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Solid-State Infrared Photosensing

Swiss Photonics Workshop, EMPA, 15 January 2015

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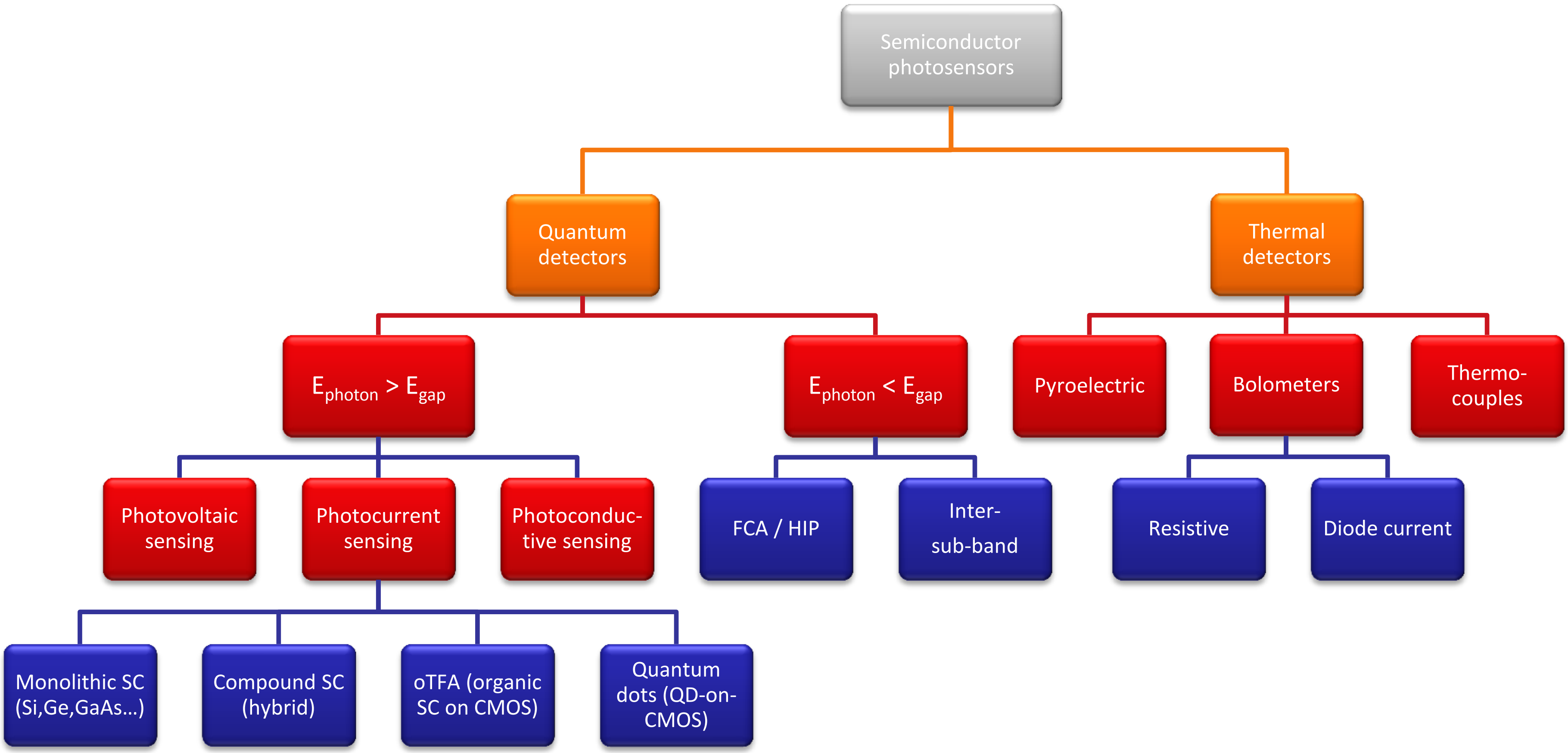
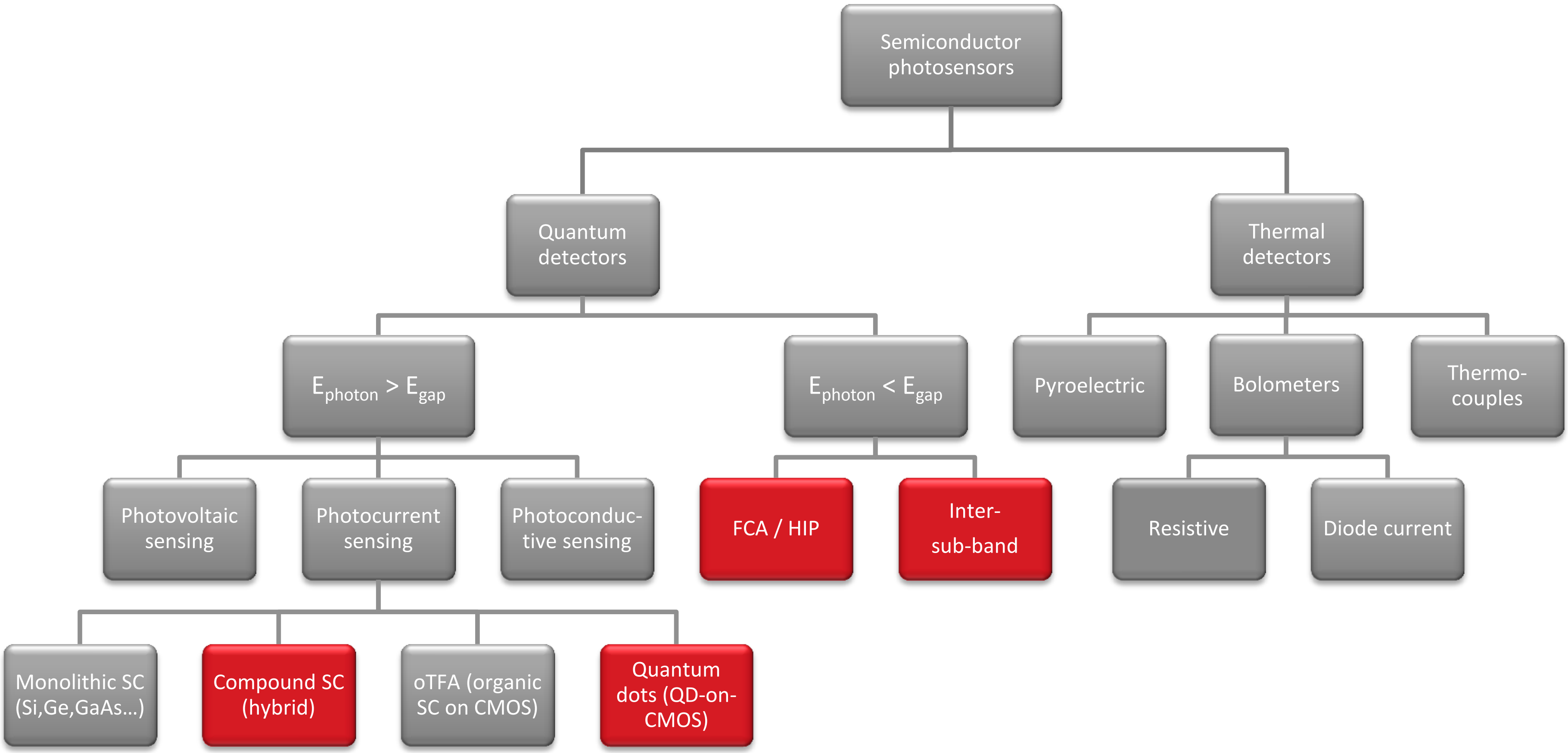
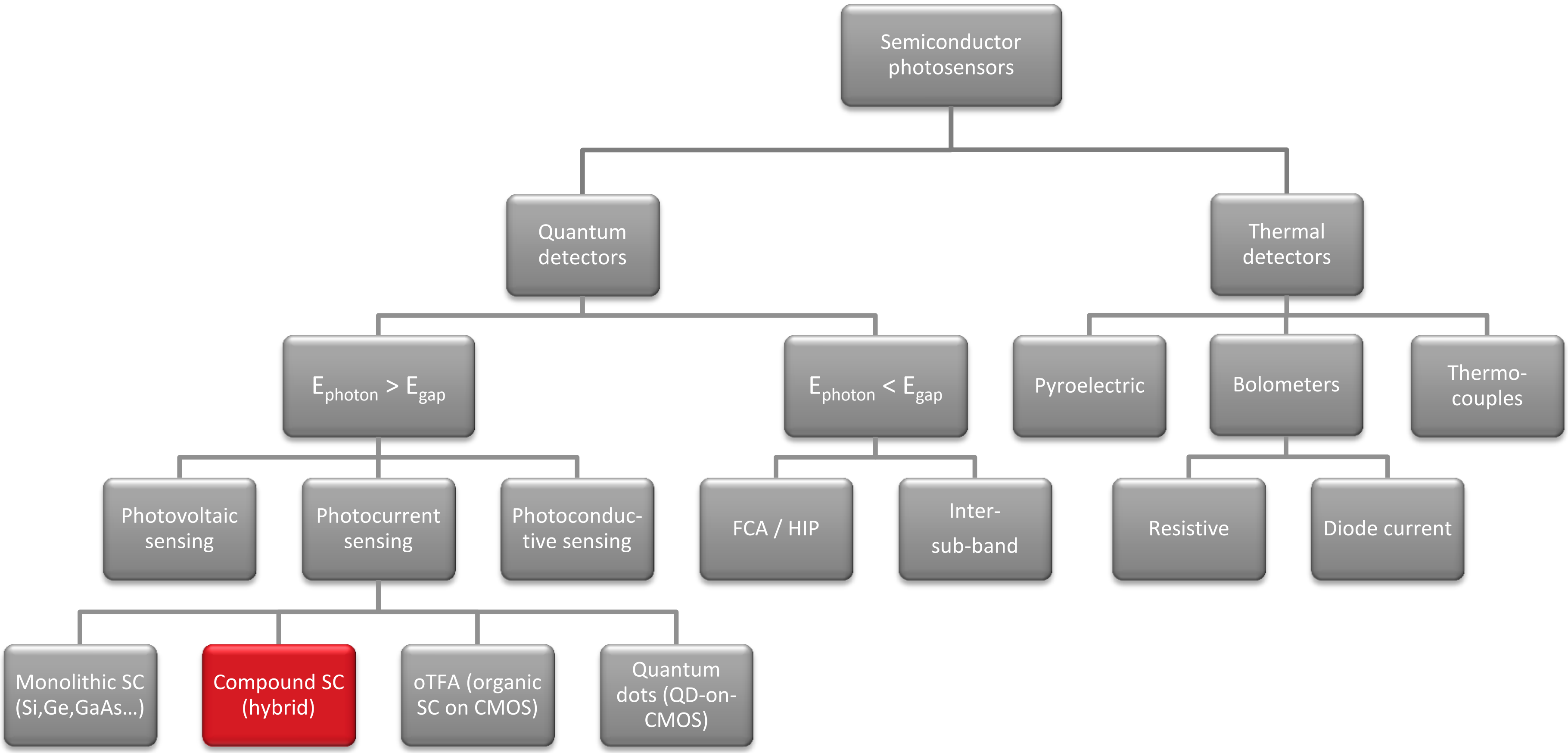
Taxonomy of Solid-State Photosensing Principles



