momentum and energy transfer between the sputtered atoms and the background gas atoms

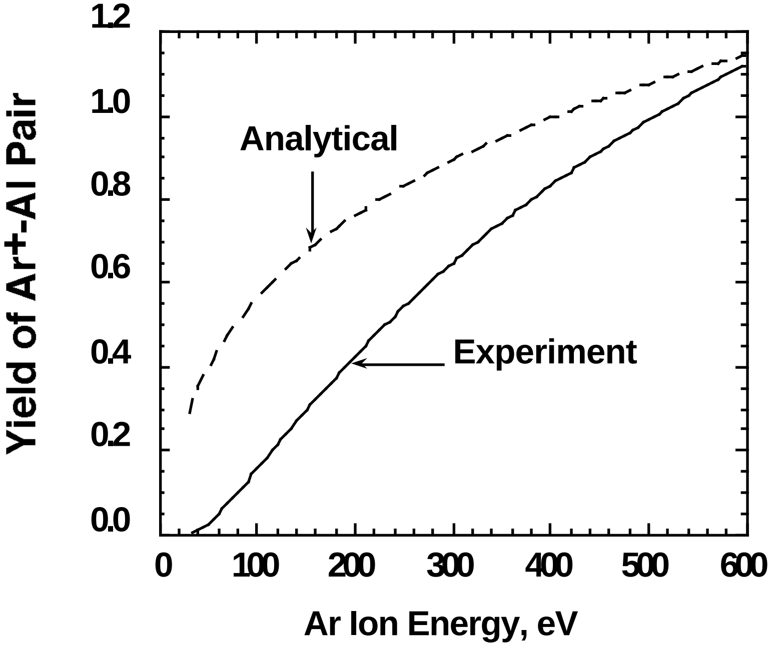
- The energy-dependent yield is computed from:
  - Experimental data* (preferred),
  - Semi-Analytical expression**.

*Masunami et al., At. Data Nucl. Data Tables 31, 1 (1984) .
**Mahan and Vantomme, JVST A 15, 1976 (1997).

- Energy of the emitted atoms obeys a cascade distribution (Thompson’s law for $E_{ion} \approx$ 100’s eV):

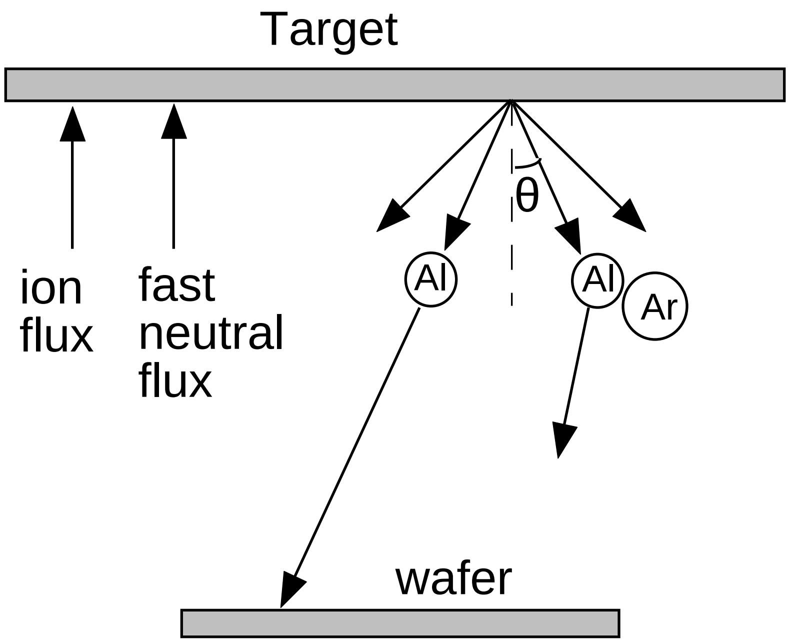
$$F(E) = \begin{cases} 2\left(1+\dfrac{E_b}{\Lambda E_i}\right)^2 \dfrac{E_b E}{\left(E_b + E\right)^3} & \text{for } E \le \Lambda E_i \\ 0 & \text{for } E > \Lambda E_i \end{cases}$$

ΛE_i: maximum recoil energy.



OVERVIEW OF SPUTTER MODEL

- The sputter model employs a kinetic Monte Carlo approach:
  - Sputter rate = Yield · (ion flux + fast neutral flux)
  - Sputtered metal atoms are emitted from the target with a cosine distribution, and a kinetic energy having a cascade distribution.
  - Collisions of the sputtered atoms with the background gas atoms are assumed to be elastic.

