Plasma diagnostics using harmonics analysis in processing plasmas

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Outline

- Introduction to Harmonics Analysis Method(HAM)
  - Principle
  - Comparison with Langmuir probes

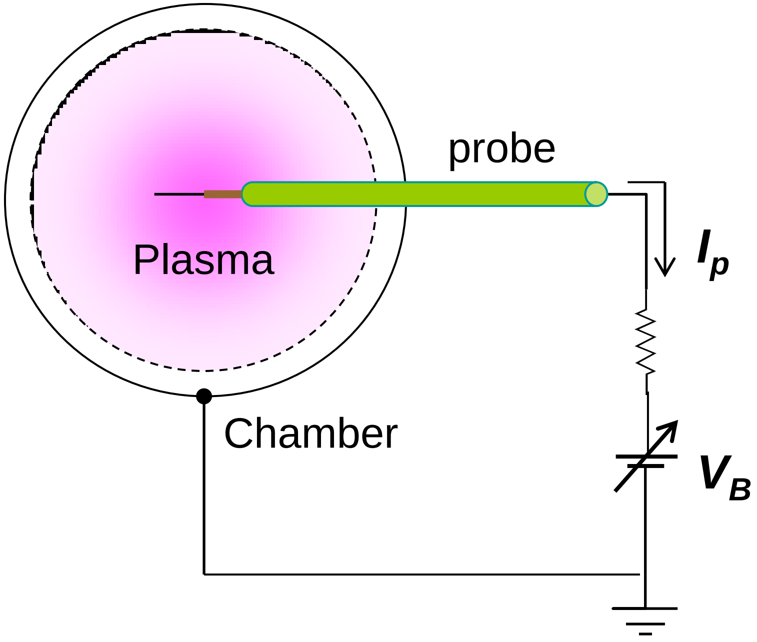
- Applications
  - Plasma diagnostics in SiH4 plasmas
  - 2D plasma measurement at wafer level
  - EEDF Measurement
  - High time-resolved measurement

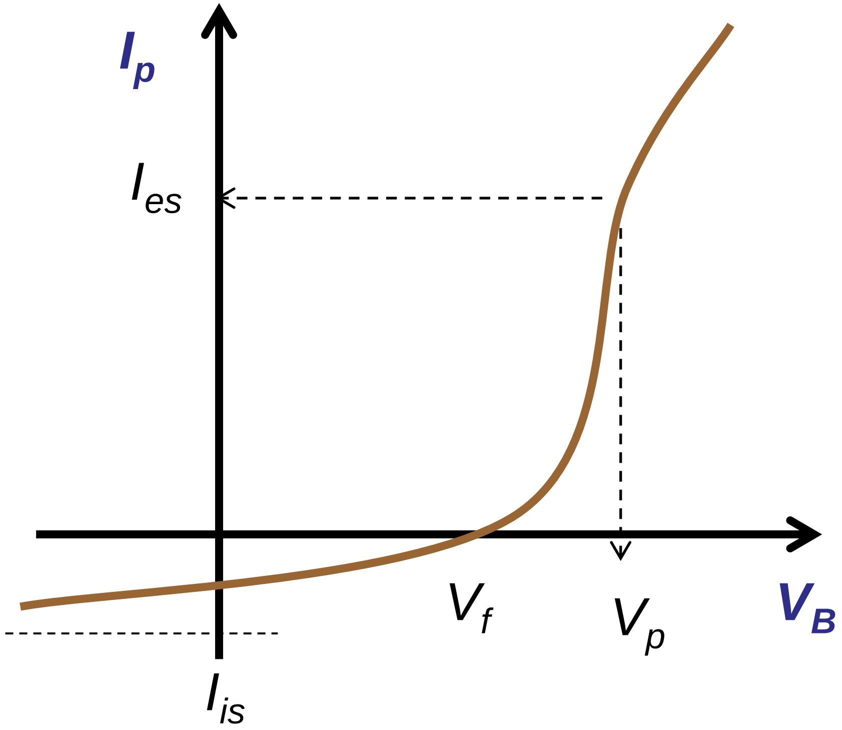
- Summary

Langmuir probes

- **I-V characteristic curve**
  - Ion, electron densities, electron temperatures from the I-V curve
  - Diagnostics for only non deposition plasma

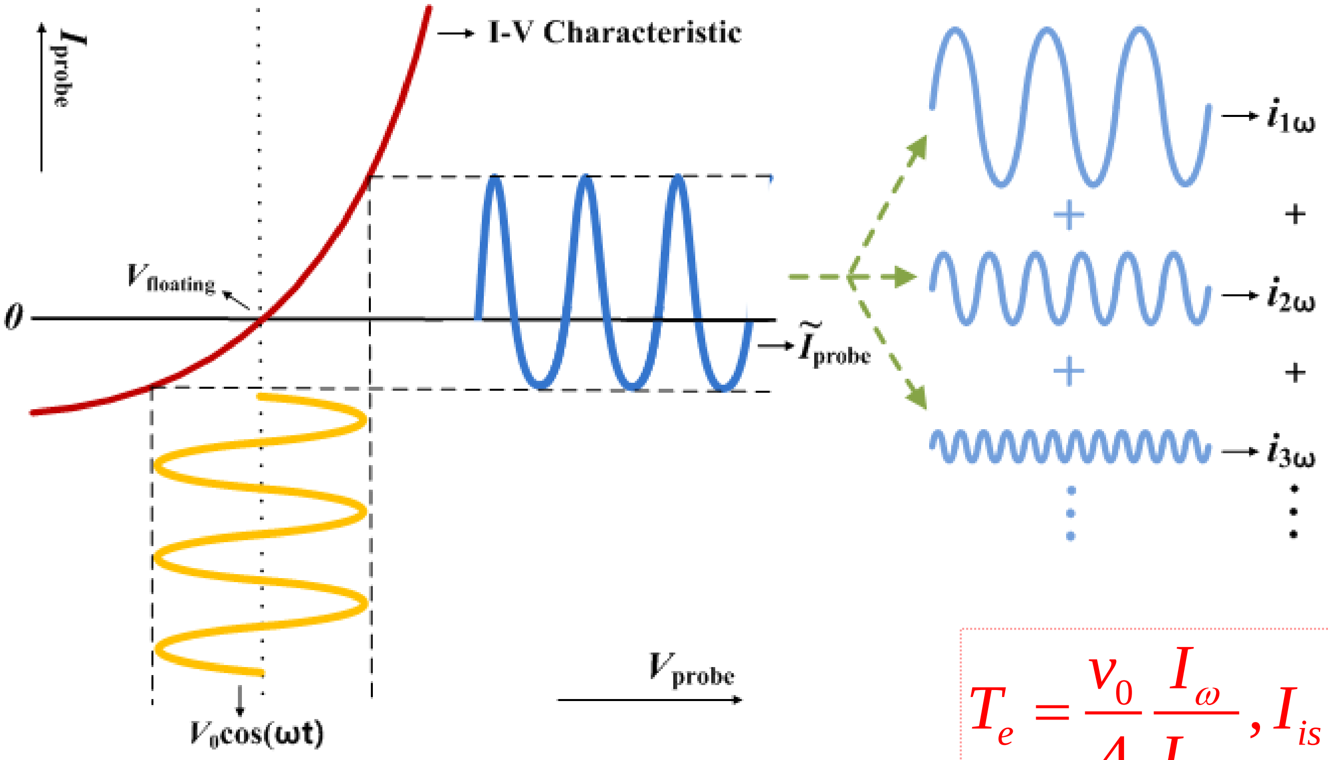
$$I(V_B) = I_{es} e^{e(V_B - V_p)/kT_e} - I_{is}$$





