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Laser beam power converters based on photo-thermionic emission for future lunar exploration

DiaTHEMA

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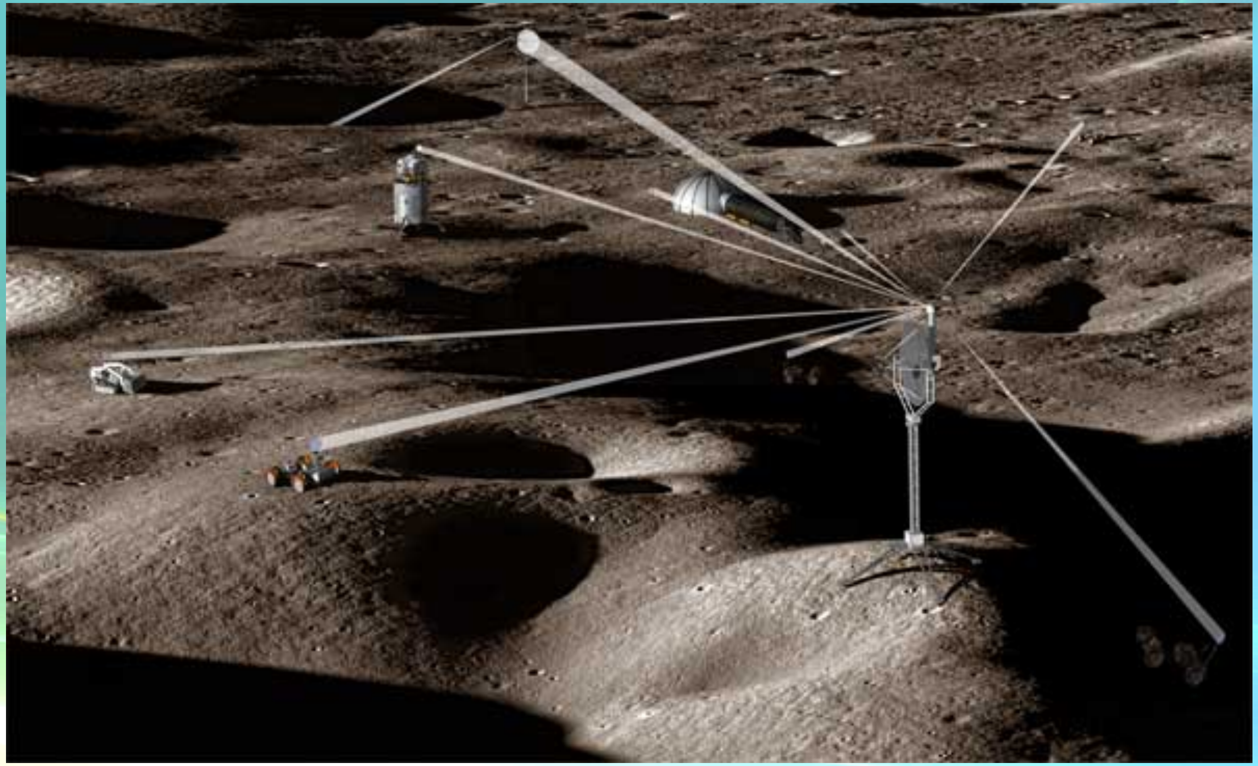
Applications

- Wireless power transfer is **the ideal power technology when fixed infrastructures are not feasible: case of satellites' power supply**
- Laser beams are the case of electromagnetic radiation (e.g., micro- and mm-wave) with the **highest transferred power density: smaller receivers and lower weight**



- Laser beaming is **ideal when sunlight is not available:** permanently shadowed regions **PSR** and **South Pole of the Moon**
- Exploration of PSR and South Pole is primarily important **for rough materials and water**
- Other planetary explorations (e.g., Mars) can exploit the laser beaming
- **Small robotic systems** such as **rovers**, **drones**, **cubesats** can be power-supplied by laser beaming

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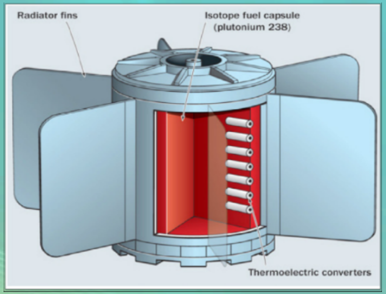
Needs & Available technologies

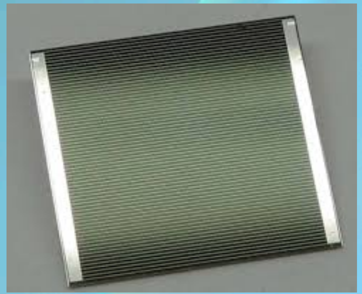
- **Thermally resistant technology** -> Operations from **-100 °C (lunar night) to +200 °C (day)**
- **Compact technology** -> Manage high radiation power densities > **50 W/cm^2**
- **Lightweight technology** -> **Solid-state** converter
- **Vacuum conditions->** from 10^{-12} mbar (night) to 10^{-10} mbar (day)

Available technologies:

- **Radioactive Thermoelectric Generators**
  - ✓ Long lifetime
  - ✓ Thermally resistant
  - ✓ Temperature independent
  - ↓ Moderate compactness
  - ↓ Low efficiency <7%
  - ↓ Use of radioactive sources (safety)
  - ↓ Moderate lightweight (screening of radioactive source)



- **Concentrated photovoltaic cells** combined with laser beaming
  - ✓ Efficiency > 40%
  - ✓ Compact
  - ✓ Lightweight
  - ↓ Extremely expensive
  - ↓ Efficiency limitations under high temperature conditions
  - ↓ Efficiency limitations at high fluxes > 30 W/cm^2



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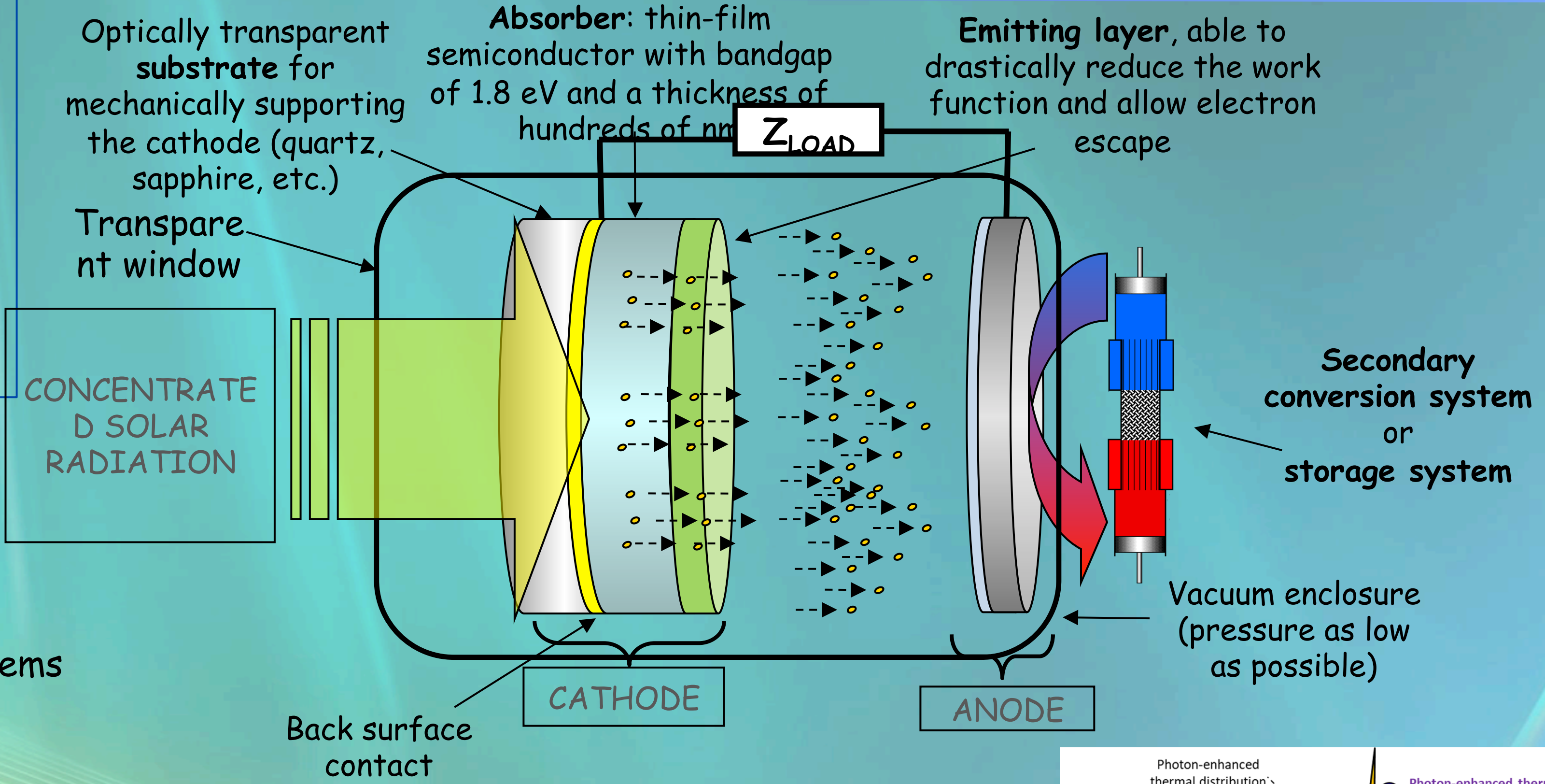
High-Temperature Solar Cells (PETE Devices)

