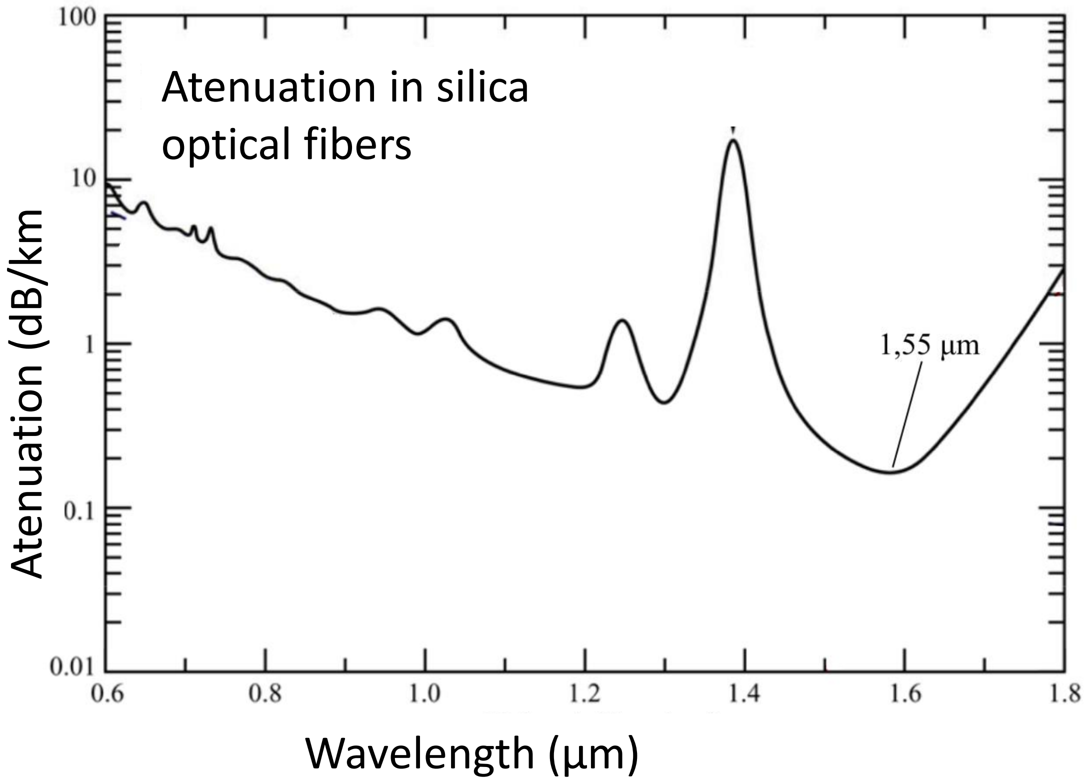
NIR laser light sensors based on nanosilicon/organic semiconductor junctions for telecom applications

***Vedran Đerek*[1], Eric Daniel Głowacki[2], Mateusz Bednorz[2],**
Niyazi Serdar Sariciftci[2], Mile Ivanda[1]*

[1] Center of Excellence for Advanced Materials and Sensing Devicesn (CEMS), Ruđer Bošković Institute, Bijenička c. 54, 10000 Zagreb, Croatia

[2]Johannes Kepler University Linz, Linz Institute for Organic Solar Cells (LIOS) / Institute of Physical Chemistry, Altenbergerstraße 69, 4040 Linz, Austria

Motivation



Fiber Optics Market worth $3.0 Billion by 2019

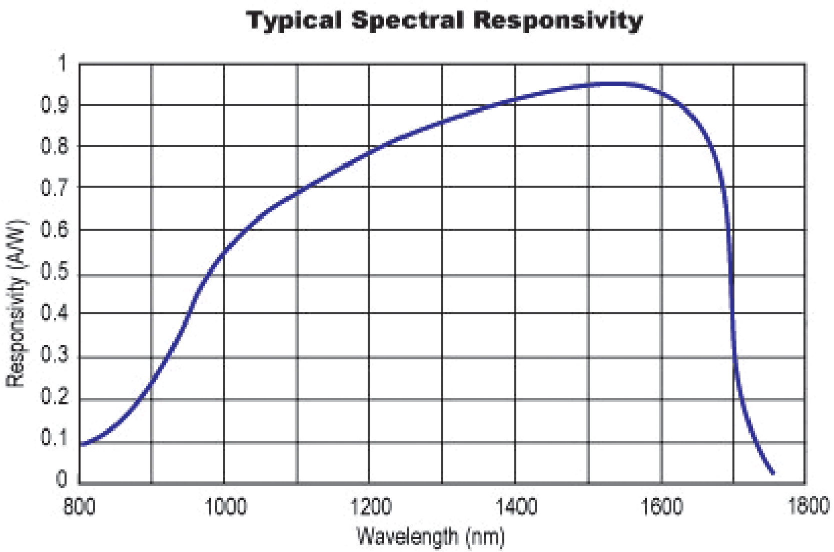
The report "**Fiber Optics Market by Application (Telecom & Broadband, Utilities, Oil & Gas, Private Data Networks, Military/Aerospace, Cable Television & Others) - Global Trends & Forecasts to 2019** " defines and segments the global fiber optics market with an analysis and forecast by region and application by value.

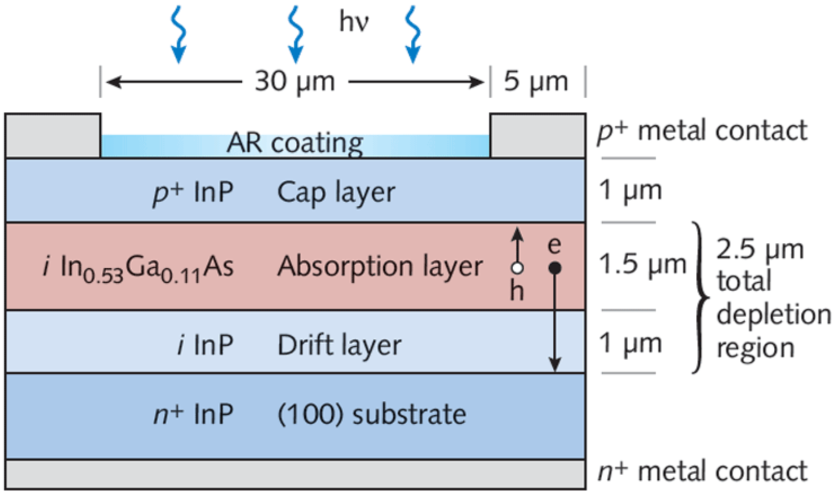
*marketsandmarkets.com, September 2014, Report Code: CH 2695

State of the art – InGaAs photodiode

- Tunable band-gap
  - GaAs (1.42 eV) to InAs (0.34 eV)
- Typical range 900nm to 1700nm
- 1.3 micron and 1.55 micron sensitivity
- High Responsivity
- Both Small Area (High Speed) and Large Area

- Not Si CMOS compatible
- Expensive (MBE)
- Toxic precursors





*http://goo.gl/hz2Q6Q
http://goo.gl/W7f1rI
http://goo.gl/H89sZG

Silicon/organic hybrid heterojunction

Silicon (p-type)

