SHEATH DYNAMICS AND ENERGETIC PARTICLE DISTRIBUTIONS ON SUBSTRATES

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OUTLINE

CAPACITIVE RF SHEATHS

- Ion energy distribution (IED) on substrate
- Ion angular distribution (IAD) on substrate

PULSED SHEATHS

- Control of ion energy distribution (IED)
- IED for implantation on conducting and insulating substrates

CAPACITIVE RF SHEATHS

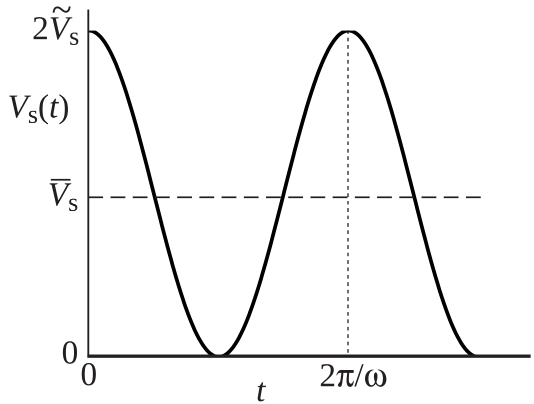
(E. Kawamura et al, 1999)

COLLISIONLESS RF SHEATHS

- Ions flow across sheath with no collisions
- Voltage across sheath

$$V_s(t) = \widetilde{V}_s(1 + \cos\omega t)$$

- Average voltage $\overline{V}_s$ = rf amplitude $\widetilde{V}_s$

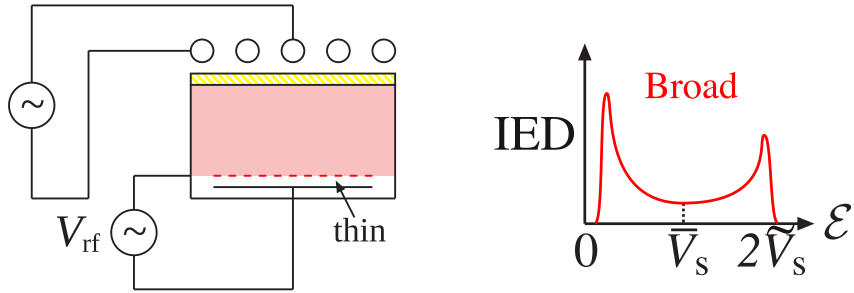


- IED's depend on

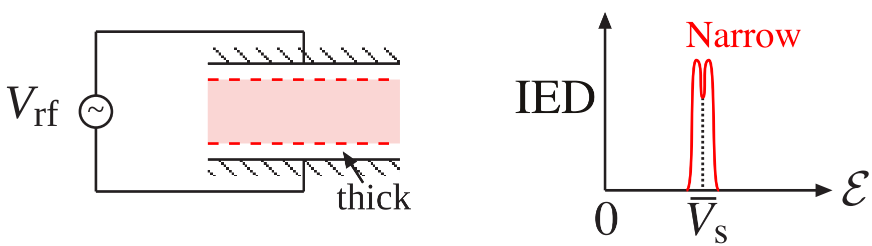
$$\omega\tau_i = \text{rf frequency} \times \text{ion transit time across sheath}$$

SHORT AND LONG ION TRANSIT TIME

- High plasma density (thin sheath), $\omega\tau_i \ll 1$



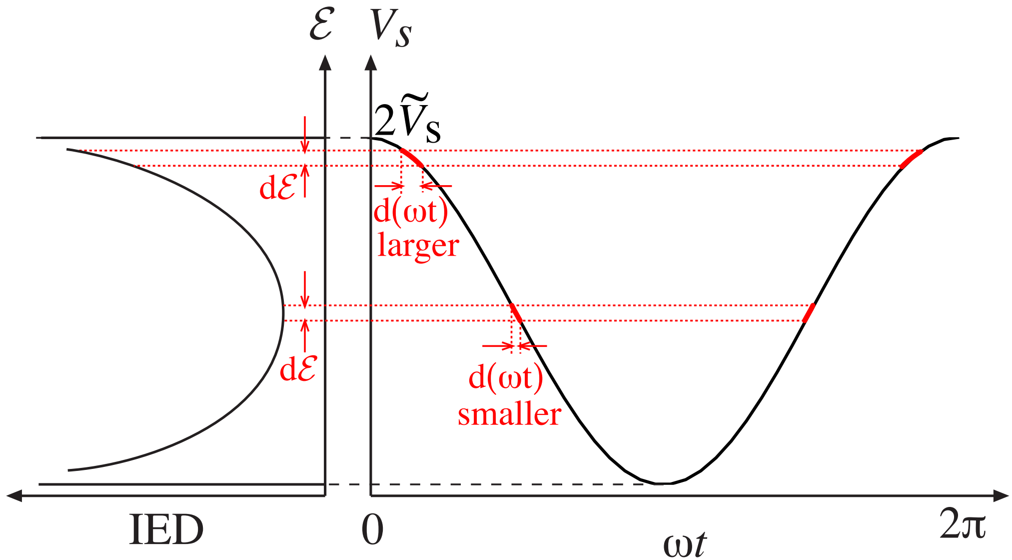
- Low plasma density (thick sheath), $\omega\tau_i \gg 1$



