SCALING OF HOLLOW CATHODE MAGNETRONS FOR METAL DEPOSITION[a]

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AGENDA

- Introduction to Ionized Metal PVD and Hollow Cathode Magnetrons
- Description of Model
- Plasma properties of IMPVD of Cu using a HCM
- Comparison to Experiments
- Deposition and Target Erosion
- Concluding Remarks

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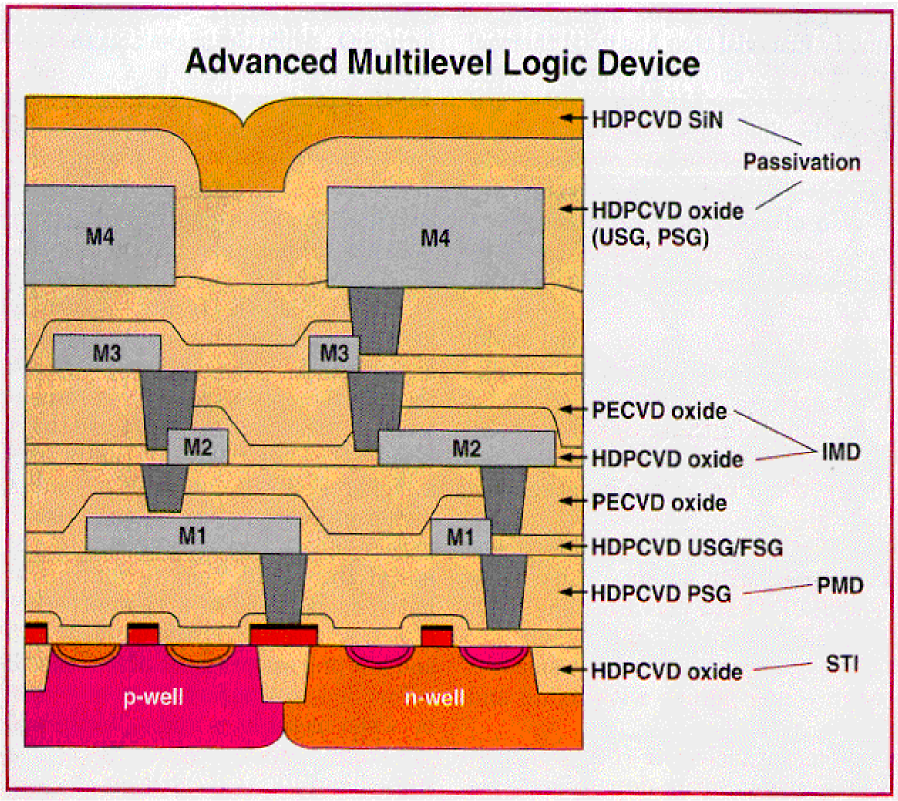
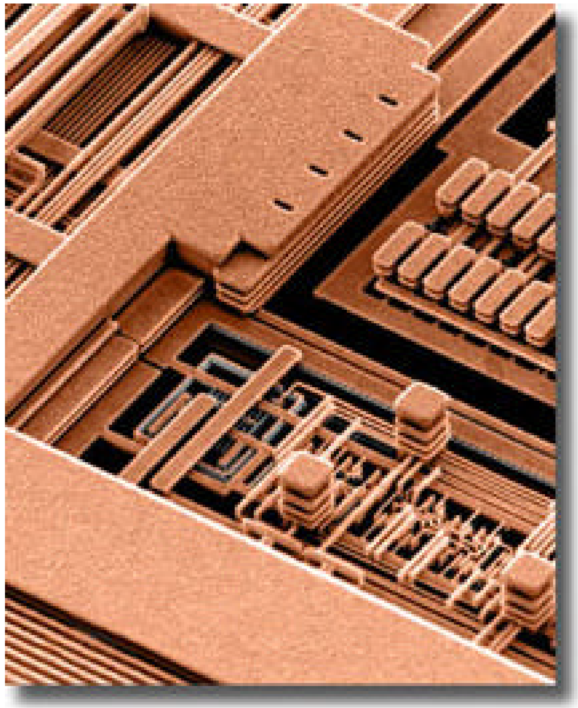
COPPER INTERCONNECT WIRING

- **The levels of interconnect wiring in microelectronics will increase to 8-9 over the next decade producing unacceptable signal propogation delays.**
- **Innovative remedies such as copper wiring are being implemented.**