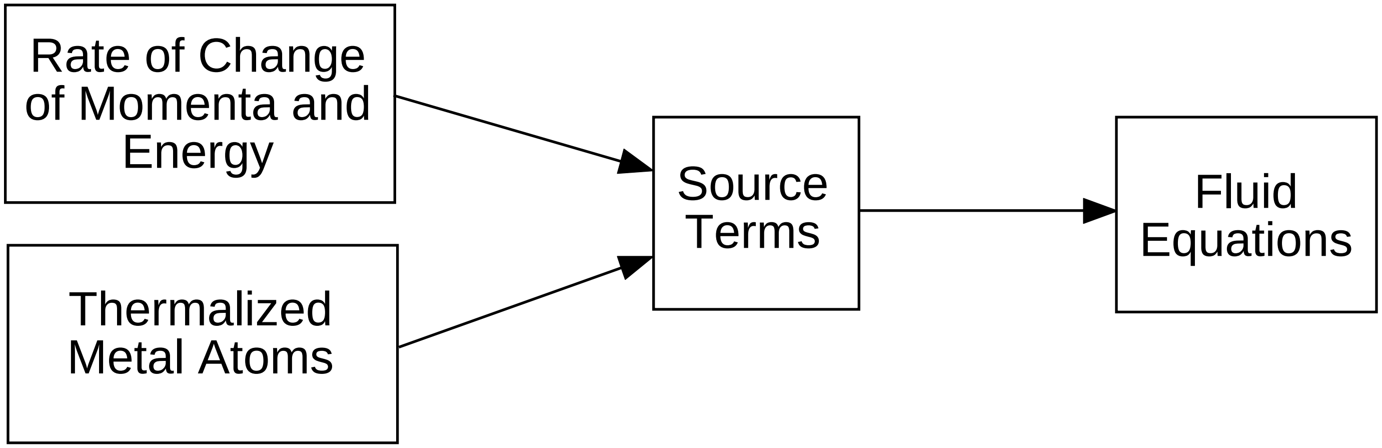


OVERVIEW OF SPUTTER MODEL (Continued)

- Recording of metal atoms:

  - Thermalized --> Green’s Function
  - In-flight --> local density

- Incorporation of statistics into fluid equations:



- Quantities of interest generated:

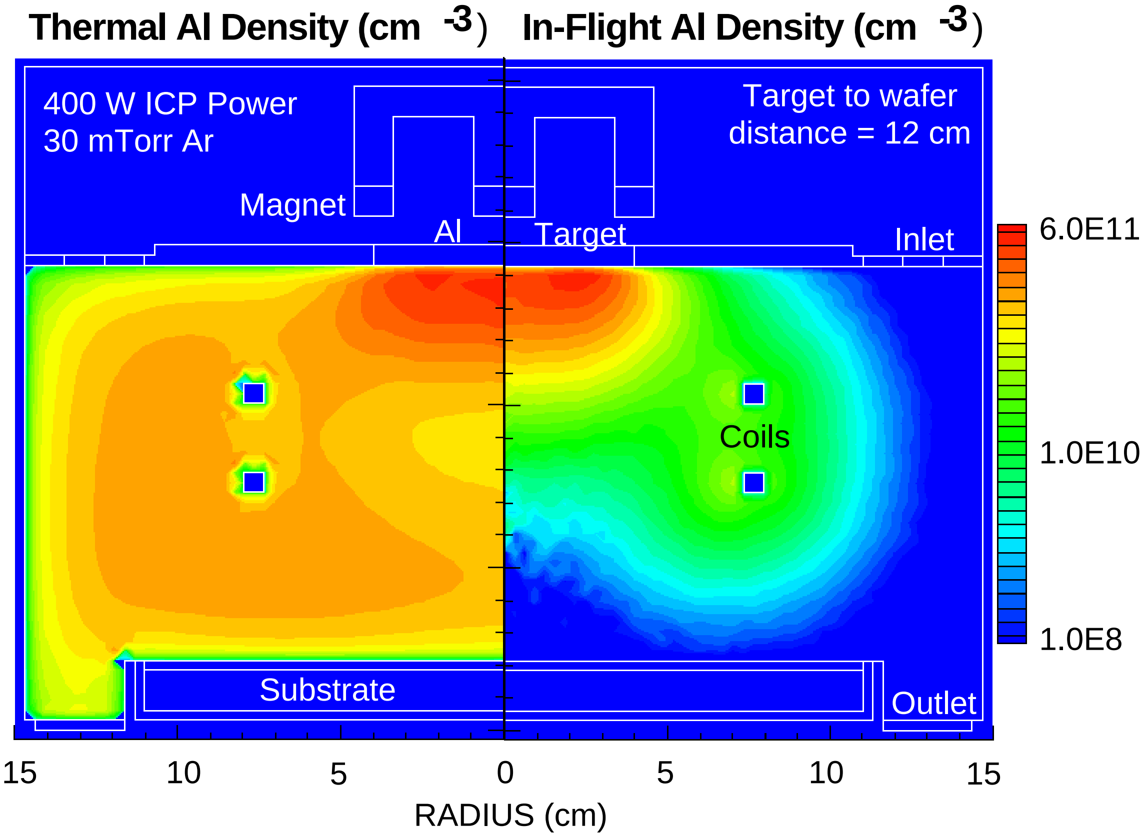
  - Metal atom densities in the plasma,
  - Metal flux to the wafer,
  - Gas heating terms.

