New Color Sensor Concept Based on Single Spectral Tunable Photodiode

Andre Wachowiak[1], Stefan Slesazeck[1], Paul Jordan[1], Jürgen Holz[1] and Thomas Mikolajick[1,2]

(1) Nanoelectronic Materials Laboratory gGmbH, Dresden, Germany
(2) Technische Universität Dresden, Dresden, Germany

Outline

Motivation

Sensor Concept with Tunable Photodiode

Functionality of Photodiode Hardware

Color Detection Based on Single Photodiode

Summary

Outline

- Motivation
- Sensor Concept with Tunable Photodiode
- Functionality of Photodiode Hardware
- Color Detection Based on Single Photodiode
- Summary

Human Color Detection

Cone cells (function → response):

- Red ($x(\lambda)$ → X)
- Green ($y(\lambda)$ → Y)
- Blue ($z(\lambda)$ → Z)
- → CIE XYZ tri-stimulus

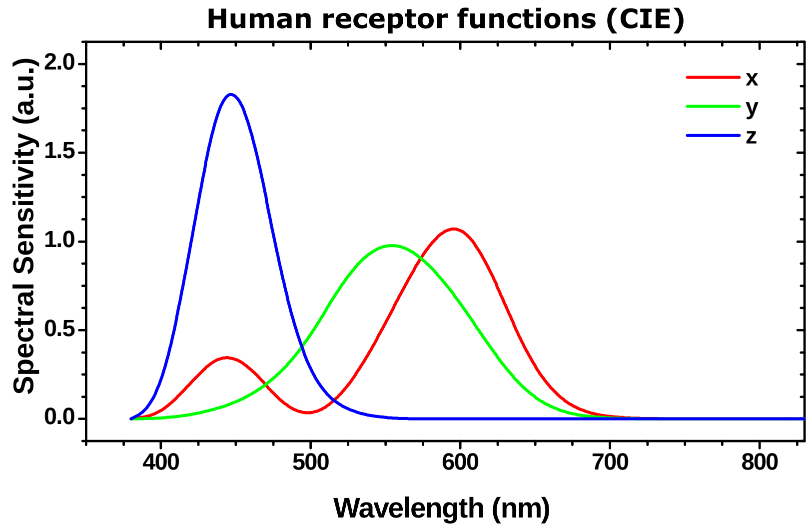
Cone response:

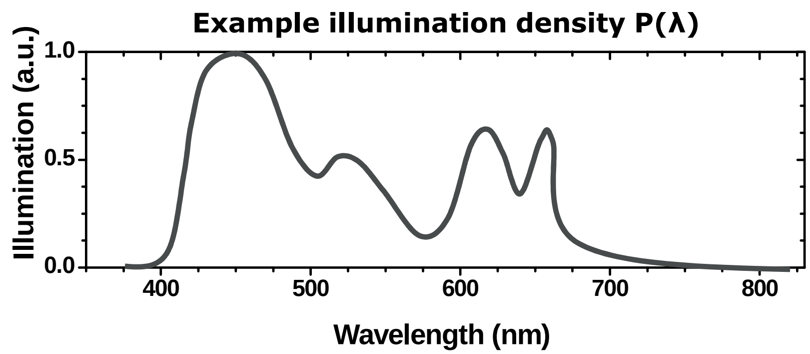
- $X = \int P(\lambda) \cdot x(\lambda)\, d\lambda$, same for Y, Z

Color impression:

- Relative ratio of cone responses X, Y, Z

Reproduction of receptor function allows color recognition in full color space

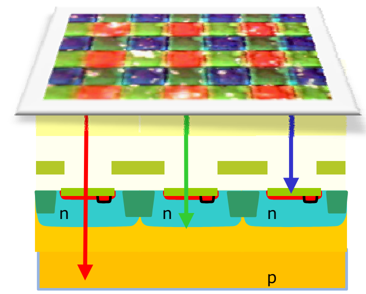




CIE: International Commission on Illumination

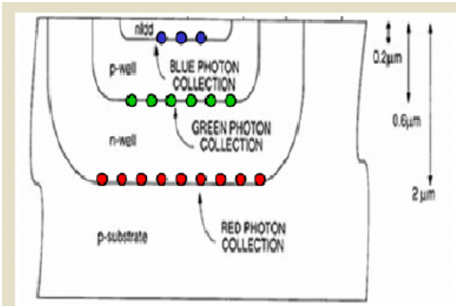
Color Sensitive Photodiodes

Conventional approach



Color Filters:

- Color filter layers on photodiode active area (RGB Bayer pattern)
- Transmission of filters defines color response



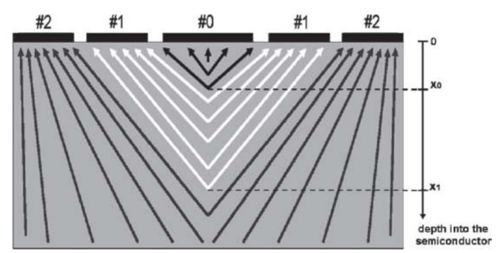
Foveon Inc., US Patent n. 5 965 875, October 1999

Multiple Junction diodes:

- Wavelength dependent absorption of Si works as color filter
- Depth of junctions defines color response

Transverse Field Detector:

- Wavelength dependent absorption of Si works as color filter
- Color response can be tuned by applied voltages

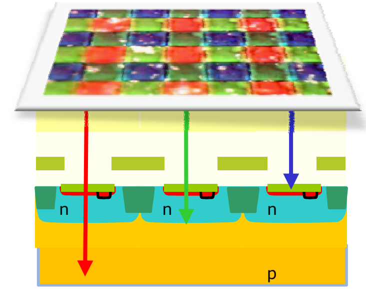


G. Langfelder, et al. IEEE Trans. El. Dev. **56**, 2563 (2009)
A. Longoni, et al. IEEE EDL **29**, 1306 (2008)

- High technical effort for color filter
- Sensor response fixed by hardware
- Limited color space

Color Sensitive Photodiodes

Conventional approach



Color Filters:

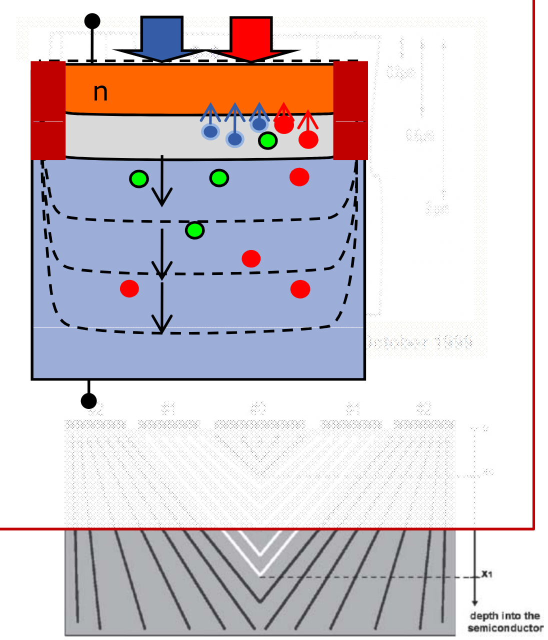
- Color filter layers on photodiode active area (RGB Bayer pattern)
- Transmission of filters defines color response