Contents of the Presentation



Compound Semiconductor Photosensors (on CMOS)



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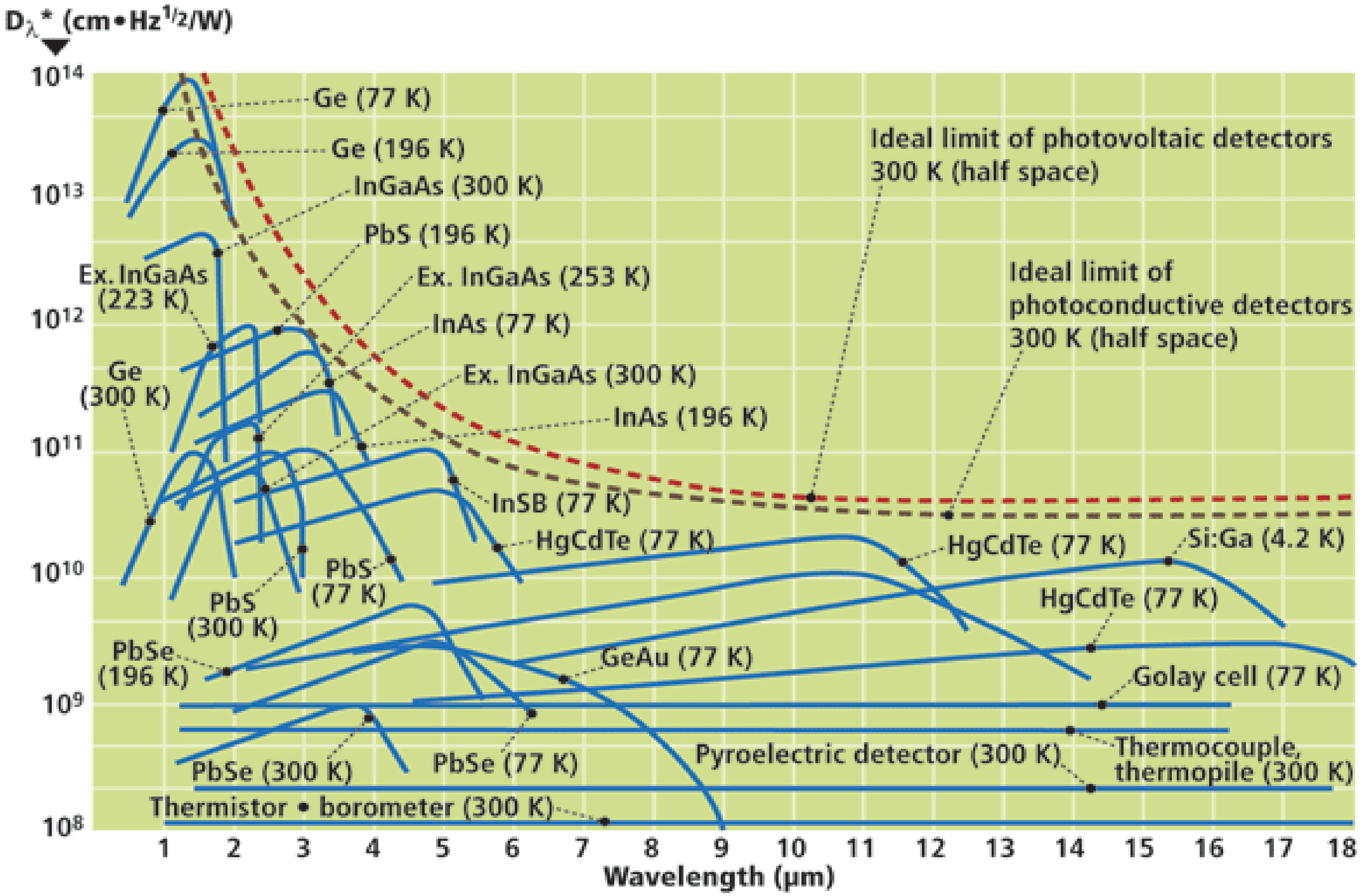
Detectivity of Different Types of Infrared Photosensor Materials



Andrew Wilson, "The Infrared Choice", Vision Systems Design, Vol. 16, 1 April 2011

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InAsSb: Longest Wavelength III-V Semiconductor

In summary, this preliminary work has demonstrated room temperature InAsSb photodetectors operating up to ≈14 μm with performance close to the theoretical limits determined by fundamental limitations. The present InAsSb devices may be already useful for some applications (CO_2 laser monitors, laser warning receivers and others). The monolithic optical immersion should increase the performance to the level comparable to the state-of -art microbolometers, but with much faster speed of response. Further optimization of devices and the use of simple Peltier coolers should bring even improved performance, so that this technology may become a serious challenger to both MCT and microbolometer technologies.

