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Silicon Photodiode Structure and Theory of Operation

Silicon photodiodes are constructed from single crystal silicon wafers similar to those used in the manufacture of integrated circuits. The major difference is that photodiodes require higher purity silicon. The purity of silicon is directly related to its resistivity, with higher resistivity indicating higher purity. Centronic products utilize silicon whose resistivities range from 10 ohm-cm to 10,000 ohm-cm.

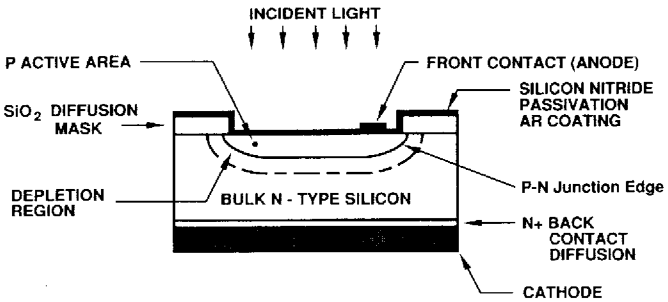

Fig. 1 - Cross Section of Photodiode

A cross section of a typical photodiode is shown in Fig. 1. N-type silicon is the starting material. A thin "p" layer is formed on the front surface of the device by thermal diffusion or ion implantation of the appropriate doping material (usually boron). The interface between the "p" layer and the "n" silicon is known as a pn junction. Small metal contacts are applied to the front surface of the device and the entire back is coated with a contact metal. The back contact is the cathode, the front contact is the anode. The active area is coated with either silicon nitride, silicon monoxide or silicon dioxide for protection and to serve as an anti-reflection coating. The thickness of this coating is optimized for particular irradiation wavelengths. As an example, a Centronic Series -5T photodiode has a coating which enhances its response to the blue part of the spectrum.

The characteristics of pn junctions are well known. However, photodiode junctions are unusual because the top "p" layer is very thin. The thickness of this layer is determined by the wavelength of radiation to be detected. Near the pn junction the silicon becomes depleted of electrical charges. This is known as the "depletion region". The depth of the depletion region can be varied by applying a reverse bias voltage across the junction. When the depletion region reaches the back of the diode the photodiode is said to be "fully depleted". The depletion region is important to photodiode performance since most of the sensitivity to radiation originates there.

The capacitance of the pn junction depends on the thickness of this variable depleted region. Increasing the bias voltage increases the depth of this region and lowers capacitance until the fully depleted condition is achieved. Junction capacitance is also a function of the resistivity of silicon used and active area size (see Fig. 2).

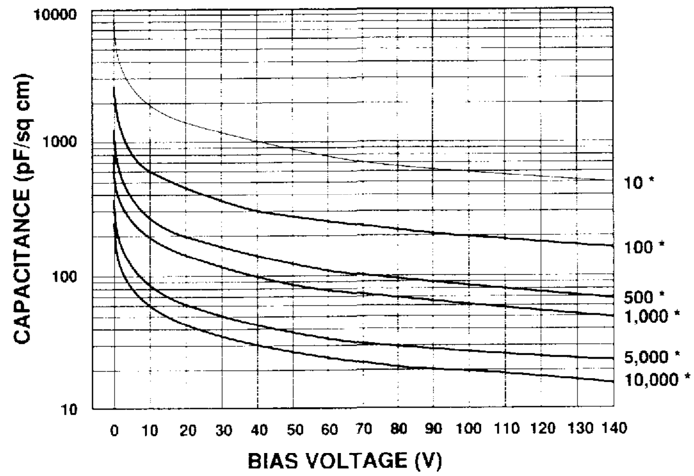

Fig. 2 - Photodiode Capacitance vs Bias Voltage for Various Silicon Resistivities (*ohm-cm)

When light is absorbed in the active area an electron-hole pair is formed. The electrons and holes are separated electrons passing to the "n" region and holes to the "p" region. This results in a current generated by light (usually abbreviated Isc). The migration of electrons and holes to their respective region is called "The Photovoltaic Effect".

Silicon photodiodes are most useful as current generators although a voltage is also generated by illumination. Most of the data supplied in this manual refers to the short circuit current characteristics of the photodiodes. The short circuit current is a linear function of the irradiance over a very wide range of at least seven orders of magnitude. The Isc is only slightly affected by temperature, varying less than 0.2%°C for visible wavelengths. A recently published independent laboratory study has shown Centronic photodiodes to have Isc stability better than ±0.25% per year (see footnote on page 11).