MODEL VALIDATION: Al IMPVD

- HPEM IMPVD model was validated by comparing with experiment*.

*Dickson and Hopwood, J. Vac. Sci. Technol. A 15(4), 1997, p. 2307

- Operating conditions:
  - ~ 240 W magnetron.
  - 0 V on wafer.



- Al density (10^{11} cm^{-3}) at radius of 4 cm:

Dis. (cm)	HPEM	EXPERIMENT
2	3.4	4.0-7.5
4	1.7	3.0-5.0
8	1.5	1.5
10	1.5	1.0-1.5

SPUTTER HEATING: Ar DENSITY

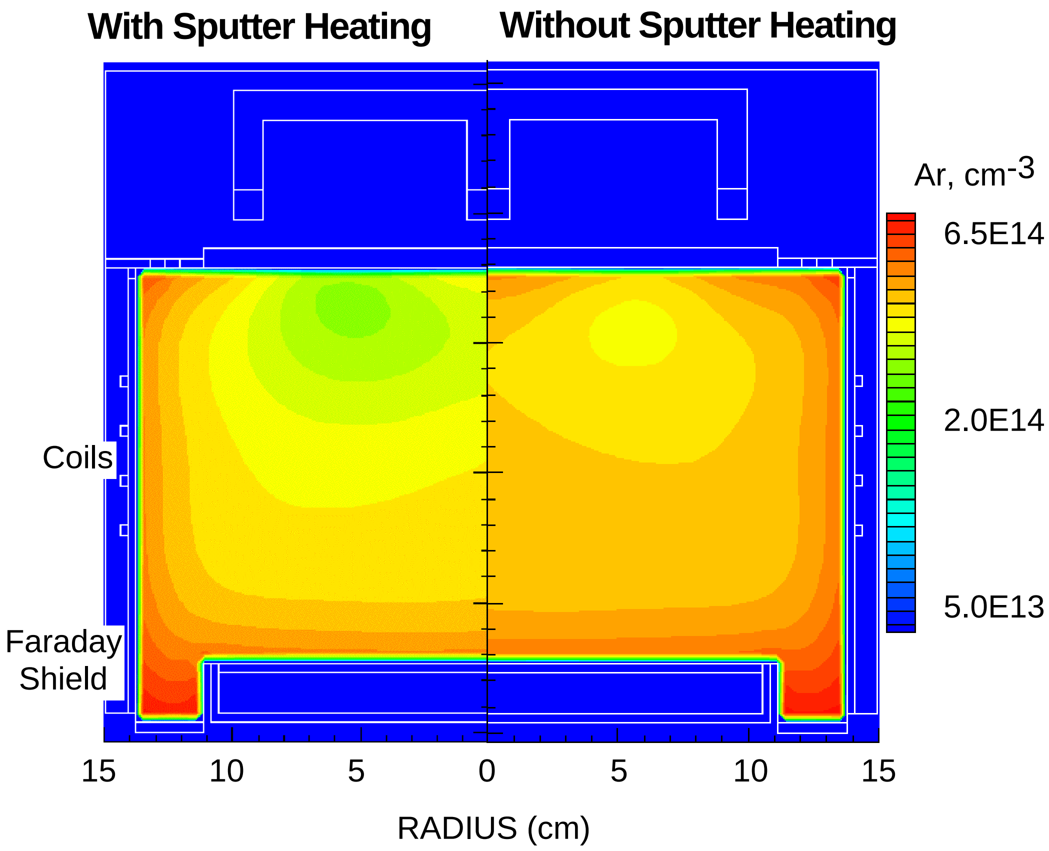
- The IMPVD reactor of interest: external coil reduces erosion, larger target area increases sputtered atom flux.

- Operating conditions:

    - 0.5 kW ICP
    - 1.0 kW magnetron
    - 30 V rf on substrate
    - 30 mTorr

- The minimum Ar density with heating is 75% of that without heating.

