MODELING OF TRENCH FILLING DURING IONIZED METAL PHYSICAL VAPOR DEPOSITION[+]

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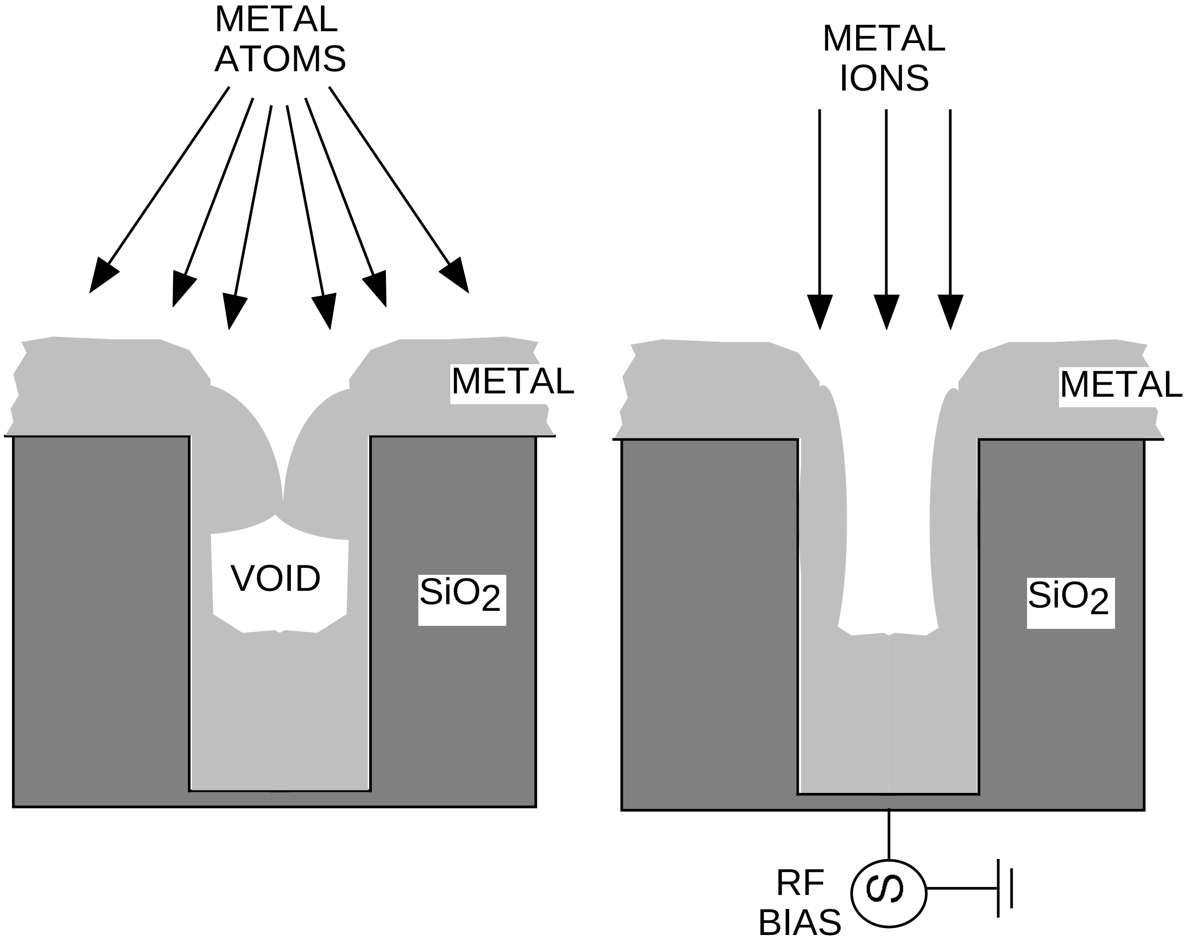
AGENDA

- Motivation and introduction to Cu IMPVD
- Description of the model and the sputter algorithm
- Metal densities in Cu IMPVD
- Ion and neutral distributions
- Surface diffusion model for profile simulation
- RF coil voltage
- Trench filling
  - Radial locations
  - Pressures
  - Magnetron and ICP power
  - Aspect ratio of the trench
- Conclusions

MOTIVATION FOR Cu IONIZED PVD

- The resistance of Cu is only half that of Al.
- To increase processor speed, Cu is replacing Al as the metal for interconnect wiring.
- The filling of large aspect ratio trenches benefits from ionized PVD.
- Ions are able to fill deep trenches because their angular distributions are narrowed by an rf bias.



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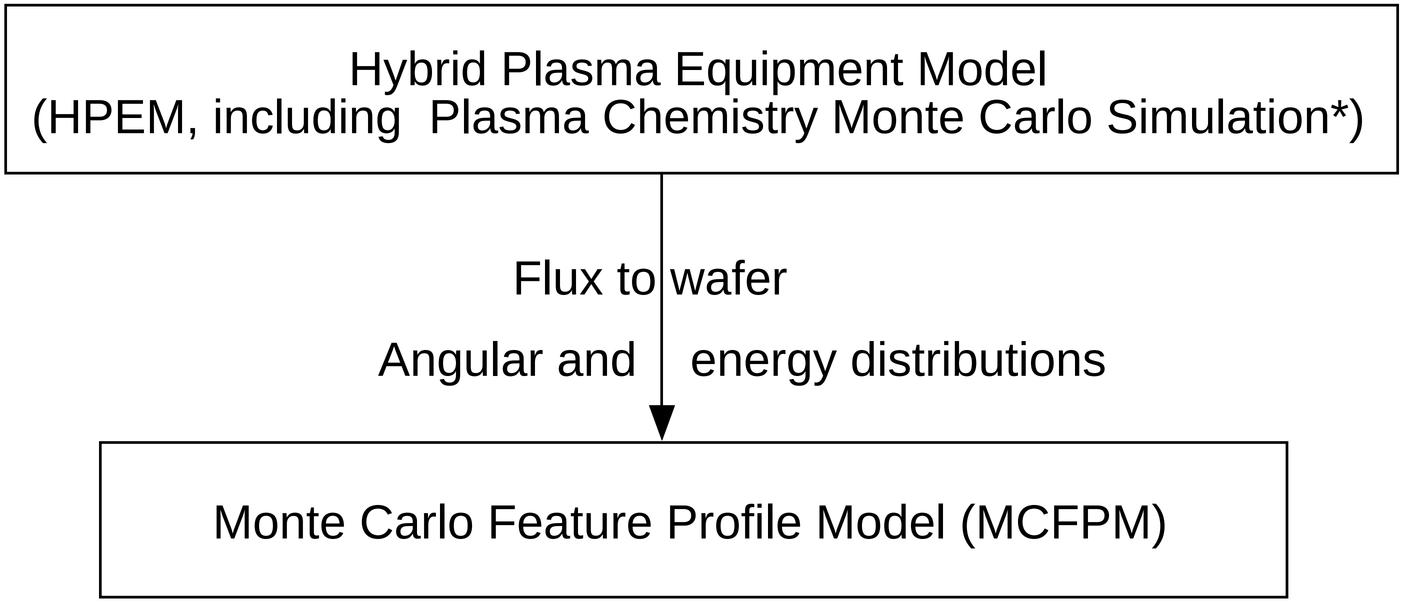
COMPUTATIONAL PLATFORM