Ref: IBM Microelectronics

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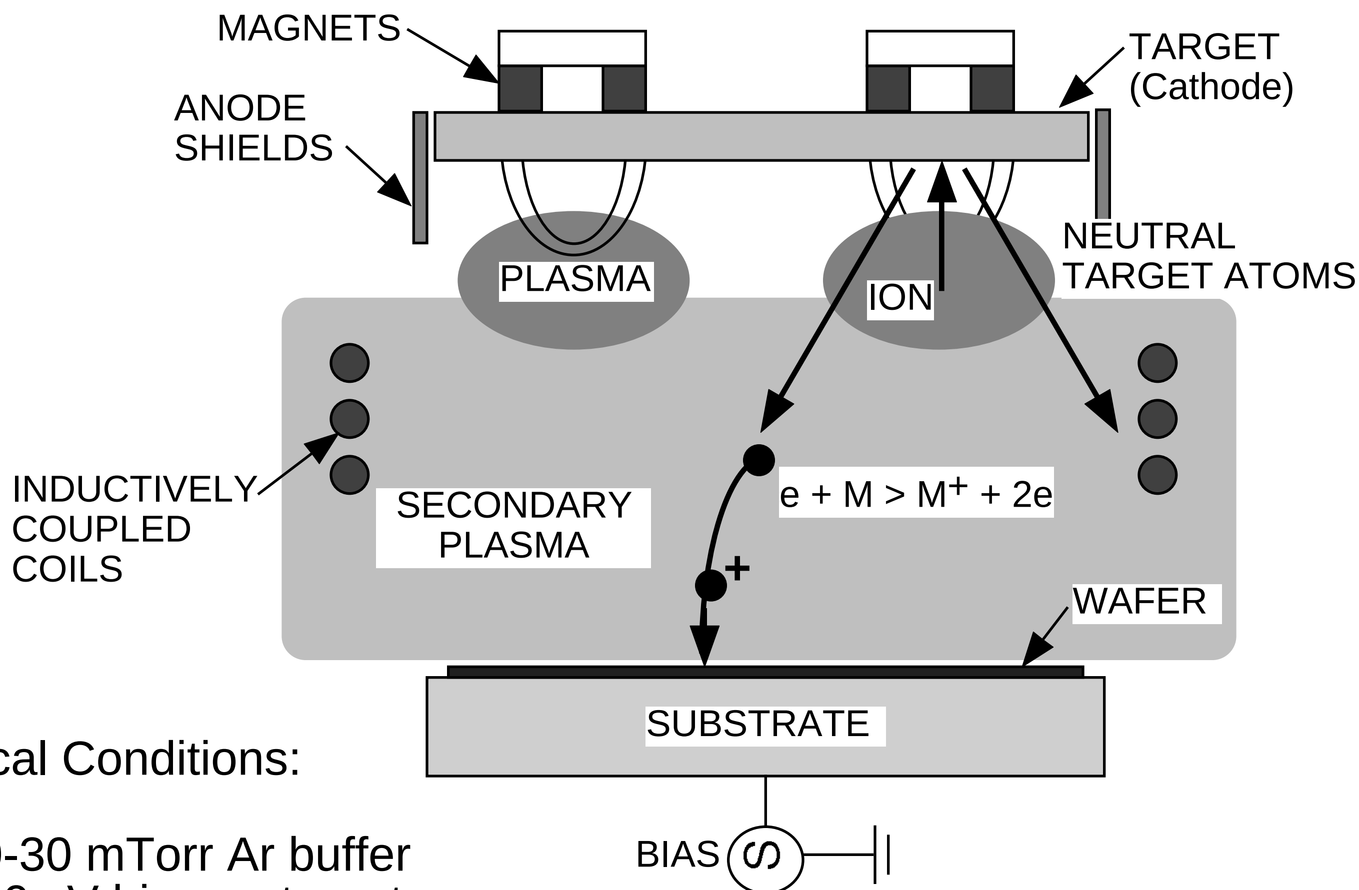
IONIZED METAL PHYSICAL VAPOR DEPOSITION (IMPVD)

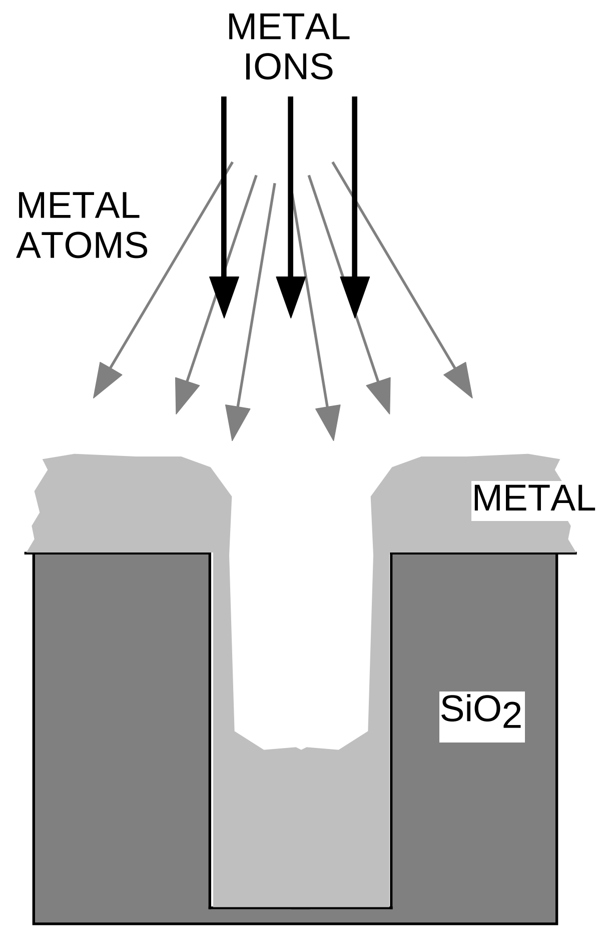
- In IMPVD, a second plasma source is used to ionize a large fraction of the the sputtered metal atoms prior to reaching the substrate.



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

IMPVD DEPOSITION PROFILES

- In IMPVD, a large fraction of the atoms arriving at the substrate are ionized.
- Applying a bias to the substrate narrows the angular distribution of the metal ions.
- The anisotropic deposition flux enables deep vias and trenches to be uniformly filled.



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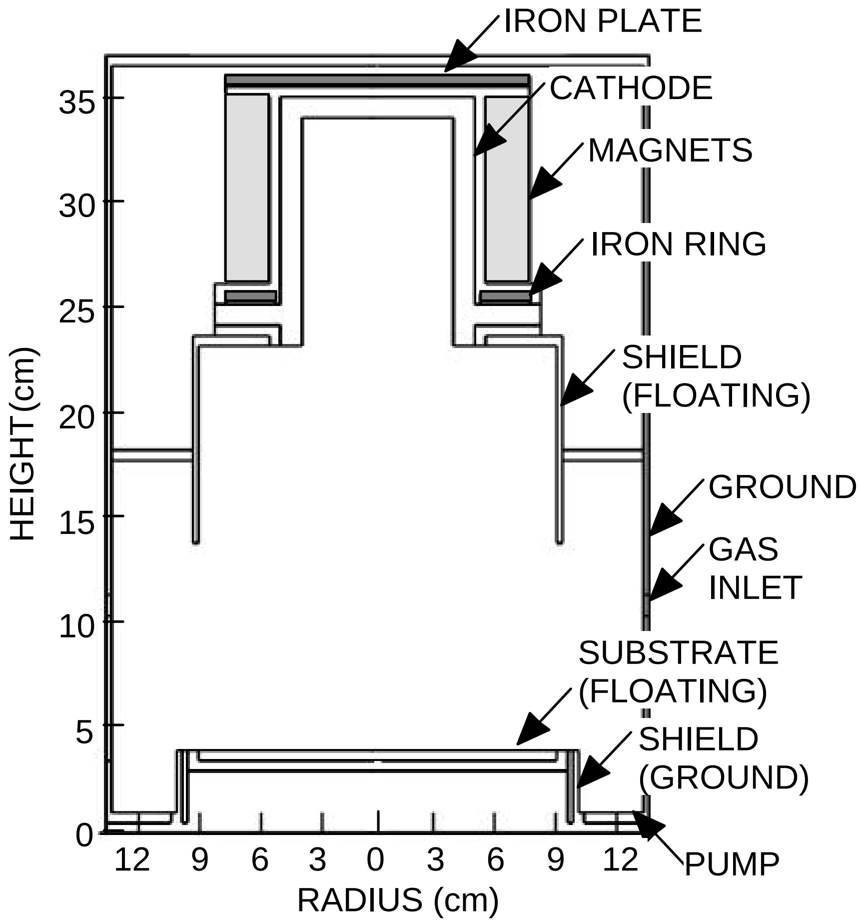
HOLLOW CATHODE MAGNETRONS

