# 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

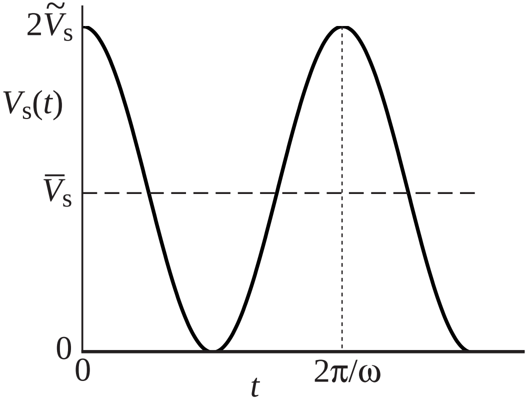
(E. Kawamura et al, 1999)

# 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

$\omega\tau_i$ =rf frequency × ion transit time across sheath

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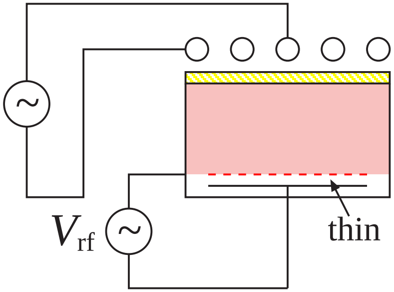
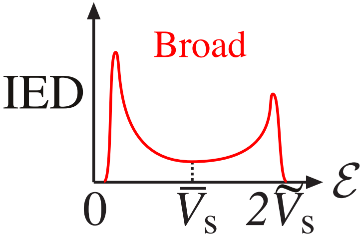
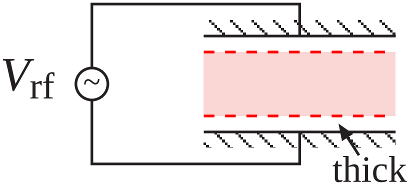
# SHORT AND LONG ION TRANSIT TIME

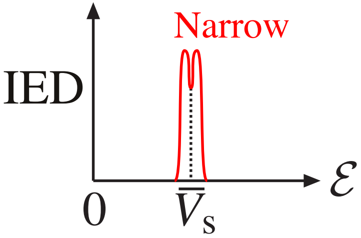
- High plasma density (thin sheath), $\omega\tau_i \ll 1$





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

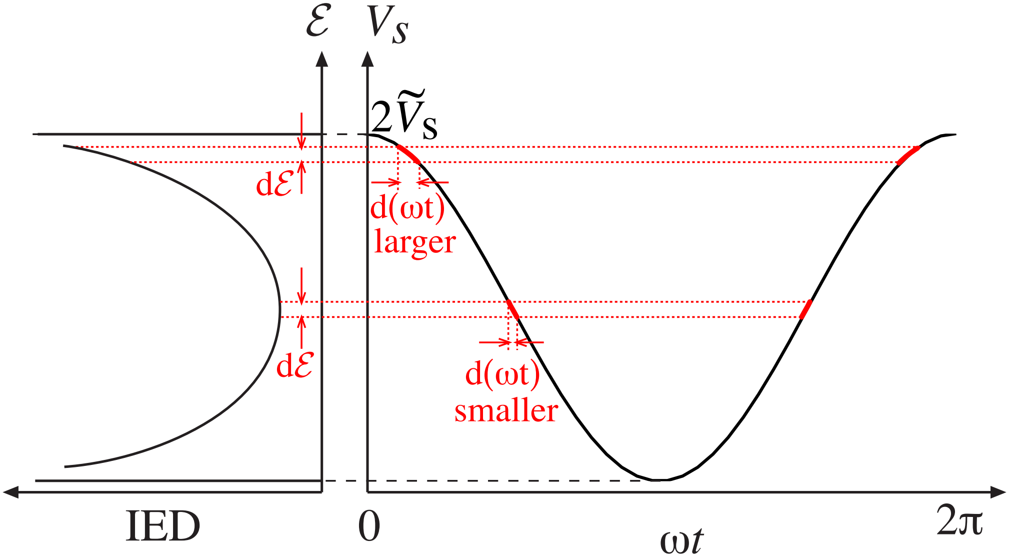




- Bi-modal (two-peak) IED's are seen

# BI-MODAL IED'S — SHORT TRANSIT TIME

- Ions "see" the instantaneous voltage across the sheath



- Two phase intervals $\mathrm{d}(\omega t)$ map into a single energy interval $\mathrm{d}\mathcal{E}$

  For a given $\mathrm{d}\mathcal{E}$, more ions strike the substrate if $\mathrm{d}(\omega t)$ 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