Hybrid Plasma Equipment Model
(HPEM, including Plasma Chemistry Monte Carlo Simulation*)

Flux to wafer

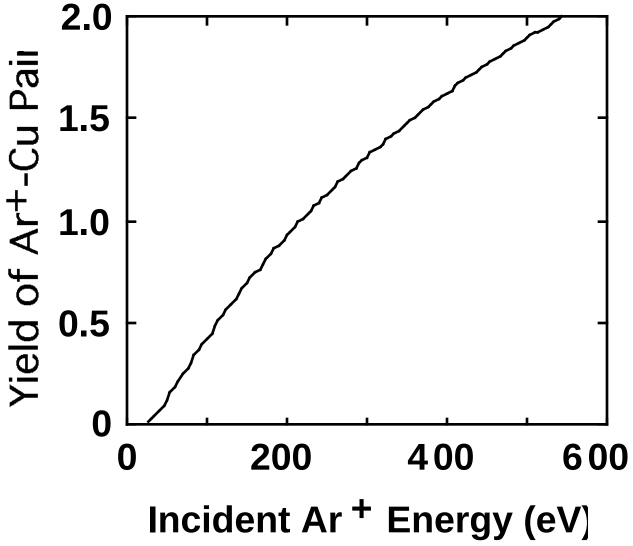
Angular and energy distributions

Monte Carlo Feature Profile Model (MCFPM)

*PCMCS generates angular and energy distributions for the depositing fluxes, using species sources and time-dependent electric fields obtained by HPEM.

FEATURES OF SPUTTER MODEL

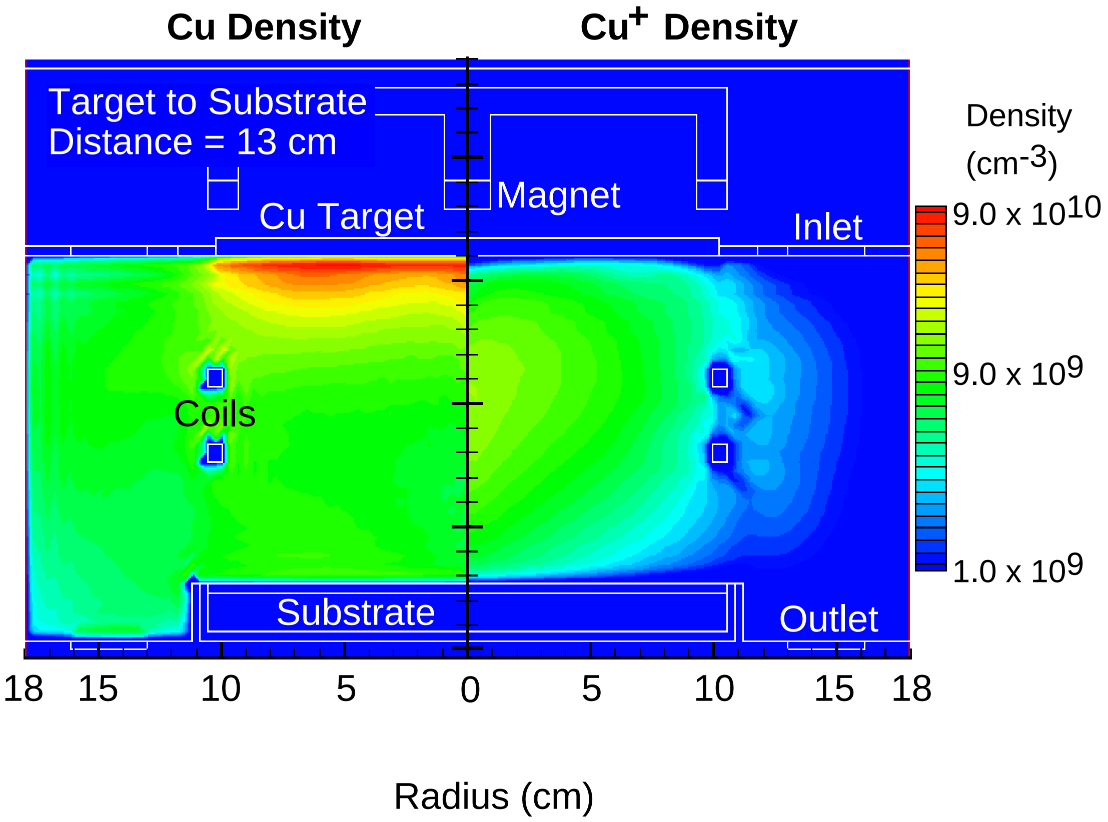
- Ion energy-dependent yield* for sputtered atoms.
- The effective yield of 1 for the reflected neutrals.
- Ion energy-dependent kinetic energy
  - Sputtered atoms: Cascade distribution
  - Reflected neutrals: TRIM** and MD***
- Cosine distribution in angle for sputtered and reflected atoms emitted from target.
- Momentum and energy transfer from sputtered and reflected atoms to background gas (sputter heating).
- Electron impact ionization for in-flight sputtered and reflected neutrals.
- Source terms for thermalized sputter species and gas heating.



*Masunami et al., At. Data Nucl. Data Tables 31, 1 (1984) .
**D. Ruzic, UIUC.
***Kress et al., J. Vac. Sci. Technol. A 17, 2819 (1999)

Cu IMPVD: METAL DENSITIES

- Reactor is based on *Cheng et al.
- Operating conditions:
  - 40 mTorr Ar
  - 1.0 kW ICP
  - 20 V rf voltage on coils
  - 0.3 kW magnetron
  - -25 V dc bias on substrate
- Cu peaks below the target since most of the sputtered Cu atoms are thermalized a few cm below the target.
- Cu^+ peaks at the center due to peak in plasma potential.



*Cheng, Rossnagel, and Ruzic, JVST 13(2), 1995, p. 203.

