Single photon detectors for biology: Present and future

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A summary of the status of present technology for the detection of single photons is presented with a view towards applications in biophotonics. Included are careful discussions of the numerous problems that can be encountered and how to get around them with the hope that this will be of help to biologists interested in doing work in the field of biophotonics. Emphasis is placed on traditional devices, but the field is one which is continuously developing and we review the status of new and very interesting technologies which are becoming available. The paper is meant to be fairly self-contained and assumes no extensive knowledge of the physics of photodetection.

Keywords: Biophotonics, Photodetectors, Single photon detection

Quantum field theory tells us that the classical electromagnetic fields we are accustomed to detecting as light are, if we have the right instruments, resolvable into tiny chunks, or quanta, called photons. These are remarkably subtle entities, moving always with the speed of light and carrying energy, momentum, and angular momentum which is always directed parallel or antiparallel to its direction of flight. While it is convenient to maintain a mental picture of these particles as tiny spinning balls, it is important also to realize that in many ways the image is deceptive. Photons in fact have no well-defined positions and cannot be localized in the intuitive sense that most people like to imagine for particles, but so far this is the best picture we have been able to come up with that meshes with our classical mental images of the world. A nice review is in reference1.

The smallest amount of energy that can be carried by a classical field oscillating at frequency $f$ is the energy carried by one of its photons, which is $E = hf$, where $h$ is Planck's constant: a very tiny $4.1357 \times 10^{-15}$ eV.sec. Despite the tiny amounts of energy carried by photons of visible light (typically a few eV), modern devices are quite capable of registering the arrival of these objects one at a time. In this review, we summarize what is available now to detect single photons and what we can look forward to in the future. References provided are certainly not comprehensive as that would make this review of ridiculous length, but those given should be enough for an interested reader to get started in any topic.

Good general references are the books2,3 and, as well as the websites of numerous manufacturers, a few of which are listed in4.

As a practical note, rather than summarizing device numbers and details from various manufacturers this review tries to paint a picture in fairly broad brushstrokes so that an interested experimenter knows what's available, how it works, and what to watch out for. A search on the WWW will reveal many suppliers, and they are all quite willing to help prospective customers and to explain their products in detail. They also typically provide detailed instructions suggesting how best to use their devices safely, and appropriate warnings about how to care for them. All of this is worth heeding.

Accessible energies

The equations of electromagnetism contain no quantities which correspond to energy scales, and it is possible, in principle, to have photons of any energy whatsoever. When we talk about energies of photons we tend to use eV (electron volts), but since photons correspond to chunks of field oscillating at a certain frequency, it is common to refer to a single photon as having a certain "frequency", or even a certain "wavelength". This means we co-opt the classical wave terminology even when we're talking about just one photon.

The way these photons of various energies ("wavelengths", "frequencies", if we're abusing terminology in the customary fashion) interact with matter varies dramatically, and we will specialize shortly to the case of photons of visible light. Before doing so, however, it may be interesting to quickly go...
over what single photon energies might be detectable. As far as I know, there has been no significant effect exerted in looking for biophotons of energies will outside the range of those carried by visible light, and there could be room here for interesting surprises! With that in mind, the following is a rough list of energies and prospects as they seem today:

- **Energies less than ~1 eV**
  - very hard to detect as single quanta
  - few places where the sort of small energy gap appears naturally.
  - noise is bad ($k_B T_{room}$, the energy characteristic of thermal fluctuations at room temperature, is $\sim 1/40$ eV).

- **a few eV (visible light from about 400 to 800 nm).**
  - the photoelectric effect is useful here whereby a photon directly knocks an electron out of the atoms of some suitable material. In this case the photon disappears, its energy being used to free the electron from being bound to an atom.
  - the cross section for this effect varies rapidly with nuclear charge $Z$ and photon energy $E$ ($\sim Z^2$ and $E^5$) making this the dominant effect out to ~keV.
  - in solid state devices, such photons can cause electron-hole pair creation.

