Tutorial on Using RF to Control DC Bias

Jim McVittie
<mcvittie@stanford.edu>
Stanford Nanofabrication Facility
Stanford University

May 2007 PEUG Mtg
Outline

• Why we use RF excited plasmas
• The Capacitive Coupled Plasma (CCP)
• The current flow in a CCP
• How the rf current across sheath leads the DC bias
• Why controlling DC bias is important for etching
• Use of Inductive coupled plasmas (ICP) as low bias source
• Use of ICP with CCP to control DC bias (Ion Energy)
• Beyond simple DC biasing for ion energy control
Why We Use RF

• DC plasmas $\Rightarrow$ Wafer Damage
  • Leads to charging and DC currents through wafer
• Microwave Plasmas
  • No self (DC) bias (Needed for directional etching)
• RF plasmas
  • RF current through wafer causes no damage
  • No charging damage if plasma is uniform
    • Exception is electron shading caused charging in high aspect ratio structures
  • Easy to get induced self or DC bias
Capacitive Coupled Plasma (CCP)
CCP Currents

**Plasma Region**
- Small E field
- Quasi neutral
  \[ n_i^+ = n_e^- \]
- e\(^-\) lighter & faster
  \[ v_e \gg v_i \]
- e\(^-\) carries current
  \[ J_{rf} = J_e \gg J_i \]

**Sheath Regions**
- Large E field – to keep mobile e\(^-\) in plasma region
- e\(^-\) depletion
  \[ n_i^+ \gg n_e^- \]
- e\(^-\) cannot carry current
  \[ J_{rf} \gg J_e \]
- Conduction currents balanced over rf cycle
  \[ J_i = - J_e \]
- \( J_{rf} \) carried by displacement (capacitor) current
  \[ J_{rf} = J_{disp} \]
- Charge transfer by sheath width oscillation
- Sheath Charge \( \Rightarrow \) Dc bias
Oscillating RF Sheath

- RF current crosses sheath by displacement $i_{rf} = dq/dt$
- For $i_{rf} = i_o \sin \omega t$, a charge of $i_o / \omega \cos \omega t$ builds up on each of the sheath
- On plasma side of sheath there is no electrode, displacement develops by the sheath moving and generating a $dq/dt$ by depleting and restoring the e’s as the plasma edge oscillates in and out.

Have neglected pre-sheath region
RF Sheath Analysis

- Assume $J_{rf} = J_o \sin \omega t$
- Sheath oscillation is near sinusoidal
  $s \sim s_o \sin \omega t$  \hspace{1em} Max Sheath width $s_m \sim 2s_o$
- Analysis gives $s_o = J_o / \varepsilon \omega n_s$
  - Sheath width, $s$, increases with $J_{rf}$
  - $s$ decreases with frequency and plasma density
- Charge stored in sheath
  $$ Q_{sh} = e \int_{0}^{s_m} (n_i - \bar{n}_e) dx $$
- Poisson’s Eq
  $$ d^2V / dx^2 = e(n_i(x) - \bar{n}_e(x)) / \varepsilon_o $$
- DC Sheath voltage
  $$ \bar{V}_s \approx 1.3 J_o / e \varepsilon_o \omega^2 n_s $$
  - DC sheath voltage increases with RF current and decreases with RF frequency
$V_{dc}$ Depends on $I_{rf}$ and Electrode Geometry

- Self bias voltage $V_{dc}$ is the externally measured voltage
- $V_{dc}$ is sum of two sheath sheath voltages

\[
J_{rf} = \frac{I_{rf}}{A}
\]

$A_1 > A_2$ (Used to avoid sputtering gnd electrode)

$J_{rf1} < J_{rf2}$

$V_{s1} < V_{s2}$

Typically $V_{s1} << V_{s2}$ and $V_{s1} \approx$ 10 to 15V

$V_{dc} = V_{s1} - V_{s2} \approx -V_{s2}$

$V_{dc} \approx 1.3 I_{rf} / e \varepsilon_0 \omega^2 n_s A_2$
Ion Directionality

- At 13.6 MHz most ions respond only to the average (DC) sheath field
- Ions gain directionality and energy crossing the sheath
- Ion directionality strongly affects
  - Etch bow (side wall etching)
  - Electron shading type charging
Collisionless Sheath Ion Directionality

- Ion directionality determined by $V_s$ and $T_i$ at sheath edge
- Mean ion arrives at wafer $\sigma_\theta$ degrees off the normal
- $T_i$ is determined by collisions in pre-sheath and energy at ion creation. Typically, $T_i \approx 0.5$ eV
- Example: If $T_i = 0.5$ eV and $V_s = 100$V $\rightarrow \sigma_\theta = 4.0^\circ$
- For anisotropic etching, typically we need $\sigma_\theta \leq 4.0^\circ$
- Sheath voltage control is essential for etch control

$$\sigma_\theta = \tan^{-1} \left( \sqrt{\frac{T_i}{eV_s}} \right)$$
Use of Inductive Coupled Plasmas (ICP) as Low Bias Source

Simple ICP

Current in coil induces current loop in plasma in glass tube

- In ICP power is transferred to plasma by the oscillating B field.
- There is minimum rf current going across a sheath, so the sheath voltage is usually small.
- For etch control, 2nd rf source is needed to increase ion energy and directionality at wafer.

Lam Style ICP

Toroid of high density plasma

B field lines have been compressed because opposing B field from induced current loop in plasma toroid
ICP Configurations

- Inductive coupling generates high density plasmas with low sheath voltages.
- ICP power controls plasma density, $n_e$.
- Capacitive coupling of rf current through wafer sheath used to control ion energy, $E_i$. 

J.P. McVittie, Stanford, PEUG May 07
Beyond DC Biasing: RF Effects on Ions Crossing Sheath

• Sheath transit time effects -- Depending on their mass, the rf frequency, the sheath thickness and when in the rf cycle, they enter the sheath, ions are affected by the rf sheath fields.

• The **ion energy distribution** IED can be shaped by changing, modulation or mixing the rf bias frequency and waveform.

• Changing the IED gives the etch engineer another for controlling profile shape.
For oscillating rf sheath ion energy distribution (IED) at wafer surface depends strongly on sheath transit effect. IED tends to be bimodal with $\Delta\varepsilon_{\text{ion}}$ decreasing with increasing RF frequency. IED strongly affects electron shading type charging. Less charging with more low energy ions. IED also affects etch profile.
Fig. 1. SEM micrographs of 1 μm trenches etched for 300 s at 6 mTorr, 40 sccm CHF₃, and 1400 W at self-bias voltage and rf bias frequency of: (a) −85 V and 1.3 MHz, (b) −120 V and 1.3 MHz, (c) −85 V and 10.5 MHz, and (d) −120 V and 10.5 MHz.
Summary

- DC self bias is a result of rf current flowing across a plasma sheath
  - Increases with rf current and decreases with rf frequency
- RF biasing applied to wafer to control $E_i$ in high density plasma systems
- Biasing is needed for controlled anisotropic etching
- Recent etch equipment designs go beyond simple DC biasing to shape energy distribution of ions bombarding wafer surface to better control etch characteristics