Whitepaper

The Evolution of Single Photon Detection

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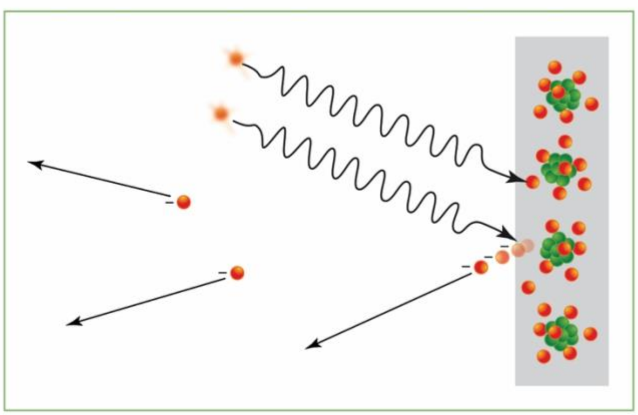
Overview

Single Photon Detection has become a vital tool in many applications – single molecule fluorescence, particle characterization through scattering, Quantum Cryptography, astronomy, LiDAR and more. The concept appears to be simple in principle; one photon creates one electron in a photodiode or when hitting a metal surface, but how easy is it to detect that single electron? This whitepaper covers the development of silicon single photon counting from the original principle as discovered by engineers at RCA in the 1960s, through to today's turn-key modules as developed by Excelitas that now provide simple, plug-and-run photon detection for Original Equipment Manufacturer instruments and laboratories alike.

Life on earth has been detecting photons since unicellular organisms started using photoreceptor proteins to sense ambient brightness. These “eyespots” led to the development of the eye, with the first proto-eyes, from which all modern eyes can be genetically traced, evolving some 540 million years ago.

For the purposes of this paper, we will skip over this long and complex evolution, and leap past almost all of those 540 million years to start with the photoelectric effect.

In the late nineteenth century, following observations made by Heinrich Hertz in 1887, a number of experiments took place investigating the effect of light, particularly UV radiation, on charged bodies. In the early twentieth century, it was discovered that while the number of particles, which we now call electrons, emitted from a surface was proportional to the intensity of the light, the maximum kinetic energy of the electron was proportional to the frequency of the radiation and that there is also a minimum frequency below which no electrons are emitted. This work, coupled with Max Planck’s studies on blackbody radiation, led to Albert Einstein’s Nobel-winning paper proposing that light energy is carried in discrete packets, where the energy contained within each packet is equal to the frequency of the light multiplied by a constant, thus explaining the photoelectric effect, and that only photons of a high enough frequency have enough energy to liberate an



electron from a particular material.

Image 1 - The photoelectric effect in a sold

The concept of a discrete packet of light, now known as a photon, capable of liberating an electron from a metal surface clearly indicates that single photons can be detected via the detection of the negatively charged electron. Although simple in concept, and relatively easy to do when large numbers of photons liberate large numbers of electrons, the detection of a single electron is no small task to achieve.

Another key discovery that occurred around the same time as the photoelectric effect was that of secondary, by L. Austin and H. Starke in 1902 in a study of the reflection of electrons by metals. They found that metal surfaces impacted by electron beams in a cathode-ray tube emitted a larger number of electrons than were incident onto the surface. This work led to the application of secondary emission to signal amplification.

It was the combination of a photocathode, creating electrons through the application of the photoelectric effect, and a secondary emission stage in the same vacuum tube that brought the first photomultiplier tube, or PMT, into the world at an RCA laboratory in 1934. This PMT had a gain of approximately eight, so now our single photon is liberating eight electrons to prove its presence. Initially, utilizing improved materials increased the single stage gain. Although, to get serious multiplication, additional stages were needed. With further improvements in photocathodes and multiple amplification stages, a typical gain of 106 is now possible in linear mode.

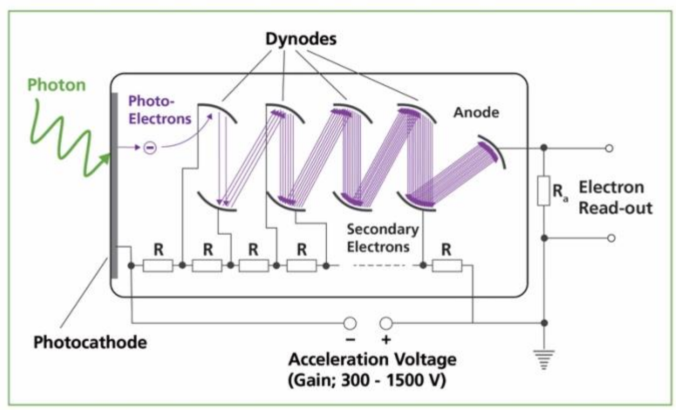


Image 2 - Schematic of a Typical Photomultiplier

However, for single-photon detection, the voltages across the multiplication stages can be increased to the level where the gain is so high that a single photoelectron from the photocathode produces a very large current at the output circuit. This process tends to be self-sustaining, so control electronics are needed to detect the current and reset the PMT, leading to a dead time where no electrons can be multiplied and therefore no photons detected. This method of operation is known as Geiger mode, as it is similar in principle to that of a Geiger counter. It should also be noted at this point that the photocathode is far from 100% efficient, so not every photon will generate an electron. The choice of materials used for the photocathode is important too – different materials respond to different wavelength ranges; remember that different materials have different photon energies below which they will not emit electrons. Electrons can be emitted for reasons other than photoemission, for example thermionic emission, where thermal energy given to the electron gives it enough of a boost to escape from the electrode. This gives rise to "dark electrons" which, when operated in Geiger mode, leads to "dark counts" with no photons present.

