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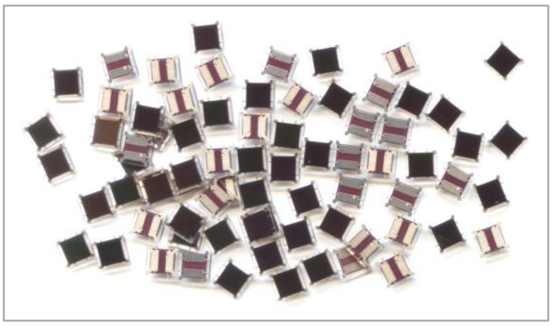
PASSION FOR LIGHT DETECTION

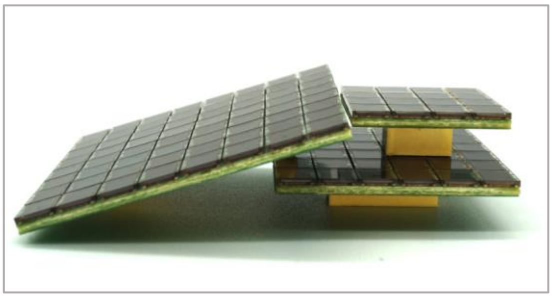
Introduction of Silicon Photomultiplier

—— Novel Photodetector with Excellent Performance

What's the Silicon Photomultiplier?

Silicon Photomultiplier (SiPM) is an innovative semiconductor photodetector with excellent performance. It consists of an array of parallel connected pixels working in Geiger mode, and each pixel is made up of a single photon avalanche photodiode (SPAD) and a quenching resistor in series with the SPAD. SiPM has excellent characteristics such as spectral response range from near ultraviolet to near infrared, excellent photon counting ability, single photon sensitivity, and fast response ability with picosecond level, excellent time resolution and high photon detection efficiency. Due to its nature as solid-state detector, SiPM is also insensitive to magnetic field, able to withstand high strength mechanical impact and not aging with the saturation of incident light. SiPM now has been regarded as the best alternative to traditional low light detectors because of its excellent performances and easy-using. At present, SiPM has been widely used in the field of medical imaging, laser detection and measurement, radiation detection, precision analysis, etc..





Principle

Photoelectric Effect

Light has a wave-particle duality, and the particles carrying energy in the light are called photons. When the energy of the photons is higher than the band gap of silicon, the incident photons will be absorbed by the silicon material. In this case, the electrons will escape from the valence band and transited to the conductive band due to absorption of the photon energy and become free electrons, with an electron vacancy (which is also called holes) left behind in the valence band. Thus the electron-hole pairs are formed. The electrons and holes are collectively called carriers. The electrons and holes are separated by electric field in PN junction as the current signal, and the photon detection is realized by detecting such signal. The photon absorption depth varies with the wavelength. Generally, silicon materials have good absorptive capacity for light with a wavelength of 200 nm-900 nm.

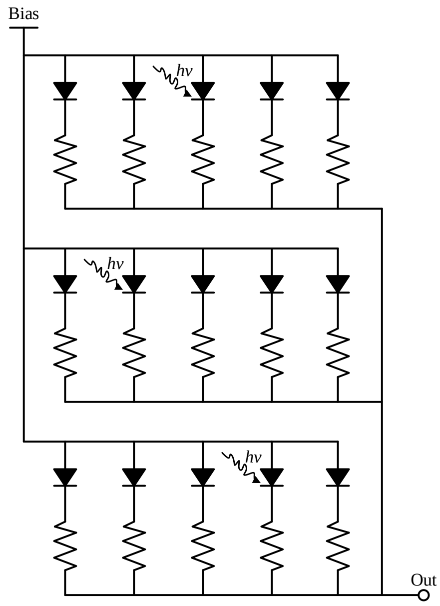


Fig.1 Schematic diagram of SiPM

Structure of SiPM

The basic structural unit (which is also called pixel) of SiPM is a Geiger mode avalanche photodiode (GM-APD) in series with a quenching resistor. Thousands of such pixels are connected in parallel and formed a space-distributed two-dimensional array with shared power supply and signal output, thus the basic structure of the SiPM is constructed. The schematic diagram of SiPM is shown in Fig.1.