It must be noted that when a reverse bias is applied some current will flow without illumination. This "dark current" is specified for every device. In cases where a very low bias is used, shunt resistance is specified. This is determined by measuring dark current with ±0.010 volts applied bias.

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Photodiode Polarity

A photodiode has two terminals, a cathode and an anode. It has a low forward resistance (anode positive) and high reverse resistance (anode negative). Normal biased operation (Figs. 11 and 12) of most photodiodes described in this catalog calls for negative biasing the active area of the device which is the anode or positive biasing the backside of the device, which is the cathode.

In the photovoltaic and zero bias modes (Figs. 9 and 10) the generated current or voltage is in the diode forward direction. Hence the generated polarity is opposite to that required for the biased mode.

Responsivity

This measure of sensitivity is the ratio of radiant energy (in watts) incident on the photodiode to the photocurrent output in amperes. It is expressed as the absolute responsivity in amps per watt. Please note that radiant energy is usually expressed as watts/cm^2 and that photodiode current as amps/cm^2. The term cm^2 cancels out and we are left with amps/watt (A/W).

Spectral Response

The wavelength of the radiation to be detected is an important parameter. As can be seen from the graph (Fig. 3) silicon becomes transparent to radiation of longer than 1100nm wavelength. It is not therefore suitable for use at wavelengths appreciably longer than this. Ultraviolet light is, conversely, absorbed in the first 100nm thickness of the silicon. Even the most careful surface preparation leaves some surface damage which reduces the collection efficiency for this wavelength. Surface coatings further affect the spectral response of the device. It is normal to apply anti-reflection coatings which enhance the response (by up to 25%) at the required wavelength. These coatings may reduce the efficiency at other wavelengths which they reflect. The package window further modifies the spectral response. The standard glass window absorbs wavelengths shorter than 300nm. For UV detection, a fused silica or UV transmitting glass window is necessary. Various filter windows are also available to tailor the spectral response to suit the application. One specific filter which is of great interest, modifies the normal silicon response to approximate the spectral response of the human eye.

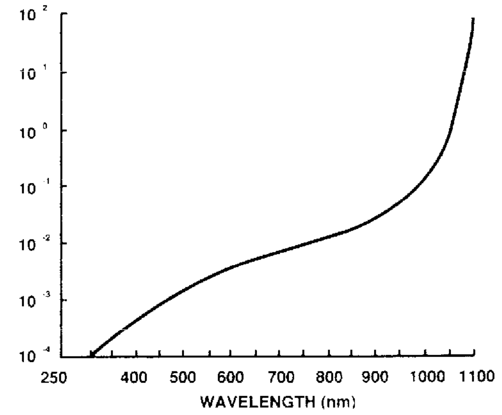

Fig. 3 - Radiation Penetration in Silicon @ Different Wavelengths

Quantum Efficiency (Q.E.)

A photodiodes's capability to convert light energy to electrical energy, expressed as a percentage, is its Quantum Efficiency (Q.E.). The sensitivity of a photodiode may also be expressed in practical units of amps of photodiode current per watt of incident illumination. The Q.E. is related to the photodiode's responsivity as follows:

$$Q.E. (\%) = \frac{1.24 \times 10^5 \times R(A/W)}{\lambda \text{ (nm)}}$$

Operating under ideal conditions of reflectance, crystal structure and internal resistance, a high quality silicon photodiode of optimum design would be capable of approaching 80% Q.E.. The following reference table identifies, at a Q.E. of 100%, the responsivity of an ideal photodiode over the 200-1100nm wavelength range. It should be noted that 100% Q.E. is not attainable.

Wavelength nm	Responsivity at 100% Q.E. A/W
200	0.161
300	0.242
400	0.323
500	0.403
600	0.484
700	0.565
800	0.645
900	0.726
1000	0.806
1100	0.887

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Temperature Effects

Increasing the operating temperature of a photodiode device results in two distinct changes in operating characteristics.

The first change is a shift in the Quantum Efficiency (Q.E.) due to changes in the radiation absorption coefficient of the device. Q.E. values shift lower in the UV region and higher in the IR region. Little shift is noted in the visible region. (Refer to Fig. 4.)