The ability to detect low levels of light, even down to the single photon, led to the PMT becoming an important tool in many different applications including astronomy, nuclear particle physics, and biomedical instrumentation.

There are downsides and difficulties associated with the use of PMTs. They are very sensitive to overstimulation and are easily damaged by exposure to ambient light. They operate typically at a 1-2000V difference between the anode and cathode, with the anode typically at low voltage to allow for easier measurement of the photocurrent by low voltage circuitry – this means the cathode is at a large negative voltage. The PMT is also very susceptible to magnetic fields, as these can cause the electron paths to curve and miss their targets leading to a loss of gain, therefore magnetic shielding is needed – this is often at the cathode potential and so causes an extra issue with the need for additional electrical insulation.

With the invention of the p-n junction at Bell Laboratories in 1939 came the possibility of another route to single photon detection — the photodiode. The p-n junction is the interface between differently doped regions within a single crystal of semiconductor. The "p", or positive side of the junction, is lacking in electrons where they would be expected within the crystal lattice, with the missing electrons being termed "holes". The "n", for negative, has an excess of electrons in the outer shells of the otherwise neutral atoms in the crystal lattice. This creates a diode, allowing the passage of electrical current in only one direction under normal operation. A photodiode in its simplest form is just a p-n junction where the materials are such that radiation of the right frequency or wavelength, will, via the photoelectric effect, release electrons and create a photocurrent within the junction. When reverse biased, with the cathode raised positive in voltage compared to the anode, this photocurrent can be usefully and quickly extracted to give a current proportional to the light level on the photodiode.

The addition of an undoped region, or "intrinsic" semiconductor, between the p-and n-type regions allows the doping levels to be increased, causing higher levels of charge carriers and therefore greater speed of operation. A PIN junction, invented by Jun-ichi Nishizawa et al in 1950, is also ideal for a photodiode. PIN photodiodes are now used routinely in many applications from fiber optic communications to medical instrumentation and laser warning systems. But from the single photon detection point of view, they are still limited to one photon creating one electron.

Fortunately, in the same way that the PMT added gain to the photocathode generation of the initial photoelectron, the addition of an internal current gain region within a PIN photodiode turns it into an avalanche photodiode, or APD. Invented by the aforementioned Professor Nishizawa in 1952, the APD uses careful structuring of the doping to allow a high voltage to be applied, creating high fields within the junction region. These high fields accelerate the photoelectrons causing them to release other electrons through impact ionization, creating the internal current gain, typically 100, that is the key feature of an APD. So now a single photon can create 100 photoelectrons – better than one, but still not enough to allow for a simple single photon detector.

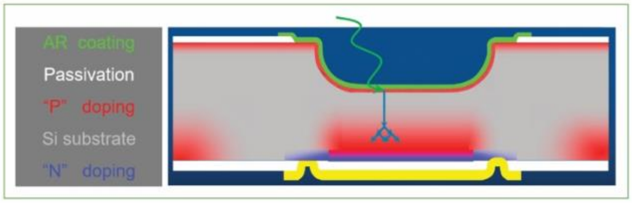


Image 3 - A typical APD structure

In the 1960s, Robert McIntyre at RCA of Canada, part of the same organization that developed the PMT and is now the operation where Excelitas makes its SPCMs, researched microplasma instability in silicon. This, in turn, led him to research the behavior of APDs in Geiger mode, where the reverse bias is now high enough to cause the dark current within the APD to spontaneously create a self-sustaining avalanche, in the same way as previously described for the PMT. With an APD in Geiger mode, the same as for the PMT, a single photon can lead to enough current to be detectable – success!

However, without a method to control the APD, once a single photon has created the avalanche, and a current is being generated, the APD is now useless. This is the ultimate definition of single photon detection – after the single photon has been detected, nothing else ever will be. Not particularly useful....

The work at RCA led to two key developments in the search for a working single photon detector. First, the improvements in silicon crystal growth led to the development in 1986 of the super-low ionization coefficient or k-factor APD, which was quickly shortened to the much easier SLiK. In the same way that ultrapure water can be heated to above 100°C but, due to the lack of nucleation sites, will not boil until contamination is added, the SLiK APD can be biased to the above breakdown without initiating an avalanche due to lack of the stimulus of a photo or dark electron. Cooling the APD can significantly reduce the thermionic emission of electrons and therefore increases the time available to detect an incoming photon.

