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Reducing Solar Module Cost with Atmospheric Plasma Surface Modification

A “Green” Technology

Presented by

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Presentation Outline

- Plasma Surface Modification
- Plasmas for Fabricating PV Cells
- PV Cell Fabrication Trend
- Atmospheric (Dry) Plasma Surface (APT) Modification Effects
- PV Cell Surface Preparation & Cleaning
- APT Prescriptions for PV Materials
- Conclusions

Plasma Surface Modification

- **Plasma surface modification technology in PV cell manufacturing:**
    - **Deposition of amorphous SiN layers**
    - **Utilize vacuum PECVD process**
- **Create anti-reflection and surface passivation on thin-film solar cells**
- **Vacuum plasma etching in barrel-type reactors for edge isolation**

Plasma Surface Modification

- Increasing chemical waste disposal issues

- New interest in plasma systems
  - dry etching
  - surface cleaning
  - adhesion promotion

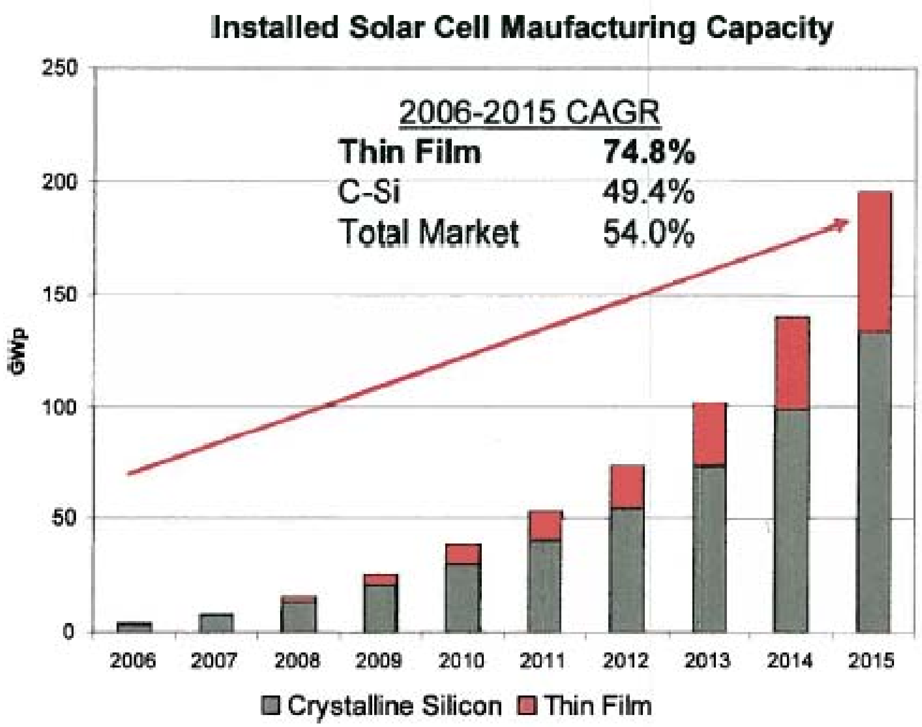
- Warrants fresh investigation of efficiencies

Plasmas for Fabricating PV Cells

- Use of plasmas dependent upon PV materials and cycle time
- Vacuum plasmas not a bridge to high volume continuous process
- SiNx deposition typically batch processes
- Can work in semi-continuous mode by exchanging materials after treatment and return to one atmosphere
- Not economical for high throughput etching, cleaning and functionalizing

PV Cell Fabrication Trends

Thin Film is Fastest Growing PV Technology



Thin Film Drivers

- Cost advantage: Thin Film reduces the amount of light absorbing material, leading to a reduction of CoO while technology increases efficiency
- Shorter energy payback period: Production of thin film modules is less energy intensive
- Temperature coefficient: The performance of modules remain more stable with increasing temperature

Source: Commerzbank and Oerlikon estimates

PV Cell Fabrication Trends

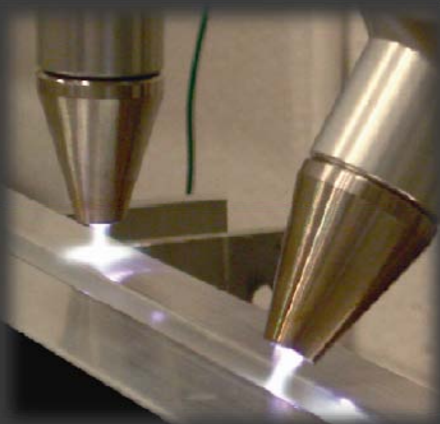
Organic Thin-Film Solar Cells on Plastic

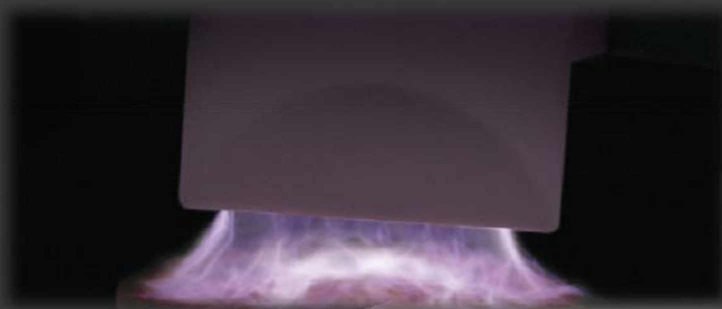
- Organic semiconductive materials are dissolved in solvents or inks and printed or coated onto a plastic substrate in a continuous roll-to-roll process.
- Less expensive than silicon, cadmium or tellurium
- Prototypes in production now.
  - Example 1: clear plastic top layer, a coating of prepolymer adhesive, then ink containing fullerene conductive nano-carbon clusters, and another liquid polymer coating, applied to PET film with an SiOx coating.
  - Example 2: Use of organic inks for solar sells. The ink lets electrons pass to an electrically conductive polymer layer on a plastic substrate.

PV Cell Fabrication Trends

- Wide range of materials being examined to maximize solar efficiencies.
- Opportunity integrate continuous in-line processes for rigid/flexible PV cells
- Utilize atmospheric (gas phase) variable chemistry surface modification technology for dissimilar materials to improve fabrication efficiency.

