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.
*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.

**D. Ruzic, UIUC.
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.

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.
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
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: \( \text{Cu}(g) + \text{Si}(s) \rightarrow \text{Cu}(s) + \text{Si}(s) \)
- Resputtering: \( \text{Ar}^+(g) + \text{Cu}(s) \rightarrow \text{Ar}(g) + \text{Cu}(g) \)

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 dendritic 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 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.

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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

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.
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.
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.
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 leave voids in deeper trenches.

- Operating conditions:
  - 40 mTorr
  - 1 kW ICP
  - 0.3 kW magnetron
  - -25 V dc bias on wafer
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.

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

Tapered Trench

Increasing Pressure

Complete Filling

Void
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.