The Eighth International Conference on Sensor Device Technologies and Applications
SENSORDEVICES 2017

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Reviewing SiC photo-sensing devices

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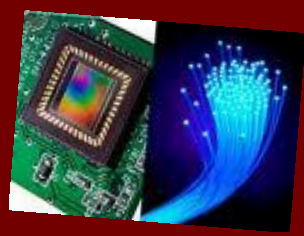
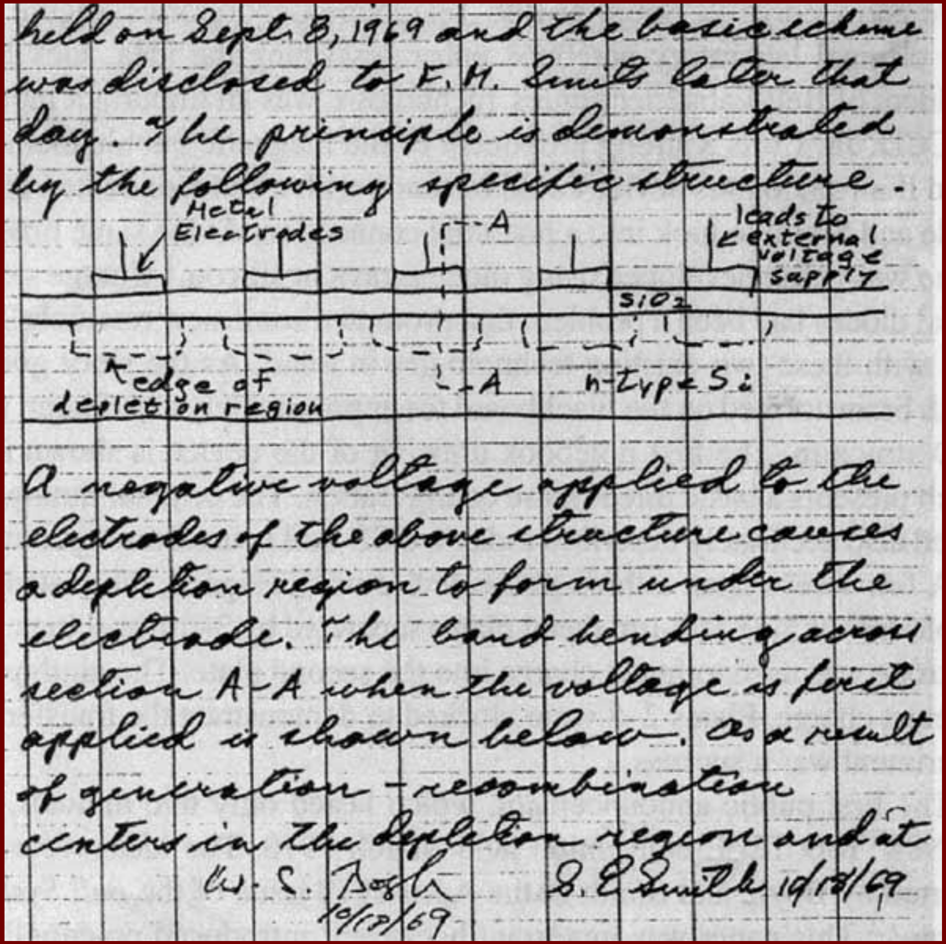
NOBEL in Physics 2009

TWO REVOLUTIONARY OPTICAL TECHNOLOGIES



"The Nobel Prize in Physics 2009 honors three scientists, who have played important roles in shaping the modern information technology, with one half to **Charles K. Kao** and with **Willard S. Boyle** and **George E. Smith** sharing the other half."

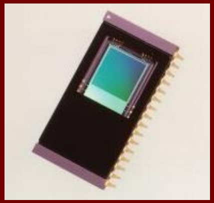
Useful reading



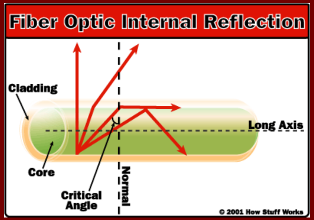
held on Sept. 8, 1969 and the basic scheme was disclosed to F. H. Smith later that day. The principle is demonstrated by the following specific structure.

A negative voltage applied to the electrodes of the above structure causes a depletion region to form under the electrode. The band bending across section A-A when the voltage is first applied is shown below. As a result of generation-recombination centers in the depletion region and at

W. S. Boyle 10/18/69 G. E. Smith 10/18/69



1. W.S. Boyle and G.E. Smith, *Bell Systems Technical Journal* 49 (1970) 587; G.F. Amelio,
M.F. Tompsett and G.E. Smith, *ibid.* 49 (1970) 593.
2. J.R. Janesick: *Scientific Charge-Coupled Devices* (SPIE Press, 2001).



1. J. Hecht, "City of light. The story of fiber optics", Oxford University Press (1999).
2. K.C. Kao and G.A. Hockham, "Dielectric-Fibre Surface Waveguides for optical frequencies"
Proc. IEEE, 113, 1151 (1966).

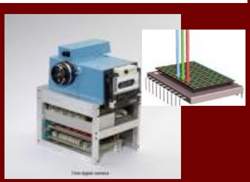
Charge-Coupled Devices

Apparently the first still remaining photograph was produced by J.N. Niépce in 1826 using a camera obscura with an 8 hour exposure time.

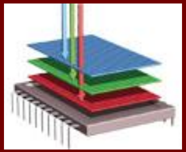
W.H.F. Talbot invented in 1841, light sensitive papers containing silver salts for first obtaining a negative image and there after, through contact copying with another light sensitive paper, a positive image. In 1888 the Eastman Kodak box camera for roll film appeared on the market.

G. Lippman was awarded the 1908 Nobel Prize in Physics for his color photographic process based on interference effects. Traditional color films consist of three light sensitive emulsions with different sensitivities for light: top layer for blue, middle layer for green, and bottom layer for red.
Film capture full color at every point in the image.

Kodak developed the Bayer filter mosaic pattern used for CCD image sensors (1975), only after the groundbreaking CCD invention (1970) W.S. Boyle and G.E. Smith.

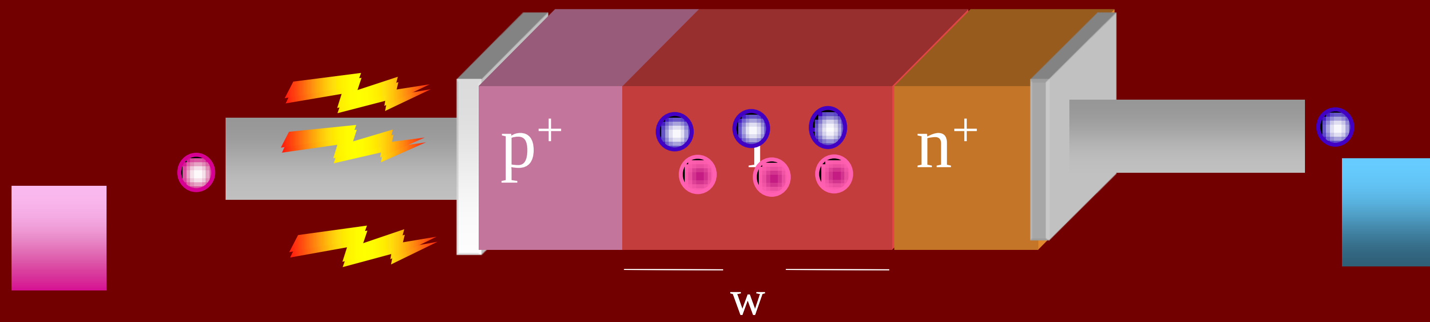


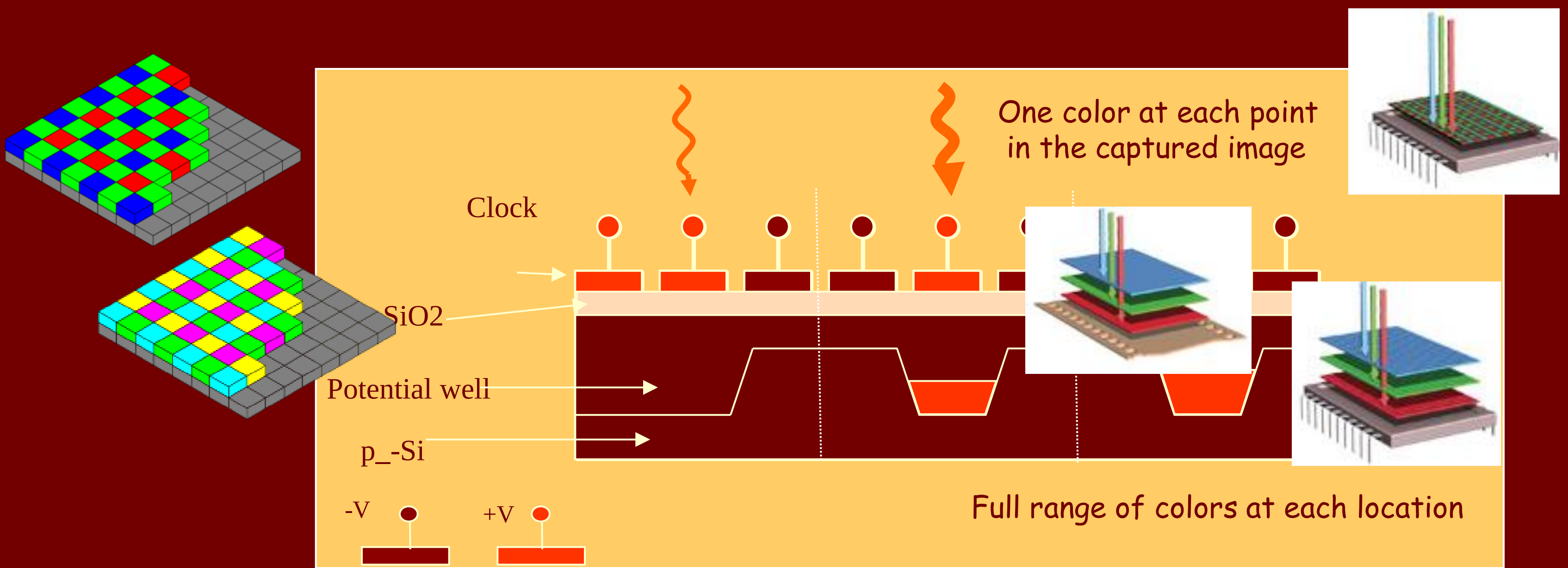
The CCD digital image sensors were only capable of recording just one color at each point in the captured image instead of the full range of colors at each location.