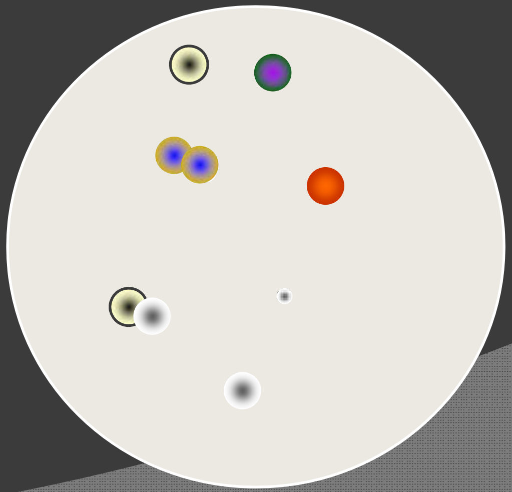
Atmospheric Plasma Surface Modification



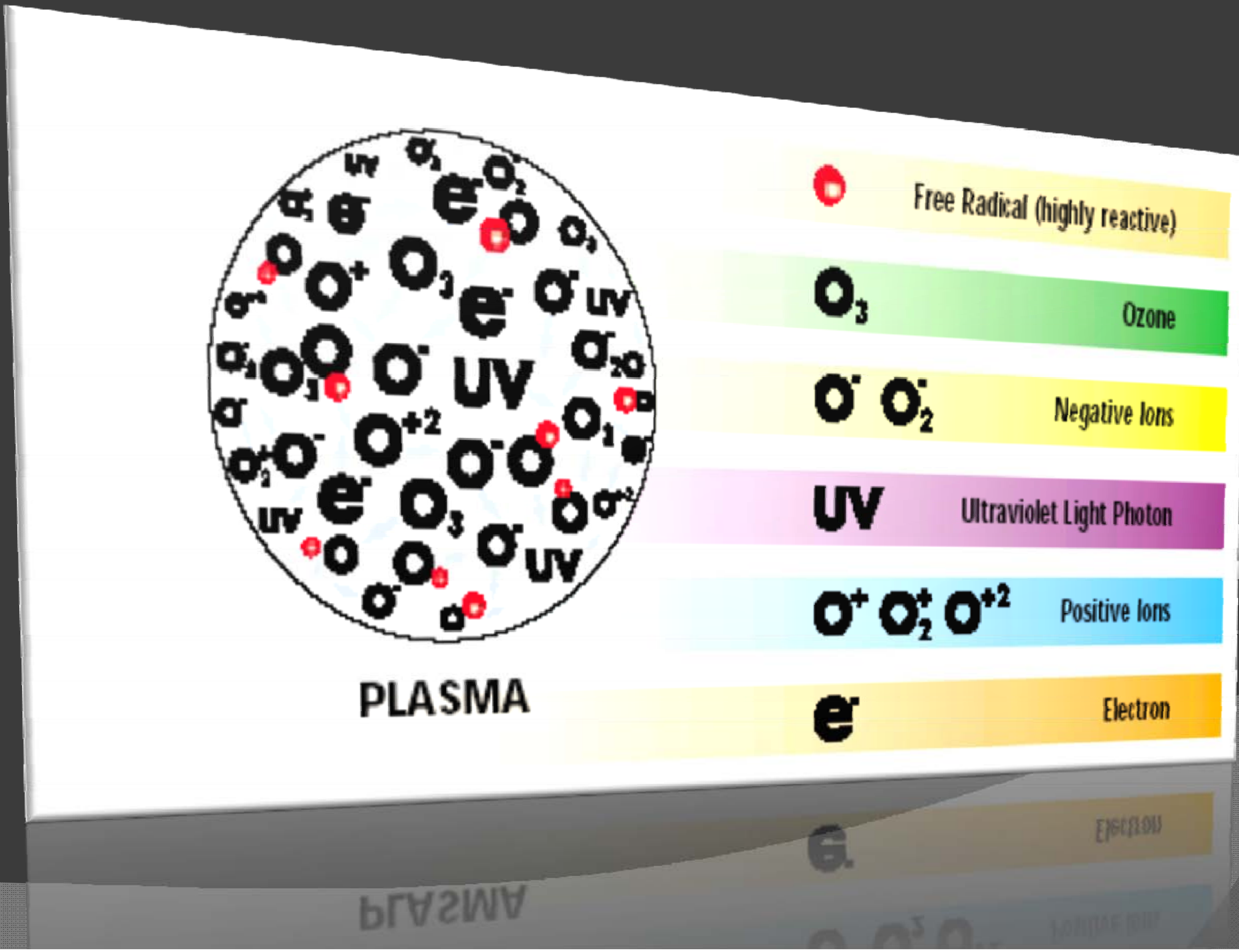


Atmospheric Plasma Surface Modification

plasma : *n* ; "Fourth state of matter", (Solid, Liquid, Gas, Plasma.) Mixture of charged ions & energetic electrons generally in equilibrium.