Geiger Mode and its Working Process

Geiger mode is the state in which the reverse bias voltage of the PN junction is higher than its breakdown voltage. If the reverse bias applied to the PN junction induces a strong electric field in the depletion layer, the carriers generated in the depletion layer will get enough kinetic energy, in this case the carriers will have a certain probability of colliding with other silicon atoms and generating new electron-hole pairs. This process is called impact ionization. And the new electron-hole pairs will also repeat the impact ionization process and generate hundreds of millions of secondary electron-hole pairs, this is known as avalanche multiplication principle. The principle of the avalanche multiplication process is shown in Fig.2.

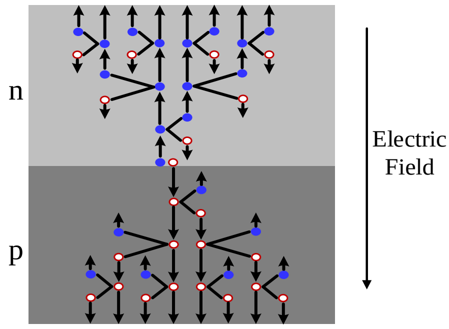


Fig.2 Principle of the avalanche multiplication process

In Geiger mode, both the electrons and the holes have a high collision ionization rate, and the avalanche multiplication process will sustain once it begins. In this state, the single photon avalanche diode is no longer sensitive to the incident photons, unless the electric field intensity in the depletion layer can no longer support the avalanche multiplication. The normal way to decrease the electric field intensity is using a quenching resistor in series with the GM-APD. The current that flows through the quenching resistor will induce a voltage drop on the resistor, resulting in a sharp decrease in the voltage on the GM-APD, which leads to a rapid weakening of the electric field in the depletion layer to stop the avalanche. This process is called quenching. After quenching, the voltage drop on the resistor reduces and the voltage applied to the GM-APD approaches the level of the bias. The single photon avalanche diode thus is back to the light sensitive state, preparing to receive the next incident photon. The single pixel working process is shown in Fig.3.

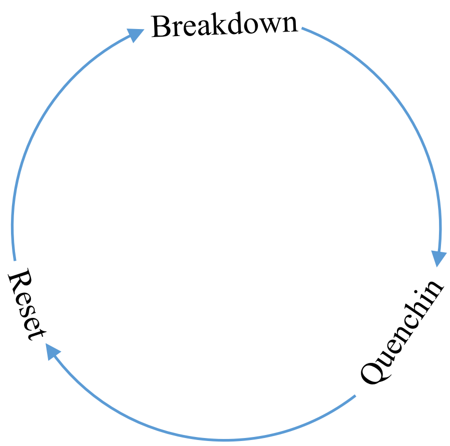


Fig.3 working process of single pixel

The single pixels of SiPM can be used to detect photons, but its output are discrete signals with same amplitude, and can't distinguish two photons arriving at the same time. The SiPM is an array consisting of a large number of compact arranged two-dimensional pixels. Each pixel is composed of a GM-APD and with a quenching resistor in series. If two pixels of the SiPM detect photons at the same time, the output of the SiPM is the sum of two single photon pulses, and the amplitude of the output is two times the amplitude of a single photon pulse. Similarly, if N pixels (N is less than the total number of pixels) detect the photons at the same time, the output signal amplitude is almost N times the single pulse amplitude. The sum of all the pixels output signals can be used to characterize the number of the photons. If the incident light intensity is strong enough, the SiPM will reach its saturation state and the output amplitude will no longer increase with the increase of light intensity.

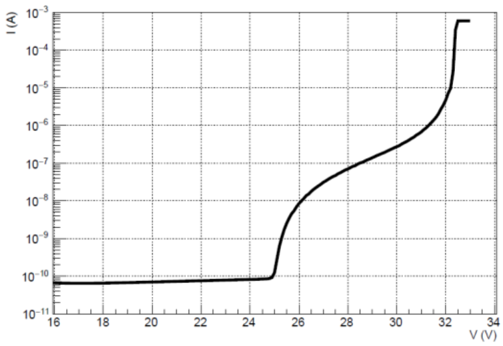


Fig.4 Typical I-V curve of SiPM

Main performance parameters

Breakdown voltage and overvoltage

In Geiger mode, the working voltage of SiPM is larger than its breakdown voltage. The breakdown voltage is the minimum voltage needed to sustain the Geiger discharge. One can read the breakdown voltage value from the I-V curve, as shown in Fig.4. The reverse bias voltage at the point where the current is increasing sharply refers to the breakdown voltage. The relationship between operating voltage and breakdown voltage can be expressed as

$$V_{ov} = V_{op} - V_{br}, \quad (1)$$

where V_{ov} is the overvoltage, V_{op} is the operating voltage and V_{br} is the breakdown voltage. The overvoltage affects the major performances of SiPM.