- **KeV**
  - the Compton effect dominates. In this case electrons are simply kicked with an energy so great that the atomic binding of them is negligible and the process is much like one of a billiard ball (the photon) hitting another billiard ball (the electron) resulting in both of them flying off. Unlike the case of the photoelectric effect, the photon is still there after the collision, although its energy and momentum will in general have changed.

- **MeV and up**
  - photons carry enough energy to make electron-positon ($e^- e^+$) pairs provided there is an atomic nucleus against which to recoil. While this process dominates, photonuclear reactions are also possible.

**Photomultipliers (Fig. 1)**

Photomultipliers, or "PMT's" as they are often called, are the traditional workhorses of single photon detection, and are based on ingenious use of the photoelectric effect, together with an analogous effect where an electron impinges on a metal surface and knocks loose several more. This latter process is called "electron multiplication", from which the name "photomultiplier" is then derived.

As cast array of geometries is possible, but the design is always pretty much based on the following basic principles:

- You get an evacuated glass tube with a transparent window allowing light to hit a suitable material which forms what is called the "photocathode".
- The photocathode is a material which binds electron to its atoms weakly enough so that light of the interesting wavelengths can release electrons from it. It is biased with a negative voltage relative to the rest of the tube to ensure that electrons which are knocked out of the photocathode are repelled and get away from the surface.
- Nearby, another electrode of a similar material, called a "dyode" is biased at a somewhat more positive voltage than the photocathode. The idea is that electrons liberated from the photocathode will be drawn towards it by the electric field between the two and gain enough energy to be able to knock loose several "secondary" electrons.
- Repeated dynode stages biased at consecutively more positive potentials produce multiplications so that after, say, 7 stages with multiplications of about 10, one finds that one single electron liberated from the photocathode will produce $10^7$ electrons at the end. This signal may now be large enough to be detected with standard electronics and amplified into a measurable pulse which

![Fig. 1 — Schematic diagram of a PMT showing electron multiplication at the first few dynodes. The photocathode is negatively biased and each dynode must be biased to a higher positive potential than the previous one. The output signal appears at the anode.](image-url)
corresponds to the arrival of a single photon at the photocathode.

Having discussed in rather general terms how photomultipliers work, let us now look in a little more detail at the various bits and pieces that make them up.

Biologists may find it interesting to note that photomultipliers act in many ways like living things. There is a wide "zoology" of them, and they exhibit many lifelike features: they can be wounded, they can heal, they get old, and eventually they die!

Spectral Sensitivity and Quantum Efficiency

In the absence of noise (a very important subject to which we will return later) there are two obviously important things you need to know about a PMT before you worry about anything else:

- Given an incident photon of a given wavelength, what are the odds that it gets detected - that is, that it produces an output signal?
- How big is the output signal for an incident photon that gets detected?

The spectral response of a PMT is determined primarily by:

- photocathode material (at large \( \lambda \)) and
- window material (at small \( \lambda \))

The idea is that at long wavelengths, photons carry so little energy that it's hard to find a photocathode material whose electrons are loose enough that it will work. The minimum energy required to just knock an electron out with zero kinetic energy is called "work function" of the material and is an oft-quoted parameter. At shorter wavelengths you tend to run into trouble finding window materials that are transparent enough.

Spectral response is usually quoted in terms of quantum efficiency (QE), given as a function of wavelength.

\[
QE = \frac{\text{Number of photoelectrons produced}}{\text{Number of photons in}} \times 100\% 
\]

It is not often particularly high, with a couple of tens of percent being common for good PMT's. We will return to the issue of how to get high quantum efficiencies later when we discuss avalanche photodiodes.

It isn't difficult to see why very high quantum efficiencies are difficult to obtain in almost any device based on a photocathode. If you make a photocathode too thick, you may find that the photons get absorbed deep in the material and photoelectrons don't make it out. If you make it too thin, photons may just pass through unabsorbed. Finally, even if you do knock an electron loose, it's a tricky business to ensure that it gets to the first stage of amplification without ever getting lost.

Another measure of quantum efficiency, is the radiant sensitivity \( S \):

\[
S = \frac{\text{Photoelectric current (A)}}{\text{Incident power (W)}} \quad \ldots (2)
\]

This is, of course, equivalent and while it lends itself a bit less clearly to the mental image of "what are the odds that a photon hitting the PMT gets detected", it is, operationally, easier to measure directly.