- Bi-modal (two-peak) IED's are seen

BI-MODAL IED'S — SHORT TRANSIT TIME

- Ions "see" the instantaneous voltage across the sheath



- Two phase intervals $d(\omega t)$ map into a single energy interval $d\mathcal{E}$
  For a given $d\mathcal{E}$, more ions strike the substrate if $d(\omega t)$ is larger
- Bi-modal IED with broad energy spread $\Delta\mathcal{E} = 2\widetilde{V}_s$, $0 < \mathcal{E} < 2\widetilde{V}_s$

BI-MODAL IED'S — LONG TRANSIT TIME

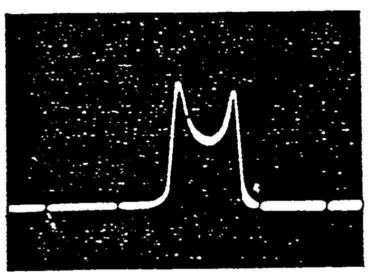
- Ions "see" nearly the average voltage $\overline{V}_s = \widetilde{V}_s$ across the sheath
- Bi-modal IED with narrow energy spread

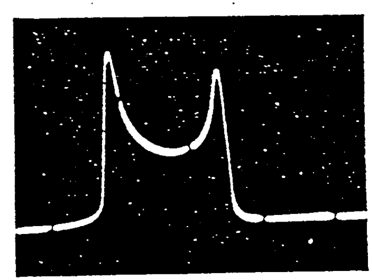
$$\Delta\mathcal{E} = \frac{4}{\omega\tau_i}\,2\overline{V}_s \qquad (\text{about } \overline{V}_s)$$

- Because ion transit time $\tau_i \propto 1/\text{velocity}$, and velocity $= \sqrt{2eV_s/M}$, there is an ion mass dependence

$$\Delta\mathcal{E} \propto \frac{1}{\sqrt{M}}$$

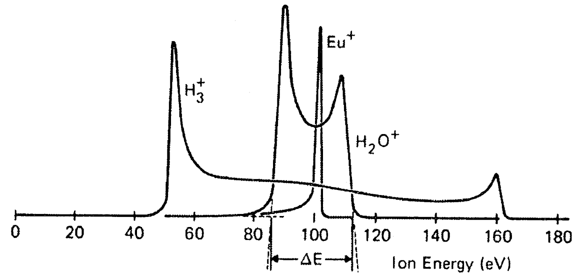
- Earliest measurement (J. Erö, 1958)



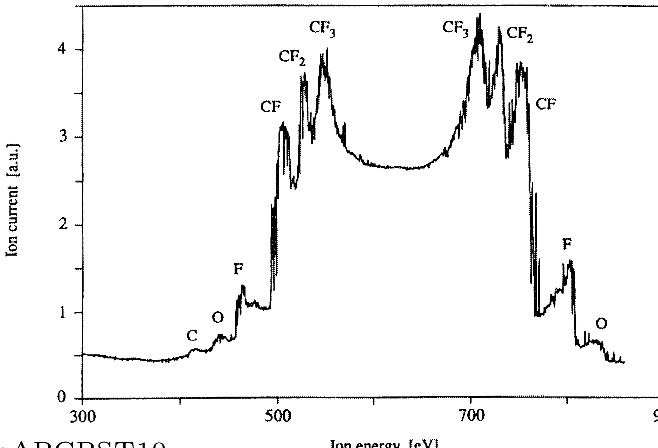


SOME EXPERIMENTAL RESULTS

- Capacitive discharge, 13.56 MHz, 75 mTorr
  Note Eu^+ (mass 152), H_2O^+ (mass 18) and H_3^+ (mass 3)
  (J.W. Coburn and E. Kay, 1972)

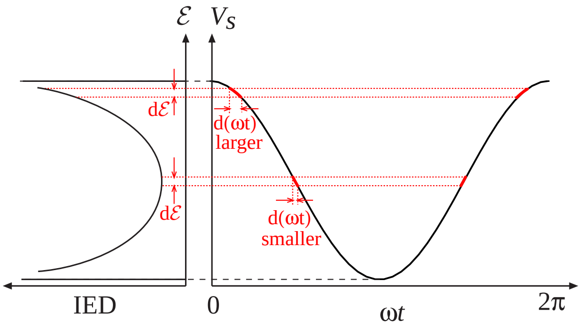


- Capacitive discharge, CF_4 at 3 mTorr (Note $\Delta\mathcal{E} \propto 1/\sqrt{M}$)
  (A.D. Kuypers and H.J. Hopman, 1990)

