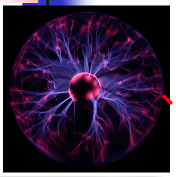
Ch7 Plasma

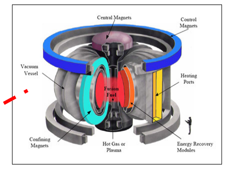
Introduction to

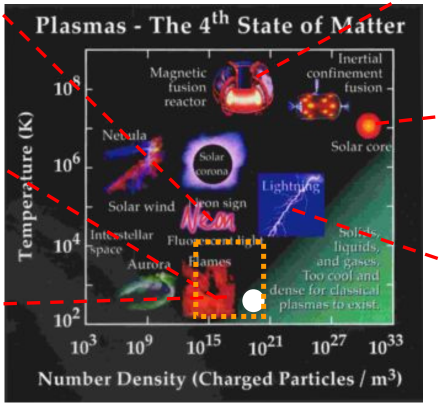
Semiconductor Processing

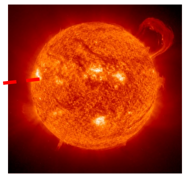
What is a Plasma?

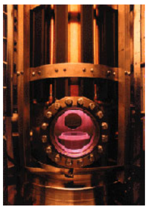


- 4th state matter
- Ionized gas
- Ions, electrons, and neutral species



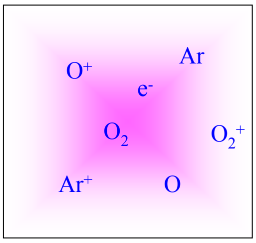






Plasma Characteristics

- 電漿是具有等量的正電荷和負電荷的離子氣體
- 電漿是由中性原子或分子、負電（電子）和正電（離子）所構成
- 在大部分的電漿製程反應室中，**游離率**都低於0.001%
- 電漿處於不平衡狀態**(non equilibrium)**
- 高密度電漿（HDP）源的游離率就高得多，大約 1%；(太陽中心處的游離率就大約100%)
- Large number of species



n_n, T_n
n_e, T_e
n_i, T_i

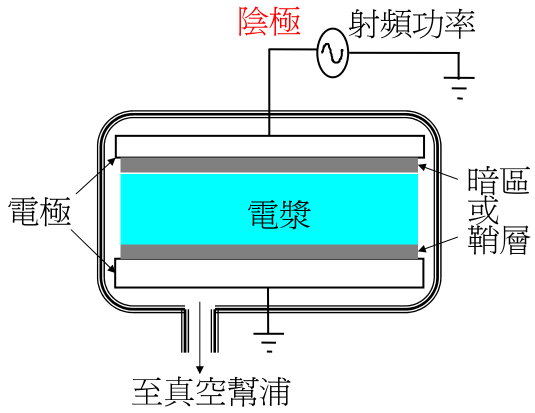
$n_i \sim n_e$
$n_n >> n_i, n_e$

$T_e >> T_i$, T_n

電漿的產生

- 需要外界的能量- 射頻（RF）電漿源是半導體製程中最普遍的電漿源
- 欲產生射頻電漿需要真空系統

平行板電漿系統



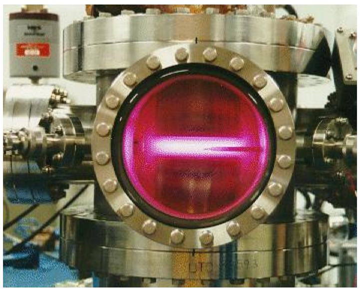


Photo Courtesy: UT Dallas

Wafer location:

Electron-Impact Reactions -- Ionization

離子化 (Ionization)