- Hollow Cathode Magnetrons (HCM) are typically cylindrical devices with inverted metal cups and floating shields. Production tools have 300 mm substates.

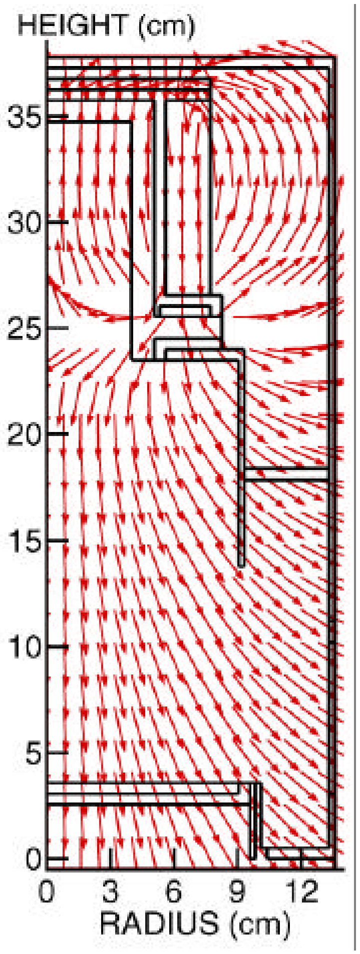


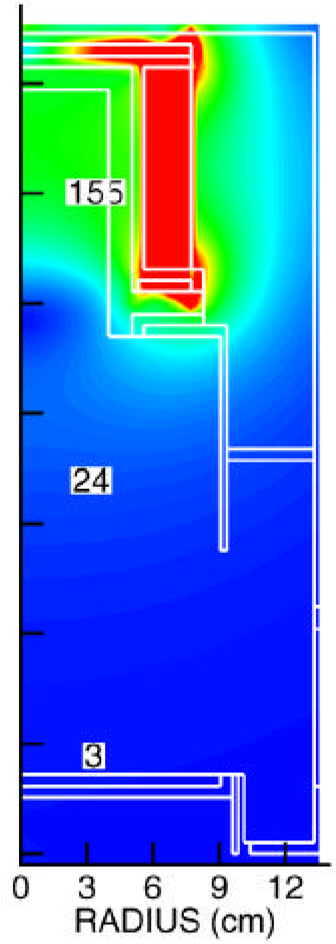
- **Typical Operating Conditions:**

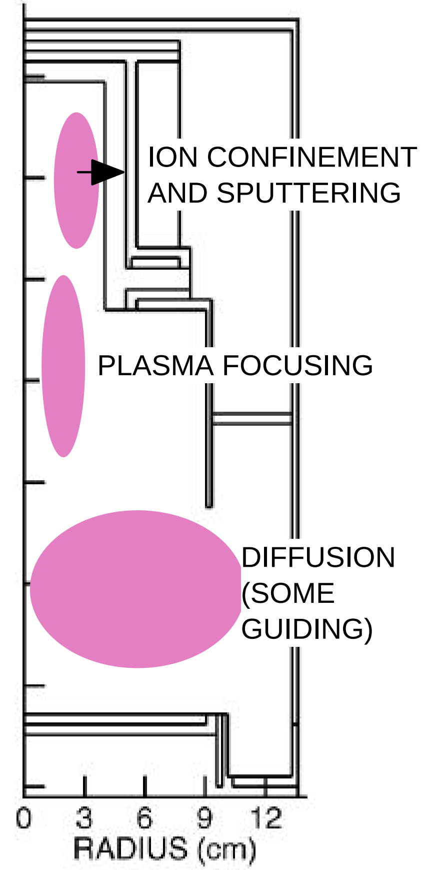
- **Pressure:** 5-10 mTorr
- **B-field:** 100-300 G atcathode
- **Voltage:** 300-400 V
- **Substrate:** Floating or biased
- **Buffer gas:** Ar, 50-100 sccm
- **Power:** 2-5 kW

HOLLOW CATHODE MAGNETRONS-IMPVD

- **HCM - IMPVD devices use magnetic confinement in the cathode for high ion densities and sputtering, and cusp B-fields to focus the plasma.**