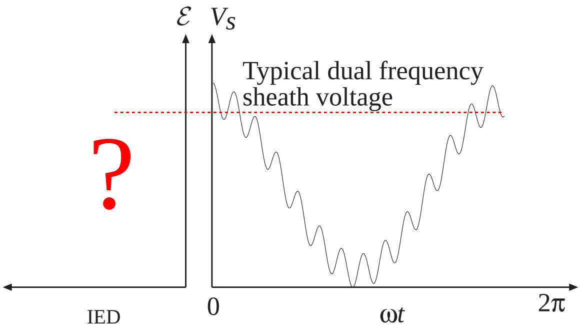


DUAL FREQUENCY CAPACITIVE SHEATHS

- Single frequency
  Two times/cycle map to a given ion energy $\mathcal{E}$



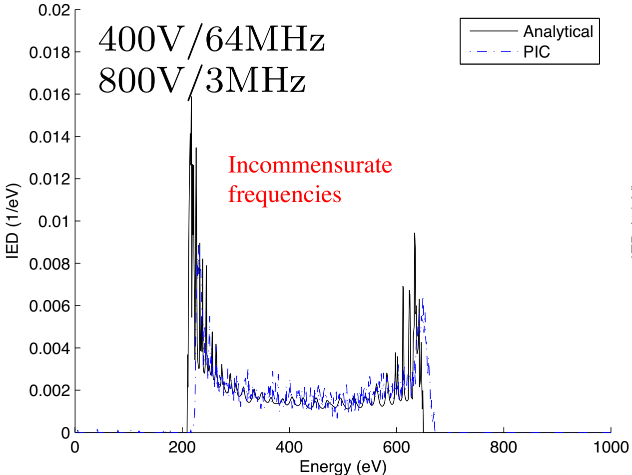
- Dual frequency
  More than two times/cycle map to a given ion energy $\mathcal{E}$

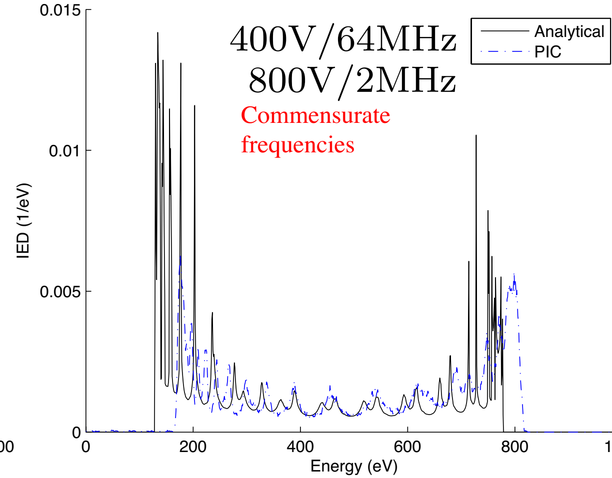


- For $\omega\tau_i \ll 1$, ions respond to the full time-varying sheath voltage
  For $\omega\tau_i \gg 1$, ions respond to the time-average sheath voltage

