Single Photon Imaging

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1. Introduction

Electromagnetic radiation can be successfully modelled as a stream of particles with zero rest-mass, the so-called photons. For this reason, the holy grail of image sensing is a two-dimensional array of photodetectors, capable of sensing each individual incident photon. Despite the simplicity of this demand, it is surprising to realize how many different solutions to the single-photon imaging problem exist today [1]. The present work provides a concise categorization of the various single-photon imaging techniques, offering a systematic approach to the methodical selection of the optimum single-photon imaging solution for given boundary conditions.

2. Solid State Photosensing

Because of their superior sensitivity and stability, only solid state photosensors are considered here, either in the form of a metallic or a semiconducting material. In both cases, the energy of incident photons is employed for the creation of mobile charge carriers, see also Fig. 1. If the energy of an incident photon is larger than the so-called work function E_W of a metallic material, then an electron can be removed from the material surface for subsequent detection. In the case of a semiconductor, the incident photon's energy must be larger than the bandgap E_G for the creation of a mobile electron-hole pair, which can be subsequently detected. If a semiconductor is employed as photocathode, the total energy E_G+E_A is required to lift an electron from the edge of the valence band to the vacuum level. E_A is called the electron affinity.
The first class of solid state photosensors includes a large family of photocathode materials whose properties have been carefully tuned for low work function, low dark current density and high quantum efficiency [2]. Obviously, the ubiquitous CCD and CMOS image sensors belong to the second class of solid state photosensors.
The performance of a photosensor is described by three main parameters:

- Quantum efficiency, defined as the fraction of free or mobile charge carriers created per incident photon. The quantum efficiency tends to zero (the material starts to become transparent) once the energy of the incident photon falls below E_W or E_G
- Dark current density, describing the number of free or mobile charge carriers per surface area and per unit time, created due to thermal excitation under dark conditions.
- Electronic charge detection noise, defined as the input-referred charge noise of the electronic circuit employed for the detection of the photogenerated free or mobile charge carriers.

3. Dark Current Density

In a semiconductor, the dark current density j_{dark} consists of three major parts, see [3] and [4]: the recombination current j_{rec} in the space charge region, the diffusion current j_{diff} describing the thermal generation of charge pairs within a diffusion length from the space charge region, and the surface dark current density j_{surf} generated by traps at the semiconductor-oxide interface:

$$j_{dark} = j_{rec} + j_{diff} + j_{surf} = \frac{q\,n_i}{\tau} w + \frac{q\,n_i^2 D}{N L} + q\,n_i\,S \qquad (1)$$

with unit charge q=1.602×10^{-16} As, intrinsic carrier concentration n_i, width of the space charge region w, generation lifetime τ, diffusion constant D, doping concentration N, minority carrier diffusion length L and surface generation velocity S.
The intrinsic carrier concentration n_i depends exponentially on the bandgap energy E_G and the inverse absolute temperature $1/T$:

$$n_i \propto T^{\frac{3}{2}}\, e^{-\frac{E_G}{2kT}} \qquad (2)$$

The thermionic emission j_{met} from a metallic surface, however, exhibits a different temperature dependence [5]:

$$j_{met} \propto T^2\, e^{-\frac{E_W}{kT}} \qquad (3)$$

Finally, the thermionic emission from the surface of a semiconducting photocathode is given by [5]:

$$j_{sem} \propto T^2\, e^{-\frac{E_G+E_A}{2kT}} \qquad (4)$$

In Fig. 2, the lowest dark current densities known to the author for various photodetector materials at 25^{0}C are plotted as a function of the bandgap energy E_G. The materials include silicon [6], germanium [7], InGaAs [8] and the two photocathode materials S-20 and S-24 [5]. The straight line corresponds to the exponential energy dependence of the intrinsic carrier density n_i, as described by Eq. (2), and the vertical offset has been chosen so that the line crosses exactly the measurement point for silicon [6].
The main conclusion from this graph is that very low dark current densities (below fA/cm^2) can be achieved at room temperature, provided one accepts a lower wavelength cutoff and one is willing to employ detection methods involving photocathodes.

