RF Magnetrons – Magnetically Enhanced RIE

Tecnologias a Plasma para Processamento de Materiais

Miguel Leitão nº 58394
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1. Reactive Ion Etching (RIE)
2. MERIE
3. MERIE – Homogeneous model
4. Experimental results vs Theory
5. Plasma properties in MERIE reactors
6. Applications
7. Advantages
8. Disadvantages
9. Bibliography
Desirable characteristics in dry etching technique:
- Anisotropy;
- Selectivity;
- Uniformity over wafer;
- Controllable process with suitable etch rates (low for RIE);
- Low damage to the wafer (high for RIE)

**MERIE - Magnetically Enhanced RIE:**
- High etch rates
- Low residual damage
- Maintains desirable RIE features
Objectives for Magnetically Enhanced RIE:

- Greater ionization efficiency
- Less electron loss to the walls (confined)
- Denser discharge
- Lower sheath fields → Lower sheath voltages

Parameters:

- Pressure \( p \sim 3-100\text{mtorr} \)
- Electrode area \( A \)
- Distance \( l \sim 3-30\text{cm} \)
- RF voltage \( V_{\text{RF}}(\omega) \)
  - \( V_{\text{RF}} \sim 50-500\text{V} \)
  - \( f = 13.56\text{ MHz} \)
- dc magnetic field \( B_0 \sim 50-300\text{G} \)
**MERIE – Homogeneous model**

(Homogeneous \(\rightarrow\) Ion density is uniform)

\[
J_x(t) = \text{Re} \ J_0 e^{j\omega t} = J_0 \cos(\omega t)
\]

\(\rightarrow\) Uniform sinusoidal current density between plates

\[
J_\alpha(t) = \text{Re} \ \tilde{J}_\alpha e^{j\omega t}
\]

\(\rightarrow\) Current density

\[
E_\alpha(t) = \text{Re} \ \tilde{E}_\alpha e^{j\omega t}
\]

\(\rightarrow\) Electric Field

\(\alpha = x, y, z\)
MERIE – Homogeneous model

Relation between J and E

\[
\begin{pmatrix}
\tilde{J}_x \\
\tilde{J}_y \\
\tilde{J}_z \\
\end{pmatrix}
= j \omega \varepsilon_0
\begin{pmatrix}
K_\perp & -K_X & 0 \\
K_X & K_\perp & 0 \\
0 & 0 & K_\parallel \\
\end{pmatrix}
\begin{pmatrix}
\tilde{E}_x \\
\tilde{E}_y \\
\tilde{E}_z \\
\end{pmatrix}
\]

Complex tensor dielectric elements

\[K_\perp = \frac{(K_l + K_r)}{2}\]
\[K_\parallel = 1 - \frac{\omega_{pe}^2}{\omega(\omega - j\nu_e)}\]
\[K_X = j \frac{(K_l + K_r)}{2}\]
\[K_{r,l} = 1 - \frac{\omega_{pe}^2}{\omega(\omega \pm \omega_{ce} - j\nu_e)}\]

\[\omega_{pe}\] Electron plasma frequency
\[\omega_{ce}\] Electron gyration frequency
\[\nu_e\] Electron-neutral collision frequency
MERIE – Homogeneous model

\[
\tilde{J}_x = J_0
\]

\[
\tilde{J}_y = \tilde{J}_z = 0
\]

\[
\tilde{E}_z = 0
\]

\[
\tilde{E}_x = \left[ j \sigma \varepsilon_0 \left( K_{\perp} + \frac{K_X^2}{K_{\perp}} \right) \right]^{-1} J_0
\]

\[
\tilde{E}_y = -\tilde{E}_x \frac{K_X}{K_{\perp}}
\]
∫Poisson→ E field in the sheat

\[ E_{xa}(x,t) = en \frac{(x - s_a(t))}{\epsilon_0} + E_x(t) \]
MERIE – Homogeneous model

Displacement current across sheat

\[ J_x(t) = \varepsilon_0 \frac{\partial E_{xa}}{\partial t} = -en \frac{\partial s_a}{\partial t} + \varepsilon_0 \frac{\partial E_x}{\partial t} \]

\[ s_a(t) = s_0 + \text{Re} \tilde{s} e^{i\omega t} \quad | \quad s_b(t) = s_0 - \text{Re} \tilde{s} e^{i\omega t} \]

(Sheat b oscillates 180° out of phase)

\[ J_0 = -enj\omega \tilde{s} + j\omega \varepsilon_0 \tilde{E}_x \]
MERIE – Homogeneous model