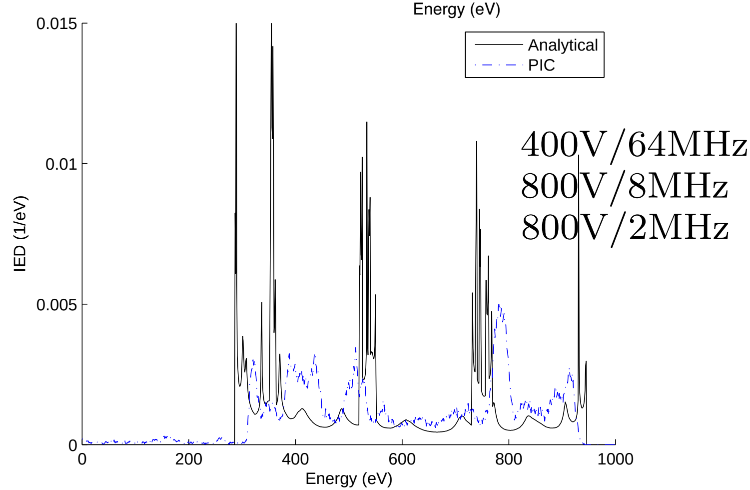
$\Longrightarrow$ low-pass filter

DUAL/TRIPLE FREQUENCY PIC SIMULATIONS





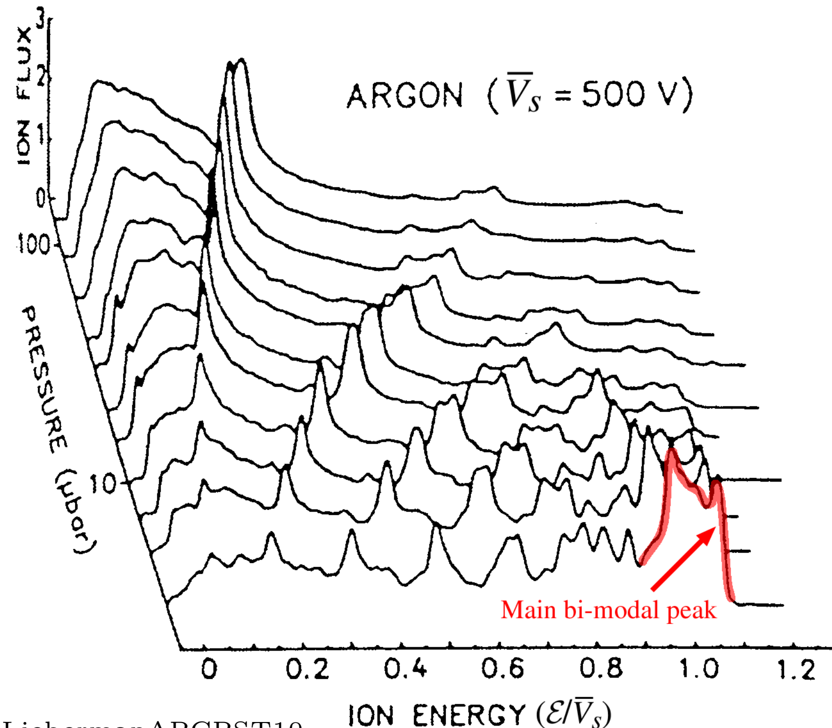
Gap=3 cm
p=30 mTorr
Collisionless ions
(A. Wu et al, 2007)



ION-NEUTRAL COLLISIONS IN THE SHEATH

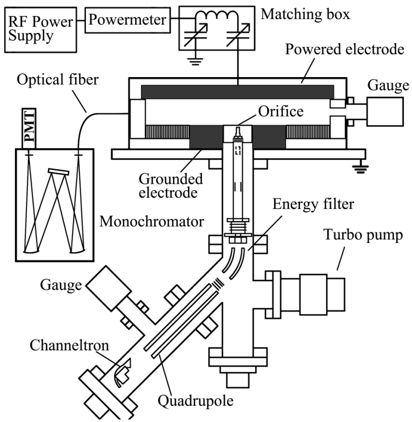
- Ion-neutral charge transfer collisions create slow ions within the sheath
- Groups of slow ions are accelerated, leading to additional peaks in the IED (C. Wild and P. Koidl, 1991)

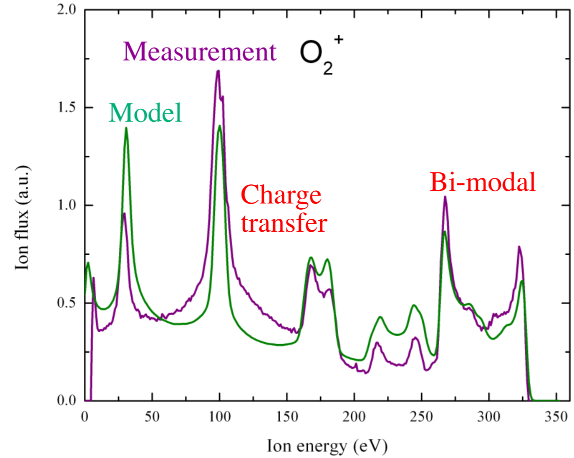
- IED's measured in a collisional rf discharge for various pressures; the low energy peaks arise from a combination of charge exchange collisions and rf modulation

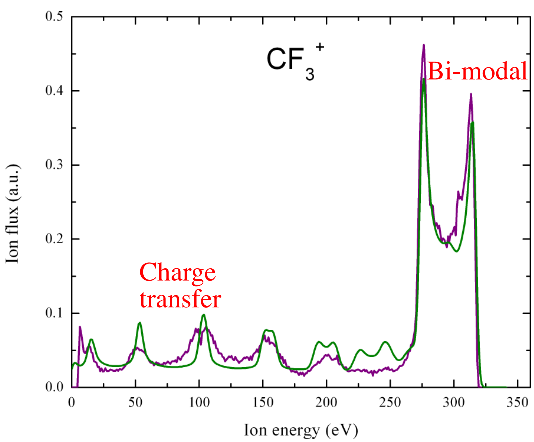


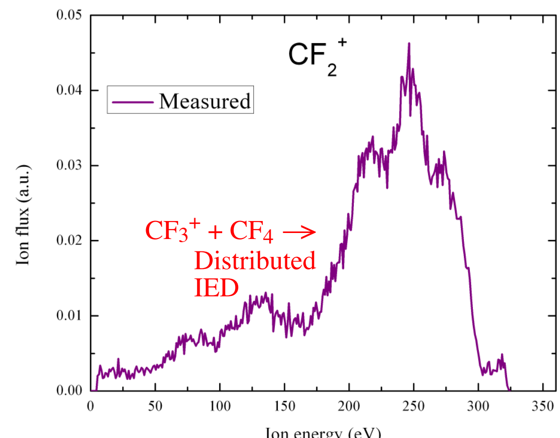
COLLISIONAL IED — MEASUREMENT AND MODEL

(13.56 MHz, 50 W, 4 cm gap, Ar/CF_4/O_2 = 30:5:10 mTorr, W.C. Chen et al, 2009)