Gain

When Geiger discharge occurs in one pixel, the uniform and quantifiable charges are generated. The gain of the SiPM is the ratio of the amount of the output charge to an element charge when the pixel detects a photon. The gain can be expressed as follow,

$$G = \frac{Q}{q} \quad \textbf{(2)}$$

in which the G is the Gain, Q is the output charge amount and q is the element charge. The output charge can be roughly estimated by the overvoltage.

$$Q = C \cdot V_{ov} \quad (3)$$

where C is the pixel capacitance. According to equation (2) and (3), the gain can be increased by increasing the pixel capacitance and the operating voltage. The gain is increasing linearly with the increasing of overvoltage, as shown in Fig.5. However, the dark count rate and after pulse will also increase with the increase of overvoltage, so that proper operating is very important for SiPM.

Except voltage, the gain of SiPM also depends on the ambient temperature. With the increase of temperature, the

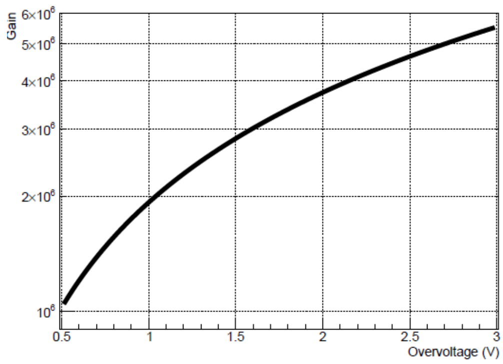


Fig.5 Gain as a function of overvoltage

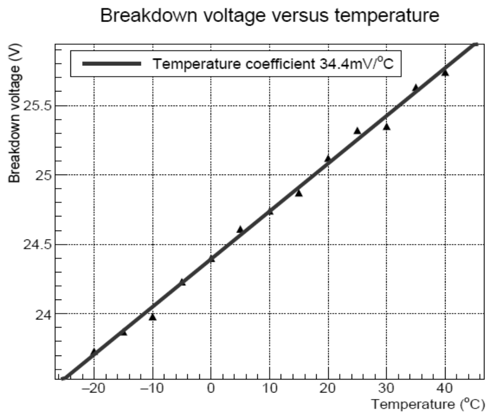


Fig.6 Breakdown voltage versus temperature

lattice vibration of the silicon material increases and the probability of the scatter between the carrier and the lattice also increases. In order to increase the kinetic energy for collision ionization, it is necessary to increase the reverse bias voltage to enhance the electric field intensity in the depletion region. That is to say, the breakdown voltage will increase with the increase of temperature. Fig.6 shows the relationship between the operating voltage and temperature under a constant gain. It can be seen that, in order to maintain a constant gain, the operating voltage must be adjusted to ensure that it matches the ambient temperature. When the working voltage is fixed, the gain decreases with the increase of the ambient temperature.

Photon Detection Efficiency

The photon detection efficiency is the statistical probability that a photon incident on the SiPM surface and then generate a Geiger pulses. The photon detection efficiency can be expressed as

$$PDE=\frac{N_{\mathrm{dete}}}{N_{\mathrm{inci}}} \tag{4}$$

in which the PDE means the photon detection efficiency , N_{dete} is the detected photon numbers, N_{inci} is the incident photon numbers. Besides, the photon detection efficiency as a function of wavelength and bias voltage, it can also be expressed by using quantum efficiency, avalanche probability and filling factor, i.e.

$$PDE(\lambda,V)=\eta(\lambda)\cdot P_b(V)\cdot F \tag{5}$$

where η（λ）is the quantum efficiency of silicon， $P_b(V)$ is the avalanche probability, and *F* is the filling factor. The avalanche probability means that not all the photon generated carrier will induce avalanche multiplication effect. What's worse, not all the area of the SiPM surface can detect photons because of the isolation of pixels and the existence of resistors and electrodes sacrificed some surface areas. As the ratio of the photosensitive area to the total area of the SiPM, the filling factor is used to characterize the size of photosensitive area of