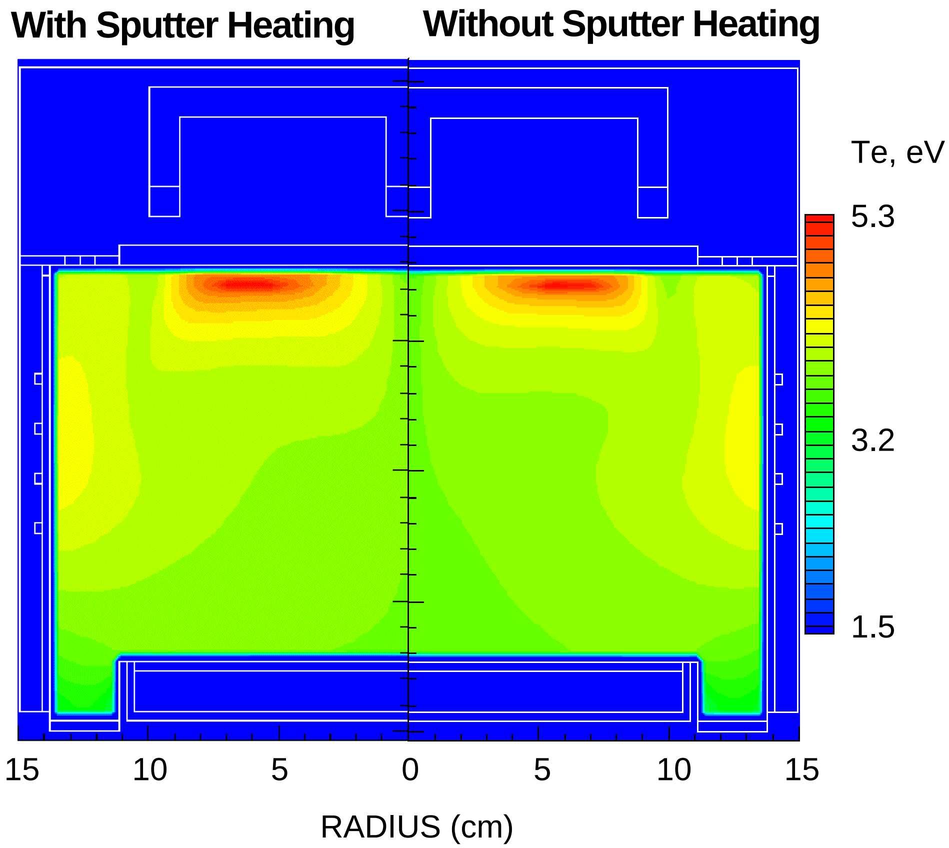
- The bias at the target is:
  -177 V with heating,
  -168 V without heating.



- The Ar^+ density decreases due to sputter heating. More voltage is required to maintain the 1 kW magnetron power with a lower ion current.

SPUTTER HEATING: ELECTRON TEMPERATURE

- The electron temperature profiles are similar, and > 3 eV throughout the plasma regions.
- The maximum electron temperature below the target is caused by energetic electrons from secondary emission.
- The relatively high electron temperature next to the Faraday shield is due to the skin effect in ICP power deposition.



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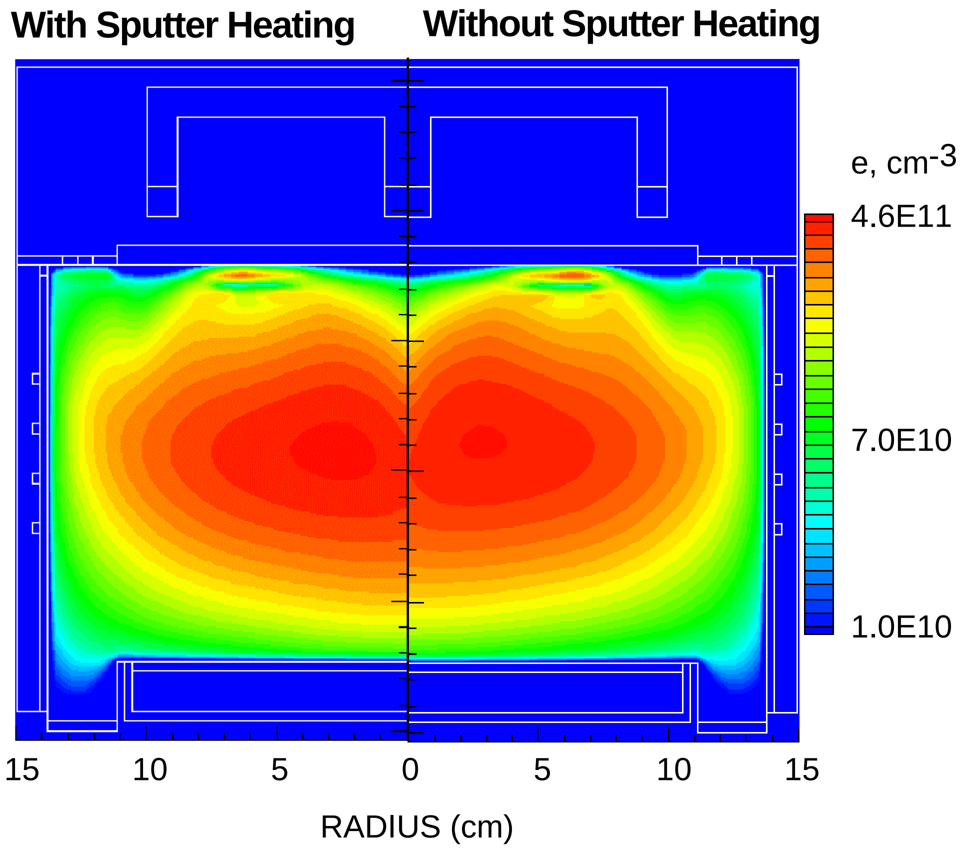
SPUTTER HEATING: ELECTRON DENSITY

- The electron density profiles are also similar, indicating the sputter heating does not significantly affect the electron density.