Principle of Harmonics Analysis Method

- Applying a sinusoidal voltage to the probe, non-sinusoidal current is generated due to probe sheath nonlinearity.
- n_p and T_e can be found from the harmonics of the current.

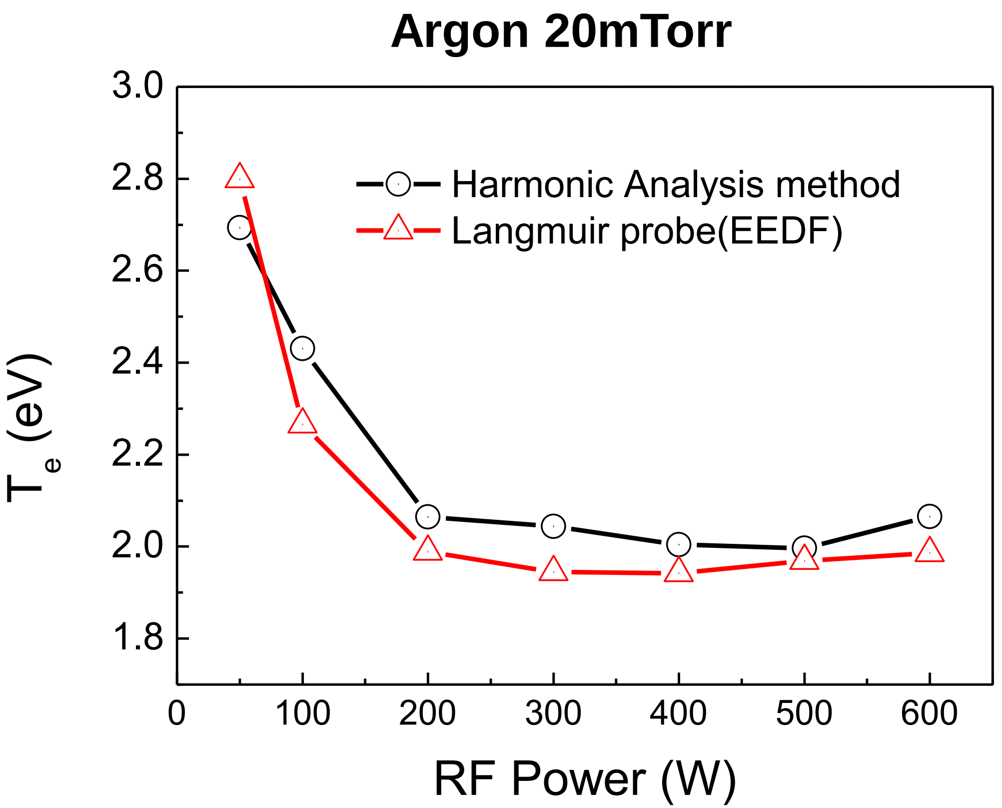


$$T_e = \frac{v_0}{4}\frac{I_\omega}{I_{2\omega}}, I_{is} = I_\omega \frac{T_e}{v_0}$$