PETE* devices can be defined **as high-temperature cells for solar concentrating systems**, since they avoid the limitations of **junction cells** and **even benefit from high operating temperatures**

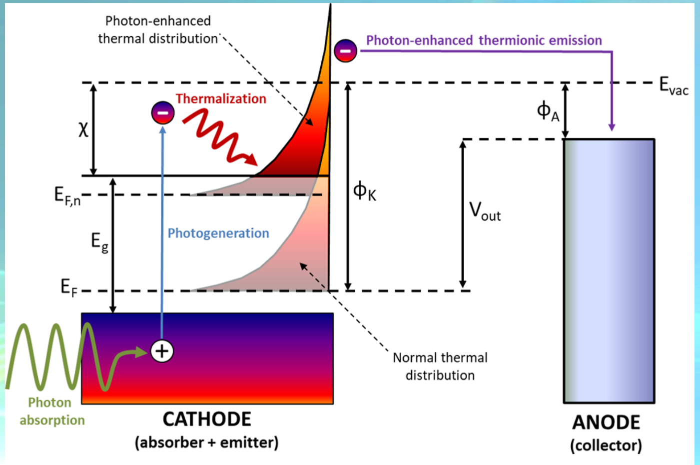
*J. Schwede,et al., Nature Materials 9 (2010) 762



Direct application of PETE:

- Solar Concentrating Systems
- Laser Beaming

- Photo-generation increases electron population at conduction band above the equilibrium level, and the emission energy barrier is reduced: more electrons are emitted from the cathode at lower cathode temperatures compared to conventional thermionic emitters
- Thermalization processes within the cathode increase temperature, thus increasing the emission current density (thermionic emission)
- PETE devices utilize both photonic and thermal processes for energy conversion, and are not subject to either the Shockley-Queisser limit or the thermal limit (Carnot)**
- ***G. Segev, Y. Rosenwaks, A. Kribus, Solar Energy Materials & Solar Cells 140 (2015) 464*



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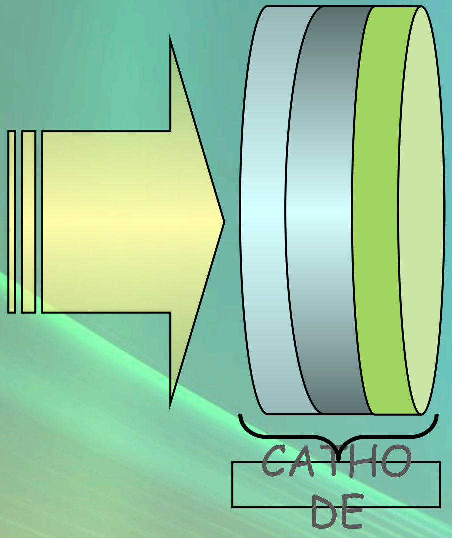
PETE Cathodes



Strategies

III-V Semiconductors

Advantages:

- Proper bandgap for absorption and photocarrier generation (about 1.8 eV)
- High electron diffusion lengths

Disadvantages:

- High electron affinity-> Necessity of coatings for "work-function-engineering"
- Instability at high-temperature of the crystal lattice and of the emitting coating

Bandgap Engineering

Diamond

Advantages:

- Low "native" work function caused by NEA conditions (surface hydrogen termination)*
- Wide range of operating temperature (<750 °C)
- High thermal stability
- High robustness

Disadvantages:

- Wide bandgap (5.47 eV @ RT)

Defect Engineering

*D.M. Trucchi et al., **Solar Thermionic-Thermoelectric Generator (ST^2G): concept, material and prototype demonstration, Adv. Energy Mater. 8, (2018) 1802310**