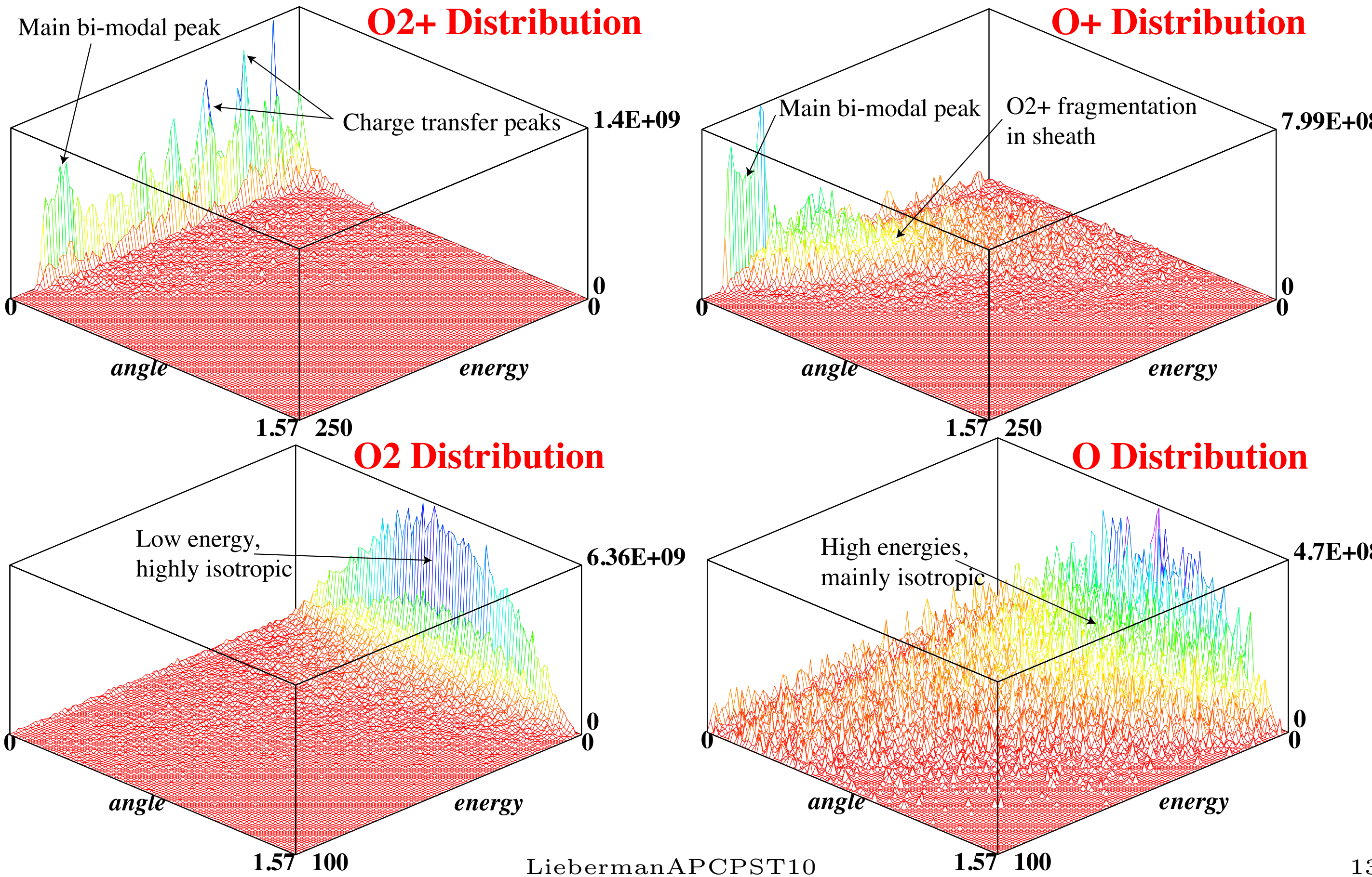






ENERGETIC PARTICLES ON THE SUBSTRATE

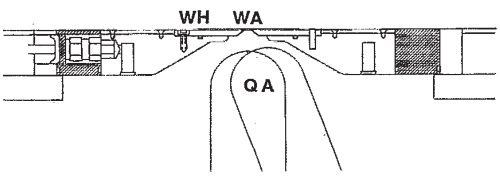
(20 mTorr O_2 capacitive discharge: 5 cm gap, 500 V at 13.56 MHz)