Organic semiconductor (n-type)

Silicon/organic hybrid heterojunction

- Silicon (p-type)
- Organic semiconductor (n-type)

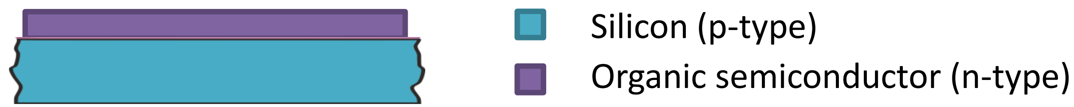
Silicon

- well- developed Si CMOS technology

if micro/nano structured:

- large surface area
- light trapping
- nano-scale phenomena

Silicon/organic hybrid heterojunction



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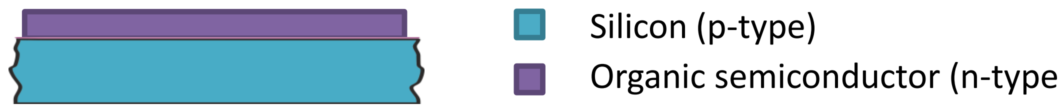
Organic semiconductor thin films

- electronics with carbon-based materials
- chemically **tunable electronic properties**
- easy and cheap processing
- low environmental impact
- low material usage

Silicon/organic hybrid heterojunction



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Hybrid electronics

integrating advantages of organics with silicon-based electronics - **going beyond Si**

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Hybrid electronics

integrating advantages of organics with silicon-based electronics - **going beyond Si**

+ advantages of nanostructuring of Silicon

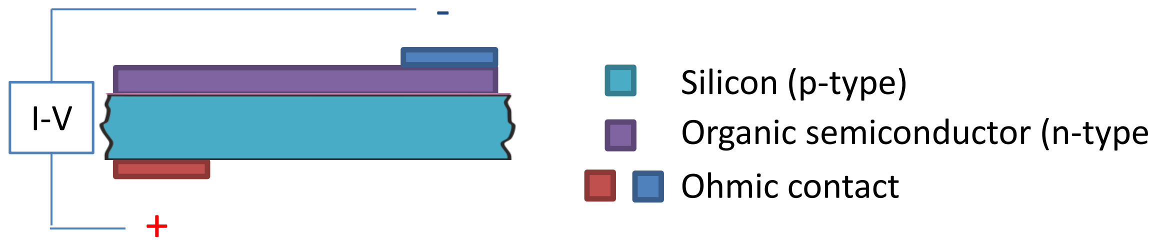
Si/organic hybrid heterojunction electronic devices