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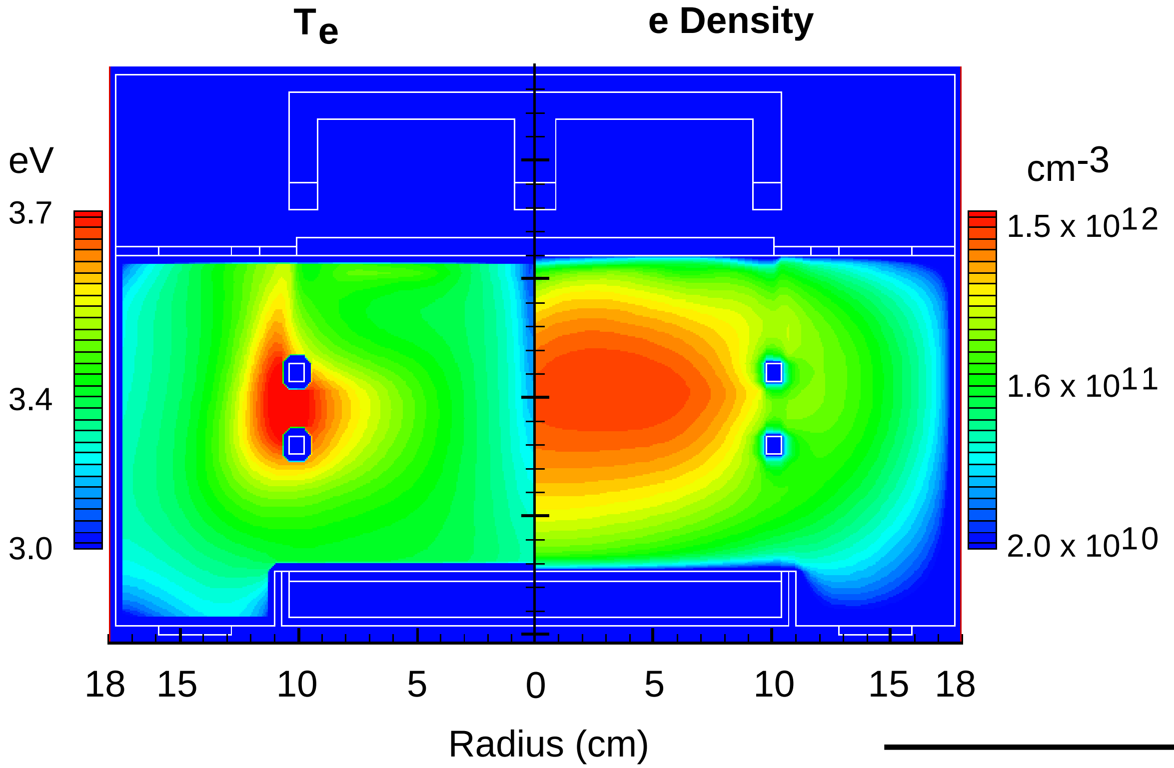
Cu IMPVD: ELECTRON TEMPERATURE AND DENSITY

- The electron temperature is > 3 eV throughout the reactor.
- The large T_e near the coils is due to the large ICP power deposition in this region.
- The electron density peaks off center due to the magnetron effect and off-axis ionization by ICP power.



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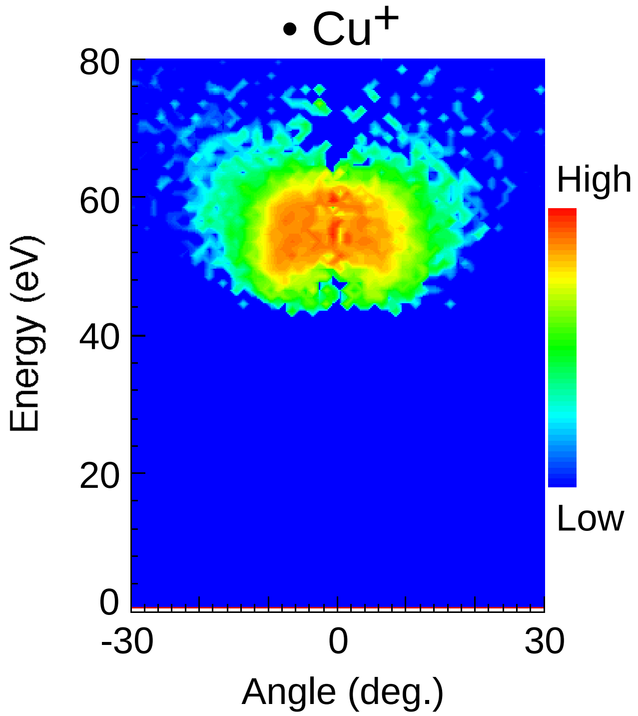
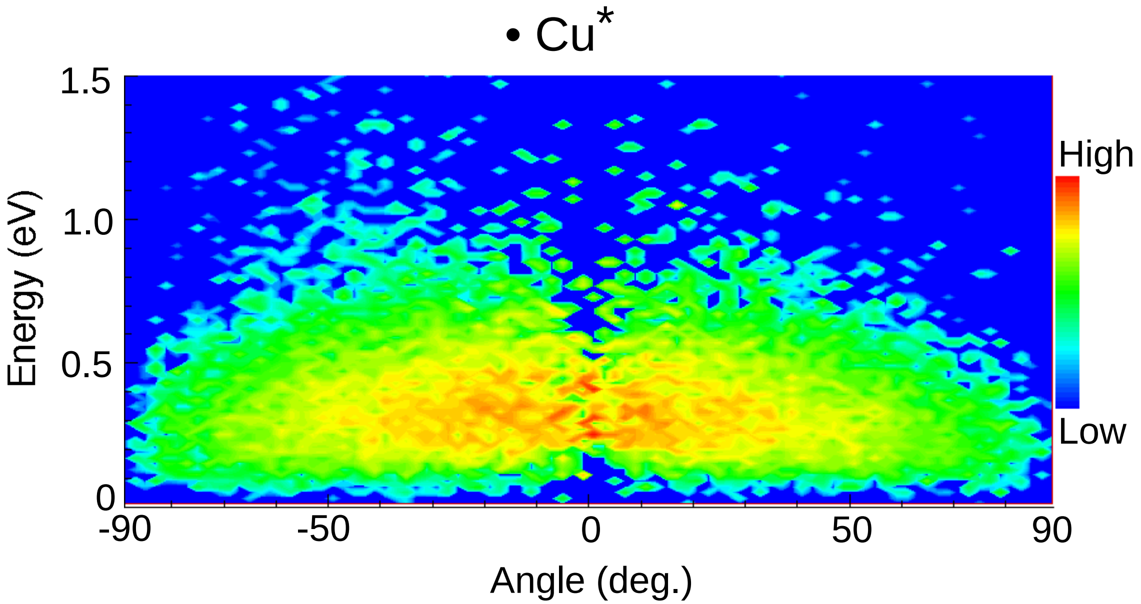
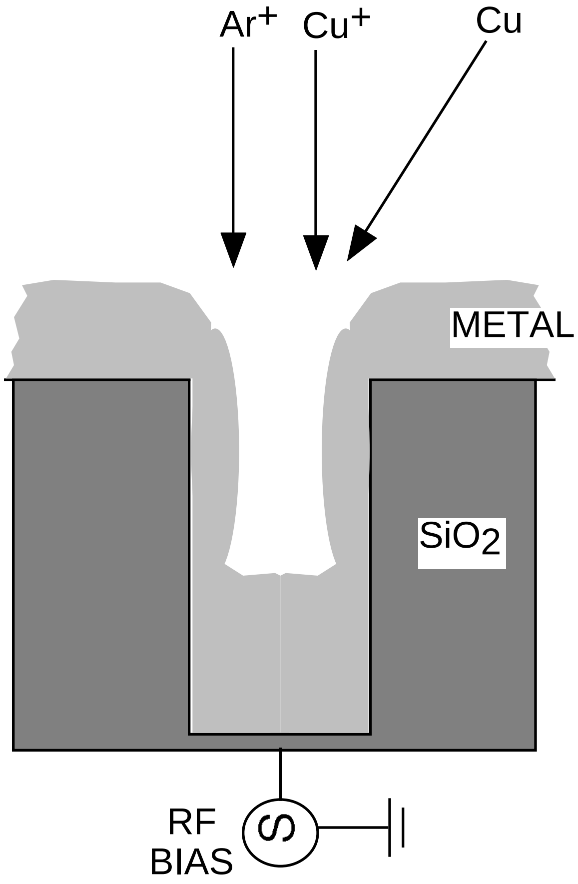
ION AND NEUTRAL SPECIES DISTRIBUTIONS