M. H. Lee, S. H. Jang and C. W. Chung, J. Appl. Phys., 101, 033305 (2007)

Comparison with Langmuir probes

- Electron temperatures @ rf powers

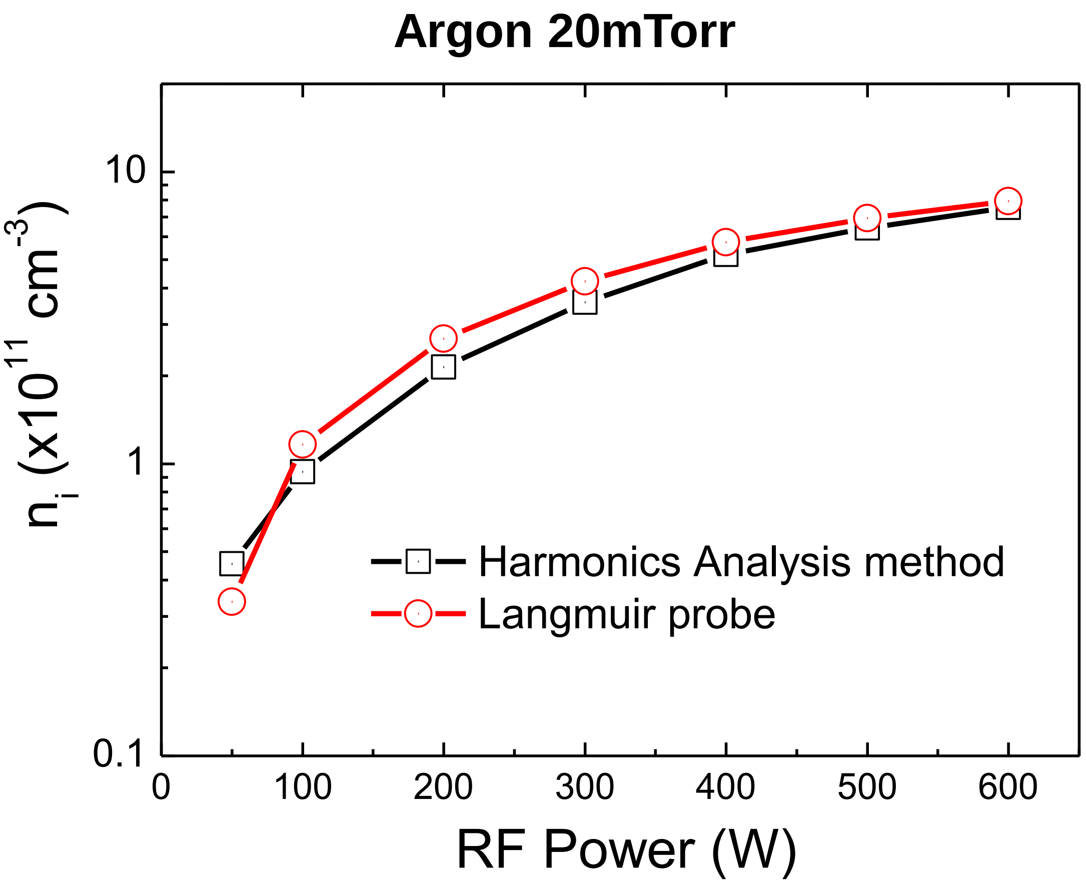


$$T_e = \frac{\upsilon_0}{4}\frac{I_\omega}{I_{2\omega}}$$

MH Lee, et. al. , J. of Applied Physics, 20007
MH Lee, et. al. Applied Physics Lett, 2008

Comparison with Langmuir probes

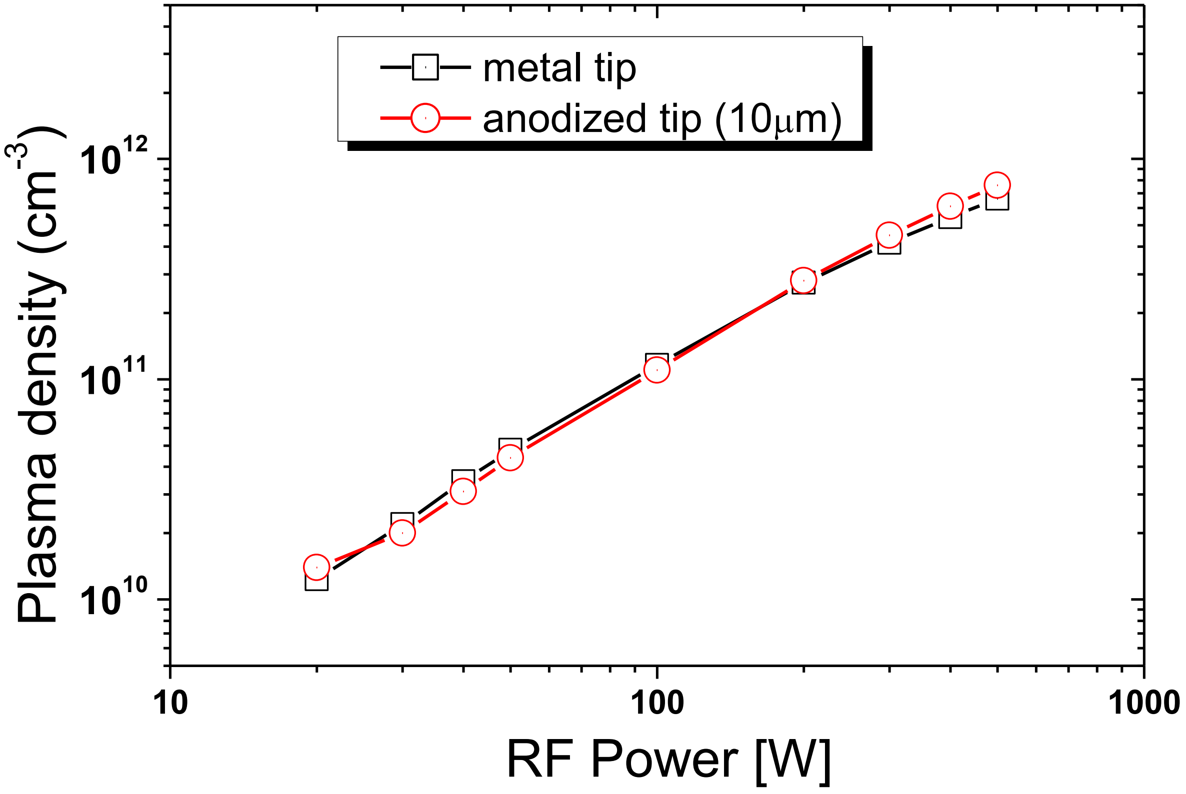
- Ion densities @ rf powers



MH Lee, et. al. , J. of Applied Physics, 20007

Measurement with a coating probe

- In order to diagnose processing plasmas (etching or deposition), the measurement has to be insensitive to an polymer or insulator on probe tip.
- Comparison with a probe with Al_2O_3 coated(~10 μm) and a metal probe