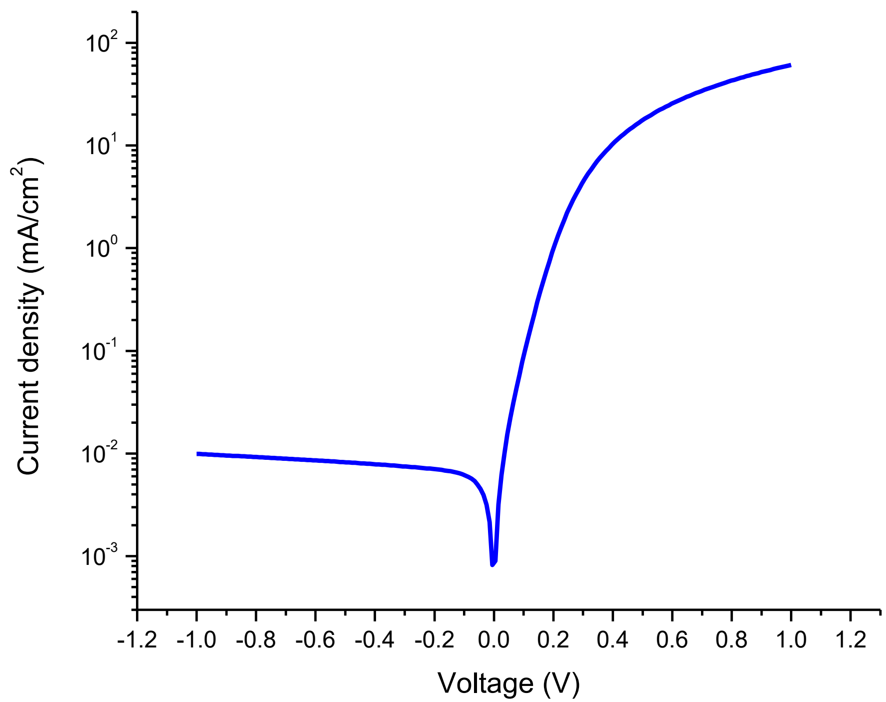
Example: diode

Silicon (p-type)
Organic semiconductor (n-type)
Ohmic contact

Si/organic hybrid heterojunction electronic devices

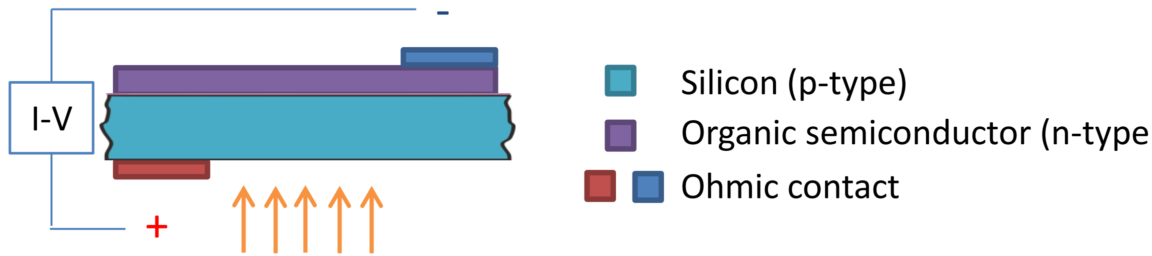
Example: diode

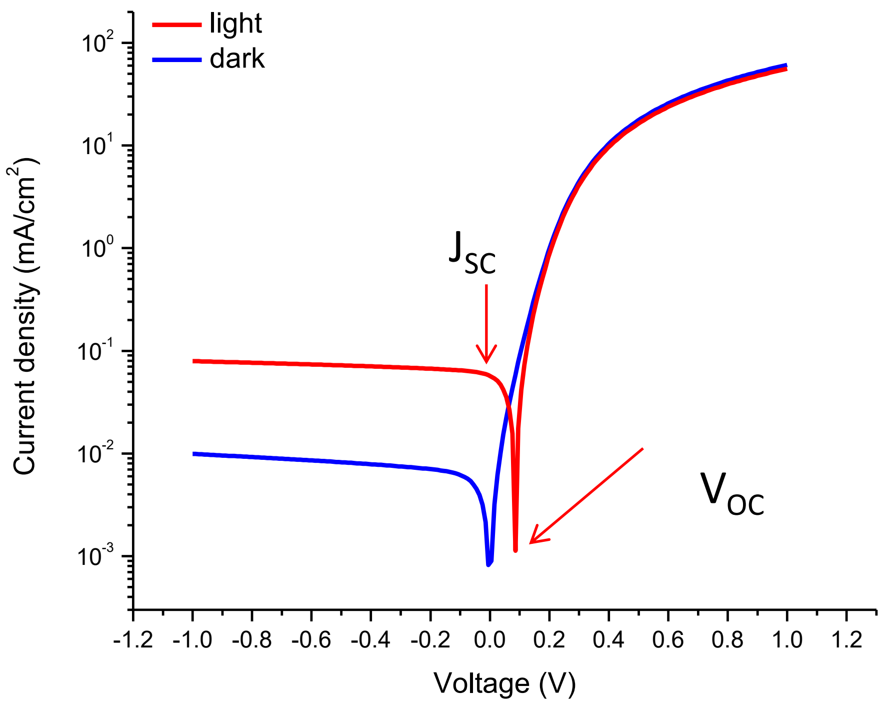




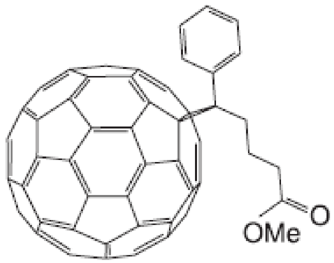
Si/organic hybrid heterojunction electronic devices

Example: photo-diode

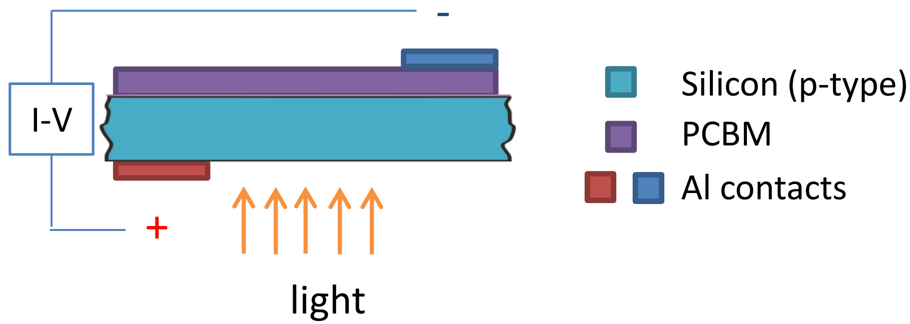




Si/PCBM photodiode



PCBM - Phenyl-C61-butyric acid methyl ester

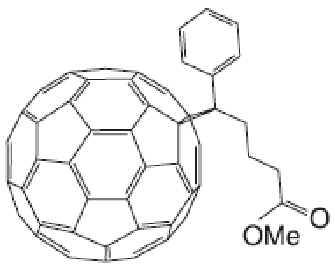


- G. Matt et. al., LIOS, 2004-2009*
- Si/Fullerene derivative (PCBM)
- Solution processed
    - Low device yield
    - LN_2 cooled

*Sensing Infrared Light with an Organic/Inorganic Hetero-junction
G. Matt, T. Fromherz , G. Goncalves, C. Lungenschmied, D. Meissner, N.S. Sariciftci
Interface Controlled Organic Thin Films, Springer Proceedings in Physics, Vol 129 (2009), 153

Si/PCBM photodiode

Responsivity: 10^{-6} A/W (room temperature, 1550 nm/0.8 eV)



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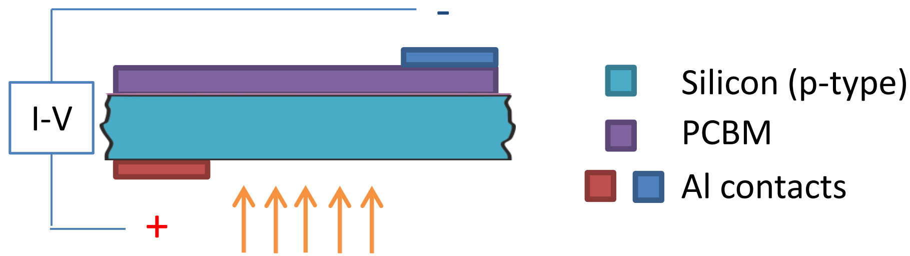


IR light

- G. Matt et. al., LIOS, 2004-2009*
- Si/Fullerene derivative (PCBM)
- Solution processed
  - Low device yield
  - LN_2 cooled