4. Electronic Charge Detection Noise

Today it is believed that the ultimate precision with which an electronic circuit can determine the size of a charge packet is limited by thermal (Johnson) noise in the channel of the circuit's input transistor. Provided that this circuit is carefully designed and makes use of suitable correlated multiple sampling (CMS) techniques, the ultimate charge detection noise σ_Q is given by [9]

$$\sigma_Q = C\sqrt{\frac{4kT\,B\alpha}{g_m}} \quad (5)$$

with the effective input capacitance C at the gate of the input field-effect transistor, Boltzmann's constant k = 1.381×10^{-23} J/K, bandwidth B, transconductance g_m and a constant α of the order of one, whose actual value depends on the operation characteristics of the transistor.

As described in the book chapters by Seitz and by Fowler in Ref. [1], image sensors with sub-electron charge noise at room temperature and at video frame rates have been demonstrated. This was achieved with commercially available CMOS processes by reducing the input capacitance C to a minimum and through careful "bandwidth engineering" with an optimized bandwidth B. It is expected that further refinement of these techniques will soon make it possible to achieved charge detection noise levels of a few tenths of an electron.

5. Requirements for Single Photon Imaging

Reliable detection of a single photon incident on an image sensor is only possible if three conditions are satisfied:

(1) The quantum efficiency needs to be close to 100%, ensuring that all incident photons are really converted into charge carriers; (2) The dark current density must be so low that the probability of thermally generating a charge carrier is much lower than photogeneration; (3) The electronic charge detection noise must attain such low values that the probability of an error (reporting a pixel charge where there was none, or failure to report a pixel charge where there was one) is sufficiently close to zero.

These requirements and their effects on an image are schematically illustrated in Fig. 3.

6. Taxonomy of Single Photon Image Sensors

In Fig. 4, a taxonomy of solid-state image sensors with single photon resolution is given. The following acronyms are employed, most of which are explained in detail in Ref. [1]:

CCD = Charge Coupled Device; CMOS = Complementary Metal Oxide; CIS = CMOS Image Sensor; EBCCD = Electron Bombarded CCD; EBCIS = Electron-Bombarded CIS; hAPD = Hybrid Avalanche Photo-Diode Array; MCP = Micro-Channel Plate; hPMT = Hybrid Photo-Multiplier Tube; EMCCD = Electron Multiplying CCD; SPAD = Single-Photon Avalanche Photo-Detector; SiPM = Silicon Photomultiplier (synonymous with APD array); BWE = Bandwidth Engineering; SF = Source Follower; DG-FET = Double-Gate Field-Effect Transistor; CMD = Charge Modulation Device; BCMD = Bulk CMD; GainPix = Pixel-level Gain stage; PixAmp = Pixel-level Amplifier; PixCM = Pixel-level Current Mirror; sCMOS = Scientific CMOS; SkCCD = Skipper CCD; SC-on-CMOS = Semiconductor on CMOS.

7. The Single Photon Imaging Selection Flowchart

The demands and boundary conditions in single-photon imaging problems are so diverse that no panacea solution exists. The various technological approaches shown in Fig. 4 and described in detail in Ref. [1] are all successfully employed in their specific application domains. As a guideline to the selection of an appropriate single-photon imaging technology, the flowchart in Fig. 5 is proposed. The main parameters for the selection are the energy E of the incident photons, the photosensitive area A of a single pixel and the typical exposure time t during which a decision is sought "has a photon arrived?". The relevant parameter is the product At, since it determines the number N of thermally generated electrons by the 10 μm^2s dark current density j_{dark} during the time t:

$$N = j_{dark}\, q\, At \quad (6)$$

As an example, a dark current density of 0.1 pA/cm^2 and an At product of 10 μm^2s correspond to N=0.062 photocharges thermally generated during the exposure time.