Atmospheric Plasma Surface Modification



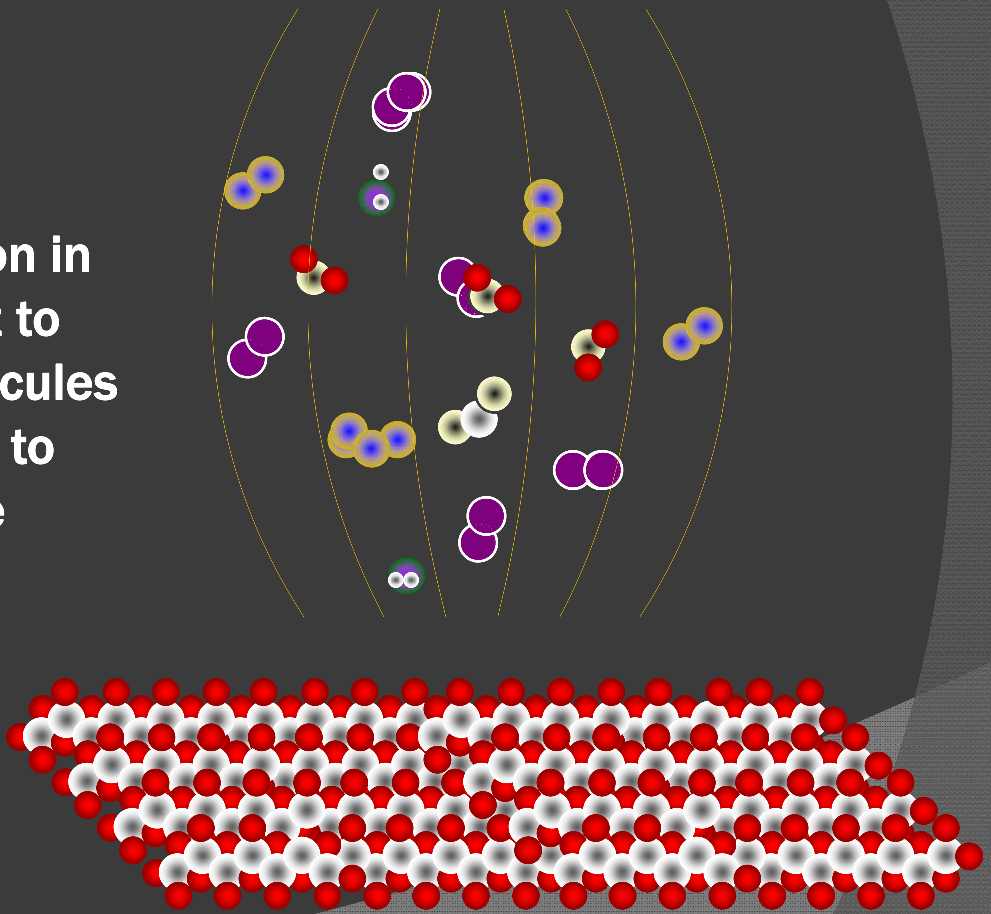
Atmospheric Plasma Surface Modification

Recipe

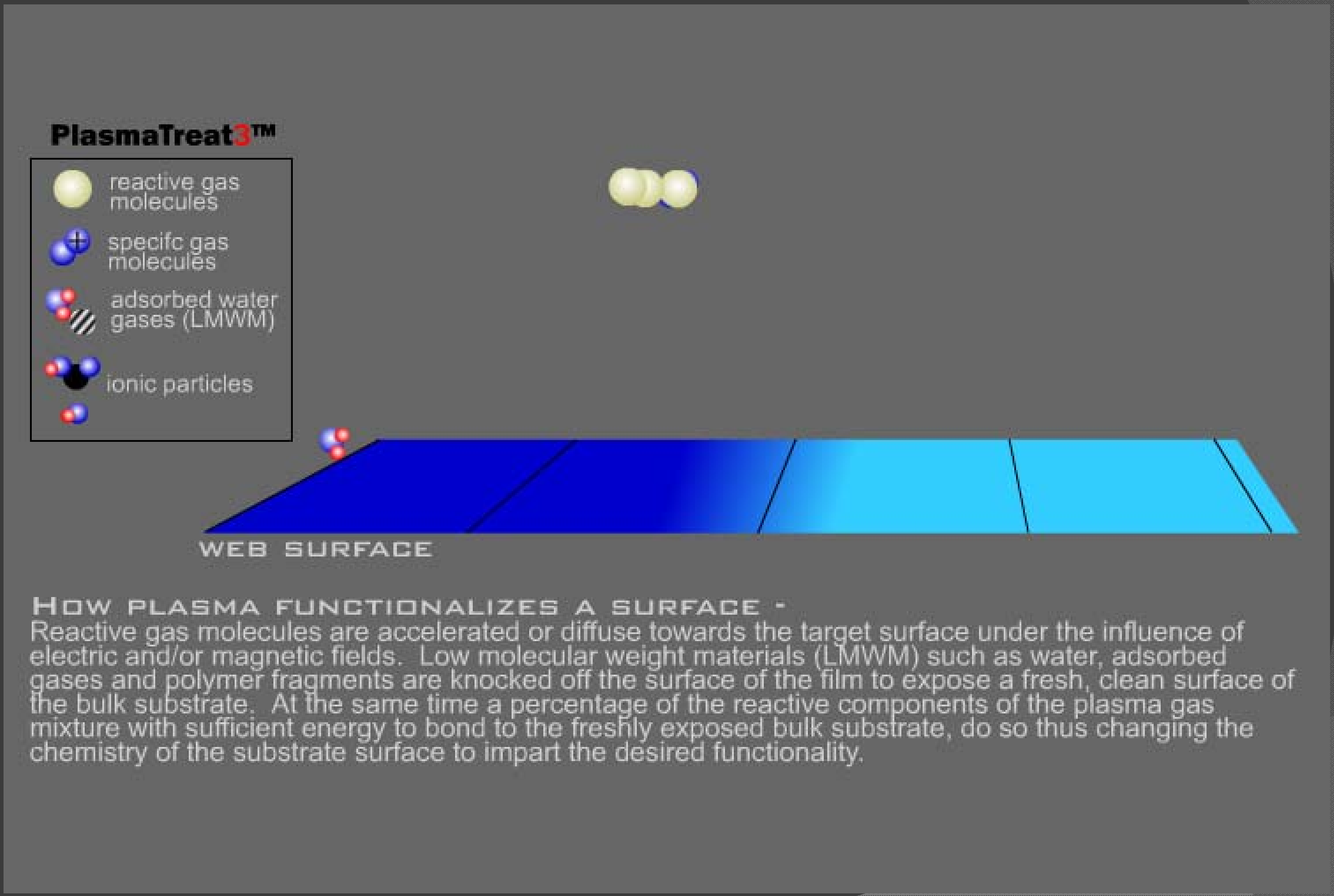
1) Take one photon, and allow it to randomly liberate one bound electron from a gas molecule.

2) Accelerate this free electron in an electrical field, forcing it to collide with other gas molecules with enough kinetic energy to separate the atoms, or free more electrons.

3) Increase power in the electric field to create an avalanche of electron collisions.



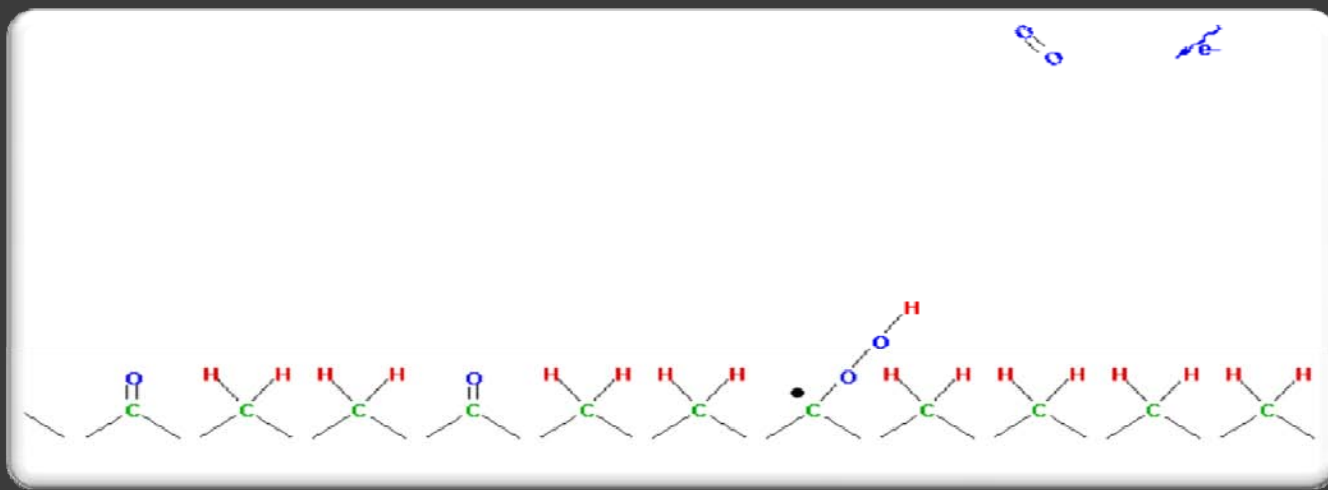
Atmospheric Plasma Surface Modification



Atmospheric Plasma Surface Modification

- Plasma Activation ⇨ Changes free radicals on the surface by substituting chemical groups on the polymer chain being modified.
- Plasma Deposition ⇨ Hydroxyl, carbonyl, carboxyl, carboxylic, amino-carboxyl, and amine chemical groups on surface
- Plasma-Induced Grafting ⇨ Free radicals are created along the polymer backbone.

