Capacitive and Inductive RF Plasma Sources for Industrial Applications

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NCCAVS Plasma Applications Group Meeting
Advanced Plasma Technology for
Semiconductor, Thin Film and Solar Processing
July 14, 2011, SEMICON West

This work was supported in part by the DOE OFES (Contract No DE-SC0001939)
Main Plasma Sources in Processing of Materials

M. Lieberman's lecture, 2007
Capacitive Coupled Plasmas (CCP) at 13.56 MHz were the first in plasma processing applications.

In CCP the discharge current and plasma density are controlled by the electrode rf sheaths at the plasma boundary.

- Good plasma uniformity over processing wafer
- Simple and relatively inexpensive construction

**But:**
- No independent control of ion flux and ion energy
- Low plasma density at low gas pressure
- At large rf power, most of it goes for ion acceleration rather than for plasma generation
CCP equivalent circuit and rf power distribution between electron and ion heating

\[ P_{\text{rf}} = P_{\text{pl}} + P_i \]  Since in plasma

\[ E_p \approx \text{conct}, N_p \sim I_d \text{ and } V_{\text{dc}} \sim V_{\text{rf}} \]

\[ P_{\text{pl}} \sim I_d \text{ and } P_i \sim I_d^2 \]
For moderate rf voltage (V < 1 kV), V/A discharge characteristics are nearly linear, does not obey to Childs-Langmuir law.

Sheath capacitance (or thickness) practically does not depend on discharge voltage and current.

13.65 MHz

Experimental observations on CCP scaling plausibly correspond to an analytical self-consistent CCP model by Godyak, Sov. J. Plasma Physics 2, 78, 1976

Basic CCP model assumes uniform ions ($A = 1$) and accounts for non-linear rf sheath dynamics, collisional and stochastic electron heating and energy balance \cite{Godyak, Sov. J. Plasma Physics 2, 78, 1976}

$$N_p = (A \omega^3 \nu_{\text{eff}} m^2 L^2 / 8 \pi e^3 V_p) \{1 \pm (\nu_{\text{eff}} / \omega)[(V_{\text{rf}} / V_p)^2 - 1]^{1/2}\}$$

where $V_p = \text{Re}(E_p L_p)$ is the minimal discharge sustaining voltage and $A$ is a geometric factor accounting for ion space non-uniformity

At large voltage ($V_{\text{rf}} \gg V_p$), $I_d \sim N_p \sim V_{\text{rf}} \omega^2$; $S_{\text{sh}} \sim \omega^{-1}$

CCP in Hg vapors at 40.8 MHz shows a linear V/A characteristic at $V_{\text{rf}} \gg V_p$

\text{V. Godyak et al, in proceedings of XII ICPIG, p. 347, Berlin, Germany (1977).}
CCP modes and transitions between them

1. Volume/boundary heating mode transition, argon 13.56 MHz, \(L=2\ cm, D=16\ cm\)

- I.V. Schweigert et al
- Experiment, (1990) 
  Godyak & Piejak

V. Godyak & R. Piejak PRL 65, 996, 1990
2. α to γ-mode transition (13.56 MHz, He, 0.3 Torr)

V. Godyak et al, PRL 61, 40, 1992
3. CCP resonant mode, (Hg 1.2 mTorr, L = 7.8 cm, D = 7 cm)

\[ N_p \sim \omega^3 \{ 1 \pm (v_{\text{eff}}/\omega)[(V_{\text{rf}}/V_p)^2 - 1]^{1/2} \} \]

- Series (geometric) resonance of inductive plasma and capacitive sheath
- Double valued rf current and plasma density with capacitive and inductive discharge impedance
- Discharge parameters are not sensitive to discharge voltage
- In the resonance, the rf current does not depend on gas pressure, while \( N_p \sim \omega^3 \)

The analytic expression above and experiments suggest to utilize a higher frequency to achieve higher plasma density at fixed discharge voltage

Very High Frequency CCP (VHFCCP)

(Dual and triple frequency CCP)

Main concept:

High frequency $f_h$ to control plasma density (ion flux),
while low frequency $f_l$ to control ion energy and specter (IED)

$F_h = 27-162$ MHz  $f_l = 2-13.56$, sometime 2 and 13.56 to tailor IED

Today, Dual (Triple) Frequency CCPs are the mainstream technology

M. Lieberman’s lecture, 2007
VHF CCP problems

- Standing surface waves \( (\lambda_r = [1+d/s]^{-1/2} \sim \lambda_0/3 \), radial non-uniformity)
- Edge effect (enhances edge plasma density)
- Skin effect (radial non-uniformity when \( \delta < 0.45d/R \))
- E to H transition (rf power is magnetically coupled to plasma, like ICP and produces plasma non-uniformity)
- Plasma-Sheath local resonances on F, 2F, 3F (destroy plasma uniformity)
- Resonance effects and mode jumps prevent smooth plasma control