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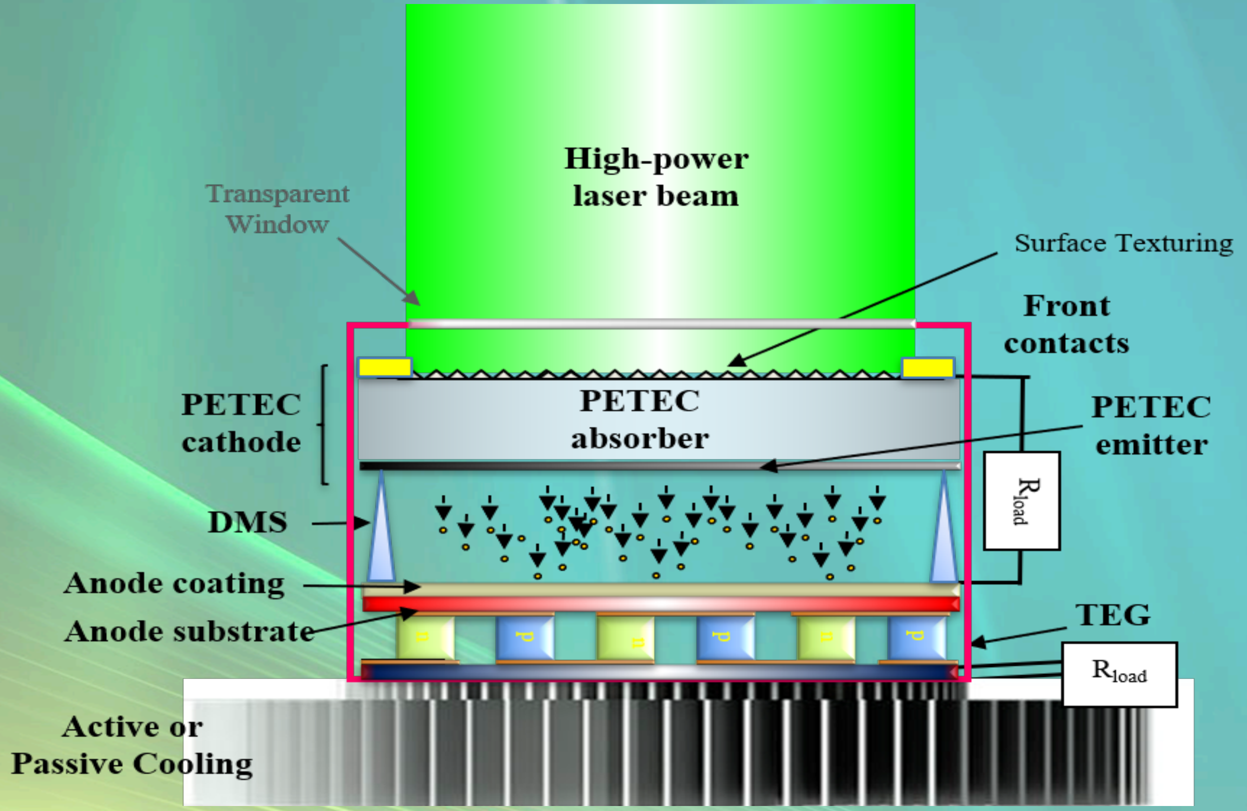
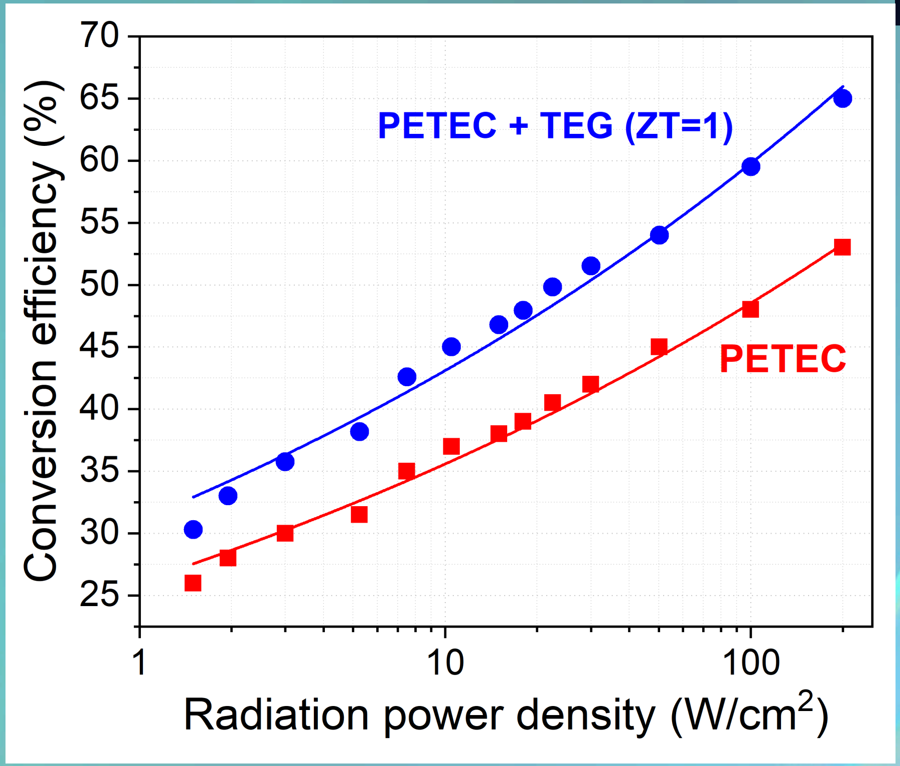
Efficiency & Structure





- Simple device structure
- Thermoelectric generator (TEG) is optional
- Additional advantage on the Moon: no need for vacuum case thanks to the absence of atmosphere

- Two possible configurations: PETEC or PETEC+TEG
- Both configurations can be highly efficient
- PETEC is more efficient than photovoltaic cells under comparable conditions since it uses also excess thermal energy

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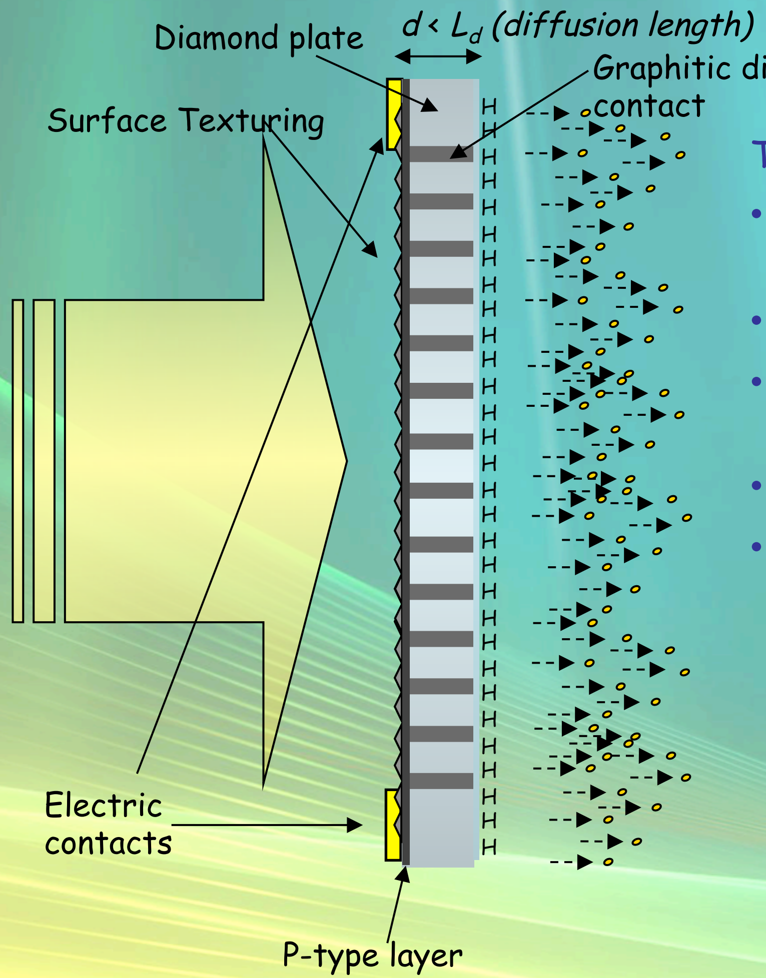
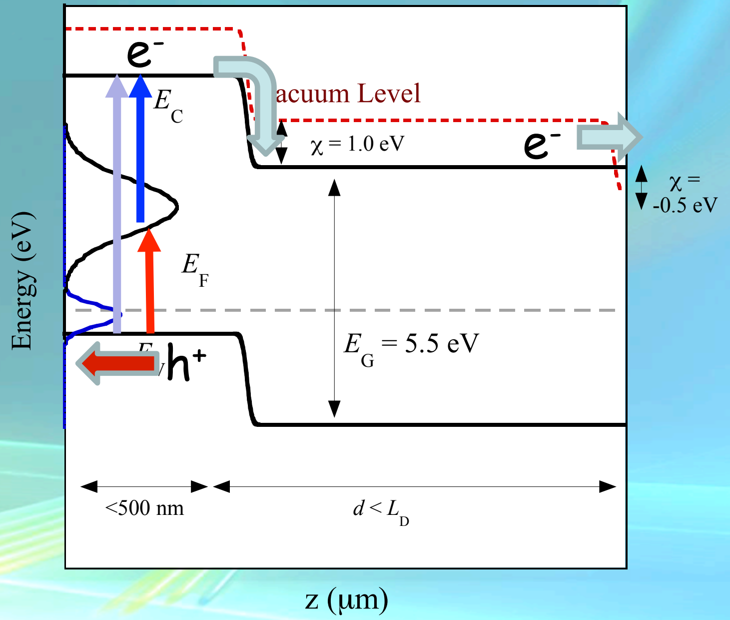


Technological steps:

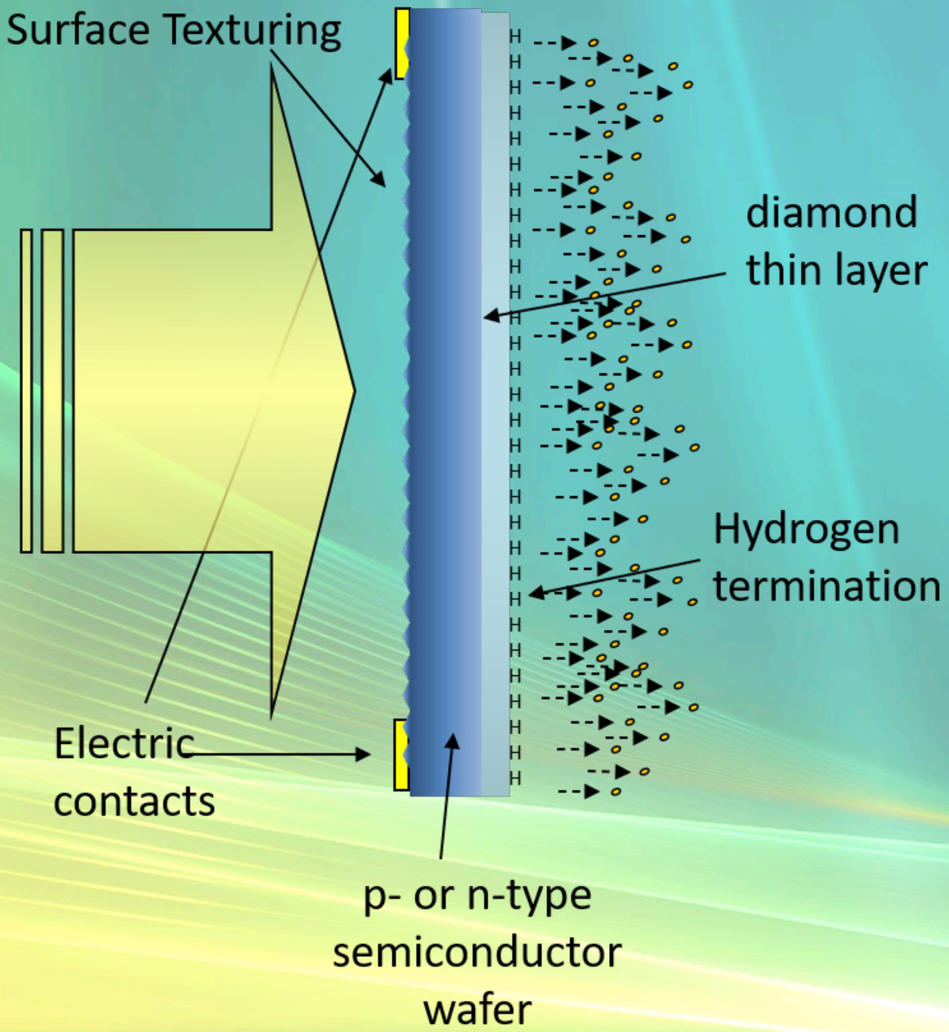
- Fs laser front surface nanoscale texturing for increasing optical absorption and photogeneration
- Implantation of B ions on front surface for a buried p-type layer
- Fs laser-induced distributed contacts for reducing device series resistance
- Emitting surface hydrogenation for NEA
- Deposition of electric contacts

p/i structure with band diagram



A. Bellucci et al., **Defect Engineering of Diamond Cathodes for High Temperature Solar Cells**, 2015 IEEE 15th International Conference on Environment and Electrical Engineering Proceedings, (2015) 1616-1619.

Selective-Response Heterostructure Diamond PETE Cathode



Semiconductor	Bandgap energy, direct (D) or indirect (I)	Operating wavelength (nm)	Melting point (°C)	Thermal expansion coefficient (K^{-1})
Ge	0.67 eV, I	< 1850	938	5.9×10^{-6}
Si	1.12 eV, I	< 1107	1414	2.6×10^{-6}
InP	1.35 eV, D	< 918	1062	4.6×10^{-6}
CdTe	1.58 eV, D	< 784	1041	5.9×10^{-6}
3C-SiC (β)	2.36 eV, D	< 525	2830	2.8×10^{-6}
GaN	3.4 eV, D	< 364	> 1600	4.5×10^{-6}

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Surface Texturing – BLACK DIAMOND

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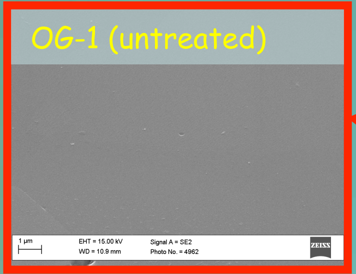
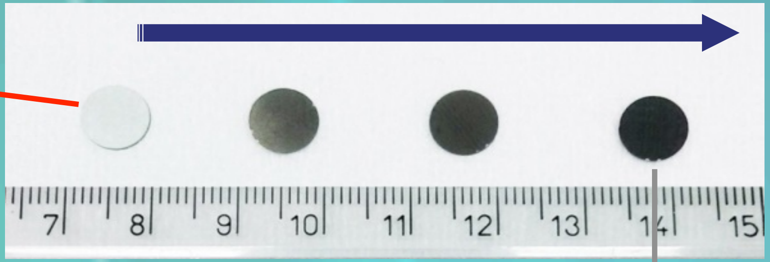


ACCUMULATED FLUENCE

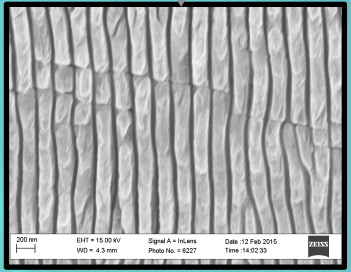


Accumulated fluence = 5.0 kJ/cm^2

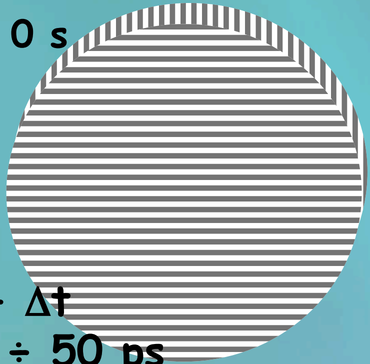
Accumulated fluence = number of pulses × fluence of pulse

LIPSS characterized by:
- Periodicity = λ_{laser} / 2n= = 160 nm
- Depth < 1 μm
- Length of several μm to mm range

Laser parameters:
- Linear polarization
- λ = 800 nm
- Pulse duration = 100 fs
- Repetition rate = 1000 Hz
- Pulse energy density = 1.6 - 5.1 J/cm^2
- Spot size = 5 - 150 um



t_0 = 0 s

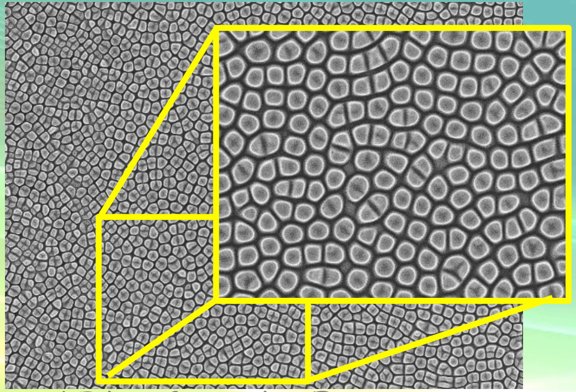


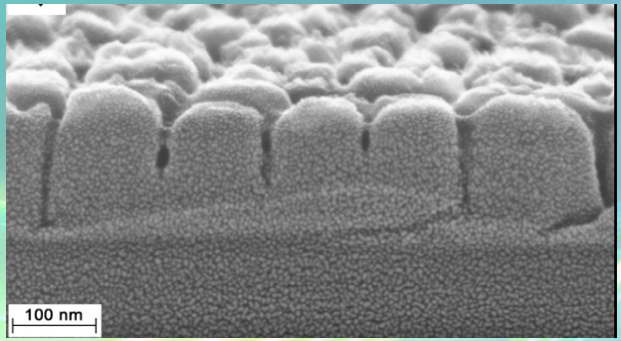
1D periodicity
vs
2D periodicity

$t = t_0 + \Delta t$

Δt = 50 fs ÷ 50 ps

System parameters:
Vacuum level < 10^{-7} mbar
or
Ambient pressure in N_2 or He





- The delay of 500 fs was found to optimize the structures' homogeneity.
- Periodicity and size can be controlled to 80 nm or 160 nm depending on the pulse fluence.