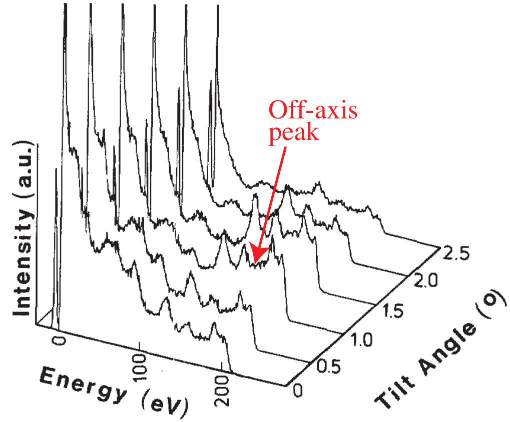
ION ANGULAR DISTRIBUTION (IAD)

(see J. Liu, G.L. Huppert, and H. Sawin, 1990)

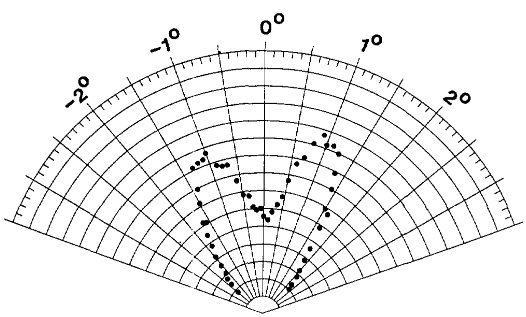
Argon ions, 13.56 MHz, 15 cm gap
(J. Janes and C. Huth, 1992)



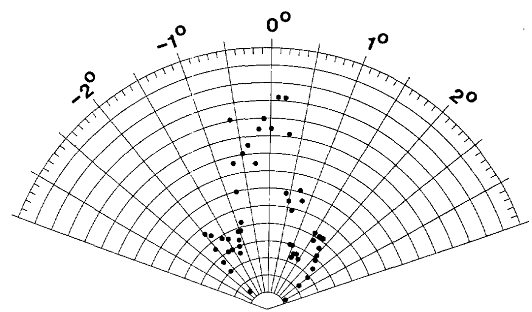
Tilting analyzer



40 mTorr, 200 V rf bias



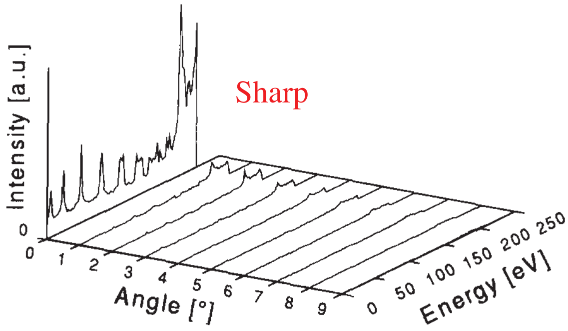
Bi-modal peak at 20 mTorr, 200 V rf bias



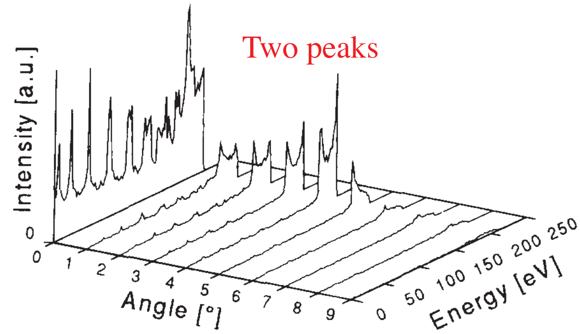
$\mathcal{E}_i = 145$ V at 5 mTorr, 150 V rf bias

MONTE CARLO SIMULATION OF IAD

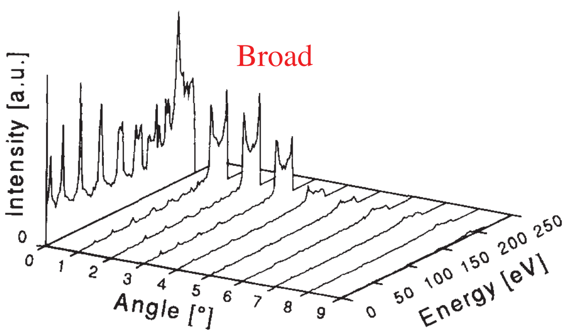
- Argon ions, 13.56 MHz, 10 mTorr, rf bias = 200 V, $n_e = 10^9$ cm^{-3}
- Charge-exchange and elastic collisions with energy-dependent differential cross sections used