Multiple Junction diodes:

- Depth of junctions defines color response

NEW APPROACH:

Photodiode with tunable space charge region



Transverse Field Detector:

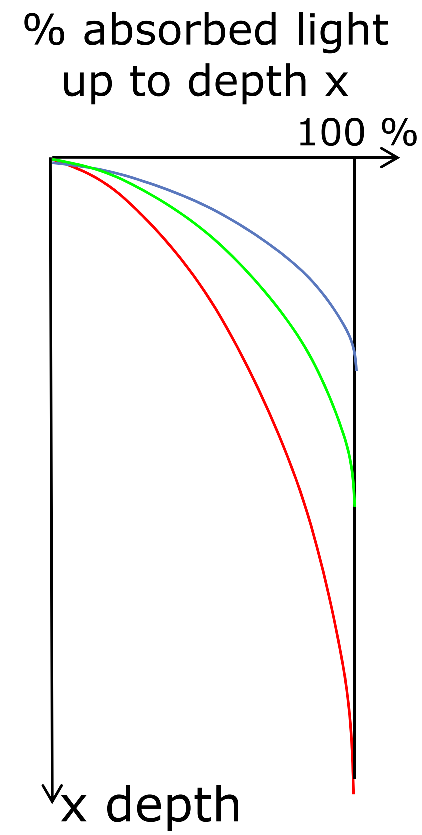
- Wavelength dependent absorption of Si works as color filter
- Color response can be tuned by applied voltages

G. Langfelder, et al. IEEE Trans. El. Dev. **56**, 2563 (2009)
A. Longoni, et al. IEEE EDL **29**, 1306 (2008)

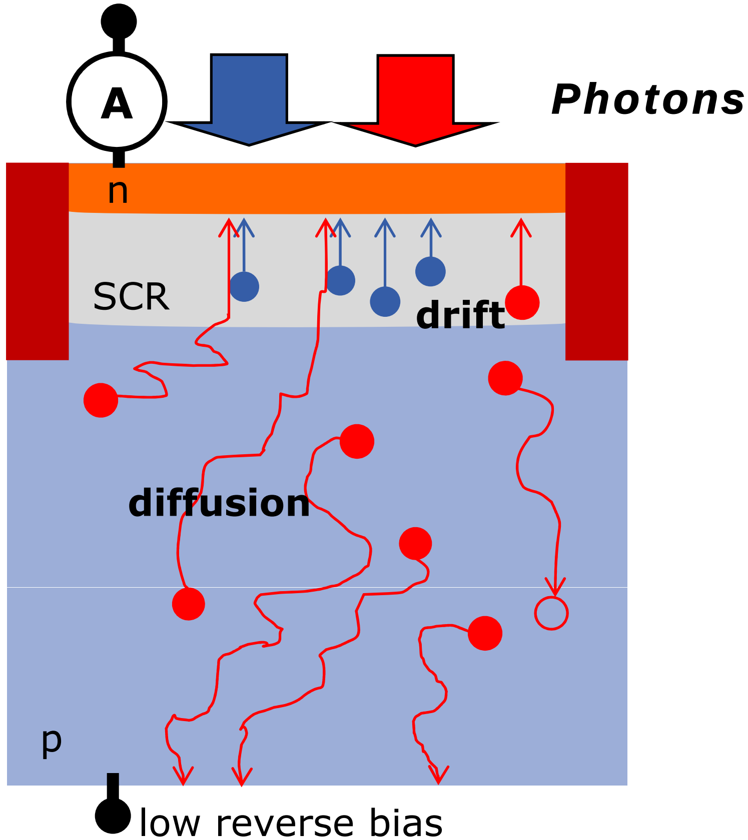
- High technical effort for color filter
- Sensor response fixed by hardware
- Limited color space