Full color image sensors

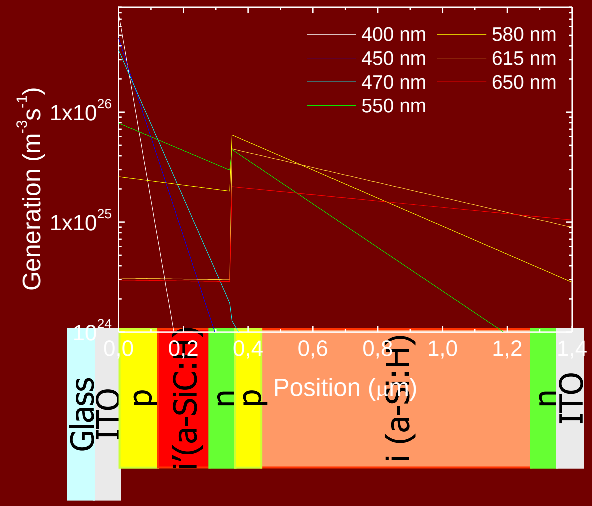
All of these devices use essentially the same light sensing mechanism. Photons penetrating a depletion region generate electron-hole pairs. These carriers are swept away by the electric field across the depletion region and generate a small transverse photocurrent.

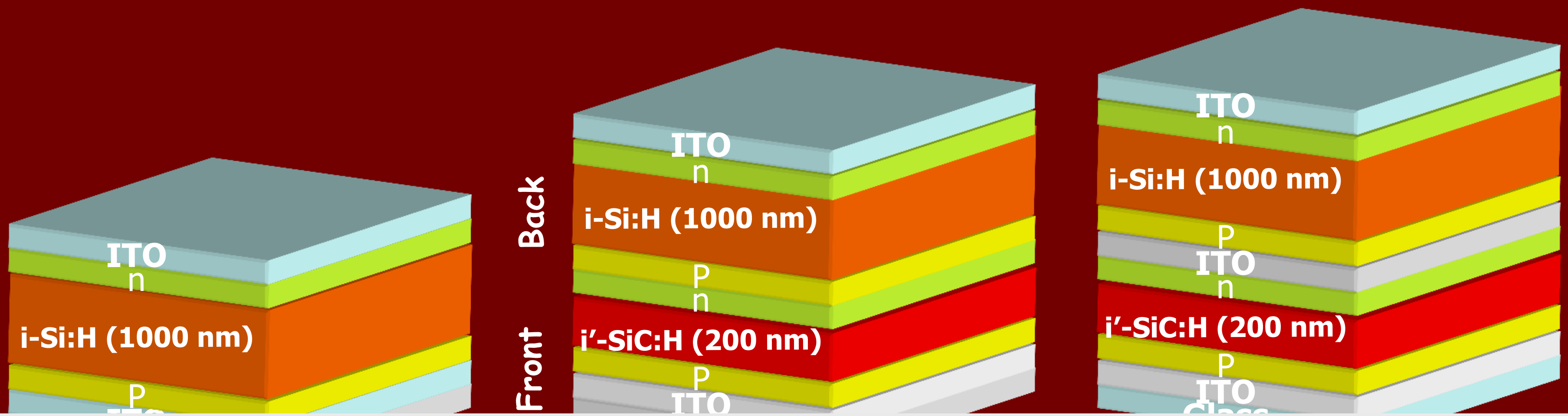




Device Architecture

- Produced by PECVD
  - The thickness of the front photodiode are optimized for blue collection and red transmittance
  - The thickness of the back photodiode was adjusted to achieve high collection in the red spectral range





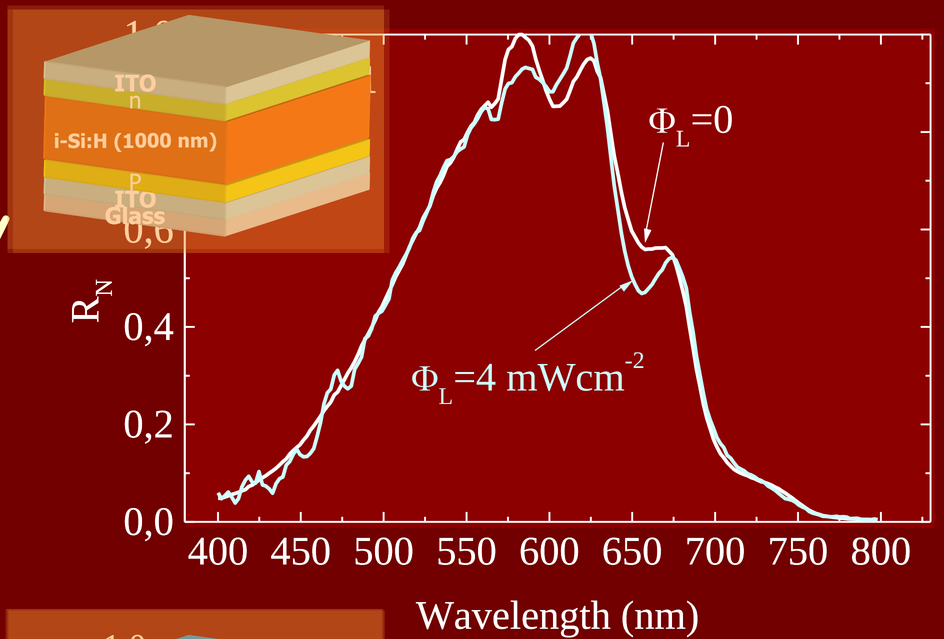
✓ Both front and back diodes act as optical filters confining, respectively, the blue and the red optical carriers, while the green ones are absorbed across both.

Light-to-dark sensitivity (Homo- vs Hetero-structures)

Homostructure:

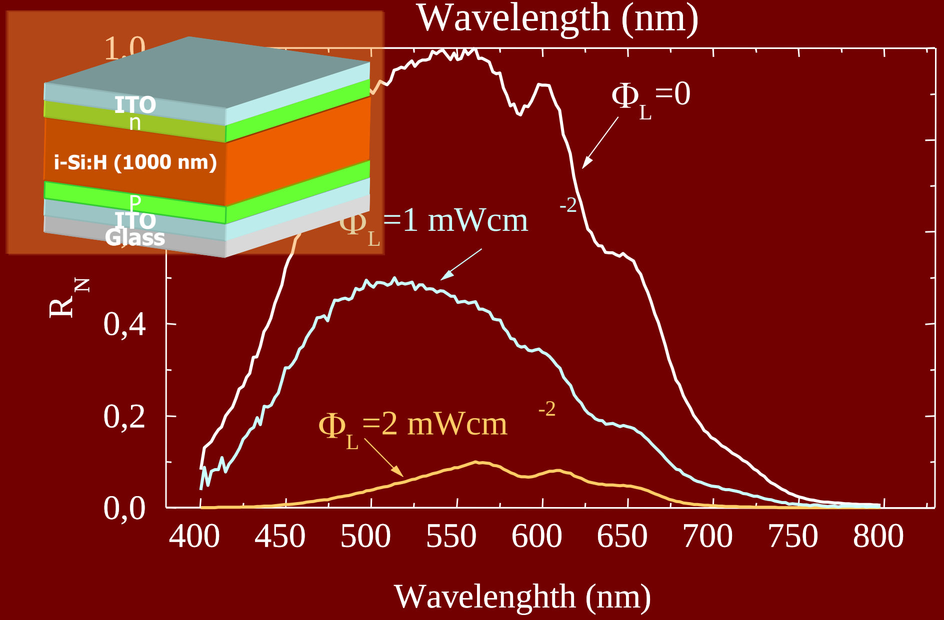
- light bias independent
- no light-to-dark sensitivity

Single films	σ_d ($\Omega^{-1}cm^{-1}$)	ΔE (eV)	σ_d/σ_{ph} —
p-Si:H	8.2×10^{-7}	0.499	7.3
p-SiC:H	2.5×10^{-9}	0.649	4.5
i-Si:H	7.6×10^{-11}	0.739	7.1×10^{4}
n-Si:H	7.8×10^{-7}	0.426	1.2
n-SiC:H	1.9×10^{-12}	0.834	21

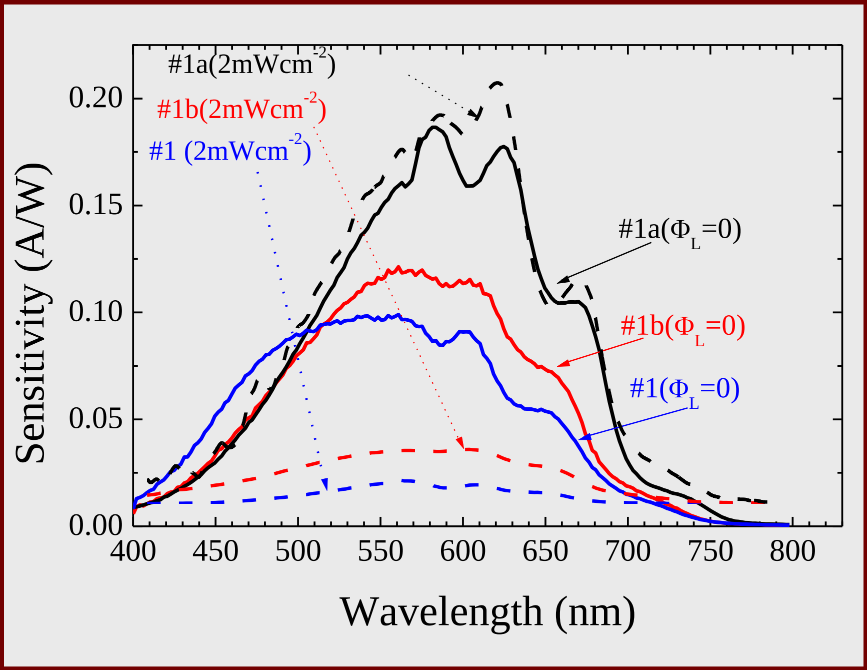


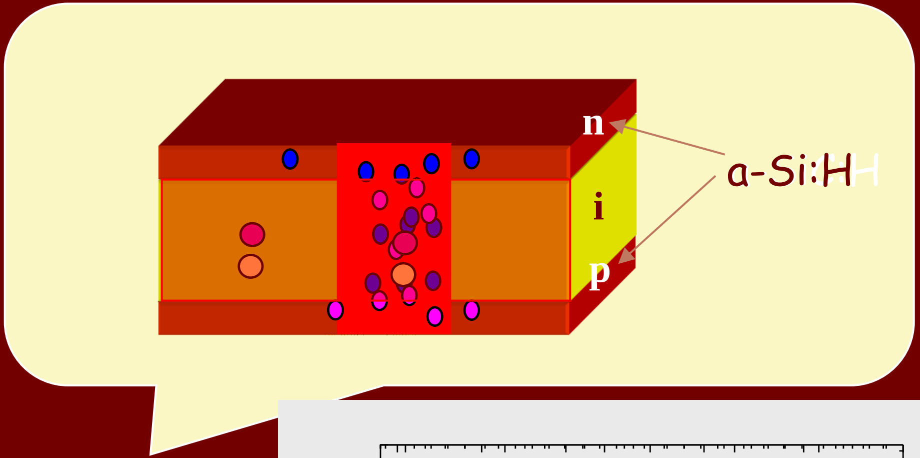
Heterostructure

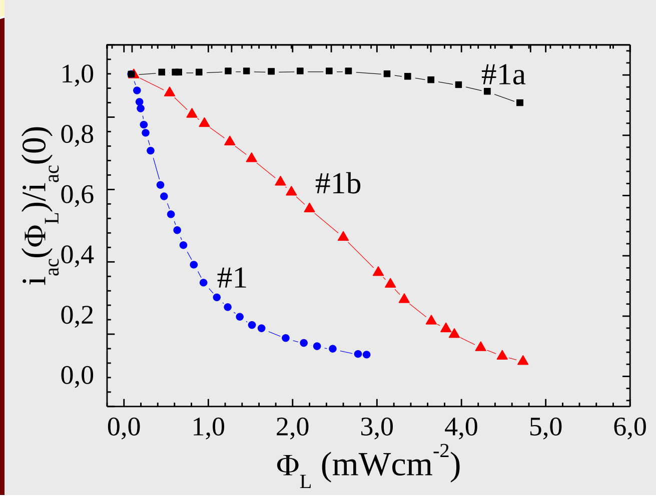
- light bias dependent.
- light-to-dark sensitivity



