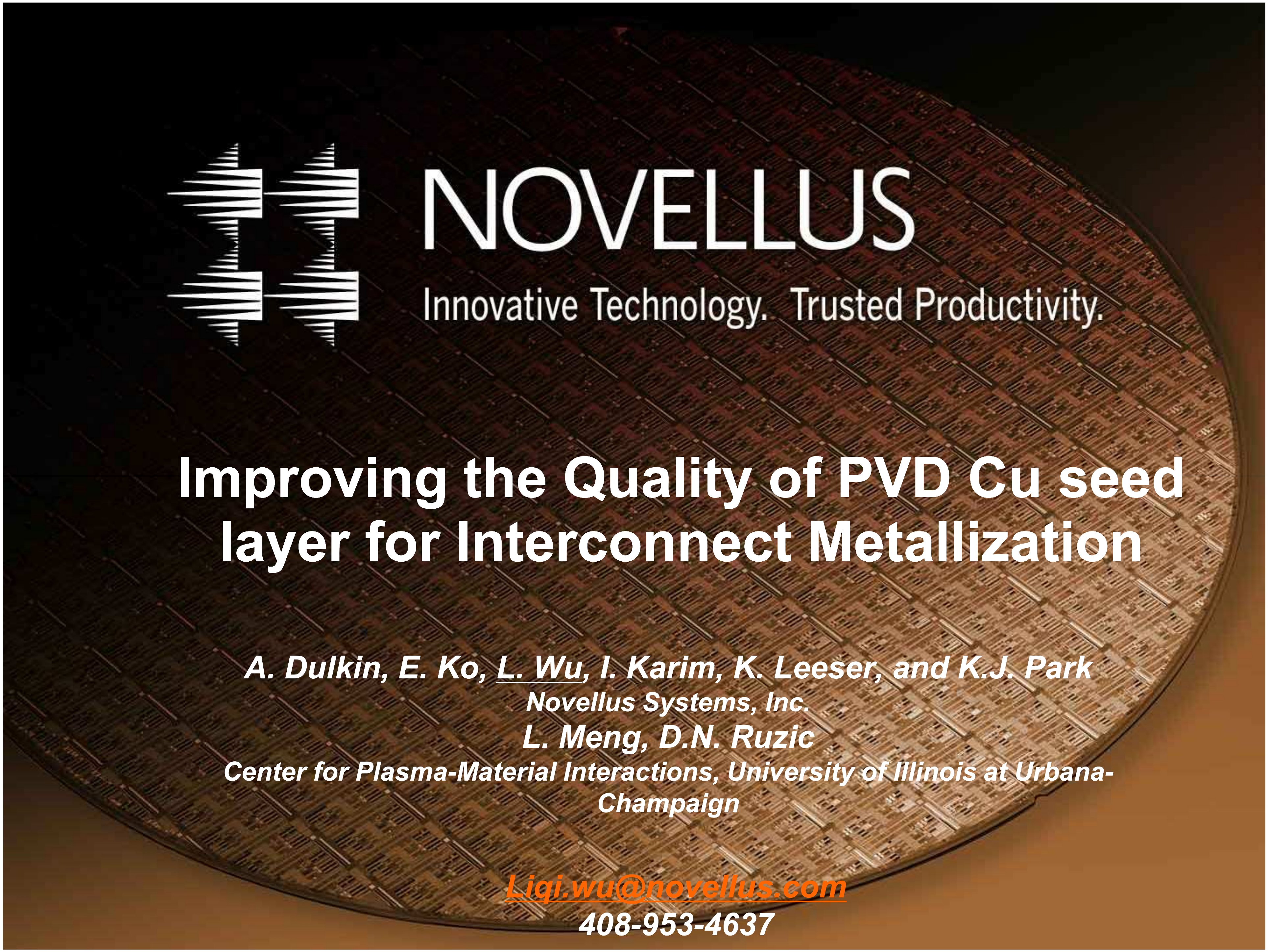

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Improving the Quality of PVD Cu seed layer for Interconnect Metallization

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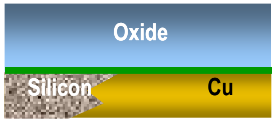
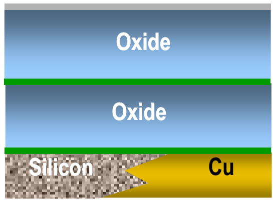
Outline

- **Introduction**
  - PVD in interconnect metallization
  - PVD challenges, evolution of PVD to iPVD
  - Hollow Cathode Magnetron (HCM)
- **Objective and approaches of the research**
  - Advantages and capabilities of HCM
- **Plasma diagnostic methods and results**
  - Langmuir probe
  - Gridded Energy Analyzer (GEA)
  - Quartz crystal microbalance (QCM)
- **Process improvement results**
  - Film morphology, stability, filling capability, etc
- **Conclusions**

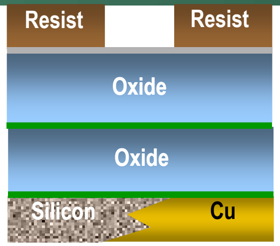
Interconnect Metallization
Dual Damascene Process



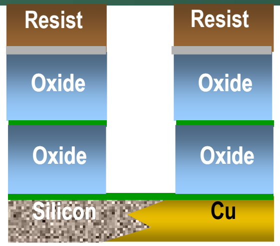
A)
SiN Cu Barrier Dep
Via Diel Oxide Dep
* CMP Diel (buff)



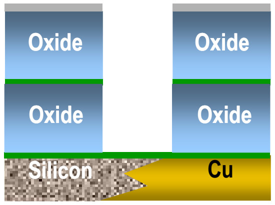
B)
SiN Etch Stop Dep
Line Diel Dep
ARL Dep



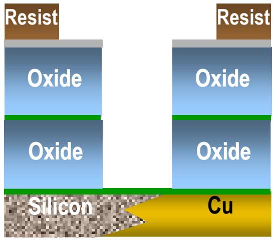
C)
Resist Via Pattern



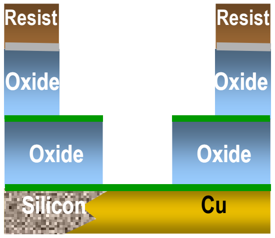
D)
Via Etch
(2 Step)