- Neither the ion energy nor the neutral energy are mono-energetic.
- The spread in ion energy is due to the rf voltage on the coil and collisional broadening.
- The neutral distributions in angle are broader than that for ions.
- Operating conditions: 40 mTorr Ar, 1.0 kW ICP, 20 V rf voltage on coils, 0.3 kW magnetron, -25 V dc bias on substrate





MONTE CARLO FEATURE PROFILE MODEL (MCFPM)

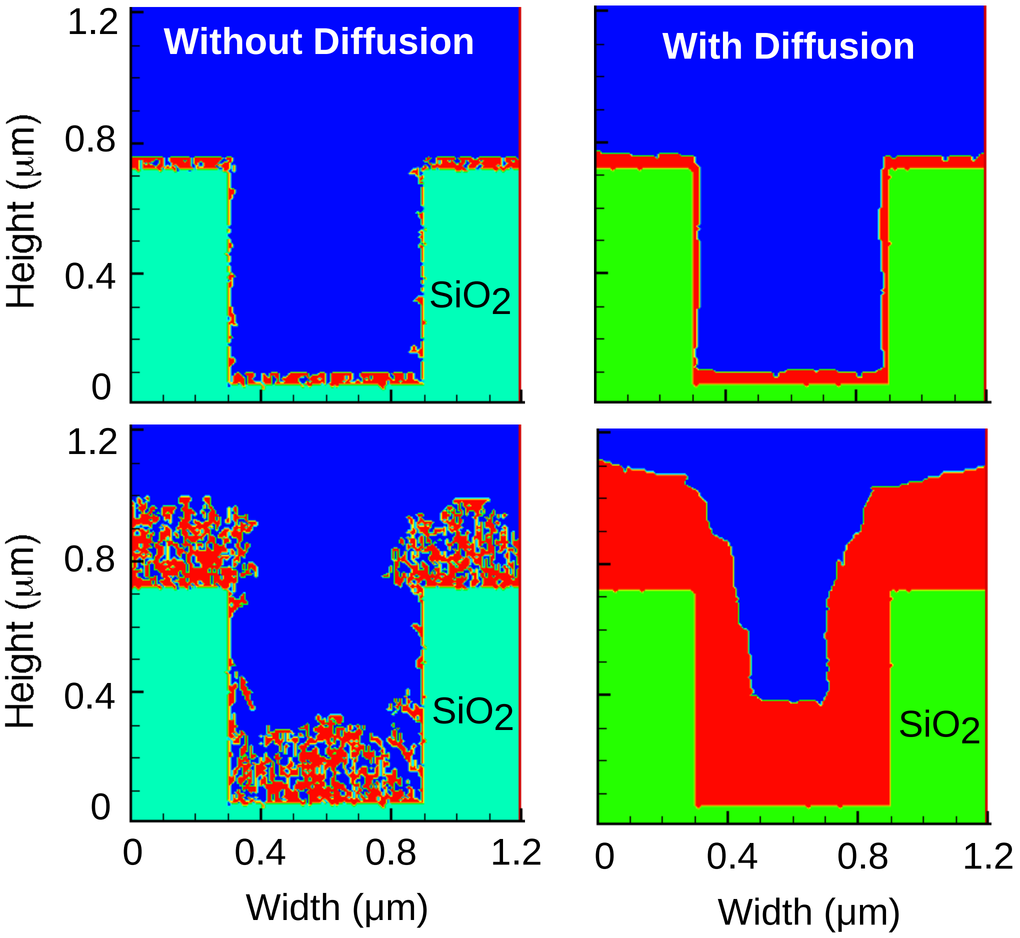


- The MCFPM obtains the etch and deposition profile using ion and neutral distributions from the HPEM.
- Surface processes are implemented using a chemical reaction mechanism:
  - Deposition: $Cu(g) + Si(s) \rightarrow Cu(s) + Si(s)$
  - Resputtering: $Ar^+(g) + Cu(s) \rightarrow Ar(g) + Cu(g)$
- The model takes account of angular and energy dependent etch and deposition rates.
- The model is able to simulate many different chemistries and materials.

TRENCH FILLING WITH AND WITHOUT DIFFUSION

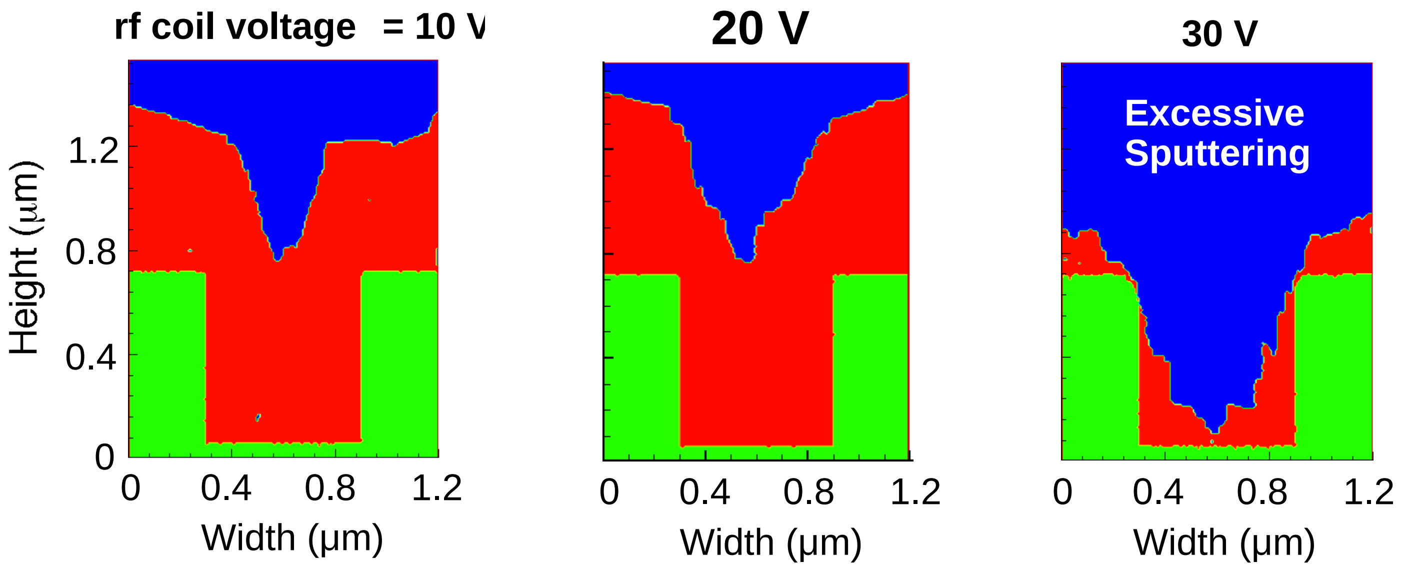
- A diffusion algorithm was incorporated into MCFPM to reduce unphysical dendric growth.
- The diffusion probability of the depositing metal depends on the activation energy for each possible diffusion site.
- Without diffusion, the Cu films are unphysically porous and non-conformal.
- With diffusion, Cu species deposit compactly and conformally.