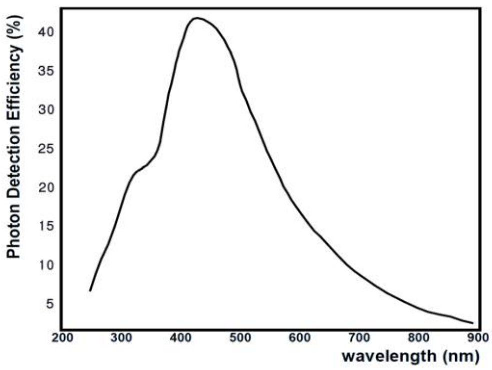


Fig.7 PDE as a function of wavelength

the photons that can be detected.

Usually, the PDE is calculated based on the photosensitivity and the gain of SiPM. The photosensitivity response is defined as the average photocurrent under the unit optical power, i.e.

$$R=\frac{I_p}{P_{op}}\ . \tag{6}$$

where R is the photosensitivity, I_p is the detected photocurrent and P_{op} the optical power of a specific wavelength incident into the SiPM. The unit of photosensitivity is A/W. According to the photosensitivity and the equation (7), the PDE can be calculated as follows,

$$PDE=\frac{R}{G}\cdot\frac{1.24}{\lambda} \tag{7}$$

in which G is the gain, λ (take μm as its unit) is the wavelength of the incident photon. Using this method to calculate the PDE, it is needed to get the gain of SiPM accurately, and the SiPM must work in its linear region. It is worth noting that the PDE obtained by this method does not exclude the effect of optical crosstalk and after pulse, so the PDE is higher than its actual value. The relationship between PDE and wavelength can be seen in Fig.7.

Noise

Noise are interference signals which superimposed on useful signals. The major noise of SiPM includes dark count rate, optical crosstalk and after pulse.

Dark Count Rate

The dark count rate is the main factor limiting the performance and the dimension of SiPM, and is also the main noise source of SiPM. The dark count of SiPM is generated by the avalanche multiplication effect induced by the thermal excited carrier in the photosensitive region, and has the same amplitude as the single photon signal, which leads to the inability to distinguish whether the incident photon is detected. The dark count rate is used to characterize the frequency of such signals. It is worth noting that the dark count always contribute to the measured signal amplitude.

The dark count rate can be measured by using a simple counting system and setting a threshold with 0.5 photon signal amplitude in the system. The typical value of the dark count rate is about 0.1-1 MHz/mm^2. Fig.8 shows the relationship between dark count rate and overvoltage. Except the bias voltage, the dark count rate also has relationship with the ambient temperature, the size of the pixel and the total area of the SiPM. With the increase of temperature, the dark count rate will increase dramatically. Conversely, with the decrease of temperature, the dark count rate will also decrease significantly. Therefore, SiPM combined with thermoelectric cooler can be applied to the application where very low noise is needed.

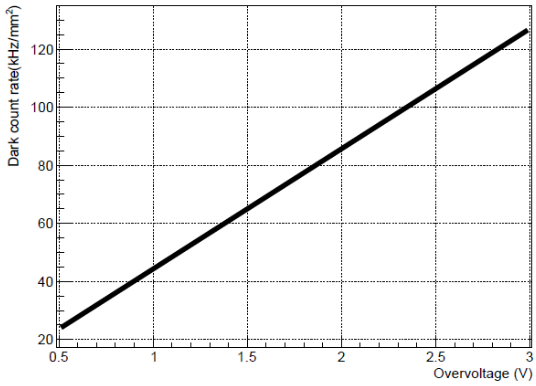


Fig.8 Dark count rate as a function of overvoltage

Optical Crosstalk

The optical crosstalk is another source of noise for SiPM. When a single pixel of SiPM detects an incident photon, the carrier generated in the process of the internal avalanche multiplication may travel to the adjacent pixels, causing the adjacent pixels to generate Geiger pulses, so that the pulses of 2 or more than 2 photon signals can be observed. The ratio of the number of detected secondary photons to the number of detected incident photons is the probability of optical crosstalk. The optical crosstalk probability of SiPM can be calculated by setting different threshold values in a counting system. Firstly, measuring the dark count rates of the output signal whose amplitude greater than the amplitude of the 0.5 photon signal. Secondly, measuring the dark count rates of the output signal whose amplitude greater than the amplitude of the 1.5 photon signal. And finally take the ratio of these two dark count rate as the optical crosstalk probability, which is

