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Photodetectors, Their Performance and Their Limitations*

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Abstract. With the human eye as a reference, a short survey of man-made photodetectors is given. The smallest number of detectable photons and the "detectivity" of present-day detectors, both as a function of the wavelength, are discussed in more detail. Finally, some special comments on the performance of photoconductive detectors are made since they are at present the most sensitive detectors for middle and far infrared radiation.

Index Headings: Photodetectors – Infrared

1. The Human Eye

The human eye, of course, is the most important photodetecting and imaging device for mankind. Therefore, when comparing the performances of man-made photodetectors the human eye is a good reference.

As a photodetector:

its threshold sensitivity is close to the photon limit, approximately 10 to 100 photons;

its sensitivity scale is nearly logarithmic through more than 12 orders of magnitude;

its spectral sensitivity matches extremely well with the daylight spectrum;

its time resolution of about 0.1 s fits very well to daily life necessities in the pre-technical age.

As an imaging device:

its spatial resolution is about 1 minute of arc which is slightly worse than the diffraction limit;

its contrast-threshold is about 1% which is close to spatial photon noise for vision at low illumination levels.

Hence, except for the time resolution it is the physics of light waves and photons which imposes the limits for the performance of the human eye – a most impressive result of evolution.

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2. Man-Made Photodetectors

Most of the modern photodetectors are photoelectronic. The photoemission of electrons out of a solid into the vacuum, the photovoltaic effect in space charge layers of semiconductors, and the photoconductivity of semiconductors and insulators are the most commonly used phenomena.

Typical properties of those detectors are presented in Table 1, the given values indicate the order of magnitude only. Time-dependent signals must not vary quicker than the response time τ in order to be detected correctly. That is its verbal definition. Thus $1/\tau = \Delta\omega$ is the bandwidth of a transmission line which can be handled by the detector. – An absorbed photon causes exactly one electron transition, thus the "gain" of the primary process is unity in all cases. If the observed value is smaller electron transition are involved which do not give rise to a photoelectric effect. For good detectors which are only illuminated in their sensitive area with light of the proper wavelength, this quantum efficiency uses to be larger than 10% and may approach nearly 100%. Since the human eye can detect some 10 photons its quantum efficiency amounts to several percent. – Except for high energetic photons each of which may induce many photoelectronic transitions by secondary processes, large gain figures are always due to a built-in amplifier which, of course, requires an extra battery. That is obvious in multi-

Table 1. Internal gain and response time of typical photodetectors

Detector	Response time [s]	Gain
Photoemissive:		
diode	10^{-11}	1
multiplier	10^{-10} to 10^{-8}	10^6
Photovoltaic:		
p-n, *p-i-n*, and metal-semiconductor junction	10^{-11} to 10^{-10}	1
junction and fieldeffect phototransistor	10^{-8} to 10^{-7}	10^2
avalanche diode	10^{-10}	10^4
Photoconductors:	$\lesssim 10^{-3}$	10^5

pliers and in the amplifying photovoltaic devices. Some comments on the gain in photoconductors will be added in Section 5.

The sensitivity scale, i.e. the output signal versus the incident radiation flux, is linear to a good approximation through some orders of magnitude for all good photoelectronic detectors. – In photoemissive devices at high illumination levels deviations from a linear response may occur by limited emission from compound photocathodes or by space charge effects in multipliers. – In photovoltaic devices it is the short-circuit current only which is proportional to the radiation flux. If the current becomes large at high illumination levels, the circuit resistance most of which uses to be internal resistance of the detector, causes the current to increase sublinearly. Actually the open-circuit voltage of a photovoltaic device is a logarithmic function of the input signal to a good approximation. – From the physics of photoconductors their conductivity may depend on the illumination level in a quite complicated manner. Nevertheless a linear response through some orders of magnitude can be obtained by proper dopings.

For completeness the photoelectromagnetic effect should be mentioned, too, which is the occurrence of a transverse voltage due to the ambipolar diffusion of photogenerated electron-hole pairs from the surface into the bulk of a semiconductor in the presence of a magnetic field. This effect is applied in some types of photodetectors but they seem to be less important than has been expected initially.

Really competitive with the common types of photoelectronic detectors, however, are thermal detectors which provide an electric output signal. Thermocouples and bolometers (i.e. resistance thermometers) are standard detectors for infrared radiation. At low temperatures the sensitivity of bolometers increases considerably. Superconductive bolometers operating at the transition temperature have been applied successfully in some cases. According to advertisements silicon bolometers are the most sensitive detectors at all for wavelengths larger than 1 μm – provided, however, that their temperature is about 1.5 K which is a rather inconvenient requirement. – Much work is being done on pyroelectric radiation detectors which operate at room temperature. At present they are still inferior to most of the commonly used detectors. But from theoretical reasons it is expected that their sensitivity can be increased considerably. – Thermal infrared detectors at room temperature may finally be as sensitive as photoelectronic detectors at low temperature. Furthermore, their sensitivity is independent of the wavelength of the radiation. That, of course, are their basic advantages.