Trench Aspect Ratio = 1.1, Trench Width = 600 nm
Cu^+ : Cu Neutrals = 4:1



TRENCH FILLING VS COIL VOLTAGE

- For ICP power of 500 W and 2 mTorr Ar, measured plasma-potential oscillation* ranges from 10 to 30 V, depending on the termination capacitance of the coil.
- The oscillation in plasma potential extends the range of ion energies, thereby regulating the degree of sputtering.
- Operating conditions: 40 mTorr Ar, 1 kW ICP, 0.3 kW magnetron, -30 V dc bias on wafer.



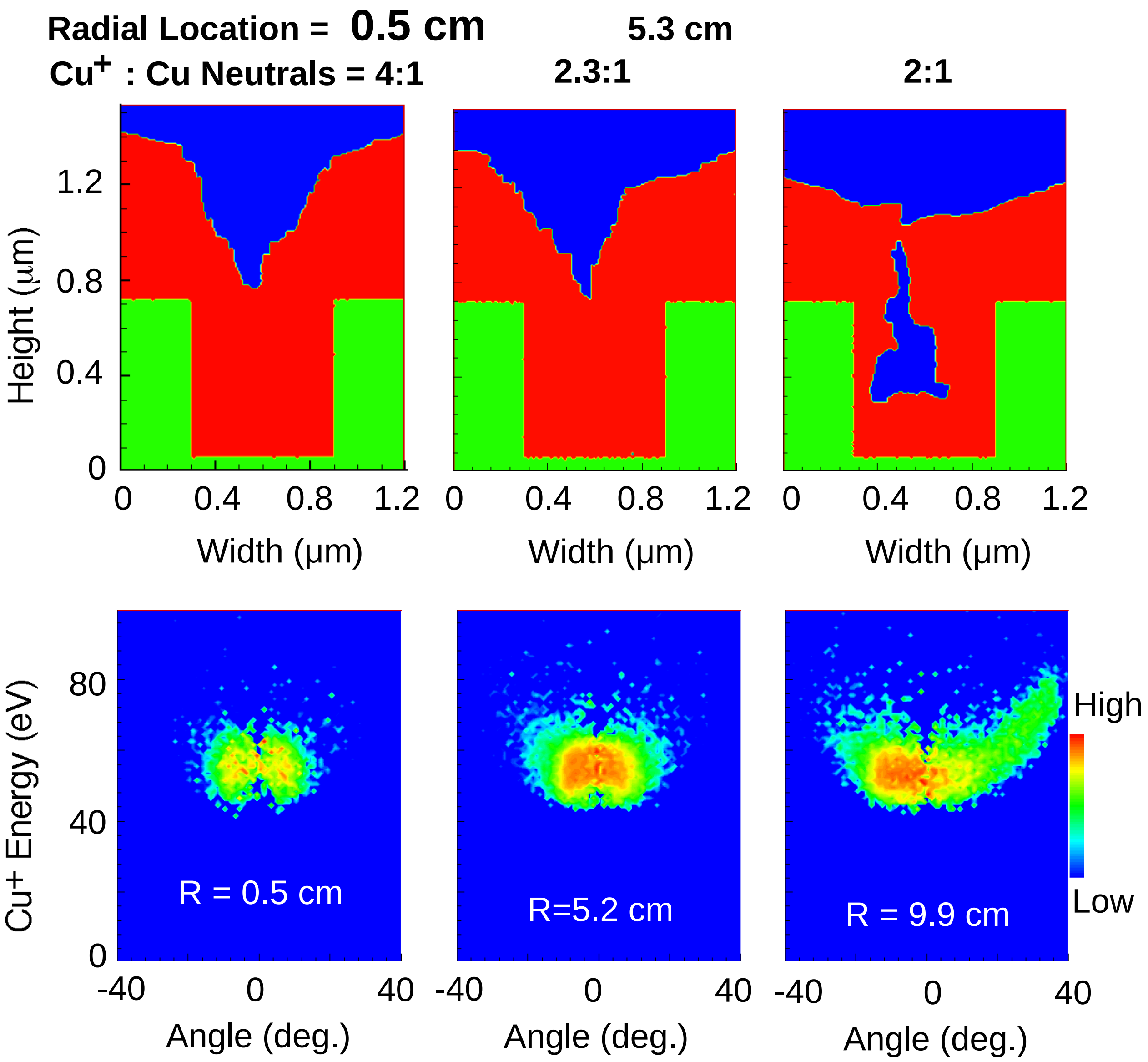
*Suzuki, Plasma Sources Sci. Technol. 9, 199 (2000).

TRENCH FILLING AT DIFFERENT RADIAL LOCATIONS

- Electric field perturbation at the edge of the wafer generates asymmetry in Cu^+ distribution, which causes asymmetry in deposition profile.

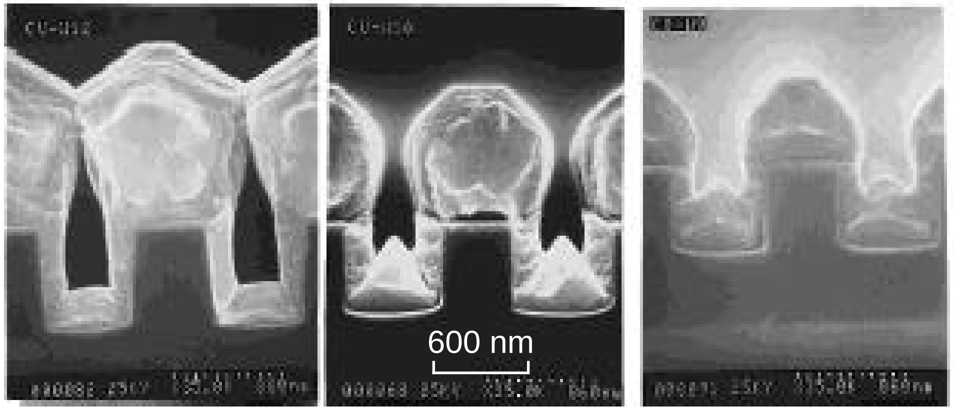
- Operating conditions:

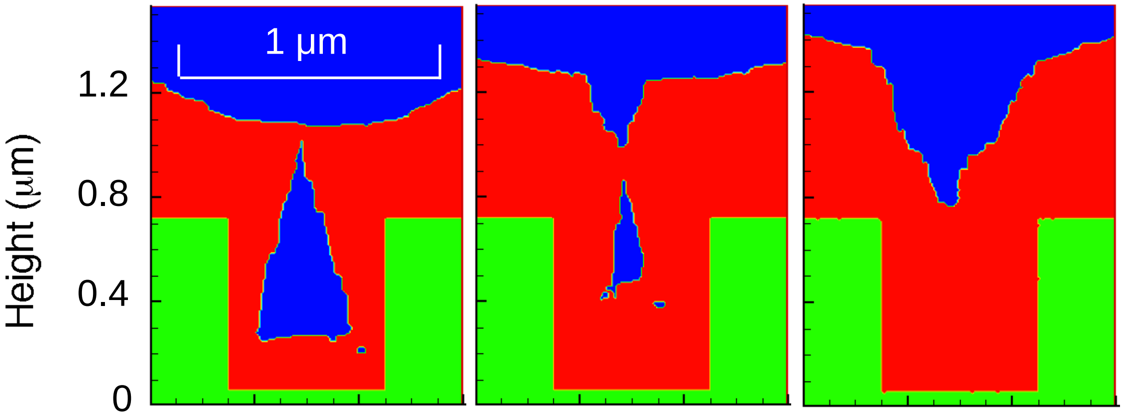
  - 40 mTorr
  - 1 kW ICP
  - 20 V rf voltage on coils
  - 0.3 kW magnetron
  - -25 V dc bias on wafer



TRENCH FILLING VS PRESSURE

- Voids form at low pressure and fill with increasing pressure.
- The ionization fraction increases with increasing pressure, due to slowing of Cu atoms which allows more ionization.
- Reasons for pinch-off:
  - Diffuse angular distribution of the neutrals
  - Less sputtering of over-hanging deposits
- Operating conditions*:
  - 1 kW ICP
  - 0.3 kW magnetron
  - -25 V dc bias on wafer





*Cheng, Rossnagel and Ruzic, JVST B 13, 203 (1995).

TRENCH FILLING WITH AND WITHOUT RESPUTTERING

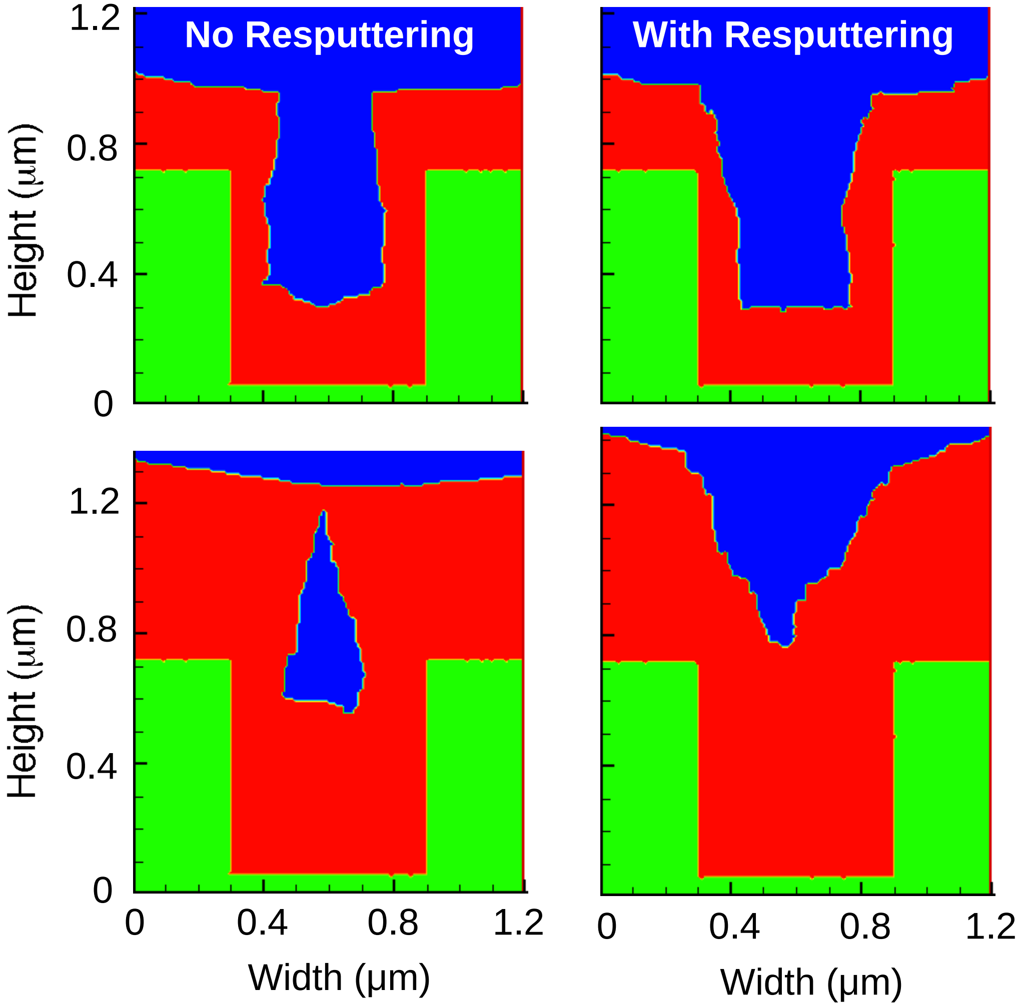
- Without resputtering, the overhang deposits grow faster than the bottom deposits, leading to pinch-off at the top.

- Resputtering reduces the overhang deposits, opens up the top of the trench, and enables more fluxes to arrive at the bottom.

- Note that Ar^+ contributes significantly to resputtering.