Potentials

• Integrating Electric field ($E_x$) from 0 to $s_a(t)/s_b(t)$

$$V_{ap}(t) = -\frac{ens_a^2}{2\varepsilon_0} + E_x s_a$$

$$V_{bp}(t) = -\frac{ens_b^2}{2\varepsilon_0} - E_x s_b$$

(Electrode-plasma voltage)

• Voltage drop across the two sheats

$$\tilde{V}_{sh}(t) = -\frac{2ens_0}{\varepsilon_0} \Re \tilde{s} e^{j\alpha} + 2s_0 \tilde{E}_x$$

• Voltage drop across plasma: $\tilde{E}_x d$, $d=l-2s_0$

$$l\tilde{E}_x - 2s_0 \tilde{E}_x$$
MERIE – Homogeneous model

Potentials

- Complex amplitude of the total discharge voltage

\[ \hat{V}_{RF} = -\frac{2ens_0 \tilde{s}}{\varepsilon_0} + \tilde{E}_x l \]

- DC voltage across single sheat

\[ \overline{V}_{pa} = \frac{3ens_0^2}{4\varepsilon_0} + \frac{1}{2} \Re \tilde{s} \tilde{E}_x * \]
MERIE – Homogeneous model

Sheat heating

Electron-neutral collision

Ohmic heating

Momentum transfer from high voltage moving sheaths

Stochastic heating
MERIE – Homogeneous model

**Ohmic heating**

\[ P_{abs} = \frac{1}{T} \int_{0}^{T} J_T E(t) dt \]

- Power absorbed by the plasma per unit volume

\[ P_{ohm} = \frac{1}{2} |\tilde{J}_T|^2 \frac{1}{\sigma_{dc}} \]

- Ohmic power absorption

Integrating over bulk plasma length \( d \)

\[ \overline{S}_{ohm} = \frac{1}{2} J_1^2 \frac{d}{\sigma_{dc}} \]

- Ohmic power flux

\[ \overline{S}_{ohm} = \frac{1}{2} J_1^2 \frac{m v m d}{e^2 n} \]
MERIE – Homogeneous model

Stochastic heating

- Gyrating electron collides once with moving sheath
- Collides again after approximately half gyroperiod ($\Delta t$):

\[ \Delta t = \frac{\pi}{\omega_{ce}} \quad \omega_{ce} = \frac{eB_0}{m} \]

- Electron trajectory coherent $\rightarrow$ Energy gains
- Coherent motion destroyed by collision with neutrals
MERIE – Homogeneous model

\[ \bar{S}_{\text{stoc}} = 2m \Gamma_e \langle \Delta u (\Delta u - u_{es}) \rangle \phi \]  \Delta u = \text{change e}^{-}\text{velocity between collisions}

\[ \Delta u = \frac{\omega_{ce}}{\pi \omega} \int_{0}^{\infty} u_{es}(\phi + \phi') e^{-\nu_{el} \phi' / \omega} d\phi' \]

\[ \phi = \omega t \]
\[ \phi' = i \omega \Delta t \]
\[ = i \pi \omega / \omega_{ce} \]
\[ u_{es} = \text{Re} \tilde{u}_{es} e^{i \omega t} \]

\[ \bar{S}_{\text{stoc}} = \frac{1}{4} mn \tilde{v}_e |\tilde{u}_{es}|^2 \frac{\omega_{ce}}{\pi (\nu_{el}^2 + \omega^2)} \left( \nu_{el} + \frac{\omega_{ce}}{\pi} \right) \]

Stochastic flux transmitted to electrons
MERIE – Homogeneous model

Equilibrium conditions of flux balance

\[ 2nu_B = nn_gK_{iz}d \]

Equilibrium conditions of electron power balance

\[ \bar{S}_{\text{ohm}} + 2\bar{S}_{\text{stoc}} = 2enu_B(\mathcal{E}_c + 2T_e) \]

\[ \bar{S}_{\text{ohm}} = \frac{1}{2} \text{Re} \bar{E}_xJ_1d \]

\[ \bar{S}_{\text{stoc}} = \frac{1}{4}mn\bar{v}_e|\bar{u}_{es}|^2 \frac{\omega_{ce}}{\pi(v_{el}^2 + \omega^2)} \left( v_{el} + \frac{\omega_{ce}}{\pi} \right) \]
Total power flux absorbed by the discharge

\[ S_{\text{abs}} = 2enu_B(\mathcal{E}_c + 2T_c + \bar{V}) \]
MERIE – Homogeneous model