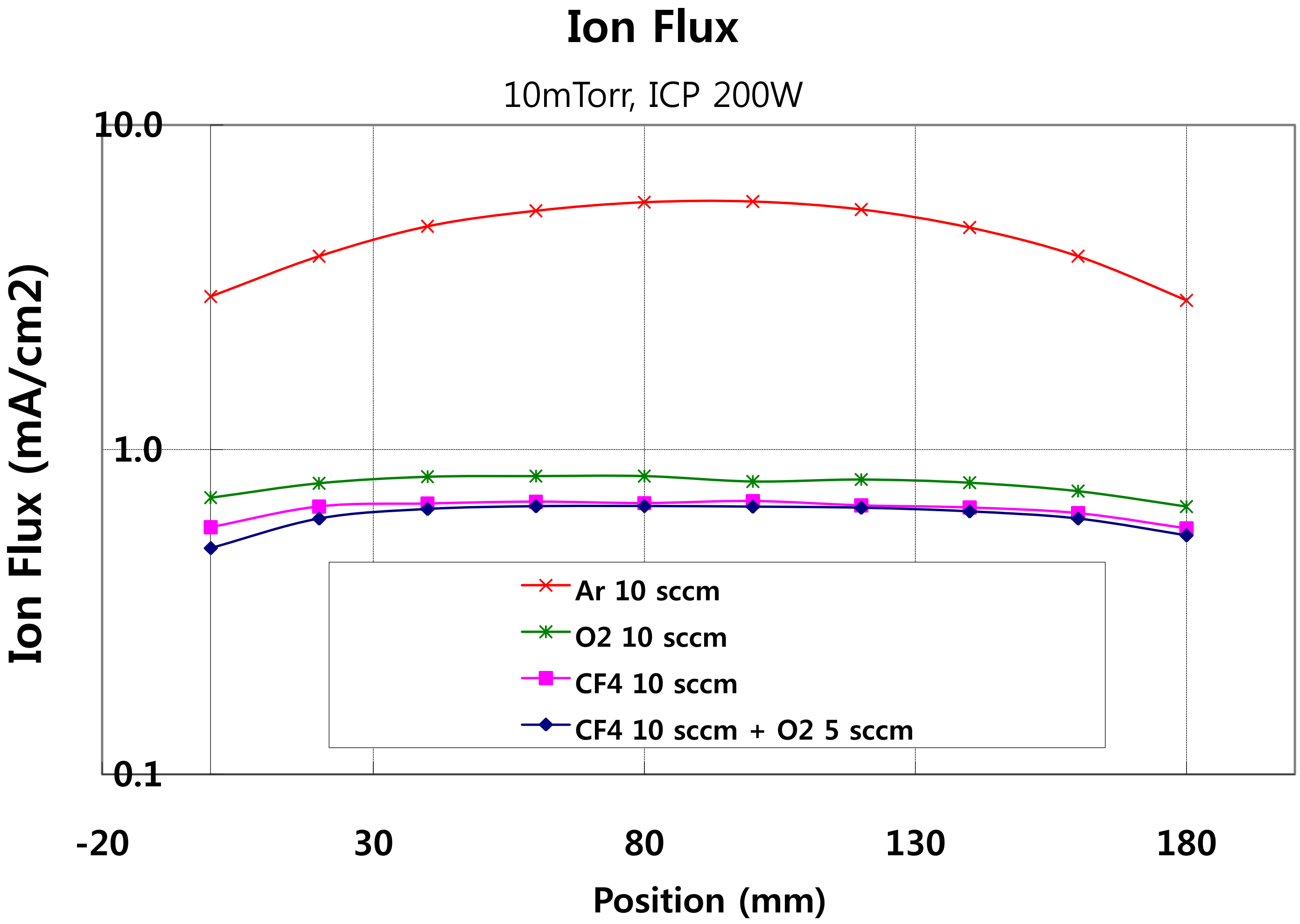


Argon plasma

20mTorr

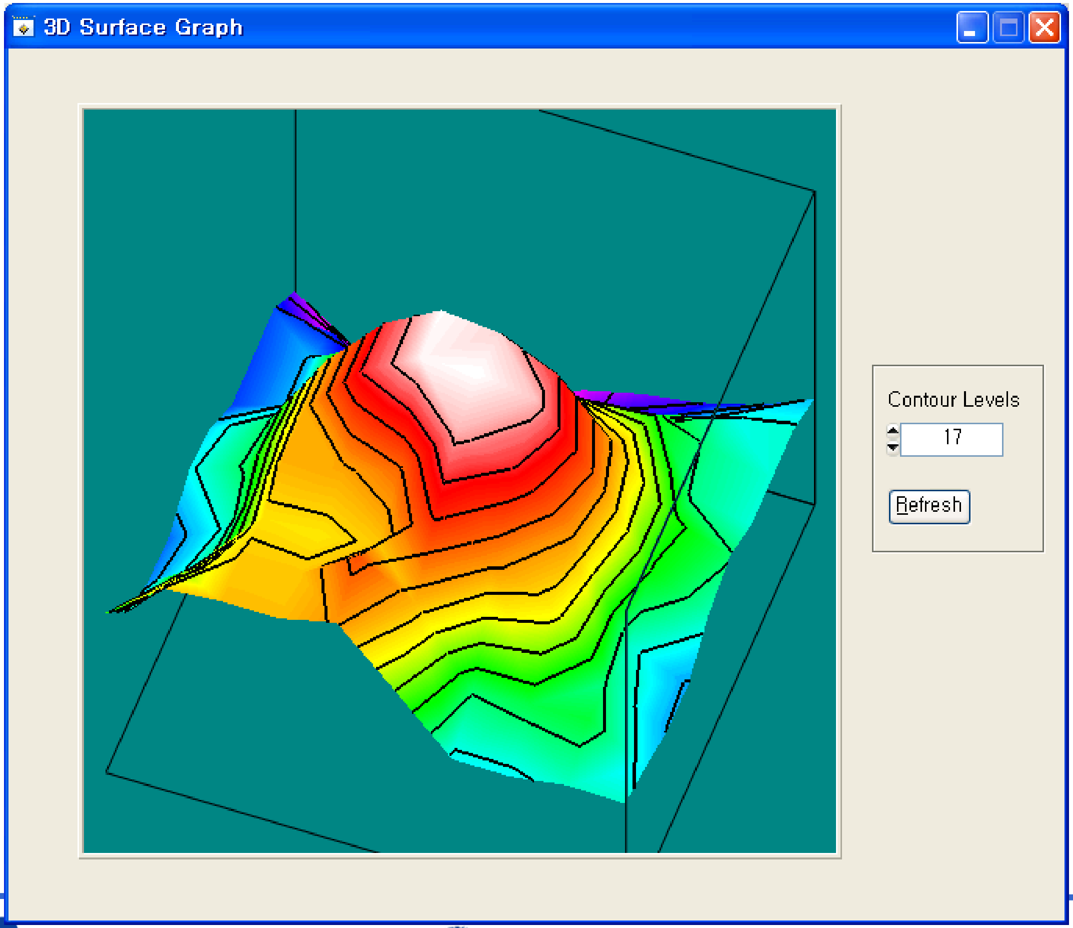
Plasma uniformity measurement

- Radial uniformity of Ion flux
  - Ar, O2, CF4, CF4/O2 plasma



2D Plasma Profile measurement

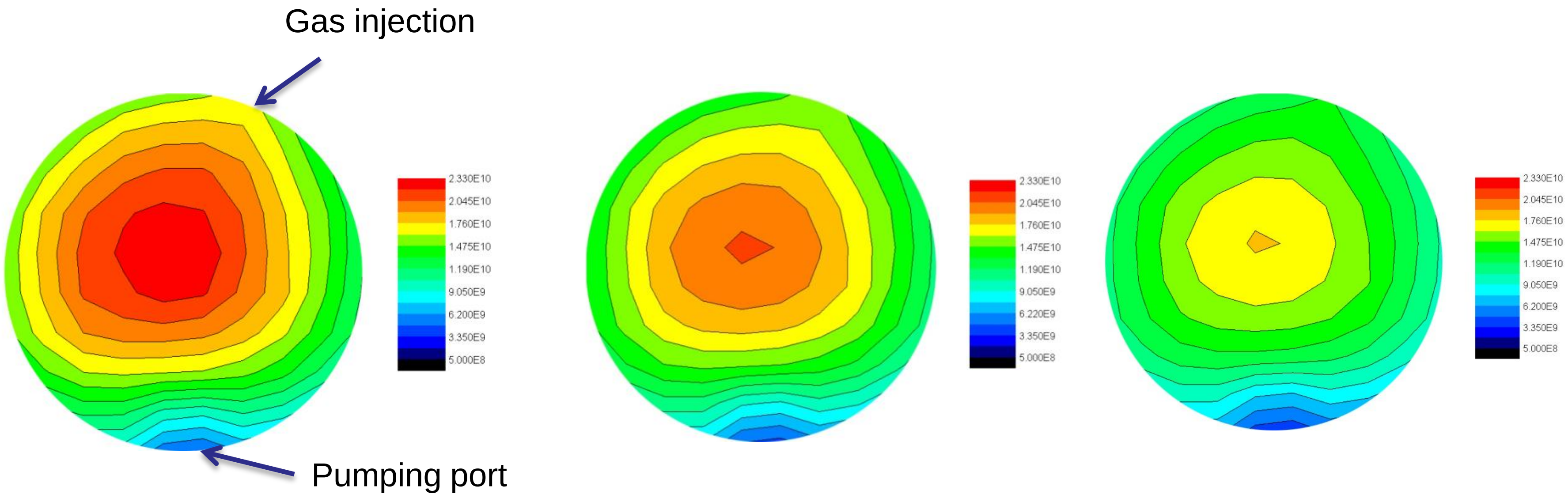
- Screen shot
  - Real time measurement (~1sec)
- New interpolation method for 2D plot was developed.



SJ Oh, Rev Sci. Instrum. 2010

2D Plasma Profile measurement

- Ion flux at various pressures