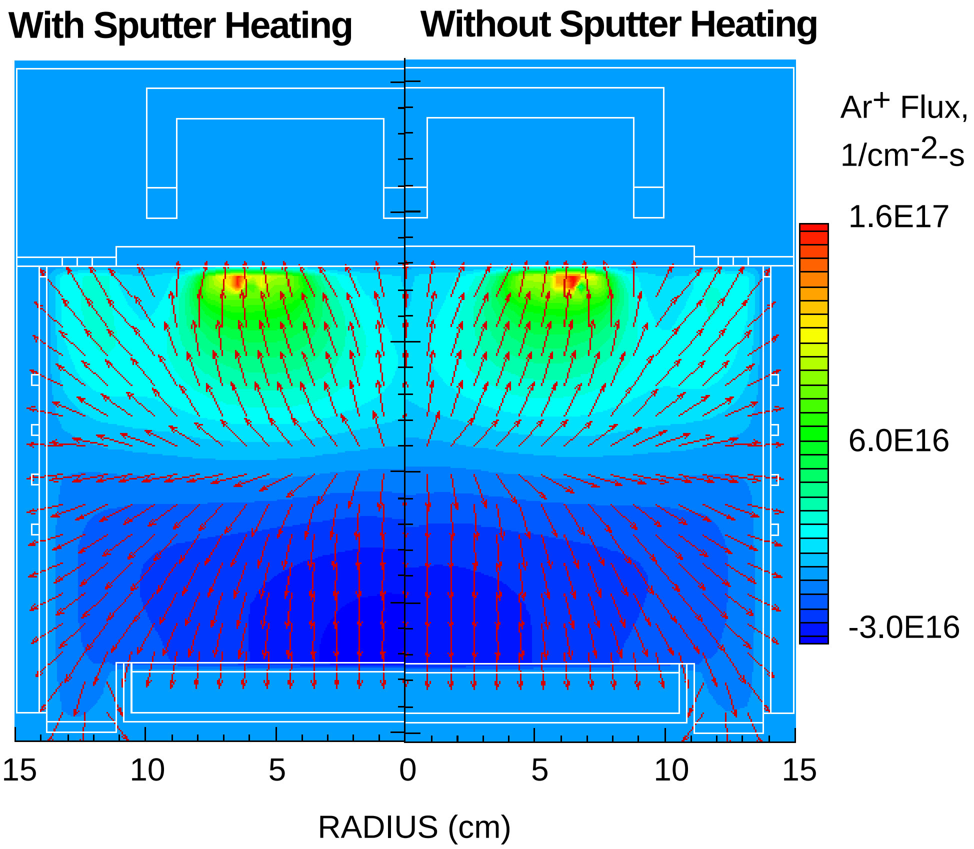
- The high electron density below the target is due to magnetron confinement.

- The maximum electron density is off-center, due to the magnetron effect.



SPUTTER HEATING: Ar^+ FLUX

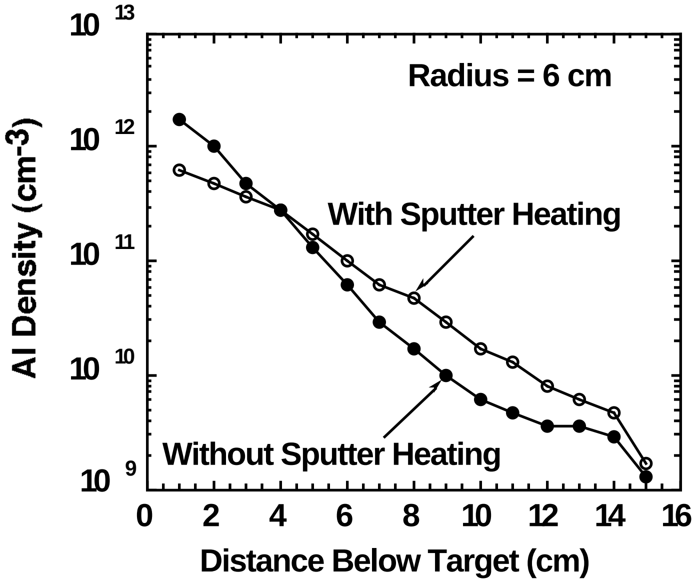
- The Ar^+ flux is high at the magnetron confinement region.
- The maximum flux below the target generates sputter track on the magnetron target.
- The Ar^+ flux above the substrate is less than half of that below the target because the rf bias on the substrate is only 1/5 of the dc bias on target.