Light-to-dark sensitivity



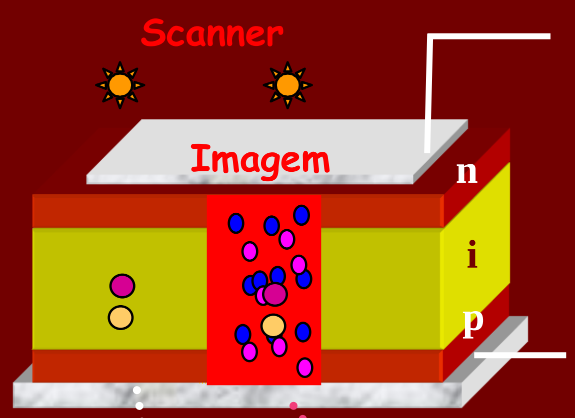




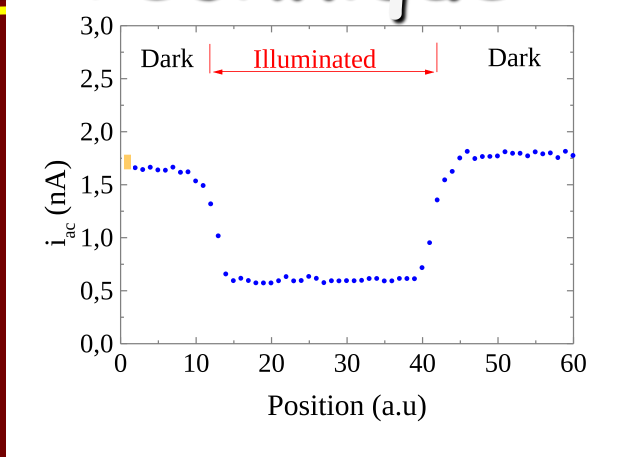
When highly resistive a-SiC:H doped layers are used its higher optical gap when compared with the active layer are responsible by charge accumulation at the illuminated interfaces which blocks the carrier collection under illumination.
Those insulator-like layers prevent excess signal charge from blooming to the nearby dark regions avoiding the image smearing.

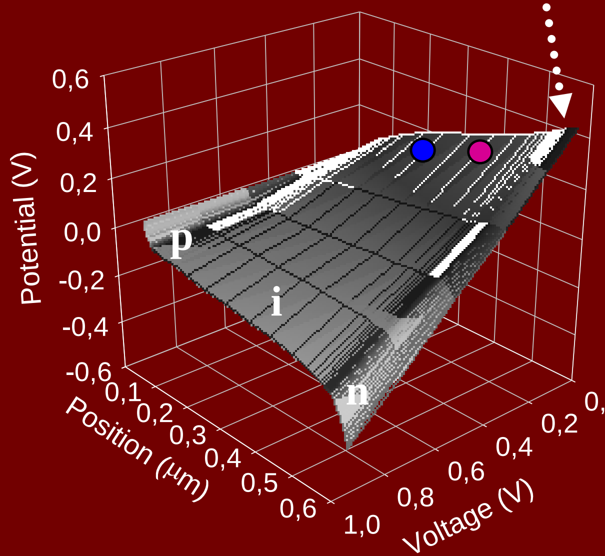
The light-to-dark ratio depends strongly on the carbon concentration of the doped layers.

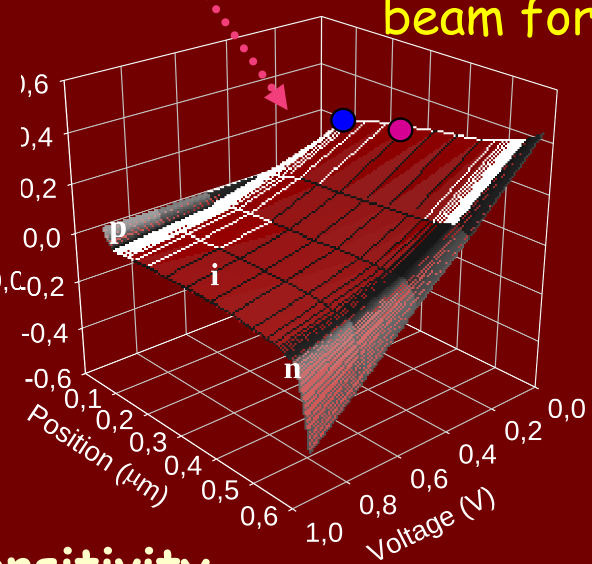
Laser Scanned Photodiode Technique



i_{ac}







- The LSP utilizes light modulated depletion layers as detector and a laser beam for readout.

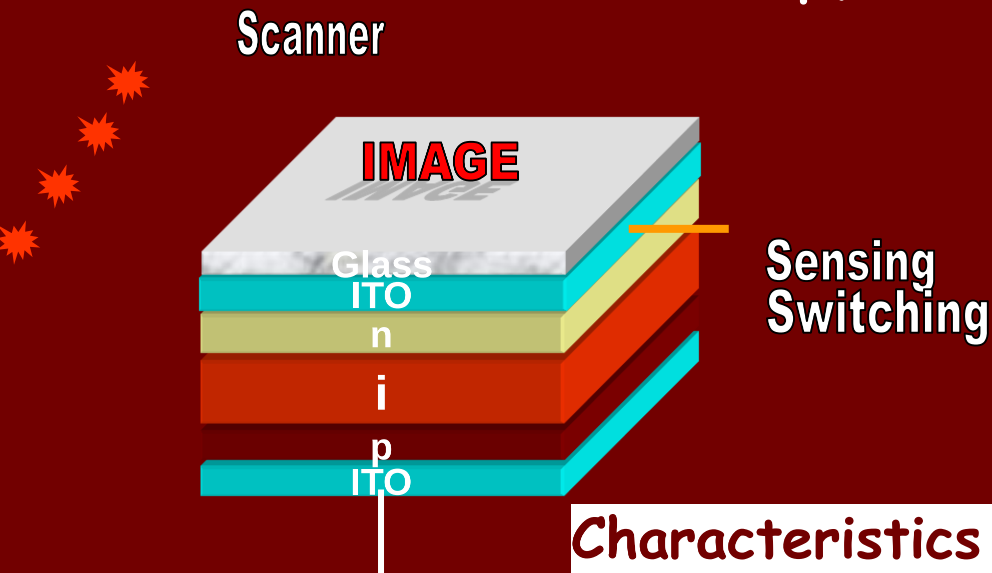
Heterostructure

·light-to-dark sensitivity

M. Vieira, M. Fernandes, J. Martins, P. Louro, R. Schwarz, and M. Schubert, "Laser Scanned p-i-n Photodiode (LSP) for image detection" IEEE Sensor Journal, 1, no.2 pp. 158-167

Laser Scanned Photodiode Image Sensor (LSP)

p(a-SiC:H)/i(a-Si:H)/n(a-SiC:H)



Characteristics

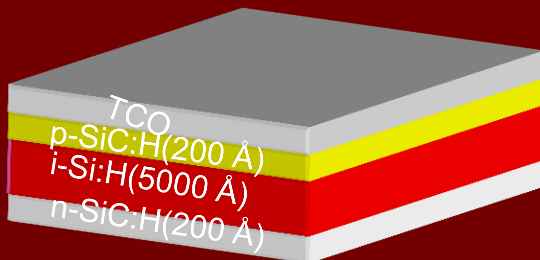
- No pixels
- p-i-n structure and two contacts
- Integrated read-write system.
- In time image processing.

Matrix intensity

$$\left\{ X_{m,n} = -(I_{m,n} - S_{m,n}) \right\}$$

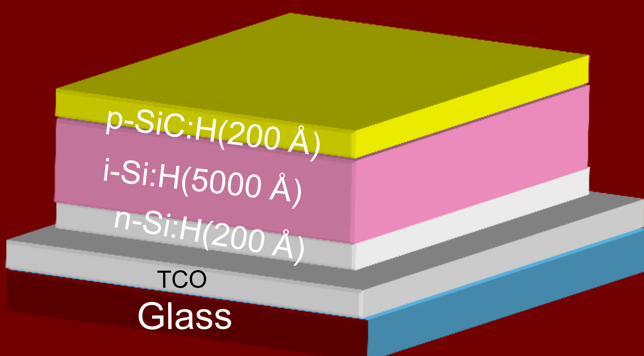
A large cell detector where the image is scanned by sequentially detecting scene information at discrete XY coordinates.

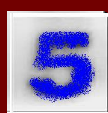
Laser Scanned Photodiode Color Sensor (CLSP)

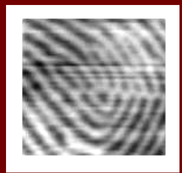


- p-i-n B&W LSP image sensors were produced and tested.
- The tandem structure takes advantage on the radiation wavelength selectivity due to the different light penetration depth inside the a-Si:H and a-SiC:H