The Tube

The tube which encloses the photocathode and dynode structure must be able to contain an excellent vacuum, on the order of \( 10^{-5} \) Pa. (standard atmospheric pressure at sea level is over \( 10^{5} \) Pa). A poor vacuum in a PMT is bad for a lot of reasons. Gas molecules can stop electrons from reaching dynodes, reducing both sensitivity and gain. It can also give rise to additional noise, a topic to which we'll return in section 2.9.

Photocathode and Dynode Materials and Geometries

Some common choices for photocathode and dynode materials are listed below.

Photocathode materials include:

1. Cs-I: solar-blind, good for detecting vacuum ultraviolet (VUV) at \( \lambda < 200 \) nm.
2. Cs-Te: solar-blind, good for detecting VUV at \( \lambda < 300 \) nm.
3. Sb-Cs: UV-visible, used often for reflection type photocathodes.
4. Bialkali (Sb-Rb-Cs, Sb-K-Cs):
   - fits emission spectra of many scintillators (NaI(Tl)).
   - higher sensitivity and lower dark current than Sb-Cs.
5. High temperature, low noise bialkali (Sb-Na-K):
   - good to 175°C (usual photocathodes only good to 50°C).
   - good for low noise applications (low dark current at room temperature).
7. Multialkali (Sb-Ba-K-Cs): good from UV to IR
8. Ag-O-Cs: good from 300 nm to 100 nm but with extra IR sensitivity.
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GaAs(Cs):
- good from 300 nm to 850 nm but with sharp IR cutoff (~900 nm)
- very susceptible to damage from excess light

InGaAs(Cs): similar to GaAs(Cs) but with better IR reach (~900 nm)

There is some choice in the photocathode geometry as well, perhaps most noticeably whether the photoelectrons are ejected from the side which faces the light or the side opposite to it.

Dynode materials are usually made of alkali antimonide, BeO, MgO, GaAs or GaAsP and typically give out 5-10 electrons per incident electron, depending on voltages applied to the dynodes. PMTs can be made to work using many possible (and usually rather self-descriptive) dynode geometries, among them:

1. Linear focused: an electric field guides the electrons in nearly straight lines giving fast response and good linearity
2. Box and grid type: good collection efficiency and uniformity, but slow
3. Box and linear focused type: good collection efficiency, good uniformity
4. Circular cage type: fast, compact
5. Venetian blind type: good uniformity and pulse linearity; position detection possible
6. Mesh type: good uniformity and pulse linearity; position detection possible
7. Multichannel plates: a very novel design based on a plate with a large number of holes, or channels, coated on their inside surfaces with dynode material to make what is effectively a huge array of tiny PMT’s providing position sensitivity
8. Channel PMT’s: which are like one long tubular channel of a multichannel plate, but often with an improved snake-like geometry so that what is really one continuous dynode looks more like the usual discrete set facing each other. This design offers very easy biasing since the role of a voltage divider network to supply ever more positive voltages to later and later dynodes is played by the one continuous dynode itself.

Window Materials

There are numerous choices of window materials, including the following:

1. MgF2
   - good down to 115 nm

2. Sapphire (Al2O3)
   - good down to 150 nm

3. Synthetic silica
   - good down to 160 nm
   - less UV absorption than fused silica
   - very different thermal expansion coefficient from glass; can’t be used with Kovar (a metal alloy used for leads that pass through glass, and which has a coefficient of thermal expansion very close to that of glass)

4. UV-transmitting glass
   - good down to 185 nm

5. Borosilicate glass
   - good down to 300 nm
   - available in special “K-free” form to avoid noise from 40K β decays due to potassium normally present in glass.

It is an important fact, often forgotten or neglected, that windows can generate losses in quantum efficiency due both reflection of incident light (and this can be polarization-dependent, and depend on the angle of incidence of the incoming light, two additional factors which are also often forgotten!) as well as due the absorption of light on its way to the photocathode.