A. Bellucci et al., Optimization of Black Diamond Films for Solar Energy Conversion, Appl. Surf. Sci. 380 (2016) 8-11
M. Mastellone et al., "Deep-Subwavelength 2D Periodic Surface Nanostructures on Diamond by Double-Pulse Femtosecond Laser Irradiation" Nano Letters 21 (2021) 4477.

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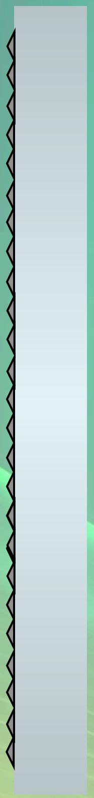
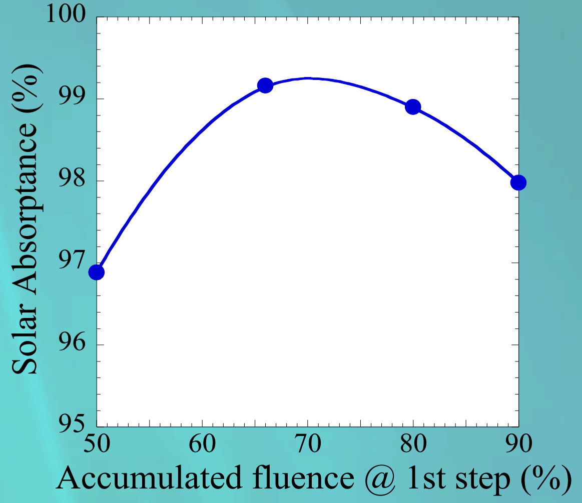
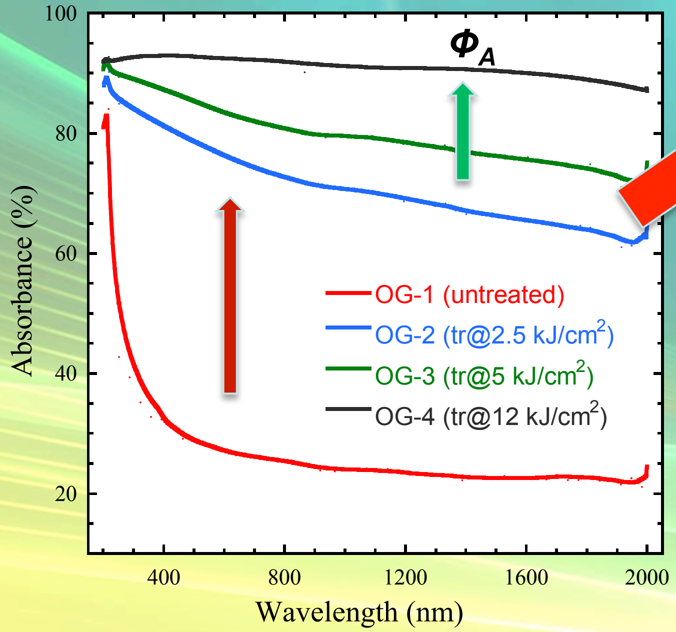


Absorptance, reflectance, and transmittance spectra highlight:

- A significant **increase in absorptance** for the treated samples
- Absorptance is an **increasing function of treatment accumulated fluence Φ_A**



- The 2-step treated films achieve unprecented solar absorptance values (>99% for the best film)



An efficient optical absorption is ONLY a NECESSARY but NOT SUFFICIENT condition for an efficient solar energy converter

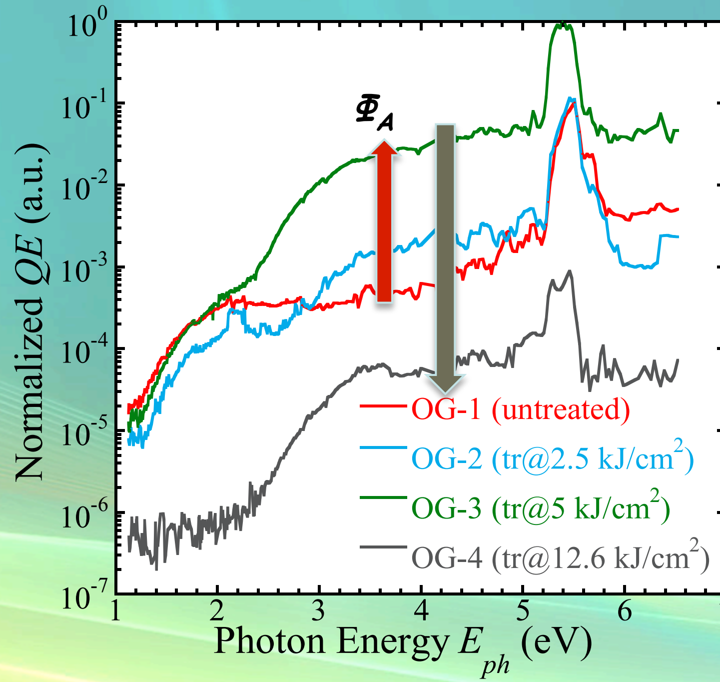
ABSORBED PHOTONS have to generate CHARGE CARRIERS

M. Girolami et al., **Optical characterization of double-nanotextured black diamond films**, Carbon 138 (2018) 384-389

BLACK DIAMOND – Photoelectronic Properties

Spectral photoconductivity measurements have been performed to quantify the photogeneration capability of useful charge carriers

Sub-bandgap QE reaches values **two orders of magnitude higher than pristine sample** for the medium treated sample (**three orders for the 2D periodic texturing**)



This indicates that a too high defect density has been introduced. But do defects act as traps or recombination centers?

The photosensitivity has a maximum in correspondence of an intermediate value of accumulated fluence: some defects act as traps for one carrier type thus increasing the carriers' lifetime

P. Calvani et al., **Black Diamond for Solar Energy Conversion**, Carbon 105 (2016) 401-407
M. Girolami et al., Transport properties of photogenerated charge carriers in black diamond films, Ceramics International 45 (2019) 9544

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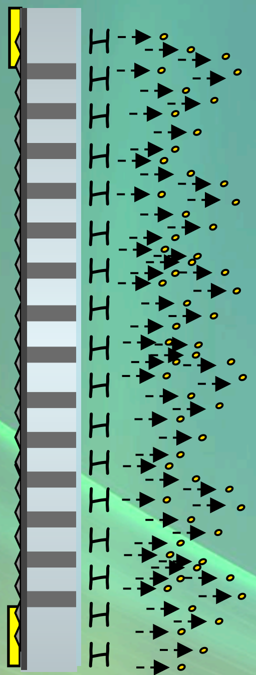
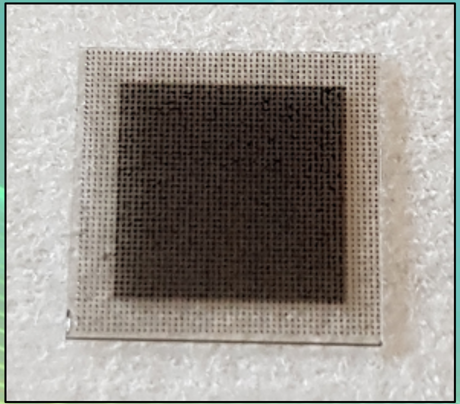
PETE Cathode / Emitting layer

