A CCP-Plasma Source with Operation in the High-VHF to UHF Frequencies and Scalability to 450mm Substrates

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Outline

First half:
• Extensible high-VHF plasma source technology
  – Unique, identifiable, enabling technology for arbitrary frequency multi-tile plasma source

Second half:
• Process applications
  – Push-pull rf power delivers VHF plasma chemistry

Conclusion: Opportunity to use high-VHF frequency to further improve process results, even on large substrates!
• All companies have the same technology
• Only difference in customer support and system stability & understanding
TCP efficiencies
Different $T_e$ (different chemistry)
- cold bulk $T_e$, hot tail $T_e$
Fig. 29. Etching profiles for TiN (500 Å)/Al (5000 Å)/TiN (1500 Å) fabricated in the Cl2 ICP and UHF plasma. In the ICP source, the Al etching was isotropically carried out and large side etching was observed. In the UHF plasma, the Al was anisotropically etched and the vertical etching profile was realized in pure Cl2 plasma. Source power: 1 kW, bias power: 100 V, pressure: 3.5 mTorr.

Dielectric etch

• ICP vs CCP
  – Lam, TEL, & AMAT (for a while)
  – Dielectric etch with CCP no longer ICP

• Frequencies?
  – 2002 → 2010
    • Lam Exelan 27MHz and Flex adds 60MHz
    • TEL SCCM 60 & 100 MHz (depends on process)
    • AMAT Enabler 162 MHz
What’s available?

• Good and bad points
• ICP, diffusion, so distance from source to wafer only good for one pressure: sol’n is inner/outer power
• CCP, increase $f$ for better process, bad uniformity: sol’n (watch this presentation)

• Lam: stable platform, - uniformity for some processes
• AMAT: highest frequency (162MHz), worst proces-window and uniformity overlap
• TEL: 60 MHz, can get 100MHz, but uniformity is an issue particularly for some processes.
• TEL: Radial Slot Antenna, loading by one slot affects power distribution
• Advantages in peak performance with increasing frequency

• We want present advantages to carry-forward to 450mm

• But challenges in terms of process uniformity and tool stability/ chamber matching
Figure 6. Emission intensity profile of an argon plasma (55 W RF power, 0.1 Torr pressure) across the front full-width window for three frequencies. The intensity is integrated across the electrode gap and normalized to the maximum intensity. The position 0 cm corresponds to the side of the reactor where the RF is connected.

Voltage non-uniformities at high f

Wavelength effects occur when \( r_{\text{substrate}} > \frac{\lambda_{\text{vac}}}{4} \sqrt{\varepsilon} \approx \frac{\lambda_{\text{vac}}}{15} \)

\( \text{Ion flux to the substrate for plasma diode versus frequency. From Appl. Phys. Lett., Vol. 83, No. 2, 14 July 2003 A. Perret, P. Chabert, J.-P. Booth, J. Jolly, J. Guillou, and Ph. Auveray Superimposed are the calculated profiles, i.e., } \cos^2(2\pi x / l) \text{ where } l = 0(1+\text{delta/s}) \text{ given by Eq. ~1/~. We chose s55 mm at 13.56 MHz and 60 MHz and s53.5 mm at 81.36 MHz. The solid line is the vacuum solution, } \cos^2(2\pi x / 10) \text{, at 81.36 MHz.} \)
**rf current**

**Tool-2-tool matching**
- Chamber access
- EMC
- Variable gap
- Match-box connection

*All much harder with Increasing frequency*
Substrate scaling

Single-electrode, or multi-tile in parallel
• Impedance scales as 1/Area
• Increasing f the loaded electrode approaches phase angle of 90-degrees: very challenging rf problem, with low power efficiency, high-stress high-sensitivity rf power delivery