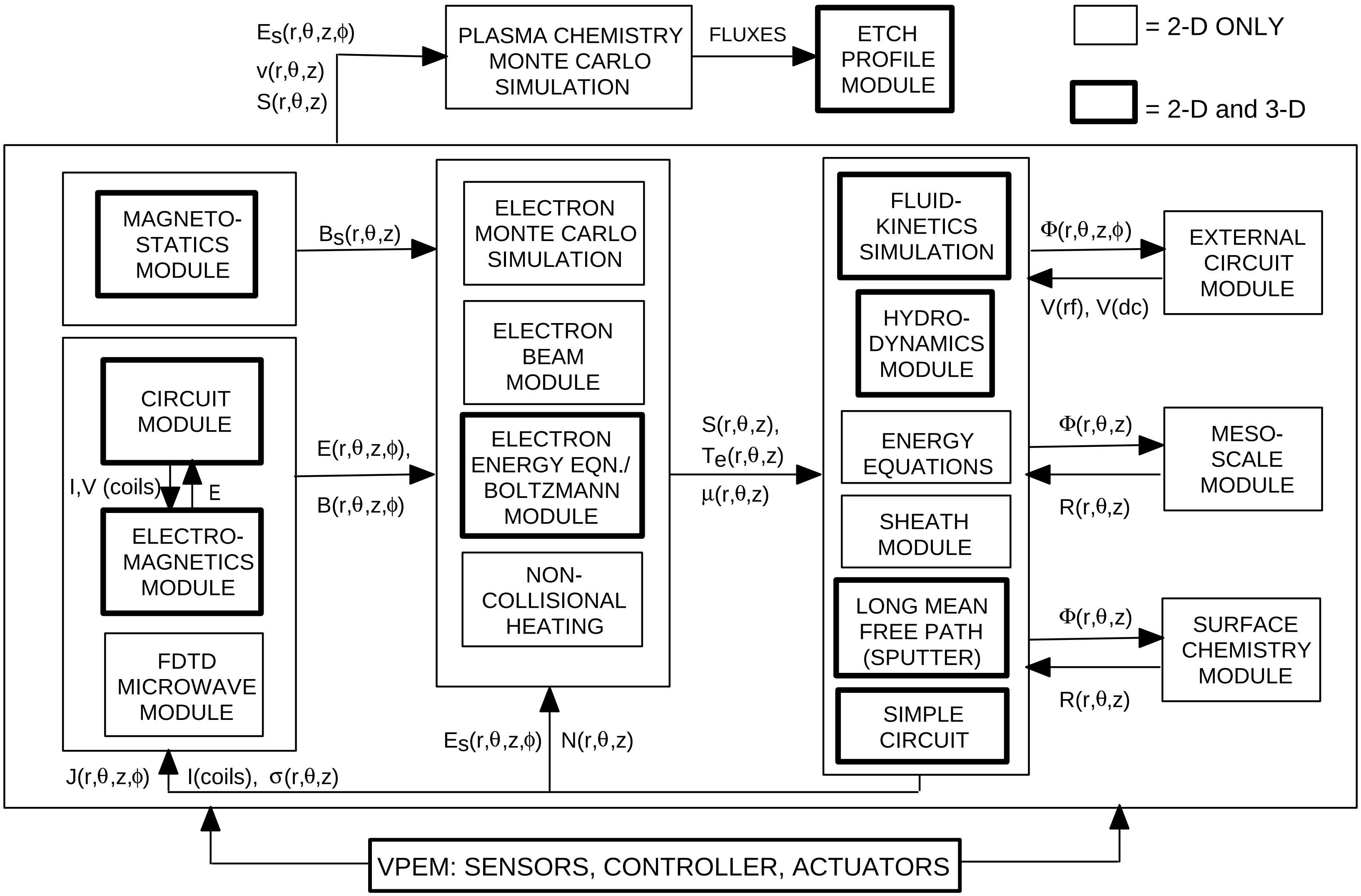






- **B-Field Vectors**
- **B-Field Magnitude**

HYBRID PLASMA EQUIPMENT MODEL



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PHYSICS MODELS USED IN HCM SIMULATIONS

- **Monte Carlo secondary electrons emitted from cathode**
- **Fluid bulk electrons (T_e from energy equation with Boltzmann derived transport coefficients)**
- **Continuity, momentum and energy for all heavy species (multi-fluid, slip and temperature jump boundary conditions)**
- **Long-mean-free path transport for sputtered atoms with sputter-heating**
- **Implicit Poisson solution simultaneous with continuity and momentum for electrons**
- **Species in Model:**

e, Ar, Ar(4s), Ar^+, Cu(^{2}S), Cu(^{2}D), Cu(^{2}P), Cu^+

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DESCRIPTION OF SPUTTERING MODEL

- Energy of the emitted atoms (E) obeys the cascade distribution, an approximation to Thompson's law for $E_i \approx$ 100's eV:

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

where

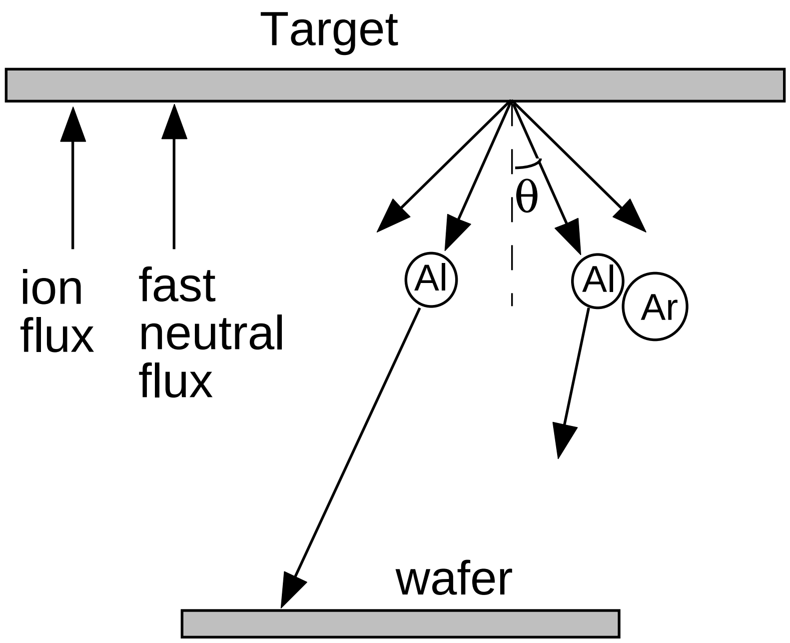
$$\Lambda = 4 m_i m_T / (m_i + m_T)^2$$

subscripts: b ~ binding, i ~ ion, T ~ target.

- The sampling of sputtered atom energy E from the cascade distribution gives

$$E = \frac{E_b \Lambda E_i \sqrt{RN}}{E_b + \Lambda E_i\left(1 - \sqrt{RN}\right)}$$

where RN is a random number in interval [0,1].