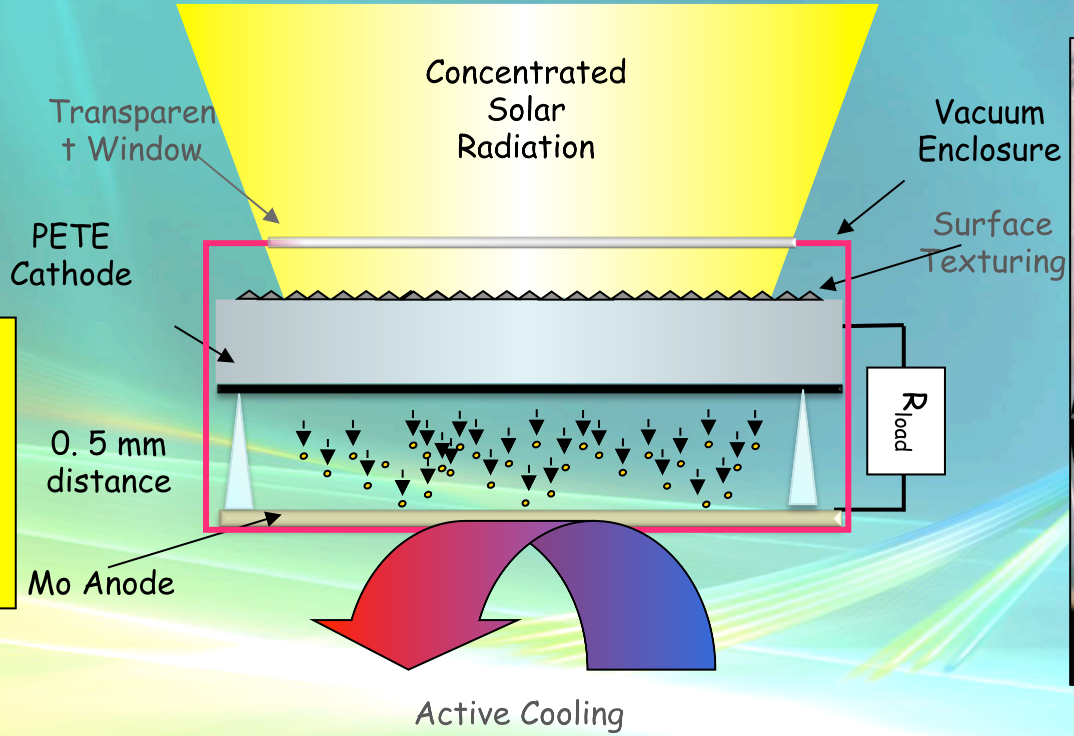


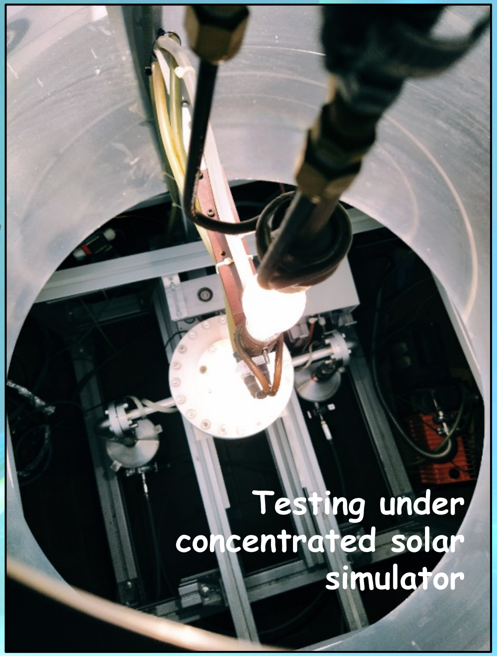
Surface hydrogenation in hydrogen plasma @
- 40 Torr
- 1.23 kW power
- 30 minutes
- 700 °C

Objective:
Negative electron affinity

Metallization of molybdenum frame-shaped front contact







3 PETE cathodes based on diamond single crystal plates with lateral size of 8x8 mm^2 and different thickness of 500, 200, 100 μm have been developed to study the influence of thickness vs electron diffusion length (150-250 μm)*

*J. Ristein, W. Stein, and L. Ley, PRL 78 (1997) 1803

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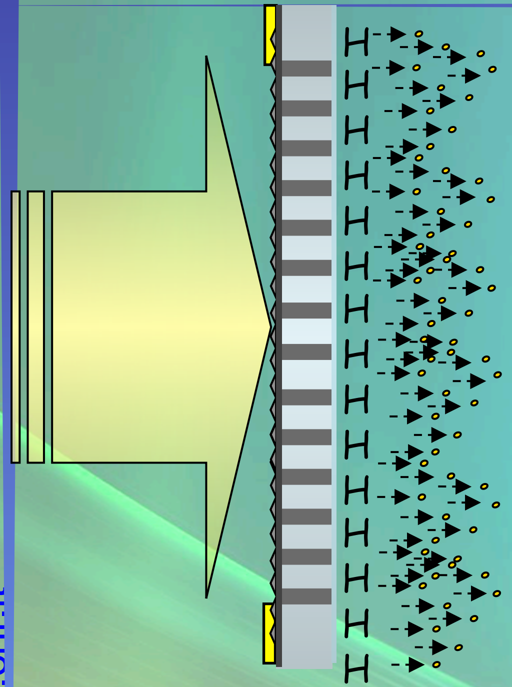
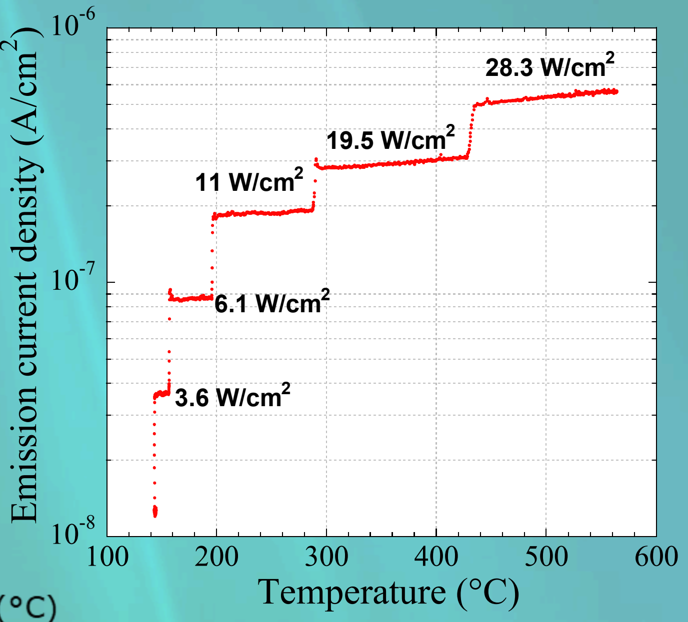
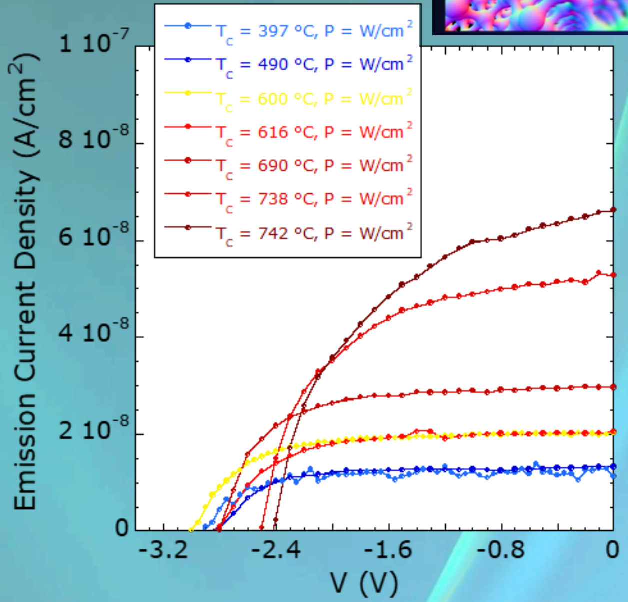
PETE Cathode / Demonstration of Proof-of-Concept