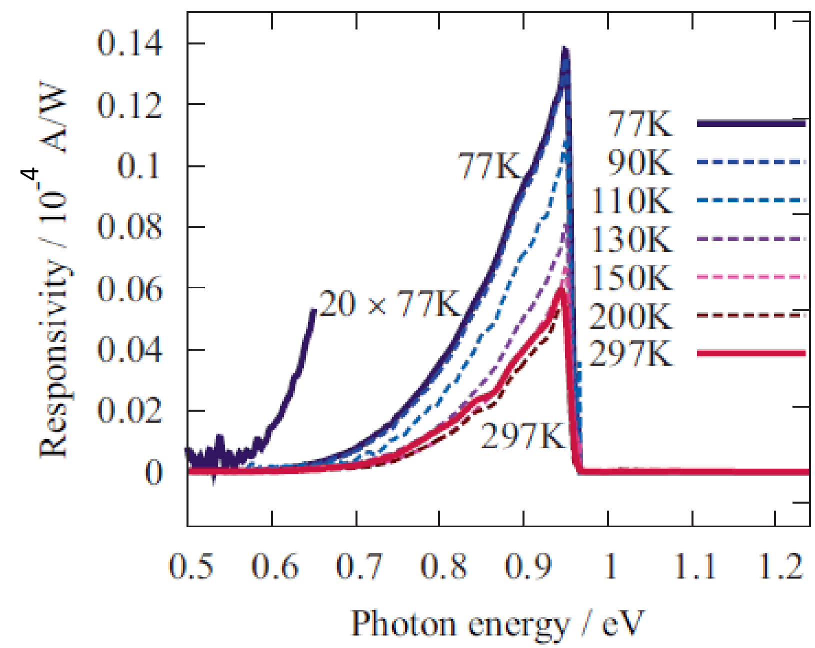
Si: 1.1 eV

PCBM: 2.4 eV

Sub-bandgap photo current generation

→ going beyond silicon ✓

→ possible important applications – telecom



(broadband light+ LP filter at 0.95 eV)*

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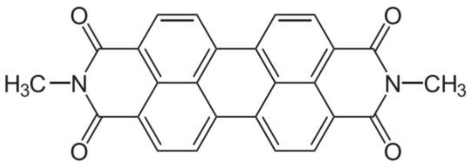
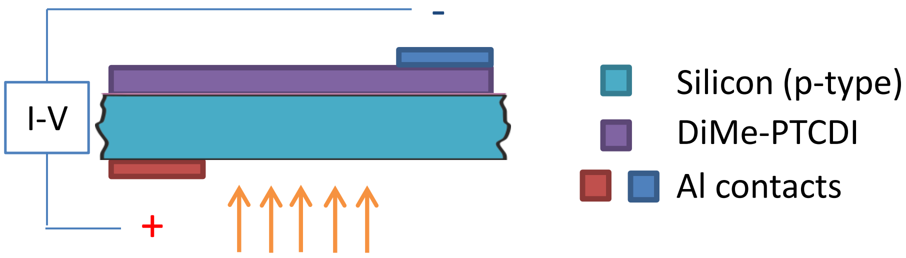
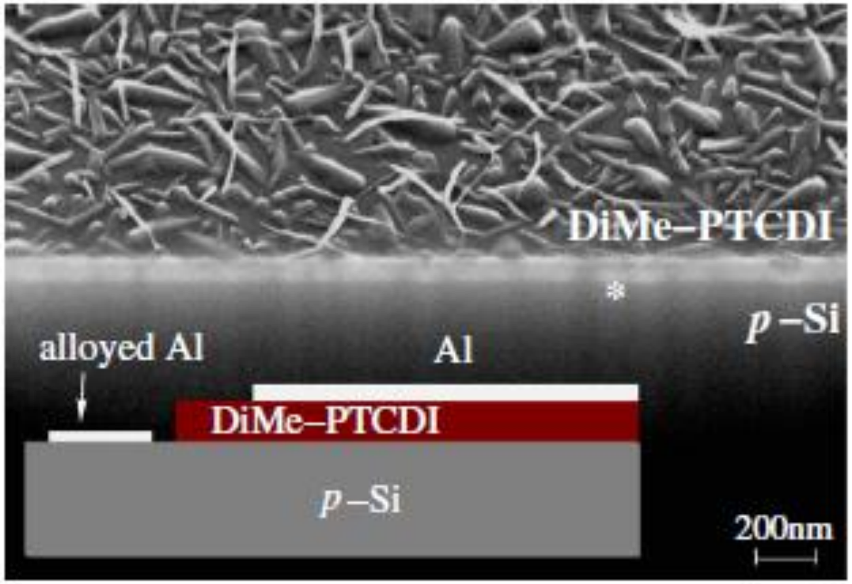
Si/DiMe-PTCDI photodiode



N,N'Dimethyl-3,4,9,10-Perylenetetracarboxylic diimide (DiMe-PTCDI)



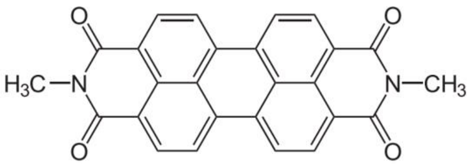
- Improvement by vacuum deposition of organic films (hot-wall epitaxy)
- Si/PCBM,Indigo,Tyrian Purple,DiMe-PTCDI



*Silicon/organic hybrid heterojunction infrared photodetector operating in the telecom regime, Mateusz Bednorz, Gebhard J. Matt, Eric D. Głowacki, Thomas Fromherz, Christoph J. Brabec, Markus C. Scharber, Helmut Sitter, N. Serdar Sariciftci, Organic Electronics 14 (2013) 1344–1350

Si/DiMe-PTCDI photodiode

Responsivity: 10^{-4} A/W (room temperature, 1550 nm/0.8 eV)



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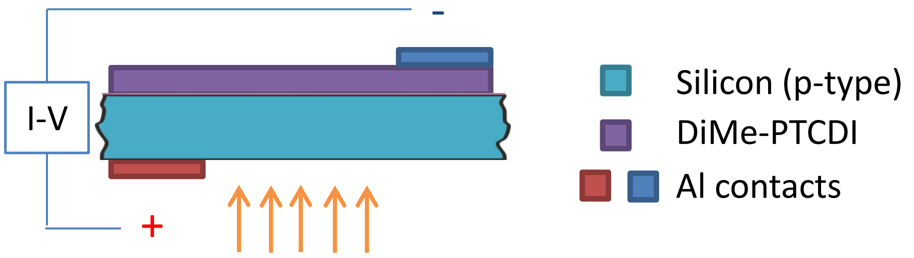
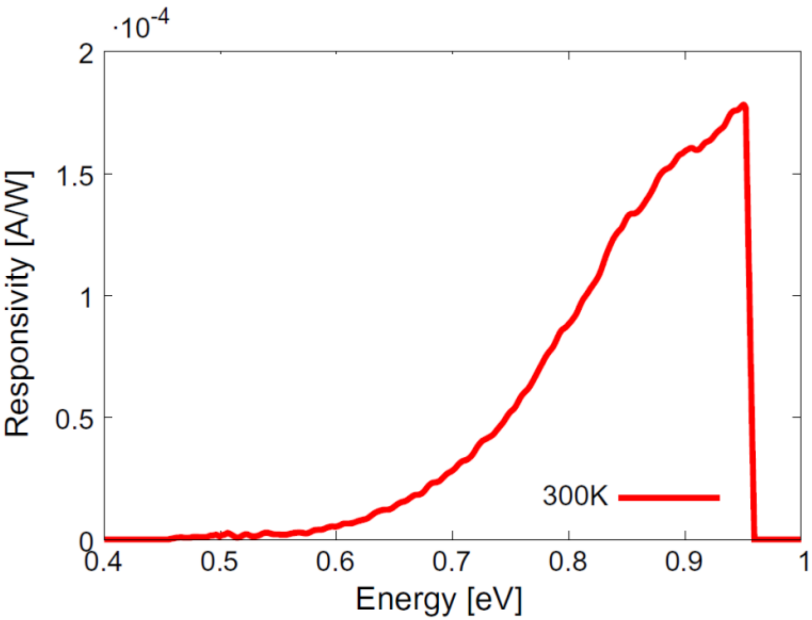


- Improvement by vacuum deposition of organic films (hot-wall epitaxy)
- Si/PCBM,Indigo,Tyrian Purple,DiMe-PTCDI

- Room-temperature diodes
- Device yield close to 100%
- >20-fold improved responsivity over 1st gen (0.2 mA/W at 300 K)



(broadband light+ LP filter at 0.95 eV)

Optimization of the organic layer

→ approaching the limits of commercial usability ✓

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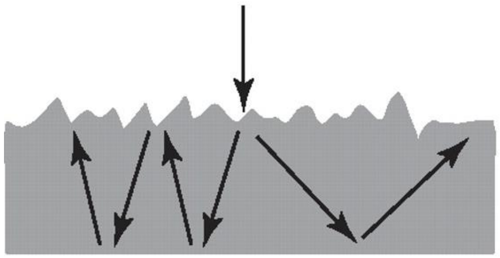
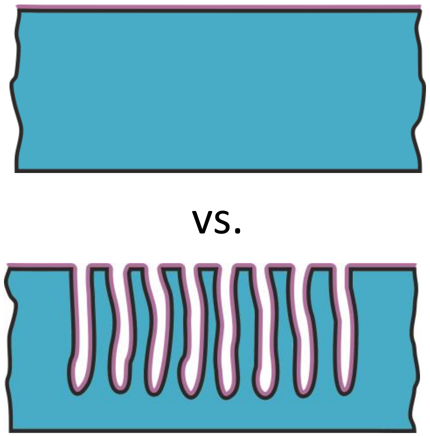
Optimization of Si in hybrid heterojunction