p-i-n p-i-n



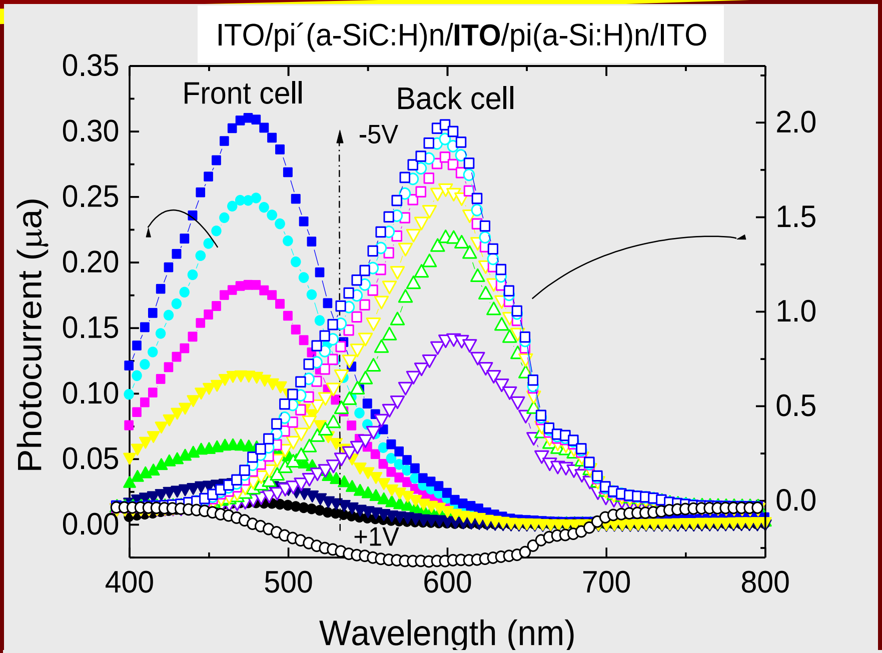


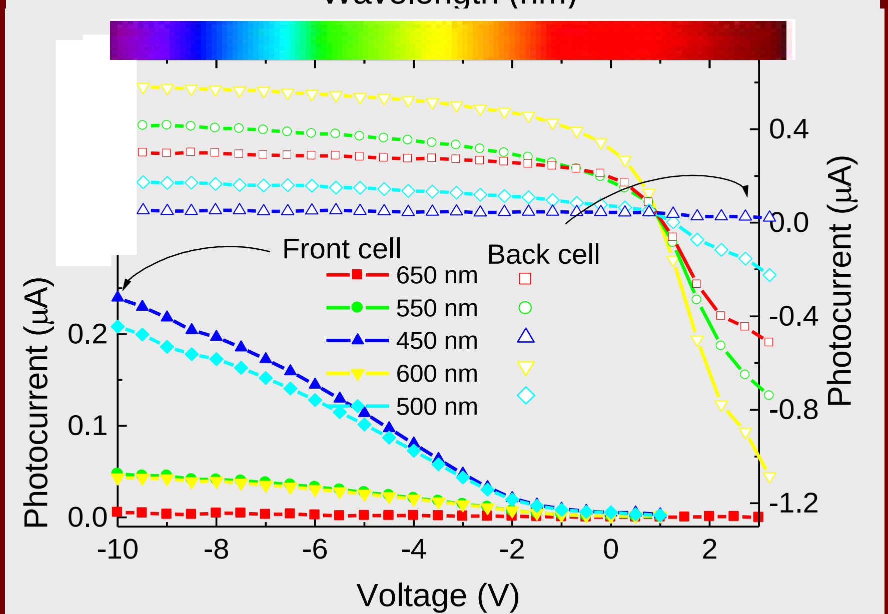


M. Vieira, P. Louro, M. Fernandes, and A. Fantoni "Optical confinement in a Double Colour Laser Scanned Photodiode (D/CLSP)" Sensor and Actuators A 114/2-3 (2004), pp. 219-223

Large area color image sensors with improved response.

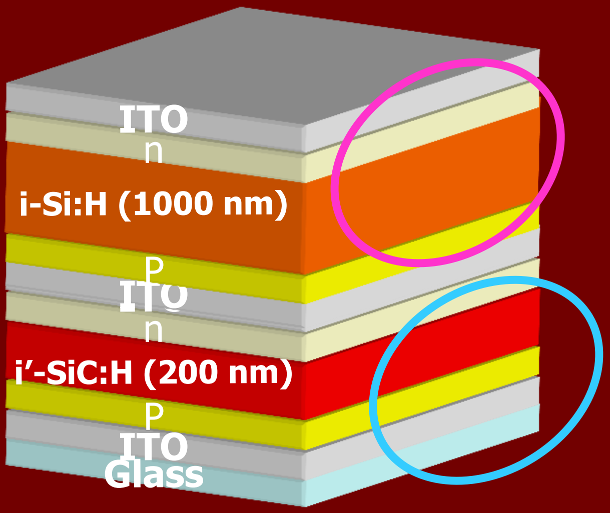
Optical filter





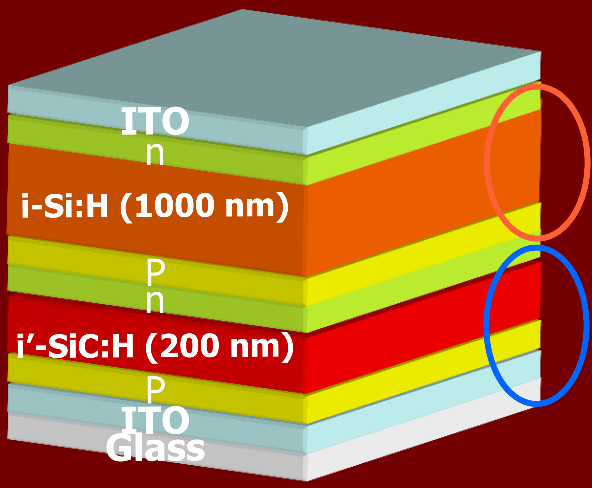
Back diode –Cuts the blue

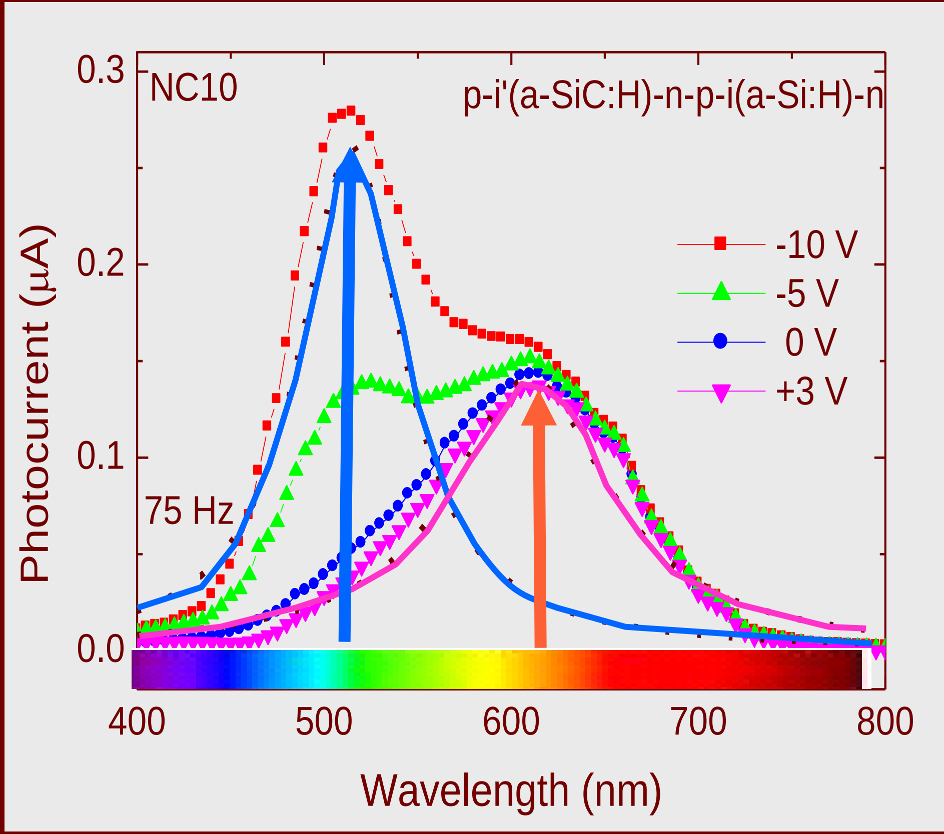
Front diode –Cuts the red



Spectral response

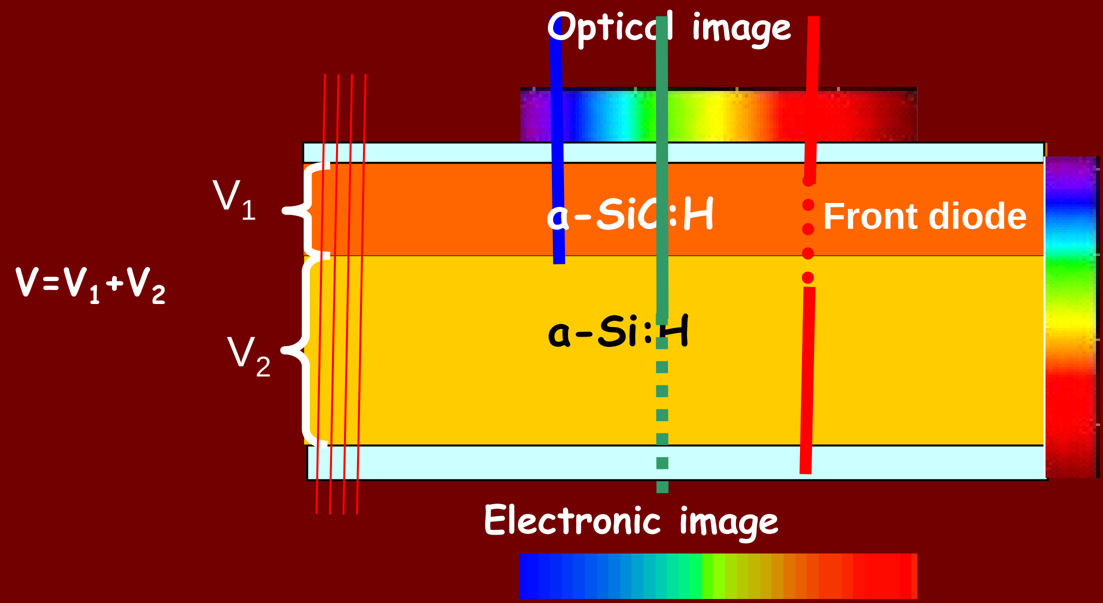
• As the applied voltage changes from forward to reverse the blue/green spectral collection is enlarged while the red one remains constant

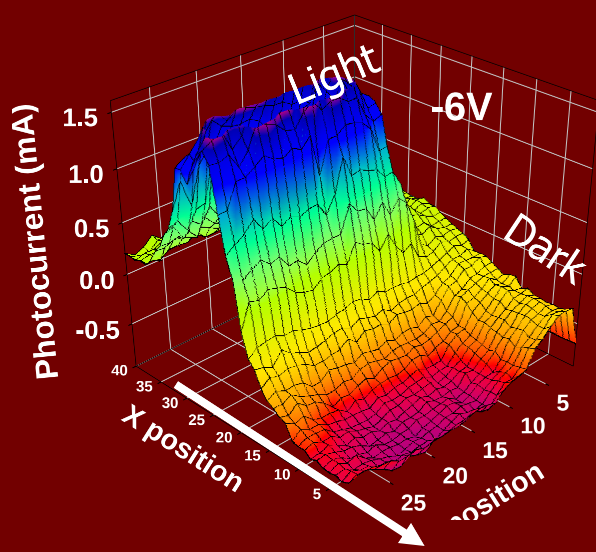




Voltage controlled spectral response.