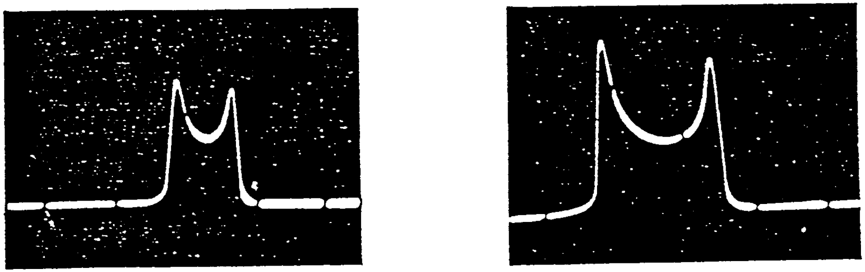
- Ions "see" nearly the average voltage $\overline{V}_s = \widetilde{V}_s$ across the sheath
- Bi-modal IED with narrow energy spread

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

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

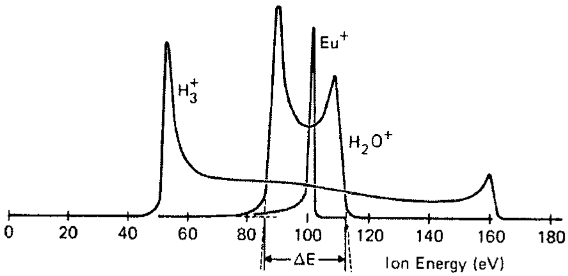
$$\Delta\mathcal{E} \propto \frac{1}{\sqrt{M}}$$

- Earliest measurement (J. Erö, 1958)

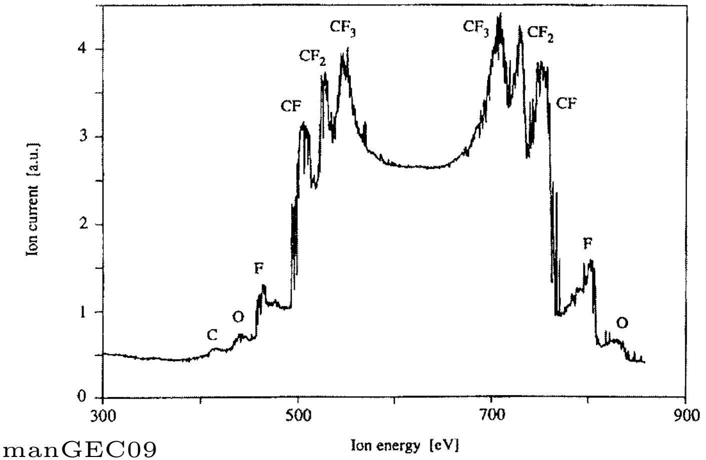


# SOME EXPERIMENTAL RESULTS

- 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)

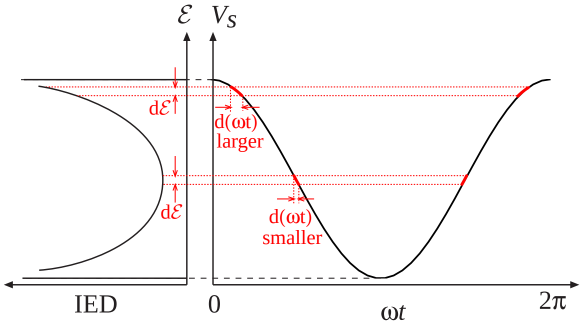


- Capacitive discharge, $CF_4$ at 3 mTorr (Note $\Delta\mathcal{E} \propto 1/\sqrt{M}$)
  (A.D. Kuypers and H.J. Hopman, 1990)