  - At fixed power (300W) in an ICP
  - Decreases in density at higher pressures at the wafer level
  - Less diffusion to the substrate even though higher density in the center or below antenna is generated.

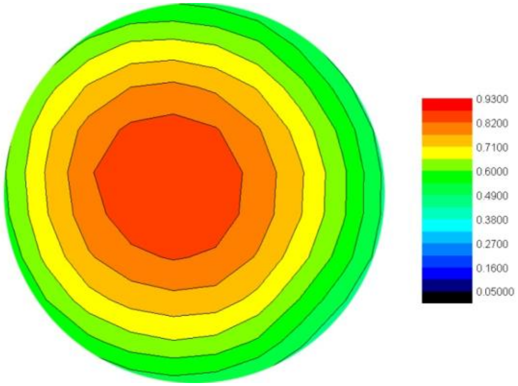


6mTorr 12mTorr 20mTorr

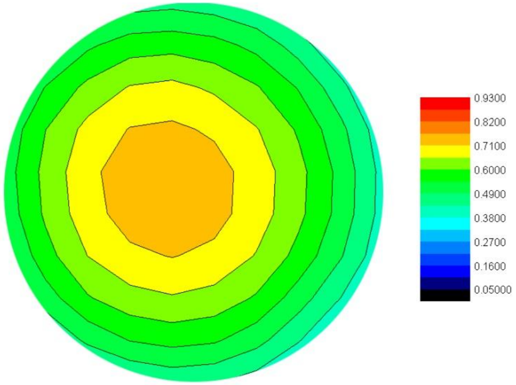
Fixed scale

2D Plasma Profile measurement

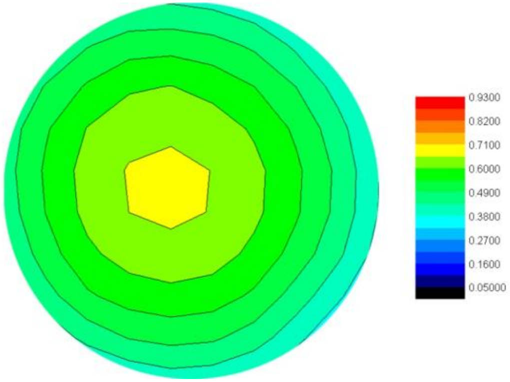
- Ion flux @ Ar/O2 mixtures
  - Pressure = 10mTorr
    - Less ion flux (or density)
    - More uniform