All these problems became more severe at larger:

frequency, wafer size and plasma density

(Gas flow distribution, segmenting and profiling of rf electrode have limited successes)

The variety of many fundamental electro-magnetic effects makes VHF CCPs too complicated for reliable their control in a wide range of parameters
Inductively Coupled Plasma (ICP) Sources

Main ICP topologies in applications
ICP in commercial products

ICP based plasma processing tool

150/100 W, 0.25 MHz fluorescent lamp

Inductor power loss only 2%
Skin Effect, $\delta \equiv E(dE/dx)^{-1}$

1. Geometric skin depth (the most important… and neglected) is due to multi-dimensionality of the real ICP structure

2. High frequency SE, $\delta_0 = c/\omega_0$ @ $\omega >> \nu_{en}$ and $\omega >> v_{Te}/\delta$ *

3. Low frequency, normal SE, $\delta_n = \delta_0(2\nu/\omega)^{1/2}$ @ $\omega << \nu_{en}$ *

4. Anomalous SE @ $\omega$ and $\nu_{en} << v_{Te}/\delta$ **

5. Non-linear SE @ $\omega << v_{rf}/\delta$ **

* Formulae 2 and 3 are valid only for an uniform plasma with planar boundary!

** Cases 4 and 5 process non exponential spatial variation of $E$ & $B$
Physicists, do not be arrogant, these eqs. are integrals of Maxwell Equations, but result in some universal relationships between ICP integral parameter independently of ICP geometry and specific mechanism of electron heating in RF field.
ICP plasma and electrical parameters

• Electron temperature is defined by the ionization balance, $T_e = T_e (pA)$

• Plasma density is defined by power absorbed by electrons, $N_p \sim P_d$

• By measuring of transmitted power, $P_{tr}$, and the coil current $I_c$, with and w/o plasma, one can infer the power absorbed by plasma, $P_p$, and power loss in antenna and surrounding hardware, $P_o$ (in antenna, matcher and chamber)

\[
\begin{align*}
P_{tr} &= P_i - P_r = I^2 (R_0 + R_p); \\
P_0 &= I_0^2 R_0 \\
P_d &= I^2 R_p = P_{tr} - P_0 I^2 / I_0^2
\end{align*}
\]

Surprisingly, this simple RF diagnostics is neglected in characterization of commercial plasma reactors and of many laboratory rf plasmas, where plasma is characterized by the power consumed from the power source, $P_{tr}$. This power is always smaller (sometimes significantly) than $P_d$, and is not proportional to $P_d$

*R. Piejak et al, PSST 1, 179, 1992*
Argon ICP electrical characteristics

(experiment, Godyak et al PSST, 11, 525, 2002)
More electrical parameters

Transformed plasma resistance

Power Transfer efficiency

Frequency dependence

Transformed plasma resistance

Power Transfer efficiency
Power Transfer Efficiency and Frequency Effect

\[ P_c = I^2 r_c \sim E^2 = E_{dc}^2 (1 + \omega^2/\nu_{eff}^2); \text{ excessive coil loss at } \omega > \nu_{eff} \]

Power transfer efficiency, \( \xi \)

Conventional transformer

\[ \xi = \frac{P_2}{P_1} \approx 1 \]

Conventional ICP

\[ \xi = \frac{P_p}{P_1} = 1 - \frac{P_c}{P_1} \approx 0.05 - 0.8 \]

Relative power loss in ICP inductor \( \frac{P_c}{P_p} \sim \frac{(1+\omega^2/\nu_{eff}^2)/k^2 Q_{10}}{} \)

\[ Y = (wL_d/kN_1^2)/(P_p/(\nu_{pl}^2))^{-1} \]

\[ t = k^2 Q_{10} P_c/P_p \]

Weak coupling in plasma processing reactors together with high plasma impedance, typical for molecular and negative gases, prevents low-density ICP regime \((n \approx > 10^{11} \text{ cm}^{-3})\)
Frequency effect exists at low density plasma in anomalous skin effect regime, but disappears at larger plasma density due to e-e collisions.

Operation at lower frequency is desirable because:

- efficiency and lower cost of rf equipment
- Capacitive coupling and transmission line effect can be eliminated
- Easier management of rf power and simpler and more reliable electrical diagnostics

\[
\begin{align*}
\text{e-e interactions diminish frequency dependence of EEDF, approaching it to a Maxwellian distribution}
\end{align*}
\]
Pros and Cons of conventional ICP sources

Positive

• Independent control of ion flux and energy to the wafer
• Operates at a wide range of gas pressure.
• Relative simple construction
• Effectively operates in wide range of frequencies.
• Possibility to operate at low frequency
• Possibility of plasma profile control with multiple coils?

Negative

• Inability to operate at low plasma density ($N_p < 10^{11} \text{ cm}^{-3}$) in inductive mode
• Can not operate with small gap (large residual time)
• Stray capacitive coupling (plasma non-uniformity and window erosion)
• Transmission line effect (plasma non-uniformity)
• Bead process uniformity control
Mentioned above negative ICP features have promoted VHFFCCP.