M. Razeghi, ''Longwavelength InAsSb Infrared Photodetectors'', ARPA Report, April 1995

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Mid-Infrared Quantum Detection: InAsSb

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NEW

InAsSb photovoltaic detector

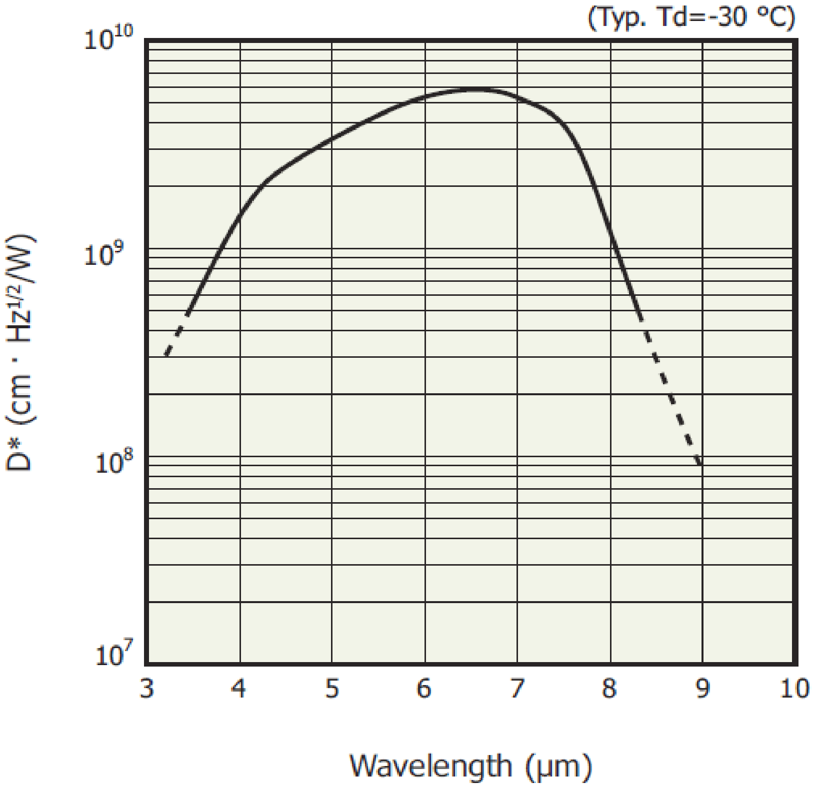
High-speed resp
Thermoelectrica
required

The P12691-201 is an infrared detector that provides high sens
tal growth technology and back-illuminated structure and by
junction that ensures high-speed response and high reliability.
and H_2S. The P12691-201 is easy to use as it uses a compact p

Features

- High-speed response
- High sensitivity
- High reliability
- Compact, thermoelectrically cooled TO-8 package
- RoHS compliant
- Can be assembled in a module with QCL

Spectral response (D*)



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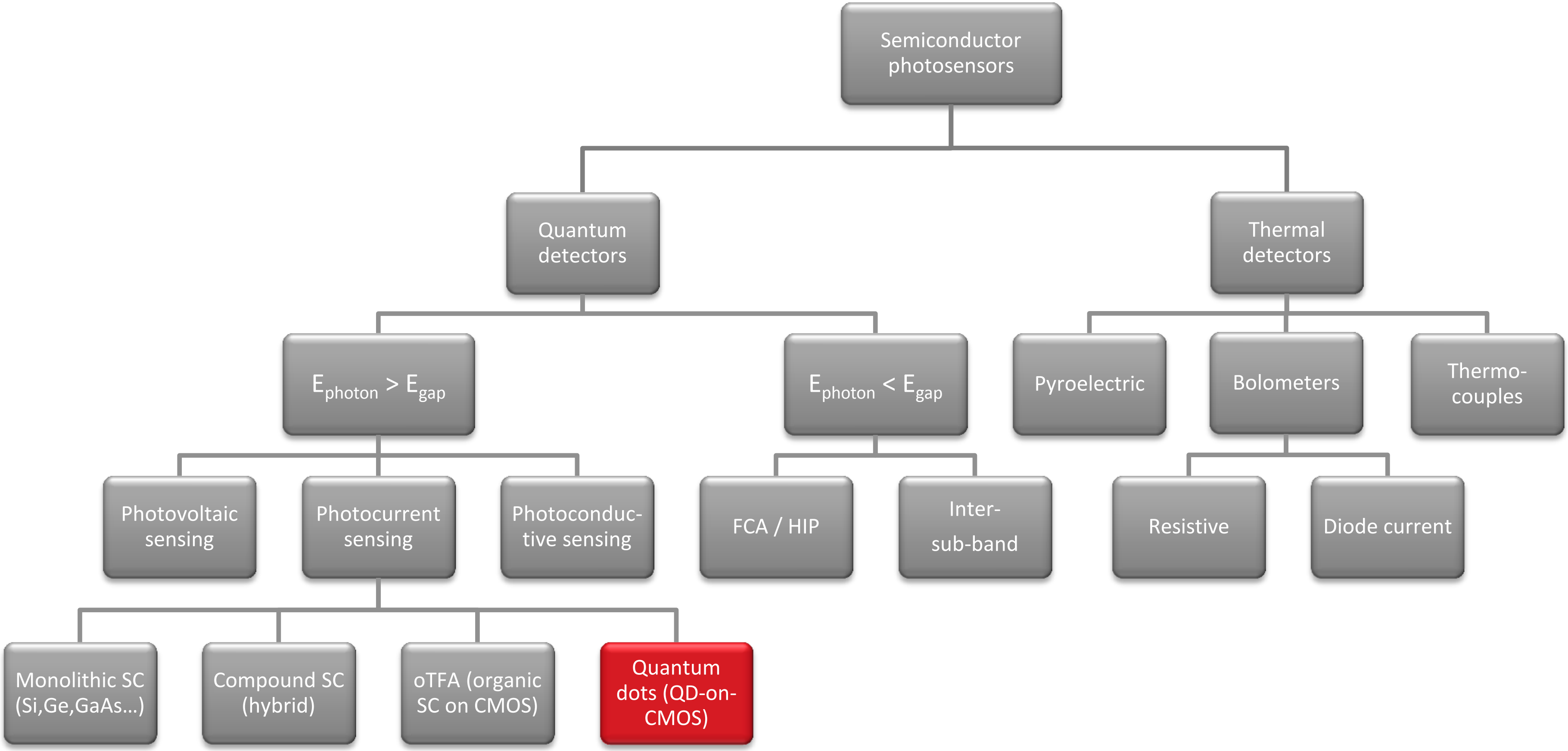
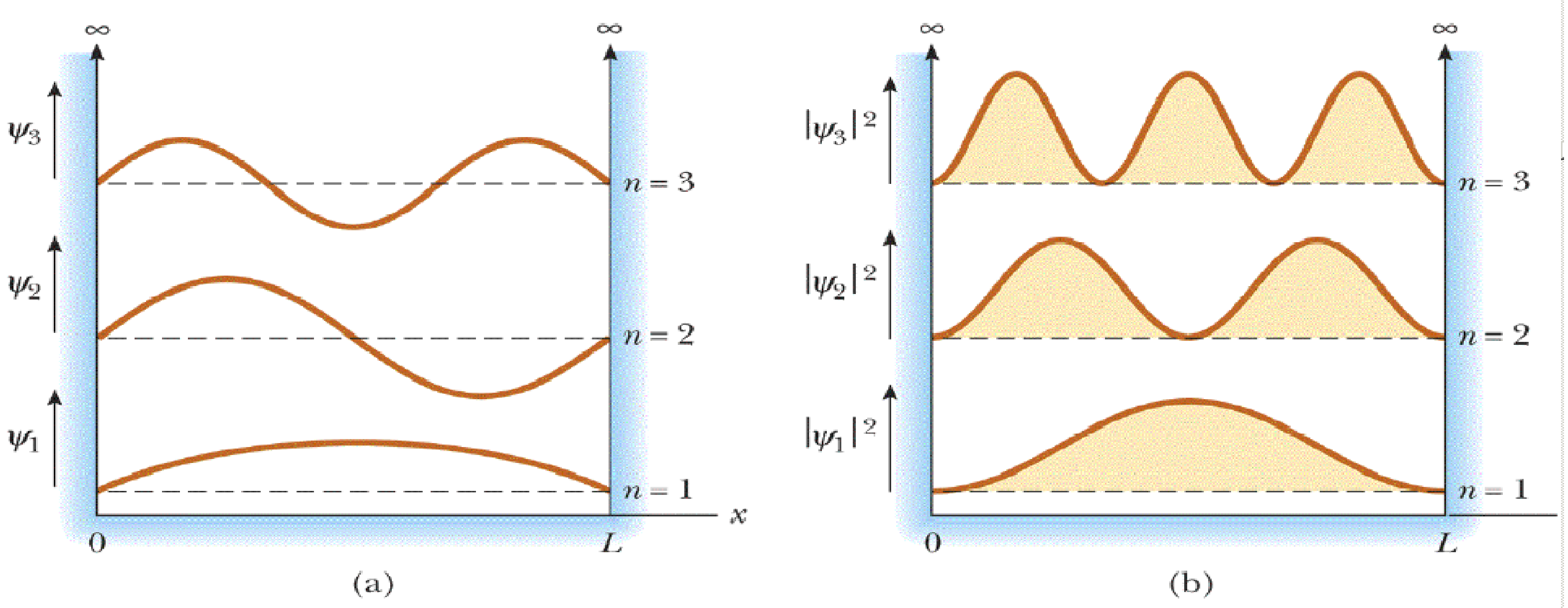
Quantum Dot Photosensing