Ar/O2 = 50/0



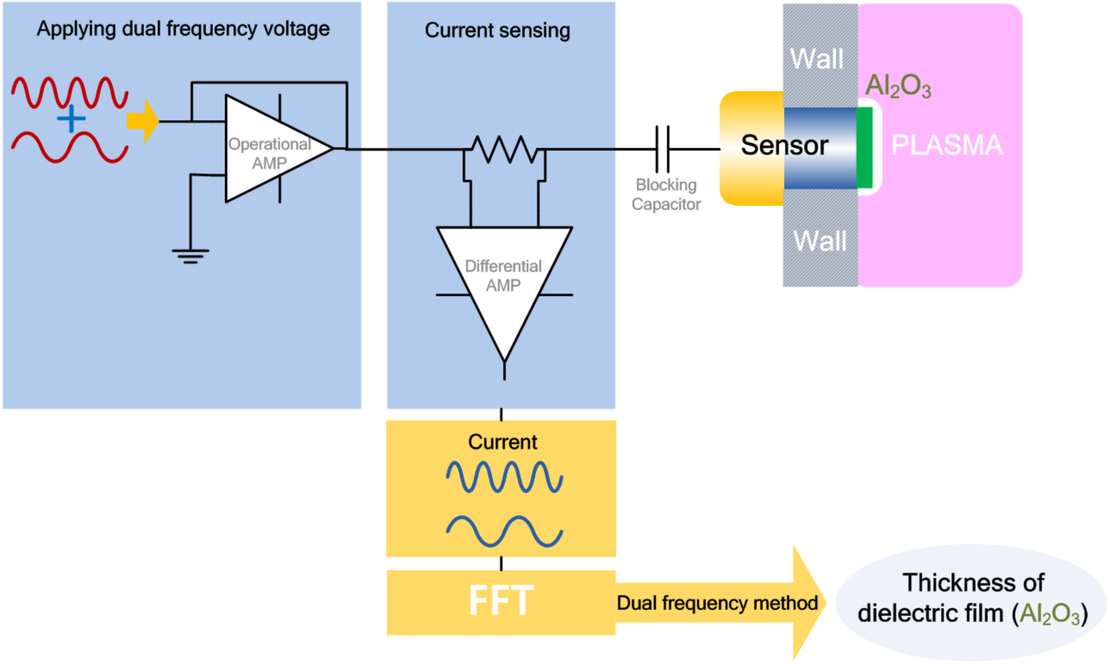
Ar/O2= 50/10



Ar/O_2=50/20

In Situ Film Thickness Monitoring

- Principle:
  - Impedance of dielectric film on a sensor is a function of frequency
  - Applying a voltage waveform with two frequencies to a probe and measuring the current at each frequency.
  - The difference between two currents is related to the film capacitance.



SH Jang, J. of Applied Phys. 2010

In Situ Film Thickness Monitoring

- For comparison, Al_2O_3 probes (1~10μm) were used
  - The thickness of Al_2O_3 (anodized Al) was measured at various plasma conditions

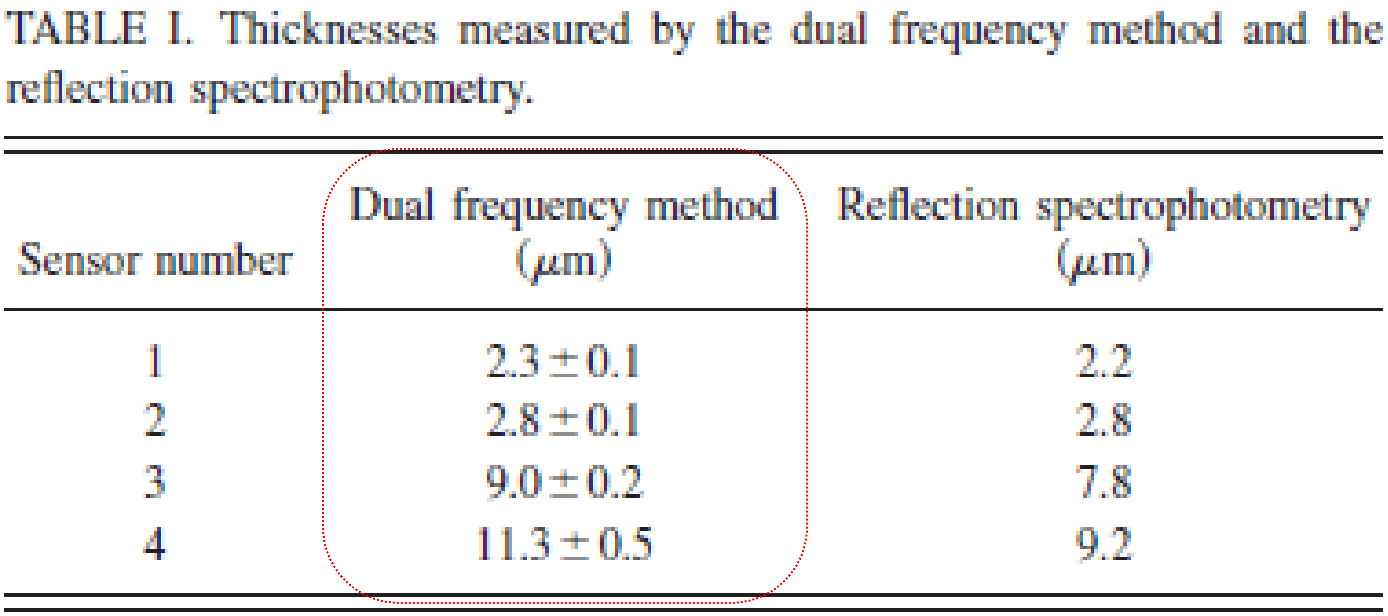


TABLE I. Thicknesses measured by the dual frequency method and the reflection spectrophotometry.