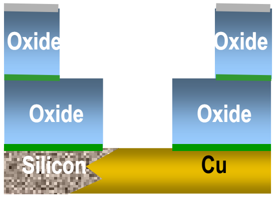
E)
Resist Strip



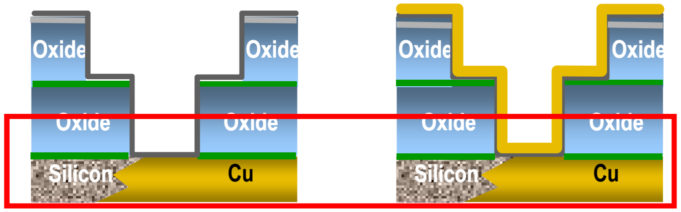
F)
Resist Line Pattern



G)
Line Oxide Etch



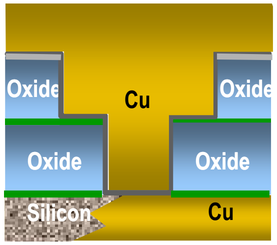
H)
Resist Strip
SiN Cu Barrier Etch



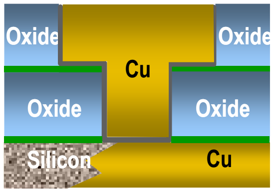
I)
Ta(N) Barrier Dep

J)
Cu Seed Dep

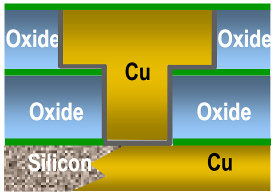
PVD Realm



K)
Electrofill



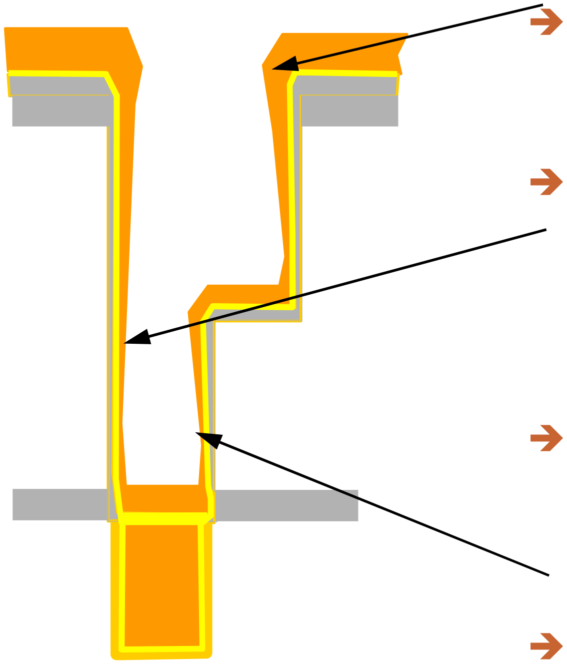
L)
Cu-CMP



M)
SiN Cu Barrier Dep

PVD Cu/barrier seed is critical for defect free interconnect metallization

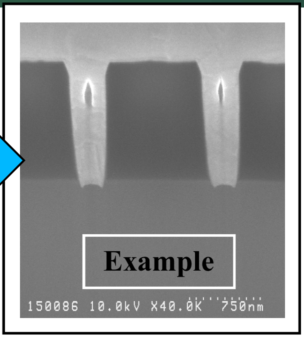
Challenges for PVD Extendibility



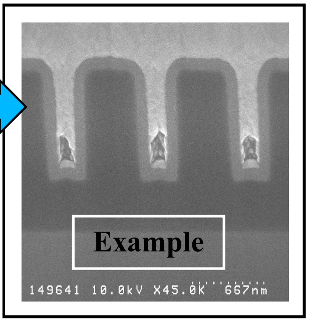
Copper Barrier/Seed

Weak Spots

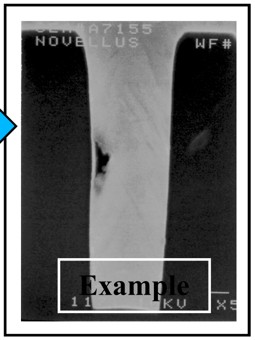
- **Overhang**
  - Amplified by barrier/seed
  - Causes "pinch-off" voiding during electrofill



- **Sidewall coverage**
  - Thin or discontinuous (agglomerated) lower sidewall coverage can cause bottom voiding.
  - Limited due to light-of-sight deposition and overhang growth



- **Edge asymmetry**
  - Asymmetry and "thinning" of films near wafer edge can cause voiding or barrier breakdown
  - Critical with thinner sidewall coverage
- **High aspect ratio**
  - Becomes higher after B/S deposition presenting challenges for plating



- **Aggressive structure**
  - Dielectrics undercut/OH
  - Low-k dielectric, damage to dielectric
  - Rough dielectric surface
- …

Significant challenge to extend PVD to sub-22nm technology

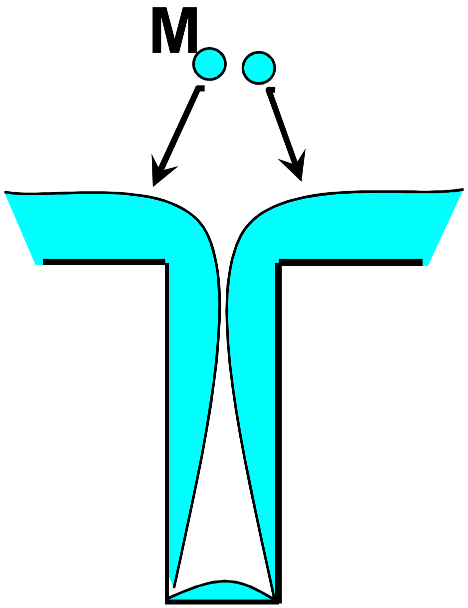
Evolution of PVD - Ionized PVD

Metal neutral deposition

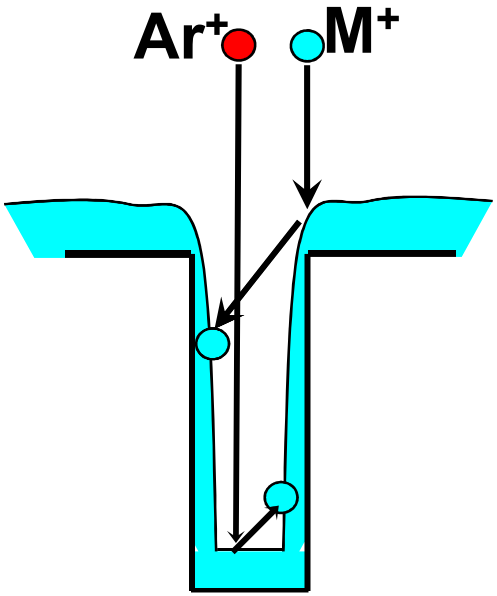
Poor Coverage, Shadows, Overhang formation

Metal ion deposition

Better Nucleation & Surface Mobility, Coverage enhancement due to Resputtering, Overhang Reduction



Conventional PVD



Ionized PVD

iPVD addresses some inherent limitations of PVD

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Objective of Research, Hypothesis, and Solutions

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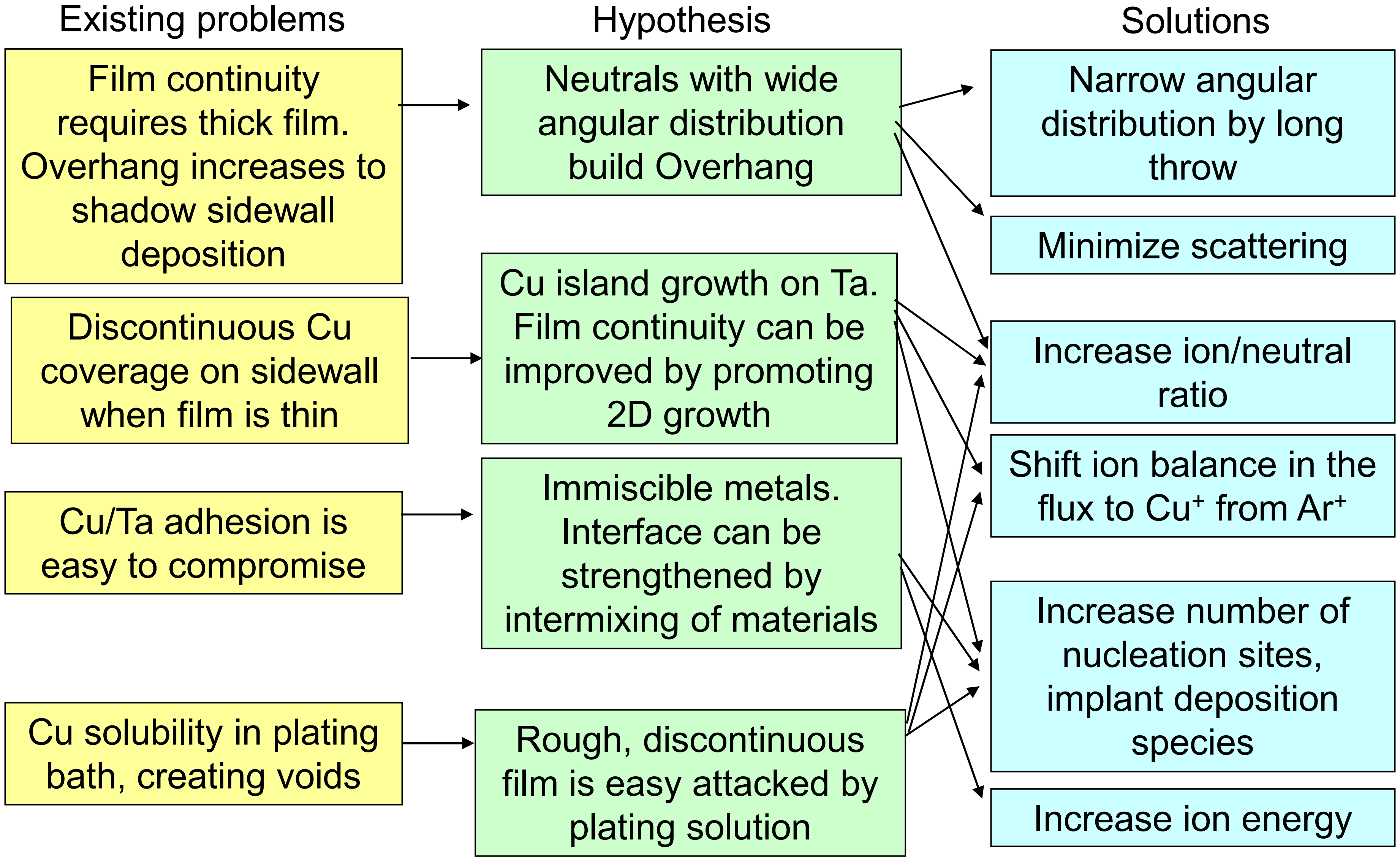