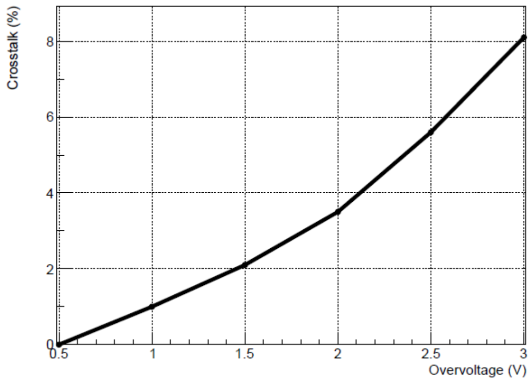


Fig.9 The optical crosstalk probability as a function of overvoltage

$$P_{crosstalk} = \frac{N_{1.5\,p.e.}}{N_{0.5\,p.e.}} \quad (8)$$

In equation (8) $P_{\text{crosstalk}}$ is the optical crosstalk probability, $N_{1.5\text{p.e.}}$ is the dark count rate whose signal amplitude is higher than 1.5 photon signal amplitude, and $N_{0.5\text{p.e.}}$ is the dark count rate whose signal amplitude is higher than 0.5 photon signal amplitude. The probability of optical crosstalk will increase with the increase of overvoltage, as shown in Fig.9. Besides, the optical crosstalk probability is also depend on the distance between two pixels. With the increase of the distance between two pixels, the optical crosstalk probability will decrease, but the filling factor will also decrease, thus the PDE is degenerated. The optical crosstalk probability can be reduced by setting trenches between pixels and filling the trenches with light isolation materials.

After Pulse

During the avalanche breakdown, a large number of carriers pass through the PN junction, thus the carriers will have a certain probability of being captured by a trap in the band gap, and the captured carrier will then be released and induce a new avalanche multiplication process. The after pulse is the signal generated by the trapped carriers. The blue curves in Fig.10 are after pulses observed on oscilloscope. The after pulse is usually expressed in probability and it depends on the overvoltage and the lifetime of the trapped carriers.

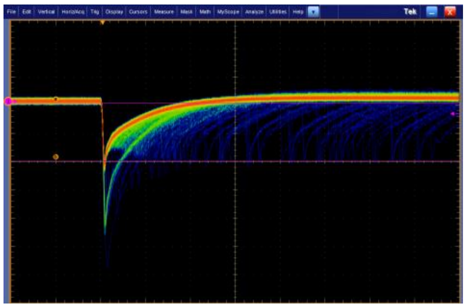


Fig.10 After pulse observed on oscilloscope (the blue pulse behind the main signal pulse is after pulse)

Time characteristics

The typical output signal of SiPM is shown in Fig.11. The rising time of the SiPM is the discharge time of the pixel, which depends on the total capacitance of the SiPM. The recovery time of SiPM is the time for charging the pixel, it can be simply expressed as

$$t_r = R_Q \cdot C \qquad (9)$$

in which t_r is the recovery time, C means the effective capacitance of the pixel and R_Q is the resistance of the quenching resistor.

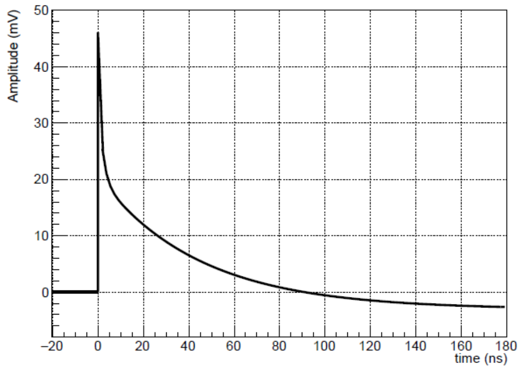
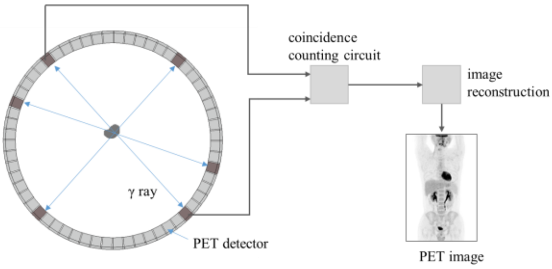


