NEP (Nonambipolar Electron Plasma)

- Introduction: TEL’s beam-plasma & Austin plasma lab’s beam-plasma & why NEP
- Experimental setup (& potential NEP applications)
- EEDf Result & Discussion
  (1) NEP Pressure
  (1) NEP heating mechanism
  (2) Sheath potential dependency on e⁻-beam power damping
  (3) EEDf dependency on Sheath potential
  (4) Mono-energetic IEDf and its half-width
  (2) ICP Pressure
  (3) ICP Power
- Conclusion

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bulk-fin Etch

good etch

RIE lag

Reverse-MOCVD
Cu Etch
“non-volatile” metal
“softer” etch
plasma beam epi
plasma beam thruster
…x-ray laser
$V_{DC} = -1kV$ constant

ballistic $e^-$ transit time $\sim 1ns$

$V_{RF}$

$V_p(t)$

$V_{RF}(t)$

$t, V_{RF} \mid t$

$\sim 35ns$

trap period

$e^-$ return to ground

$DC$ must oppose RF

$13.56$Mhz electrode

axis $x$

thermal e$^-$

dump

$V_{RF}$

$V_p(t)$

$V_{RF}(t)$

$V_p(t)$

$V_{RF}(t)$

$V_{RF}$

$t, V_{RF} \mid t$

$\sim 35ns$

trap period

$e^-$ ballistic (BE)

$e^-$ thermal

$e^-$ return to ground

DC electrode

RF electrode

DC electrode

RF electrode

$35ns$

trap period

$e^-$ ballistic (BE)

$e^-$ thermal

$e^-$ return to ground

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DC electrode

RF electrode

$35ns$
DC/RF background (continue)

\( v_z \) vs \( z \) phase space plot (PIC)

- Top-down heating
  - DC electrode (3cm spacing)
  - RF electrode
  - ballistic electrons (BE)
  - thermal core
  - middle-energy peak
  - \( j_{\text{ion}} = e n_e v_B \)

- Bottom-up heating
  - Top electrode (3cm spacing)
  - RF electrode
  - Maxwellian tail ionization
  - generic RF CCP
DC/RF background (continue)

EEPf of the previous page (30mt / –1kV)

DC+RF Hybrid vs Generic RF-ccp

50eV to 200eV range got bumped up through Landau Damping

energetic non-Maxwellian

beam-wave interaction

ballistic e–

EEPf

dN(E)

EEDf

= EEPROMf √E

Energy (eV)

example | RF power | DC power | total | plasma density | Ion-beam DC cathode heating | e– beam power
---|---|---|---|---|---|---
RF-only (13.56Mhz RIE) | 1500W | 0 | 1500W | ~1E(10) | N.A. | N.A.
DC/RF | 800W | 400W | 1200W | ~4E(10) | ~ >360W | ~ <40W
**summary of DC/RF plasma characteristics**

As the RF sheath collapses, the trapped BE and the localized plasma waves are dumped onto the wafer, prompting e–beam stimulated surface chemistry and reducing HAR feature shadings.

1. injected BE are trapped and grow
2. BE generate localized plasma waves as BE lose their energy
3. standing wave resonance localizes a preferred mode becoming the middle-energy peak whose energy is in the range of efficient ionization
4. A single Maxwellian regardless the run condition (could simplify gas-phase chemistry)
5. <25eV EEDf all Maxwellians merge \( T_e \approx 1.8\text{eV} \)

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**SWR model**

**EEDf**
Figure 1

plasma-1 = electron-source plasma: e.g., ICP, 5E(-3)<P<15E(-3) torr
e.g., V_p~25V

plasma-2 = NEP: e.g., 1E(-4)<P<3E(-3) torr
injector double layer
e.g., V_p~700V

note, plasma-1 is the “electron source” which could be any type of plasma,
e.g., filament, Helicon, ion-beam plasma; partially or fully ionized.
plasma-1 = electron-source plasma:
e.g., ICP, 5E(-3)<P<15E(-3) torr
e.g., $V_p \sim 25V$

plasma-2 = NEP:
e.g., 1E(-4)<P<3E(-3) torr
$V_p \sim 700V$

**Electron Source side:**
- mono-energetic homogeneous plasma beam epi
- Plasma Beam thruster
- EUV (stimulated emission?)

**NEP side:**
- HARC or mask etch by space-charge neutral Plasma Beam (momentum activated)
- Electron Beam stimulated surface reaction
- Neutral Beam etching (with insulator neutralizer grid)
Figure 2
Pressure dependence

$V_S$ is shown controllable from $80V$ to $580V$ with the accelerator voltage from $V_A=80V$ to $V_A=600V$.