Existing problems

Film continuity requires thick film. Overhang increases to shadow sidewall deposition

Discontinuous Cu coverage on sidewall when film is thin

Cu/Ta adhesion is easy to compromise

Cu solubility in plating bath, creating voids

Hypothesis

Neutrals with wide angular distribution build Overhang

Cu island growth on Ta. Film continuity can be improved by promoting 2D growth

Immiscible metals. Interface can be strengthened by intermixing of materials

Rough, discontinuous film is easy attacked by plating solution

Solutions

Narrow angular distribution by long throw

Minimize scattering

Increase ion/neutral ratio

Shift ion balance in the flux to Cu^+ from Ar^+

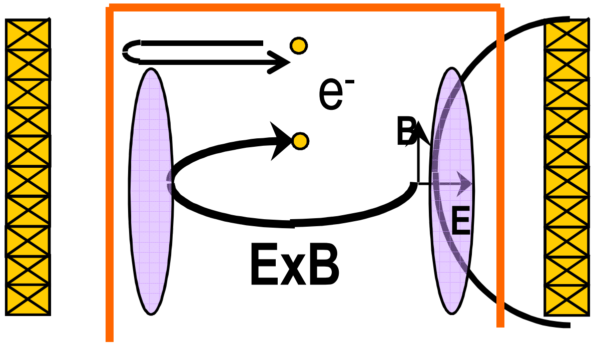
Increase number of nucleation sites, implant deposition species

Increase ion energy

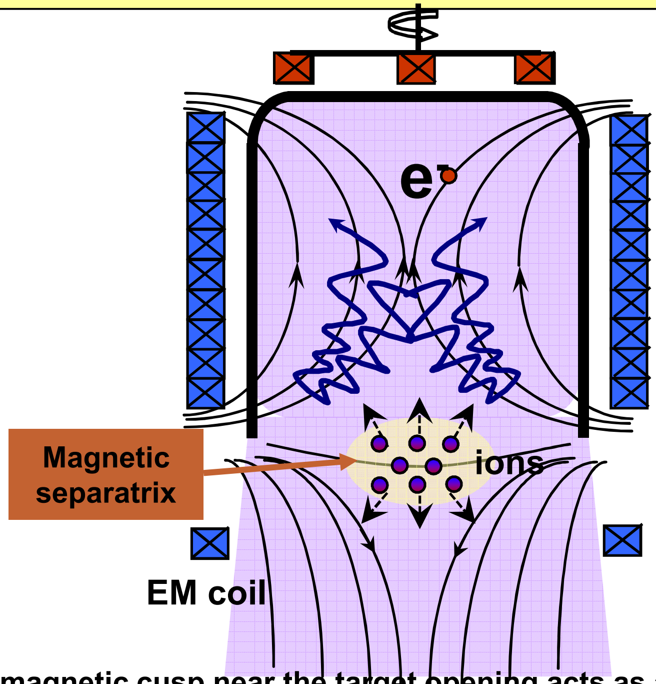
Hollow Cathode Magnetron (HCM) iPVD
General Principles of Operation

- ➔ **HCM combines magnetron action with electrostatic confinement of hollow cathode, and magnetic mirror to create very high density plasma in a concave target**
- ➔ **High density plasma produces high ionization fraction in the deposition metal flux**

Hollow Cathode Magnetron



Magnetic mirror

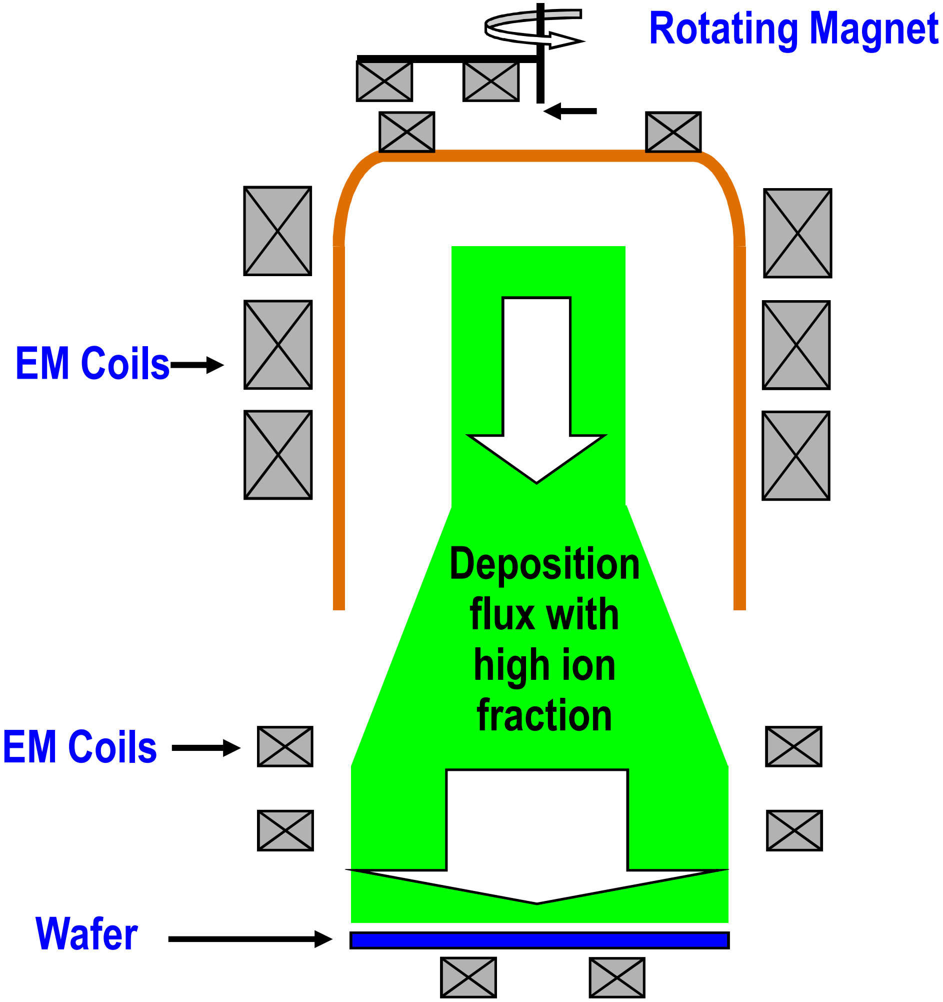


A magnetic cusp near the target opening acts as an aperture for plasma extraction into the downstream region