Micro- and nano-structuring of the Si surface

LIGHT TRAPPING

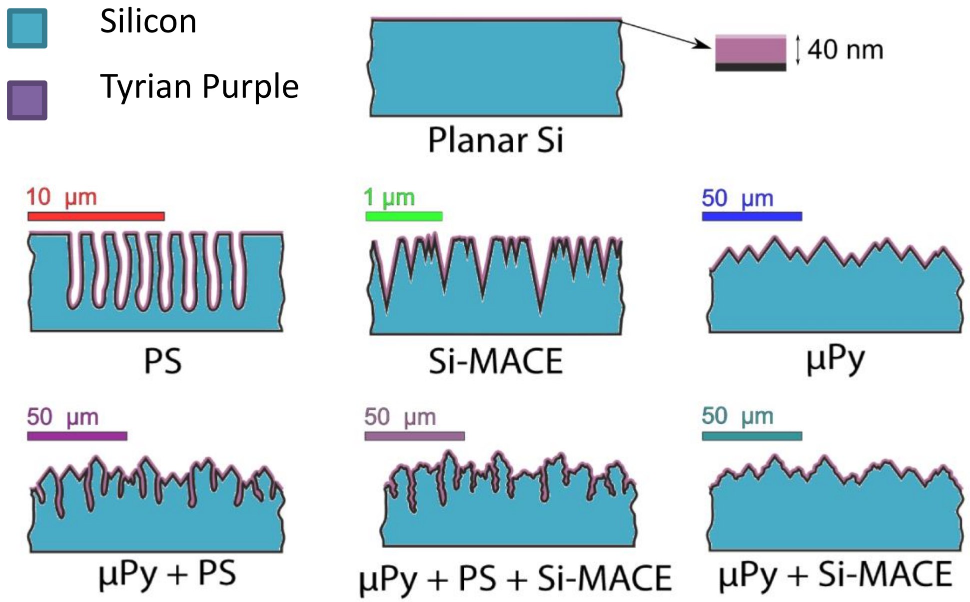
> EFFECTIVE JUNCTION AREA





Micro- and nano-structuring of the Si surface

- methods of wet chemistry -

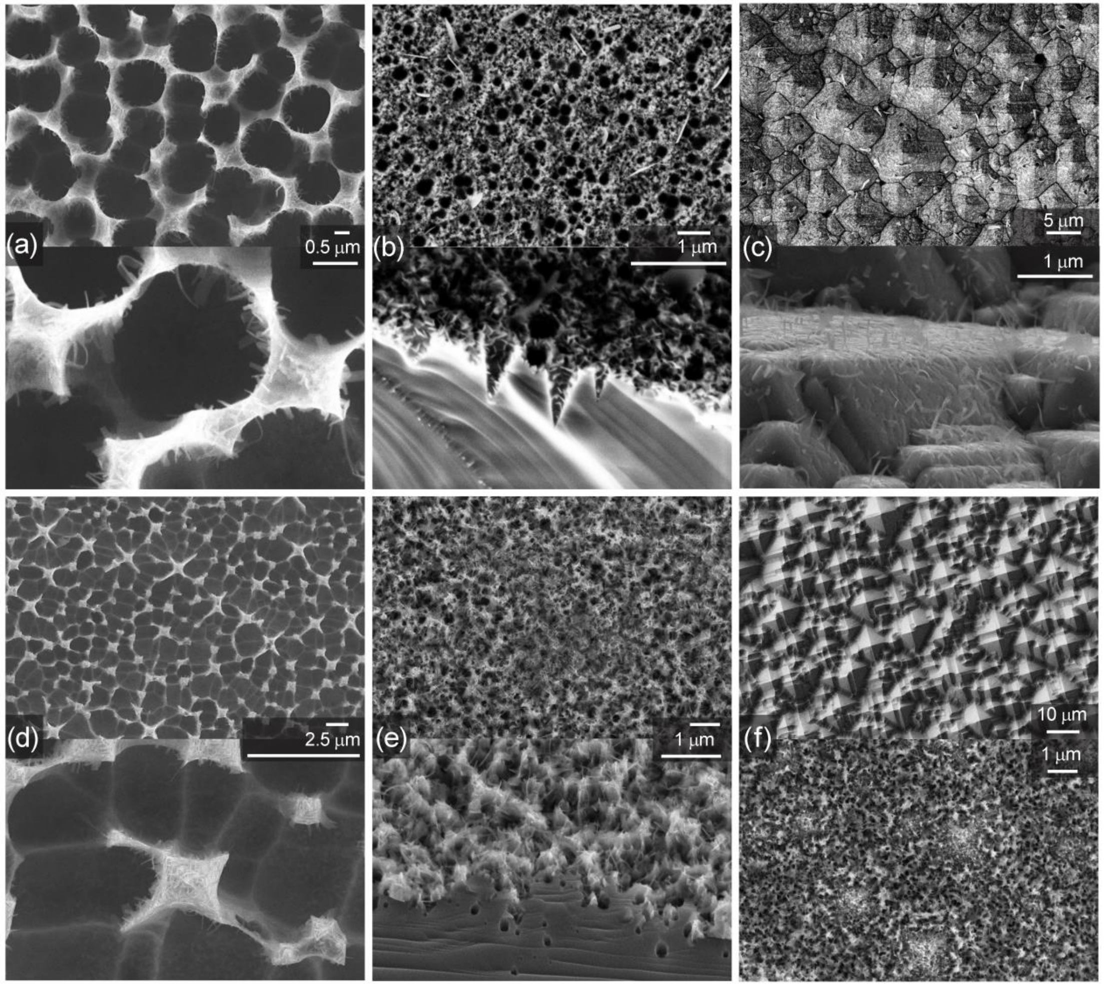


- Porous Si by anodisation in HF
- Silicon metal assisted chemical etching
- Si micropyramids by anisotropic KOH/IPA etch of (100) Si
- Hierarchical structures
  - Micropyramids+porous Si
  - Micropyramids+porous Si+MACE
  - Micropyramids+MACE

Both micro- and nano-scaled features

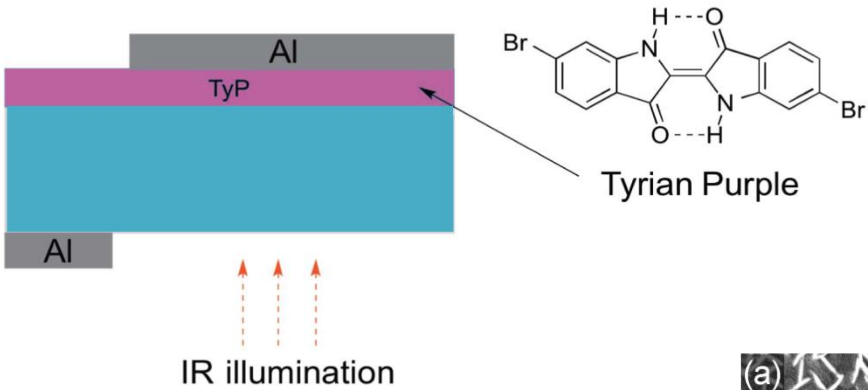
Micro- and nano-structuring of Si surface