3. The Number of Detectable Photons

This section is a short summary of what has been achieved with man-made photodetectors. In Fig. 1 the smallest number of photons which can be detected is shown schematically as a function of the wavelength and of the photon energy. Single photons can be detected if their energy is larger than several eV. Obviously, no more than this quantum limit can be achieved. At long wavelengths the thermal limit is the borderline. The detector requires an energy kT for a signal which is equal to noise. Hence the minimum number of detectable photons increases proportional to the wavelength which is reciprocal to the energy of a single photon.

Forgetting the two maxima in Fig. 1 for a moment, it is the infrared regime only where the present state of art is really not satisfactory (to the author's opinion the sensitivity of present infrared detectors is even worse than according to Fig. 1). The reason is obvious: In the infrared regime the photon energy is so small that a photon cannot be detected as a single event. On the other hand, coherent amplifiers which make it easy to approach and even to go beyond the thermal limit, are only available for radio frequencies but not yet for the infrared regime.

The two maxima in Fig. 1 are examples of how much can be achieved by coherent detection. It is well known that repeated signals which are buried in noise can be detected by mixing them with reference signals. Superheterodyne detection, lock-in amplifiers, and cor-

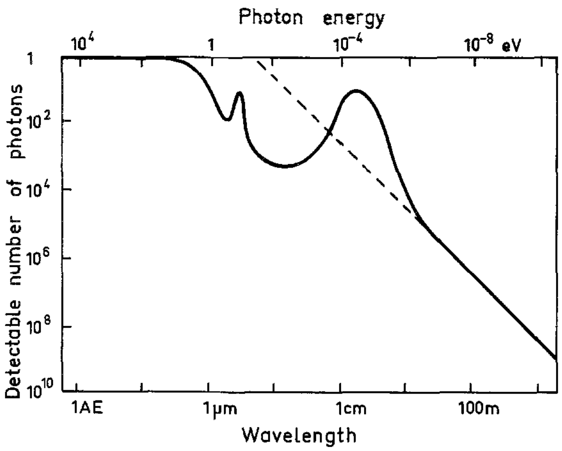

Fig. 1. The smallest number of photons which can be detected with present devices, as a function of wavelength and photon energy. Redrawn from [12], p. 363, originally due to C. H. Townes

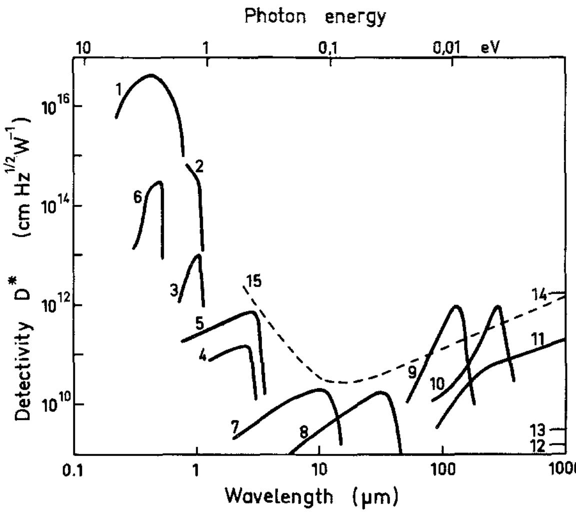

Fig. 2. Spectral detectivity of present photodetectors. Compiled from many review articles and advertisements. The numbers in this figure are explained in Section 4

relators are widely used for that purpose. Actually the long wavelength maximum in Fig. 1 indicates achievements by such techniques in long range radar, in radio astronomy, etc. The other maximum in Fig. 1 at 10 µm is concerned with coherent detection by mixing radiation from a CO_2-laser with doppler-shifted scattered radiation. Again the sensitivity is much larger than for incoherent detection at this wavelength. That is the reason for intensive efforts in many places to develop coherent infrared detection into a routine method.

4. Spectral Detectivities

The spectral sensitivities of present-day photodetectors for wavelengths between 0.1 µm and 1 mm are collected in Fig. 2 which has been compiled from a rather large number of publications and advertisements. The "detectivity" D^* as a function of wavelength is plotted to characterize the different detectors.