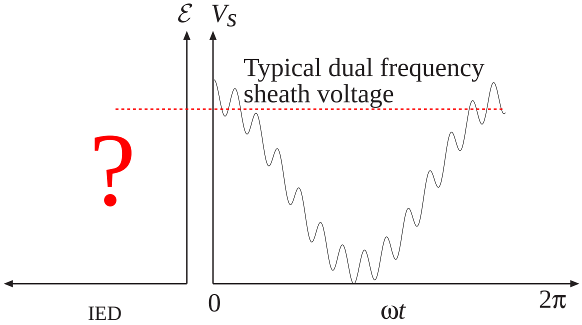


# DUAL FREQUENCY CAPACITIVE SHEATHS

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



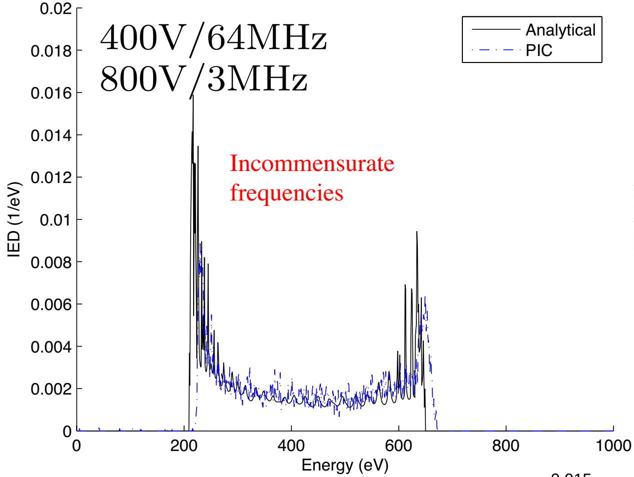
- Dual frequency
  More than two times/cycle map to a given ion energy $\mathcal{E}$

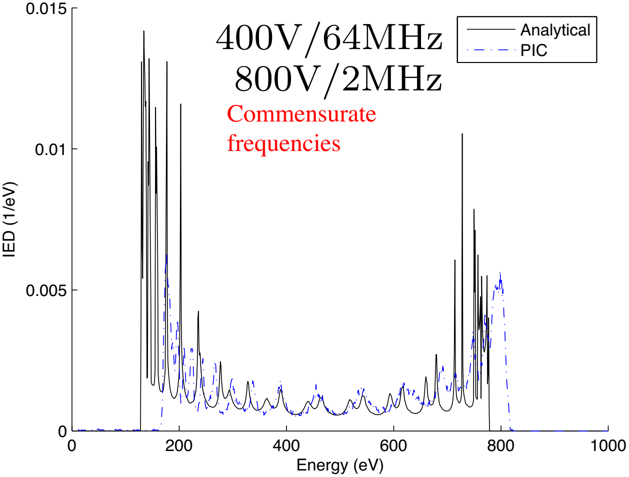


- For $\omega\tau_i \ll 1$, ions respond to the full time-varying sheath voltage
  For $\omega\tau_i \gg 1$, ions respond to the time-average sheath voltage

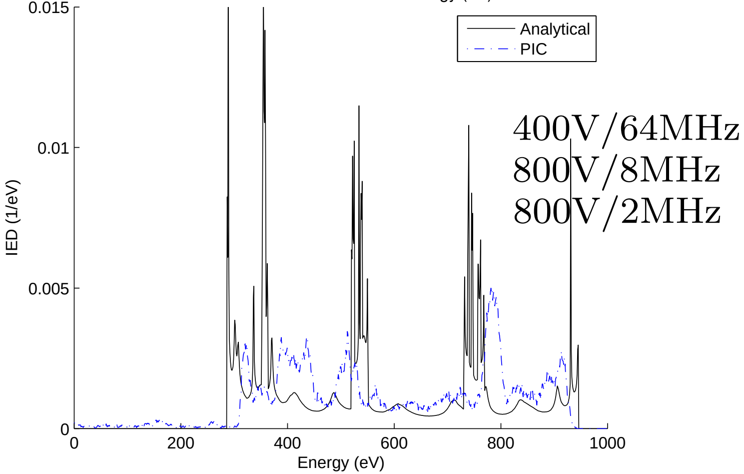
$$\boxed{\Longrightarrow \text{low-pass filter}}$$