Outline

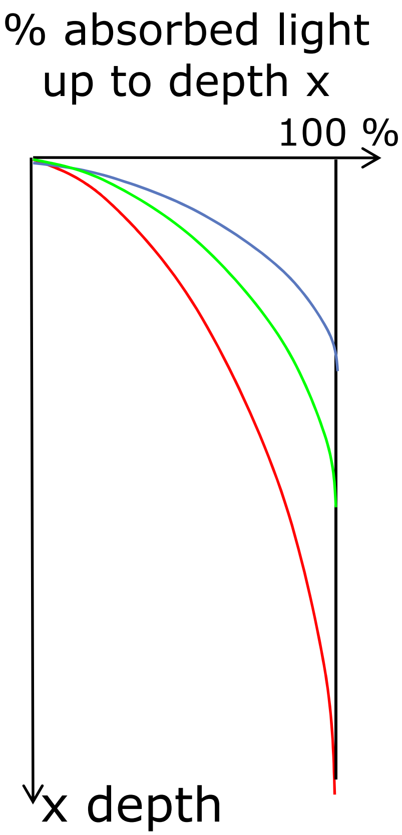
Principle of Color Resolution



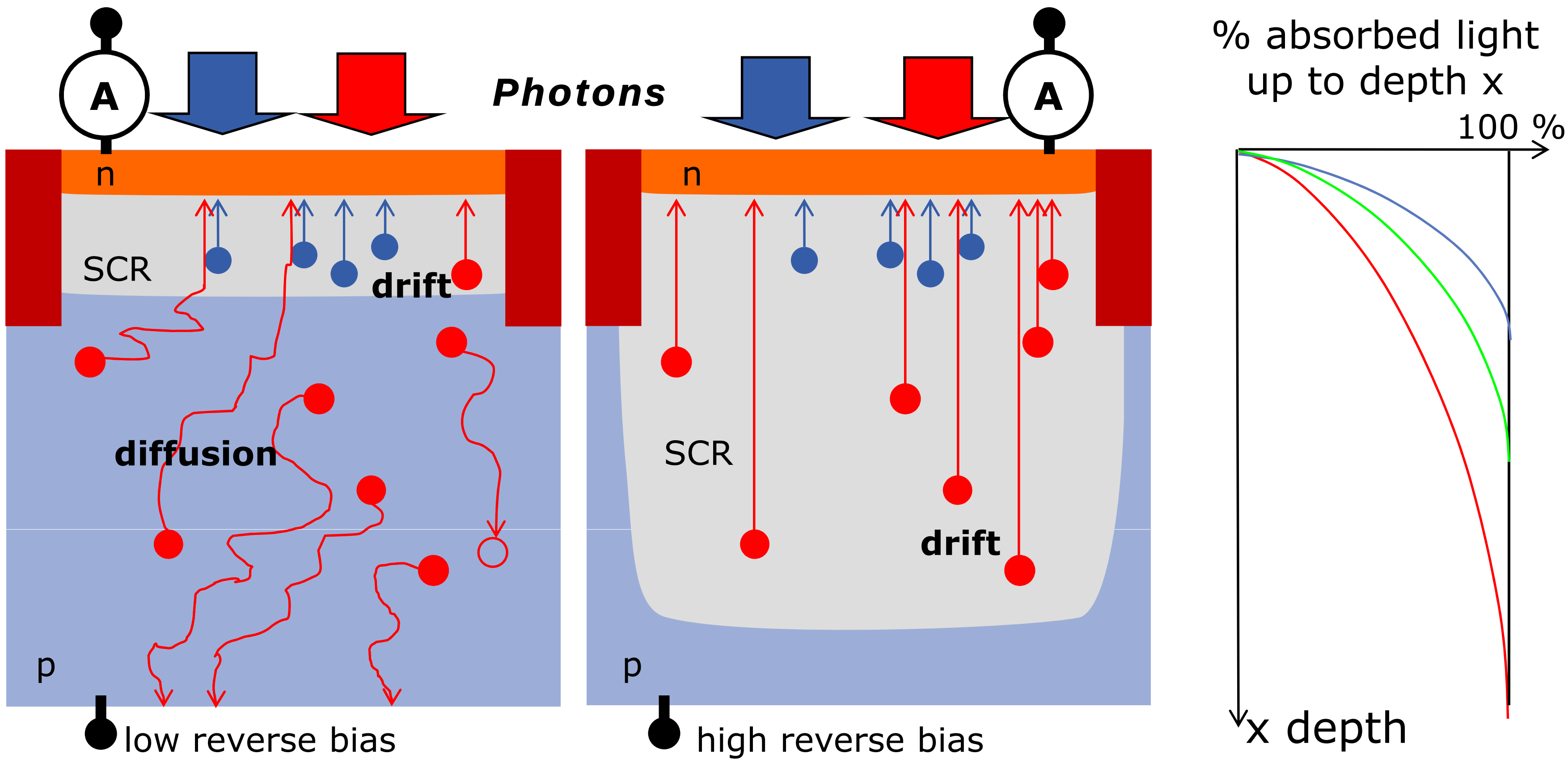
Principle of Color Resolution



blue sensitive
not red sensitive



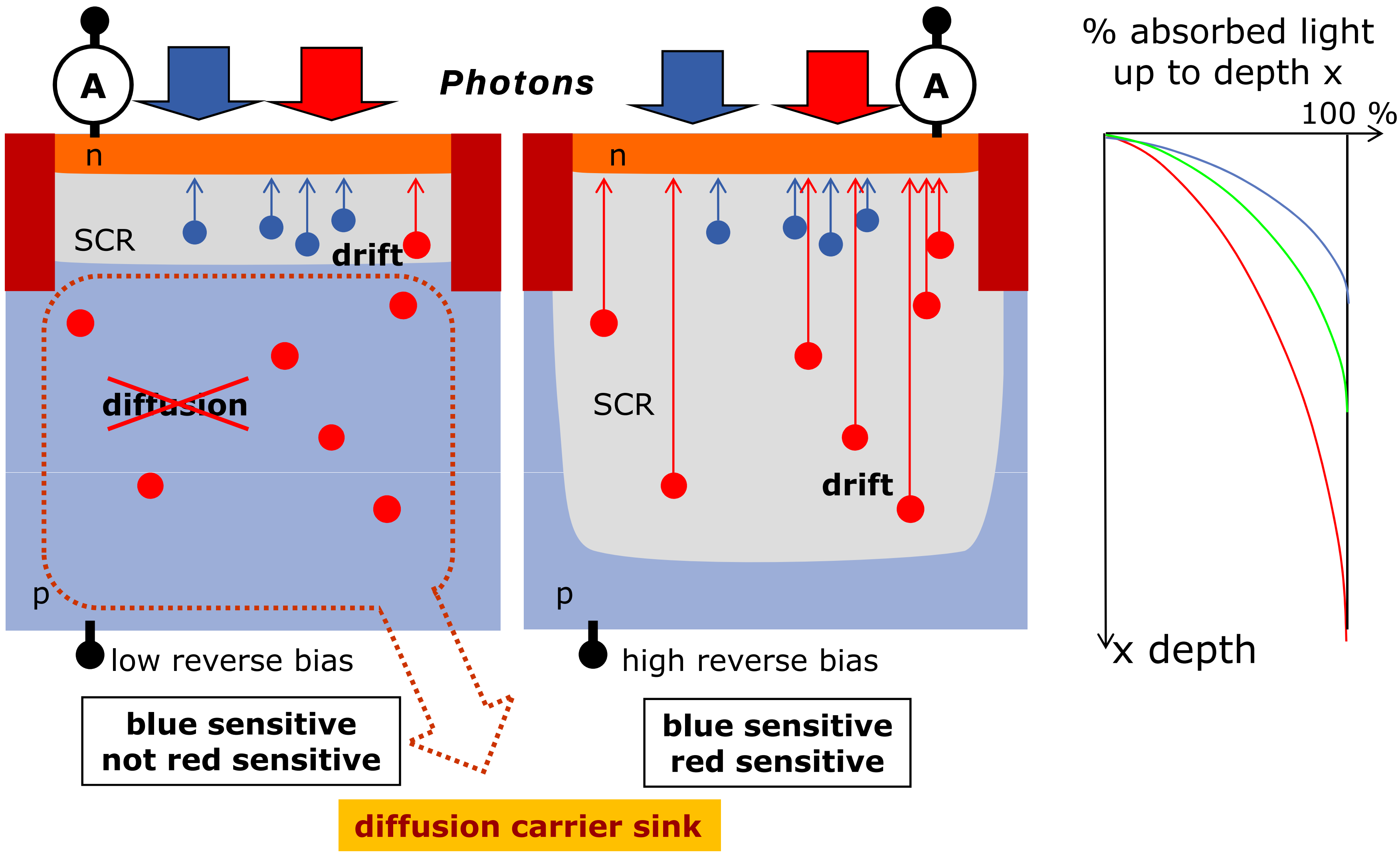
Principle of Color Resolution



blue sensitive
not red sensitive

blue sensitive
red sensitive

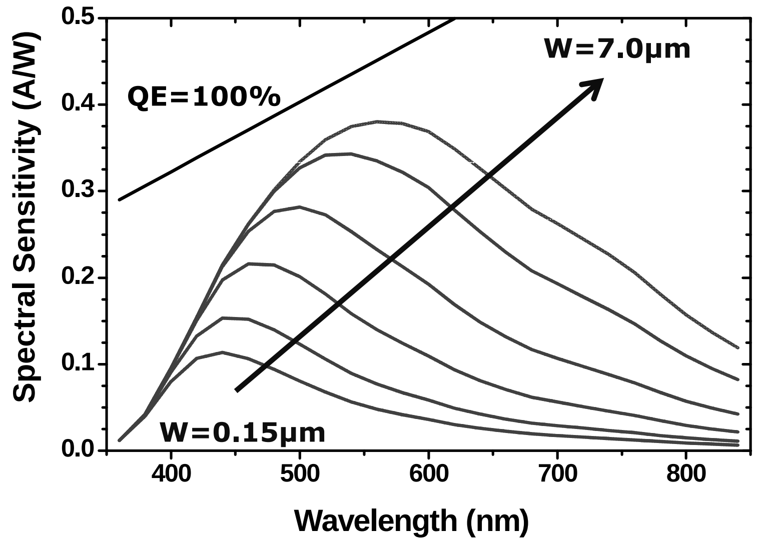
Principle of Color Resolution



Variability of Spectral Response of Photodiode

Model assumption:

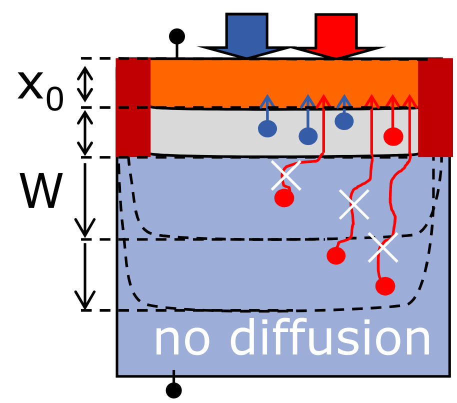
- Photo current contribution:
  - 100% drift carriers
  - 0% diffusions carriers



Sensitivity calculation:

$$S(\lambda, W) = \frac{e \cdot \lambda}{h \cdot c} \int_{x_0}^{x_0+W} \alpha(\lambda) \cdot exp^{-\alpha \cdot x} dx$$

α(λ) … absorption coefficient

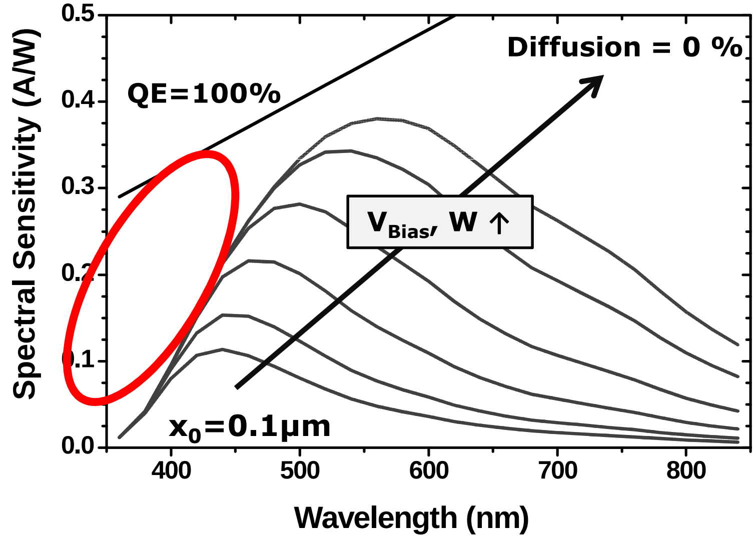


- x_0 … surface near SCR boundary, x_0=0.1µm
- W… width of SCR, 0.15µm < W < 7.0µm

Variability of Spectral Response of Photodiode

Model characteristics:

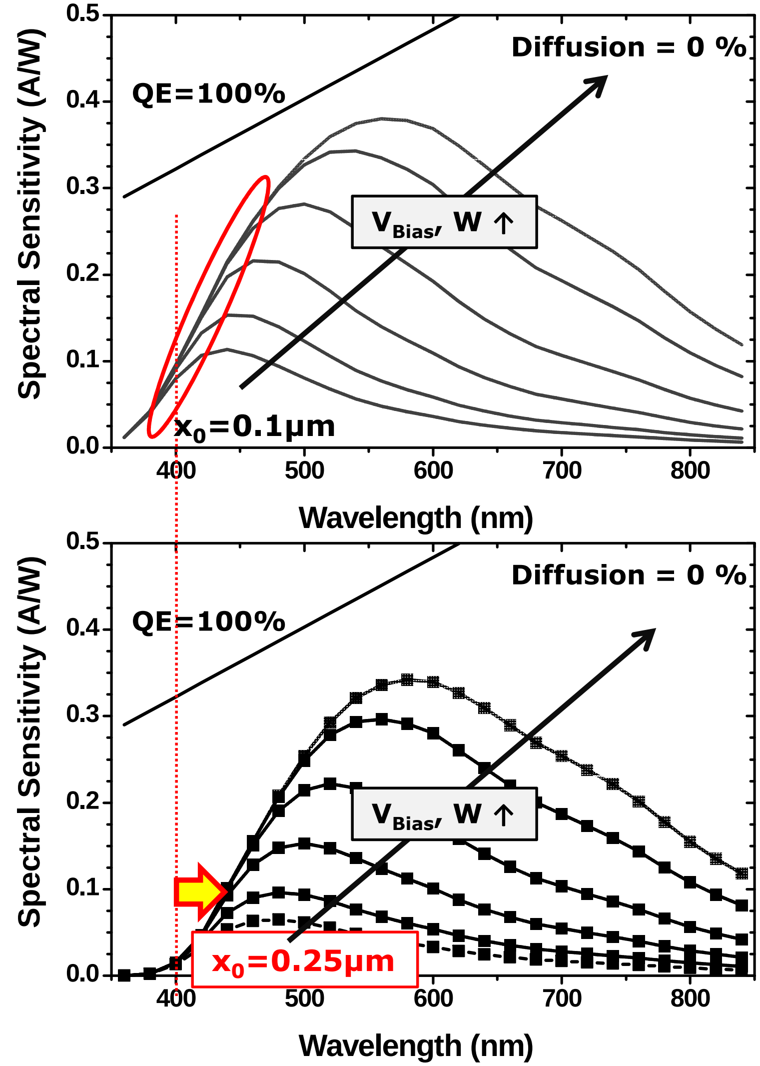
- Very short wavelength:
  - Model sensitivity ~ 0, charge losses from recombination in upper n-region and surface defects



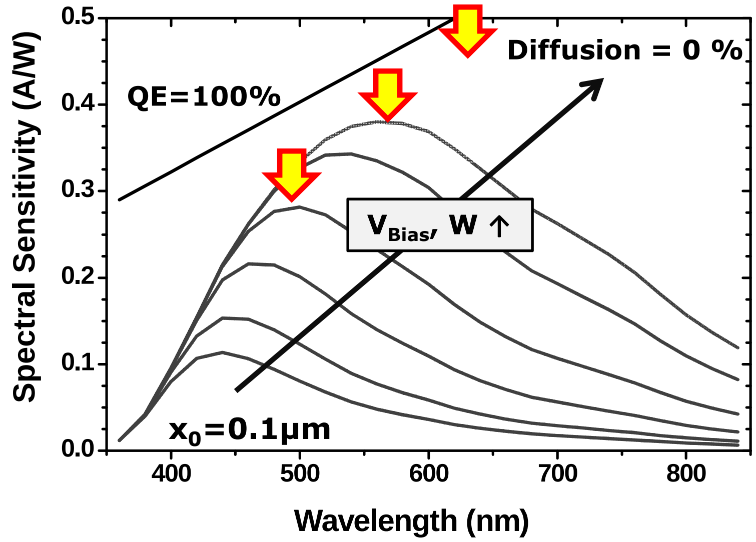
Variability of Spectral Response of Photodiode

Model characteristics:

- Very short wavelength:
  - Model sensitivity ~ 0, charge losses from recombination in upper n-region and surface defects
- Blue sensitivity:
  - Almost independent of W
  - Strongly dependent on x_0