For a detector with an output signal V_s which is proportional to the incident radiation power P the "responsivity" V_s/P is a straightforward figure of merit. The smallest detectable signal, however, depends on the noise of the detector, too. In important cases the rms noise output V_n is proportional to $(A \cdot \Delta f)^{1/2}$ where A is the sensitive detector area and Δf the bandwidth of the detector. Therefore it is common practice to compare the responsivity V_s/P of a detector with its normalized noise $V_n/(A \cdot \Delta f)^{1/2}$. By definition the detectivity is the ratio of both:

$$D^* = V_s \cdot (A \cdot \Delta f)^{1/2} / V_n P \quad [\mathrm{cm\,Hz^{1/2}/W}]\,. \tag{1}$$

Obviously, $1/D^*$ is the normalized radiation power which generates a signal-to-noise ratio $V_s/V_n = 1$. At $\lambda = 0.5$ µm the detectivity of the dark adapted human eye is of the order of $D^* \simeq 10^{17}$ cm Hz$^{1/2}$/W.

In Fig. 2 curve *1* applies to photomultipliers with an alkali photocathode. Their detectivity and their spectral sensitivity are similar to those of the human eye. Hence they are the most important photosensitive devices for the visible part of the spectrum both for detection and for imaging in television pick-up tubes. Curve *2* is another example for a photoemissive device. It represents a multiplier with a III-V-compound photocathode. Its detectivity is smaller but its infrared cut-off wavelength is significantly larger. That is a remarkable progress in the detection of near-infrared radiation. Some further progress in that respect can be expected. But photoemissive devices for the detection of middle and far-infrared radiation are out of any discussion.

Curve *3* is the only example in Fig. 2 for a photovoltaic device, it represents a silicon pin-photodiode. The curves for Ge and III-V-compounds are similar but with a maximum, of course, at the bandgap energy. Usually D^* decreases if the infrared cut-off wavelength increases. With a built-in amplifier D^* becomes larger. For Si avalanche diodes values $D^* \simeq 10^{14}$ cm Hz$^{1/2}$/W have been reported. On the other hand, because of noise the very convenient field effect phototransistors with $D^* \simeq 10^{11}$ cm Hz$^{1/2}$/W are not so well suited for the detection of small signals. – Much work is being done on the narrow-band-gap compounds $Cd_xHg_{1-x}Te$ and $Pb_xSn_{1-x}Te$. These materials are considered to be the best candidates for photovoltaic devices which can detect middle-infrared radiation especially in the "atmospheric window" around $\lambda \simeq 10\,\mu$m. Detectivities which are quite similar to curve *7* in Fig. 2 have been reported, but at present all commercially available detectors for that regime are still Ge photoconductors.

Now turning over to photoconductors curves *4* and *5* in Fig. 2 represent commercial PbS photodetectors, curve *4* for room temperature and curve *5* for 193 K. These two curves are an example how the detectivity increases with decreasing temperature. The temperature dependent noise of these detectors is the main reason. Actually any photoelectronic detector for the middle- and far-infrared spectrum must be operated at low temperatures. Otherwise the photoelectronic processes would be masked completely by thermal excitations. – For comparison curve *6* represents CdS which is perhaps the best known of all photoconductors. Its detectivity at room temperature is in fact much larger than that of any other commercial solid state photodetector. At lower temperatures, however, similar values of D^* can be obtained with Si or Ge if care is taken that the photogenerated minority carriers are not swept out of the sample by the applied electric field. Deep traps in compensated material or a high frequency ac-bias are suitable means.

The examples in the preceding paragraph were concerned with intrinsic photoconductivity which is due to the photogeneration of free electron-hole pairs. In contrast curves *7–10* represent impurity photoconduction which arises from electron transitions between localized levels and a band. Thus free majority carriers only are generated by the absorbed photons. In the examples curve *7* (Ge : Hg at 28 K) and curve *8* (Ge : Zn at 4.2 K) deep levels from special dopings are involved, their energetic distance from the majority carrier band determines the long wavelength cut-off. In curve *9* (Ge : Ga at 4.2 K) and curve *10* (GaAs at 4.2 K with no comment on the doping in the advertisement) the commonly used conductivity dopings provide the localized states which are shallow levels and hence give rise to very long cut-off wavelengths.

A magnetic field adds new possibilities for operating a photoconductor. The photoelectromagnetic effect has already been mentioned above. – In the presence of a magnetic field photogenerated free carriers can be detected by cyclotron resonance. That is by no means an exotic method. On the contrary, it is an excellent method to avoid carrier sweep-out and thereby increase the detectivity considerably. Furthermore, the Zeeman effect of the localized states and the Landau splitting of the free carrier band introduce new electron transitions at smaller energies. By these means radio frequency radiation beyond 1 mm wavelength has been recorded with photodetectors. Curve *11* in Fig. 2 as an example represents an InSb photodetector operated at 1.5 K in a magnetic field of 7 kG. Actually, curve *11* is also an example for a third type of photoconductivity, namely free carrier photoconduction. It arises from transitions of free carriers between states in which their mobility differs strongly.