8. Conclusions and Outlook

Semiconductor technology for image sensors – in the form of CIS and CCD processes – has made impressive progress over the past few decades, bringing dark current densities close to their physical limits. Since this is of the order of 0.1 pA/cm^2 for silicon at room temperature ([4], [6]), single-photon imaging applications in the vis/NIR spectral range demanding At products of more than 10 μm^2s are not expected to find monolithic solutions soon. Rather, as suggested in Fig. 5, hybrid techniques making use of photocathode materials in vacuum devices will still be required in these applications for quite some time.

References

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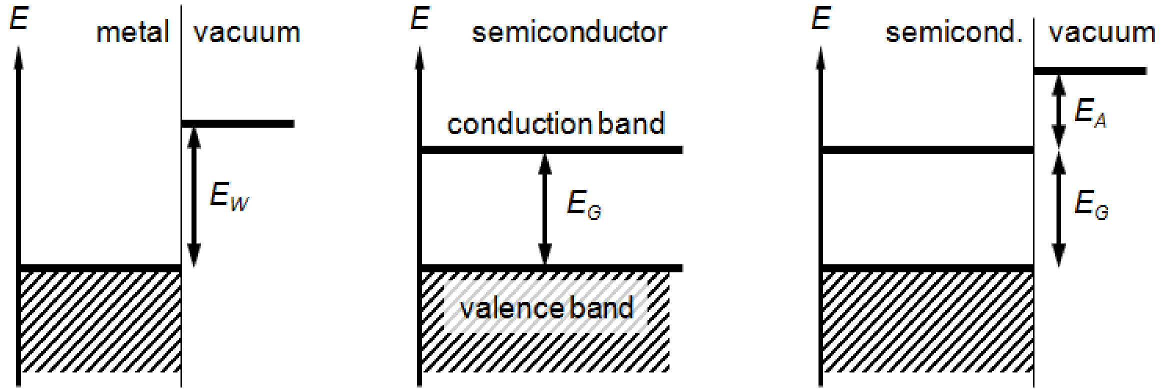


Fig.1: Energy model for solid-state photosensors implemented with (a) a metallic photocathode, (b) a semiconductor and (c) a semiconductor photocathode