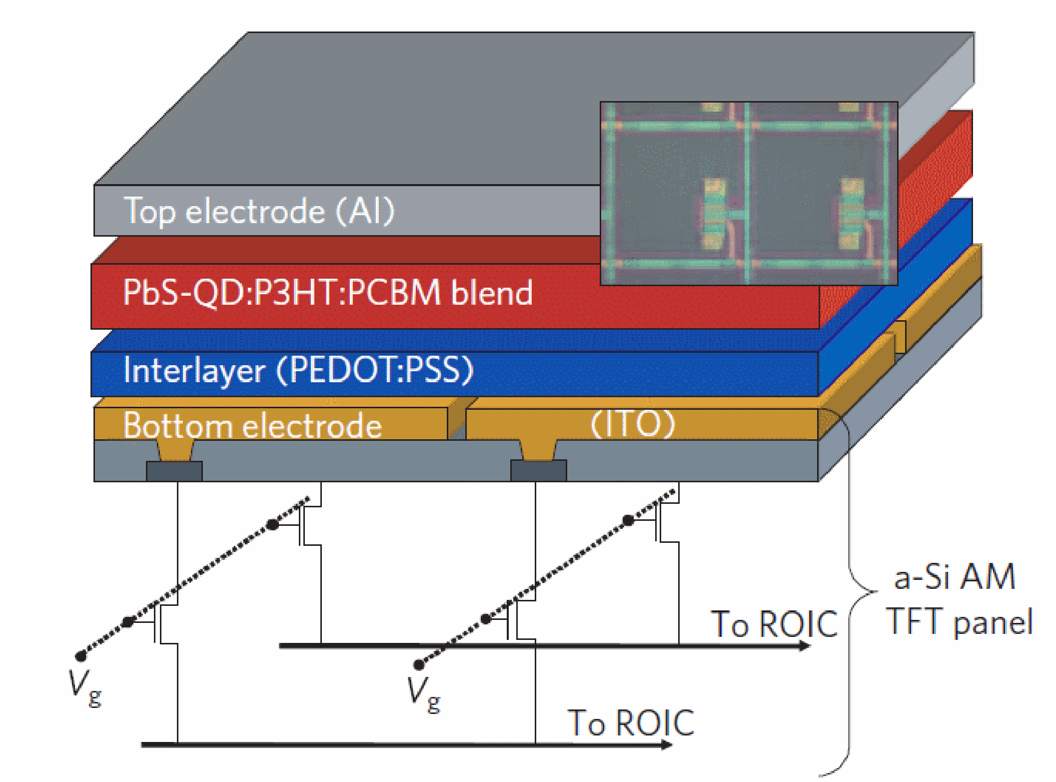
Reminder: Quantum Confinement Photodetection (Electron in a Box)

Potential energy: U = 0 in the box (0..L), and U = ∞ outside the box

$$\Psi_n(x) = \sqrt{\frac{2}{L}} \sin \frac{n\pi}{L} x \qquad n = 1,2,3,\ldots \qquad E_n = \frac{h^2}{8mL^2} n^2$$



NIR/MIR Cutoff-on-Demand: Quantum-Dots on CMOS Image Sensors



T. Rauch et al., "Near-infrared imaging with quantum-dot-sensitized organic photodiodes", Nature Photonics, Vol. 3, 17 May 2009

MIR Wavelengths Accessible to Quantum-Dot Photosensing

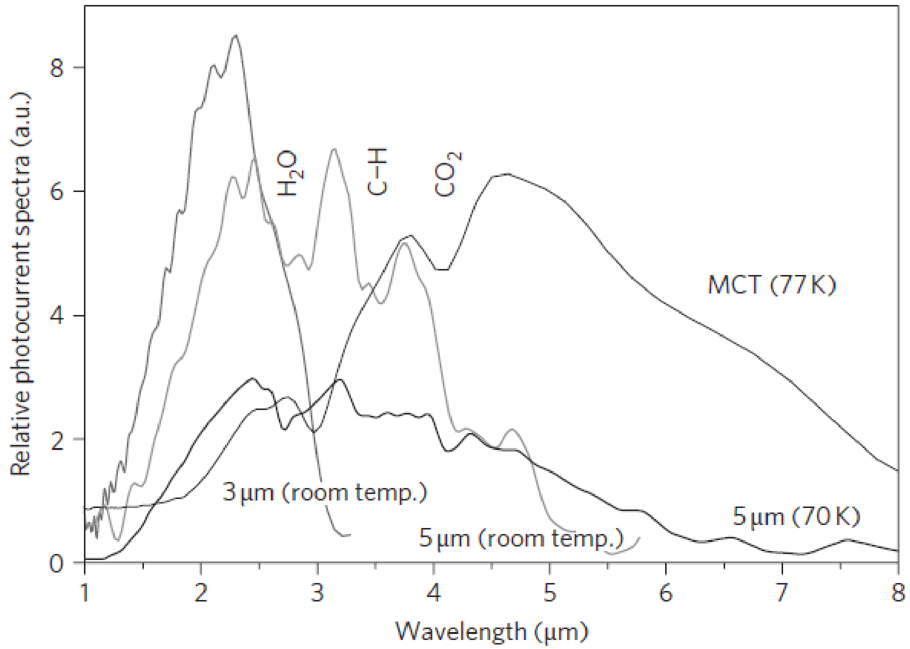


Figure 3 | Fourier transforms of interferograms measured for the two devices under identical conditions with 0.3 V bias. The 5 μm sample is shown at room temperature and at 70 K, and the 3 μm device at room temperature.