Multi-tile w/ independent rf power delivery paths
• Impedance of each tile constant, larger area → more tiles, impedance at each tile constant.
• Circulating currents lower, rf-power-efficiency higher, low-stress low-sensitivity rf power train
• What we want is arbitrary frequency
  – Use frequency for process improvement
• And scalable to large size
  (including 450mm)
Scalable plasma source with arbitrary frequency
- Pick the frequency that gives you the best process
- Deploy on system that has best economic value

- Checkerboard with neighboring tiles out-of-phase
- No wavelength effects
  - Wavelength effects occur when $r_{\text{tile}} > \lambda_{\text{vac}} / 4/\sqrt{\varepsilon} \approx \lambda_{\text{vac}} / 15$
CCP: Increased efficiency with frequency

- rf power driving into a dielectric-loaded (plasma) capacitor
- Impedance drops with frequency

\[ z_c = \frac{-j}{\omega C} \]

- For fixed power:
  - Frequency ↑, |z| ↓, Current ↑, Voltage ↓
  - Ohmic power into plasma (I^2R) Increases
  - Ion energy drops in-scale with Voltage
'Hawaii’ Plasma Source

Diameter: 300 mm quartz wafer facing plasma
Electrodes: 55mm wide
           65mm high
           10mm gap
Power: Checkerboard
Vacuum: 400 mm diameter
        300 mm long

Langmuir probes:
Scanned across the diameter of the chamber across the 4 electrode direction
Distance to quartz wafer of 3.5 cm

Ion Flux proportional to voltage across a sense-resistor
400 MHz Operation in ‘Hawaii’

- 400 MHz
- 500 W max

3-stub tuner

2-D electrode array
300mm diameter source size

\[ f \approx 400 \text{ MHz} \]

\[ \lambda_{\text{vac}}/4/\sqrt{\varepsilon} \approx 5 \text{ cm} \]
Higher frequency delivers more power into the electrons:
- lower power, larger area, yet higher Ion-current

20x (+) increase in ion flux efficiency
(88eV / e-ion pair)
Multi-tile Plasma Source

- Operates at 400 MHz, *no wavelength effects!*
- Power division / distribution technique demonstrated.
- Breakdown at 100 mTorr - 3 mBar below 200 W
- Operation between 0.5 mTorr – 7 mBar
- High-frequency reduces voltage (and power into ion energy), increases current (and power into plasma electrons), therefore more ion flux per watt rf power.
So what’s next?

• High-VHF to UHF looks good
• What remains?

1. Higher pressure & smaller tiles
   – Issue: Plasma localized to one tile-gap?

2. How do you power all these tiles?
Using conventional rf-power splitters we need:
\[ \div 64 \text{ rf power splitter} \]
\[ \div 2 \text{ @ } 180^\circ \]
Followed by 5-banks of \( \div 2 \) splitters
… Followed by 64 match-boxes!
Tile layout for round substrates?

• This requires ÷24 (/2/2/2/3) ÷3 is new technology, more parts, more problems.
• 3-rows is ÷54! (/2/3/3/3)
• An 8x8 array using existing technology is comprised of:
  - \( \div 2, 180^\circ \) splitter
  - 5-layers of \( \div 2, 0^\circ \) splitters

• And still, each splitter is 50-Ohm in, 50-Ohm out, so each tile needs its own match-box (!)
• Power splitting accurate to +/- 3°, +/- 3%
  - Neighboring tile could have errors of:
    - 15°, 75% vs 125% power imbalance

• Other customer with different aspect ratio glass and 6x10 array
  - \( \div 2, 180^\circ \) splitter
  - \( \div 3, 0^\circ \) splitter, and \( \div 5, 0^\circ \) splitter (!) at high power (!)
Motivation

(Multi-tile source is based on high-number multiple of tiles facing the plasma)

*Need new power splitter technology:*
- Balanced push-pull on tile pairs for zero net current
- Divide by arbitrary-N
  - 8x8 array same technology as 6x10 array
- Operate in the high-Q section
  - Single match-box for cost and stability requirements
- Provide high isolation between output ports
  - Plasma formation at one tile does not load other tile
- DC isolation so no series capacitor needed
- Broadband
  - Same technology for 60MHz – 500 MHz
PSTLD: Power Splitter and Transmission Line Driver

