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Materials, devices and applications

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'Where were you when I laid the foundation of the Earth?'

Job 38:4–(RSV)

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Preface

The ability to sense light within a narrow wavelength range is an integral part of our visual perception, enabling us to distinguish a rich range of colours. An equivalent function in electronics is carried out by devices called narrowband photodetectors, which deliver an electric signal when interacting with light of a particular 'colour', i.e. light within a narrow wavelength window that falls in the visible, or the near-infrared, or the ultraviolet range. While in many ways mimicking our visual function (e.g. for digital photography), narrowband photodetectors have been developed over the years to address a very broad range of applications, including areas such as computer vision and chemical fingerprinting for biology, medicine, etc. Conventional semiconductors inherently lack 'colour' (i.e. narrowband) selectivity, hence a work-around has been devised to equip them with this capability: the use of input filters that block off all light except that of the target 'colour'. In spite of its technological success, this approach, however, is laden with challenges and limitations.

In recent years, organic semiconductors have emerged as a class of materials that can uniquely address the demands of narrowband photodetection. Indeed, manifold colours in nature result from π-conjugated molecular structures akin to those of organic semiconductors. Therefore, organic semiconductors with particular composition and structure can inherently and selectively respond to these same colours, precisely matching the scope of narrowband photodetection. In fact, this capability goes beyond the visible range and is also applicable to the ultraviolet and the near-infrared ranges. In addition, organic semiconductors possess key processing advantages over conventional technologies, as they can be deposited over large areas (e.g. on flexible plastic foils) via simple and potentially low-cost methods (e.g. by printing and coating). All these attractive properties make organic semiconductors particularly well suited for the development of narrowband photodetectors and imagers that can be placed ubiquitously in the objects and environments of our daily lives—e.g. so as to function as smart sensors for emerging application areas. Going beyond the limitations of conventional semiconductors, organic semiconductors have consequently enabled a paradigmatic shift in narrowband photodetection technology. A rich research landscape has thus emerged, with manifold new materials, device configurations and narrowband strategies being explored.

This book arises from the need for a comprehensive and unified picture of the subject of narrowband organic photodetection. While a few review articles covering this area have appeared in scientific journals over the years, such works have placed emphasis on particular aspects and are specialistic in nature. Additionally, the relevant literature is particularly heterogeneous, not only because it presents a wide range of materials, narrowband strategies and descriptions thereof, but also because it provides performance figures in a way that may not allow a straightforward comparison between different works. Considering that by now narrowband organic photodetection builds on a vast body of literature and varied interdisciplinary knowledge, the need is thus manifest for a comprehensive and unified treatment of this topic. Addressing this very need, the present book in fact constitutes—to the best of the author's knowledge—the first ever and most extensive monograph on the subject. For the sake of comprehensiveness, this book covers organic photodetectors with narrowband character in the visible, near-infrared and ultraviolet ranges. Aiming for a self-contained treatment, this book additionally covers the background of pertinent physical, material and device engineering aspects. In order to overcome the heterogeneity of the literature, this book presents a unified treatment of the narrowband strategies employed with organic semiconductors, and offers a contextualisation of the material innovations in terms of families of compounds and molecular design approaches. In the same direction, this book additionally offers a comprehensive and cross-sectional analysis of the literature, highlighting performance trends in relation to material and device physics aspects, and providing an extensive tabulated collection of performance data.

In regard to its structure, the present book takes the reader on a journey from the basic concepts to the latest scientific literature on narrowband organic photodetection, while covering the subject from several angles—materials, physical properties, device physics and engineering, and technological implications. The foundation layer (*chapter 1*) illustrates the motivation for an organic route to narrowband photodetection. It does so by surveying the wealth of relevant application areas and the properties that make organic semiconductors particularly attractive for such applications. The book then presents a discussion of the essentials of organic semiconductors and photodetectors thereof (*chapter 2*). This discussion identifies the key aspects underlying the capability of organic semiconductors to deliver narrowband photodetection. After presenting the physical mechanisms through which light in such materials is converted into an electric signal, the devices which implement this functionality are illustrated, along with the corresponding performance metrics. The specifics and significance of narrowband photodetection are then presented (*chapter 3*). This is coupled with a detailed treatment of the many narrowband strategies that have been pursued with organic semiconductors. The book finally delivers an in-depth analysis of the literature implementations of organic narrowband photodetectors and associated integration works. The discussion examines the numerous aspects involved: materials and processing (*chapter 4*); performance metrics and underlying trends (*chapter 5*); and integration schemes for specific applications (*chapter 6*).

