Low Pressure RF Plasma Sources for Industrial Applications (ICP versus CCP)

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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 due to rf sheath ballasting effect*
- 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 and low gas pressure, most of it goes for ion acceleration rather than for plasma production

*Sheath stabilizing effect is due to different sheath and plasma impedance dependence on plasma density, \( Z_p \sim N_p^{-1} \); \( Z_{sh} \sim N_p^{-1/2} \) (a good subject for study)
CCP equivalent circuit and rf power distribution between electron and ion heating

\[ P_{\text{rf}} = P_{\text{pl}} + P_{i} \]

Since in plasma

\[ E_{p} \approx \text{const}, \quad N_{p} \sim I_{d} \quad \text{and} \quad V_{dc} \sim V_{\text{rf}} \]

\[ P_{\text{pl}} \sim I_{d} \quad \text{and} \quad P_{i} \sim I_{d}^{2} \]
According to CCP analytical model

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

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

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

\[ V. \ Godyak, \ Sov. \ J. \ Plasma \ Physics \ 2, \ 78, \ 1976 \]

**CCP in Hg vapors** at 40.8 MHz shows a linear V/A characteristic at \( V_{\text{rf}} >> V_p \)

Due to large \( M \) and relatively small rf voltage, \( P_i \) is negligibly small

\[ V. \ Godyak \ et \ al, \ in \ proceedings \ of \ XII \ ICPIG, \ p. \ 347, \ Berlin, \ Germany \ (1977). \]
Electrical characteristics of a symmetrical CCP, Argon, 13.56 MHz

$L = 6.7 \text{ cm}, D = 16 \text{ cm}$

For moderate rf voltage ($V_p < V < 1 \text{ kV}$), V/A discharge characteristics are nearly linear, that does not obey to Childs-Langmuir law followed from Lieberman rf sheath model.

*V. Godyak et al, IEEE Trans. PS, 19, 660, 1991*
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. $\alpha$ to $\gamma$-mode transition  (S. Levitsky, half century ago)

(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)

\[ N_p \sim \omega^3 \left( 1 \pm \left( \frac{\nu_{\text{eff}}}{\omega} \right) \left[ \left( \frac{V_{\text{rf}}}{V_p} \right)^2 - 1 \right]^{1/2} \right) \]  (1976)

- 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 when \( \omega > \nu_{\text{eff}} \)
- 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.

VHF CCP operates close the resonance condition

Very High Frequency CCP (VHFCCP)
(Dual and triple frequency CCP)

Main concept expectations:
Typical for CCP uniformity, large plasma density \(N_p \sim f_h^2\) and independent control of ion flux and ion energy. High frequency \(f_h\) to control plasma density (ion flux), while low frequency \(f_l\) to control ion energy and its specter (IED)

\[f_h = 27-162\ \text{MHz}, \ f_l = 2-13.56, \text{ sometime both } 2 \text{ and } 13.56\ \text{MHz to tailor IED}\]

Today, Dual (Triple) Frequency CCPs are the mainstream technology
Ion flux vs RF power: are 27 MHz and 2 MHz decoupled?

Ion flux and ion energy in VHFCPP are not independable!

*J-P Booth et al*, Dry Process Symposium, Jeju, Korea, 2005
Plasma density profile in CCP for different source frequency

50 W, 200 mTorr (Chauffage local)

60 MHz
\[ J_{\text{max}} = 0.15 \text{ mA.cm}^{-2} \]

81.36 MHz
\[ J_{\text{max}} = 0.17 \text{ mA.cm}^{-2} \]

Increase in \( f_1 \) leads to increase in plasma (and process) non-uniformity!

Plasma non-uniformity in front of 300 mm wafer in CCP driven at 100 MHz in Argon and processing gas mixtures (mode jump)

VHF CCP problems

I. Low frequency bias significantly affects plasma parameters

II. Standing surface waves \( (\lambda_r = [1+d/s]^{-1/2} \sim \lambda_o/3, \) radial non-uniformity) 

III. Edge effect (enhances edge plasma density)

IV. Skin effect (radial non-uniformity when \( \delta < 0.45d/R \) )

V. E to H transition (rf power is magnetically coupled to plasma)

VI. Plasma-Sheath local resonances on F, 2F, 3F (destroy plasma uniformity)

VII. Resonance effects and mode jumps prevent smooth plasma control*

All these problems became more severe at larger:

rf frequency, wafer size and plasma density

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

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

Main ICP topologies in applications

Wafer processing

Lighting

Remote plasma sources

Lighting
Skin Effect, $\delta \equiv E(dE/dx)^{-1}$

In ICP, the rf current forms closed loop within plasma without rf sheath.

Rf power absorption is localized within a skin layer at the plasma boundary.