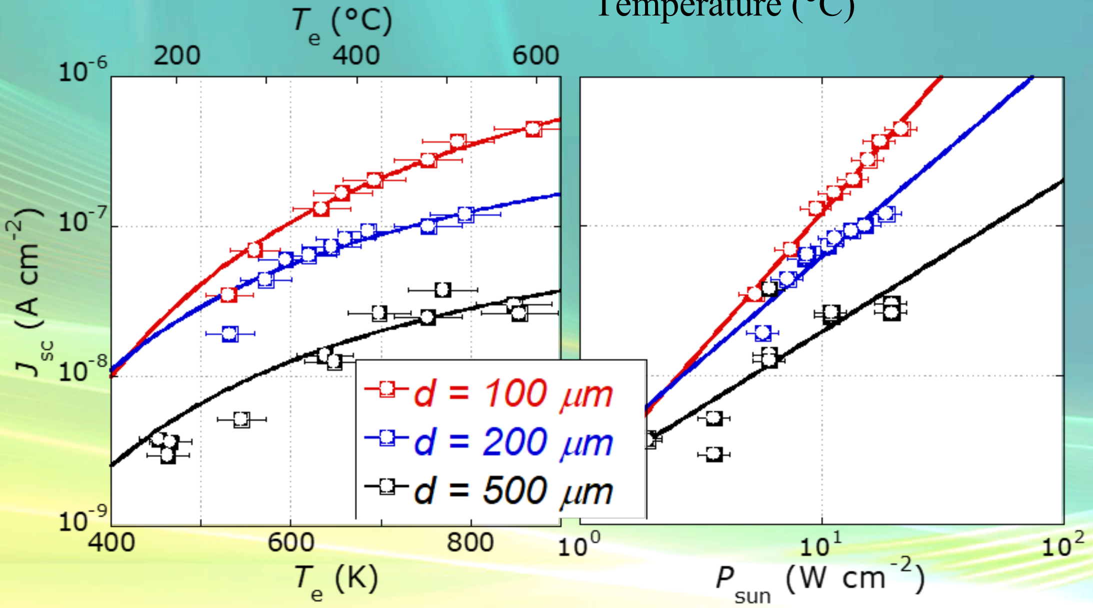


Electron emission increases with radiation power density and, also with cathode temperature but at high temperature values



Power generation is demonstrated by a positive current with a retarding voltage





Thermionic saturation current depends

- on *T* according to the modified Richardson-Dushman equation
- on input power *P* with a power law

D.M. Trucchi et al., **Demonstration of photon-enhanced thermionic energy conversion by black-diamond cathodes**, in preparation

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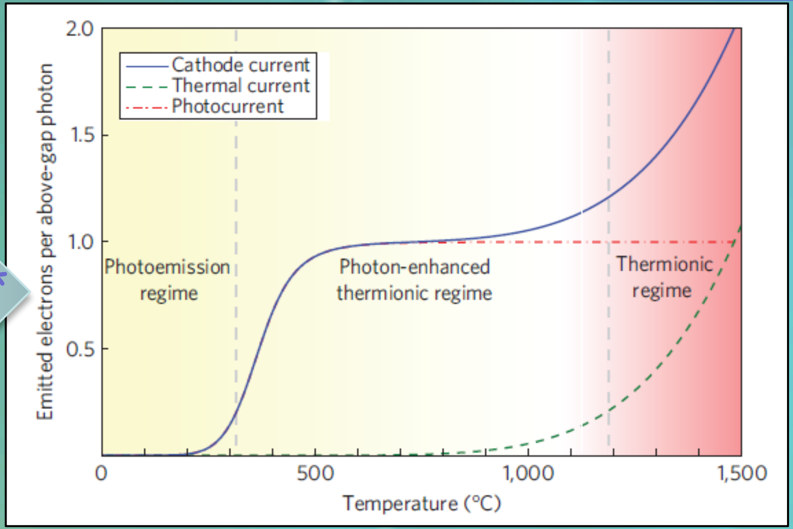
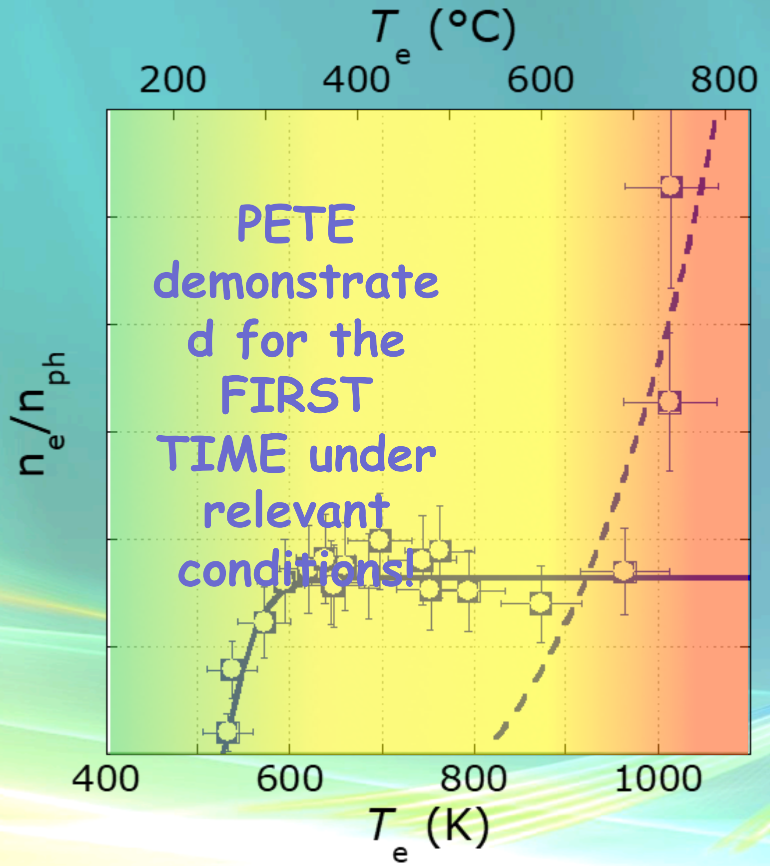
PETE Cathode / Demonstration of Proof-of-Concept

Theory*



*J. Schwede,et al., Nature Materials 9 (2010) 762

Experiment



Three regions can be clearly distinguished:

- *T* < 300 °C, **photoemission** is predominant;
- 300 < *T* < 600 °C, PETE regime is demonstrated for the FIRST TIME;
- *T* > 600 °C, **thermionic emission** is predominant.