The comprehensive and harmonised treatment of narrowband organic photodetection provided in this book is particularly relevant to researchers and technologists active in the area of photodetection and/or organic semiconductors. In view of its extensive survey of the literature, this book additionally serves as a useful reference text for experts and practitioners working in organic semiconductors, printed and flexible optoelectronics, and/or sensors and imaging devices. Finally, by covering both the basics and the latest trends in organic narrowband photodetection, this book is also relevant to physics, chemistry and engineering students and enthusiasts, especially those interested in organic semiconductors, optoelectronics and/or colour/imaging science.

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Author biography

Vincenzo Pecunia

Vincenzo Pecunia is a Principal Investigator and an Associate Professor at the Institute of Functional Nano & Soft Materials, Soochow University (China). He earned his Bachelor's and Master's in Electronics Engineering from Politecnico di Milano (Italy). Subsequently, he was at the Cavendish Laboratory of the University of Cambridge (UK) for over six years. There he obtained his PhD in Physics and also worked as a postdoctoral scientist.

His research has addressed the physics of printable optoelectronic materials—e.g. organic, perovskite and amorphous-metal-oxide semiconductors—and their application to optoelectronics. The Thin-Film Optoelectronics Group that he leads researches the charge transport physics and photoelectronic properties of solution-processed semiconductors, related optoelectronic devices (e.g. solar cells, photodetectors and thin-film transistors) and their application to large-area electronics. His research has led to numerous publications in top scientific journals. Additionally, drawing from his research experience, he has also lead-authored a monograph for Cambridge University Press titled Organic and Amorphous-Metal-Oxide Flexible Analogue Electronics.

Abbreviations[1]

A	Acceptor
AI	Artificial Intelligence
BHJ	Bulk heterojunction
CCN	Charge collection narrowing
CCNx	Charge collection narrowing with gain
CFA	Colour filter array
CIE	Commission Internationale de l'Eclairage
c-Si	Crystalline silicon
CT	Charge transfer
D	Donor
D:A	BHJ between a D and an A
D|A	PHJ between a D and an A
DBR	Distributed Bragg reflector
EA	Electron affinity
EQE	External quantum efficiency
ETL	Electron-transport layer
FWHM	Full width at half maximum
HOMO	Highest occupied molecular orbital
HTL	Hole transport layer
InpF	Input optical filtering
IntF	Internal filtering
IntF-1	Single-component internal filtering
IntF-1x	Single-component internal filtering with gain
IOEF	Internal optoelectronic filter
IoT	Internet of Things
IP	Ionisation potential
IQE	Internal quantum efficiency
LDR	Linear dynamic range
LUMO	Lowest unoccupied molecular orbital
MEMS	Micro-electro-mechanical system
NBA	Narrowband absorption
NBAx	Narrowband absorption with gain
NEP	Noise equivalent power
NIR	Near infrared
NIRS	Near-infrared spectroscopy
NP	Nanoparticle
NR	Nanorod
NW	Nanowire
OLED	Organic light emitting diode
PCL	Photoconversion layer
PHJ	Planar heterojunction
PMT	Photomultiplier tube
QD	Quantum dot
R2R	Roll-to-roll

[1] Abbreviations of chemical compounds referred to in the text are not listed here, as they follow the relevant journal papers or the dominant nomenclature in the literature.

RC	Resistor-capacitor
RGB	Red-green-blue
RMS	Root mean square
UV	Ultraviolet
VLC	Visible light communications
μC	Microcavity
μL	Microlens

Symbols

[*adj*]	Spectral range adjacent to [*targ*]
B	Noise measurement bandwidth
c	Speed of light in free space
C_p	Photodetector capacitance
D	Detectivity
D^*	Specific detectivity
E	Electric field
E_B	Exciton binding energy
$E_g^{(opt)}$	Optical bandgap
EQE_p	Peak EQE
f	Modulation frequency
f_{3dB}	3dB frequency/bandwidth
f_{RC}	RC-limited 3dB frequency
f_{tr}	Transit-time-limited 3dB frequency
$FWHM_\alpha$	FWHM of $\alpha(\lambda)$
$FWHM_{EQE}$	FWHM of $EQE(\lambda)$
$FWHM_R$	FWHM of $R(\lambda)$
$FWHM_{Voc}$	FWHM of $V_{oc}(\lambda)$
G^*	Photocurrent/photoconductive gain
h	Planck constant
$h\nu$	Photon energy
i_{dark}	Dark current
i_n	Noise current
$i_{n,RMS}$	RMS value of the noise current
i_{ph}	Photocurrent
$i_{ph,max}$	Upper photocurrent limit of the LDR
$i_{ph,min}$	Lower photocurrent limit of the LDR
i_{tot}	Total photodetector current
J_{dark}	Areal dark current density
J_{ph}	Areal photocurrent density
J_0	Reverse-bias saturation current density
K	LDR prefactor
k_B	Boltzmann constant
L	Interelectrode distance
l_{cav}	Geometrical length of a resonance cavity