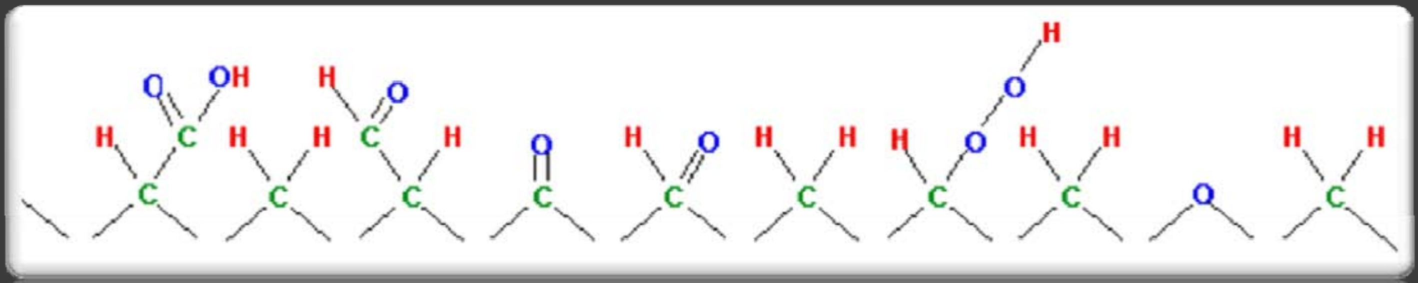
Atmospheric Plasma Surface Modification



- **Animation demonstrates only one of the possible reaction pathways during plasma-chemical oxidation of polyolefins.**
- **Reaction initiated with atomic oxygen, which abstracts an hydrogen atom from the surface.**
- **Results in a free radical on the surface, which can react with an oxygen molecule to produce a hydroperoxide group, which can decay into a keton group.**

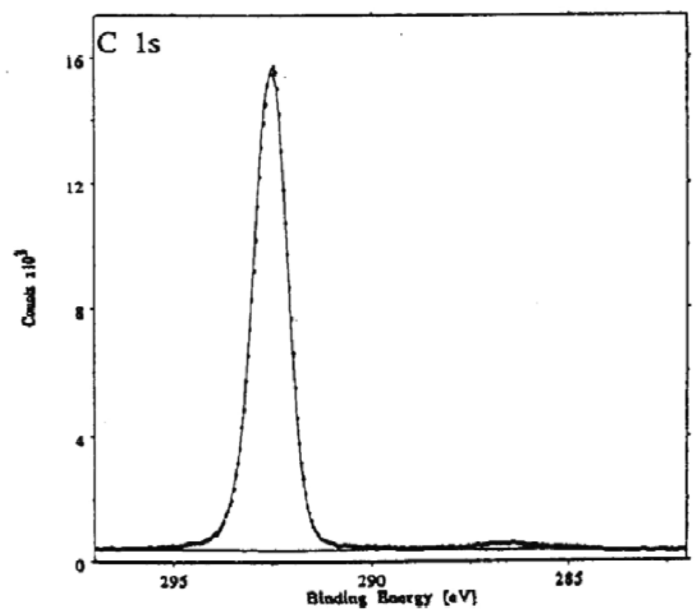
Source: Fraunhofer IGB

Atmospheric Plasma Surface Modification

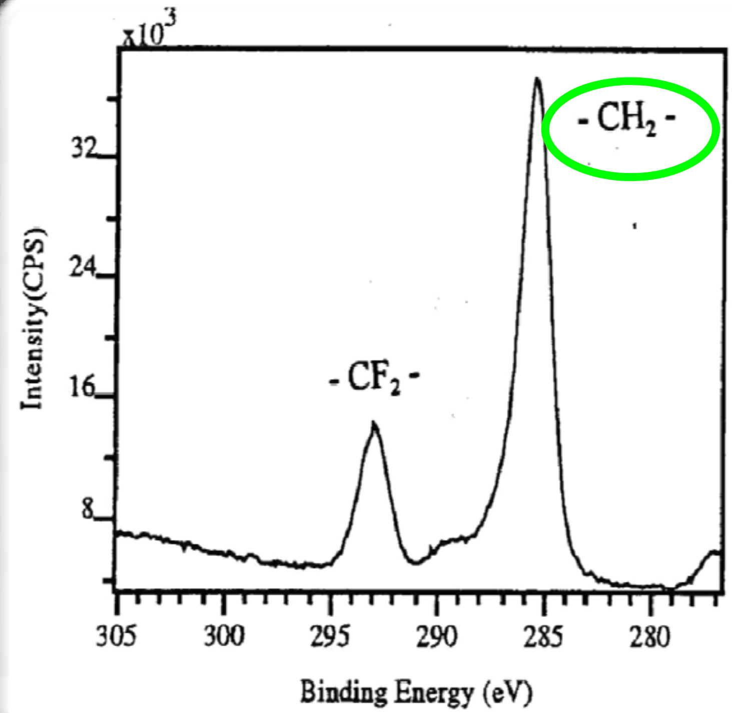


- Besides keton groups, also formed aldehyd, carboxyl, hydroperoxide, hydroxide, and ester groups (above).
- Plasma oxidation results in breaking the polymer chains and material removal (ablation)
- Specific surface functionalization possible under precise control of the reaction conditions.

Atmospheric Plasma Surface Modification



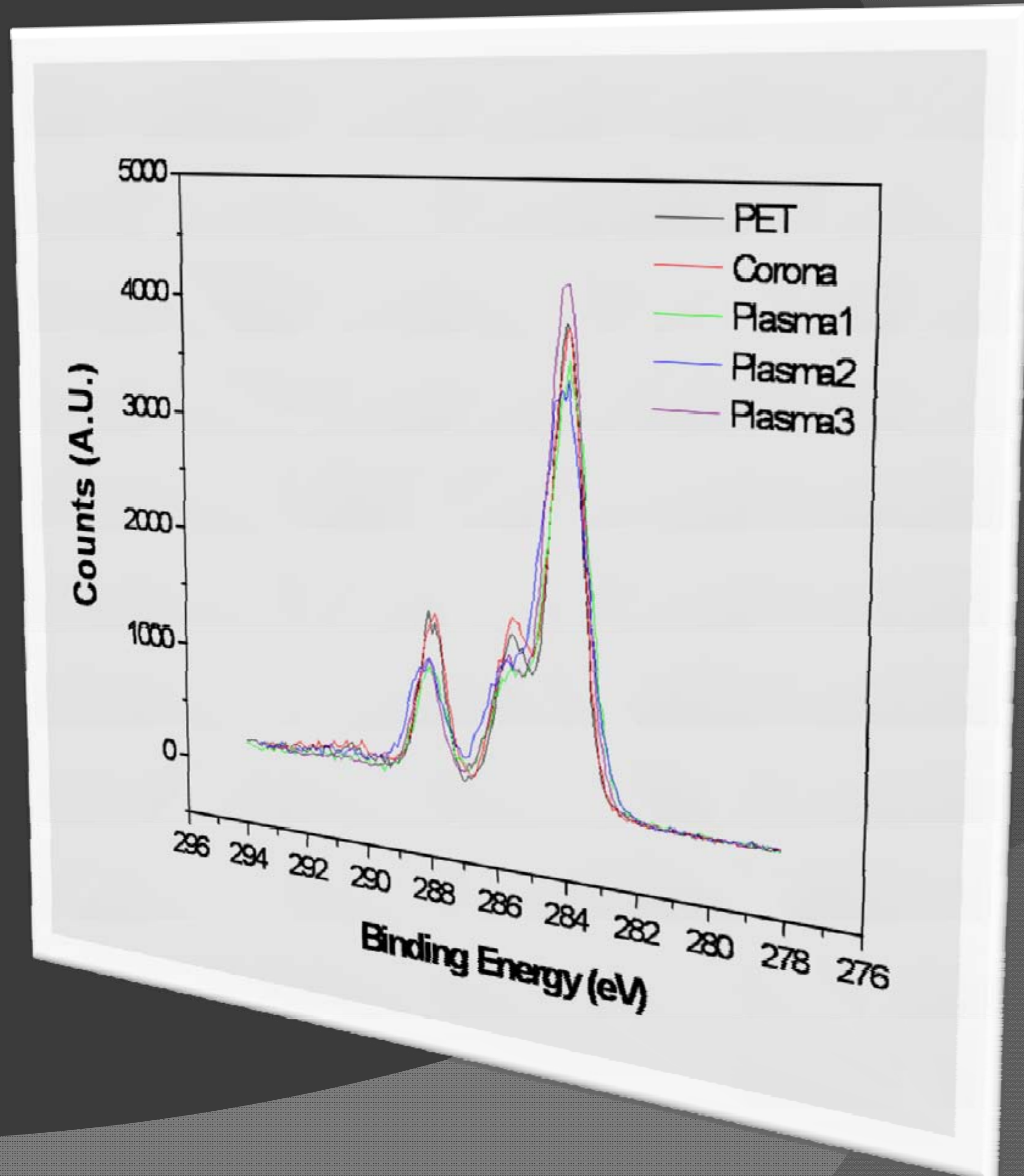
XPS spectrum results of untreated PTFE sample



XPS spectrum results of treated PTFE sample

Atmospheric Plasma Surface Modification

Peak Broadening occurs due to multiple functional groups being present on the surface.