Fig.11 Typical signal of SiPM

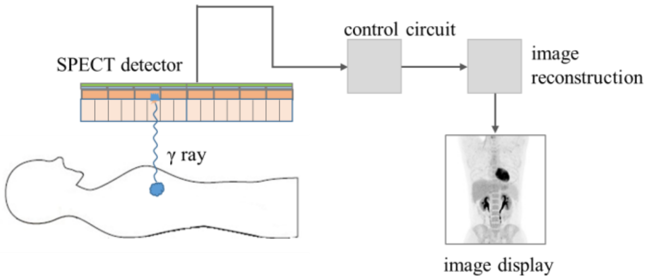
Dynamic Range

The dynamic range of a given SiPM can be defined as the optical signal range over which the sensor provides a useful output. When all the pixels are fired at the same time, the output signal of the SiPM will be saturated, that is, no more pixels can be used to detect other incident photons until some of the pixels are recover to their detectable stage. Therefore, the dynamic range of SiPM is a function of the total number of pixels and the PDE. At the same time, because the PDE is related to the bias voltage and the wavelength of incident photon, the dynamic range of SiPM is also a function of bias voltage and wavelength. When the number of incoming photons in a unit time is far less than the number of pixels, the response of the SiPM is linear. However, as the number of incoming photons increases, the response of the SiPM tends to saturate. That is, at the weak light signal level, the output photocurrent of SiPM is proportional to the incident light power and SiPM presents a linear response. With the increase of the incident light power, the output photocurrent begins to deviate from the linear response region and eventually become saturation because of the limitation of the pixel number.

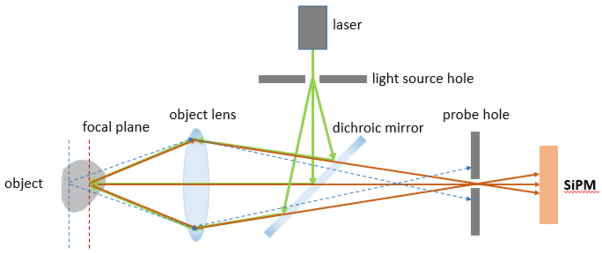
Application Examples



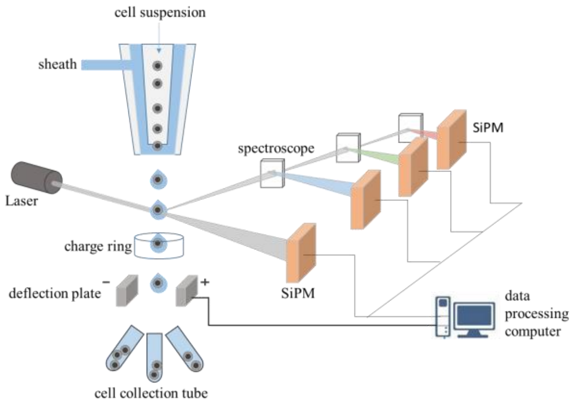
Application 1 Positron Emission Tomography



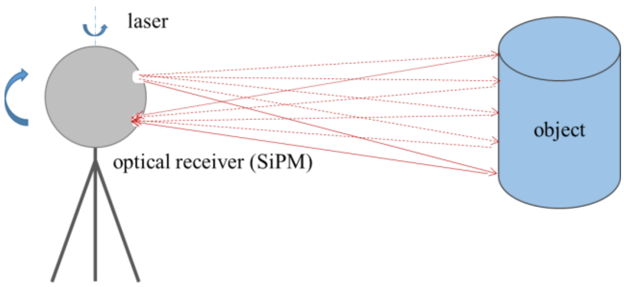
Application 2 Single Photon Emission Tomography



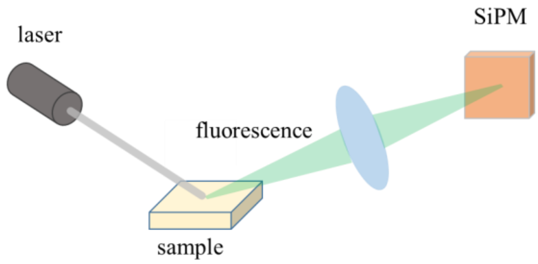
Application 3 Confocal Laser Scanning Microscope



Application 4 Flow Cytometer



Application 5 Laser Detection and Measurement



Application 6 Fluorescence Analysis

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