# DUAL/TRIPLE FREQUENCY PIC SIMULATIONS





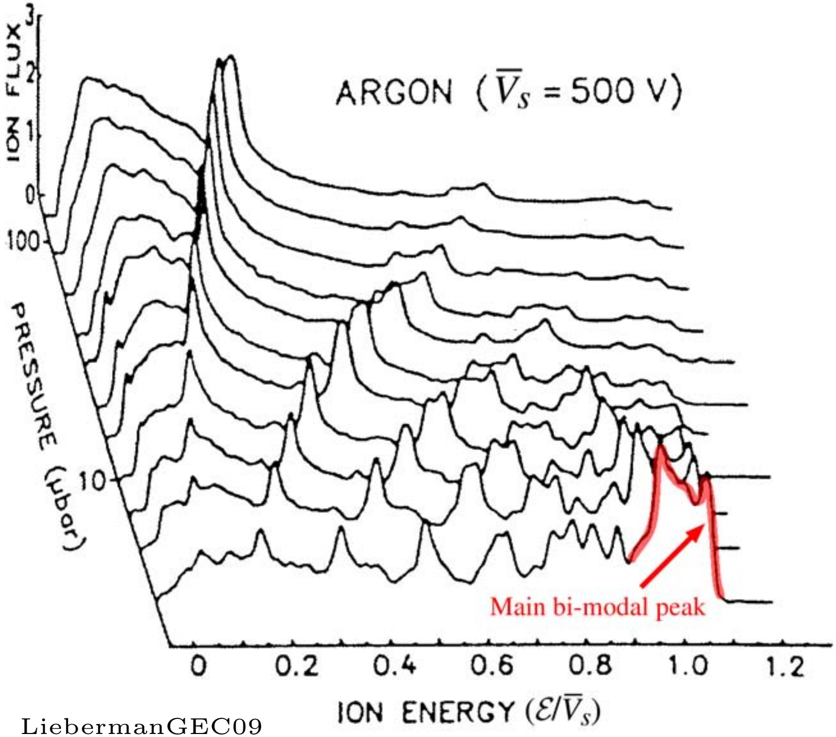
Gap=3 cm
p=30 mTorr
Collisionless ions
(A. Wu et al, 2007)



# ION-NEUTRAL COLLISIONS IN THE SHEATH

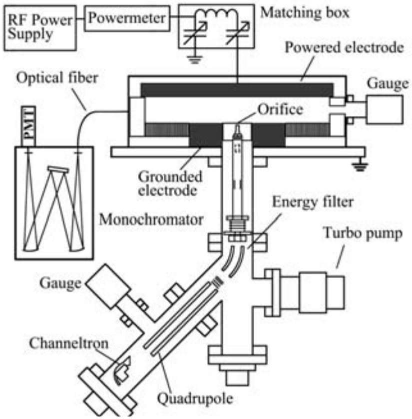
- Ion-neutral charge transfer collisions create slow ions within the sheath
- Groups of slow ions are accelerated, leading to additional peaks in the IED (C. Wild and P. Koidl, 1991)

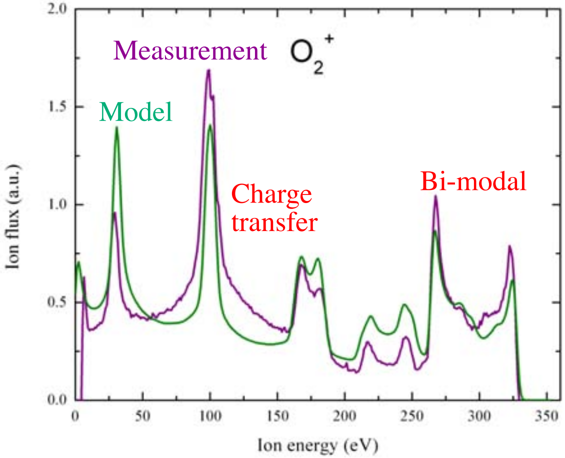
- IED's measured in a collisional rf discharge for various pressures; the low energy peaks arise from a combination of charge exchange collisions and rf modulation



# COLLISIONAL IED — MEASUREMENT AND MODEL

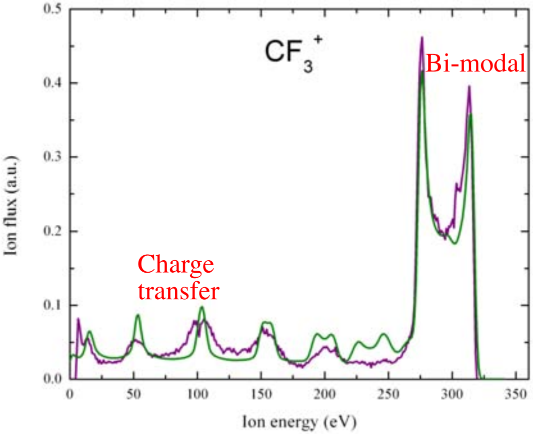
(13.56 MHz, 50 W, 4 cm gap, Ar/$CF_4$/$O_2$ = 30:5:10 mTorr, W.C. Chen et al, 2009)