Full colour recognition





$$V = \eta V_T \ln \frac{(I + I_1)(I + I_2)}{I_{01} I_{02}}$$

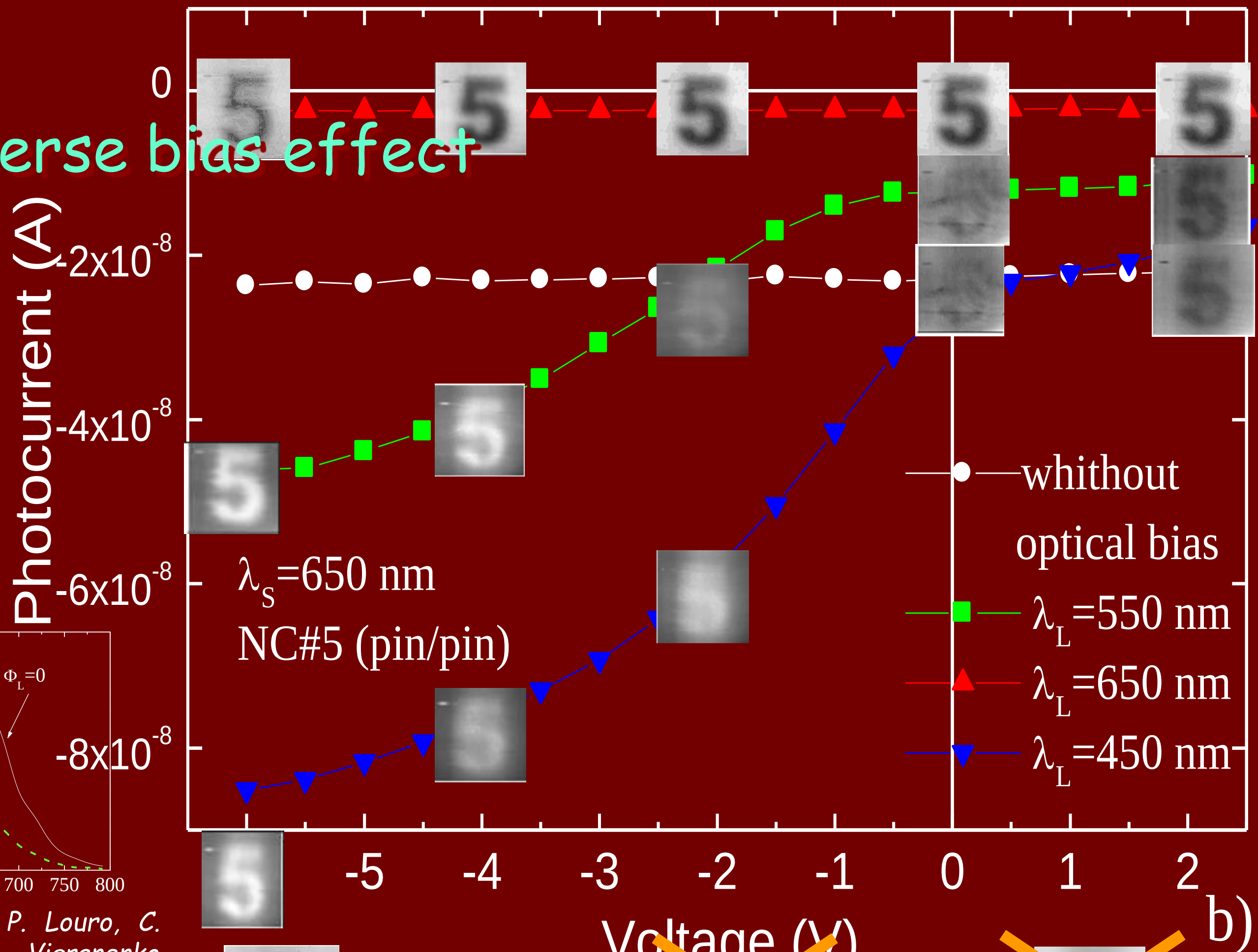
$$V_{2,light} = \eta V_T \ln\left(\frac{(I(V) + I_2)}{I_{02}}\right) \neq V_{2,dark} = \eta V_T \ln\left(\frac{(I(V) + I_{02})}{I_{02}}\right)$$

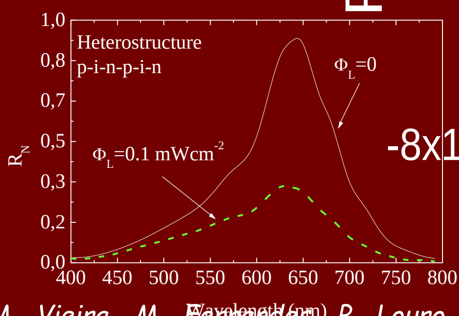
• **Image recognition**

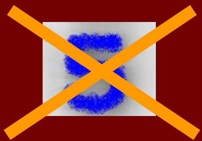
CLSP take advantage of the fact that red, green, and blue light penetrate silicon to different depths forming an image sensor that captures full color at every point in the captured image without the need of pixels.

Color recognition

Self reverse bias effect

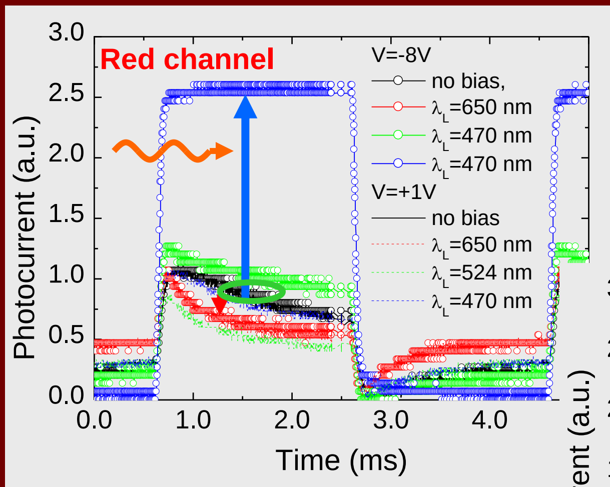


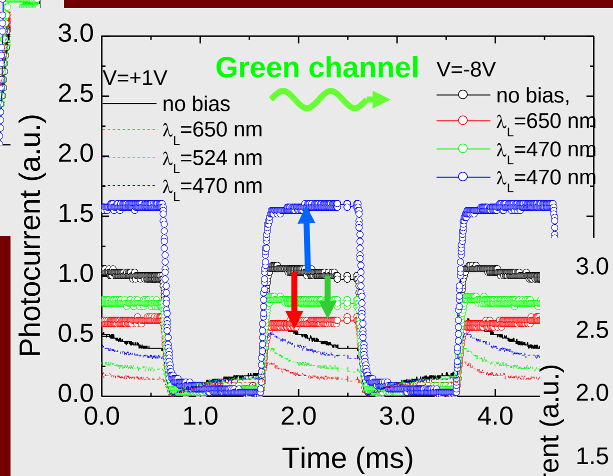


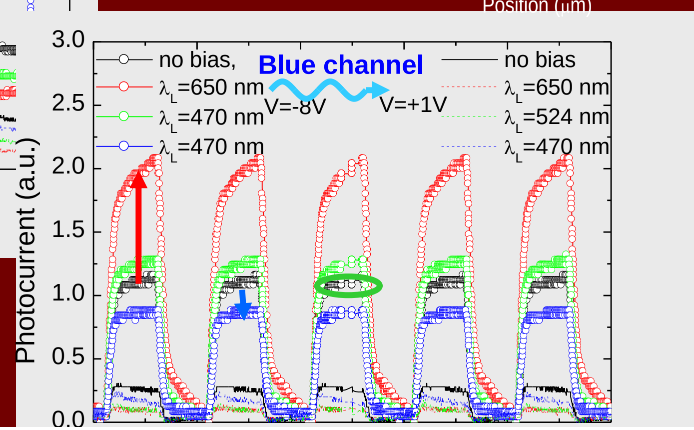


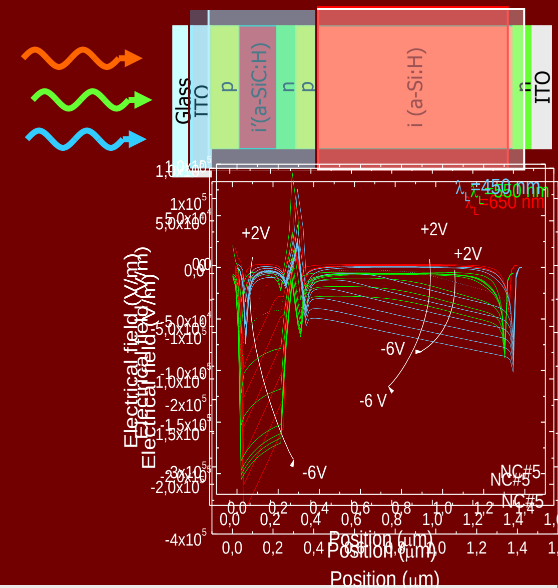
M. Vieira, M. Fernandes, P. Louro, C. Mendes, R. Schwarz, Y. Vigranenko "OSIP Optical signal and image processing device optimized for optical read-out" Sensor and Actuators A: Physical, 120 (2005) pp. 88-93

Optical amplification





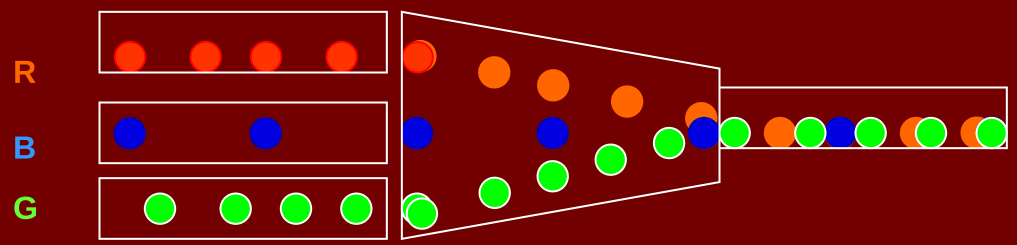




Self reverse bias effect

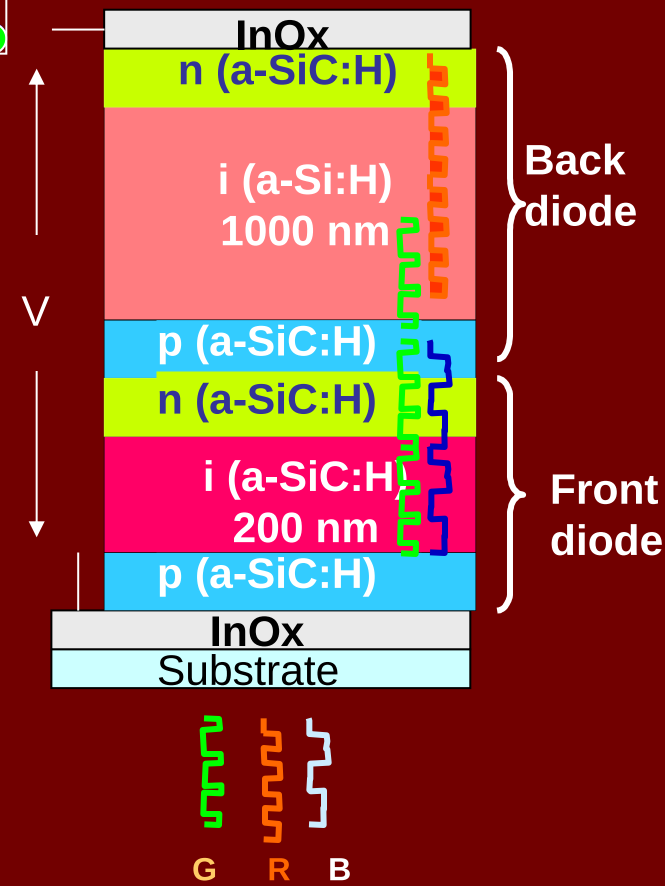
Blue bias amplifies the red and the green channels and reduces the blue.
Red bias reduces the red and green channels and amplifies de blue.
Green bias reduces the green channel keeping the others almost constant.