- 電子與一個原子或分子相碰撞
- 使一個軌道電子脫離核子的束縛

$$e + A \rightarrow A^+ + 2\,e$$

- 離子化碰撞產生電子和離子
- 它維持穩定電漿
- Threshold energy ~ ionization energy

Electron-Impact Reactions -- Dissociation

- 當電子和分子碰撞時，可以打斷化學鍵並且產生自由基:

$$e^- + AB \rightarrow A + B + e^-$$

- 自由基至少有一個未成對電子，化學上非常活潑
- 增進化學反應速率
- 對蝕刻製程和CVD來說非常重要
- Not important for sputtering (Why?)
- Eg.: $O_2 + e \rightarrow$

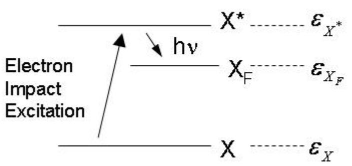
  $Cl_2 + e \rightarrow$

  $SiH_4 + e \rightarrow$

激發-鬆弛 (Excitation – Relaxation)

$$e + A \rightarrow A^* + e$$

$$A^* \rightarrow A + h\nu \text{ (Photos)}$$

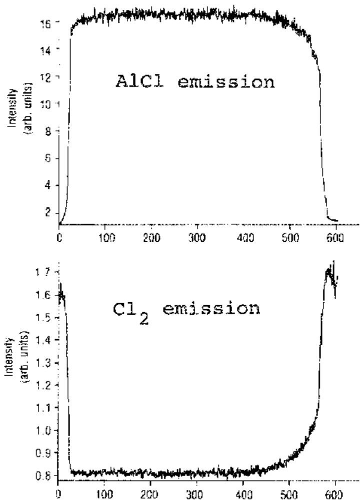


- 不同的原子或分子有不同的軌道結構和能階，因此它們的發光頻率也就不同，這說明了爲何不同的氣體在電漿中會呈現出各種不同的顏色
- 發光顏色的改變被用來作爲決定蝕刻和反應室清潔步驟的終端點（endpoint）

Endpoint Detection

Forming Cl radicals
$Cl_2 + e \rightarrow 2Cl + e$

Al etching:
$Al + x\, Cl \rightarrow AlClx$ (x=1~3)



電漿蝕刻

- CF_4 氣體在電漿中分解，產生氟自由基以進行氧蝕刻製程

$$e^- + CF_4 \rightarrow CF_3 + F + e^-$$

$$4F + SiO_2 \rightarrow SiF_{4(g)} + O_{2(g)}$$

- 增進蝕刻化學反應

電漿增強化學氣相沈積法

- PECVD 使用 SiH_4 和 NO_2 (笑氣)

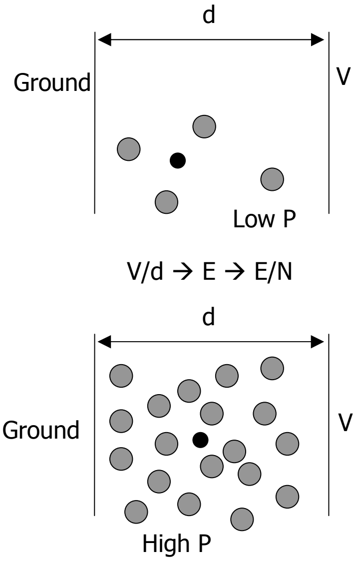
$$e^- + SiH_4 \rightarrow SiH_2 + 2H + e^-$$

$$e^- + N_2O \rightarrow N_2 + O + e^-$$

$$SiH_2 + 3O \rightarrow SiO_2 + H_2O$$

- 電漿增強化學反應
- PECVD 可以在較低的溫度下達到較高的沈積速率

Mean Free Path vs. Plasma Stability



- 爲什麼需要真空反應室來產生穩定電漿?
  1. 電子在碰撞時會失去能量(fast electron vs. slow molecules/atoms)
  2. 二次碰撞間必須要得到足夠的能量(由電場來), 方能有足夠的能量在下次碰撞時得到足夠能量，以誘發反應。
  3. 大氣壓力 (高壓，760 torr)狀態下的平均自由路徑很短，需要較強之電場(Electric field)，才能使電子獲得足夠能量以離子化氣體。但在高電場下，容易形成電弧放電(glow-to-arc transition)
- Calculation of mfp:

$\lambda=$

n: density, σ: cross section

熱速度vs. 電子溫度

- 電子伏特與絕對溫度

  1 eV = 11594 K
- 電子熱速度 (~2 eV)

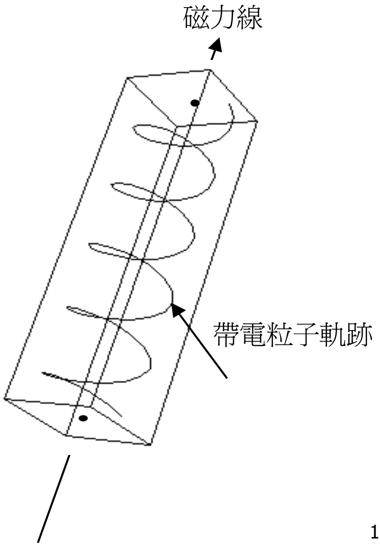
  $\upsilon \sim 5.9 * 10^7$ cm/sec ~ $1.33 * 10^7$ mph
- Ar^+ 熱速度 (~0.05 eV)

  $\upsilon \sim 3.46 * 10^4$ cm/sec ~ 774 mph
- Room Temperature (~0.026 eV)

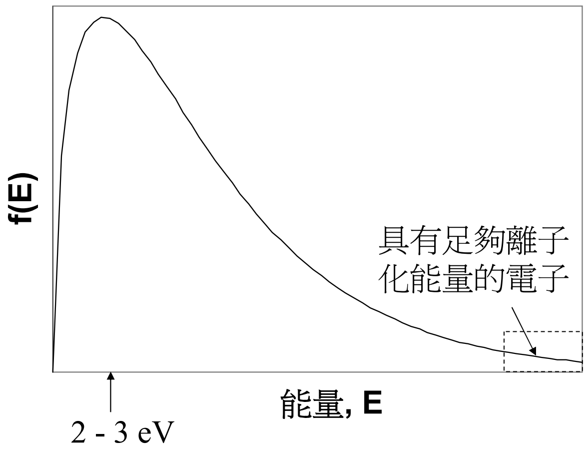
磁力與螺旋運動

- 施於帶電粒子上的磁力:

  $\mathbf{F} = q\mathbf{v}\times\mathbf{B}$
- 磁力總是和粒子速度互相垂直
- 帶電粒子會沿著磁場線成螺旋狀旋繞
- 稱爲螺旋運動

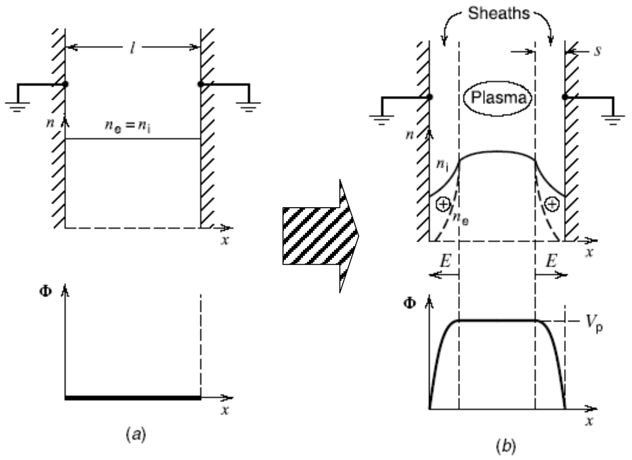


波茲曼分佈 (Boltzmann Distribution)