S. Keuleyan et al., "Mid-infrared HgTe colloidal quantum-dot photodetectors", Nature Photonics, Vol. 5, 17 Aug. 2011

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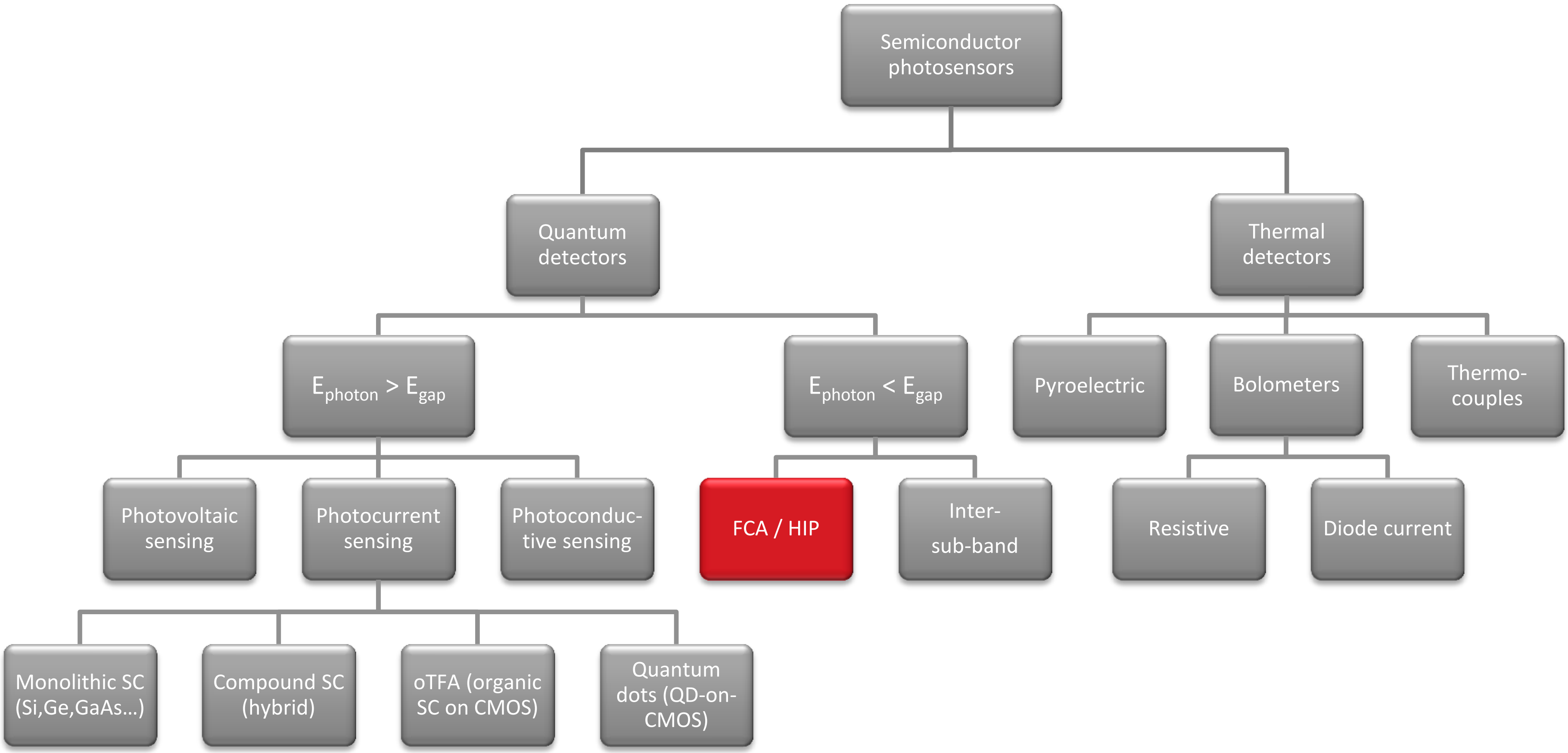
Free Carrier Absorption – Homojunction Internal Photoemission



Silicon-Based (CMOS-Compatible) MIR/FIR Photosensing?

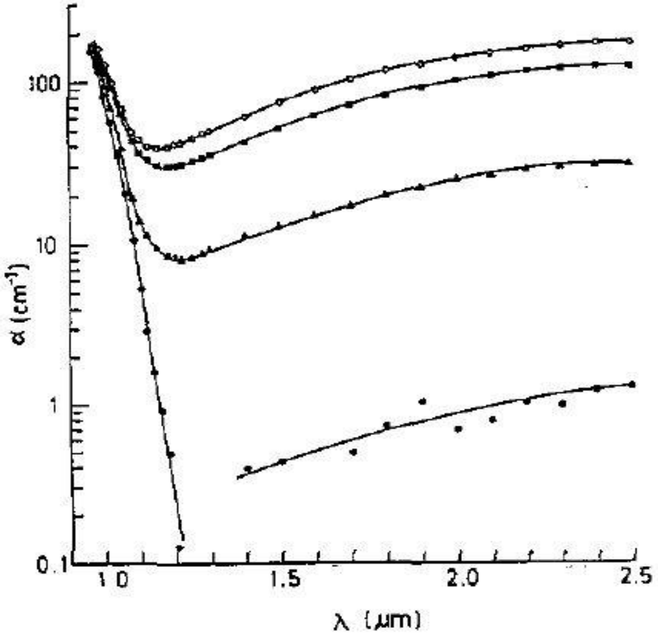


Figure 1. The absorption curves for n-Si samples at 294 K. (●) 6.5×10^{16} cm^{-3}; (▲) 1.6×10^{17} cm^{-3}; (■) 6.4×10^{18} cm^{-3}; (○) 9.2×10^{18} cm^{-3}.

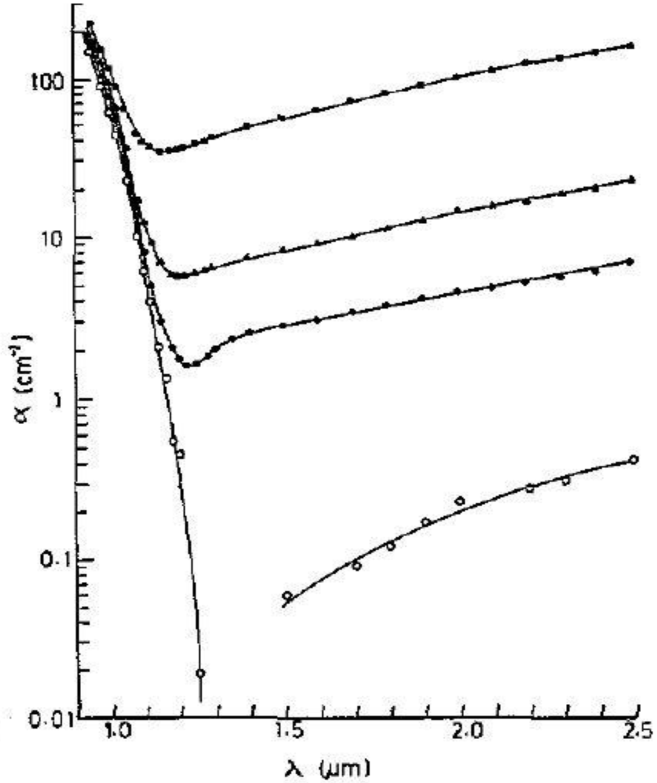


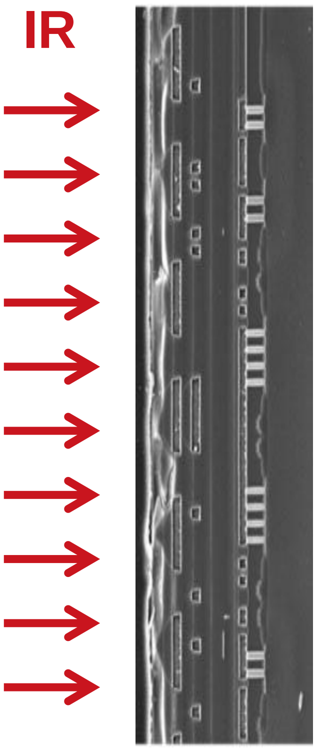
Figure 2. The absorption curves for p-Si samples at 294 K. (○) 1.5×10^{16} cm^{-3}; (●) 3.3×10^{17} cm^{-3}; (▲) 1.2×10^{18} cm^{-3}; (■) 7.3×10^{18} cm^{-3}.