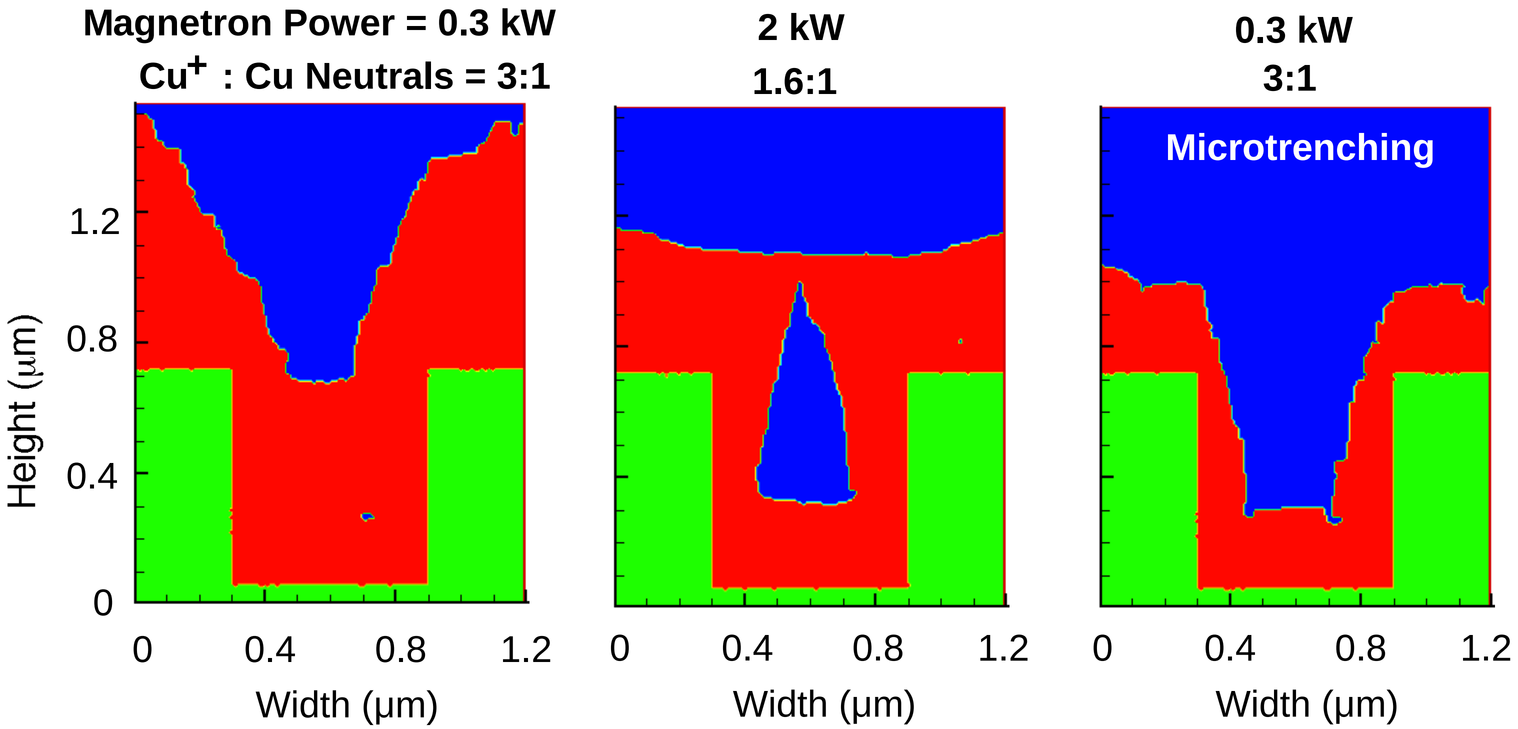
Ar^+ : Cu Total = 7 : 1

Cu^+ : Cu Neutrals = 4 : 1



TRENCH FILLING VS MAGNETRON POWER

- As magnetron power increases, the incident ion flux and the target bias increase, and more Cu atoms are sputtered into the plasma.
- The ionization fraction of the Cu atoms decreases since more ICP power would be required to maintain the same ionization fraction.
- The small void at low magnetron power was caused by microtrenching.
- Operating conditions: 30 mTorr Ar, 1 kW ICP, -30 V dc bias on wafer.



Magnetron Power = 0.3 kW

Cu^+ : Cu Neutrals = 3:1

2 kW

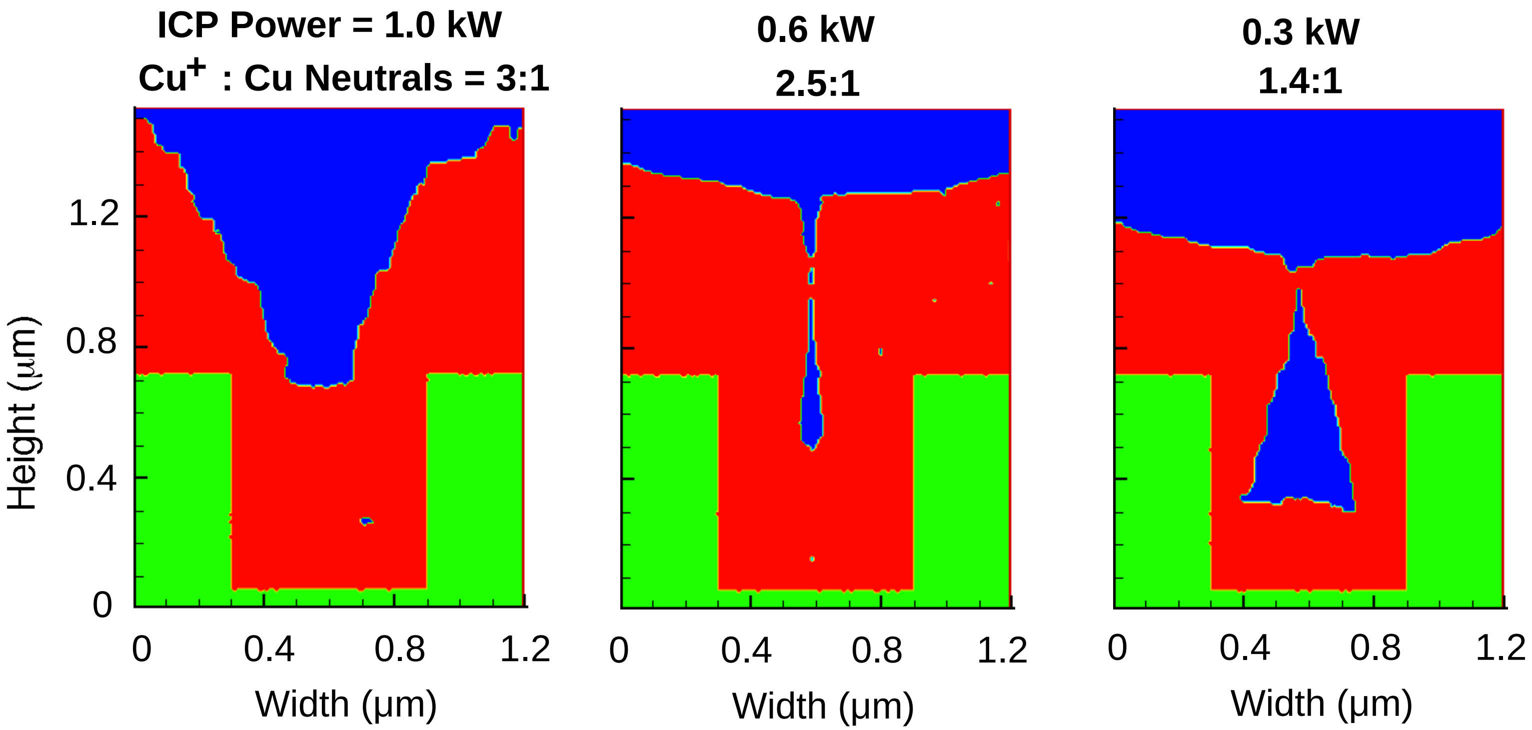
1.6:1

0.3 kW

3:1

TRENCH FILLING VS ICP POWER

- As ICP power decreases, the power available for Cu ionization decreases, and the Cu ionization fraction decreases.
- The pinch-off at low ICP power is caused by low ionization fraction.
- Operating conditions: 30 mTorr Ar, 0.3 kW magnetron, -30 V dc bias on wafer.