具有足夠離子化能量的電子

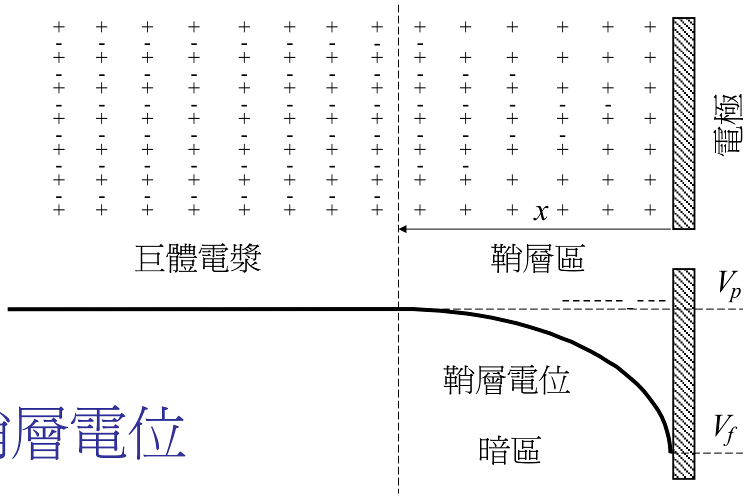
Sheath Formation



Why “+” potential??

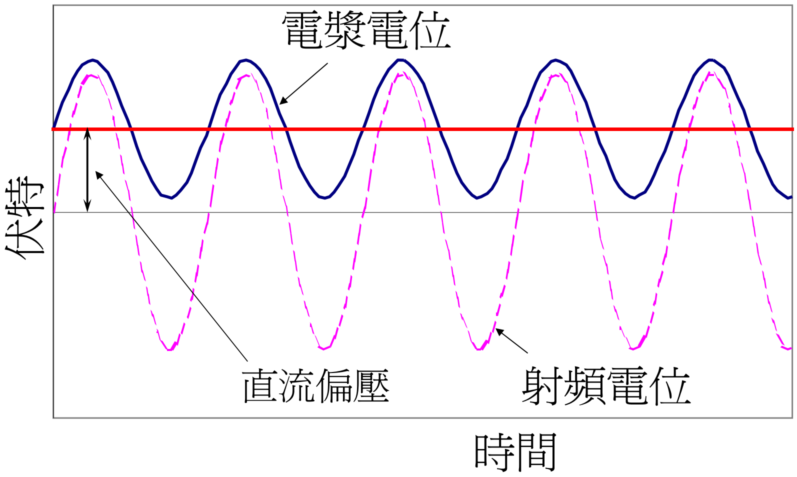
*Figure Courtesy: Michael A. Lieberman, Principles of Plasma Discharges and Materials Processing

離子轟擊 (Ion Bombardment)

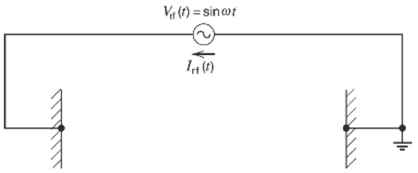


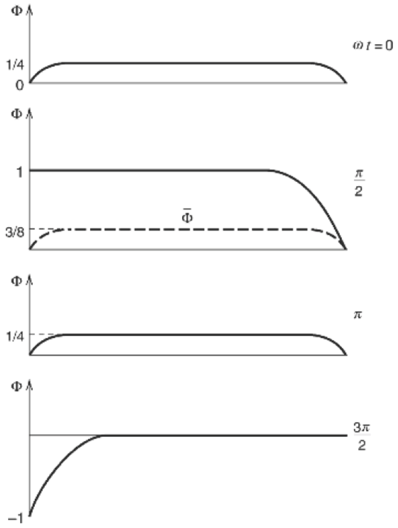
鞘層電位

直流偏壓與射頻功率關係



Spatial and Temporal Potential Distribution





- Plasma always remains positive in the bulk.
- The time-averaged bulk potential depends on the driving electrode voltage amplitude.
- When the frequency is high, electrons "see" the change of the field; ions (heavy) only "see" the averaged field.