Sensor number	Dual frequency method (μm)	Reflection spectrophotometry (μm)
1	2.3±0.1	2.2
2	2.8±0.1	2.8
3	9.0±0.2	7.8
4	11.3±0.5	9.2

SH Jang, J. of Applied Phys. 2010

EEDF Measurement

- Basic idea
  - To sweep probe potential with a small ac voltage.
  - The EEDF is directly related to the second derivative of the I-V curve.

$$f(\varepsilon) \propto \frac{d^2 I_p}{dV^2}$$

- 2nd harmonics

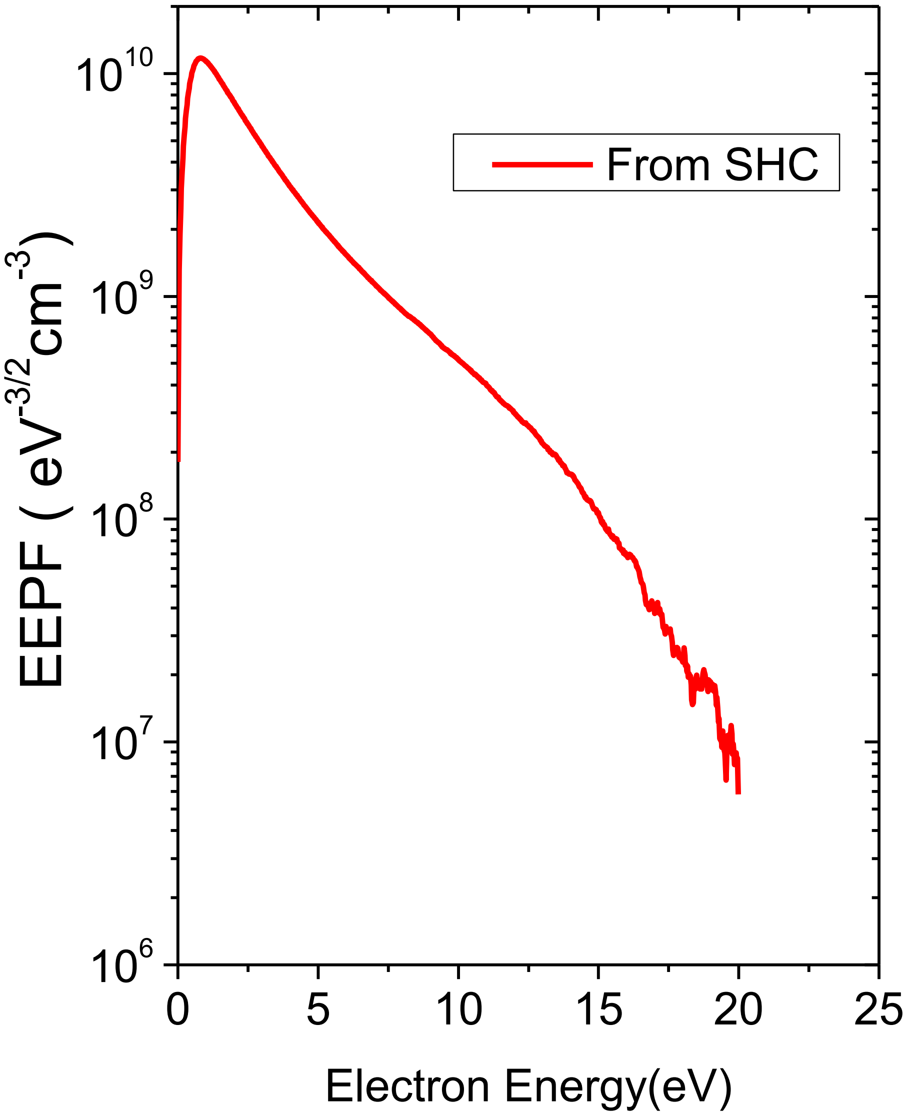
$$I_{2\omega} = \frac{v_0^{\,2}}{4}\left(\frac{d^2 I}{dV^2}\right) + \frac{v_0^{\,4}}{48}\left(\frac{d^4 I}{dV^4}\right) + \frac{v_0^{\,6}}{1536}\left(\frac{d^6 I}{dV^6}\right) + \ldots$$

$$\Omega = \frac{\text{fourth derivative}}{\text{second derative}} \approx 0.02\text{when } \frac{v_o}{T_e} = \frac{1}{2}$$