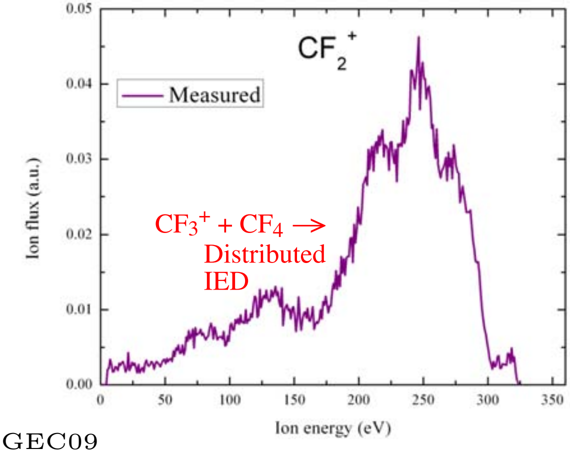
Charge transfer

Bi-modal



Bi-modal

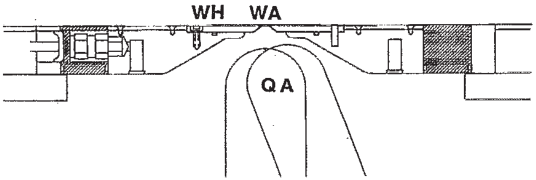
Charge transfer



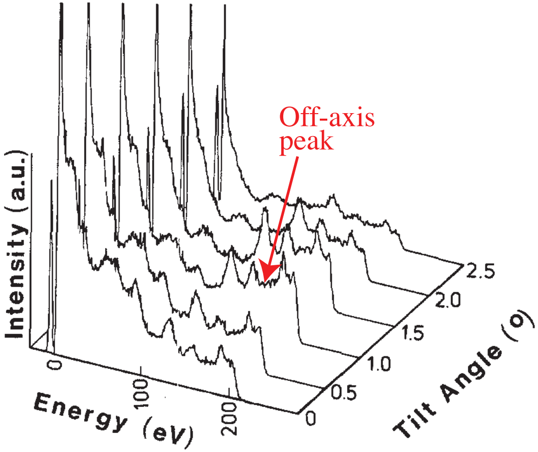
$CF_3^+ + CF_4 \rightarrow$ Distributed IED

# ION ANGULAR DISTRIBUTION (IAD)

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

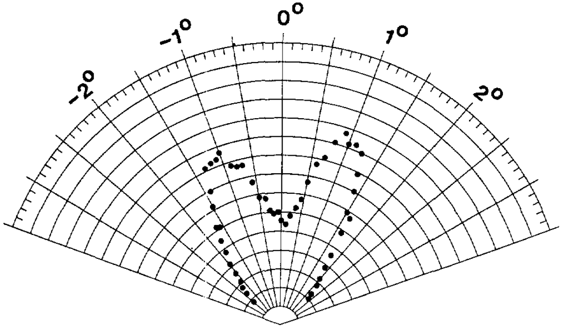


Tilting analyzer

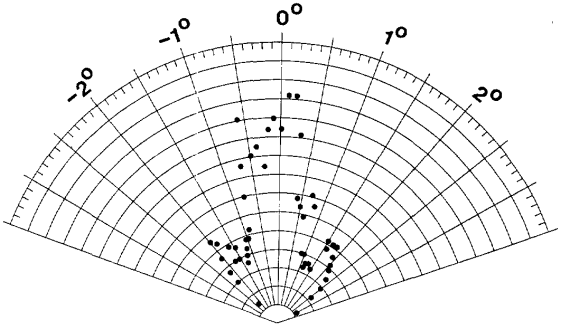


Off-axis peak

40 mTorr, 200 V rf bias



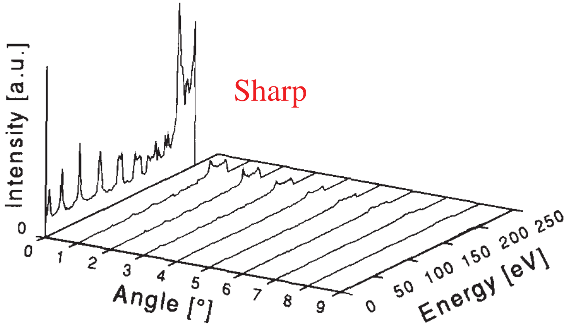
Bi-modal peak at 20 mTorr, 200 V rf bias



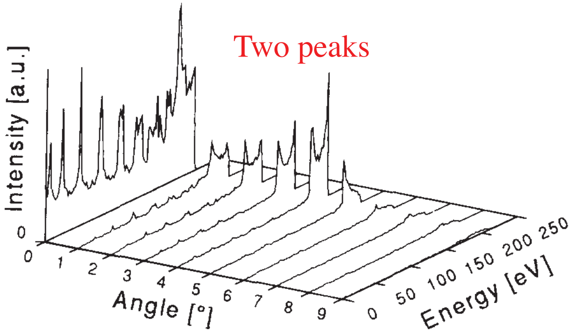
$\mathcal{E}_i = 145$ V at 5 mTorr, 150 V rf bias