Anisotropic ion starting distribution



Isotropic angular starting distribution



Cosine angular starting distribution

(K. Börnig and J. Janes, 1995)
Also O_2^+, O^+, CF_3^+, CF_2^+, CF^+

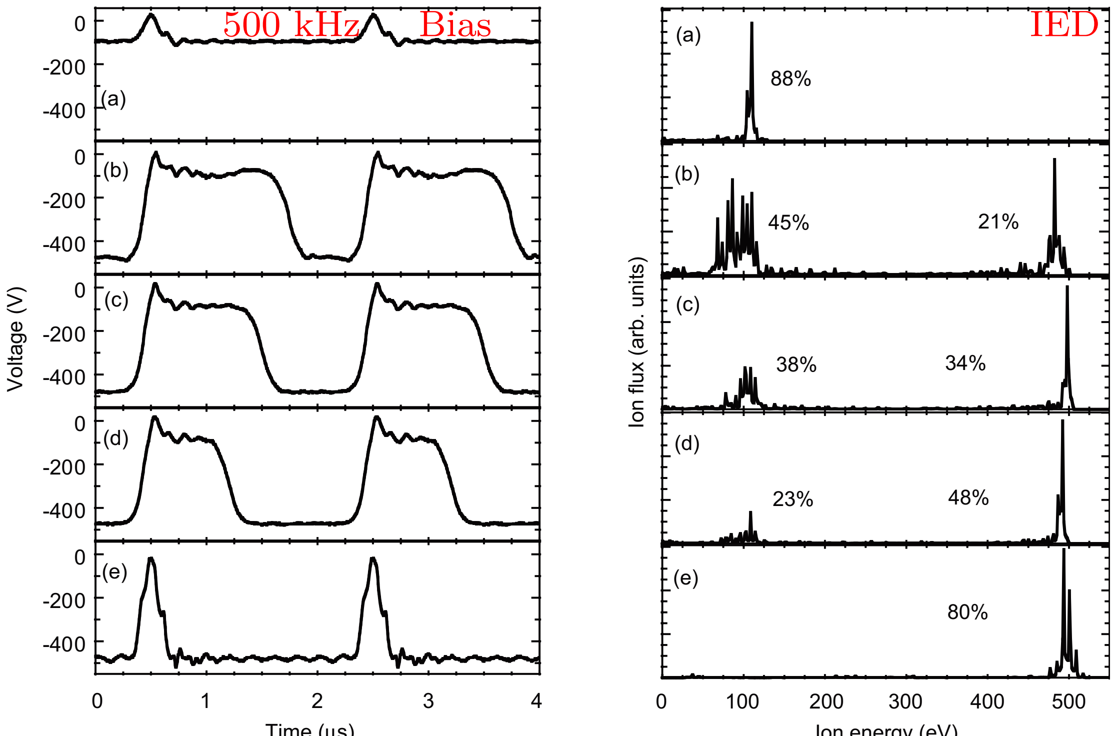
PULSED SHEATHS

Pulses are "long" ($\sim$ few μs)

IED CONTROL USING PULSED WAVEFORMS

(F.L. Buzzi et al, 2009)

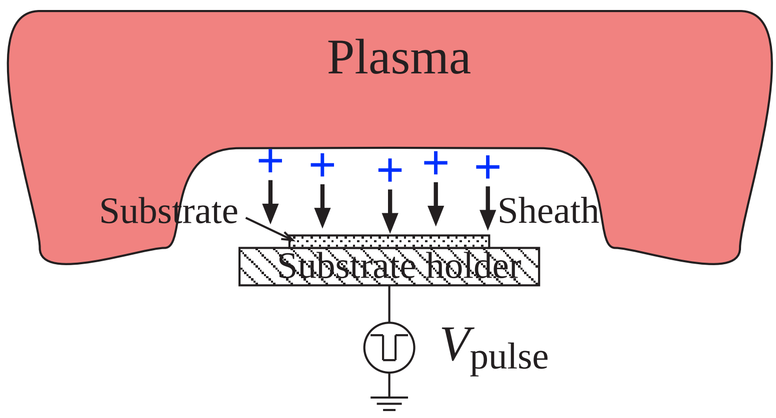
- Tailor the shape of the bias waveform on the substrate
- 18 mTorr, 700 W, $Ar/C_4F_8/O_2$ helicon plasma



PLASMA IMMERSION ION IMPLANTATION (PIII)

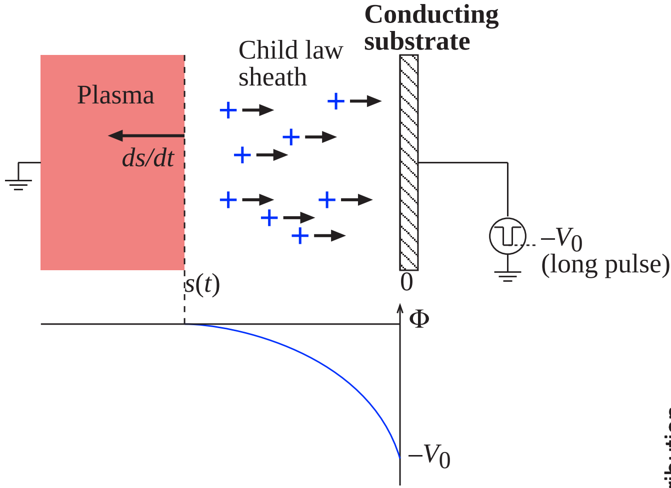
(A. Anders, 2000)