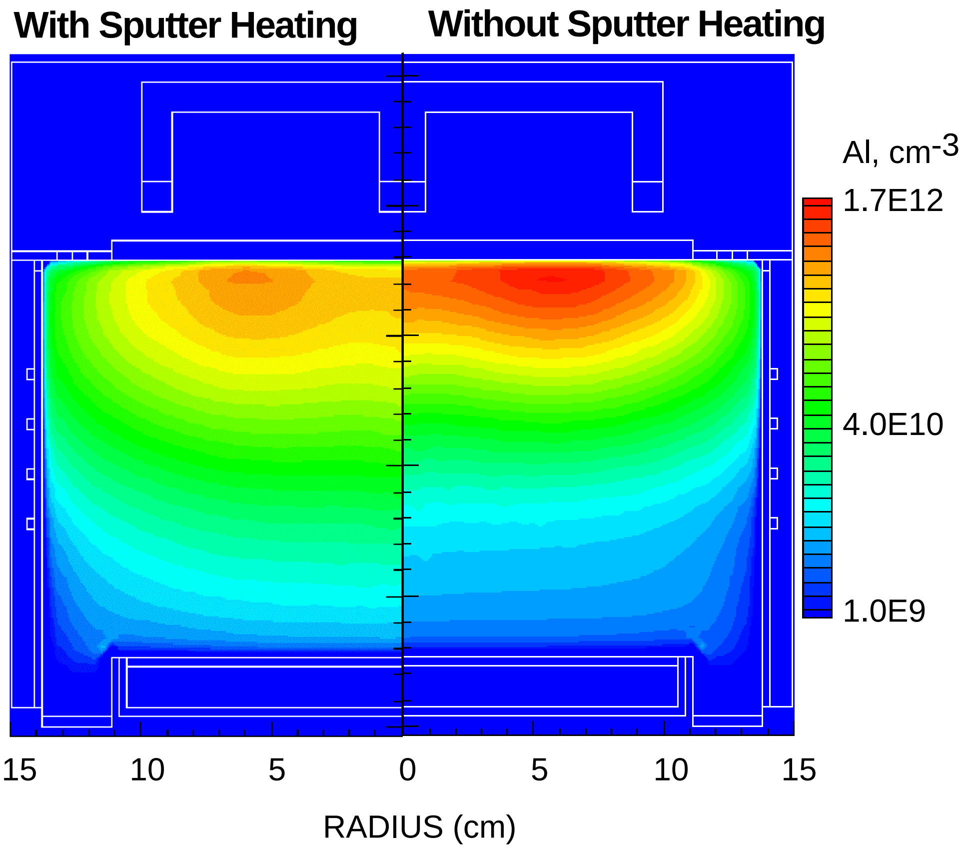


SPUTTER HEATING: Al DENSITY

- The maximum Al density with sputter heating is half that without heating, though its gradient to the substrate is smaller.

- The magnetron power is 1 kW in both cases, so the sputtered atom fluxes and Al inventory should be approximately the same.