Biasing

Biasing simply means providing each successive dynode with more positive voltage than the previous one in order to make sure that electrons move from dynode to dynode and amplification takes place. It is most commonly done passively, using a chain of resistors in series which acts as a voltage divider. Each dynode is connected to the junction between two resistors. A long and detailed discussion of all the issues involved is beyond the scope of this review, but most of the important points are mentioned at least briefly below.

Two particularly important things to keep in mind are:

- The resistor chain is passive, but the PMT is most definitely not. You should be sure that the current in the divider network is at least 20 times the maximum current you expect from the tube. You may find in bright light that the gain is lower than you would have expected due to
the PMT itself loading the voltage divider network so much that the voltage across it starts to drop with an attendant loss of gain. Even if the voltage divider network is up to the job, you should also be aware that space charge effects can kick in at high tube currents and also drop the effective gain.

Capacitors across the resistors can help offset the effects of sharp pulses of current, caused, for example, by momentary exposure to brighter-than-average light. For linearity better than x%, choose
\[ C > \frac{100}{k} Q_{max}, \]
where \( Q_{max} = I_t/V \), with \( I_t \) the current in the pulse, \( t \) its width and \( V \) the voltage across the capacitor.

PMT gain is a strong function of voltage and generally grows as a power law. This is easy to see: the voltage determines the energy with which an electron will hit a dynode, and thus pretty much sets the number of electrons which will be released. Each stage of multiplication will then provide a gain which is roughly proportional to the voltage \( V \), so that the overall gain for \( n \) stages will go like \( V^n \). This means that, depending on your application, you may need to have quite a well-regulated power supply in order to avoid unacceptable gain variations. Most PMT’s will exhibit a plateau of relatively stable signal to noise (we return to this later) ratio where voltage sensitivity is reduced, and operating a tube in such a region is usually a good idea.

There are a couple of special biasing cases that are worth keeping in mind. One is the channel PMT, which requires no special voltage division network, that task being provided by the one long dynode itself. The other is the use of what is called “Cathode Potential”. The idea here is to ground the anode and have successively more negative voltages applied to the dynodes leading up to the photocathode. This may sound sort of trivial, but actually leads to some significant practical issues:

- The grounded anode makes potential difference between readout point and other things (meters, oscilloscopes, etc.). This is, in general, a good thing.
- You really have to be careful of HV between the cathode and grounded housings, shielding etc. — stray currents even through glass (!) can cause electrolysis of the photocathode, leading to flashing and noise!

A useful practical trick for doing cathode potential (grounded anode) biasing is to paint a PMT with black conductive paint (a so-called “HA coating”) and connect it to the cathode supply. This repels stray electrons from the glass so they don’t strike it and cause noise flashes—a useful and non-obvious result of what might otherwise seem like a small modification in biasing!

One final issue to keep in mind is that the timing response of a PMT is affected by the applied voltage. The speed of light is about 1 foot per nanosecond, so you can imagine that even at the speed of light, there is a delay between a photon coming out which is not necessarily negligible, depending on the application. Electrons in a PMT never get near the speed of light (they are relativistic at a few hundred thousand electron volts where their kinetic energies are comparable to their rest energy of 0.511 MeV, but in PMTs, voltages are orders of magnitude lower). The upshot of this is that, in general, higher voltages lead to faster responses.

Readout Electronics

Space considerations preclude a detailed description of the readout electronics which has to be associated to a PMT (or, for that matter, any other photodetector), but it’s something that’s worth being aware of and thinking about carefully. For single photon counting you’ll usually want to have a very high gain final output stage that “decides” if a pulse from the PMT was large enough to be considered a photon. Some issues to keep in mind are: noise generated in the electronics, drift in gain, timing, and other circuit parameters, how pulse shapes are affected, etc.

Life, Aging, and Death of PMTs

Photomultipliers don’t last forever, and there are many reasons for them to grow old and die. They can gradually lose their vacuum, but by far the main reason for tubes to fail is that they are exposed to bright light while biased. This is a very important warning! Photocathodes are usually rated for life in terms of the total current that they deliver over their useful lives. The fewer electrons you knock loose (i.e. the dimmer the light to which you expose them), the longer the PMT will last.