HCM generates high density plasma source and high metal ion fraction

Advantages of HCM

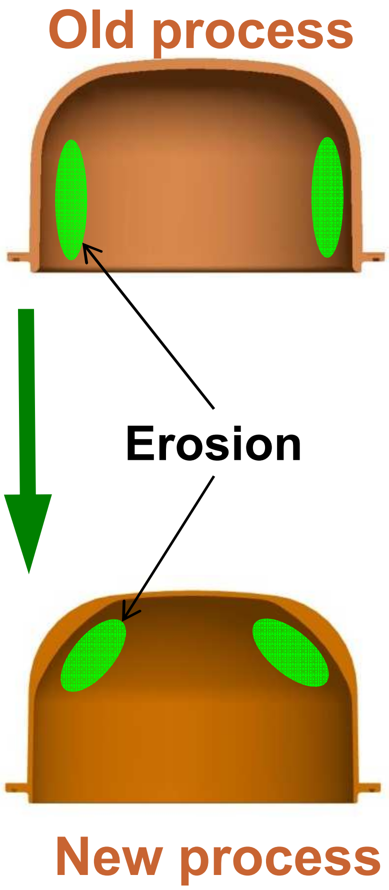
- The target erosion profile can be changed by changing magnetic field
- Electrical and magnetic fields in the module modulate the plasma flux
- Ion energy can be controlled by changing plasma density which defines the potential drop in the wafer sheath



Uniform and energetic ion component in deposition flux can be achieved

Approaches

- **Increase neutral directionality to improve step coverage:**
  - Long throw mode of deposition by shifting target erosion from sidewall to corner by changing magnetic confinement
  - Low pressure to minimize scattering: reduced from 0.4mTorr to 0.1mTorr
- **Change the primary ion species from Ar to Cu**
  - By decreasing Ar pressure and utilizing Cu self-sputtering
- **Increase the Cu ion/neutral ratio**
  - By increasing ionization via increase of the plasma density
- **Improve ion flux uniformity and increase ion energy at wafer level**
  - By changing magnetic field configuration at the wafer level



Both plasma diagnostics and film characteristics were performed to confirm the Cu seed improvement by modified process

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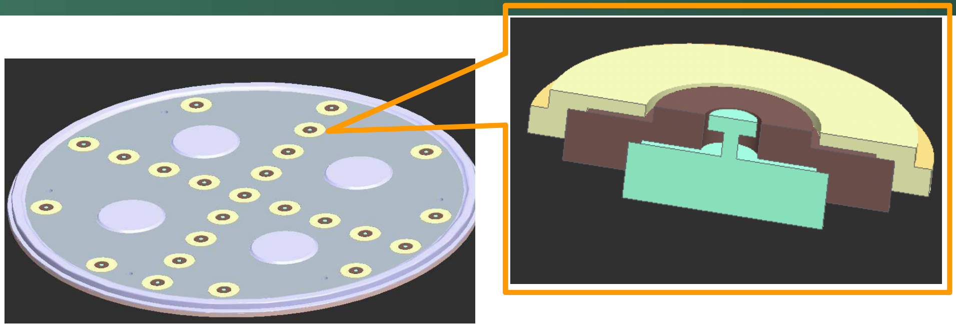
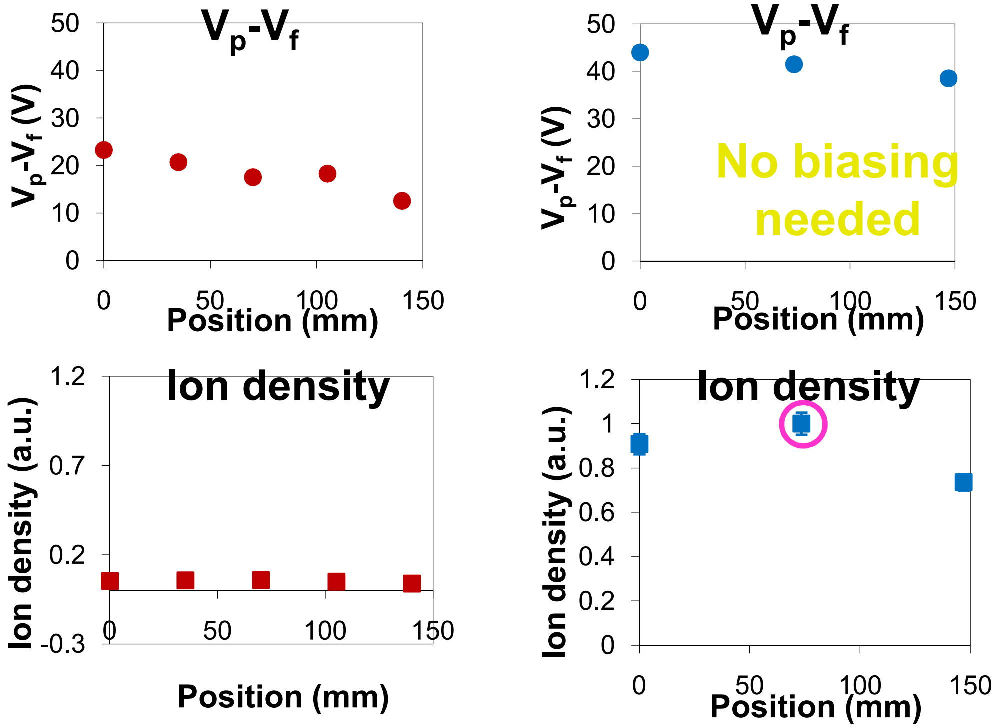
Plasma Diagnostics

Planar Langmuir Probe

- Planar Langmuir probes developed and placed on wafer level
- n_e, T_e, n_i, V_p and V_f were measured
- Ion energy (estimated as sheath potential V_p-V_f) increased about twice and became more uniform across the wafer
- Ion density increased by one order of magnitude on wafer level



Old process → **New Process**



New process has higher plasma density and ion energy with better uniformity across the wafer

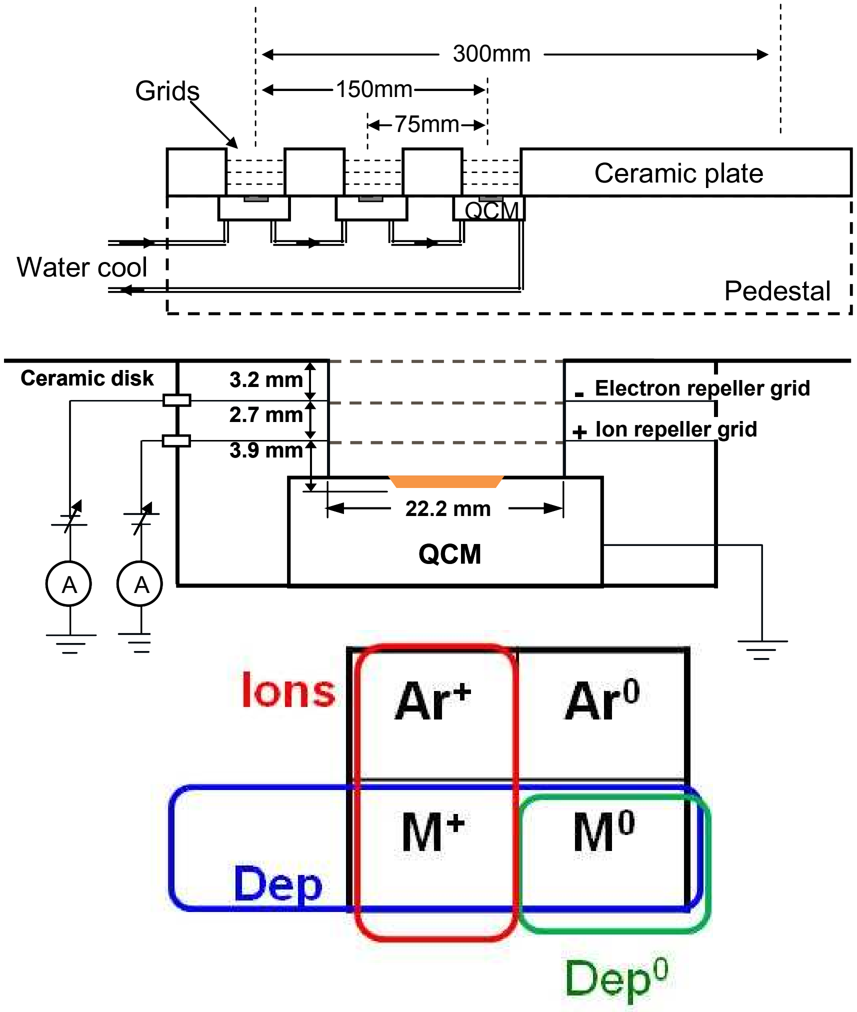
L. Wu, E. Ko, A. Dulkin, K.J. Park, S. Fields, K. Leeser, L. Meng, and D.N. Ruzic, *Rev. Sci. Instrum.* November 10, 2010.