Many of negative opinions on ICP limitations are based on experience with poorly designed commercial ICP reactors.

Contrary to prevailed lore:

- ICP can operate in inductive mode at small wattage and low plasma density
- ICP can operate with small gap (small residual time)
- ICP can provide uniformity control over the large processing area
- Capacitive coupling and transmission line effect can be eliminated
- ICP source can operate at much lower frequency, more efficient and less expensive than VHFFCCP and ICP used today in the plasma processing of semiconductor materials

All above can be achieved by properly designed ICP source
ICP does operate in inductive mode at low plasma density

Small power ICP in RF lamps and in lab experiments, $P_d < 2.5 \text{ W}$!

2R = 20 cm, L = 10 cm

$r = 0, \ z = 5 \text{ cm}$

Spherical ICP
Ar-Hg at 0.5 Torr

$\eta = \frac{P_a}{P_d}$

Inefficient coupling and huge antenna loss prevent low plasma density operation in commercial ICPs. $P_a \leq P_d \sim n$ is the condition for stable ICP operation
Today ICP reactor designs are based on 100 year old concept
Groovy ICP, Process: Ar/C4F6/O2. FOI (Japan)

Ar sputter rate uniformity: +/- 2.5%

Th-Ox etch rate uniformity: +/- 2.6%

300 mm, Th-Ox wafer (blanket)
ICP with Ferromagnetic Core

What is the difference between:

a conventional transformer and a conventional ICP

Ferromagnetic core ($\mu \gg 1$) provides a strong coupling, $k \approx 1$

$\omega L_s << R_1$, $Q_1 = L_s/R_1 << 1$

$V_1/V_2 = N_1/N_2$, $I_1/I_2 = N_2/N_1$

No core ($\mu = 1$), thus a weak coupling, $k = 0.2 - 07$, loss $\propto k^{-2}$!

$\omega L_s >> R$, $Q_1 >> 1$, $\rightarrow V_2 < V_1/N_1$

Needs a resonant matching network to compensate large $j\omega L_s \rightarrow \cos \phi << 1$

Enhancement of ICP with ferromagnetic core makes it operate closer to an ideal transformer (more efficient and larger power factor)
Toroidal ICP plasmas with ferromagnetic core in industrial applications

Toroidal plasmas for fusion, 1960

Induction lighting, Andersen, 1970

Kogan & Ulanov, 1993
100 kW, 10 kHz, 1 atm.

Smith et al, 1998
(5-10) kW, 400 kHz, 1-10 Torr
ICP enhanced with ferromagnetic core

2.5 MHz, spherical ICP with internal inductor, D = 7 cm, Ar-Hg 0.5 Torr

Introduction of a ferromagnetic core reduces antenna coil current and voltage, together with increasing ICP power factor (Cosφ) and power transfer efficiency.

V. Godyak, Proc. XVth Intern. Conf. on Gas Discharge and their Appl. V. 2, p. 621, Toulouse, France, 2004
Distributed ICP with 18 core ferrite toroidal cores

$2R = 10 \text{ cm}$, $h = 4.7 \text{ cm}$, $400 \text{ kHz}$, $400 \text{ W}$, Xe $0.3-100 \text{ mT}$

V. Godyak, PEUG, Santa Clara, 2003
18 core distributed ferrite ICP

Xenon, 400 kHz, 10 mTorr, 400 W

V. Godyak, PEUG, Santa Clara, 2003
Plasma uniformity control and coupler losses

@ 400 W, p = 0.3-100 mT, Cosφ = 0.95-0.97 and $P_o/P_d = (16 - 1)\%$

$I_i @ 2 \text{ mm from the chamber bottom}$  Coupler loss versus coupler voltage

Power factor and efficiency exceed those in a conventional transformer at 60 Hz!

V. Godyak, PEUG, Santa Clara, 2003
ICP Enhanced with Ferrite Core, 2 MHz, argon, d = 1.5 - 8 cm
Increased coupling provides better plasma spatial control

V. Godyak, PSST 20, 025004, 2011
power transfer efficiency and plasma density control

Commercial ICPs with two antennas do not produce peripheral maxima.
The reason is: too large gap between the window and the wafer and too low antenna to plasma coupling

V. Godyak, PSST 20, 025004, 2011
Summary

• VHFCPPs have fundamental limitations preventing them to scale up for next generation wafers processing (450-670 mm)

• The main problems in commercial ICPs are weak rf coupling and poor gas flow management. They are far from the optimal design and thus have room for improvement

• Properly designed ICP can operate at low plasma density, small gap and provide good process uniformity control

• Low frequency distributed ICPs with ferromagnetic cores and free of capacitive coupling, transmission line effect can do everything that other plasma source do, but more efficiently and cost effective