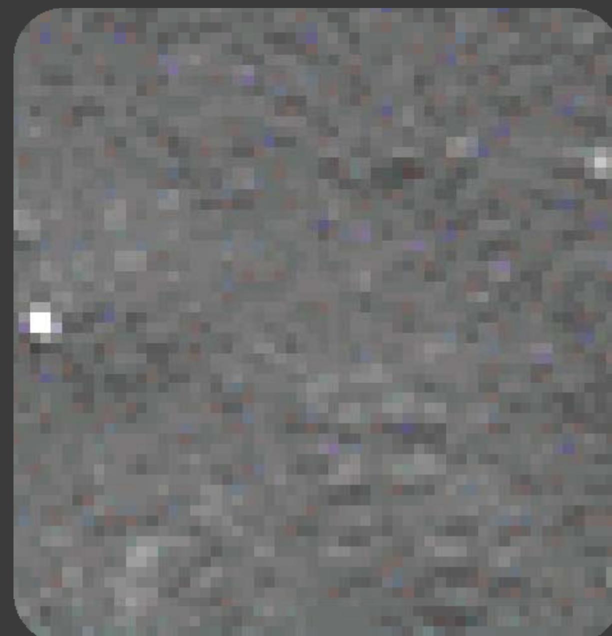


Atmospheric Plasma Surface Modification

Plasma Treatment Micro-Etching Effect

Polyethylene (30,000 SEM magnification)

Original Polymer



Plasma-Treated

Roll-to-Roll PV Surface Cleaning Prior to Si Deposition

Base Materials

- Lightweight, Flexible
- Will not shatter or be damaged during manufacture, handling, and subsequent operation in the field
- Thin stainless steel substrates, for example, have thermal time constant <10 ms - can be quickly heated and cooled to eliminate waiting for temperature stabilization
- Typically carry rolling oil deposits which must be removed
- Transport in deposition chambers is simple and reliable with little component wear, resulting in very low machine maintenance costs.

Polymer Encapsulation Materials

- Polymers such as EVA and Tefzel are flexible and lightweight
- Contaminated with residual organic polymer fragments, water, adsorbed gases

Roll-to-Roll PV Surface Cleaning Prior to Si Deposition

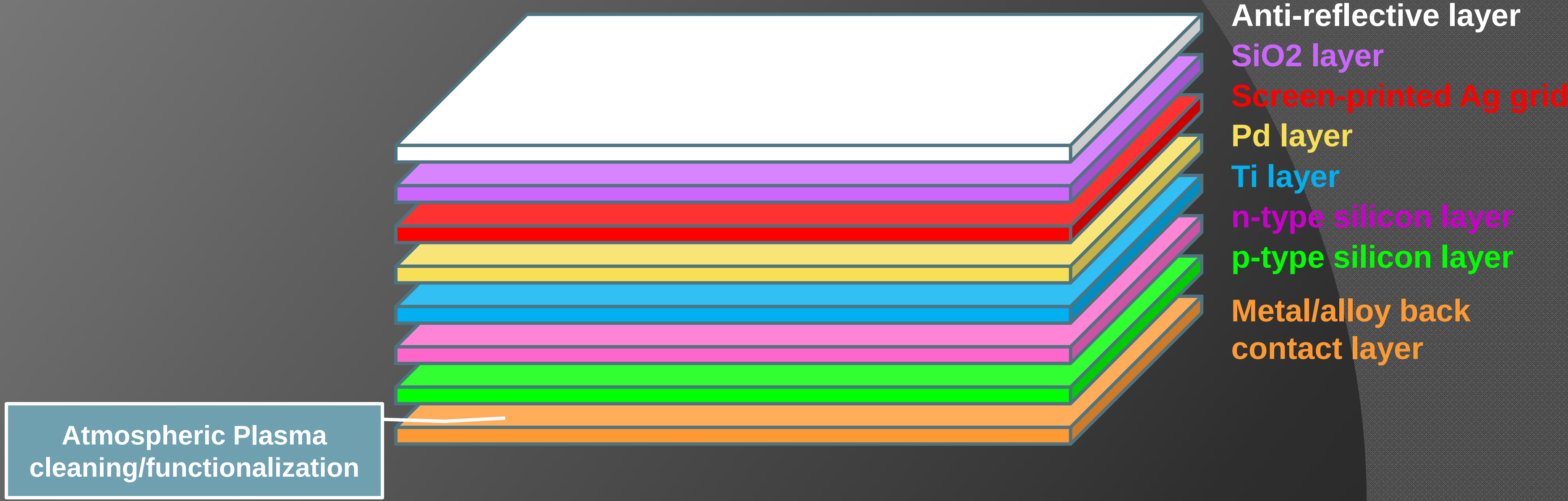
Existing Base Material Wet Cleaning

- Roll material washed to produce clean, dry, particle-free substrate material suitable for Si deposition
- Web transported though detergent cleaning station, de-ionized water rinsing, IR drying

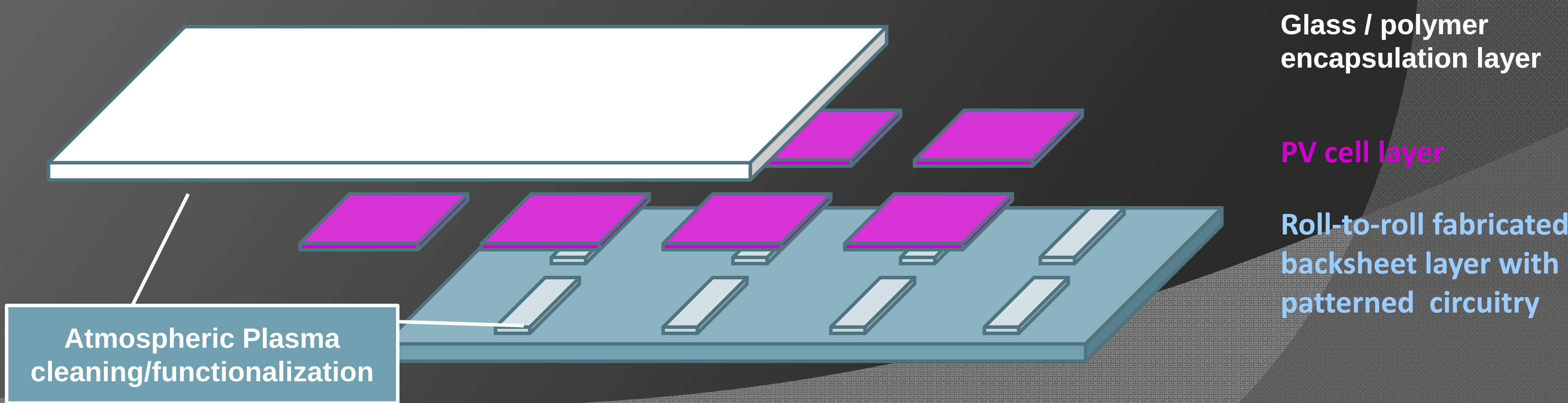
Advantages of APT Cleaning/Functionalizing of Base, Encapsulation Films