The EEPF measurement

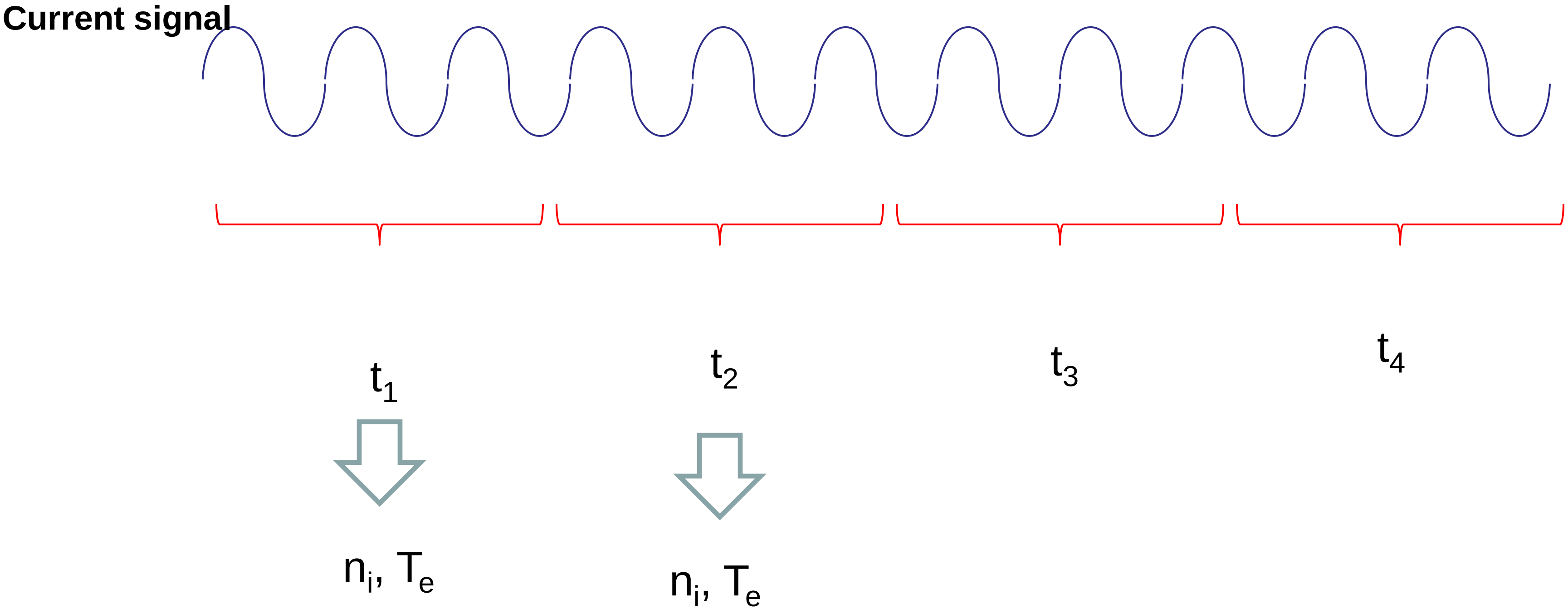
- v_0= 1V, frequency = 10kHz
- Ar 15mTorr, 100W

$$\frac{d^2 I_p}{dV^2} \approx 4 I_{2\omega} \frac{1}{v_0^2}$$



High time-resolved measurement

- How it works
  - Storing all the current signal during the measurement,
  - After the measurement, chopping the stored current signal into the desired time frame.
  - Calculate the frequency spectrum at each time frame.
  - Time resolution : 0.1 msec (present)



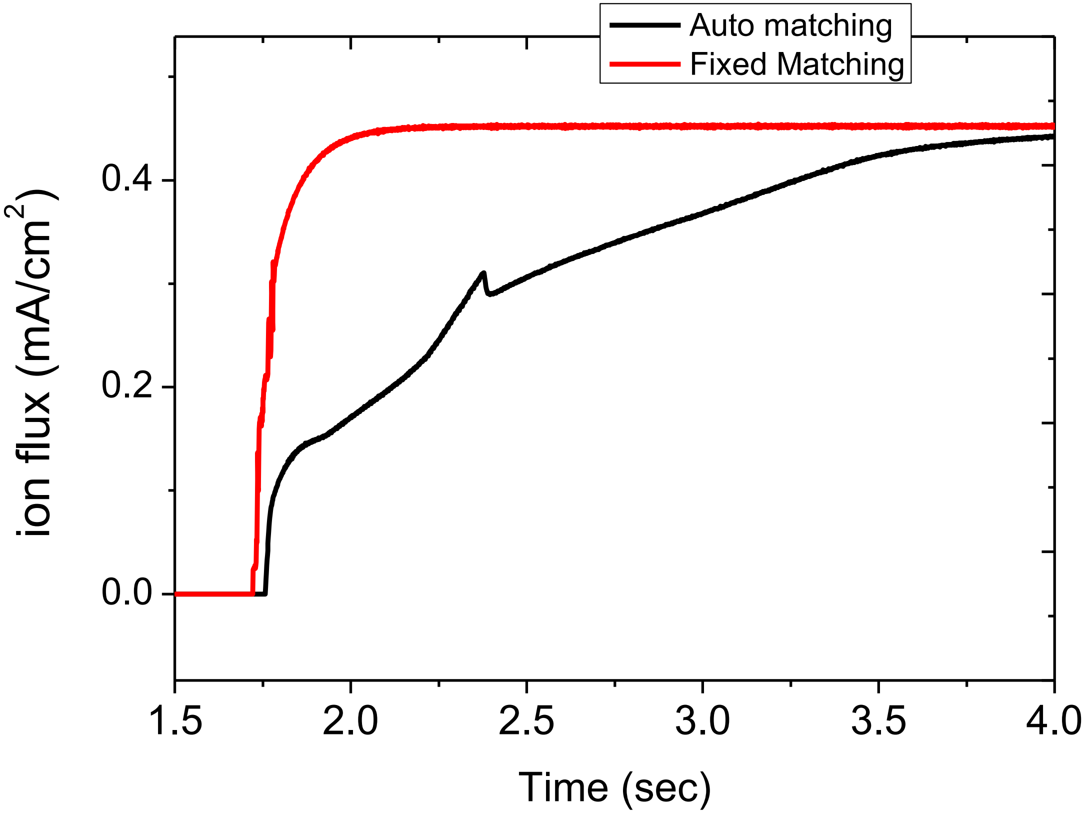
Current signal

t_1 t_2 t_3 t_4

n_i, T_e n_i, T_e

High time-resolved measurement

- Plasma ignition against impedance matching setting
  - Transient behavior during plasma ignition



Summary

- Harmonics Analysis Method(HAM) provides reliable, high time resolution measurement.
- By applying HAM, we are able to achieve
    - Plasma diagnostics in SiH_4/H_2 plasmas
        - Relationship between plasma parameters and Si particles
    - Real time 2D plasma profile
    - In situ film thickness monitoring
    - EEDF measurement with better low energy resolution
    - High time-resolved measurement(~0.1 msec)
- HAM appears to be a good diagnostic method for understanding basic plasma physics as well as plasma processing.

- A Commercial diagnostic system (Wise Probe) using HAM is available.
    - Plasma & Analytic Solutions (http://www.pnasol.com)