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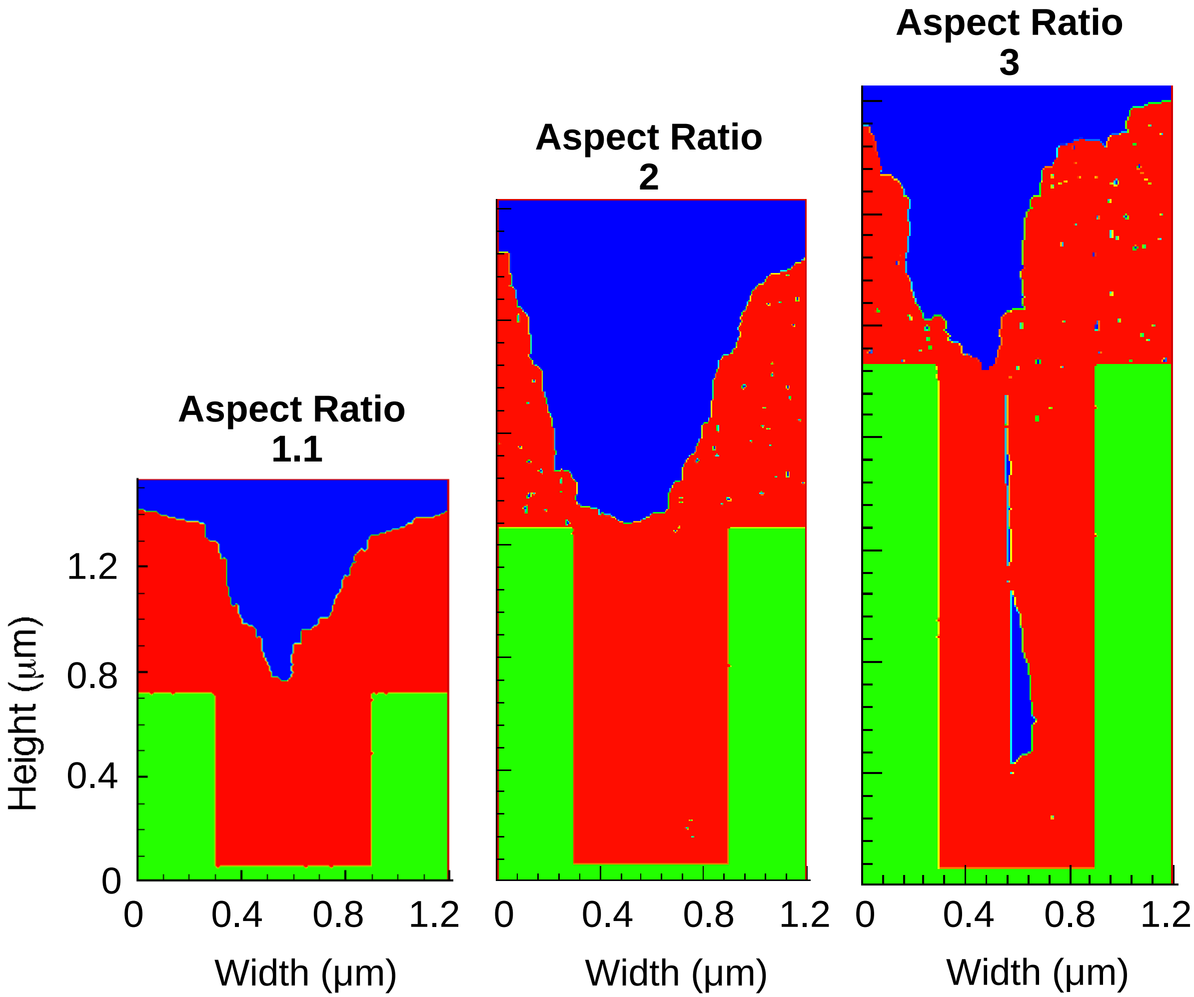
TRENCH FILLING AT DIFFERENT ASPECT RATIOS

- As the aspect ratio increases, trench filling becomes more difficult.
- The fluxes that are able to completely fill shallow trenches may left voids in deeper trenches.
- Operating conditions:
  - 40 mTorr
  - 1 kW ICP
  - 0.3 kW magnetron
  - -25 V dc bias on wafer

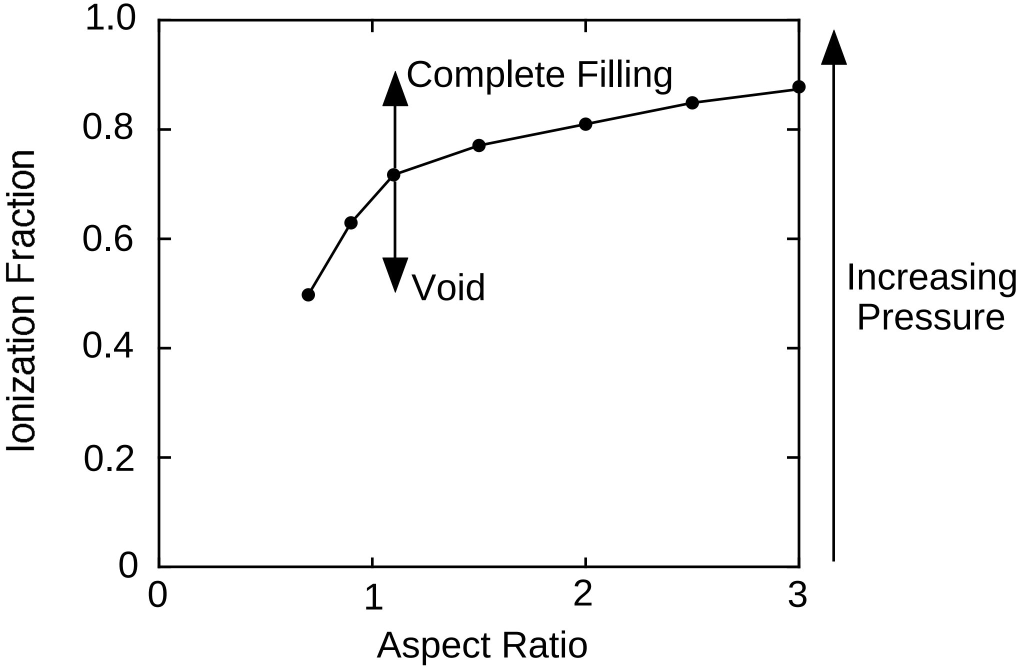


COMPLETE TRENCH FILLING AT DIFFERENT ASPECT RATIOS

- The ionization fraction required for complete filling increases with the aspect ratio.

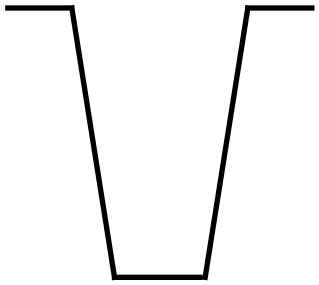
- The highest possible ionization fraction is about 90%, due to gas heating.

- The simulated results indicate the largest aspect ratio for a complete filling is 3, the consensus in literature for highest aspect ratio filling is 4.



- For aspect ratio > 4, experimental results suggest that tapered trench walls are needed for seed layer deposition at the bottom.

Tapered Trench



- Operating conditions:
  - 1 kW ICP
  - 0.3 kW magnetron
  - -25 V dc bias on wafer
  - Radius = 0.5 cm

CONCLUDING REMARKS

- An integrated plasma equipment-feature scale model has been developed and applied to IMPVD modeling.

- The depositing ions have a broadened energy distribution due to oscillation of the plasma potential.

- Surface diffusion is an important process in metal deposition.

- Electric field enhancement at the wafer edge may cause asymmetry in trench filling.

- Formation of voids in trench filling occurs when the ionization fraction of the depositing metal flux is low.

- As aspect ratio of the trench increases, the ionization fraction for complete filling also increases.

- The desirable conditions for complete trench filling are high pressure, low magnetron power, and high ICP power.