- Single stage power splitter for arbitrary-N output push-pull pairs
Coaxial transmission line with a short

$Z_1 \approx 0$ Ohms
Plot the voltage and current vs position

The PSTLD

The standing wave Current (Iz) profile Produces a standing wave Bt

Place loops in the Bt to couple power to the output ports.
Properties of The PSTLD

- Fully differential rf current and voltage
  - Zero net current at all rf phases
- Provides DC isolation
- Arbitrary N output ports
  - One solution independent of number of tiles
- Non-50-Ohm
  - Post match, so only one match for the whole system
- Auto-transformer
  - I/V on output ports match the load
FEM Modelling of The PSTLD

- 15 Winding PSTLD Modelling
  - EM wave propagation inside a PSTLD.
  - E/H fields in various scenarios (winding spacing, density, length, etc.)
  - Reflection losses (VSWR) vs. frequency
  - Minimum applicable winding proximity
  - Input impedance estimation
• 45 Winding PSTLD Modelling
  – EM wave propagation inside a PSTLD.
  • 50 Ohm Characteristic Impedance
    • 32 cm Outer Diameter, 14 cm Inner
    • 23 cm axial extent (λ/8 at 162 MHz)
-30 dB isolation between 2 output ports
Maintains high isolation for 45-winding PSTLD
(dk-blue, nearest neighbors, li-blue furthest separation)
• Films are grown in the *Mameluke* chamber installed at SKKU.
• 600mm x 720mm (substrates: Gen 3.5)
• Multi-tile plasma source operating at 162 MHz
  – also 600x720 mm²
  – Operated in push-pull configuration: zero net current
Low Temperature Poly-Silicon

- Poly-Silicon with electron mobility greater than 20 is needed for high performance TFT used to drive pixels in AM-OLED displays.
  - Present manufacturing is performed by using laser crystallization of a-Si grown by PECVD
  - Direct deposition of LTPS using advanced PECVD would give huge cost savings
• Boland @ IBM 1992, Iqbal @ Zurich 1982:
  – Hydrogen dilution $\rightarrow$ increase in crystallinity

• Growth starts amorphous, then transition to nc–Si:H over 100nm or so.

• Multi-step process of Si-growth $\rightarrow$ H-treat, repeat, ...

• Have to grow very slowly for faster transition to nc-Si:H
  (÷10 Silane flows)
• Expectations:
  – High plasma density
    • Low impedance sheath \(\rightarrow\) high ohmic plasma current
    • High conversion fraction of silane into film
  – High H* density
    • Fast formation of \(\text{SiH}_3^*\) (\(\text{SiH}_4 + \text{H} \rightarrow \text{SiH}_3 + \text{H}_2\))
      – \(\text{SiH}_3\) has high surface mobility, finds grain boundaries
    • Hydrogen abstraction from the surface
    • Dynamic local annealing of silicon growth surface for very-low-temperature PS

  \(\triangleright\) nc-Si:H growth

  – Low \(V_p\)
    • No amorphization of nano-crystalline film
100nm ncSi:H (LTPS)

- Process conditions:
  - T=220°C
  - 150 – 300 mTorr
  - 1600 – 2400 Watts (162 MHz)
    - (0.4 → 0.6 W/cm²)
  - 3% Silane flow, 1000sccm total flow
  - Gas-residence time, 75-100 m-sec
  - 600mm x 720mm substrate
  - Plasma gap, 1.5 – 2.0 cm
100nm ncSi:H

Spatial position across tiles (cm)

Dep-rate Å/sec

Crystalinity (%) (Volume Averaged)

Reasonable uniformity
High crystallinity across tile boundary
high-VHF for LTPS conclusions