Variability of Spectral Response of Photodiode



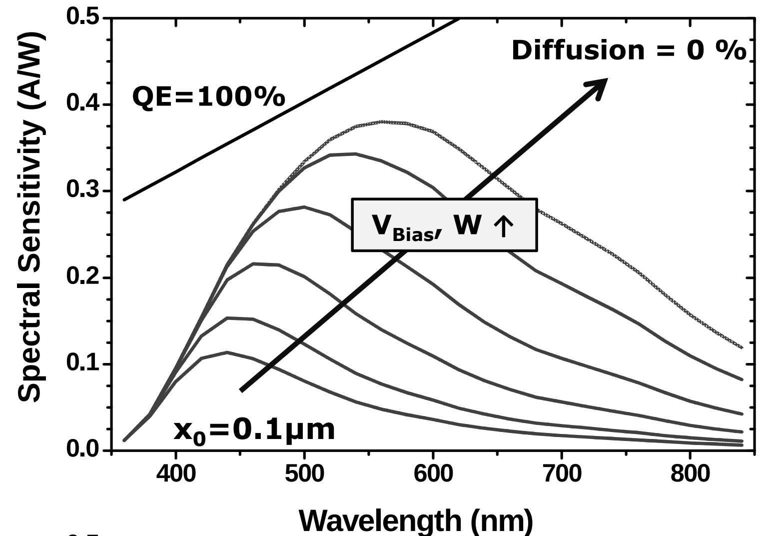
Model characteristics:

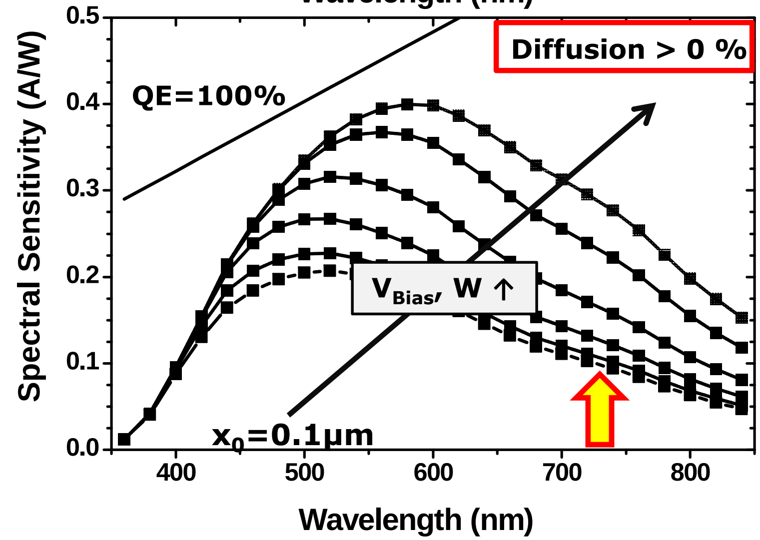
- Very short wavelength:
  - Model sensitivity ~ 0, charge losses from recombination in upper n-region and surface defects
- Blue sensitivity:
  - Almost independent of W
  - Strongly dependent on x_0
- Red / Green sensitivity:
  - Strongly dependent on W
  - Curve shape changes

Variability of Spectral Response of Photodiode

Model characteristics:

- Very short wavelength:
  - Model sensitivity ~ 0, charge losses from recombination in upper n-region and surface defects
- Blue sensitivity:
  - Almost independent of W
  - Strongly dependent on x_0
- Red / Green sensitivity:
  - Strongly dependent on W
  - Curve shape changes
- Long wavelength:
  - Photocurrent contribution from absorption below SCR → "Diffusion carriers"

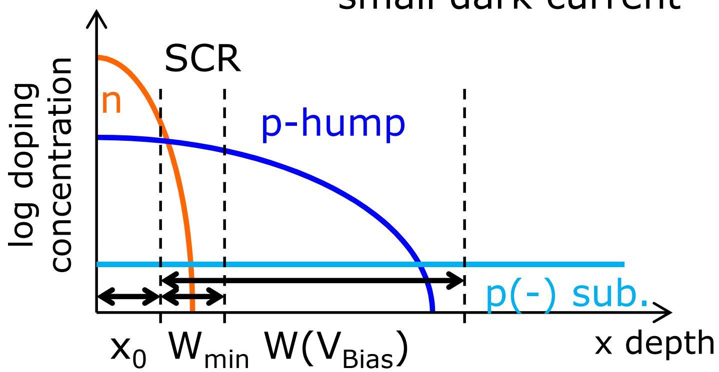


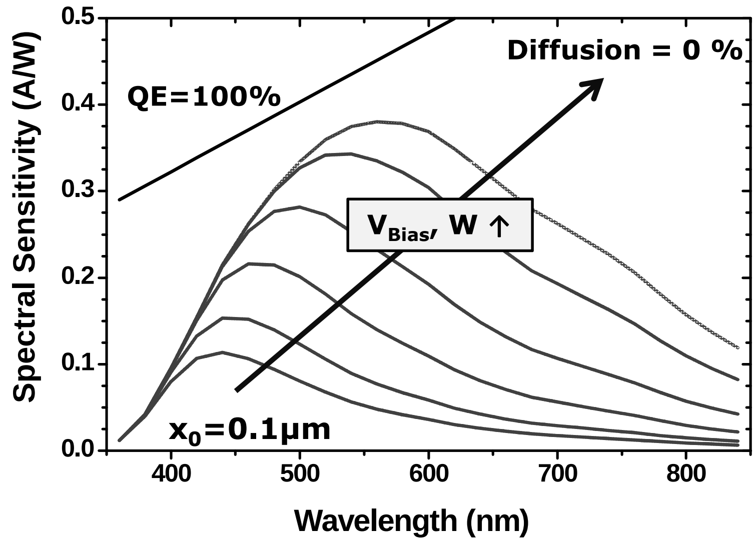


Requirements on Photodiode

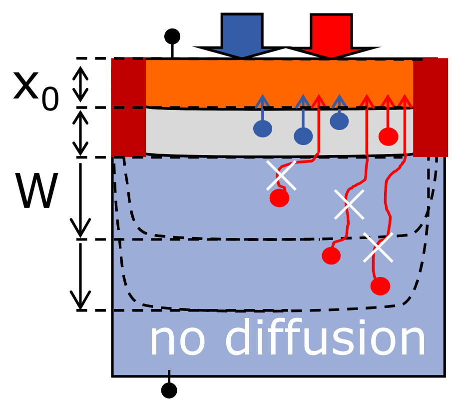
Features enabling color resolution

- Tunable SCR for drift carriers:
  - Upper SCR boundary x_0 fixed close to surface
  - Varying W of SCR over wide range
  - Constraint: - low reverse bias voltage
    - small dark current





- Competing sink for elimination of diffusion carriers



Outline

Motivation

Sensor Concept with Tunable Photodiode

Functionality of Photodiode Hardware

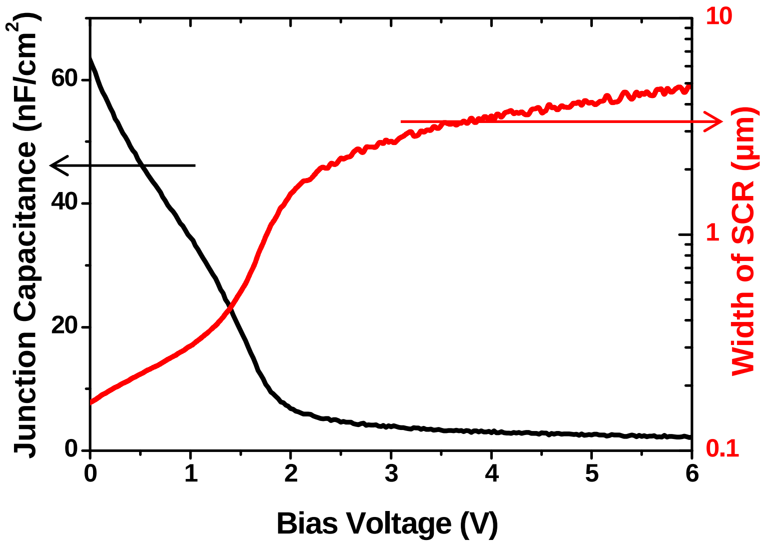
Color Detection Based on Single Photodiode