Porous Silicon | Si MACE | Si micropyramids

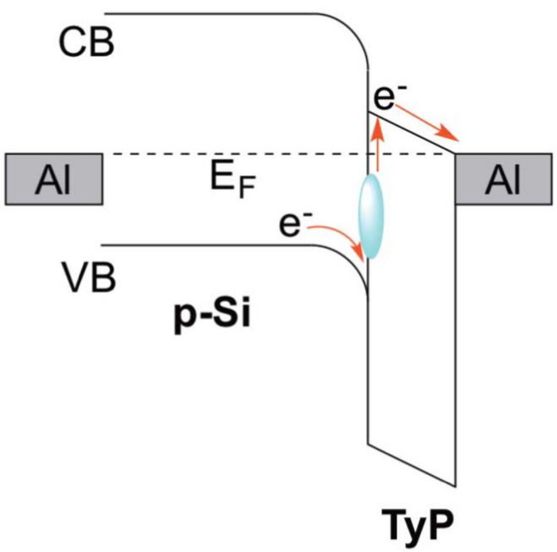


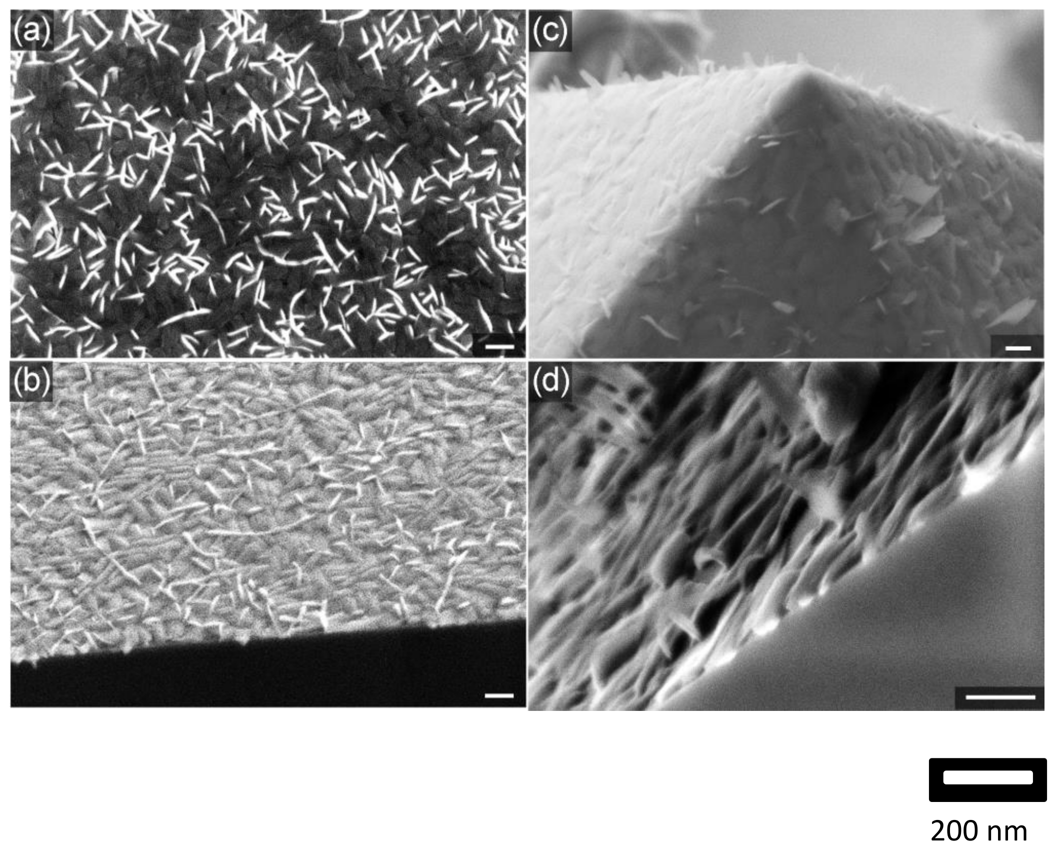
Mircopyramids+PS | Mircopyramids+MACE | Mircopyramids+MACE + Pourous Si

Structured Si/Tyrian Purple photodiode



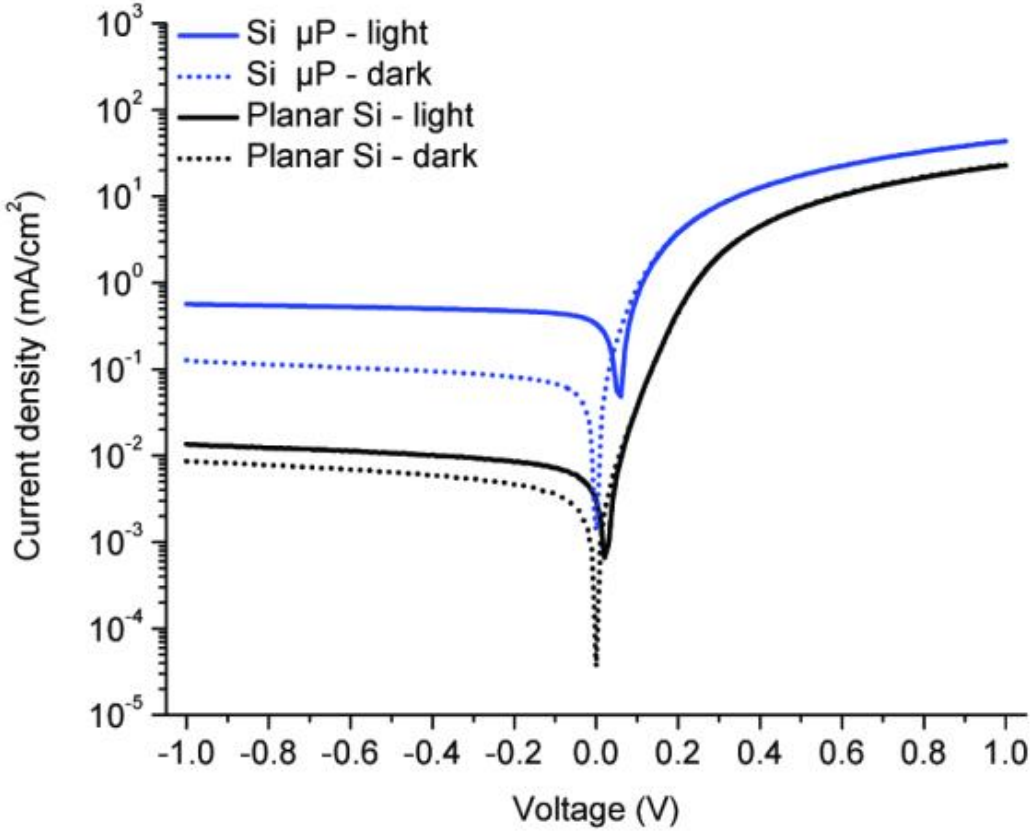
- 6,6′-dibromoindigo – Tyrian Purple
- Hydrogen-bonded pigment
- n-type organic semiconductor
- Thin films by hot-wall epitaxy





Structured Si/Tyrian Purple photodiode

- Up to **700-fold** increase in short-circut photocurrent over planar diodes
- Highest responsivity:
  silicon micropyramids/TyP
- Responsivity: **4 mA/W** at 1,55 µm (room temperature, -1 V biased)
  - ~100-fold increase over gen 2
  - ~1000-fold increase over gen 1
- InGaAs: max 1A/W



light = 1,48 µm laser diode (200 mW/cm²)