Even brief exposure to bright light at low gain may not destroy a PMT, but can make it behave poorly for a period of several hours and incur serious downtime in the lab. A very good idea then is to keep a shutter
in front of the photocathode ensuring that it stays in the dark as much as possible and isn't exposed to bright light unnecessarily.

Exposure to bright light at high gains can cause so much current to flow that the tube itself (not just the photocathode) will be permanently damaged.

**General Warnings**

Just as a couple of odds and ends that don't always get discussed, you should be aware that photomultipliers can be affected by both temperature and magnetic fields.

Temperature can either raise or lower the signal you get, while magnetic fields can deflect the paths of electrons in the tube and give rise to huge changes. You can get around both of these problems with temperature control (and we'll have a few more words to say about temperature later when we discuss noise) and magnetic fields can be shielded with soft (in the magnetic sense) ferromagnetic materials like mumetal. Sensitivity to magnetic fields can be largely controlled by careful tube design and may be one of the parameters that you want to look into when you're thinking of purchasing a tube for application where you think magnetic fields might be an issue.

**Noise in PMTs**

The main idea of this section is: "Just because it went click doesn't necessarily mean there was a photon!"

The following is a list of some of the numerous reasons that a signal can appear even though there was no incident photon:

1. **Thermionic emission**: As mentioned earlier, room temperature corresponds to an average thermal energy scale of about $\frac{1}{40} eV$, but this is just an average. There are fluctuations well in excess of this amount, and those that are equal to or greater than the work function can knock electrons from a photocathode or dynode just as an incident photon or electron would. This "Richardson" current, $I_{Richardson}$ is proportional to $T^2 \exp\left(-\frac{W}{k_B T}\right)$ where $W$ is the work function in eV, $T$ is the absolute temperature measured in Kelvin (i.e., degree Celsius from absolute zero, or about $-273$ C) and $k_B$ is Boltzmann's constant, $8.63 \times 10^{-5} eV.K$. Thermionic emission:
   - can be alleviated by cooling the tube if possible. This sounds nice but poses a lot of technical challenges. Rapid or non-uniform cooling can crack a PMT, and of course glass is not a very good conductor of heat. Even then, uniform and gradual cooling of materials with different coefficients of thermal expansion can lead to cracks, and cooling below the dew point can cause condensation on the PMT face, making a vacuum insulation jacket necessary.

2. **Ionization of residual gas in the PMT by photoelectrons**: This:
   - can show up as "afterpulsing"
   - can be worked around by rejecting pulses closely following a signal pulse. This is obviously a bit dangerous as one might be rejecting a physically interesting pulse that was due to a real incident photon.

3. **Glass scintillation**: 
   - which can occur when electrons hit the glass PMT envelope and make it glow,
   - gets worse at higher voltages, so reducing voltage (at the cost of gain) may help, and
   - can be minimized by operating the PMT with anode at HV and cathode at ground and possibly using the HA coating described above.

4. **Ohmic leakage**: 
   - which can contribute to constant dark current,
   - can be due to bad bases and sockets, and
   - can be worsened by dirt and humidity.

5. **Field emission**, whereby electrons are pushed out of the photo-cathode in regions where the electric field just happens to be high. This can be reduced by running the tube at least 200-300 V below its specified maximum.

6. **Radioactivity due to**
   - internal sources (components, glass) and
   - external sources (radon, cosmic rays, . . . )
   - and which may necessitate a careful choice of components and the use of shielding (which itself should not be radioactive!)

7. **Electronic noise**: 
   - since even passive devices like resistors will generate noise, and
   - you may need to minimize passive and stray impedances and try cooling electronics.
More General Comments on Noise

This section is somewhat more mathematical (following [2] than others and is meant to deal with noise in photodetectors as shown in Fig. 2 is a somewhat more general way without necessarily referring to PMTs. Here we have:

1. Current from detector $\sigma_P$ which is proportional to the incident power $P$.
2. Intrinsic (shot) noise due to photons being discrete: $I^2_{in} = 2e(I_{ph} + I_d)B$, where $I_{ph}$ and $I_d$ are the signal current (due to photons) and dark current respectively.
3. Capacitance of the detector which leads to a high frequency cutoff of $B = \frac{1}{2\pi RC}$.
4. Johnson (thermal) noise current given by $I_j = 4k_BTB / R$.