Plasma Diagnostics
Gridded Energy Analyzer/QCM

- **Gridded energy analyzer (GEA) / QCM**
  - **Measure ionization fraction of Cu**

$$\text{Metal ion fraction} \equiv \frac{M^+}{M^0 + M^+}$$

  - **Measure Ar^+/Cu^+ flux ratio**
  - **Measure ion energy distribution**
- **Typical Bias Setup**
  - **Top grid floating**
  - **Electron repelling grid -45 V (lower than V_f)**
  - **Ion repelling grid -75 to 75 V**
  - **QCM to record the metal dep rate**



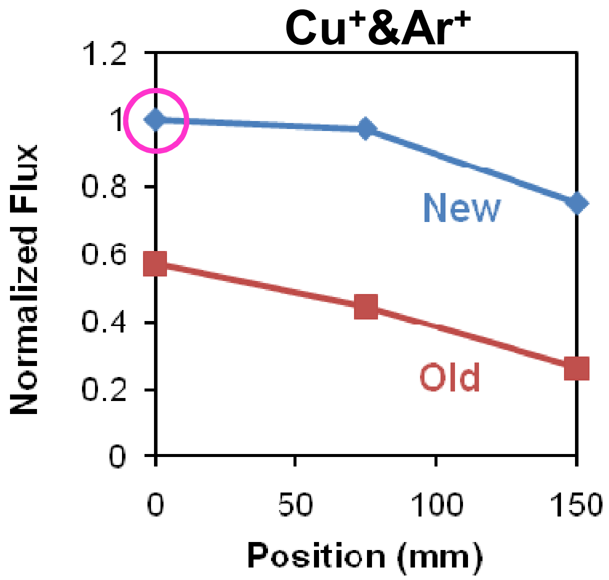
Deconvolution of Ar^+, Cu^+ and Cu^0 fluxes was achieved by measuring the ion current, Cu neutral dep rate and total Cu dep rate using the GEA/QCM assembly.

L. Wu, E. Ko, A. Dulkin, K.J. Park, S. Fields, K. Leeser, L. Meng, and D.N. Ruzic,, *Rev. Sci. Instrum.* November 10, 2010.

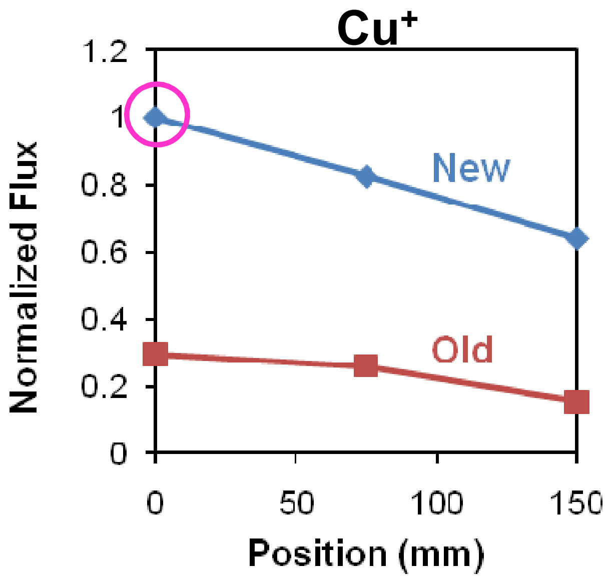
Plasma Diagnostics Results

Fluxes of Different Species

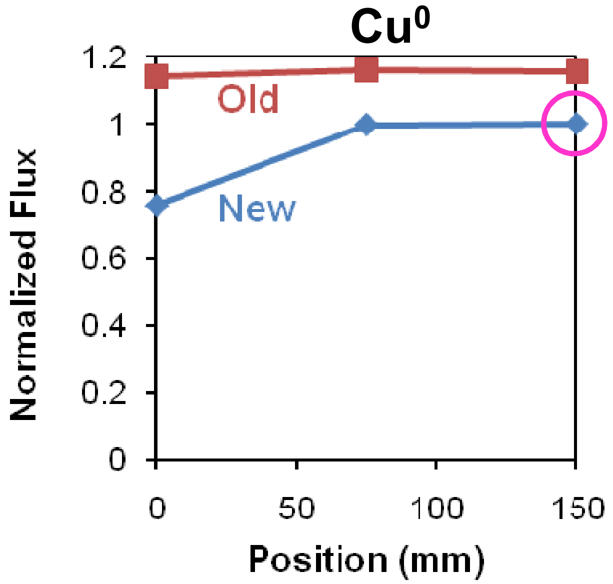
Old process → **New process**



Cu^+&Ar^+



Cu^+



Cu^0

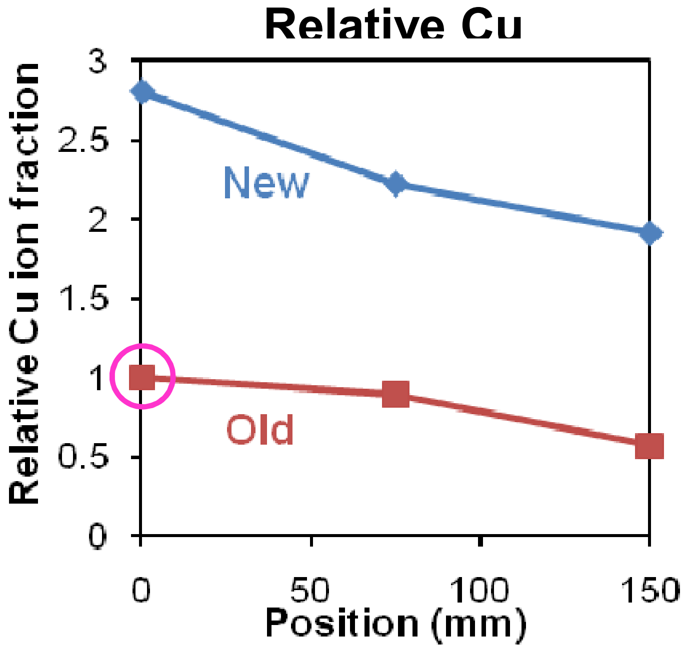
→ **Fluxes of different species**

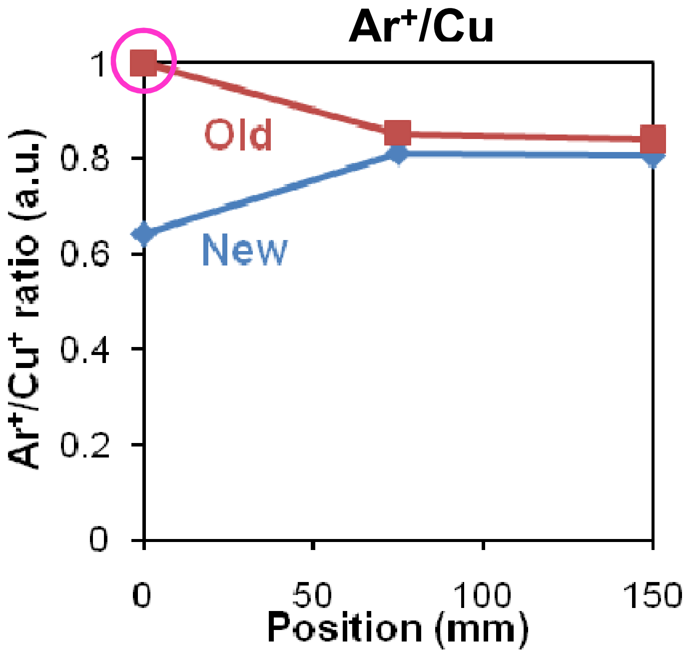
- **Total ion flux (Ar^+ and Cu^+) increases (higher plasma density)**
- **Improved ion flux uniformity**
- **New process has lower Cu^0 flux while higher Cu^+ flux. More Cu atoms are ionized**