D.M. Trucchi et al., **Demonstration of photon-enhanced thermionic energy conversion by black-diamond cathodes**, in preparation

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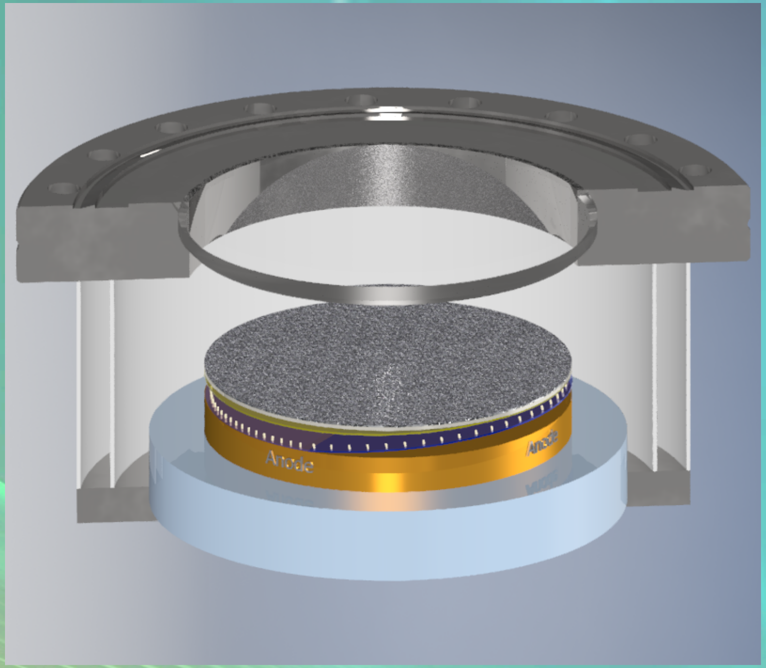
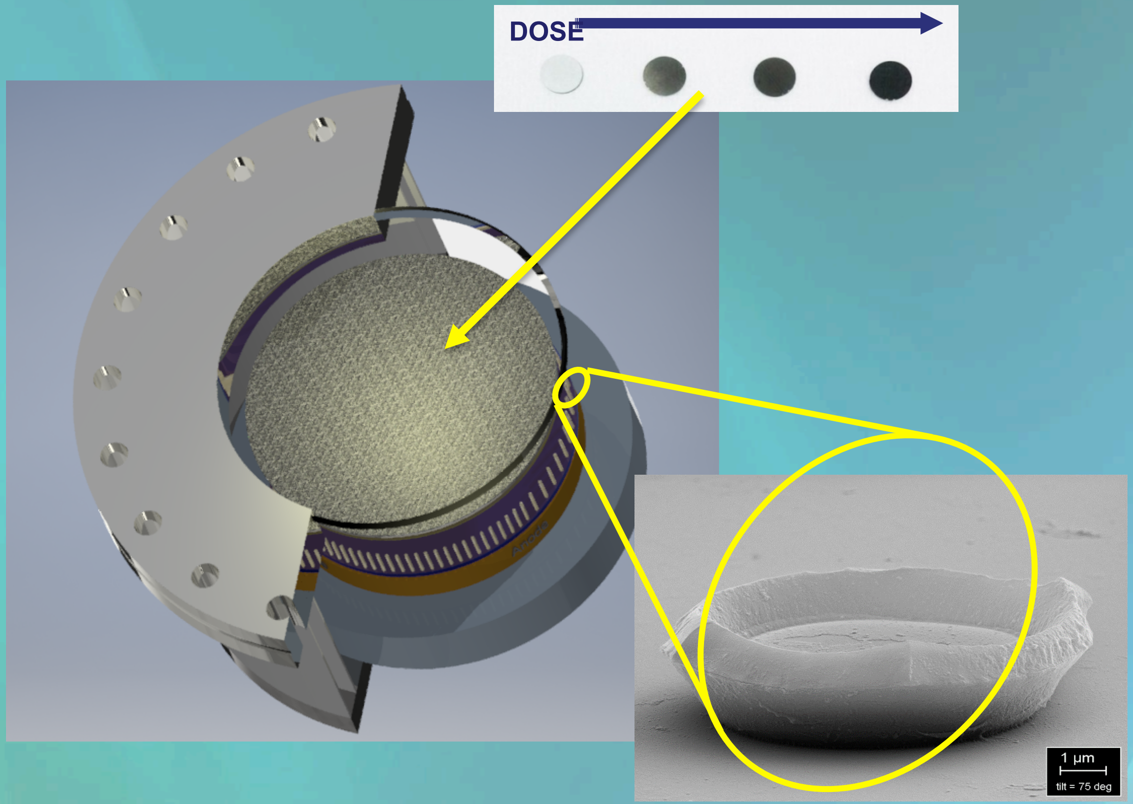
Our PETEC technology





High temperature solar cells adapted to laser beam operating with **photon-enhanced thermionic energy conversion (PETEC)** can satisfy all the conditions:

- Manage high radiation power densities **up to 200 W/cm^2**
- Operations from **-200 to +500 °C**
- Lightweight technology -> **About 2 g/cm^2 (excluding the stainless-steel enclosure, necessary only for lunar powder)**

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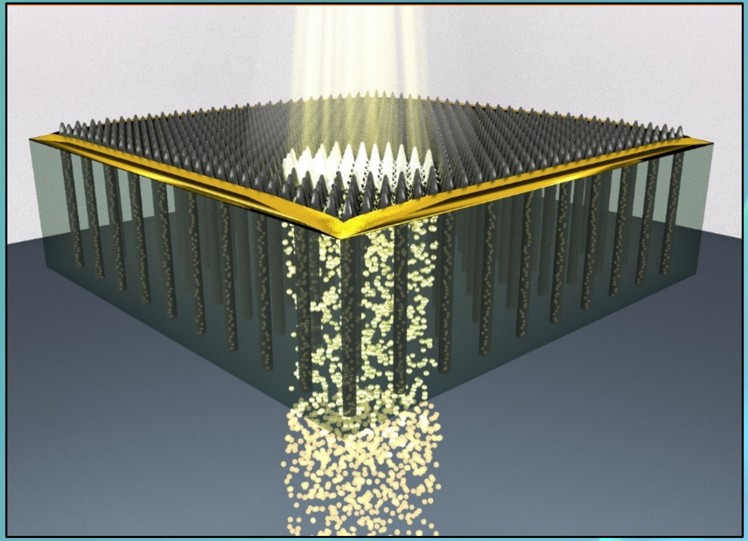
- ✓ BLACK DIAMOND can be defined as a new defect-engineered nanotextured material, characterized by the excellent physical properties of diamond and enhanced interaction with solar light, lithography steps are not necessary, and able to absorb about 99% of sunlight
- ✓ BLACK DIAMOND is the KEY ENABLING MATERIAL of an ADVANCED TECHNOLOGY COMBINATION for developing EFFICIENT HIGH-TEMPERATURE SOLAR CELLS & LASER BEAMING RECEIVERS (in a vacuum environment on the Moon)
- ✓ PETE concept was demonstrated for the FIRST TIME with a TESTING under HIGHLY-CONCENTRATED SUNLIGHT



Perspectives

- ➢ Extension of the recipes to polycrystalline diamond
- ➢ Extension to heterostructured cathodes
- ➢ Reduction of diamond plate thickness
- ➢ Extension to other wide bandgap semiconductors
- ➢ The fs-laser based techniques can be exported for developing optoelectronic devices with high integration capability

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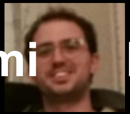
 A. Bellucci  V. Valentini  A. Ranieri

 M. Girolami  M. Mastellone

 S. Orlando  V. Serpente

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Ionvac Process SRL

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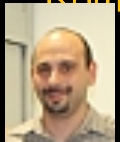
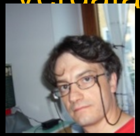
R. Polini 

Dipartimento di Scienze e Tecnologie Chimiche, Università di Roma "Tor Vergata"

 A. Orsini  S. Salvatori

Electronic Engineering Dept., Università di Roma "Niccolò Cusano"

IN FUTURE COLLABORATION WITH

The Lunar Grid

Thank you for the Attention!

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- **FET-ILP TECSAS project – GA 101034922**

TECSAS

PROMETHEUS

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