The total RMS (root-mean-square) fluctuation is then:

$$I_{rms}^2 = 2e(I_{ph} + I_d)B + 4k_BTB / R \quad \ldots \quad (3)$$

If there is a fluctuating gain $M$ with variance $\sigma_M^2$, we can introduce an excess noise factor $F = 1 + \sigma_M^2 / M^2$ so that

$$I_{rms}^2 = 2e(I_{ph} + I_d)BM^2F + 4k_BTB / R \quad \ldots \quad (4)$$

and we have a signal-to-noise ratio:

$$SNR = \frac{I_{ph}}{\sqrt{2e(I_{ph} + I_d)BF + 4k_BTB / RM^2}} \quad \ldots \quad (5)$$

These equations can be used to provide quick estimates of how noise will affect a given photodetection setup.

Photodiodes

Regular photodiodes are not well-suited to single photon detection as they lack gain and this, combined with too much noise, makes them almost hopeless as single photon detectors. That being said, in conjunction with other components (as in a hybrid photodiode) or with some design modification (as in an avalanche photodiode) they are actually quite important, so we describe them briefly here and later turn to the more complex devices which incorporate them.

A solid state diode is basically made of two abutting pieces of semiconducting material, one doped to be “n-type” so that it carries currents of electrons, and the other doped to be “p-type” so that it carries currents of “holes”. Holes are vacancies in the crystal lattice where electrons ought to have been, but which have been taken up by electron-hungry dopants added to the semiconductor. Similar doping with electron-donating dopants produces the “n-type” material. (Undoped, or “intrinsic” semiconductors conduct electricity very poorly). If the “n-type” side is connected to a negative potential and the “p-type” to a positive one, then electrons in the “n-type” material move away from the negative potential and are collected on the “p-side” and vice-versa. In this way, an electrical current flows and the diode is said to be “forward-biased”. If the electrical connections are reversed, then (in the ideal case) no current flows, all the carriers being swept out of a so-called “depletion region”. The diode is then said to be “reverse-biased”.

This radical difference in the way it behaves for two different biasings leads to the name “diode”, for “two ways”.

A photodiode is just a reverse-biased solid state diode which has been designed so that photons can reach it and liberate electron-hole pairs which then can contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current. Of course there will also be thermally a generated electron-hole pairs which then contribute to a small current.

Despite the noise, a nice feature of photodiodes is that they tend to have high quantum efficiencies simply because one avoids the loss mechanisms present in a PMT. A photon, when absorbed, produces and electron-hole pair pretty much right where it's needed to be part of the current through the device.

Hybrid Photodiodes

A hybrid photodiode (HPD) is just a regular photodiode placed in an evacuated tube with a photocathode in front of it. A high voltage (a few thousand volts typically) is applied across the device to pull...
electrons from the photocathode to the diode, and that’s all there is to it. An avalanche photodiode (discussed later) can also be used to provide additional gain.

The idea here is that single photons can liberate electrons from the photocathode as is done in a PMT, but then, rather than multiplying them in number through interactions with successive dynodes, they simply gain a large kinetic energy by passing through the potential difference between the photocathode and the diode.

These devices suffer the same sort of low quantum efficiency which is associated with devices that have photocathodes, but there is no fluctuation associated with the multiplication at each stage—each photoelectron passing through 1000 V, say, gets 1000 eV of energy and can then liberate a large number of electron-hole pairs in the diode, producing a large signal.

**Avalanche Photodiodes**

Avalanche photodiodes are essentially just reverse-biased photodiodes with a twist: a high electric field region in which carriers can gain enough energy to release new electron-hole pairs. If the electric field is sufficiently high, this process can repeat and lead to an avalanche. A schematic figure of how one particular APD is made is shown in Fig. 3. This is not the only possible design, and is the case for PMT’s, many are possible. While there are many similarities between APD’s and PMT’s, APD’s offer a number of distinct advantages:

- APD’s are quite compact devices, which require only a few hundred volts to run.
- They can be very mechanically robust, having neither bulky glass envelopes, nor a vacuum.