Magnetic field effect on plasma

1) Stochastic heating increases with increasing $B_0$

2) Significant fraction of the total rf discharge voltage can be dropped across the bulk plasma at high magnetic fields

\[
\begin{align*}
\text{Low pressures} & \quad \text{(stochastic heating)} \\
V_{\text{rf}} & \propto \frac{S_{\text{abs}}^{1/2}}{B_0} \\
n & \propto S_{\text{abs}}^{1/2} B_0 \\
s_0 & \propto B_0^{-1} \\
\bar{S}_{\text{stoc}} & \propto S_{\text{abs}}^{1/2} B_0 \\
\text{High pressures} & \quad \text{(ohmic heating)} \\
V_{\text{rf}} & \propto S_{\text{abs}}^{2/3} \\
n & \propto S_{\text{abs}}^{1/3} \\
s_0 & \propto S_{\text{abs}}^{1/6} \\
\bar{S}_{\text{ohm}} & \propto S_{\text{abs}}^{1/3}
\end{align*}
\]
Experimental results vs Theory

$V_{bias} \ vs \ B(G)$

Gas: Ar
$f = 13.56$ MHz

- 10 G
- 30 G
- X 100 G

- 10% model predictions
- Almost exactly same dependence on $P_{RF}$
Experimental results vs Theory

- 10 G
- 30 G
- X 100 G

- 25% model predictions
- Accurate power scaling

P = 30 mtorr

Diagram showing the relationship between $V_{bias}$ (V) and $P_{rf}$ (W/m$^2$) with points and lines for different magnetic fields.
Experimental results vs Theory

- P = 10 mtorr
- ○ 10 G
- □ 30 G
- X 100 G

- Larger discrepancy
- Good power scaling
Experimental results vs Theory

The graph shows the relationship between $V_{bias}$ (V) and $B$ (G) for different values of $S$ (W/cm²). The lines represent the theoretical predictions, while the symbols represent experimental data for $S = 0.25$ W/cm² (circles), $S = 0.5$ W/cm² (triangles), and $S = 1$ W/cm² (squares).
Experimental results vs Theory

$n \text{ vs } B(G)$

- $P = 100 \text{ mtorr}$
- $\bigcirc$ 10 G
- $\square$ 30 G
- $X$ 100 G

- Measured density increases more strongly with power than predicted (x2)
Experimental results vs Theory

P = 30 mtorr

○ 10 G
□ 30 G
X 100 G
Experimental results vs Theory

P = 10 mtorr

○ 10 G
□ 30 G
X 100 G
Experimental results vs Theory

$n$ vs $B(G)$

- Theory
- $S = 0.25$ W/cm²
- $S = 0.5$ W/cm²
- $S = 1$ W/cm²
Plasma properties in MERIE reactors
Plasma properties in MERIE reactors

Time averaged argon ion density for 100 W, 40 mTorr discharges for increasing magnetic field strength:

(a) $B=0$
(b) $B=50 \text{ G}$
(c) $B=100 \text{ G}$,
(d) $B=150 \text{ G}$
(e) ionization source as a function of height at $r=5 \text{ cm}$. 
Plasma properties in MERIE reactors

Time averaged ionization source by bulk electrons for 100 W, 40 mTorr discharges for increasing magnetic field strength:

(a) $B=0$
(b) $B=50$ G
(c) $B=100$ G,
(d) $B=150$ G
(e) ionization source as a function of height at $r=5$ cm.
Plasma properties in MERIE reactors

Time averaged electron temperature 100 W, 40 mTorr discharges for increasing magnetic field strength:

(a) B=0
(b) B=50 G
(c) B=100 G,
(d) B=150 G
Plasma properties in MERIE reactors

Ion flux to the substrate as a function of radius for different magnetic fields (100 W, 40 mTorr):
(a) 0–75 G
(b) 100–250 G.

The maximum ion flux occurs at approximately 150 G.
Aplications

• Industrial coatings:
  - low friction
  - corrosion resistant
  - Specific optical/electrical properties

• Microelectronics fabrication (thin films)

• Food packaging
Advantages

- Higher ion density leads to higher etch rates, anisotropy, selectivity.
- Magnetic field reduces the electron flux to the sheath, making the sheath-plasma potential drop.
- Reduced sheath potentials reduce the ion energy and wafer damage (good for pre-treatment of polymers).
Disadvantages

- Magnetic field B causes non uniformities in the plasma (ExB drift)
- Higher magnetic fields increase ion energy (damages to the wafer)
Sources

Websites:
- http://www.eecs.berkeley.edu/~lieber/EmiKHeating27Apr05.pdf

Articles:
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Book:
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