Divison Wavelength Multiplexing Device (WDM)



Wavelength
Division
Demultiplexing

Wavelength
Division
Multiplexing

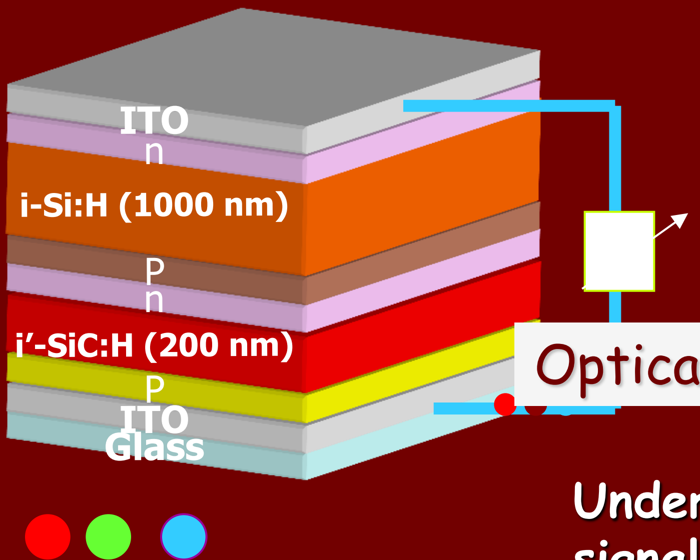


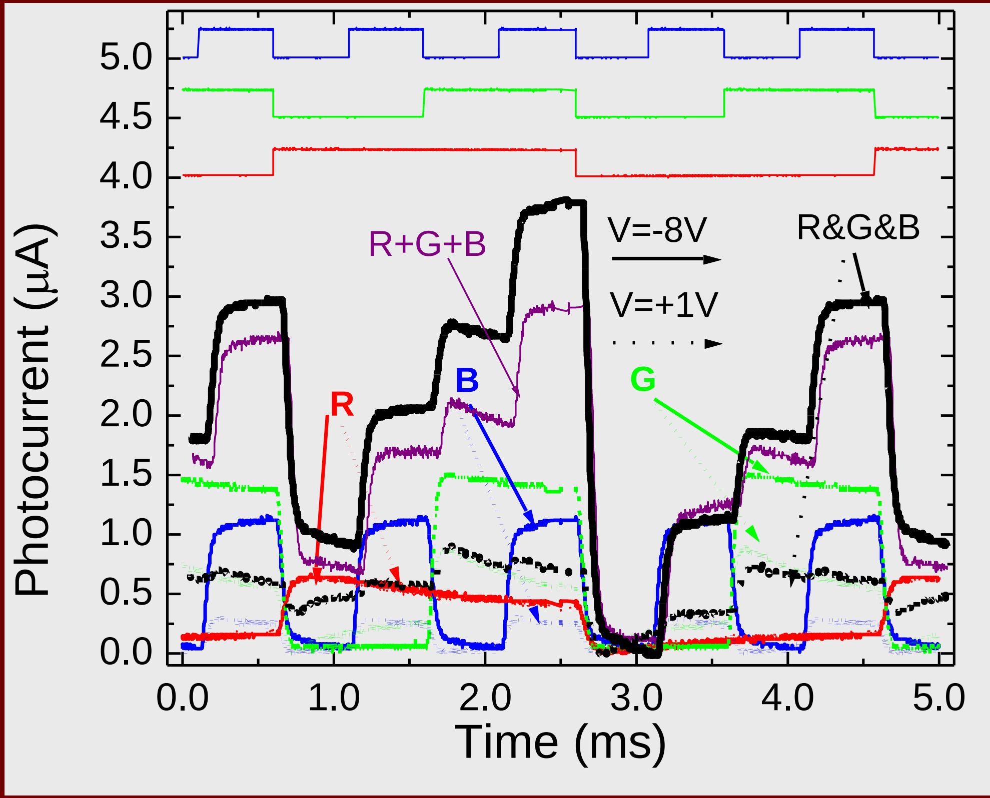
- The tandem structure takes advantage of the radiation wavelength selectivity due to the different light penetration depth inside the a-Si:H and a-SiC:H

M. Vieira, P. Louro, M. Fernandes, M.A. Vieira, A. Fantoni and M. Barata, "Large area a-SiC:H WDM devices for signal multiplexing and demultiplexing in the visible spectrum", Thin Solid Films 517 (2009), pp. 6435-6439.
DOI:10.1016/j.tsf.2009.02.096

Bias sensitive WDM device

- High: all the channels ON
- Low: all the channels OFF
- The signal due to the mixture of two input channels (R&B, R&G, G&B) are higher than only one (R, G, B).



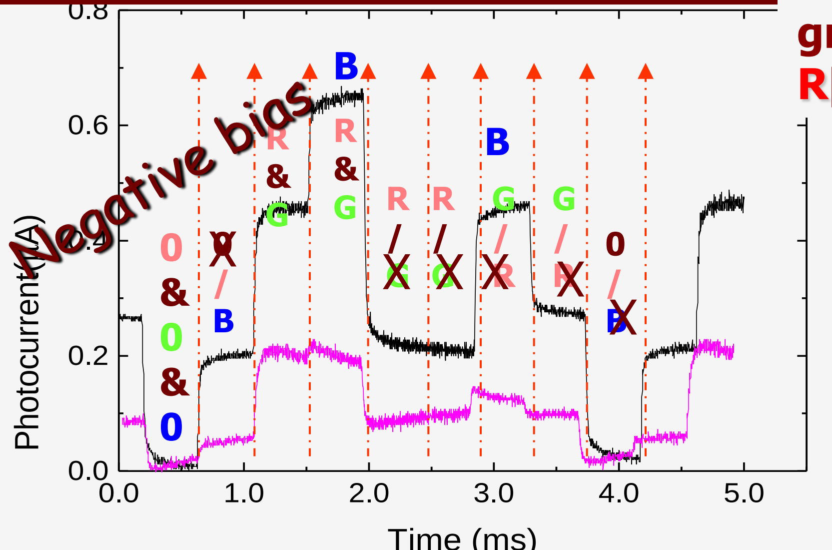


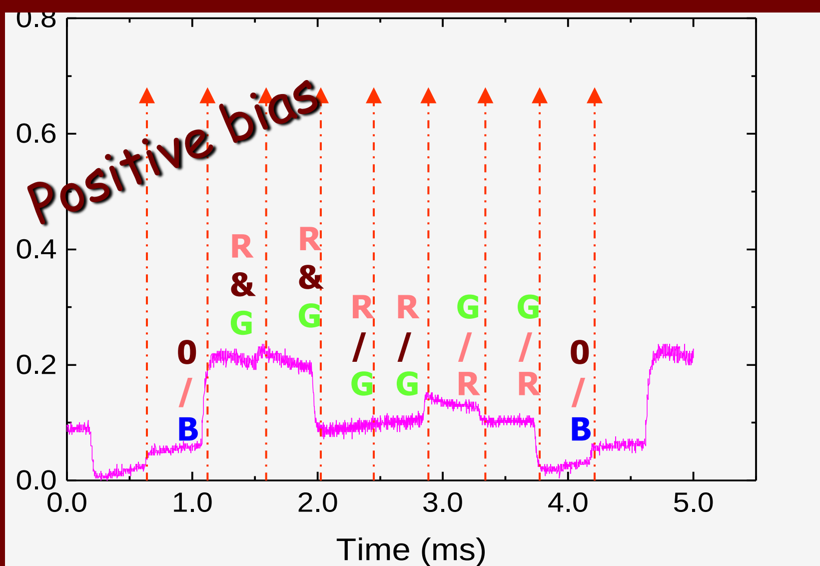
Optical amplification under negative bias. !!!!!

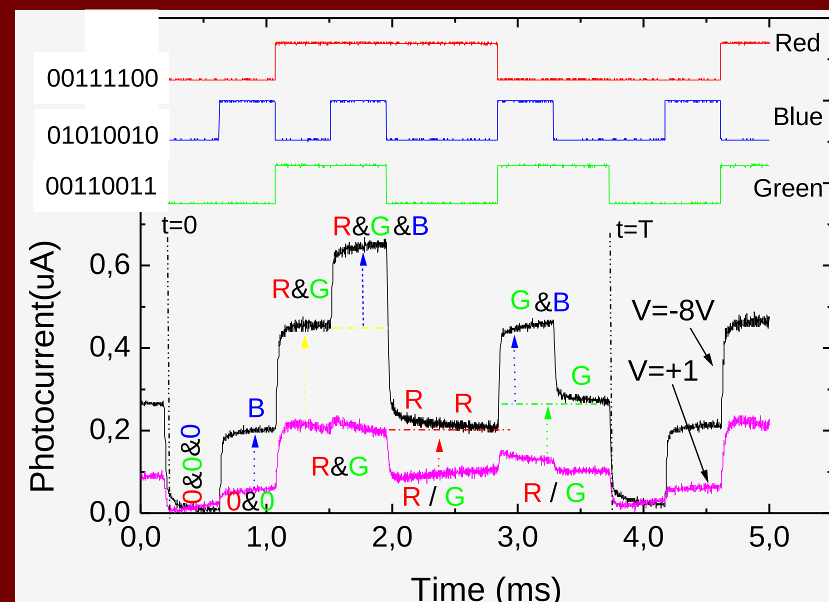
Under negative applied voltages, the multiplexed signal keeps the memory of the single input channels.

WDM - Recovery of the input channels

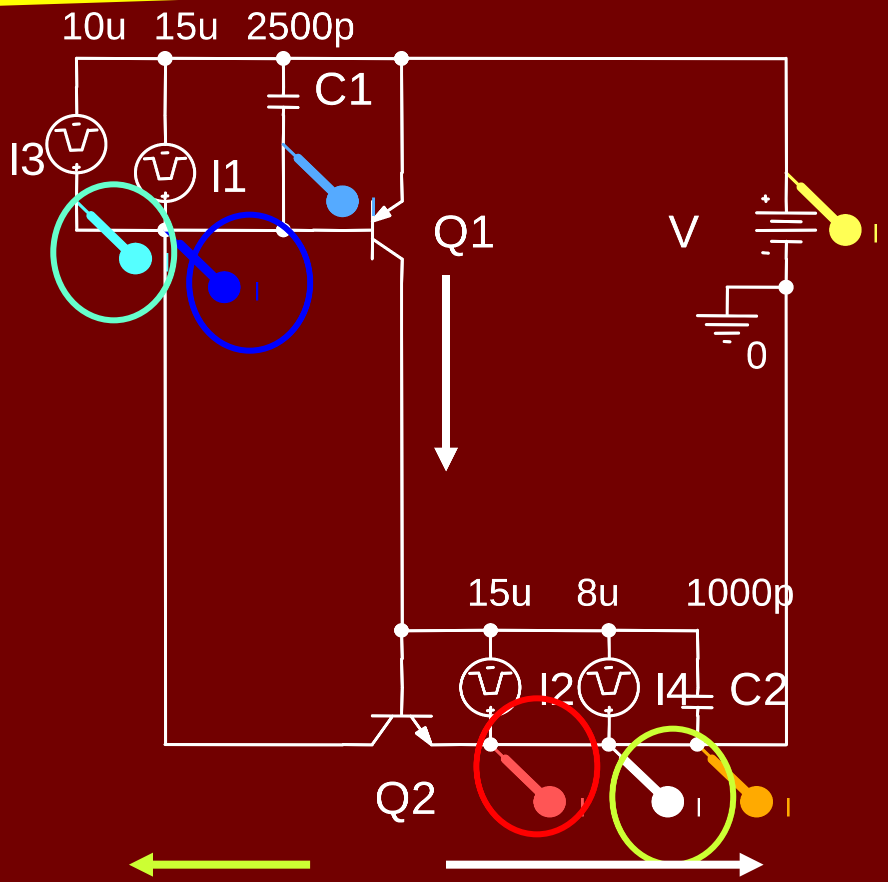
Using this simple algorithm the independent red, green and blue bit sequences can be decoded as: R[00111100], G[00110011] and B[01010010].