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

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

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

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

5. Non-linear SE @ $\omega << v_{rf}/\delta$ ** ($eB_{rf}v_{rf}/c > eE_{rf}$)

* 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)

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

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
- Frequency dependence
Argon pressure dependence of EEDF and plasma parameters in ICP driven at 6.78 MHz, 50 W

Transition from normal to anomalous skin effect

Collision dominated and Near-collisionless

Inelastic collisions and escape to the wall
EEDF power and frequency dependence

In a high density plasmas, EEPF at low energy must be Maxwellian
Power Transfer Efficiency and Frequency Effect

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

Power transfer efficiency, \( \xi \)

Conventional transformer

\[ \xi = P_2 / P_1 \approx 1 \]

Conventional ICP

\[ \xi = P_p / P_1 = 1 - P_d / P_1 \approx 0.05 - 0.8 \]

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

\[ Y = (wL_0 / kN_1^2) / (P_p / V_{pl}^2)^{-1} \]

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

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:

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

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

Positive (expected)

• Independent control of ion flux and energy to the wafer

• Operates at a wide range of gas pressure.

• Relative simple construction

• Operates in wide range of frequencies.

• Possibility to operate at low frequency

• Possibility of plasma profile control with multiple coils?

Negative (experienced)

• 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 VHFFCP.

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)
- Many commercial ICPs with two antennas do not produce peripheral maxima.
- ICP can provide process uniformity control over the large area
- Capacitive coupling and transmission line effect can be eliminated
- ICP source can operate at much lower frequency, more efficient and is less expensive than VHFFCP 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, $P_d < 2.5$ W!

ICP pancake configuration
$2R = 20$ cm, $L = 10$ cm
$r = 0, \ z = 5$ cm

Spherical ICP with and without ferrite core Ar-Hg at 0.5 Torr

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
Groovy ICP, Process: Ar/C4F$_6$/O$_2$. FOI (Japan)

Ar sputter rate uniformity: +/- 2.5%
Th-Ox etch rate uniformity: +/- 2.6%
300 mm, Th-Ox wafer (blanket)

In 4 cm gap the uniformity is better than in any VHFCPP

G. Vinogradov, FOI, 2006
ICP with Ferromagnetic Core

What is the difference between:
a conventional transformer and a conventional ICP

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

$\omega L_s \ll R_1$, $Q_1 = L_{s1}/R_1 \ll 1$

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

No core ($\mu = 1$), thus a weak coupling, $k = 0.2 - 0.7$, loss $\propto k^2$

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

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

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 ($\cos \varphi$) and power transfer efficiency.

V. Godyak, Proc. XV$^{th}$ Intern. Conf. on Gas Discharge and their Appl. V. 2, p. 621, Toulouse, France, 2004
ICP with ferromagnetic toroidal cores

Magnetic flux is closed in ferromagnetic core

E & B field distribution

Inductor current

\[ \vec{B} \]

\[ \vec{E} \]
Distributed ICP with 18 core ferrite toroidal cores

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

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, \( \cos \varphi = 0.95-0.97 \) and \( P_o/P_d = (16 - 1)\%

\( I_i @ 2 \) 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
6 core large diameter ICP operating at 400kH

C-W Chang. 2005
Plasma and Electrical parameters

C-W Chang. 2005

![Graph of electron density vs power]  
- Electron density $N_e$ in cm$^{-3}$ as a function of power [W] for different pressures.

![Graph of power transfer efficiency vs power]  
- Power transfer efficiency as a function of power [W] for different pressures.

![Graph of position vs power]  
- Position [mm] vs power [W] for 2 mTorr and 2.5 kW, showing 28.07% and 27.78% efficiency respectively.

![Graph of power factor vs power]  
- Power factor as a function of power [W] for different pressures.
Low Frequency ICP Reactor Enhanced with Ferrite Core

0.4-2 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

- Coil voltage and current are falling with power!? The inductor coil voltage follows the plasma EMF (negative plasma V/A characteristic)
- High power transfer efficiency is due to strong coupling (thin window and ferrite core)
- Wide range of plasma density, including low plasma density in inductive mode
- Ability to create peripheral plasma maximum (spatial power transfer selectivity)

V. Godyak et al, PSST 20, 025004, 2011
Etch profile control in two inductor ICP

Plasma density profiles for different gases and fixed power in the coils, $P_1=400$ W, $P_2=300$ W

Plasma density profiles for different etch rate non-uniformities.

- Strong local coupling provides effective control of the plasma profile
- Etch profile uniformity takes place at non-uniform plasma profile

V. Nagorny & D. Lee, 20th ISPC, Philadelphia, PA, 2011
Twelve reasons why the future belongs to the distributed ICPs with ferromagnetic core

- No external E-M radiation (all E-M flux is directed to plasma)
- No capacitive coupling (no plasma rf potential, no window erosion)
- No transmission line effect (no azimuthal non-uniformity)
- Ability to operate at low power and low plasma density
- Low driving frequency (0.4 - 2 MHz) reduces cost of rf equipment
- Simple, compact and ridged construction
- Good plasma spatial control due to strong local coupling
- High power transfer efficiency reduces power dissipation in hardware
- High power factor allows for considerable simplification of matching network
- Effective thermal management due to large contact area of the rf inductor
- Wide processing window (mixture, pressure, plasma density)
- Possibility of scaling up for uniform processing of very large substrates
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 inductive and large capacitive coupling. They are far from the optimal design and thus have room for improvement.

• Properly designed ICP can operate without capacitive coupling and transmission line effect at low plasma density, small gap and can provide good process uniformity.

• Low frequency distributed ICPs with ferromagnetic cores can do everything that other plasma source do, but more efficiently and cost effective.