The single most spectacular feature of APD’s for biophotonic work is that they can offer enormous quantum efficiencies, going over 90%. This sort of performance, which is quite impossible for PMT’s or in fact any device with a photocathode, is intrinsic to their design: a photoproduced carrier is essentially already where it has to be to get multiplied!

While APD’s are just two-terminal devices, like so many other photodetectors they are amazingly subtle and complex. Their parameters, including capacitance, noise, and excess noise factor in addition to the more obvious ones such as dark current and the wavelength-dependent quantum efficiency and gain can all vary with voltage and temperature.

![Fig. 3 — Schematic picture of an APD. In applications where radiation hardness is not an issue, silicon dioxide is often used in place of the silicon nitride shown here as a window material.](image)

They can be run in either “proportional” mode, where the size of the signal depends on the number of photons incident at once, or in “Geiger” mode whereby very high gain completely saturates the device giving a huge yes/no type of signal. Geiger mode tends to be noisier and incur longer recovery times between photon detection events unless fancier techniques such as active quenching are used. A detailed discussion of such points is, unfortunately, well beyond the scope of this article, but it’s good to bear these concepts in mind.

A significant downside of APD’s is that, at room temperature, they have large dark currents (with Richardson-like temperature dependence) which make them unusable as single photon detectors unless operated in a “gated” mode where one knows just when a photon might be anticipated—rarely the case in biological experiments. Recent work has shown that this may be dramatically reduced by cooling, while retaining high quantum efficiency. Dark count rates of millihertz for active areas of a few cm² look quite feasible.

**Position-Sensitive Detectors**

There are a lot of ways to achieve some position sensitivity with single photon detectors, but they all basically come down to making a lot of little subdetectors. For example, you can:

- Replace a single anode in PMT with multiple anodes.
- Replace the single channel in a channel PMT with many making a multichannel plate.
- Replace a single avalanche photodiode with an array of photodiodes.
In a single HPD replace the photodiode with an array of photodiodes. The electrons from the photocathode go in pretty much straight (or at least, non-intersecting) lines so this works fine.

An important point to keep in mind with position-sensitive devices (and for that matter even with devices with one single detection surface) is that response is never completely uniform across the detector face. The easiest way to compensate for this is usually to do so during offline analysis of data.

**Charge Coupled Devices**

Charge coupled devices, or CCD’s are familiar to many in the form of solid-state television cameras. They use arrays of semiconducting photodetector pixels and are read out by a systematic marching along (“shift-register style”) of charge accumulated and stored in each pixel to readouts along the edges of the array. A good general reference is 8. They have been made with some avalanching in the cells to provide gain and can be used to count photons, although the gain they provide is typically not enough to do real single photon counting. Thresholds of about ten photons per pixel are not unusual. This means that what starts out looking like a pretty sensitive detector may not quite be what one was thinking of. With single photon sensitivity, it may take quite a while for the photons from a biological specimen, now shared among all the pixels, to make even a single pixel reach threshold.

The primary advantage of CCD’s is that they give a picture of where the photons are coming from, and can have relatively good quantum efficiencies, although usually somewhat less than those available from APD’s.

A significant disadvantage for many applications is that it takes time to read out the device, and this leads to significant delays and deadtimes (tens of milliseconds) which can be significant in experiments where timing is important.

Their sensitivity to light can be increased by placing an image intensifier in front, which is basically a microchannel plate or hybrid photodiode type of device where rather than having the multiplied electrons collected electronically, they are made to strike a fluorescent plate and emit light. This, of course, comes with attendant loss of quantum efficiency associated with the image intensifier photocathode.