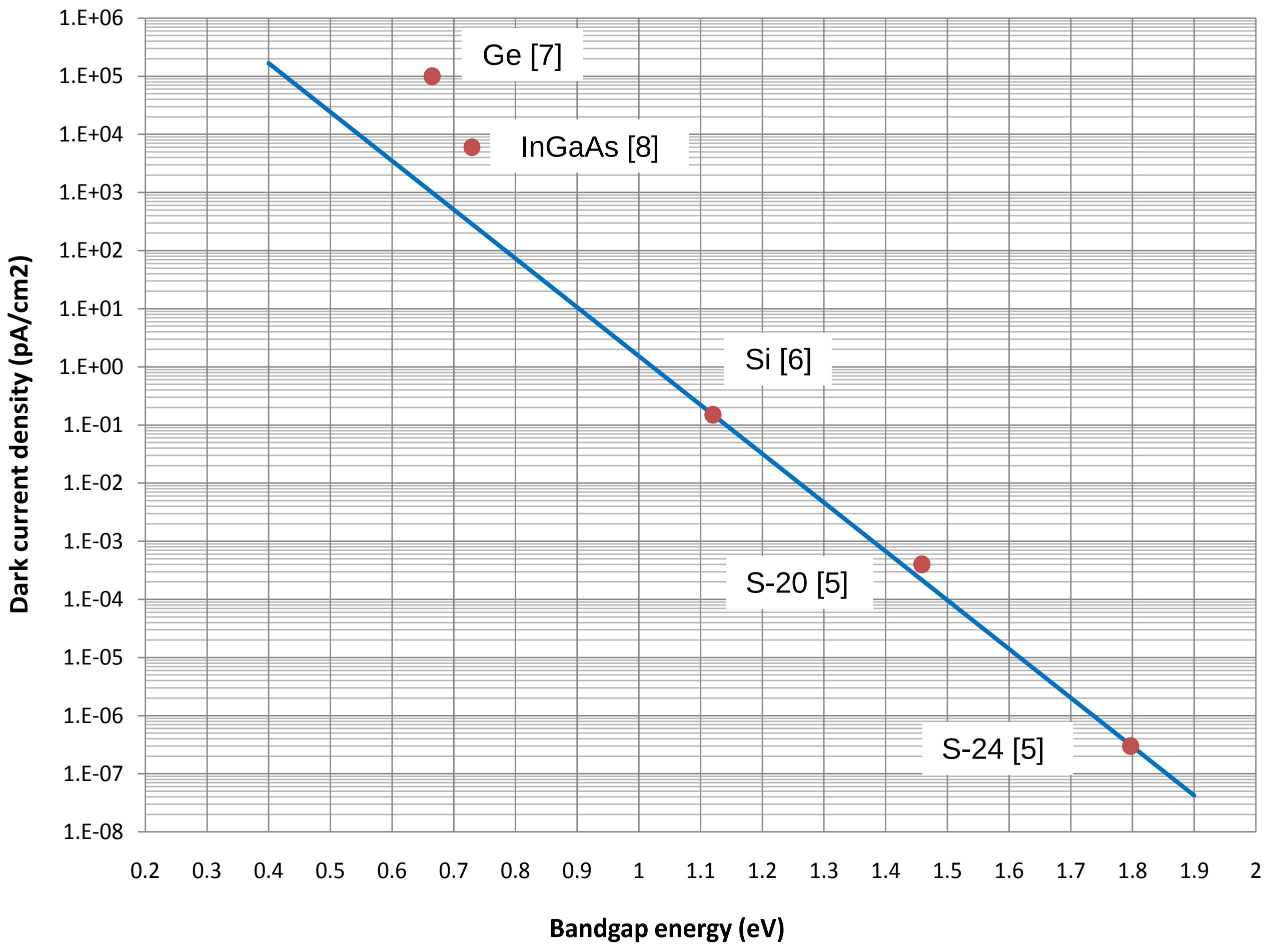
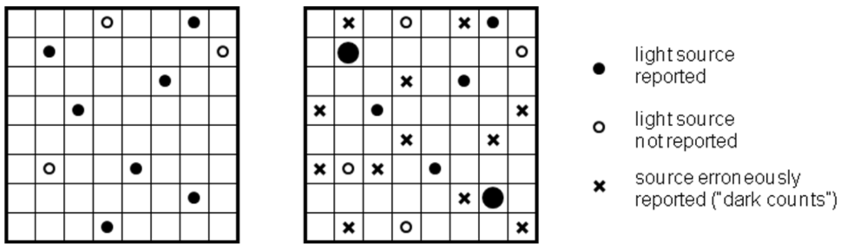


Fig. 2: Dark current density of various semiconductors and photocathodes used in photosensing at ambient temperature (25^{0}C) as a function of bandgap energy. Dots represent the lowest achieved values in literature (for details, see text) and the line corresponds to the energy dependence of the intrinsic charge density n_i; the vertical offset has been chosen such that the measurement value for silicon lies exactly on the line.

Fig. 3: Illustration of the effects of the three main performance parameters quantum efficiency, dark current density and electronic charge detection noise