# MONTE CARLO SIMULATION OF IAD

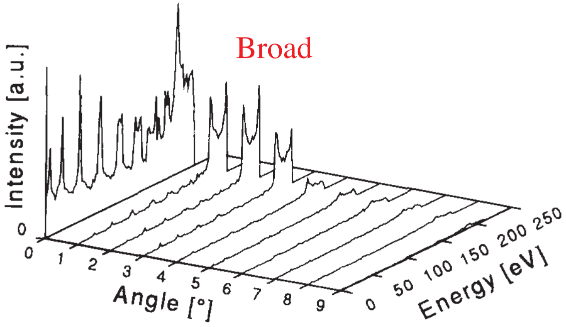
- Argon ions, 13.56 MHz, 10 mTorr, rf bias = 200 V, $n_e = 10^9\ \text{cm}^{-3}$
- Charge-exchange and elastic collisions with energy-dependent differential cross sections used



Anisotropic ion starting distribution



Isotropic angular starting distribution



Cosine angular starting distribution

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

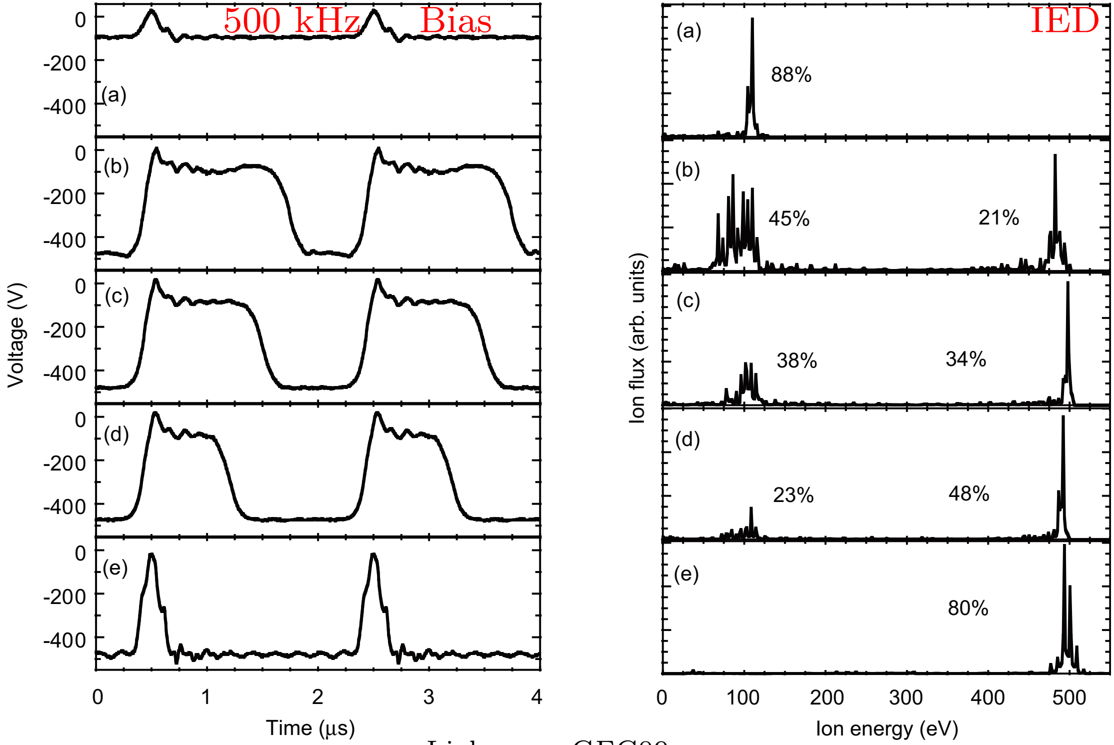
# PULSED SHEATHS

Pulses are “long” ($\sim$ few $\mu$s)

# IED CONTROL USING PULSED WAVEFORMS

(F.L. Buzzi et al, 2009)