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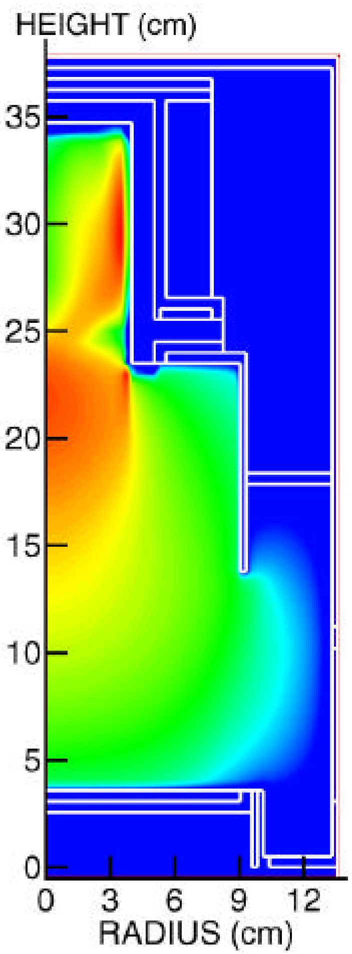
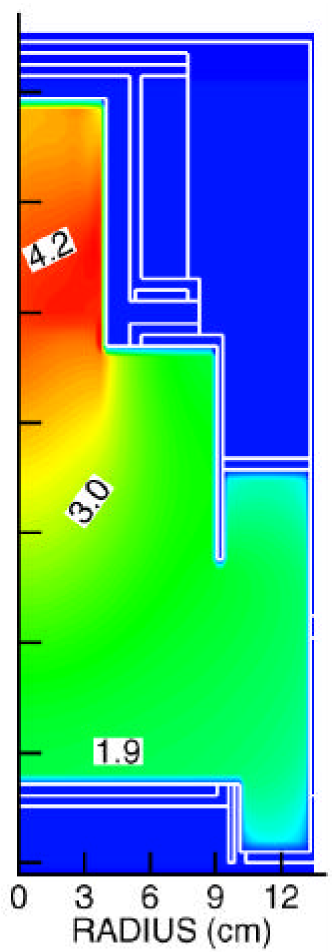
HCM- Cu IMPVD: ELECTRON DENSITY, TEMPERATURE



- E-Density (6.6 x 10^{12} cm^{-3})



- E-Temperature (4.8 eV)

- **Electron densities in excess of 10^{12} cm^{-3} are generated inside and in the throat of the cathode.**
- **Fractional ionizations are £ 10%.**
- **Electron temperatures peak at 4-5 eV in the cathode, and are a few eV downstream.**
- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

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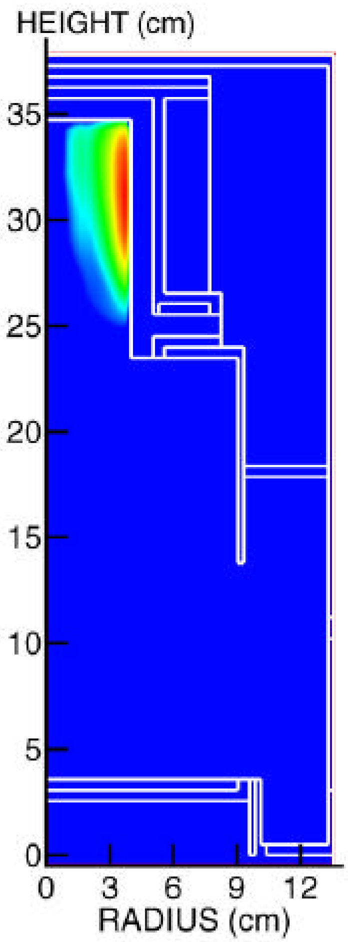
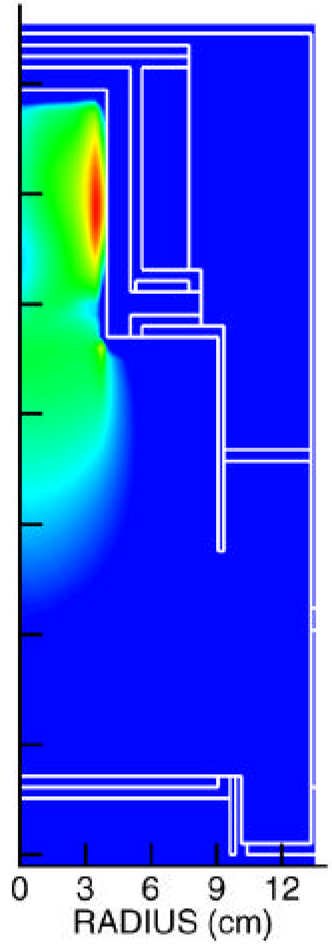
HCM- Cu IMPVD: ELECTRON SOURCES



- E-beam

(3×10^{17} cm^{-3}s^{-1})



- Bulk

(5×10^{18} cm^{-3}s^{-1})

- **Secondary electron emission and beam ionization produce electron sources in the cathode.**
- **Ionization in the bulk plasma, however, is the major electron source.**
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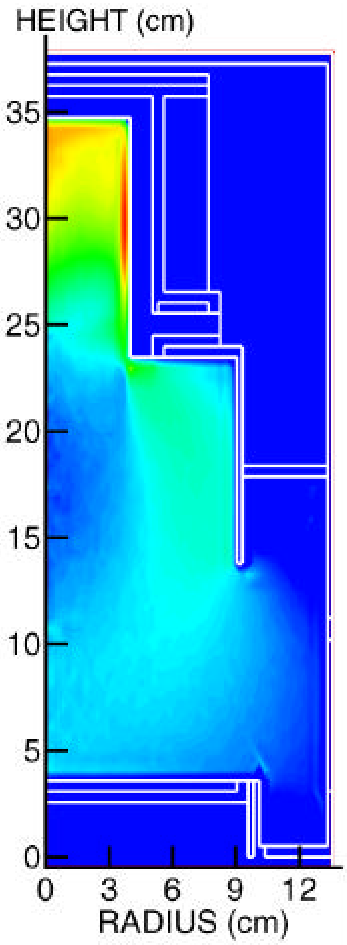
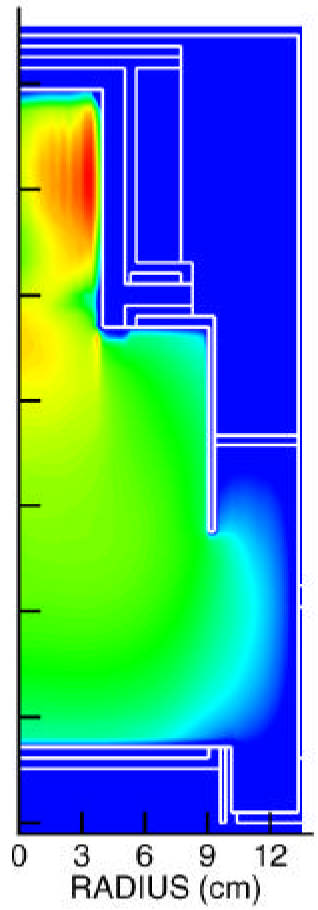
HCM- Cu DENSITIES