**VLCPs and SSPMs**

“Visible Light Photon Counters”, or “VLPCs” were developed by Rockwell International originally for military applications. They have since been used by civilians at the DØ experiment at Fermilab to detect the faint optical signals from scintillating fibers that flash as charged particles pass through them. They offer quantum efficiencies of 90% and gains of 40,000, with timing responses of 1 nsec, but must run at 7K (i.e. liquid helium is required), making them very difficult to use for many applications. They also have rather high dark count rates (in the kHz range even for very small -nm² devices). They are actually an outgrowth of an earlier, similar technology of “Solid State Photomultipliers” or SSPMs which had good performance quite a way into the infrared, but were not available for general civilian use.

These are rather unusual devices, similar to APD’s in many ways with a gain region in which there is a linear field gradient as well as a drift region with a constant field. Instead of conventionally doped semiconductors, they use impurity band conduction, which occurs when a semiconductor is very heavily doped with shallow donors or acceptors. This makes an impurity band 0.05 eV below the conduction band and electrical transport is by charges hopping from impurity site to impurity site. The normal 1.12 eV valence band is used to absorb photons, while the 0.05 eV gap is used to make an avalanche of electrons and so-called “D” holes. This tiny gap means that a power supply delivering only a few volts is needed, but also clearly means that thermal fluctuations are going to be problematic except at very low temperatures. Even then, as discussed above, noise issues are not inconceivable.

**Superconducting Tunnel Junctions**

An ideal device would deliver photon counting/timing AND wavelength measurement AND position information. While this sounds like too much to ask, in fact there is something close, but it still not in common use.

Developed only recently, superconducting tunnel junction detectors look like almost perfect devices (aside from their requirement of extreme cryogenics)9. Work continues today and there is a very strong interest from the astronomy community, who, of course, have problems in detecting very weak photon sources from vast distances.

To understand how these works, we first remind the reader that superconductors are materials in which
electrons can exert weak attractive forces on other electrons through the intermediary of the lattice. You might imagine a heavy bowling ball on a sofa making a dent that would tend to drag another bowling ball towards it. Should the lattice be cold enough (below the material's "critical temperature") so that thermal fluctuations don't overwhelm this weak attractive force, electrons can pair up into *Cooper pairs* and form spinless current carriers with a charge twice that of a single electron. Many of these can condense together and form a macroscopic quantum state which will carry current perpetually with no losses whatsoever, and this is what one calls a superconductor.

A Superconducting Tunnel Junction (STJ) is made of two thin films of a superconducting metal such as niobium, tantalum or hafnium separated by a thin insulating layer. When operated at temperatures well below the superconductor's critical temperature (typically below 1 K), the equilibrium state of the junction is easily perturbed by any visible photon striking it—such photons carry energy well in excess of the energy needed to break up the Cooper pairs that make up the superconducting state. The greater the energy of the absorbed photon, the more of these pairs are broken up. This means that if one measures the amount of charge released from the superconducting state, one can measure the energy of the incident photon! Because the binding energy of a Cooper pair is so tiny, even an infrared photon can release thousands of electrons worth of charge. By measuring the total charge, it is then straightforward to measure the energy carried by an individual photon from infrared (a couple of microns in wavelength) to ultraviolet with a few percent resolution (depending essentially on the square root of the number of electrons released).

Detectors based on arrays of these devices could one day offer single photon detection with high quantum efficiency where not only would you know where and when a photon hit, but also what colour it was!

**Quantum Dots**

Quantum dots, like STJ's are still pretty much academic and experimental devices, but they do offer interesting possibilities for the future. They are basically transistors with very small sizes so that quantum effects are large and, in many ways, they are like large custom made atoms. They can be used for single photon detection but still at low quantum efficiency. One interesting feature of these devices is that they have been used to detect single THz photons.

**Outlook**

Photomultiplies still remain the main workhorses of photodetection, but several devices are catching up rapidly and some really amazing things should be out of the labs soon. Ultimately, really high quantum efficiencies approaching 100% are probably only attainable with solidstate devices. While noise remains a problem, prospects are improving and there are a lot of very interesting development on the horizon!

Finally, it's worth mentioning that single photon detection is almost as much an art as it is a science, and there is no real replacement for the help and advice of experienced colleagues, and a lot of trial and error.

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