For completeness detectivities of thermal detectors which are independent of the wavelength are indicated on the right-hand scale in Fig. 2. They apply to the Golay cell (curve *12*), a triglycine sulphate (TGS) pyroelectric detector (curve *13*), and a Si bolometer at 1.5 K (curve *14*), respectively. Finally the broken line (curve *15*) in Fig. 2 denotes the detectivity of an ideal photoconductive detector if photon noise from a thermal background radiation at 300 K out of a solid angle 2π were the only source of noise.

Summarizing the contents of Fig. 2 one arrives at two conclusions: 1) The smallest detectable radiation power is still larger by orders of magnitude in the infrared than in the visible part of the spectrum. 2) At present photoelectronic solid-state devices are the most sensitive infrared detectors, more specifically photoconductors for the middle and the far-infrared regime. Therefore some special comments on the performance of photoconductors should be added in the final section.

5. Some Special Comments on Photoconductive Detectors

It is the photogeneration of free electrons and/or holes which increases the conductivity of a photoconductor. If nothing else would occur the response time τ of the photoconductor would equal the recombination life time of the electrons and holes. Actually, however, things become much more complicated by trapping and because of sweep-out of the charge carriers by the electric field which must be applied in order to measure the conductivity. As an example consider a photoconductor with contacts which are blocking both for majority and for minority carriers. Then obviously the highest achievable gain is "1". If both contacts are ohmic which replenish each swept-out carrier, in order to avoid space charges "secondary" carriers are injected from the contacts. They increase the gain to $(\mu_{maj} + \mu_{min})/\mu_{min}$ where μ denotes the mobilities of the carriers. Finally, if the minority carriers become trapped in localized states (or if they remain localized from the beginning in impurity photoconductors) the gain increases further as τ/T. Here $T = L/v_D = L^2/\mu V$ is the transit time of the majority carriers through the photoconductor (L = electrode distance). Hence the gain increases proportional to the applied voltage V. An upper limit, however, exists for two reasons: 1) The drift velocity v_D of the majority carriers becomes constant i.e. it does no longer increase as V, if v_D approaches their thermal velocity $v_{th} \simeq (3\ kT/m)^{1/2}$. 2) Due to space charges by carrier injection (or by carrier sweep-out if the contact is emission-limited) the gain cannot become larger than τ/τ_R. Here $\tau_R = \varepsilon\varepsilon_0/\sigma$ is the dielectric relaxation time of the photoconductor under operating conditions with ε = dielectric constant, $\varepsilon_0 \simeq 8.86 \cdot 10^{-14}$ As/Vcm = permittivity of the vacuum, σ = conductivity.

A thorough discussion of all complications which arise from carrier trapping and from carrier sweep-out in a photoconductor is far beyond the scope of this paper. For more details the interested reader is referred to [8] and [11] and to the literature which is cited there. One general property of photoconductors, however, must be mentioned here: For given operating conditions L and V, the transit time T as well as v_D and τ_R which determine the upper limit of the achievable gain $G = \tau/T$, are intrinsic properties of a given photoconductor. The response time τ, on the other hand, is not. It can be varied through orders of magnitude by proper doping. Thus $G/\tau = G \cdot \Delta\omega$ which obviously is the gain-bandwidth product, is an intrinsic property of a photoconductor whereas G or $\Delta\omega$ can be manipulated for optimal performance in a given situation. That is the main advantage of photoconductors (as compared with photovoltaic detectors from the same material) if a very large bandwidth is not required.

To some extent the noise sources which determine the detectivity, can be manipulated in a photoconductor, too. The input photon noise of the signal and of the background radiation clearly are the same for all types of detectors. Hence the internal noise of a detector must be considered for a comparison. In photoconductors the generation-recombination noise of free carriers is one important contribution. Obviously it depends strongly on the kinetics of the electronic trapping and recombination processes in the photoconductor, i.e. on its doping. But so does the response time, too. Therefore in general a compromise must be found in order to obtain the desired response time and a noise minimum simultaneously.

Developments and progress in the future are hard to guess. For most photoconductive detectors the theoretical detectivity is larger or even much larger than the present experimental values. Therefore remarkable improvements can still be expected. On the other hand, thermal detectors and photovoltaic ones for the middle infrared will become stronger competitors than they are now. The long-term result of present and future developments, however, will probably be coherent infrared amplification and detection. Detectors, of course, will then still be necessary. But they are likely to be quite different from present ones. By now semiconductor point-contact diodes as well as Josephson junctions between superconductors have been tested to be fairly good coherent infrared detectors for wavelengths $\lambda \geqq 100\ \mu m$. Other types of detectors are expected to be developed, too. Obviously their performances and their limitations remain problems for the future.

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