Enhanced near-infrared response of nano- and microstructured silicon/organic hybrid photodetectors, V. Đerek, E. D. Głowacki, M. Sytnyk, W. Heiss, M. Marciuš, M. Ristić, M. Ivanda, and N. S. Sariciftci, Appl. Phys. Lett. 107, 083302 (2015)

Structured Si/Tyrian Purple photodiode

- Up to **700-fold** increase in short-circut photocurrent over planar diodes
- Highest responsivity:
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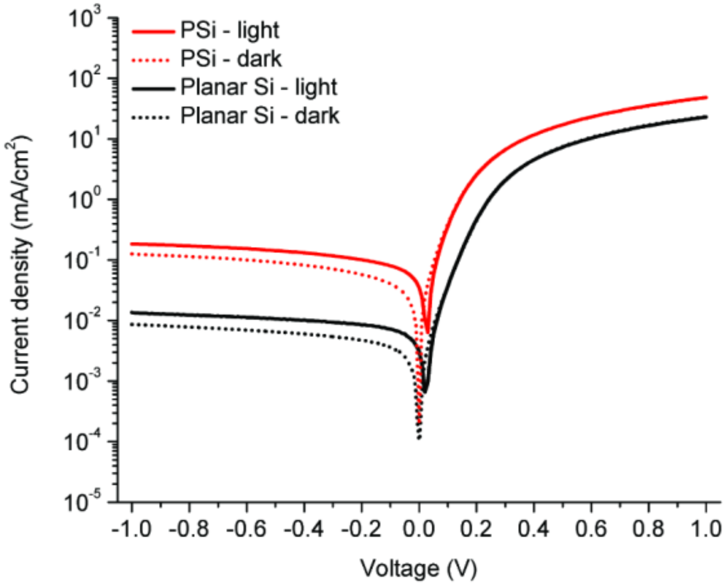
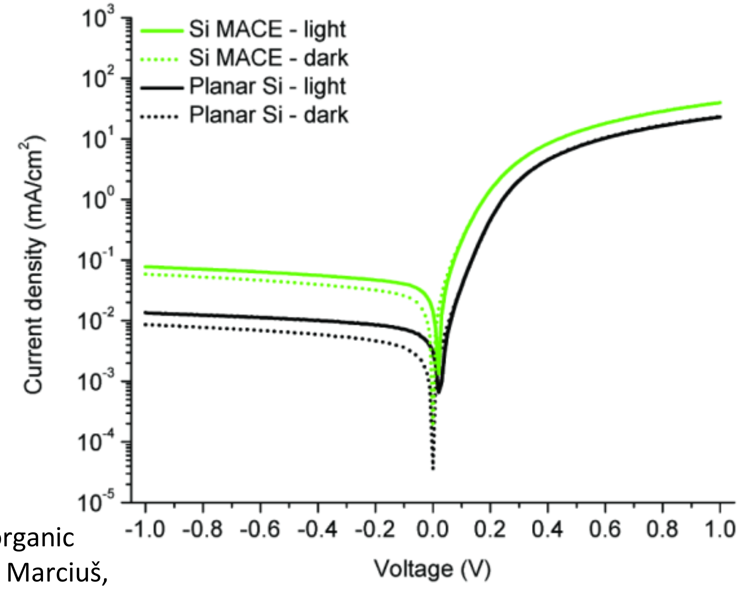
- Improvement for all methods of structuring





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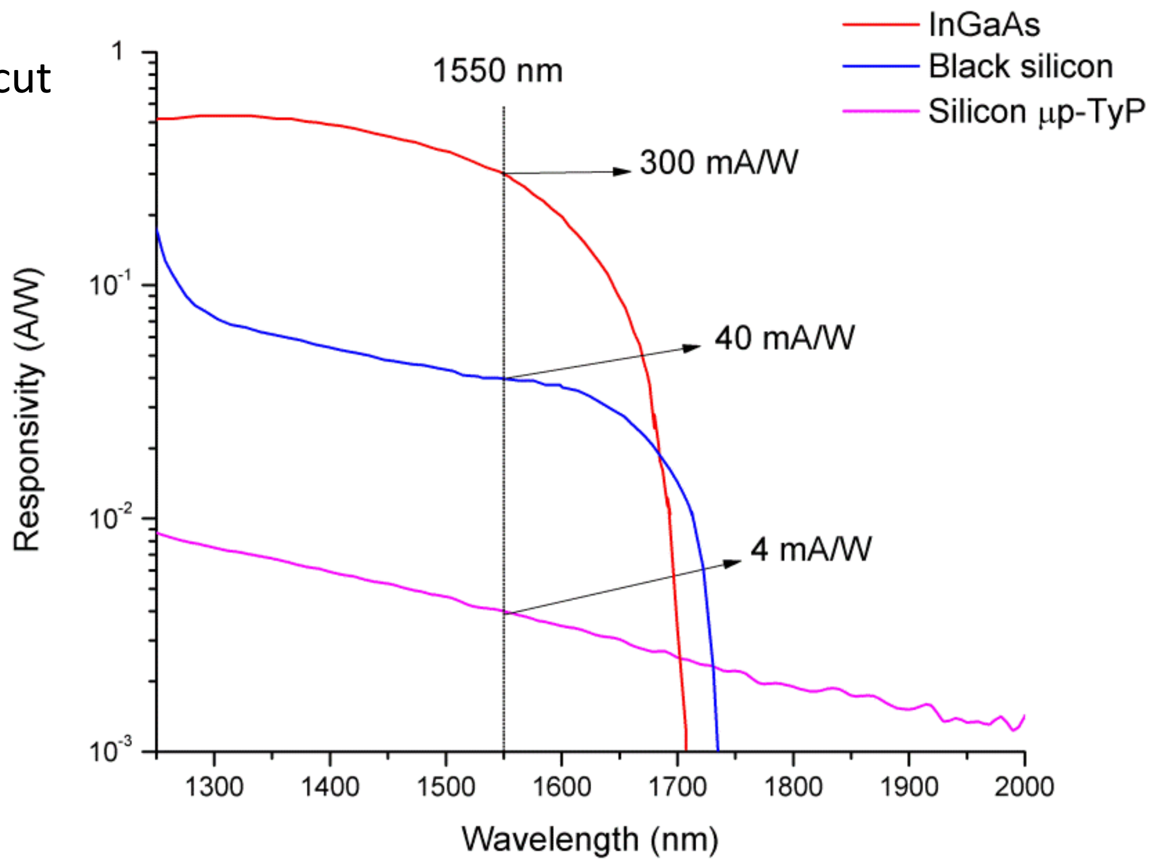
Structured Si/Tyrian Purple photodiode

- Up to **700-fold** increase in short-circut photocurrent over planar diodes
- Highest responsivity:
  silicon micropyramids/TyP
- Lower responsivity than competing technologies (black Si, InGaAs)
- But, broader response and plenty of space for improvement!