ELECTRICAL MODEL

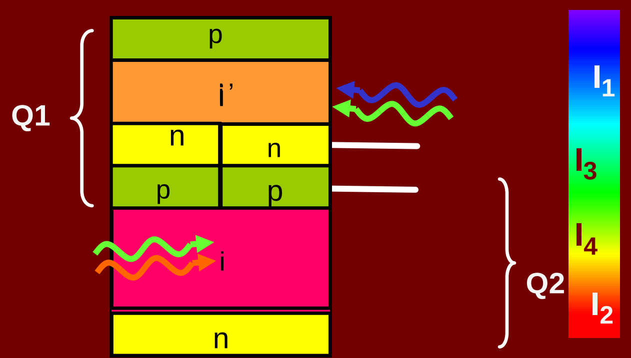


Negatively biased

The p-n internal junction is forward-biased

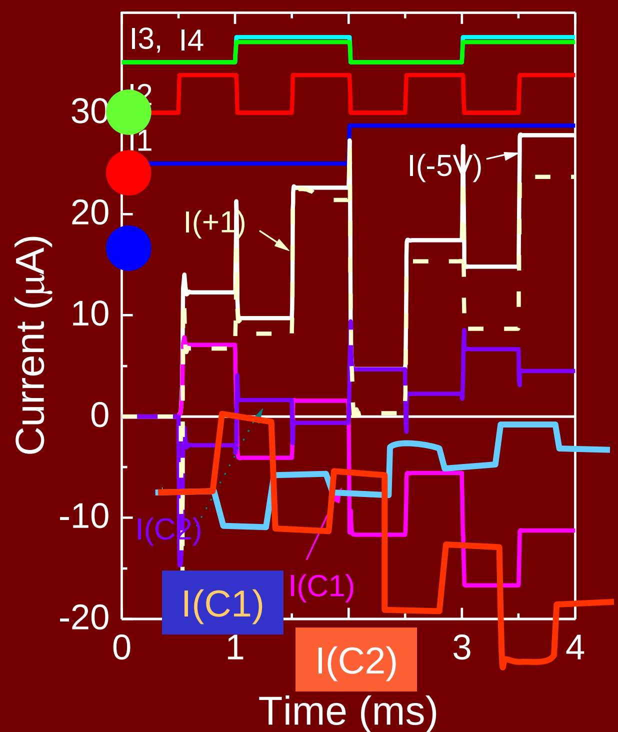
Positively biased

The p-n internal junction is reverse-biased



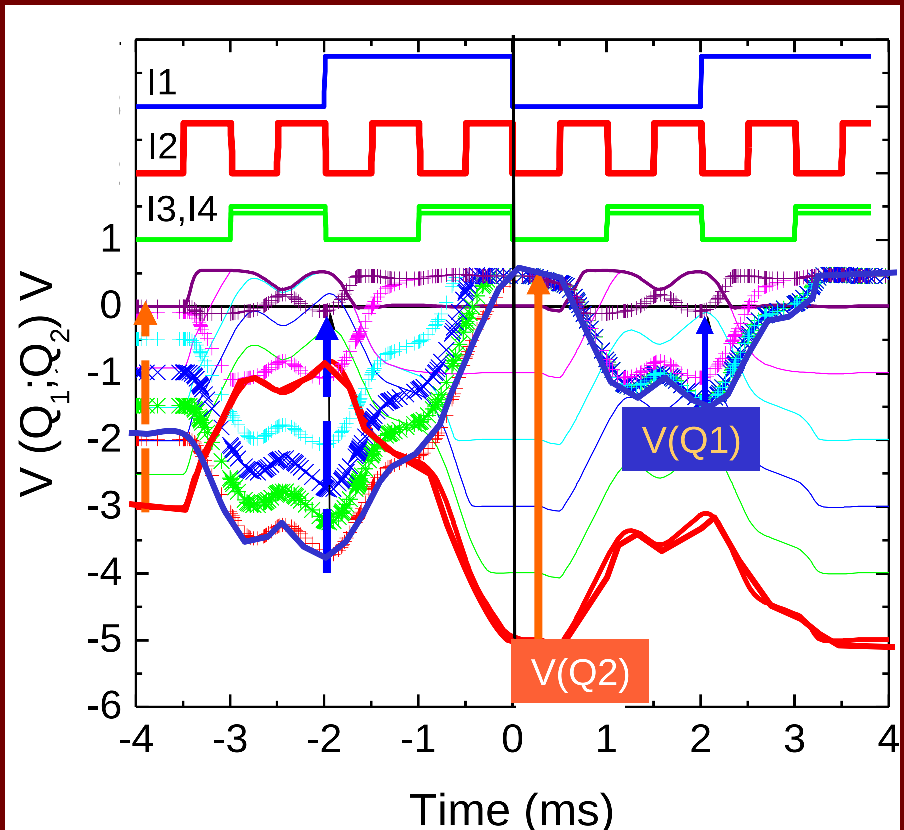
M A Vieira, M. Vieira, M. Fernandes, A. Fantoni, P. Louro, M. Barata, Amorphous and Polycrystalline Thin-Film Silicon Science and Technology — 2009, MRS Proceedings Volume 1153, A08-03

Current&Voltage (SPICE simulation)

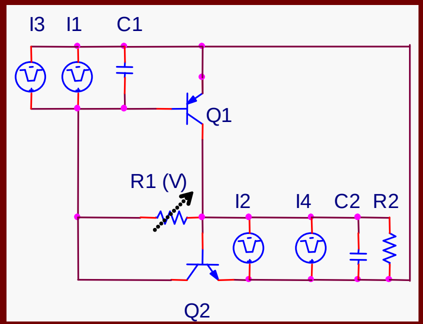


Blue the emiter-base of Q1 becomes optically forward biased and C2 is rapidly charged in inverse polarity of C1
Red changes, in the opposite way.

Green the current is the balance between the blue- and the red-like contributions

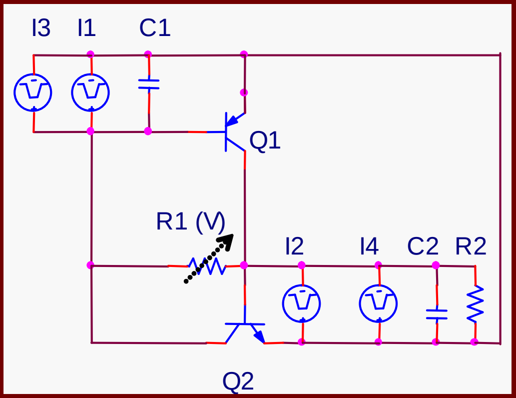


$$\begin{cases} i_{C1,2}(t) = C_{1,2}\dfrac{dv_{1,2}}{dt} \\ i_{C1}(t)C_2 = -i_{C2}(t)C_1 \end{cases}$$