*Figure Courtesy: Michael A. Lieberman, Principles of Plasma Discharges and Materials Processing

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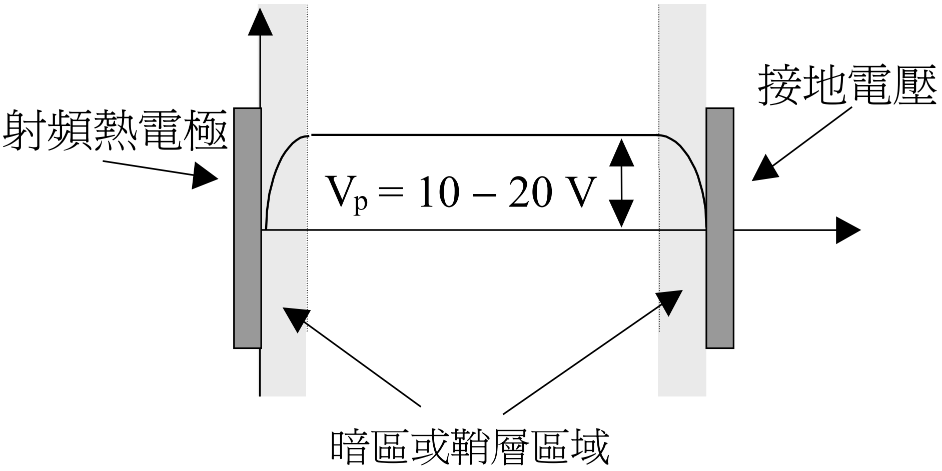
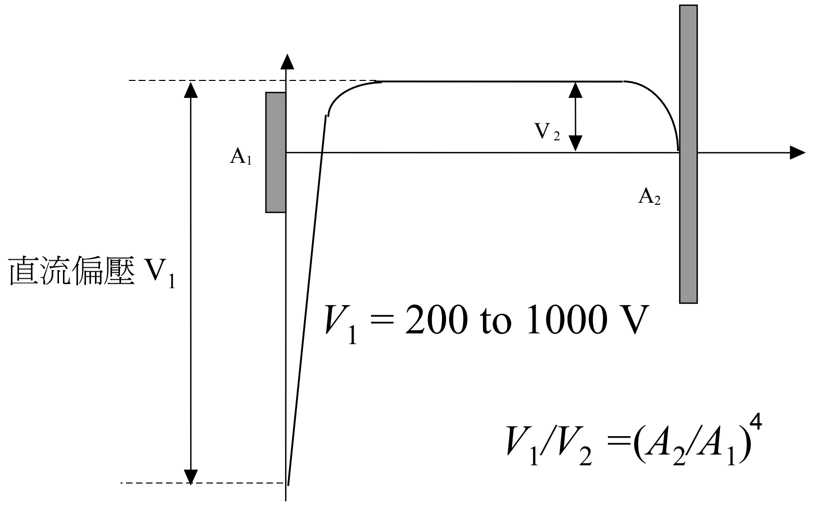
CVD反應室電漿的直流偏壓



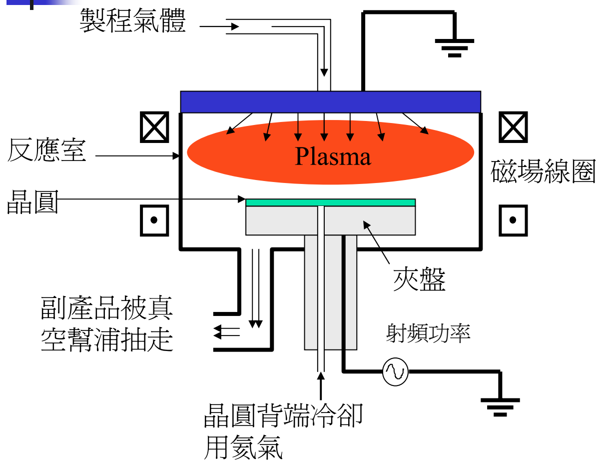
非對稱電極系統的電漿電位



$$V_1 = 200 \text{ to } 1000 \text{ V}$$

$$V_1/V_2 = (A_2/A_1)^4$$

電漿蝕刻反應室的示意圖



- Shower head:
- ESC ( )
- BSC ( )
- B-field

Key challenge:

遙控電漿光阻剝除系統圖

Remote-plasma key features:
1.