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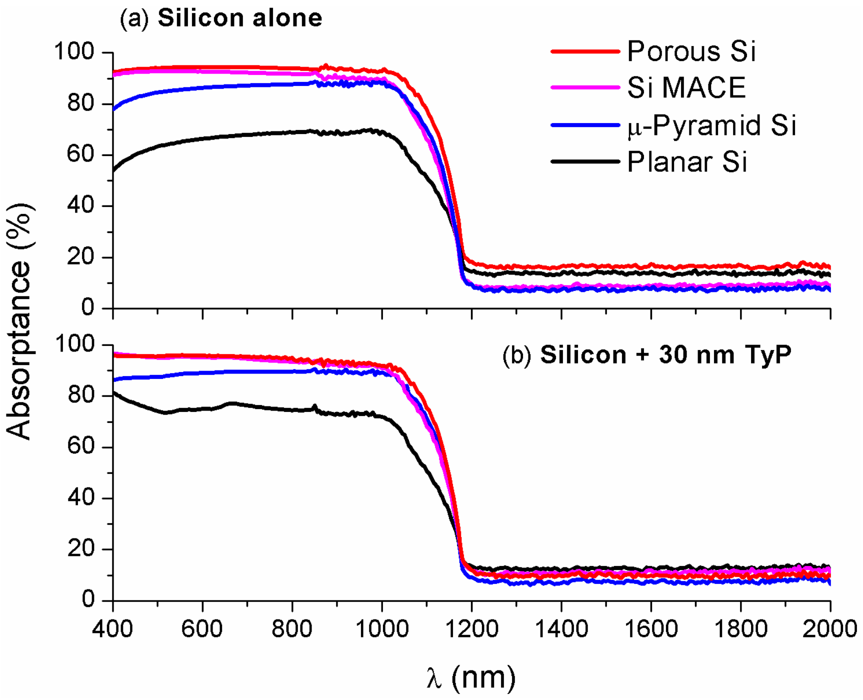
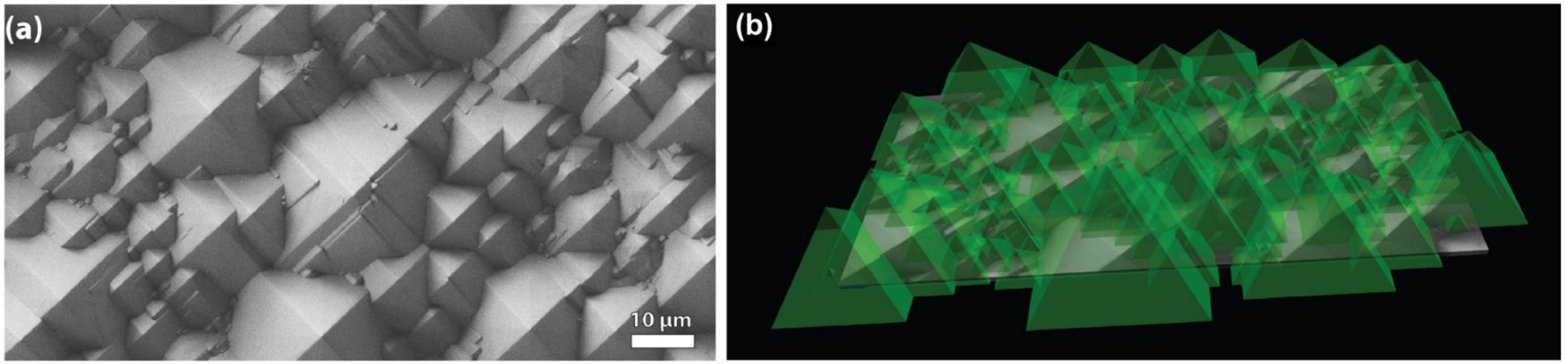
Mechanisims of improvement



Light trapping – ruled out

Mechanisims of improvement



- 3D model of the µ-pyramid structured surface based on the SEM image
- Surface area: 1.55 times that of the planar sample
- J_{SC} > 100 times of the planar sample
- Other structuring methods give larger surface areas, but the micropyramid samples give the highest improvement in photocurrent

- Increase of junction surface ruled out as mechanism of improvement

Overview

- Silicon / organic semiconductor heterojunction – NIR photodetector
  - Origin of the effect –type II heterojunction and/or surface mid-gap states
- Micro/nano structuring increases the photoresponsivity **~100 fold**
  - Origin of the effect – not increase of surface area nor light trapping
  - Electric field effects?
- Responsivity – already interesting for telecom industry
- Work in progress

Team

- Dr. Eric D. Głowacki (LIOS)
- Dr. Mateusz Bednorz (LIOS)
- o.Univ. Prof. Mag. Dr. DDr. h.c. Niyazi Serdar Sariciftci (LIOS)
- Dr. Mile Ivanda (IRB)

Special thanks to:

- Dr. Gebhard Matt (former LIOS)

LIOS team:

- M. Sytnyk, M. Scharber, P. Stadler, M. White, M. Havlicek, D. Apaydin, L. Leonat, C. Enengl, S. Enengl, P. Denk, G. Kalab...

IRB-CEMS team:

- D. Ristić, L. Mikac, H. Gebavi, M. Kosović, M. Marciuš, M. Ristić, S. Musić, T. Janči, V. Đurina

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Publications

SPRINGER PROCEEDINGS IN PHYSICS 129

Sensing Infrared Light With an Organic/Inorganic Hetero-Junction

Gebhard J. Matt[1], Thomas Fromherz[1], Guillaume Goncalves[2], Christoph Lungenschmied[3], Dieter Meissner [4] and Serdar N. Sariciftci[4]

Phys. Status Solidi B 247, Nos. 11–12, 3043–3046 (2010) / DOI 10.1002/pssb.201000200

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Fullerene sensitized silicon for near- to mid-infrared light detection

G. J. Matt[1], T. Fromherz[1], M. Bednorz[1], H. Neugebauer[2], N. S. Sariciftci[2], and G. Bauer[*,1]

JOURNAL OF APPLIED PHYSICS 112, 114508 (2012)

CrossMark

Electrical properties of pSi/[6,6] phenyl-C61 butyric acid methyl ester/Al hybrid heterojunctions: Experimental and theoretical evaluation of diode operation

Mateusz Bednorz,[1,a)] Thomas Fromherz,[1] Gebhard J. Matt,[2] Christoph J. Brabec,[2] Markus Scharber,[3] and N. Serdar Sariciftci[3]

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Silicon/organic hybrid heterojunction infrared photodetector operating in the telecom regime

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Mateusz Bednorz[a], Gebhard J. Matt[b,*], Eric D. Głowacki[c], Thomas Fromherz[a], Christoph J. Brabec[b], Markus C. Scharber[d], Helmut Sitter[a], N. Serdar Sariciftci[c]

APPLIED PHYSICS LETTERS 107, 083302 (2015)

Enhanced near-infrared response of nano- and microstructured silicon/organic hybrid photodetectors

Vedran Đerek,[1] Eric Daniel Głowacki,[2,a)] Mykhailo Sytnyk,[3] Wolfgang Heiss,[3] Marijan Marciuš,[1] Mira Ristić,[1] Mile Ivanda,[1,a)] and Niyazi Serdar Sariciftci[2]

Thank you for your kind attention!