• Achieve growth of nc-Si:H
• Reasonable growth rates, dynamic growth and anneal, no post-growth process
• Transition region from a-Si to nc-Si very shallow, <50Å
• 40 → 55% of the silane incorporated into film

• Much as expected for VHF system
• “1st go” at 162MHz is somewhat better than optimized 60MHz system
• Data as expected for VHF
• Our “high-VHF” somewhat better than 60MHz

• 785nm laser exciting optical phonon modes and crystalite surface modes.
• a-Si has mode at 480 cm\(^{-1}\) shift
  – c-Si has mode at 517 cm\(^{-1}\) shift
  – ~508 cm\(^{-1}\) peak: c-Si, surface-bound phonon mode
  – calculate crystalline fraction \(X_C = \frac{A_{518} + A_{508}}{A_{518} + A_{508} + \alpha A_{480}}\)
  and \(\alpha\) corrects for higher absorption by a-Si, we use \(\alpha = 1\)
  – Curve-areas fit using ‘Fi-tyk’,

nc-Si:H for Thin-Film Silicon Solar

- Tandem-cell yields higher efficiency
- nc-Si layer must be much thicker
- High Dep-rate for nc-Si:H is critical
a-Si:H dep-trends

FROM SMETS, MATSUI AND KONDO;
OPTIMIZATION OF THE HIGH RATE MICROCRYSTALLINE SILICON DEPOSITION CONDITIONS OF THE MICROHOLE-CATHODE VERY HIGH FREQUENCY SIH4/H2 PLASMA
Cell Efficiency
(Film quality)

Å/sec

13 MHz
40 MHz, Oerlikon, dielectric lense
75 MHz, UniSolar, 20cm x 20cm test-cell
95 MHz, FZK Julich, ~2cm x 2cm test-cell

How far will f-scaling go?

- a-Si:H and μc-Si:H film deposition rate scales with rf frequency
  Also, see Smets, Matsui, and Kondo (IEEE, 10.1109/WCPEC.2006.279790)
Differential-fed multi-tile plasma source trending above the line

Power density (Wattcm⁻²)

- 60 MHz, HPD, 12A/s, 0.1 W/cm²
- 162 MHz, ~HPD, 18A/s, 0.24 W/cm²

FROM SMETS, MATSUI AND KONDO; OPTIMIZATION OF THE HIGH RATE MICROCRYSTALLINE SILICON DEPOSITION CONDITIONS OF THE MICROHOLE-CATHODE VERY HIGH FREQUENCY SiH₄/H₂ PLASMA
• Solar cell application
80mm tile-length
8mm plasma gap

Film uniformity:
10% left-to-right
30% top-to-bottom

720 mm, some "banding" in deposition profile
600mm, (almost) no tile-2-tile boundary
Spatial profiles of material properties

- 600mm x 720mm
- 162MHz
Trends in Silane fractional flow

- Total silane exposure constant 1000 scc
- %silane into film ≈50%
- Crystallinity increases with decreasing Silane flow-rate
- In nc-Si:H growth region, have good crystallinity uniformity and OK film uniformity
• Total silane exposure constant 1000 scc
• Increased rf power increases Silicon depletion, and $X_c$
• Increased rf power enables increased dep-rate of nc-Si:H
• In nc-Si:H growth region, have good crystallinity uniformity and OK film uniformity
high-VHF for high-rate nc-Si:H

• Source behaves like expected
  – Hydrogen dilution
  – rf-Power

• Works in High-Pressure-Depletion

• Great uniformity both in film thickness and crystallinity (reasonable without optimization!)
Summary

• VHF systems have better process performance for many applications
  – Higher f $\rightarrow$ higher performance
• Multi-tile enables high-VHF without wavelength-effect non-uniformity
• PSTLD provides elegant solution to power splitting
  – Zero net current
  – No high-VHF current through the chamber

• For processes that are enhanced by increasing rf-frequency
  ➢ There is a tech-solution to enable high-VHF
  ➢ Solution for 300mm and forward scalable to 450mm