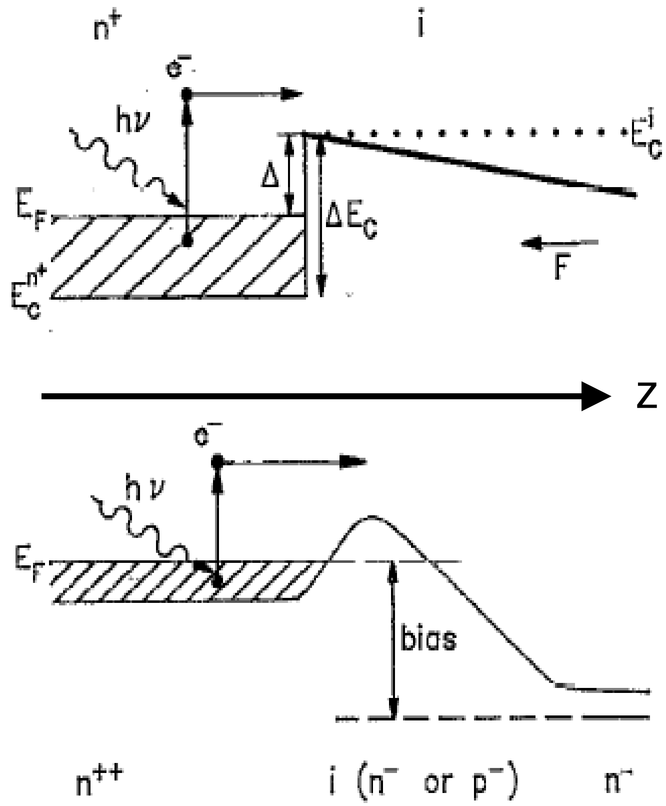
IR absorption in doped Si is increasing with the square of the wavelength

Relationship holds up to wavelengths of several 100 µm (FIR / THz)

S.E. Aw et al., "Optical absorption measurements of bandgap shrinkage in moderately and heavily doped siliocn", J. Phys.Cond. Matter Vol. 3, 1991

Ultra-Wide-Band NIR/MIR/FIR/THz Silicon Photodetection: FCA/HIP





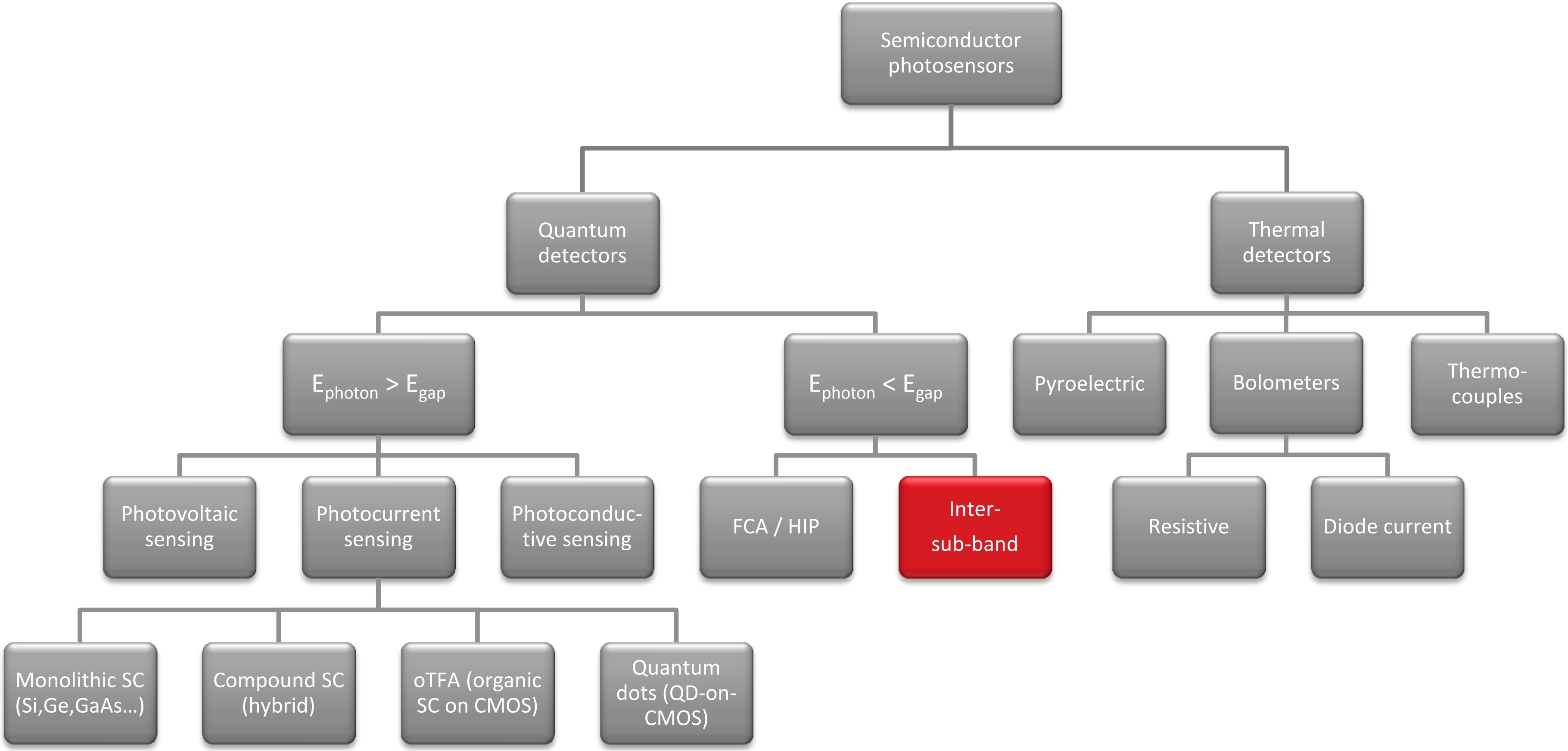
A.G.U. Perera et al., "Homojunction internal photo-emission far-infrared detectors: Photoresponse performance analysis", J. Appl. Phys. 77 (2), 1995

Potential barriers close to the surface, next to highly doped silicon, act as filters for charge carriers excited by the incident IR photons:

Only higher-energy electrons/holes can pass over the barrier, for collection and detection by adjacent electronic circuits

HIP = Homojunction internal photoemission

Intersubband Infrared Photodetection



Infrared Photodetection With A Silicon Gate (MOS) Structure

US006420707B1

(12) **United States Patent**
Anthony et al.