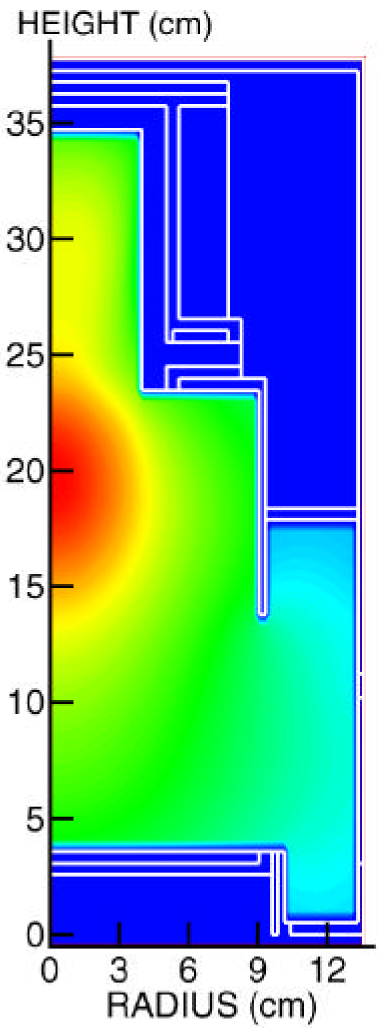
- **Cu**
(1.9 x 10^{13} cm^{-3})



- **Cu^{+}**
(1.5 x 10^{12} cm^{-3})

- **Neutral copper [Cu(^{2}S) + Cu(^{2}D)] undergoes rapid ionization and rarefaction in the throat of the cathode.**
- **The majority of neutral copper is in metastable Cu(^{2}D).**
- **Fractional ionization of Cu in the bulk is 10's %.**
- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

HCM- GAS TEMPERATURE



- **Average Gas Temperature (max = 1530 K)**
- **Gas heating occurs dominantly by symmetric charge exchange between Ar neutrals and ions, and produces significant rarefaction.**
- **Slip between neutrals and disparate rates of charge exchange produce differences in their maximum temperatures:**

  Ar: 1546 K Cu: 900 K

- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

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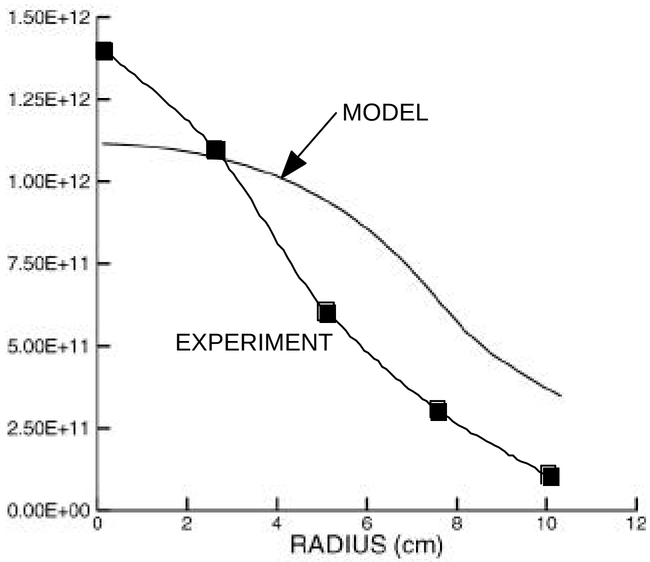
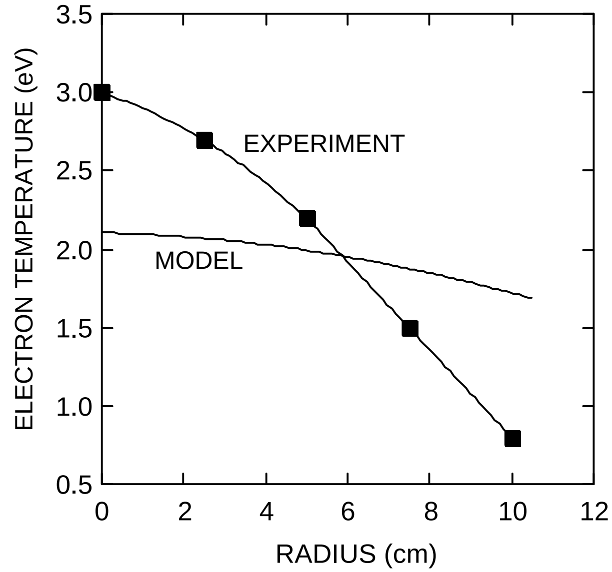
ELECTRON DENSITY AND TEMPERATURE vs EXPERIMENT





- **Electron Density**
- **Electron Temperature**

- **Langmuir probe measurements of electron density (2.8 cm above substrate) show densities and temperatures more highly peaked on axis.**

- **The model underpredicts the "jetting" of plasma from the throat of the cathode which likely results from long-mean-free path effects not captured by the ion model.**

- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

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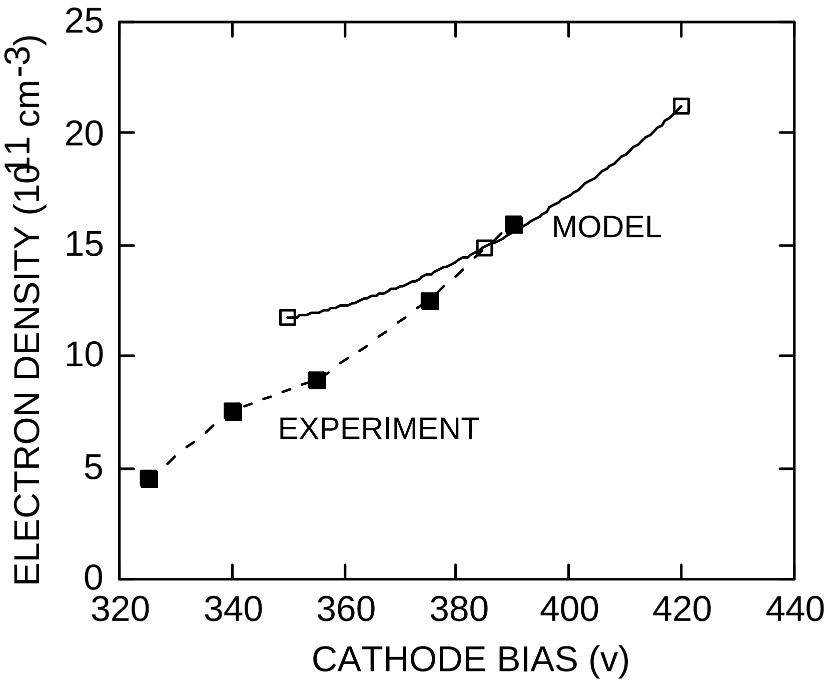
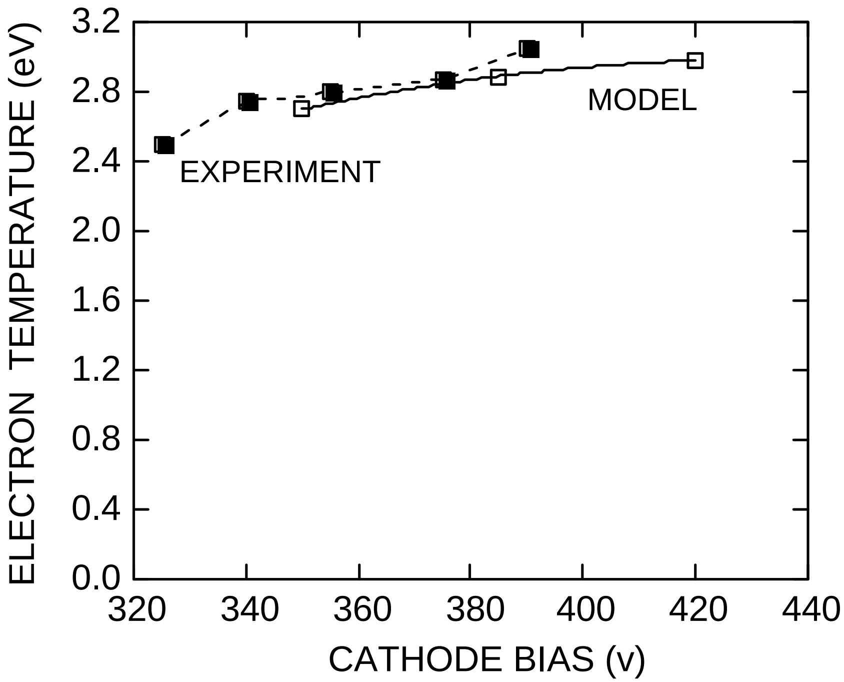
ELECTRON DENSITY, TEMPERATURE vs BIAS

- HCM devices have significantly "less steep" I-V characteristics compared to conventional magnetron discharges.

- For example, downstream plasma densities and power deposition scale nearly linearly with bias. Electron temperatures are weak functions of bias.





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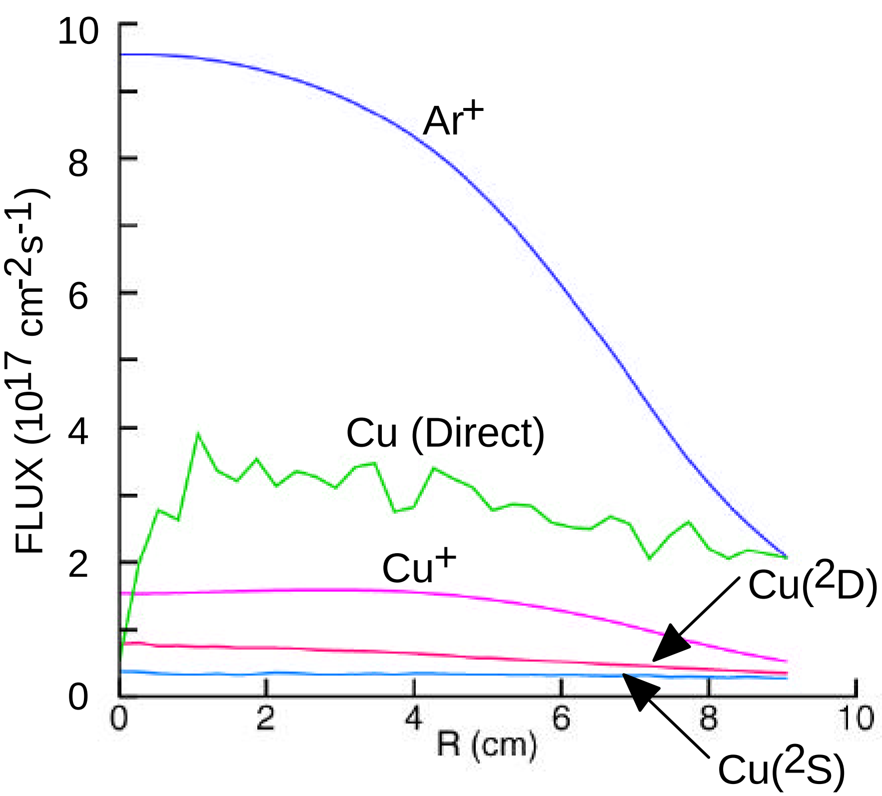
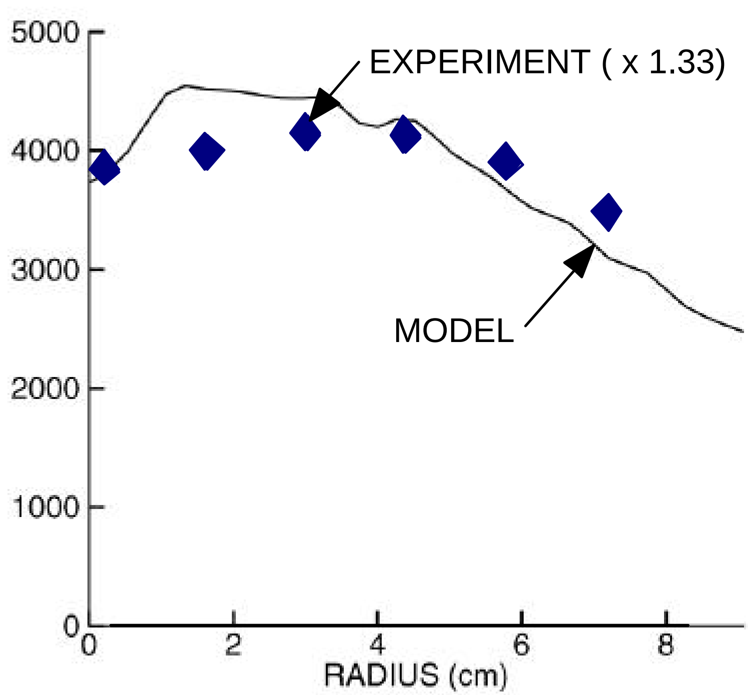
HCM- ION AND CU FLUXES TO THE SUBSTRATE