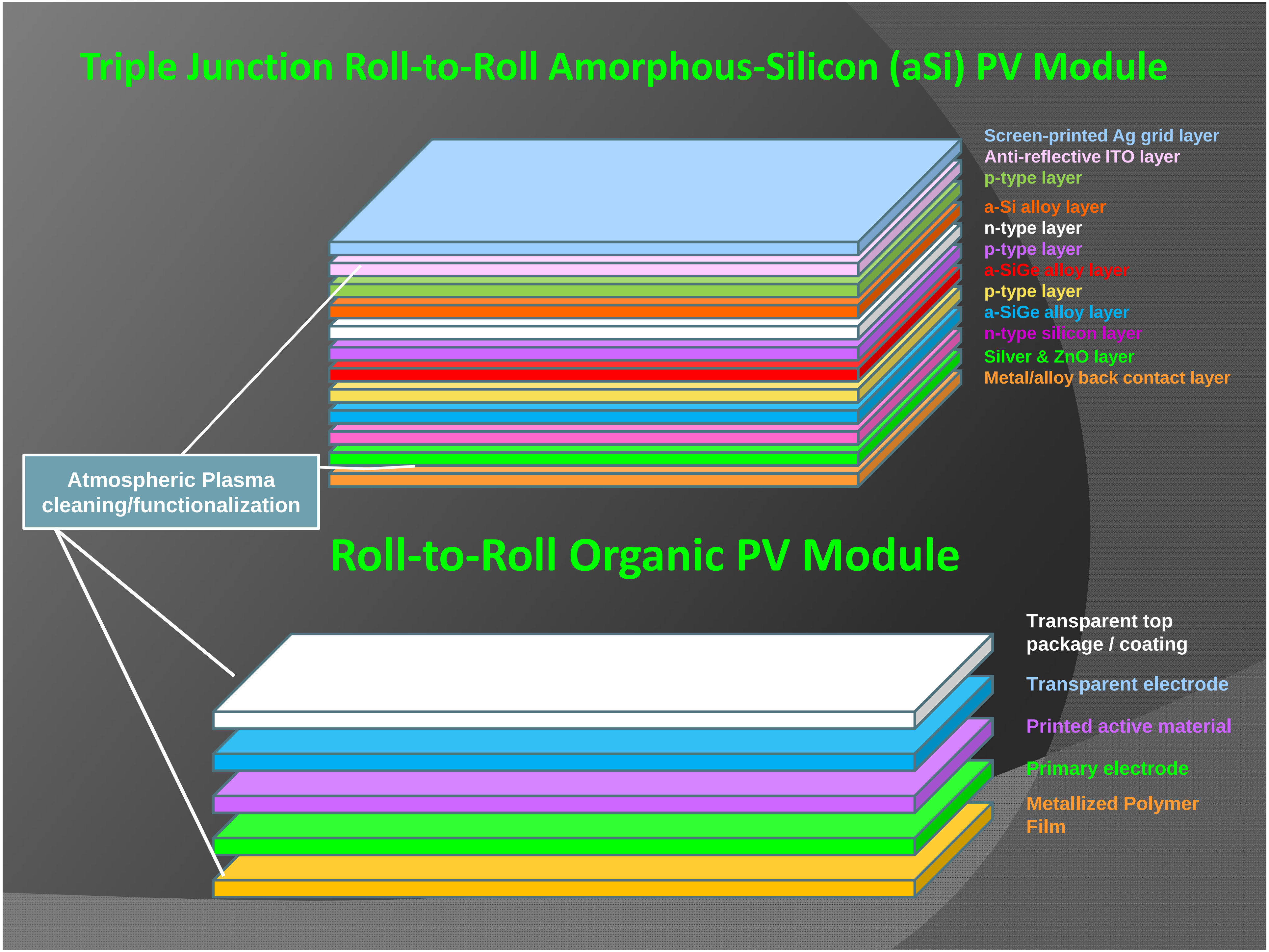
- Base material contaminates volatilized/vaporized, increasing cleaning process efficiency.
- Encapsulant functionalization increases surface-to-reactive adhesive and surface-to-primer bond strength to flexible structures, and glass.