(10) **Patent No.:** **US 6,420,707 B1**
(45) **Date of Patent:** **Jul. 16, 2002**

(54) **INFRA-RED DETECTOR**

(75) Inventors: **Carl J. Anthony**; **Kevin M. Brunson**; **Charles T. Elliott**; **Neil T. Gordon**; **Timothy J. Phillips**; **Michael J. Uren**, all of Malvern (GB)

(73) Assignee: **Qinetiq Limited**, London (GB)

(*) Notice: Subject to any disclaimer, the term of patent is extended or adjusted under U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/297,176**

(22) PCT Filed: **Nov. 6, 1997**

(86) PCT No.: **PCT/GB97/03053**

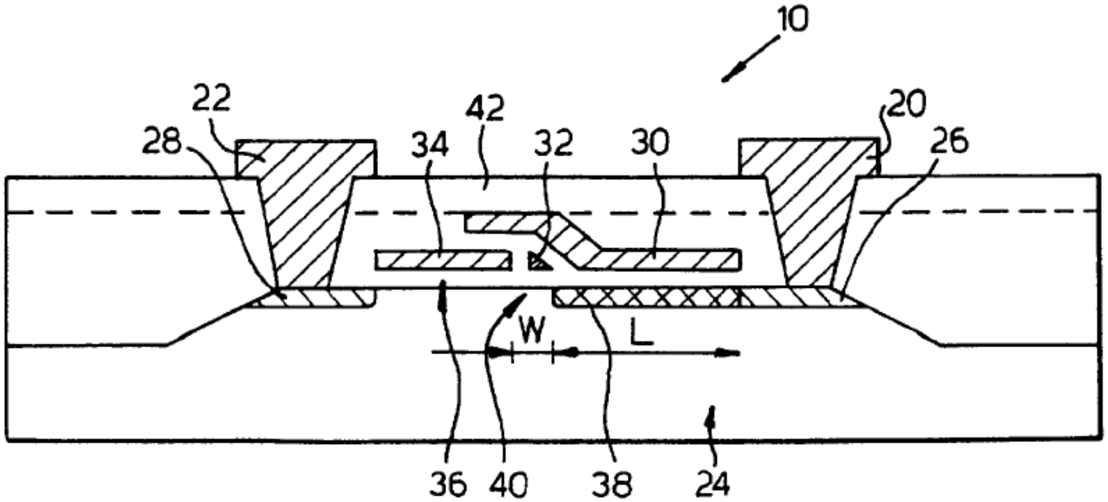
§ 371 (c)(1), (2), (4) Date: **Jul. 21, 1999**

(87) PCT Pub. No.: **WO98/21757**

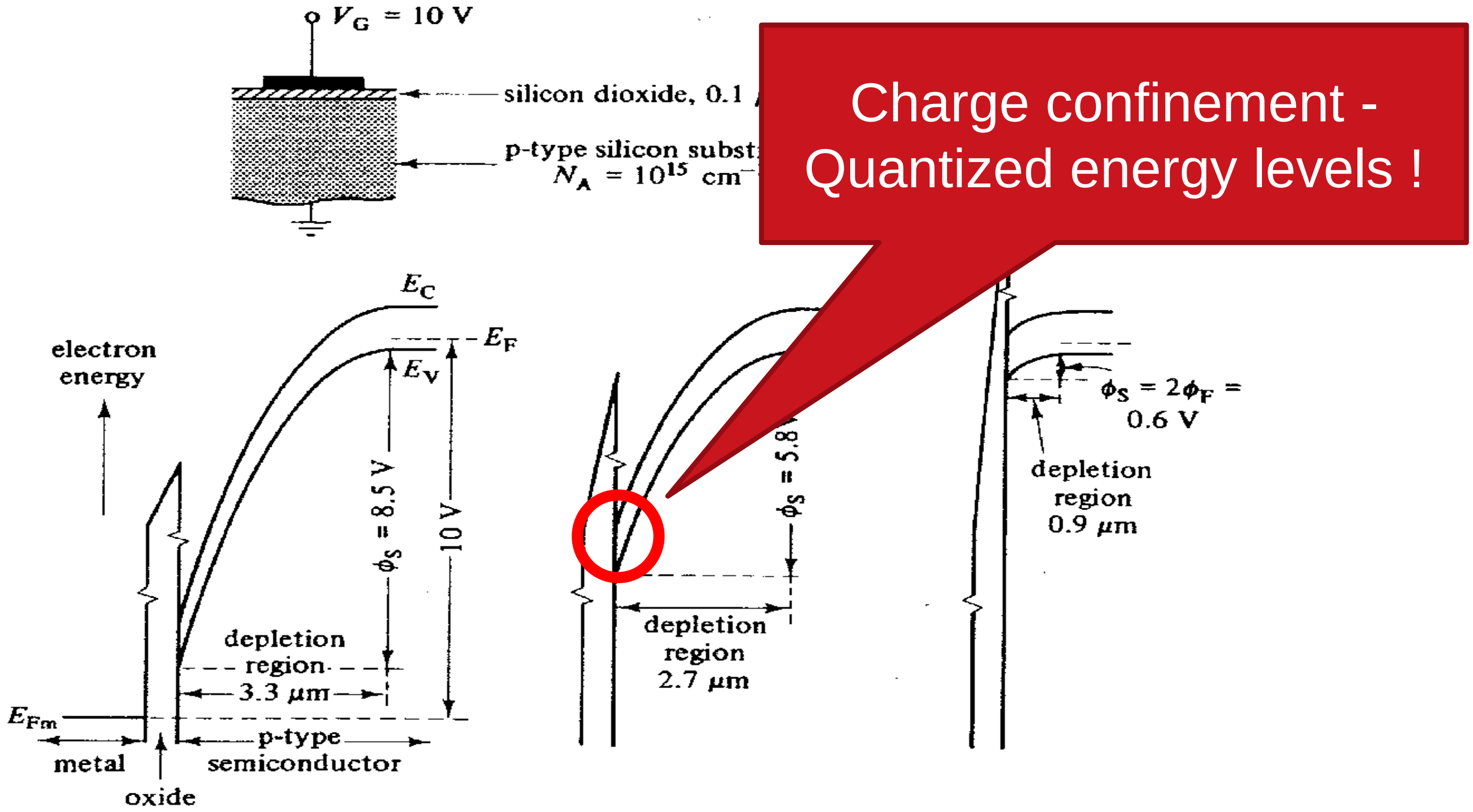
PCT Pub. Date: **May 22, 1998**

OTHER PUBLICATIONS

T. Ando, "Inter–Subband Optical Absorption in Space–Charge Layers on Semiconductor Surfaces" *Z. Physic B,* 26, pp. 263–272 (1977).
Ryzhii V: "An Infrared Lateral Hot–Electron Phototransistor" Semiconductor Science and Technology, vol. 9, No. 7,