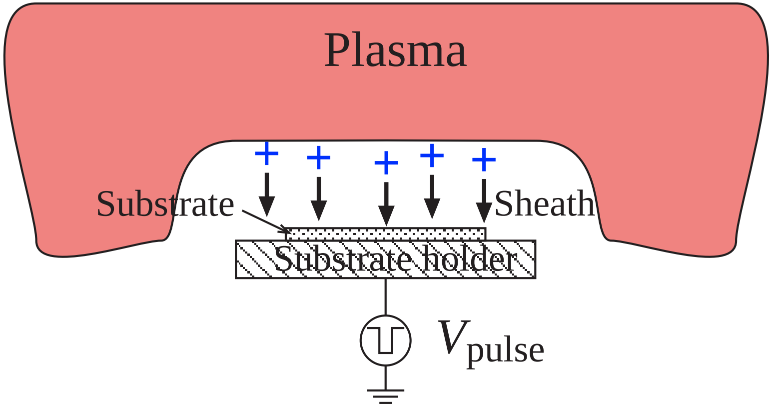
- Tailor the shape of the bias waveform on the substrate
- 18 mTorr, 700 W, Ar/$C_4F_8$/$O_2$ helicon plasma



# PLASMA IMMERSION ION IMPLANTATION (PIII)

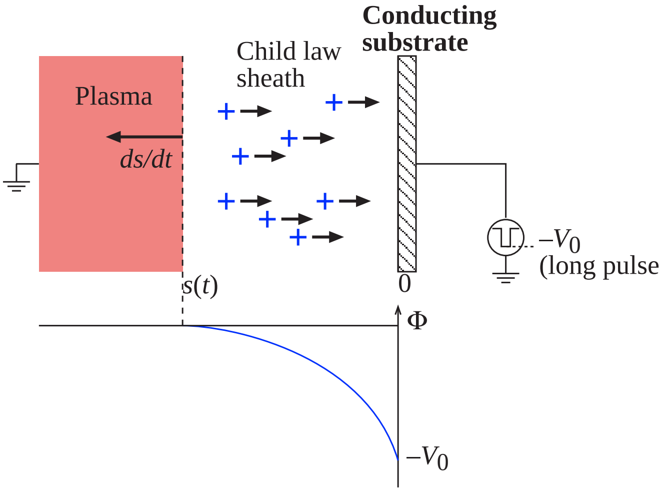
(A. Anders, 2000)

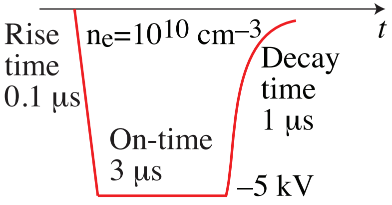
- Apply a series of (negative) high voltage pulses to implant ions into a substrate
- Plasmas are low pressure (collisionless ions) with $n_e \sim 10^{10}$ cm$^{-3}$
- Pulses are 1–10 $\mu$s at 3–30 kV, with pulse rate of 100–$10^4$ Hz



# CONDUCTING SUBSTRATES

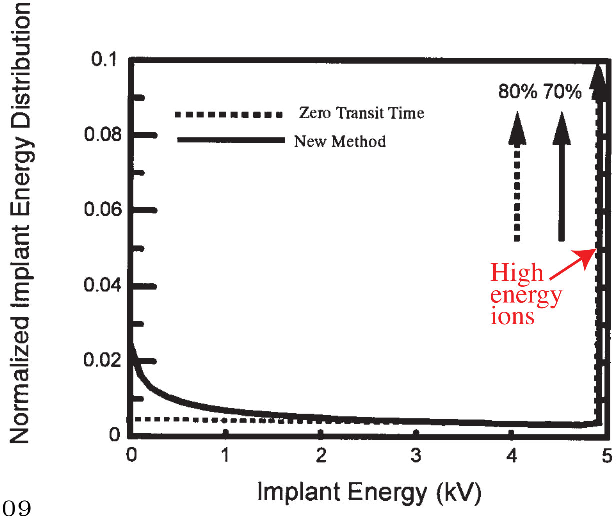
(M.A. Lieberman, 1989; J.T. Scheuer et al, 1990)





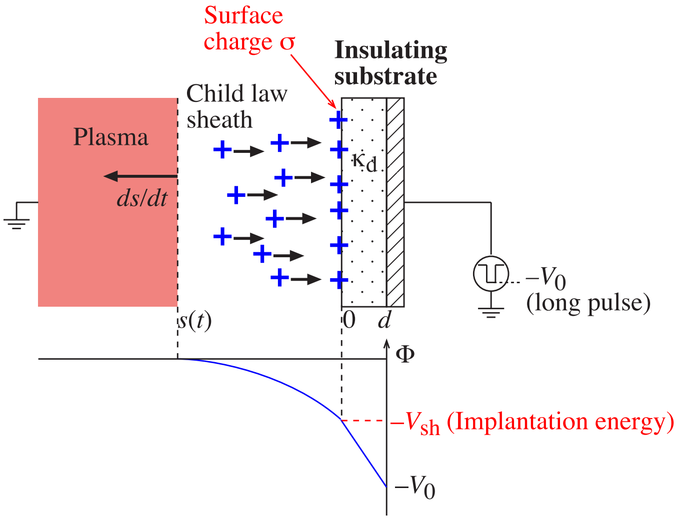
- High energy monoenergetic ions — pulse on-time
- Low energy ions — Rise and decay times, initial uniform density ("matrix") sheath, ion transit time effect