New process has higher ion density and Cu ion flux

Plasma Diagnostics Results

Ionization Fraction





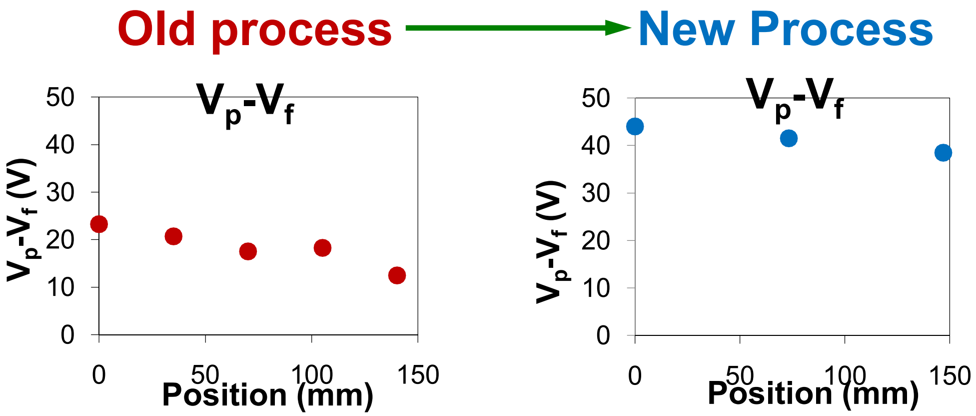
- ➔ **Cu ionization fraction increases more than twice and is more uniform**
  - **Lower at edge due to the diffusion process from source axis (separatrix opening)**
- ➔ **Decreased Ar^+/Cu^+ ratio.**
  - **Energetic Cu ions are preferred over Ar ions for transferring energy to Cu atoms on surface**

New process has higher Cu ionization and lower Ar+/Cu+ ratio

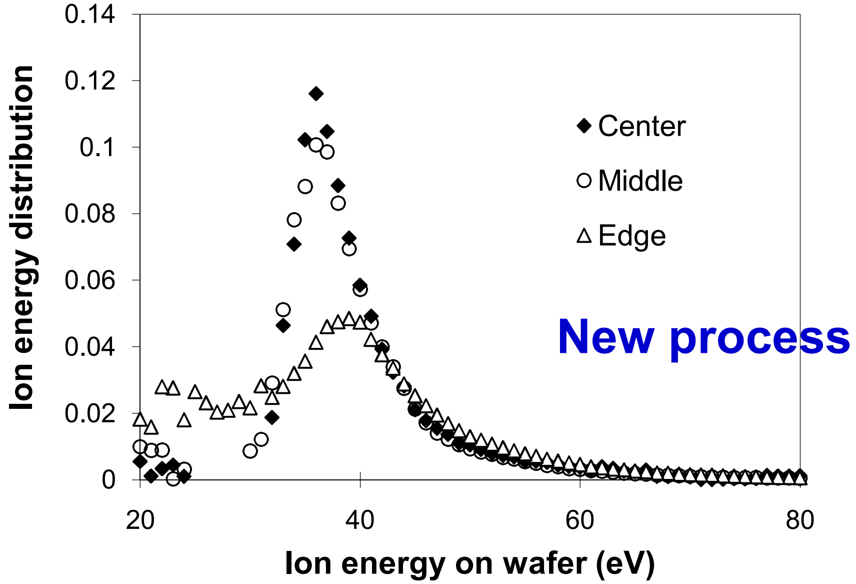
Plasma Diagnostics Results

Ion Energy Distribution

- Ion energy distribution was resolved with the use of GEA
- The average ion energies agree with the V_p-V_f measurement
- At the center and middle radius, narrow ion energy distributions were observed.
- At the edge, the IED was broadened and extended to the low energy side. This is caused by the non-perpendicular ion incident angles and the direction of magnetic field lines.



IED obtained by taking the derivative of the collected current with respect to the energy.



Increased ion energies in the new process were confirmed with GEA measurements

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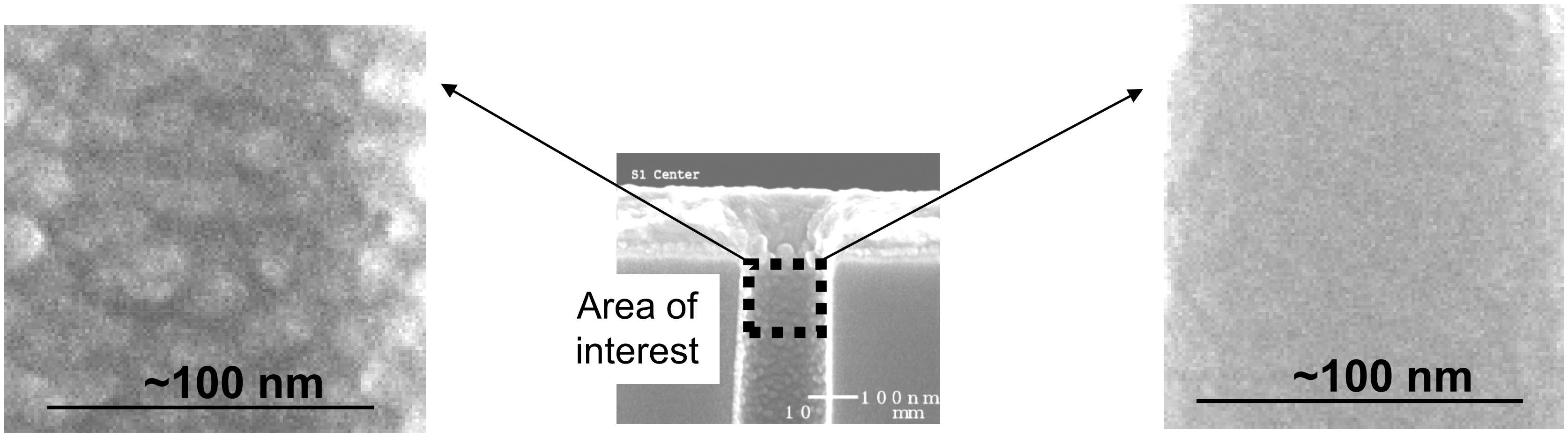
Improvement in Cu film Characteristics

Film Morphology

Old process → **New process**



- Backwall of the seeded via was used as the test structure.
- Continuous seed is required for electrofill.
- Smooth film becomes continuous at the smaller thickness.

Improved seed morphology can result in continuous film with lower thickness

Improvement in Cu film Characteristics

Film Stability

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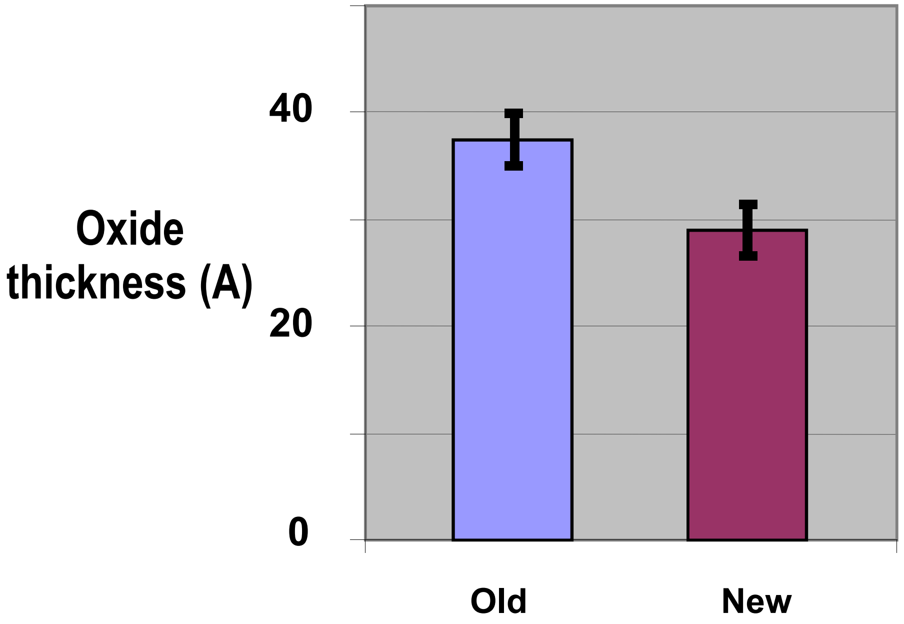
Improvement in Resistance to oxidation