- **Ion flux to the substrate is dominated by Ar+**
- **Direct non-thermal Cu dominates the Cu fluxes to the substrate.**
- **The Cu flux is 25-30% ionized.**

- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

Cu DEPOSITION RATE



- Cu Deposition Rate (A/min)

- The off-axis peak in direct sputter flux produces an off-axis peak in the deposition rate.

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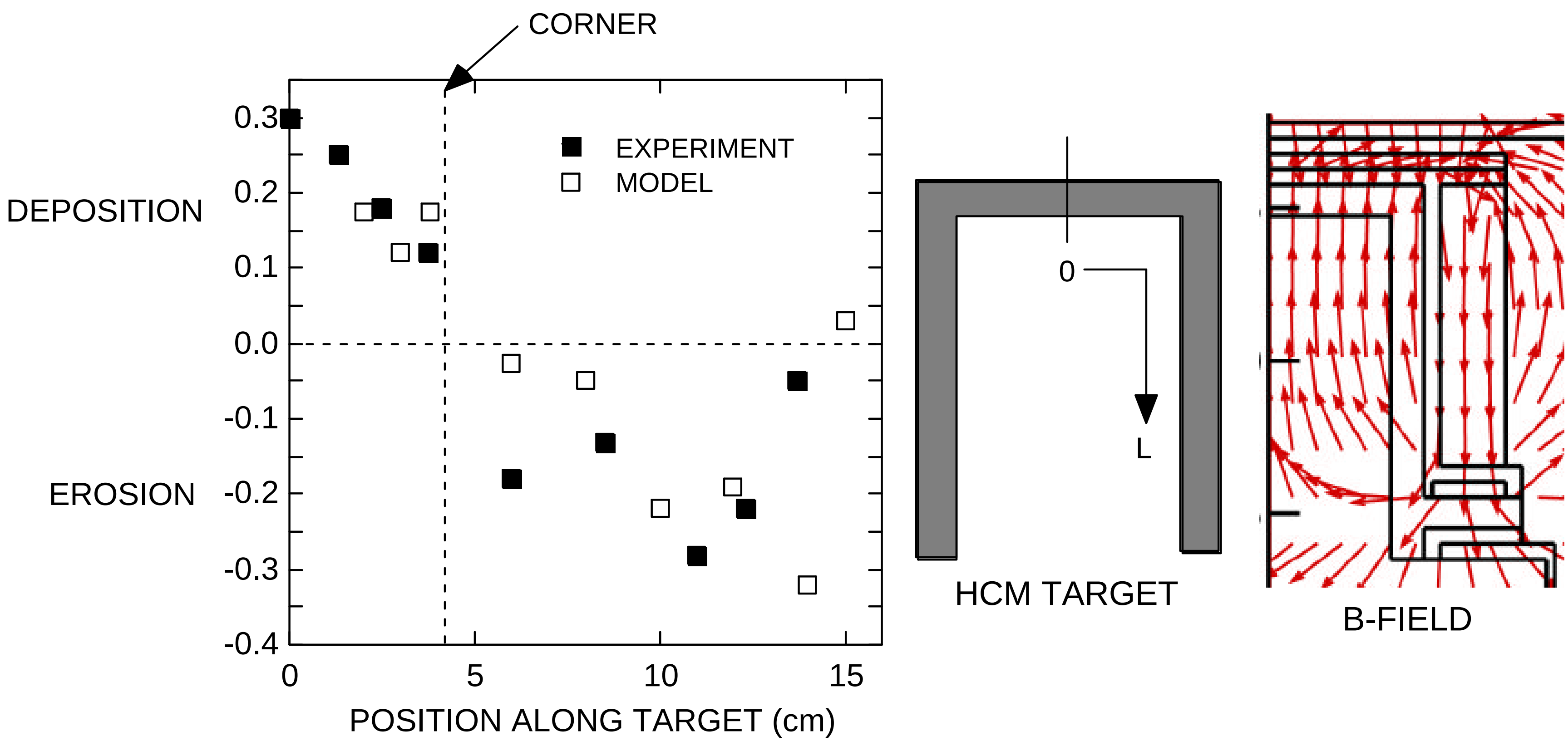
TARGET EROSION



- **Magnetron trapping and the resulting large ion fluxes to the target occurs at the side walls.**
- **Net deposition of sputtered Cu occurs on the end walls while the side walls experience net erosion.**
- **Ar, 6 mTorr, 150 sccm, 325 V, 160 G**

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CONCLUDING REMARKS

- Hollow Cathode Magnetrons (HCM) are capable of producing metal deposition with plasma densities of 10^{12} cm^{-3}.

- The HCM operates somewhat as a remote plasma source with moderate electron temperatures near the substrate compared to the cathode interior.

- The configuration of the magnetic field is important in at least two respects:
  - Jetting of plasma at throat of cathode
  - Erosion profile inside the cathode

- Small HCMs having higher power densities experience significant rarefaction which ultimately limits their capability to produce high plasma densities and deposition rates.

- Large HCMs (10-20 cm diameter) which avoid these problems have been designed and built based on these scalings studies.

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