2.

Major idea:
1. Electron decays rapidly upon formation
2. No E-field to “heat” the electrons at the downstream

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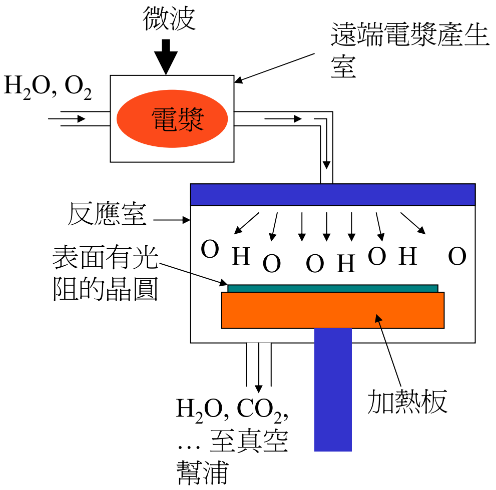
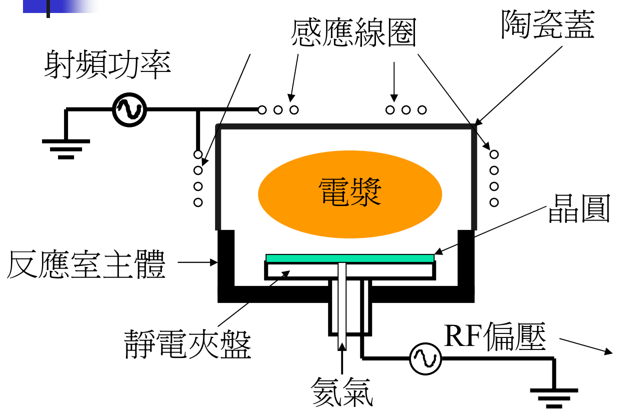
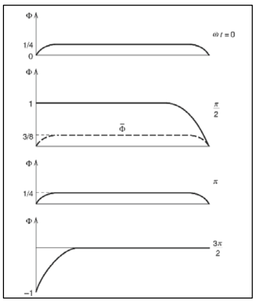


ICP (Inductively Coupled Plasma)

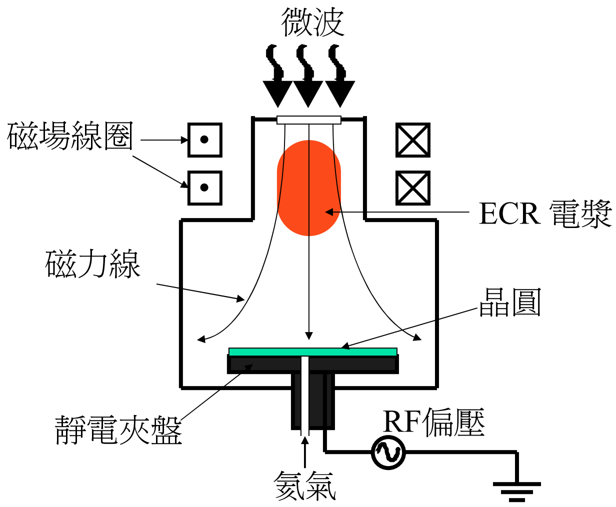




ICP Key Feature: independent control of

________________ and ___________________

ECR 反應室



Advantages/Uniqueness of Plasma Processes

- Existing of reactive radicals under low temperature
- Unique reaction pathway
- Adjustable ion bombardment energy
- Gap filling capability (e.g. 50 nm trench)
- Low operating cost (gas vs. wet chemicals)
- System (chamber) cleaning (gas phase process)
- ….