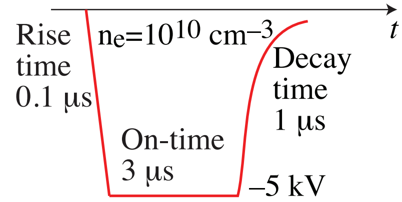
- Apply a series of (negative) high voltage pulses to implant ions into a substrate
- Plasmas are low pressure (collisionless ions) with $n_e \sim 10^{10}$ cm^{-3}
- Pulses are 1–10 μs at 3–30 kV, with pulse rate of 100–10^4 Hz



CONDUCTING SUBSTRATES

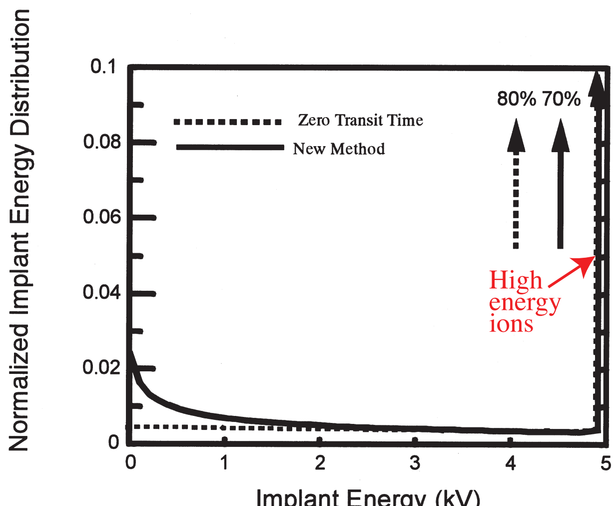
(M.A. Lieberman, 1989; J.T. Scheuer et al, 1990)





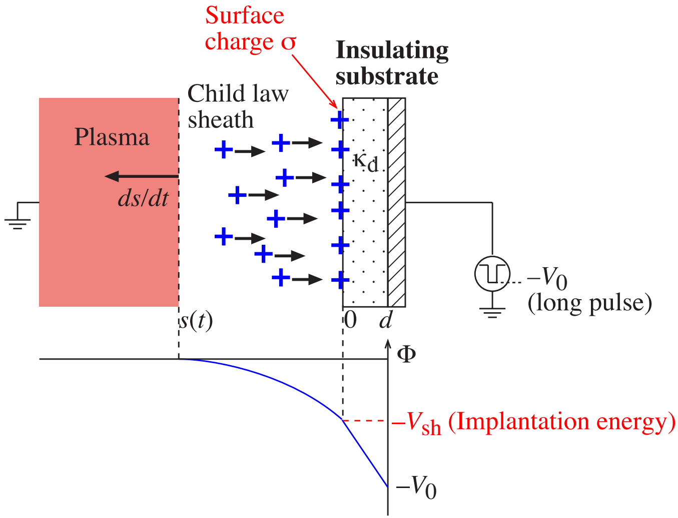
- High energy monoenergetic ions — pulse on-time
- Low energy ions — Rise and decay times, initial uniform density ("matrix") sheath, ion transit time effect

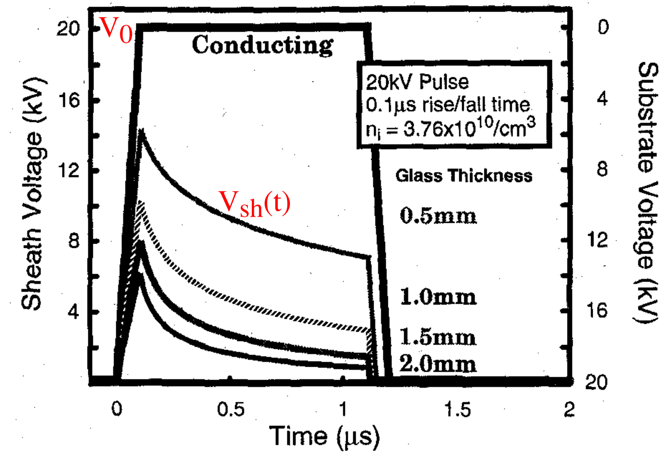
(B.P. Linder and N.W. Cheung, 2001)



INSULATING SUBSTRATES

(G.A. Emmert, 1994)





(B.P. Linder and N.W. Cheung, 1996)

- $V_{\rm sh}(t)$ is the pulse on-time ion implantation energy
- Initial $V_{\rm sh} < V_0$ because V_0 divides across {sheath + dielectric}
- $V_{\rm sh}$ decreases with time due to charge build-up on dielectric
- $V_{\rm sh} \to 0$ when dielectric fully charges

$\Longrightarrow$ broadened, reduced energy IED's

SUMMARY

CAPACITIVE RF SHEATHS

- Ion energy distribution — good data, simulations, and models
- Ion angular distribution — limited data, incomplete understanding and models

PULSED SHEATHS

- Pulse shaping — a promising approach
- Ion implantation energy distribution — basic understanding, hardly any data

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