Crystalline-Silicon (cSi) PV Module

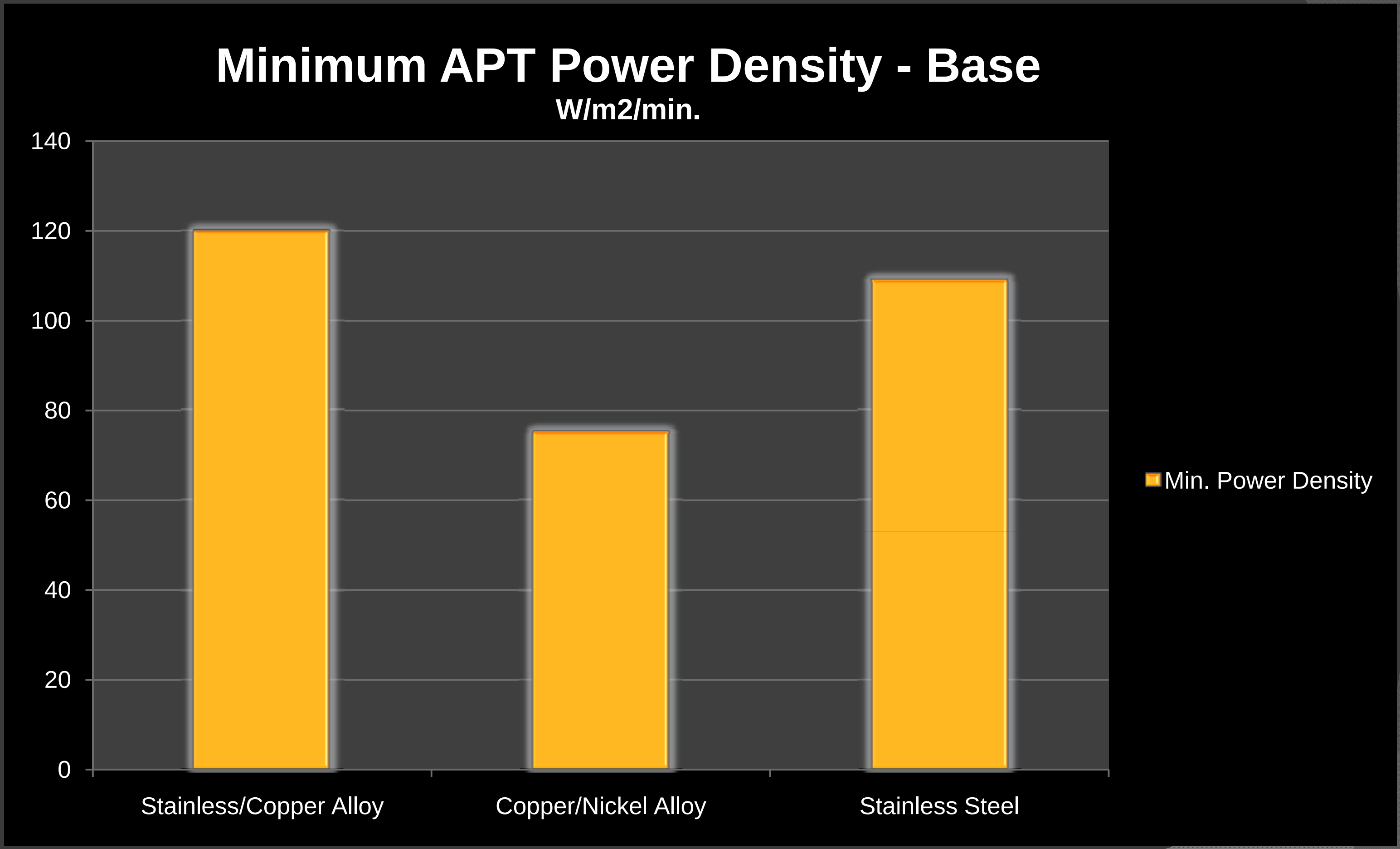


Monolithic PV Module



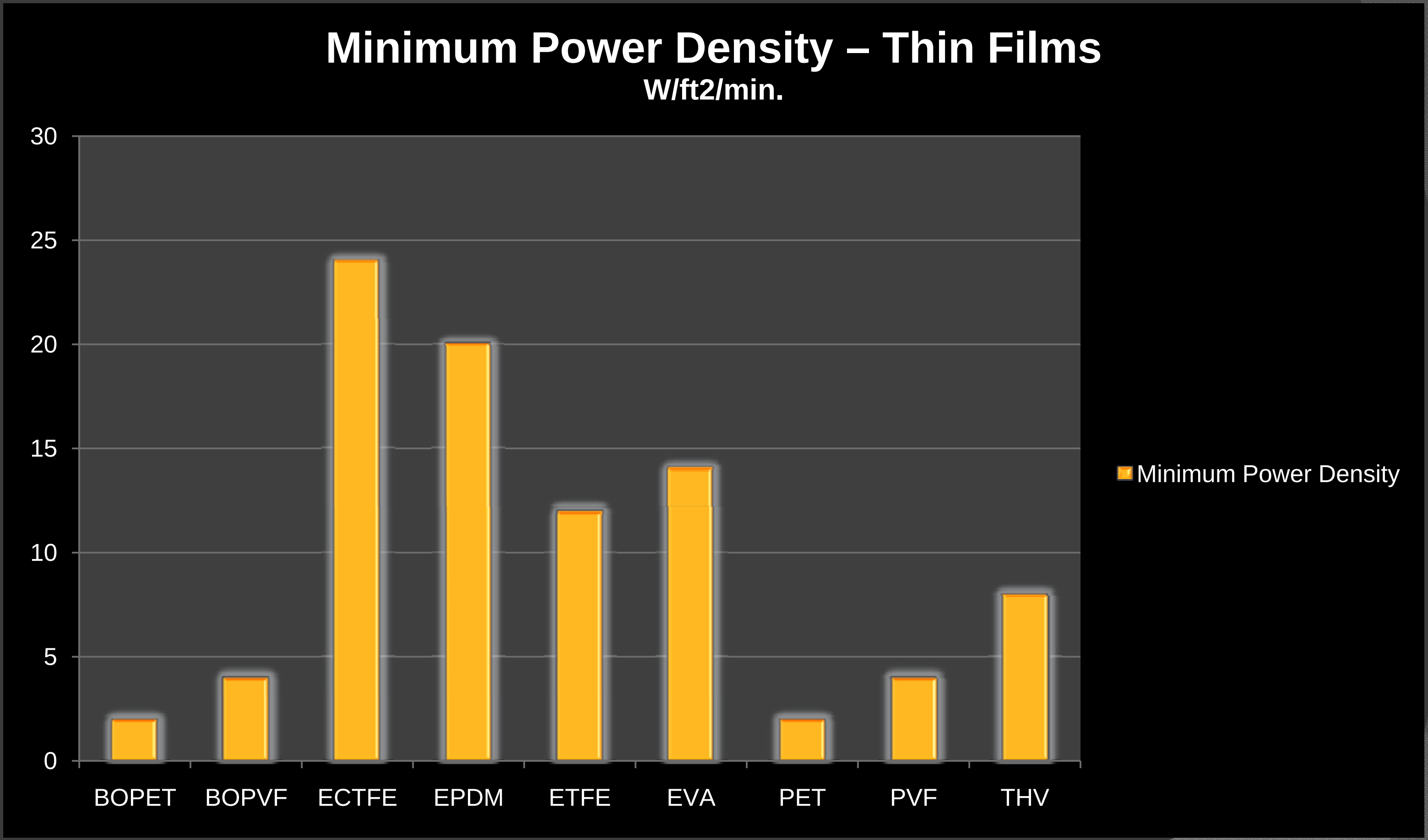

Triple Junction Roll-to-Roll Amorphous-Silicon (aSi) PV Module
Screen-printed Ag grid layer
Anti-reflective ITO layer
p-type layer
a-Si alloy layer
n-type layer
p-type layer
a-SiGe alloy layer
p-type layer
a-SiGe alloy layer
n-type silicon layer
Silver & ZnO layer
Metal/alloy back contact layer
Atmospheric Plasma cleaning/functionalization
Roll-to-Roll Organic PV Module
Transparent top package / coating
Transparent electrode
Printed active material
Primary electrode
Metallized Polymer Film

APT Prescriptions for Flexible PV - Base



Note: Inert/Reactive gas proportions influence minimum power densities.