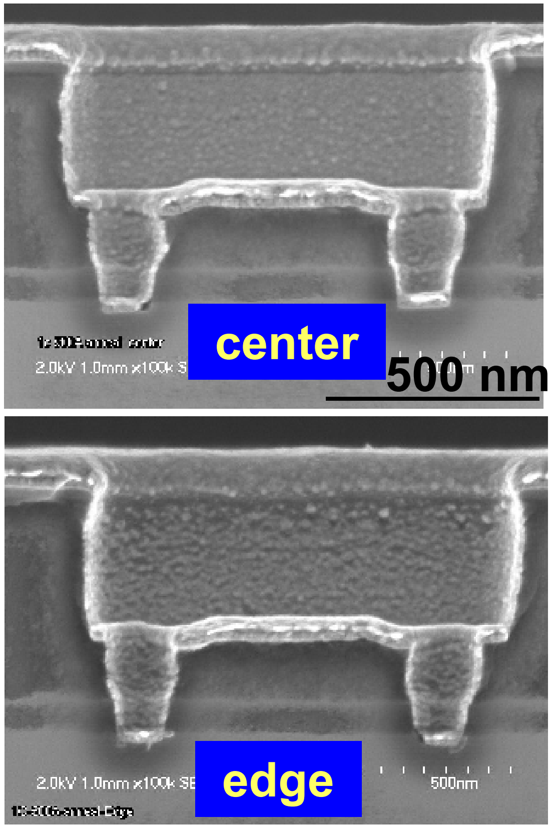
Oxidation plasma grown oxide



Smooth film with the less defined grains demonstrates improved resistance to oxidation

Improvement of Cu Seed
Interface Stability and Adhesion

Old process



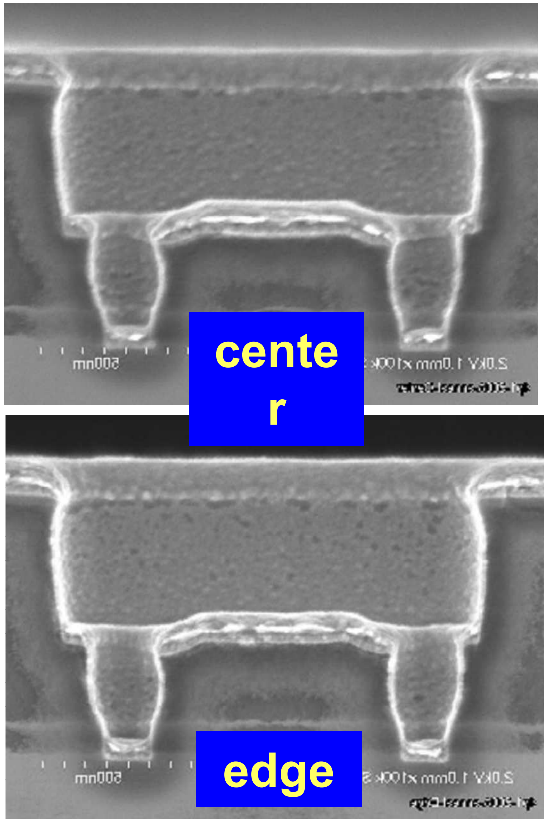
Resistance to dewetting

Barrier/seed interface was subjected to H_2 anneal to test the adhesion and stability of it.

Wafer Center: No Cu dewetting from the barrier for both processes

Wafer Edge: Cu dewetted and agglomerated in old process case while the new one demonstrated adhesion similar to the center

New process

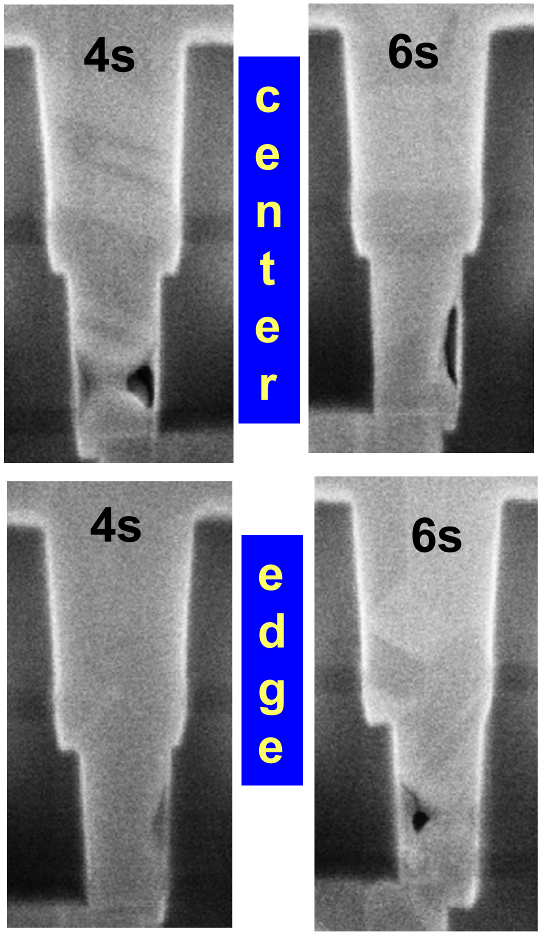


New process ensures that seed adhesion is uniform across the wafer

Improvement of Cu seed

Seed Stability

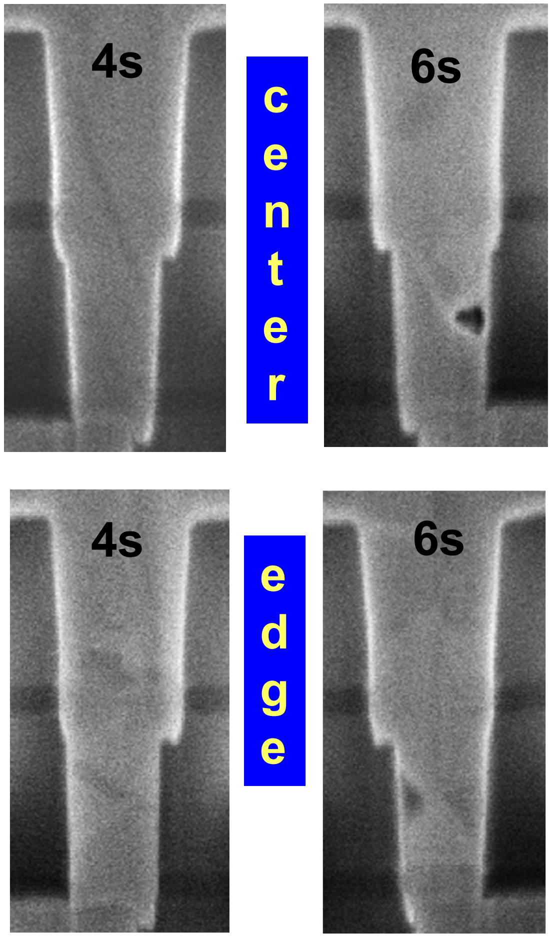
Old → **New**



Cold plating stability

DD features with seed layer (800A field thickness) were “cold” plated with variable delay time.