NEP $V_P \sim V_A$
$V_S \sim V_A - V_{fB}$
accelerator current $\sim$ injected energetic $e^-$-beam current and $150mA$ total current $\sim 19Acm^{-2}$.

$V_A \geq 250V @ 3mT$, sheath collapses.
Figure 10

Electron decay instability (all electrostatics, for $\omega_0 > \omega_p$)

Just one possible NEP heating mechanism: e.g., recurring electron decay instability + Landau damping

$v_b = \text{beam-electron velocity}$
$v_\phi = \text{primary } e^- \text{ wave phase velocity}$
$v_{b2} = \text{slowed energetic electrons velocity}$
$v_{\phi2} = \text{secondary } e^- \text{ wave phase velocity}$
$\omega_0 = \text{high-}v_\phi \text{ primary } e^- \text{ wave}$
$\omega_2 = \text{low-}v_\phi \text{ } e^- \text{ wave continuum}$
Figure 3

$V_A=250\text{V} \text{ EED}_f$ shows a “signature transition” this looks similar to the NEP EED$_f$ with all the <40eV population cut off
Figure 4

(a) 1mT

(b) 2mT

(c) 3mT

(d) 500V

Different scale

IEDf (a.u.)

Ion energy (eV)
Langmuir solution to the plasma equation:

\[ |\phi_S| > kT_e/2 \) (0.854\( kT_e \); \( v_B \sim 1.3v_S \))

\[ \phi(z) \]

equilibrium plasma

e- free sheath

thermal presheath

ionization volume

anisotropic presheath

presheath

\[ \frac{d^2\phi}{dz^2} = 4\pi n_0 \left[ \exp\left(\frac{\epsilon\phi}{kT_e}\right) - \frac{1}{\sqrt{1 - \frac{2\epsilon\phi}{Mv_B^2}}} \right] \]

\[ \phi(w) \]

\[ z = 0 \]

\[ \phi_s \]

\[ \phi_S \]

\[ \phi_W \]

\[ n_o \exp\left(\frac{\epsilon\phi}{kT_e}\right) + n_{b0} \int_{\epsilon}^{\epsilon_{max}} \frac{1}{\sqrt{1 + \frac{\epsilon\phi}{\epsilon}}} f(\epsilon)d\epsilon - n_0 \int_{\epsilon}^{\epsilon_{max}} \frac{1}{\sqrt{1 - \frac{2\epsilon\phi}{Mv_B^2}}} g(\epsilon)d\epsilon \]
Figure 5

300W ICP & 2mT NEP

(a) Accelerator current (mA) vs. Accelerator voltage (V)

(b) Floating potential (V) vs. Accelerator voltage (V)

(c) Sheath potential (V) vs. Accelerator voltage (V)
Figure 6

(a) Electron energy (eV)

(b) Electron energy (eV)

Figure 7

(a) Ion energy (eV)

(b) Ion energy (eV)
Figure 8  10mT Ar ICP & 2mT N$_2$ NEP

Figure 9

EEDf (a.u.)

200W ICP

250W ICP
ICP10mT400W_NEP2mT vs. Probe location

Accelerator voltage: 450V

Intensity (dBm) vs. Frequency (Hz) for different probe locations:
- 170mm
- 145mm
- 115mm
- 85mm
- 50mm
- 25mm
- 5mm
The experiments are conducted with NEP in the 1-3mT pressure-range and its accelerator voltage varied from $V_A=+80$ to $V_A=+600$V. The NEP EEDf has a Maxwellian bulk followed by a broad energy-continuum and a pronounced population in the electron-beam energy regime. The non-ambipolar beam-current injected into NEP is quite high, in the range of 10s Acm$^{-2}$ and it heats NEP through beam-plasma instabilities. The remnant of the injected electron-beam power terminates at the NEP end-boundary floating-surface setting up sheath potentials from $V_S=80$ to $V_S=580$V in response to the applied values of $V_A$. As a result, the floating-surface is bombarded by a space-charge neutral plasma-beam whose IEDf is near mono-energetic. When the injected electron-beam power is adequately damped by NEP, its end-boundary floating-surface $V_S$ can be linearly controlled at almost 1:1 ratio by $V_A$. In addition, NEP does not have an electron-free sheath in the traditional sense and instead, its “sheath” is a widen presheath that consists of a thermal presheath followed by a “anisotropic” presheath, leading up to the end-boundary floating-surface. As a result, the ion-current of the plasma-beam is much higher than what a conventional thermal presheath could supply. If the NEP parameters cannot damp the electron beam sufficiently, leaving an excess amount of electron-beam power dumped on the floating-surface, $V_S$ will collapse and becomes irresponsive to $V_A$. 

**conclusion**