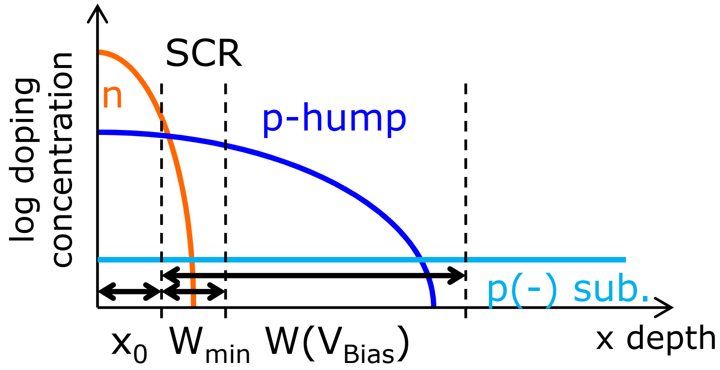
Summary

Tuning of Space Charge Region

Photodiode prototype:

- 130 nm CMOS technology
- Low doped substrate ($<5*10^{15}$ cm^{-3})
- Measurement of junction capacitance:
  - $W = \varepsilon_{Si} A/C$
- SCR tunable over wide range:
  - W_{min} ~ 200 nm @ V_{Bias} ~ 0V
  - W_{max} ~ 4 µm @ V_{Bias} ~ 5V

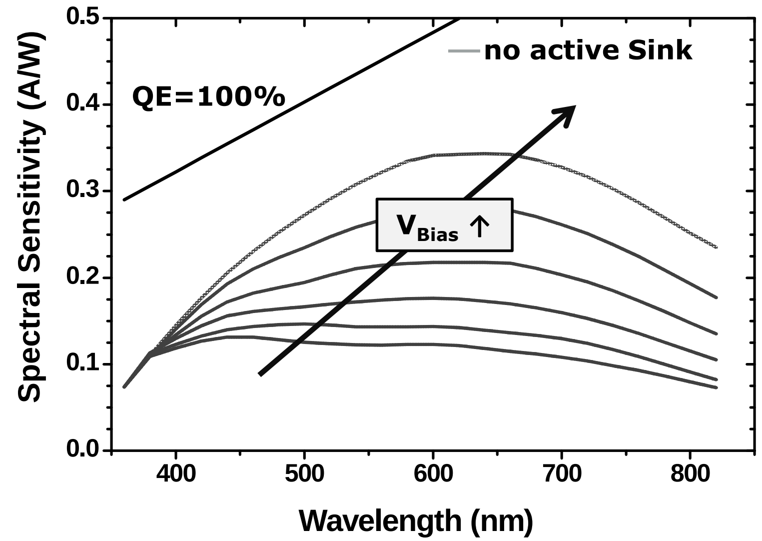


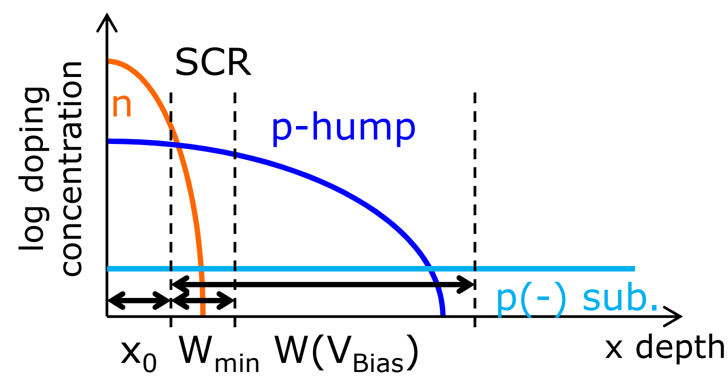


Verification of Spectral Response

Electrical-optical measurements:

- Without activation of competing sink
- Reasonable high sensitivity for high V_{Bias}
- Blue sensitivity independent of applied bias:
  - Fixed and shallow x_0 ~ 200 nm
- No strong decrease of sensitivity for long wavelength at low bias:
  - Diffusion contribution ≠ 0 %

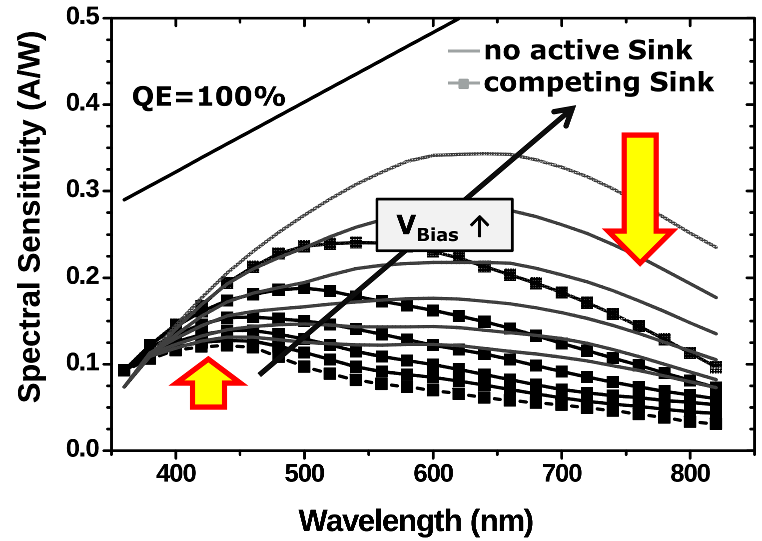


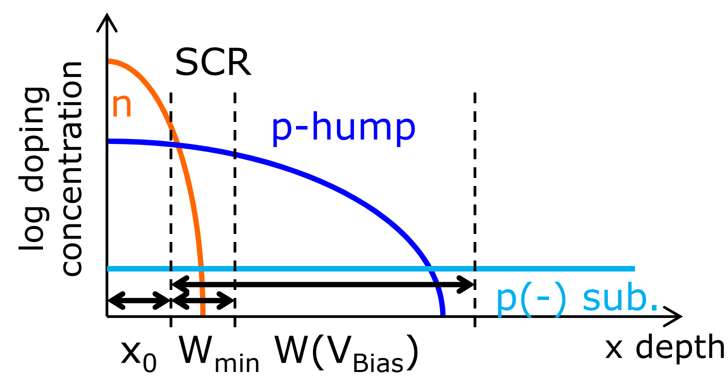


Verification of Spectral Response

Activation of competing sink:

- <u>Short wavelength:</u>
  - Sensitivities almost unchanged
- <u>Longer wavelength:</u>
  - Low V_{Bias}: sensitivities → 0
  - High V_{Bias}: stronger decrease of sensitivities with increasing wavelength
  - Minimal diffusion contribution ≈ 0 %

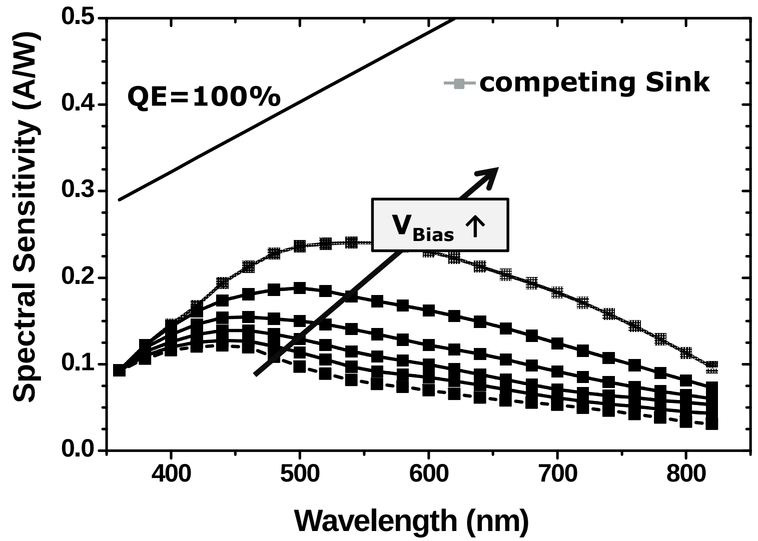




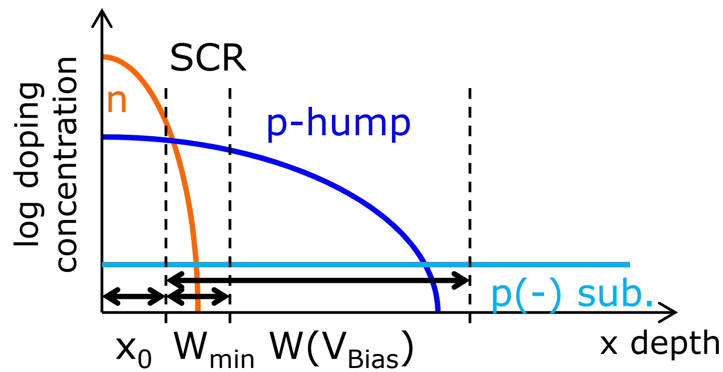
Verification of Spectral Response

Activation of competing sink:

- Short wavelength:
  - Sensitivities almost unchanged
- Longer wavelength:
  - Low V_{Bias}: sensitivities → 0
  - High V_{Bias}: stronger decrease of sensitivities with increasing wavelength
  - Minimal diffusion contribution ≈ 0 %



Improved linear independency of response curves enabling true color perception



Outline

- Motivation
- Sensor Concept with Tunable Photodiode
- Functionality of Photodiode Hardware
- Color Detection Based on Single Photodiode
- Summary

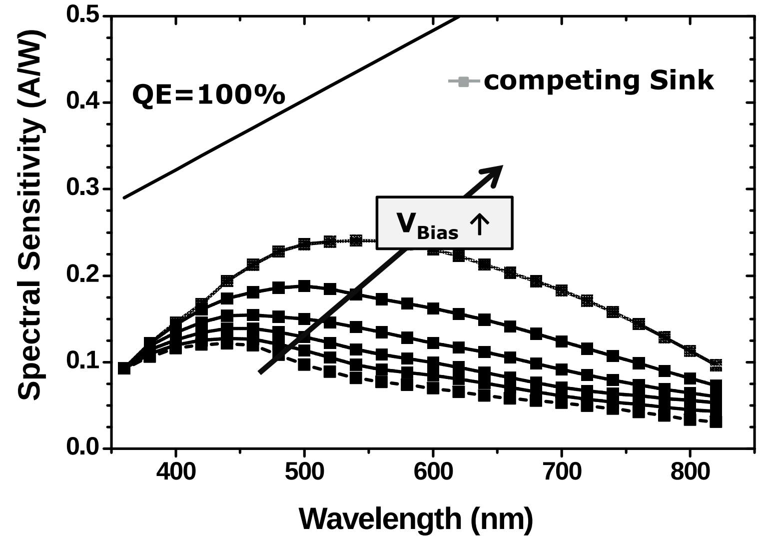
Modeling of Human Receptor Functions

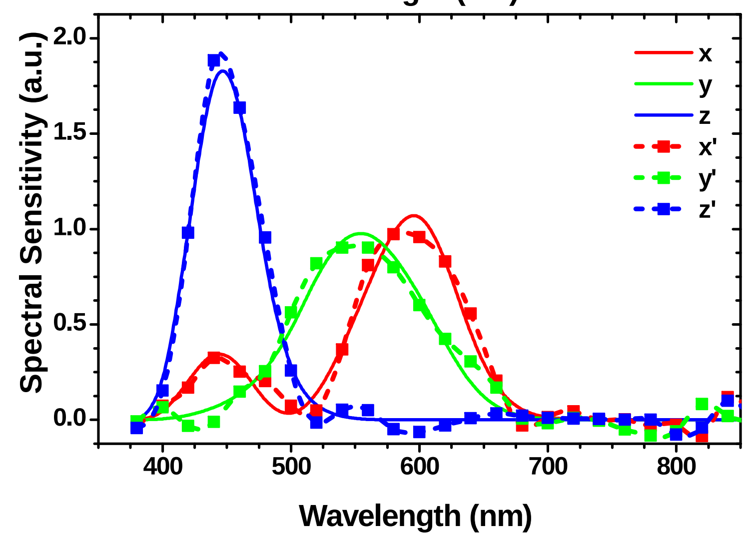
Sensor Calibration:

- Measurement of photodiode sensitivities ($S_j(\lambda)$) for a series of applied reverse biases

- Linear combination of spectral sensitivities to fit human receptor functions:
  - $x(\lambda) \leftarrow x'(\lambda) = \sum \mathbf{a_j} \cdot S_j(\lambda)$, same for green, blue

Sensor adaption by linear combination factors a_j allows color recognition in full color space