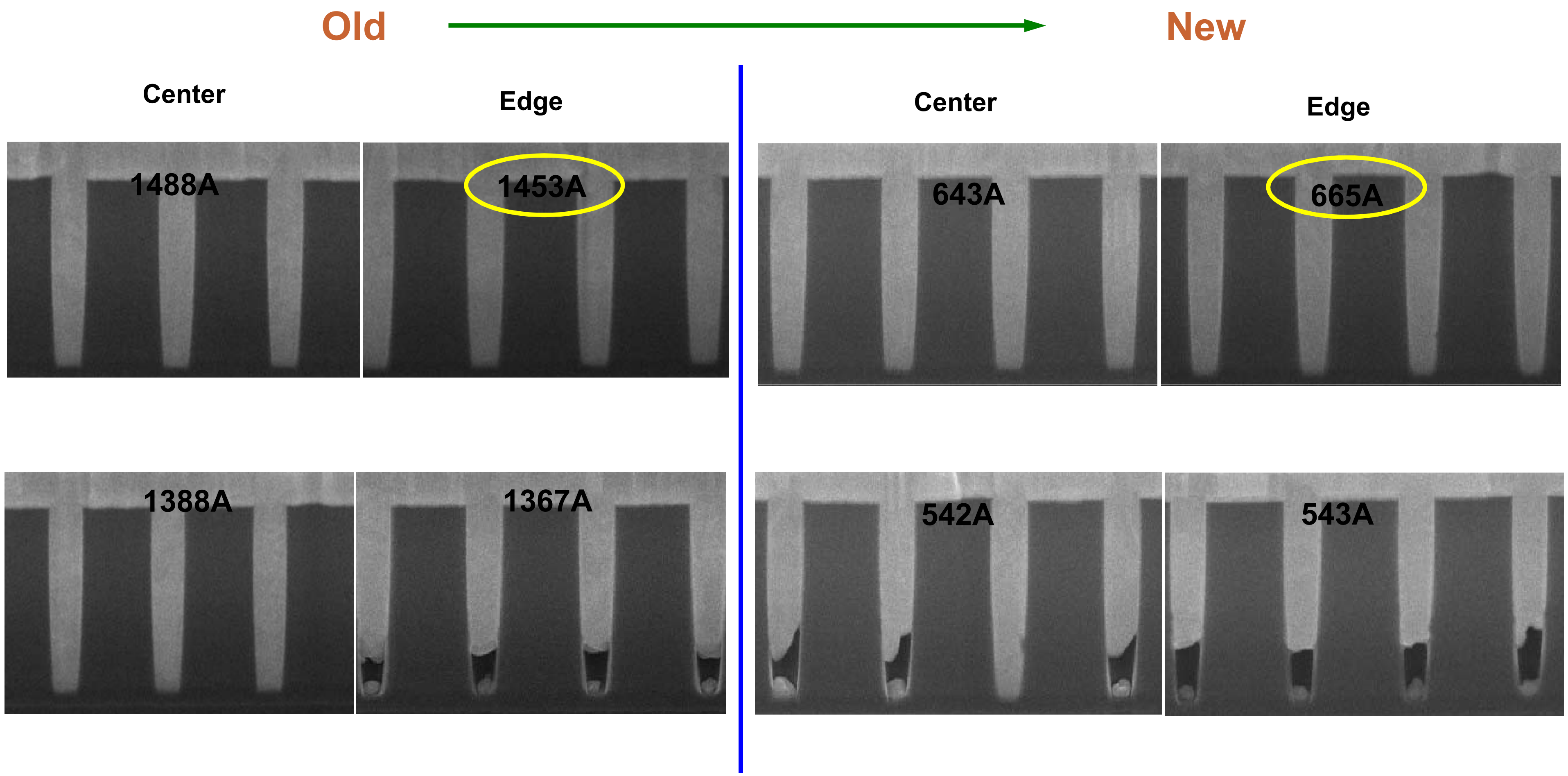
New seed demonstrated longer “life” in the plating bath as a result of better film continuity



Better stability in the plating bath indicates improved seed continuity and results in the wider electrofill process window

Improvement of Cu seed

Electrofill of High Aspect Ratio Vias



The new process ensures electrofill with 2x thinner seed.
Uniformity is improved across the wafer

Conclusions

- **The emphasis of research was placed on improving Ta/Cu barrier/seed interface characteristics such as stability, adhesion, and morphology on feature sidewalls with good uniformity across the wafer.**
- **Deposition flux was alternated by simple changing of magnetic confinement and operating pressure.**
  - Planar Langmuir probe, GEA and QCM diagnostics have been utilized in assisting of changing the parameters in desired direction.
- **Improved deposition was achieved due to**
  - Long throw effect for the neutral flux
  - Increased plasma density and high metal ion fraction in the total deposition flux
  - Increased ion energy
  - Improved uniformity of plasma parameters
  - Enhanced Cu ion fraction in total ion flux
- **Resulting seed demonstrated improved performance, which allowed for better and more uniform electrofill with less seed thickness, as well as better resistance to oxidation and agglomeration, which can transform into better resistance to electro and stress migration.**

References

- L. Wu, E. Ko, A. Dulkin, K.J. Park, S. Fields, K. Leeser, L. Meng, and D.N. Ruzic, "Flux and Energy Analysis of Species in Hollow Cathode Magnetron Ionized Physical Vapor Deposition of Copper", *The Review of Scientific Instruments*, 81, 123502, (2010)

- L. Meng, R. Raju, R. Flauta, H. Shin, D.N. Ruzic, and D.B. Hayden, *J. Vac. Sci. Technol.* A 28, 112 (2010)

Thanks for your attention!

Improvement in Cu film Characteristics

Step Coverage

Backup slide

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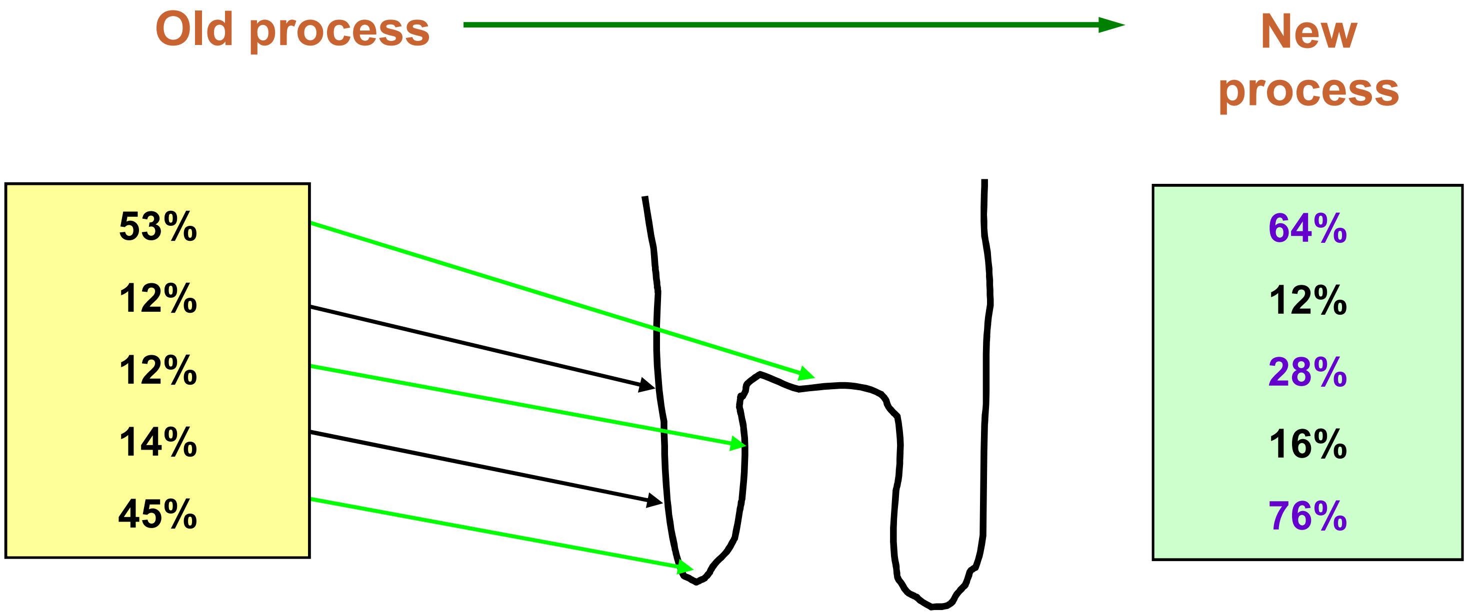

Old process → New process

Old process	New process
53%	64%
12%	12%
12%	28%
14%	16%
45%	76%

Improved step coverage as a result of more directional deposition flux