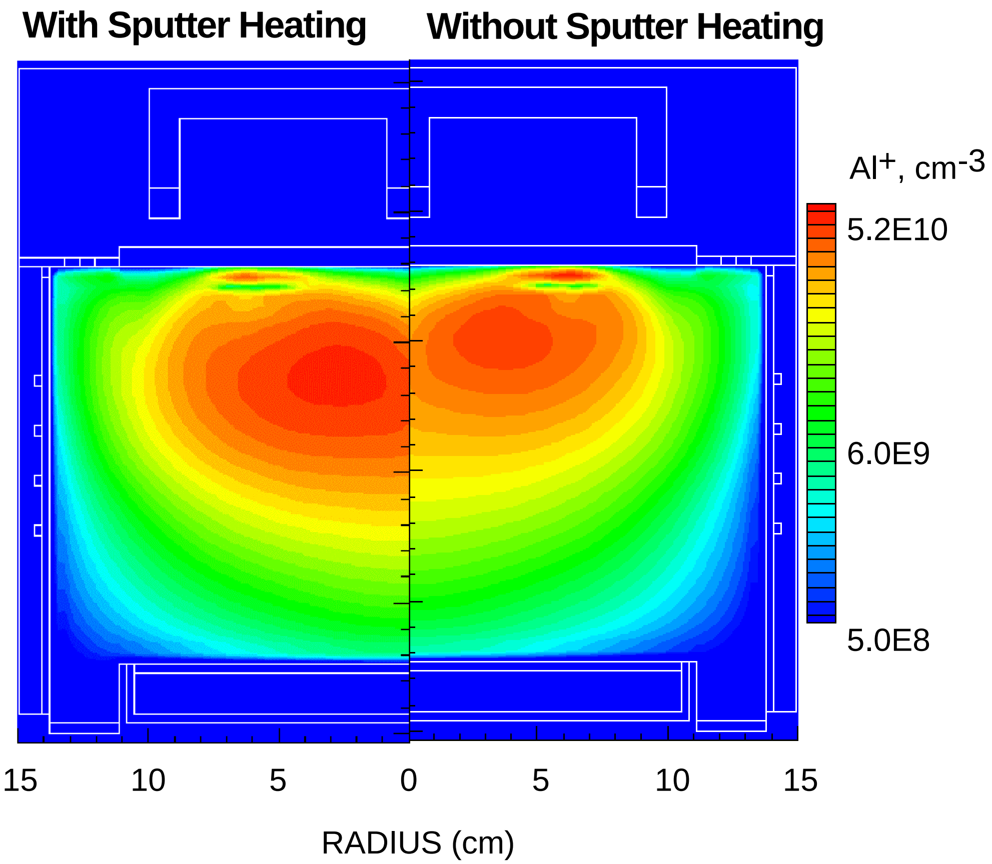




- Sputter heating redistributes Al in the reactor to conserve the inventory.

SPUTTER HEATING: Al^+ DENSITY

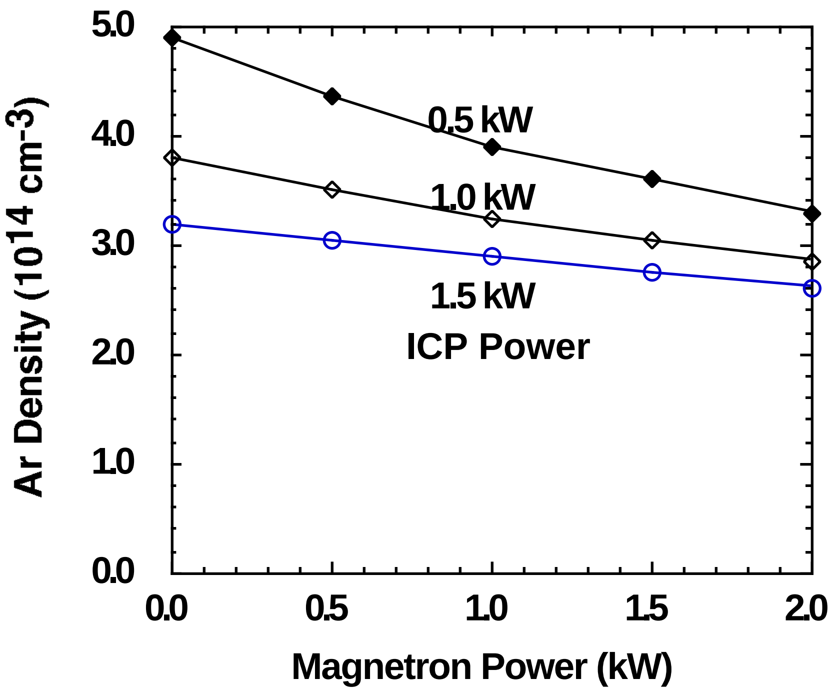
- The maximum Al^+ density is approximately the same.
- The Al^+ distribution is determined by the Al atom distribution and the mean free path for ionization.
- The background gas density is reduced by 25% by sputter heating, so the mean free path for Al ionization increases.
- Because the metal flux to wafer consists mostly of ions, the depositing metal flux with heating is about 15-25% larger.

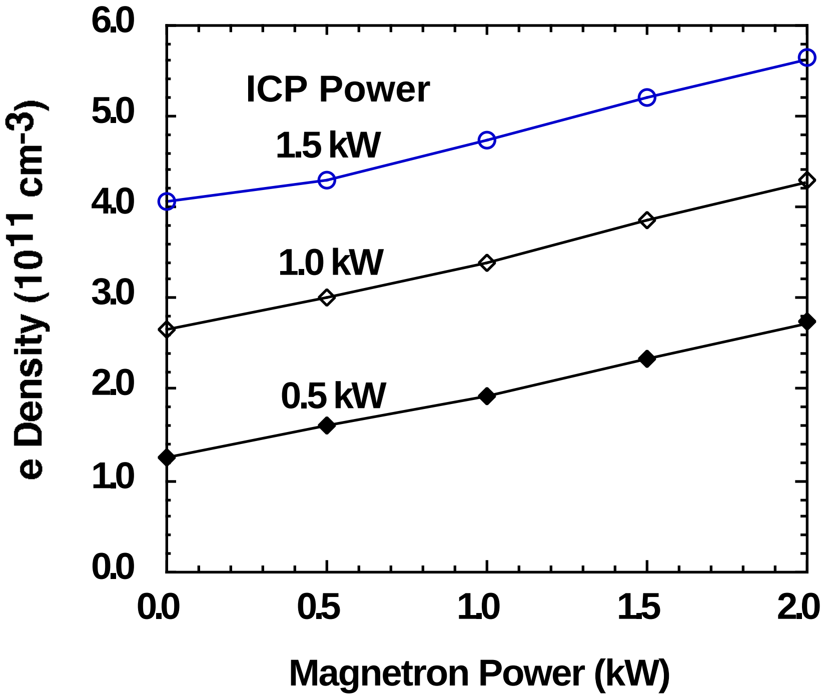


Ar AND e DENSITIES vs MAGNETRON AND ICP POWER

- The trends shown agree with expectation: more power, more heating, more rarefaction and more ionization.