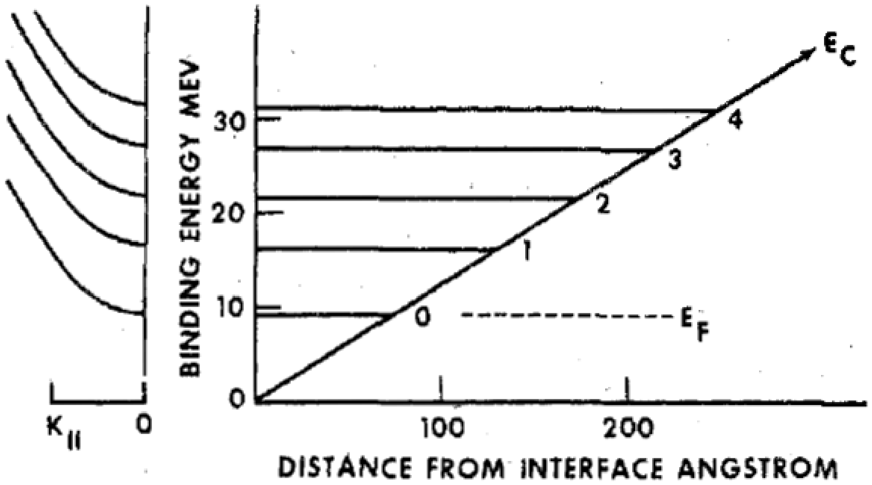


Potential Distribution In A (Silicon) MOS Structure



Fully depleted (10V) **Potential well 1/3 full** **Thermal equilibrium**

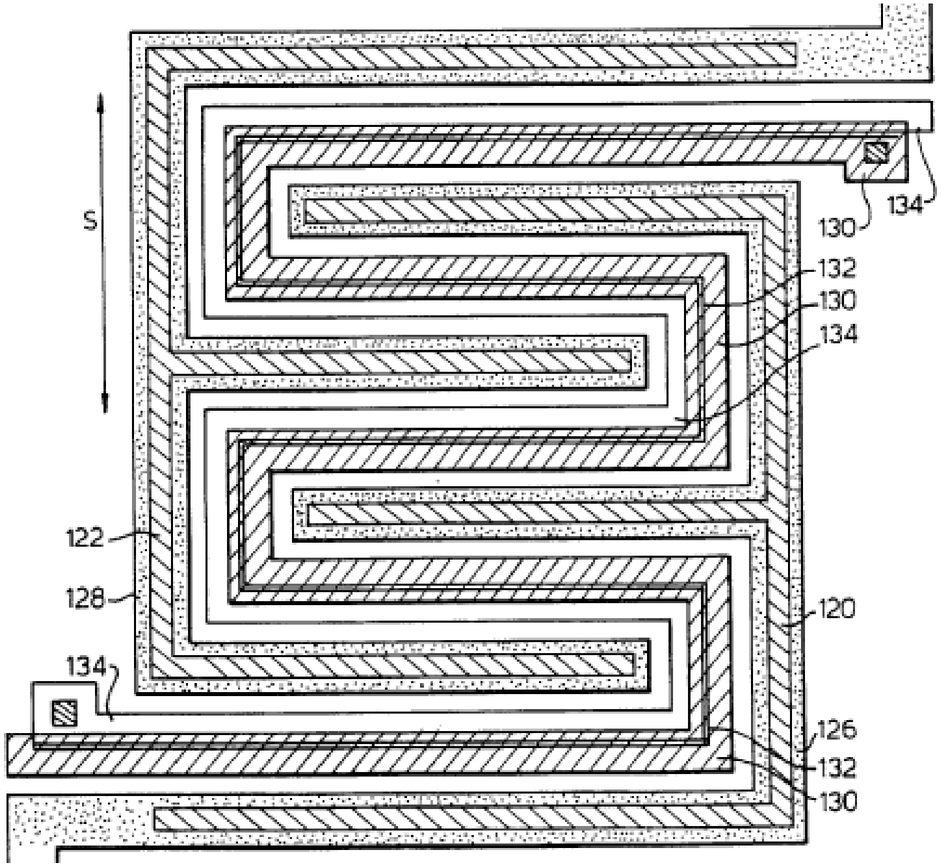
Silicon-Based Inter-Subband Voltage-Tuneable Infrared Detectors



Energies of the lowest four electric subbands for a 001 silicon surface whose p-type substrate contains 4.5×10^{14} acceptors/cm^3 uniformly distributed. The ellipsoidal nature of the electron conduction bands implies two possible m_z values leading to two discrete electric band ladders. Since transitions between states derived from different mass are forbidden in the dipole approximation, the diagram does not show the light mass ladder.

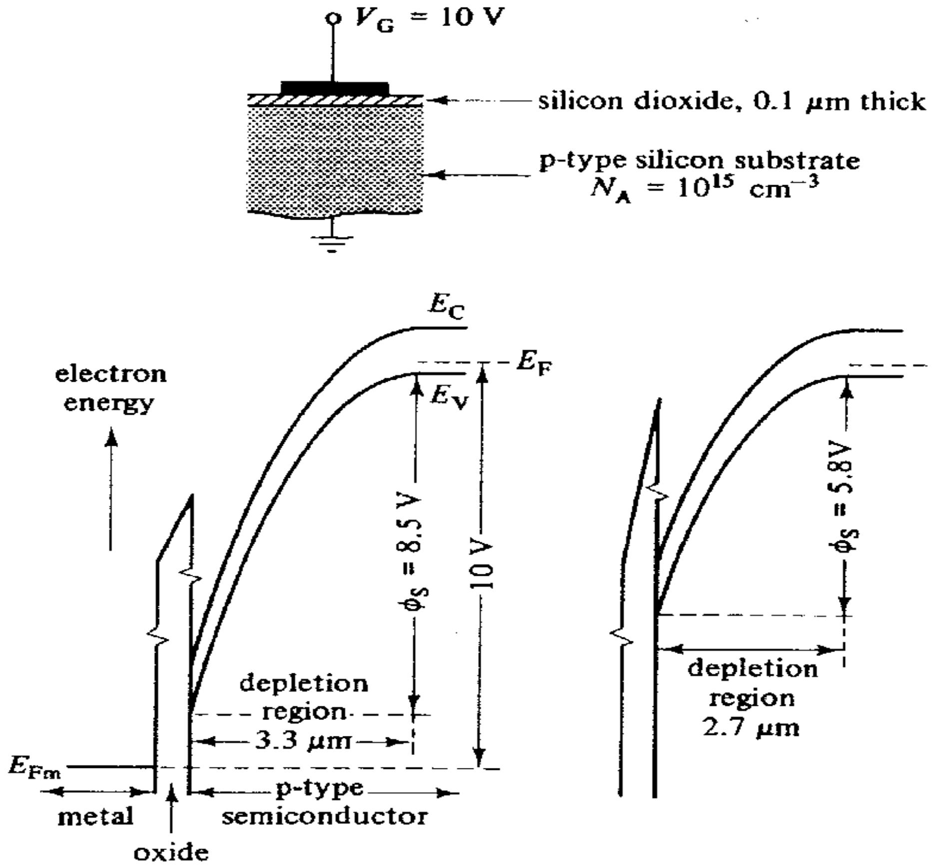
R. G. Wheeler and H. S. Goldberg, ''A Novel Voltage Tuneable Infrared Spectrometer-Detector'', IEEE Trans ED-22 (1975)

Silicon-Based Inter-Subband Voltage-Tuneable Infrared Detectors



C.J. Anthony et al. (Qinetiq), "Infra-Red Detector", US Patent No. 6,420,707 B1, 2002

Inter-Subband Voltage-Tuneable Silicon Infrared Detectors



Fully depleted (10V) **Potential well 1/3 full**

Potential slope dV/dz (max. electric field) at silicon/oxide interface:

$$E_{max}=\sqrt{\frac{2q}{\varepsilon_0 \varepsilon_{Si}} N_S V_G}$$

V_G : Gate voltage
N_S : Substrate doping

Device design and Si technology !

Affordable Solid-State Infrared Photodetection and Image Sensing


2. Photonics Research and Innovation Challenges 61

Photonic technologies can help retailers and customers to judge the ripeness of fruit and vegetables, and so reduce the percentage

and condensed phases. Finally, the far infrared and THz region (up to 1000 µm) offers complementary fingerprinting capabilities using specific spectral signatures, with the additional benefit of deep penetration in standard packaging materials such as paper, plastics or textiles.

Some of these critical measurements in the extended infrared (EIR) spectral domain (1–1000 µm) can be performed today, albeit with very expensive active and passive photonic components. For example, a moderate-power MIR laser costs €10,000, an uncooled FIR bolometer camera costs at least €50,000, a 128x128 NIR image sensor (InGaAs) costs €4000, a single photodiode (InAsSb) for the 1–5 µm band costs €1000, and even a single silicon microlens (for wavelengths above 1.1 µm) costs €50. Clearly it is not currently possible to realise

conductor materials, offeri… EIR properties.
- CMOS-based charge det… low-noise/low-power/hig… formance that can be … classes of semiconduct…
- novel measurement te… beneficial properties … EIR detectors for ind…
- affordable non-toxi… (in particular thermo-elec… EIR photo-sensing and light … forms
- a wide range of l… assive optical components, to enab… integration of complete EIR systems.

The overall goal is to conquer the EIR spectral range with a complete toolbox of low-cost active and

The overall goal is to conquer the EIR [*Extended Infrared Spectral Range*] with a complete toolbox of low-cost active and passive photonic devices [*100x cheaper*] …

Thank you very much!

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