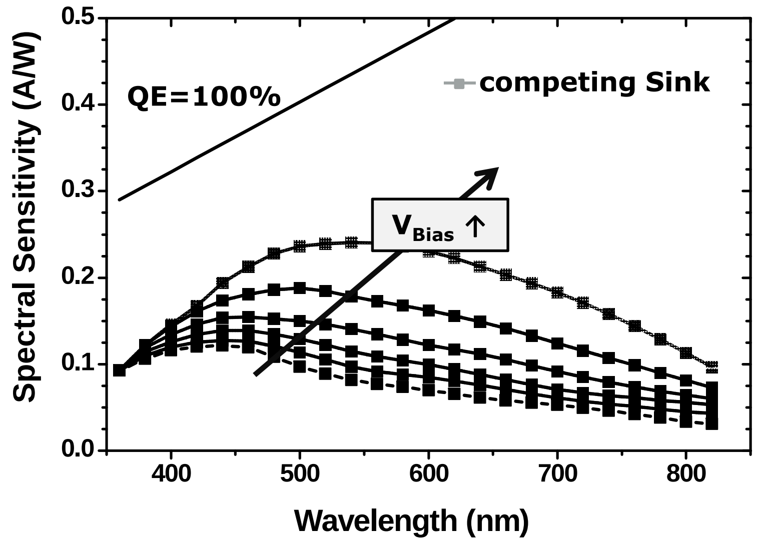


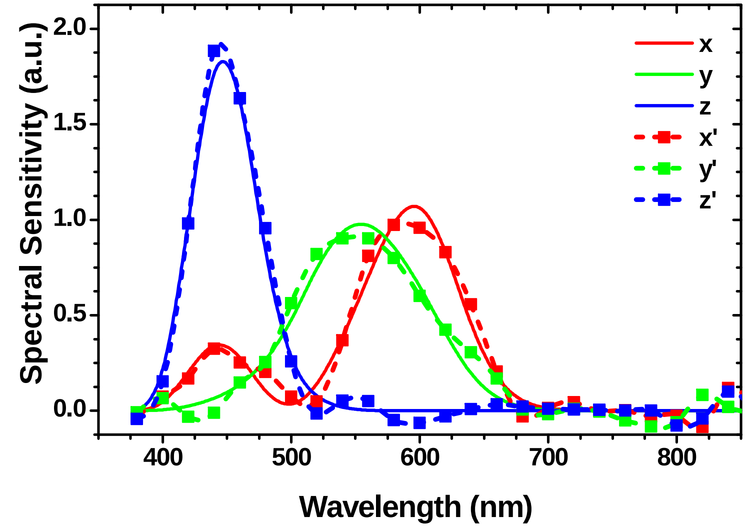
Modeling of Human Receptor Functions

Color Detection:

- Serial photocurrent measurement with varying bias conditions:
  - $I_j = \int P(\lambda) \cdot S_j(\lambda)\, d\lambda$
- Data post processing for adapted cone response:
  - Weighting photocurrents with linear combination factors of sensor calibration
  - $X' = \sum \mathbf{a}_j \cdot I_j$ same for Y', Z'

→ Sensor response:
X', Y', Z' = all color information



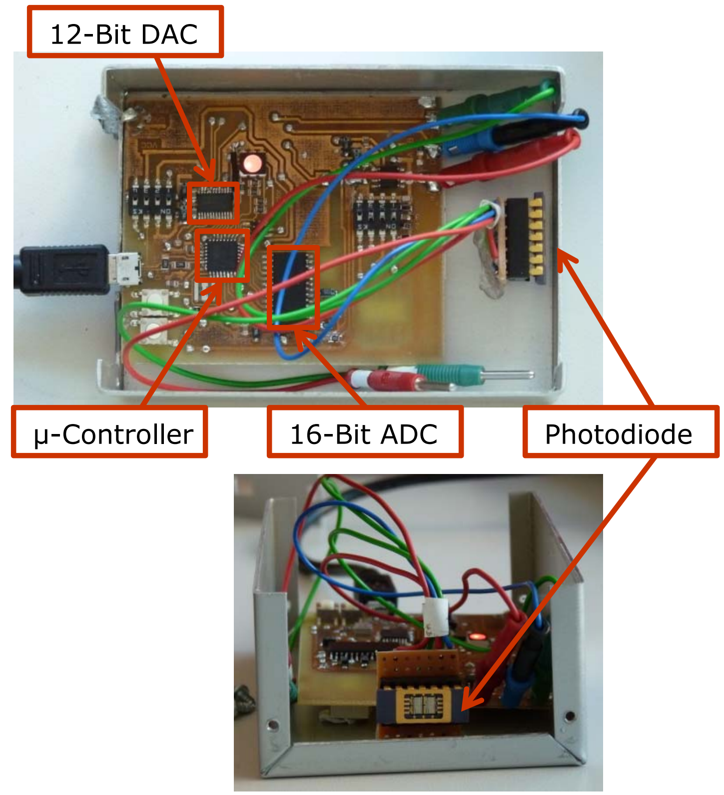


Sensor System for Optimization of Measurement

Demonstrator built with standard electronic modules:

Topics:

- Compensation of dark current
- Determine temperature dependence
  - $x(\lambda) = x'(\lambda) = \sum a_j(T) \cdot S_j(\lambda,T)$
- Optimum: measurement time ↔ color resolution
  - Integration time (t_{in}) (typ. 20ms)
  - Number of applied biases (j) (typ. 10)
  - Limit of fit parameter ($a_j\,(T)_{,max}$) (typ. <30)
- Target:
  - Color resolution ~10 nm



Outline

Motivation

Sensor Concept with Tunable Photodiode

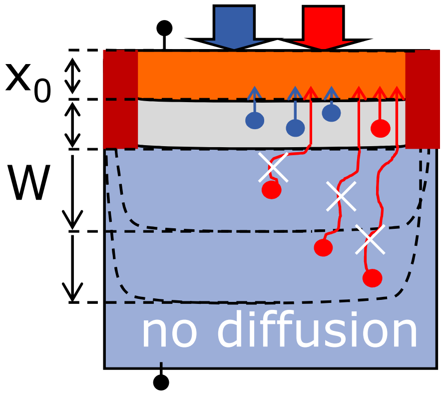
Functionality of Photodiode Hardware

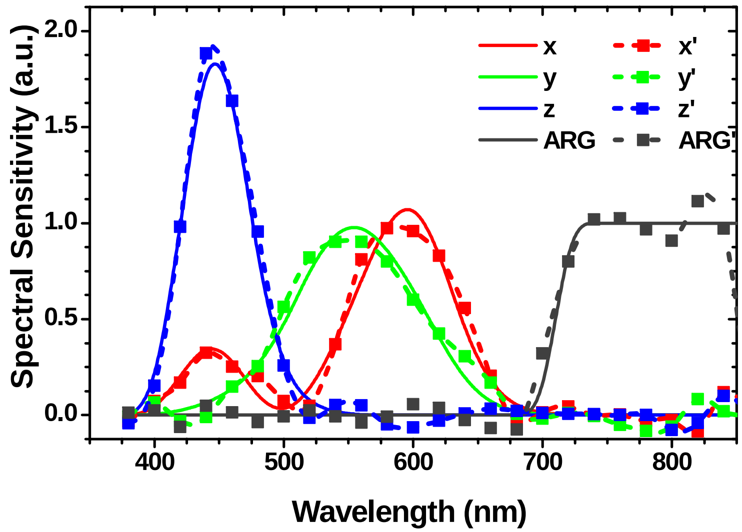
Color Detection Based on Single Photodiode

Summary

New Color Sensor Concept Based on Single Spectral Tunable Photodiode

- Based on single photodiode
- Adaptive spectral sensitivity
- No optical filters needed
- Realization in standard CMOS technology
- Good reproduction of receptor functions
- Transformation of arbitrary filter function by algorithmic initialization, no change of hardware necessary





Thank you for your attention

The work for this paper was supported within the scope of technology development by the EFRE fund of the European Community and by funding from the Free State of Saxony (Project MERLIN).

E-mail: Paul.Jordan@namlab.com