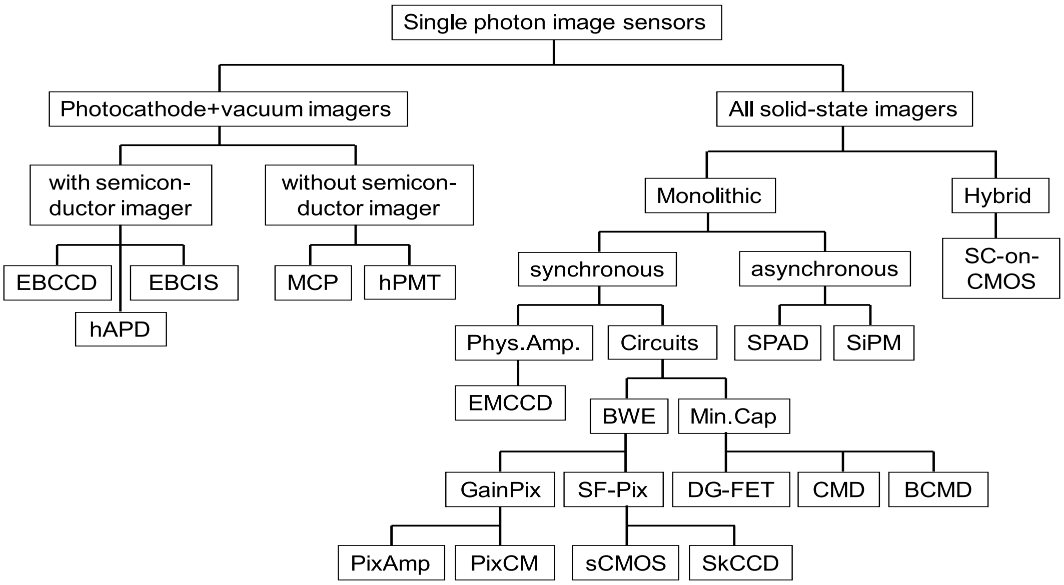


Fig. 4: Taxonomy of solid-state image sensors with single-photon resolution capability

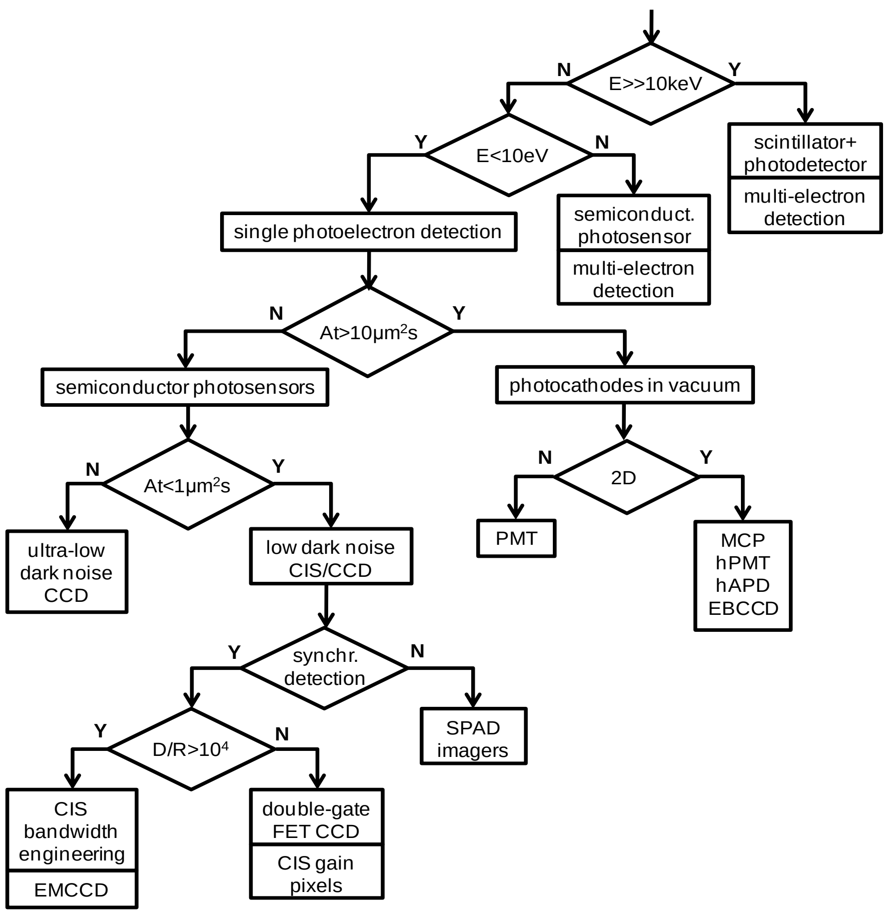


Fig. 5: Flowchart for the selection of an appropriate photosensor technology with single-photon resolution, depending on the photon's energy *E* and the product *At* of the photosensitive area *A* times the typical exposure time *t*.