L_D	Exciton diffusion length
m	Resonance order
n	Ideality factor
$\hat{n}$	Average refractive index of a resonance cavity
$NEP_{A,\sqrt{B}}$	Noise equivalent power per unit bandwidth and area
$NEP_{\sqrt{B}}$	Noise equivalent power per unit bandwidth
N_e	Number of collected photocarriers per unit time
N_{gen}	Number of photogenerated electron-hole pairs per unit time
N_p	Number of photons incident on a photodetector per unit time
PB_n	Passband of the *nth* photodetector
P_{opt}	Incident optical power
$P_{opt,max}$	Upper power limit of the LDR
$P_{opt,min}$	Lower power limit of the LDR
q	Elementary charge
R	Responsivity
R_L	Load resistance
R_p	Peak responsivity
$R_{PD}(\lambda)$	Unfiltered spectral responsivity in an InpF photodetector
R_s	Series resistance
R_{sh}	Parallel (shunt) resistance
$S_{ct,ij}$	Spectral crosstalk between photodetectors *i* and *j*
$S_{i_n,g-r}$	Generation-recombination-noise power spectral density
$S_{i_n,shot}$	Shot-noise power spectral density
$S_{i_n,th}$	Thermal-noise power spectral density
S_n	Noise power spectral density
$S_{n,w}$	White-noise power spectral density
$S_{n,flicker}$	Flicker-noise power spectral density
S_{sct}	Spectral self-crosstalk
$SRR_R(\lambda_{p,R}, \lambda_{adj})$	Responsivity spectral rejection ratio
$SRR_{EQE}(\lambda_{p,EQE}, \lambda_{adj})$	EQE spectral rejection ratio
S/N	Signal to noise ratio
T	Absolute temperature
$[targ]$	Target spectral range
$T_{if}(\lambda)$	Transmittance of input filter
$t_{fall}^{(50)}$	50% fall time
$t_{fall}^{(10\text{-}90)}$	10%–90% fall time
$t_r^{(10\text{-}90)}$	10%–90% response time

$t_r^{(50)}$	50% response time
$t_r^{(99.5)}$	99.5% response time
$t_{rise}^{(10\text{-}90)}$	10%–90% rise time
$t_{rise}^{(50)}$	50% rise time
t_{tr}	Average carrier transit time
$t_{tr,n}$	Electron transit time
$t_{tr,p}$	Hole transit time
V_{BIAS}	Applied voltage
V_{oc}	Open circuit voltage
$W_F^{(a)}$	Anode workfunction
$W_F^{(c)}$	Cathode workfunction
α	Absorption coefficient
$\hat{\alpha}$	Effective absorption coefficient
$\hat{\alpha}_{act}$	Effective absorption coefficient of the photoactive material
α_p	Peak absorption coefficient
γ	Exponent of the power-law relationship between i_{ph} and P_{opt}
η_{abs}	Absorption efficiency
η_{coll}	Collection efficiency
$\eta_{diff}^{(ex)}$	Exciton diffusion efficiency
$\eta_{diss}^{(ex)}$	Exciton dissociation efficiency
η_{extr}	Extraction efficiency
η_{gen}	Photocarrier generation efficiency
$\eta_{gen}^{(ex)}$	Exciton generation efficiency
η_{tr}	Transport efficiency
θ	Internal angle of incidence
λ	Wavelength
λ_{adj}	Selected wavelength in $[adj]$
λ_m	Resonance wavelength
λ_{onset}	Absorption onset
λ_p	Peak absorption wavelength
$\lambda_{p,EQE}$	EQE peak wavelength
$\lambda_{p,R}$	Responsivity peak wavelength
μ_n	Electron mobility
μ_p	Hole mobility
Σ	Cross-sectional area of a photodiode
τ	Effective optical depth of the mirrors in a µC-based device
τ_n	Electron lifetime