Image 4 – The SLiK Avalanche Photodiode, optimized for single photon detection

This gets us halfway to an APD-based single photon detector, but we still need to stop the avalanche once it is started. This led to the creation of a passive quench circuit, where the addition of an in-line resistor to the bias circuitry means that when the current starts flowing, some of the bias voltage is dropped across the resistor, leaving less voltage across the APD. Eventually, and this can occur quite quickly, the voltage across the APD becomes so low that statistical variations in the photocurrent cause it to drop to zero and be unable to self-start. This causes the voltage across the resistor to return to zero leaving the full voltage across the APD, which is now ready to detect another photon.

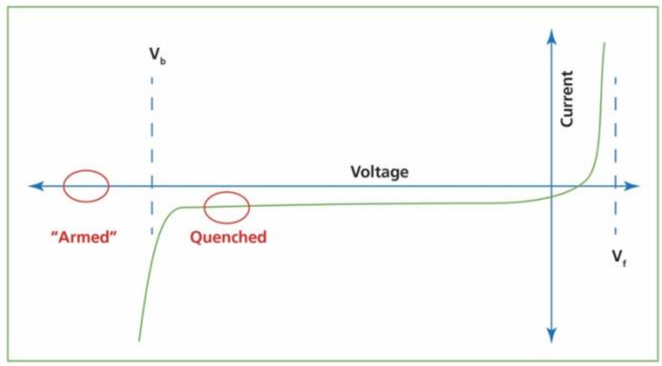


Image 5 – Current vs. voltage diagram of an APD, showing "armed" and "quenched" states

Launched by RCA in 1987, the SPCM-100 was a self-contained, user-friendly device with built-in temperature control, stabilized high-voltage supply and a Geiger-mode avalanche photodiode passive quenching circuit. An on-board logic circuit detected the avalanche current pulse and generated a simple TTL pulse of 35ns, and the passive quench circuit had the APD ready for the next photon after only 60ns. With its low dark count, low timing jitter, low after-pulse and a photon detection efficiency (PDE) of more than 50 percent, this first-generation module enabled single-photon studies to move deeper into the red and near-infrared regions of the electromagnetic spectrum that were difficult to reach with PMTs. In addition, APD bias voltages are much lower than those needed for PMTs, and their immunity to magnetic fields means there is no need for complex shielding. They are also less vulnerable to accidental exposure to ambient light; so while there are negative effects, these effects are temporary and not catastrophic.

True success – single photon detection is now readily achievable and can be used as a tool to enable new discoveries and applications!

Image 6 - The RCA SPCM-100, the world's first single photon counting module

In 1990, RCA Canada became EG&G, and the SPCM continued on its development path. Passive quenching was replaced by a patented active quench circuit, where the logic that detected the avalanche current was used to actively control the bias across the APD, rather than relying on voltage build-up across a resistor. Pulse width and dead-time were reduced and better control of bias voltage and silicon purity now allowed PDE to increase to >65% and dark count rates to reduce to as low as 25 counts per second.

EG&G acquired the Analytical Instrumentation Division of Perkin Elmer in 1999, assumed the acquired Perkin Elmer identity, and, amongst other achievements, upgraded the SPCM to have a pulse width of 20ns and dead time of 35ns, as well as establishing RoHS compliance for the instrument. In 2010, the Optoelectronics division of Perkin Elmer was spun out to create Excelitas Technologies. Development of the SPCM continued and in 2011 improvements to the control electronics allowed PDEs as high as 70% while retaining industry-leading specifications for dark count and after-pulsing. The pulse width and dead time were both further reduced, affording 10ns and 24ns respectively, allowing over 37 million single photon events per second to be reliably detected.

Image 7 - The Excelitas SPCM-AQRH single photon counting module

Today, the market and applications for single photon detection continue to grow. There are single photon avalanche detectors using micro APDs on top of a CMOS structures targeted at automotive LiDAR, where cost in volume production is the most important feature, and small APDs where minimal variation in time to convert the single photon into the avalanche photocurrent is their main advantage.

It has been over 540 million years since the first proto-eyes appeared on our planet, over 100 years since the principle of the photoelectric effect was defined by Einstein, over 70 years since the first PMT was invented, and over 30 years since the first APD-based single photon counting module was launched. The Excelitas SPCM, with versions now optimized for near infrared PDE and for Timing Resolution, continue to support applications including astronomy, flow cytometry, fluorescence lifetime, particle sizing, quantum computing, quantum key distribution, single molecule analysis, wind LiDAR, and many more.

About Excelitas Technologies

Excelitas Technologies® Corp. is a photonics technology leader focused on delivering innovative, high-performance, market-driven solutions to meet the lighting, optronics, detection and optical technology needs of our OEM customers.

Serving a vast array of applications across biomedical, scientific, safety, security, consumer products, semiconductor, industrial manufacturing, defense and aerospace sectors, Excelitas stands committed to enabling our customers' success in their end-markets. Our photonics team consists of 7,000 professionals working across North America, Europe and Asia, to serve customers worldwide.

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