APT Prescriptions for Flexible PV – Thin Films

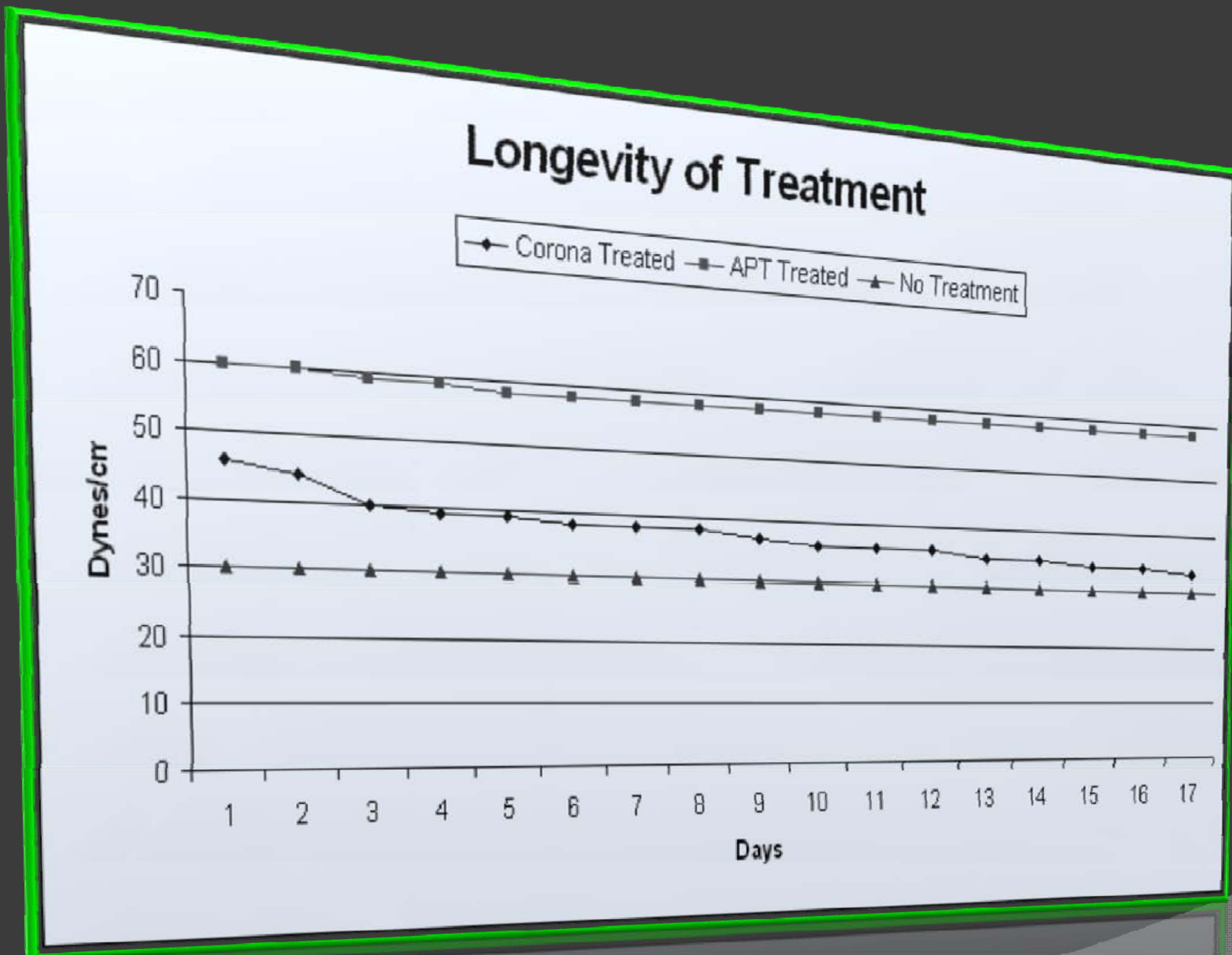


Note: Inert/Reactive gas proportions influence minimum power densities.

APT Prescriptions for Flexible PV – Thin Films

Substrate	Corona Watt Density (W/ft²/min.)	Corona Surface Tension (Dynes/cm)	Plasma Watt Density (W/ft²/min.)	Plasma Surface Tension (Dynes/cm)
Polyimide	16.6	60	5.3 6.0	60 72
PLA	2.0	46	1.0 3.0	46 50
Tyvek®	2.0	54	1.0 2.0	46 60

APT Prescriptions for Flexible PV – Thin Films



APT Prescriptions for Flexible PV – Corona Issues

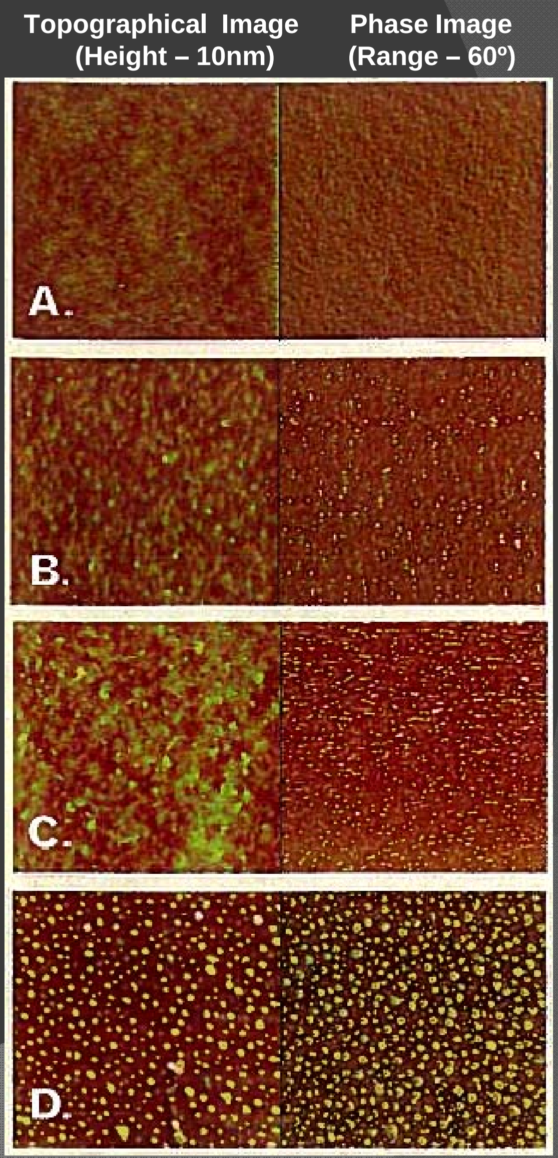
2x2 micron images of PET film

A. No Treatment

B. WD = 1.16W/ft^2/min (12.5W/m^2/min)

C. WD = 1.93W/ft^2/min (20.8W/m^2/min)

D. WD = 2.71W/ft^2/min (29.2W/m^2/min)



APT Prescriptions for Flexible PV – Emissions

Wet Vs. Dry Metal/Metal Alloy Cleaning

Metal Cleaning Process	➢Chemical Wet Cleaning	➢Atmospheric Plasma Dry Cleaning
Active Cleaning Agent(s)	➢Water-base Sulphuric Acid ➢Alkaline Solutions ➢Alcohol Solutions ➢ Detergent Solutions	➢Ion/Electron/Photon Bombardment ➢Inert + Oxygen Gas
Dissolved within Chemical Agent(s)	➢Rolling Oils ➢Metal Oxides ➢Water-Soluble Metal Derivatives	➢n/a
Entrained in Process Exhaust	➢n/a	➢Volatilized hydrocarbon particles ➢Aluminum oxide particles ➢Water-Soluble Aluminum Derivatives
Emissions	➢Water Laden w/ Chemical Wastes	➢15 ppm Ozone ➢2,336 ppm Inert gas (98%) ➢185 ppm Reactive O2 (70%) ➢ <10 ppm CO2 ➢ <10 ppm Water Vapor ➢Volatized surface particulates
Recurring Process Costs	➢Fresh Water, Additional Chemicals ➢Handling, Disposal Costs	➢Process Gases

Conclusions

- Vacuum Plasma Surface Modification
  - Anti-reflection
  - Surface passivation
  - Surface etching
  - Layer deposition

- Process Evolutions
  - Increasing chemical waste disposal issues
  - Module per unit process cost reductions

- Thin Film PV Cell Fabrication CAGR expected to be 74.8% to 2015.

Conclusions

- Atmospheric (Dry) Plasma surface modification parameters (power density, gas chemistry) established for all flexible module components.
- Suitable for rigid module component surface preparation, such as frame and junction box sealing.
- In-line, continuous process
- No surface morphology effects
- Green technology, with no hazardous byproducts

Thank you for attending…

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