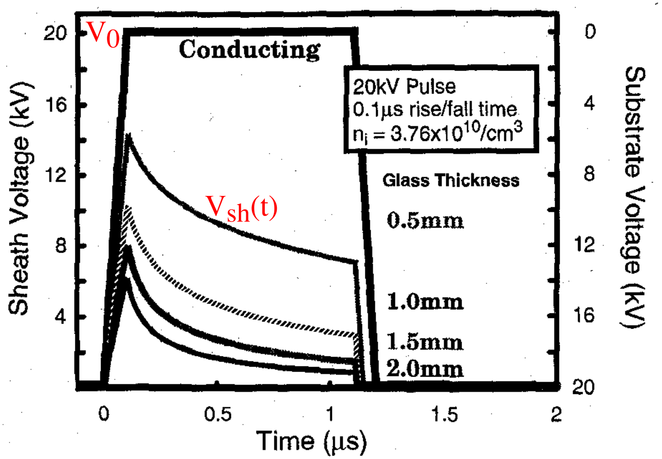
(B.P. Linder and N.W. Cheung, 2001)



# INSULATING SUBSTRATES

(G.A. Emmert, 1994)





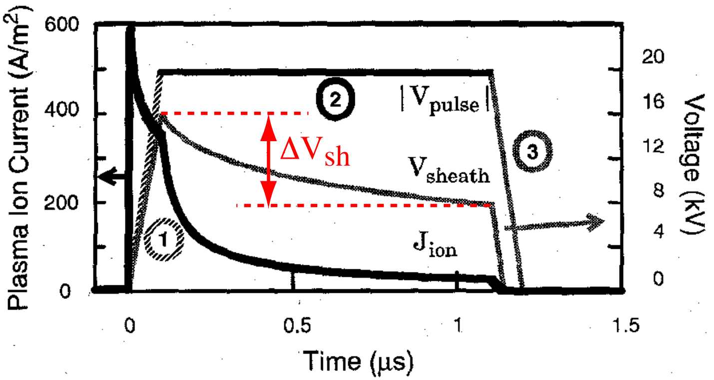
(B.P. Linder and N.W. Cheung, 1996)

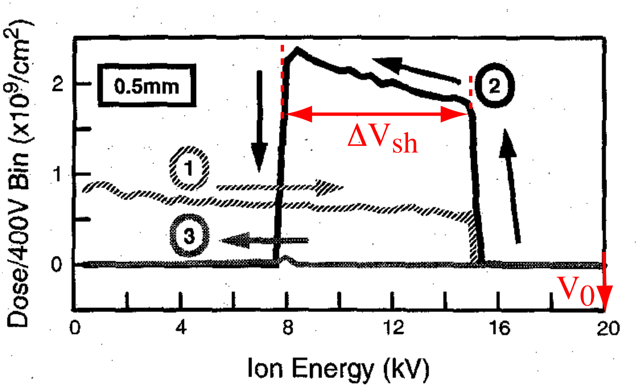
- $V_{\mathrm{sh}}(t)$ is the pulse on-time ion implantation energy
- Initial $V_{\mathrm{sh}} < V_0$ because $V_0$ divides across $\{$sheath + dielectric$\}$
- $V_{\mathrm{sh}}$ decreases with time due to $\sigma$ build-up on dielectric
- $V_{\mathrm{sh}} \longrightarrow 0$ when $\sigma = (1+\gamma_{\mathrm{sec}})en_e s(t) \longrightarrow \kappa_d \epsilon_0 V_0/d$
  ($\gamma_{\mathrm{sec}}$ = secondary emission coefficient of dielectric)

# ION ENERGY FOR DIELECTRIC SUBSTRATES

- Dielectric charging leads to a broadened IED at high energies

($n_e = 10^{10}$ cm$^{-3}$, 0.5 mm glass substrate, B.P. Linder and N.W. Cheung, 1996)





(1) Rise time yields broad IED

(2) Pulse on-time yields broadened, reduced energy IED

(3) Decay time yields (small) broad IED

# 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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