- The Ar and e densities change linearly with magnetron power, to first order. More nonlinearity occurs at low ICP powers.

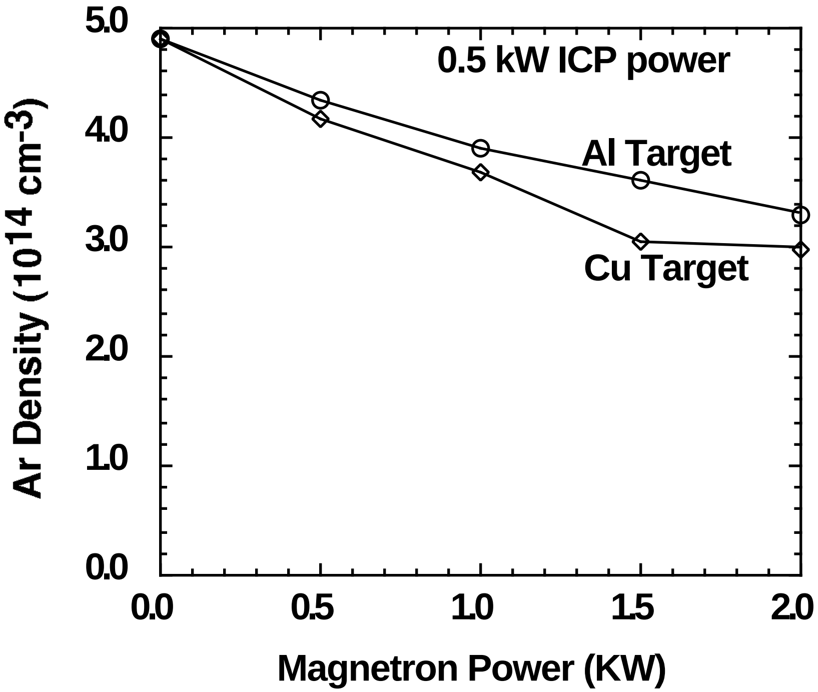


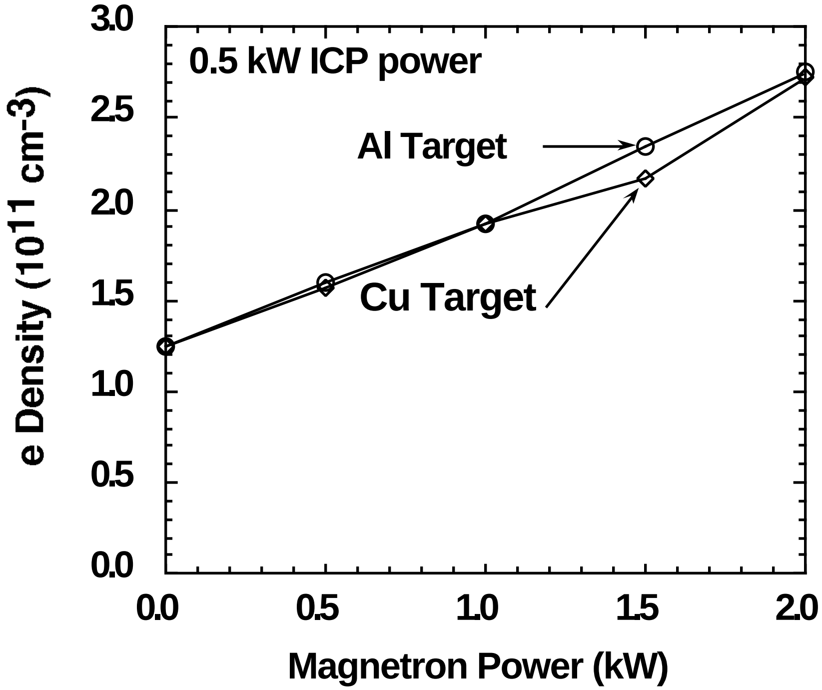


Ar AND e DENSITIES vs MAGNETRON AND ICP POWER

- The Ar density for the Cu target is smaller than that for Al target. The sputter yield for Cu is twice that of Al, hence Ar gas is more rarefied for Cu target.

- The electron densities for the two targets are approximately the same, because electron density is strongly affetced by magnetron and ICP powers, and insensitive to gas rarefaction.





SUMMARY OF IMPVD STUDY

- The magnetron confinement of the electrons leads to higher ionization of background gas atoms below the target.

- The background gas density decreases due to sputter heating, which redistributes the metal species inventory.

- Sputter heating increases as the yield of the target material increases.

- The electron density scales with the ICP and the magnetron power, and is insensitive to the sputter heating.