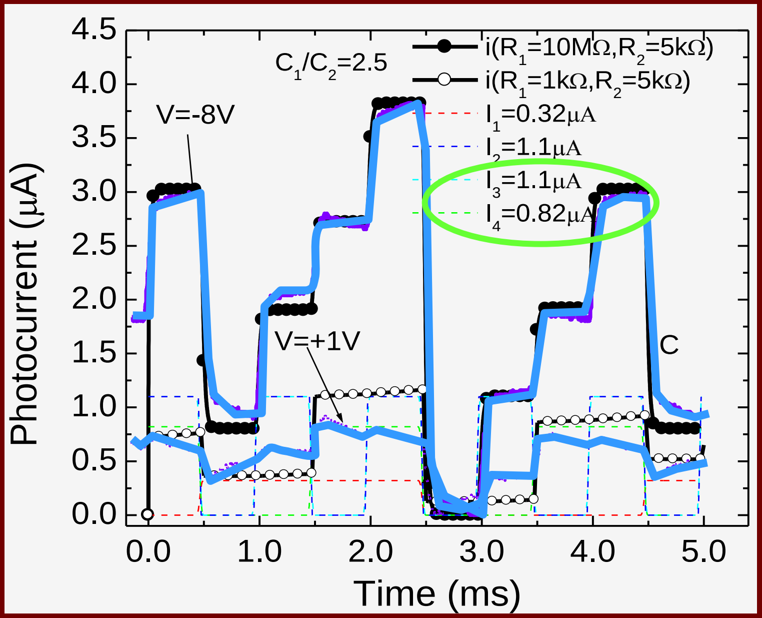
NUMERICAL SIMULATION

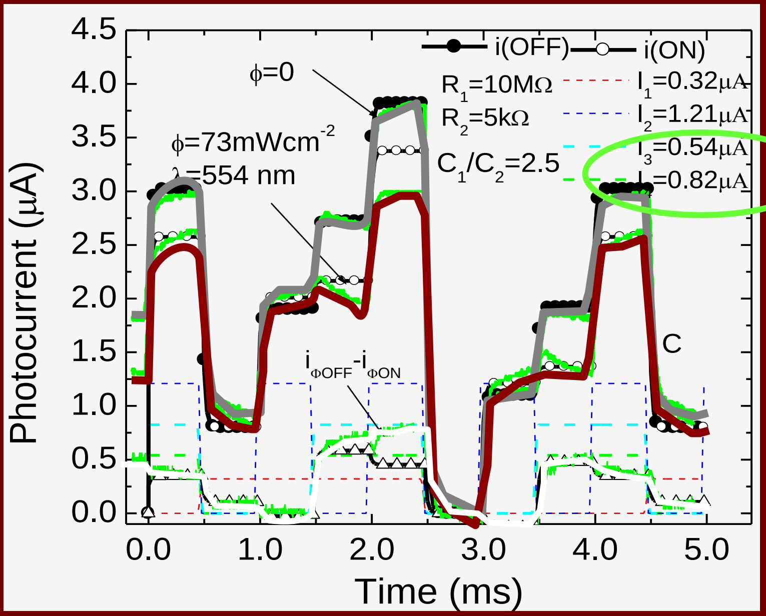
***ac* equivalent electrical circuit**



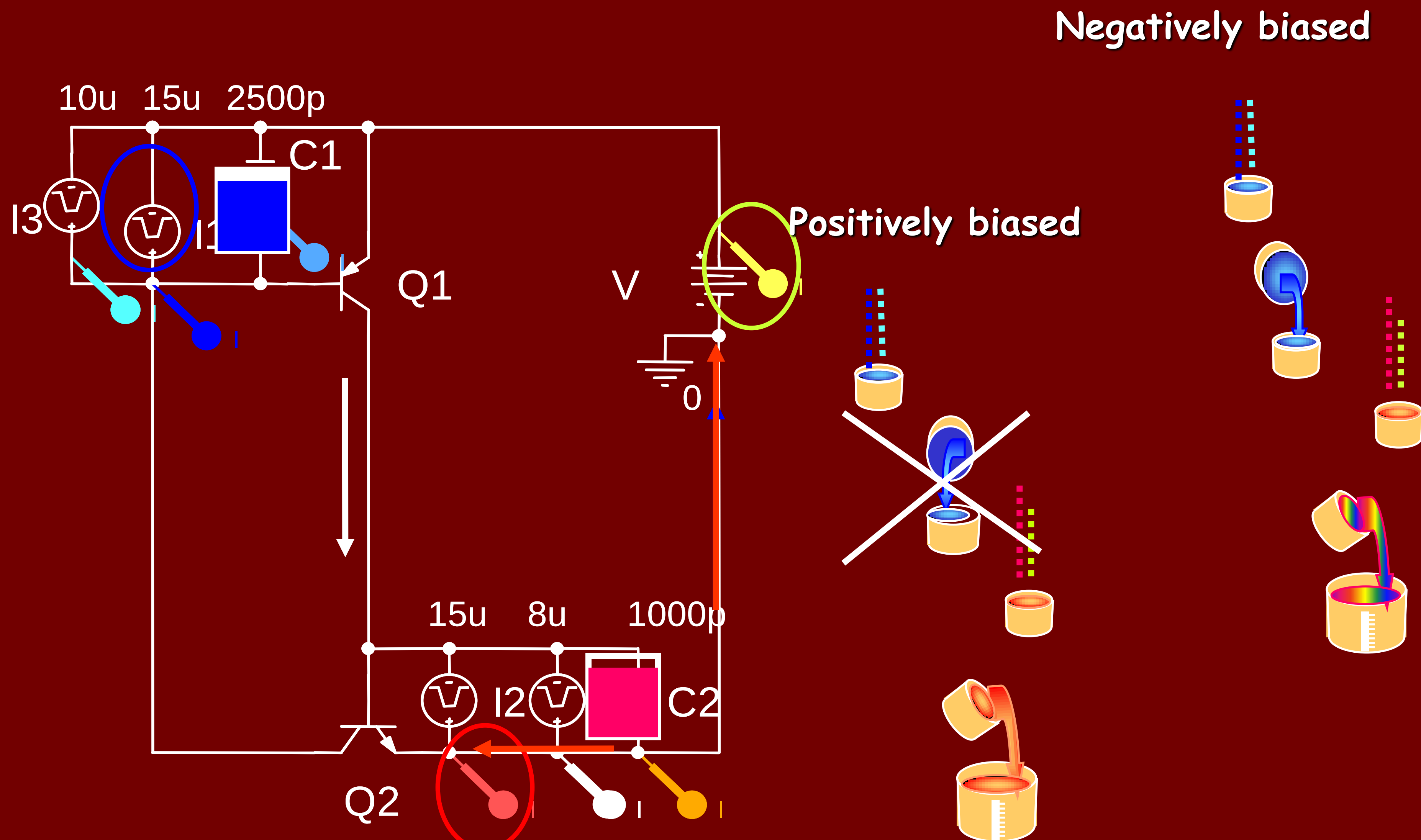
$$\begin{cases} \frac{dv_{1,2}}{dt} = \begin{bmatrix} -\frac{1}{r_1c_1} & \frac{1}{r_1c_1} \\ \frac{1}{r_1c_2} & -\frac{1}{r_1c_2}-\frac{1}{r_2c_2}\end{bmatrix} v_{1,2}(t) + \begin{bmatrix}\frac{1}{c_1}\\ \frac{1}{c_2}\end{bmatrix} i_{1,2}(t) \\ i(t) = \begin{bmatrix} 0 & \frac{1}{r_2}\end{bmatrix} v_{1,2}(t)\end{cases}$$

MATLAB as a programming environment and the four order Runge-Kutta method to solve the state equations





THEORETICAL MODEL

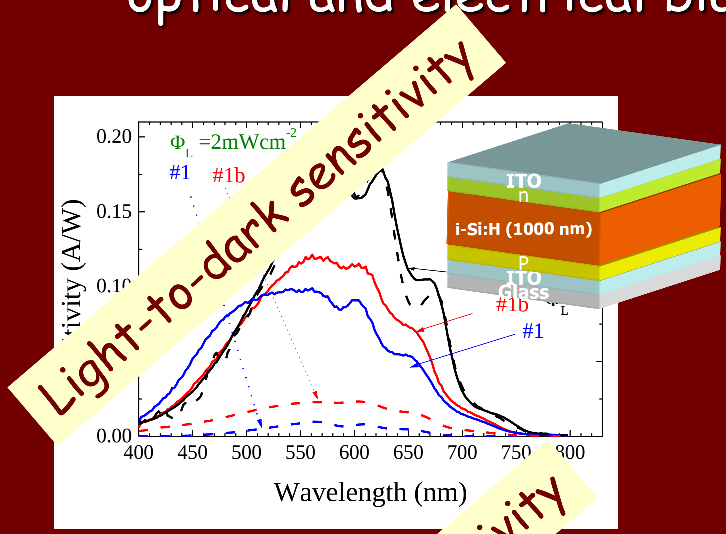


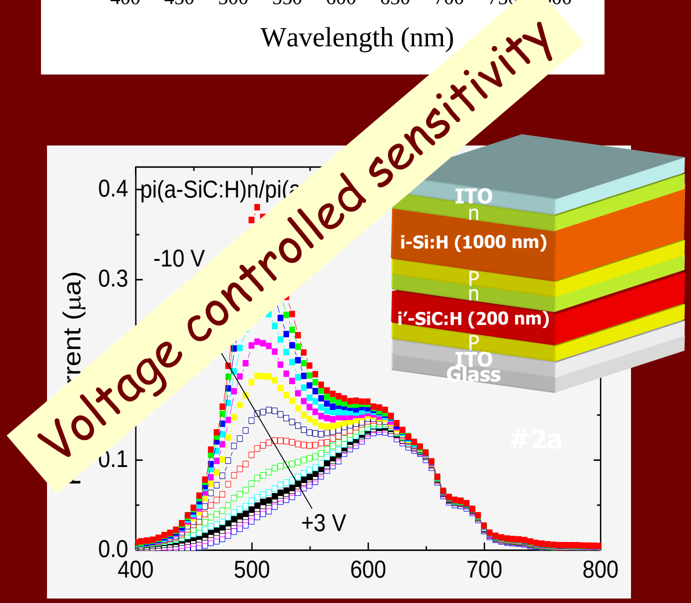
$$i_{C1}(t)C_2 = -i_{C2}(t)C_1$$

M A Vieira, M. Vieira, M. Fernandes, A. Fantoni, P. Louro, M. Barata,
Amorphous and Polycrystalline Thin-Film Silicon Science and Technology —
2009, MRS Proceedings Volume 1153, A08-03

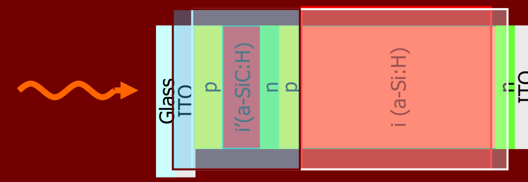
CONCLUSIONS

- Single and stack a-SiC:H pin devices were compared under different optical and electrical bias conditions and readout techniques.

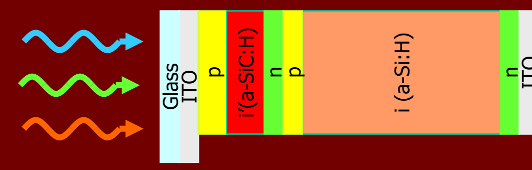




Readout techniques



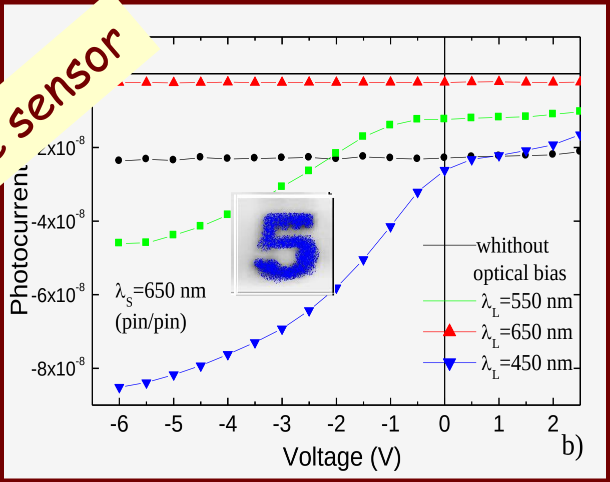
LSP



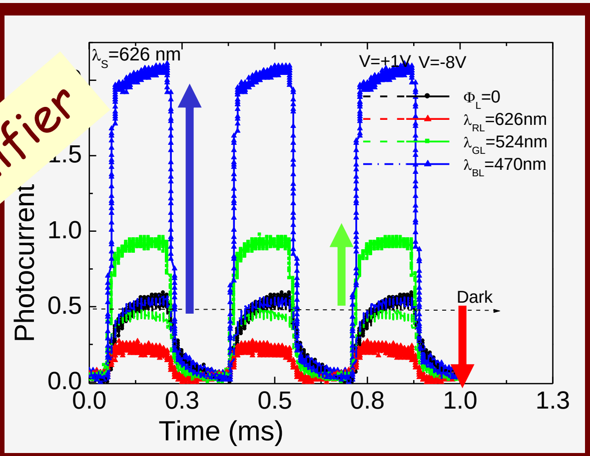
WDM

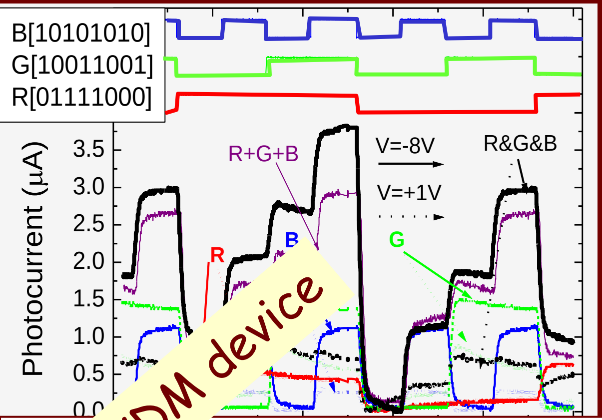
CONCLUSIONS

- If a light scan with a fixed wavelength is used to readout the generated carriers it can recognize a color pattern projected on it, acting as a color and image sensor.



- When triggered by light with appropriated wavelengths, it can amplify or suppress the generated photocurrent working as an optical amplifier.





- If the photocurrent generated by different monochromatic pulsed channels or their combination is readout directly, the

Three integrated transducers
in one single photodetector

TEAM

Thanks for your attention

A group of experienced and young researchers covering the areas of materials and devices processing; materials and devices characterization and optimization, well supported by the physics modelling of the devices and the corresponding software for information extraction

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