The second change is caused by exponential increases in the thermally excited electron-hole pairs resulting in increasing dark current. The leakage doubles for each 8° to 10°C temperature increase. (Refer to Fig. 5).

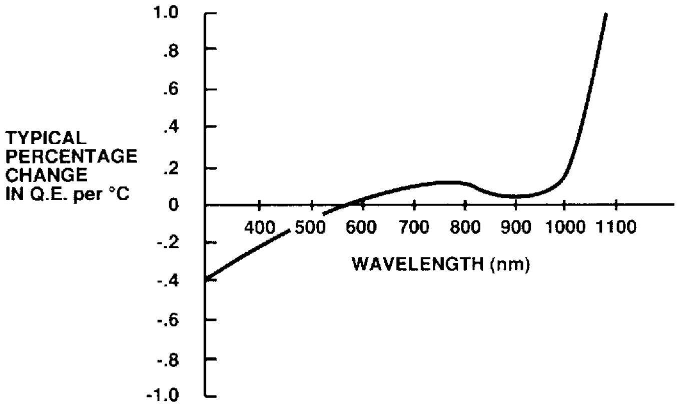

Fig. 4 - Temperature Dependence of Q.E.

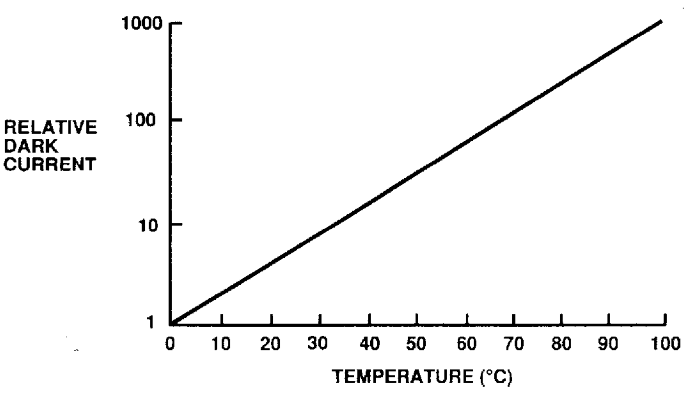

Fig. 5 - Temperature Dependence of Dark Current

KEY DEVICE PARAMETERS

Noise Equivalent Power (NEP)

In many design applications, the designer needs to know the minimum detectable light (power) of the photodiode. The minimum incident power required on a photodiode to generate a photocurrent equal to the total photodiode noise current is defined as the noise equivalent power, or NEP. As a mathematical expression this may be written as:

$$NEP = \frac{\text{noise current (A)}}{\text{responsivity (A/W)}}$$

The NEP is dependent on the bandwidth of the measuring system; to remove this dependence the figure is divided by the square root of the bandwidth. This gives NEP the units of watts/Hz$^{1/2}$. Since the photodiode light power to current conversion depends on radiation wavelength, the NEP figure is quoted at a particular wavelength. The NEP is non-linear over the wavelength range, as is responsivity.

The noise generated by a silicon photodiode, operating under reverse bias, is a combination of shot noise, due to dark leakage current, and Johnson noise due to the shunt resistance of the device and the ambient temperature. The Shot Noise current produced by the reverse leakage current of a device is given by the formula:

$$I_S = (2e\, I_d\, B)^{1/2}$$

where I_S = shot noise current
e = electronic charge (1.6×10^{-19} coulomb)
I_d = dark leakage current (amps)
B = bandwidth of system (Hertz)

The Johnson noise contribution is provided by the shunt resistance of the device, series resistance and the load resistance. The Johnson noise current is given by:

$$I_J = \left(\frac{4KTB}{R}\right)^{1/2}$$

where I_J = Johnson noise current
K = Boltzmann constant ($1.38 \times 10^{-23} JK^{-1}$)
T = absolute temperature (K)
R = Resistance giving rise to noise

The total noise current is the root mean square sum of the individual noise current contributions.

$$I_N = (I_S^2 + I_J^2)^{1/2}$$

and $$NEP = \frac{I_N}{R_\lambda}$$

As an example; if a photodiode has I_D = 2nA and a shunt resistance of 5 x 10^8 ohms, and responsivity (R_λ) = 0.5 A/W (typical of present day performance) and letting B = 1Hz,

Shot noise, I_s = 2.5 x 10^{-14} A
Johnson noise, I_J = 5.6 x 10^{-15} A
Total noise = 2.6 x 10^{-14} A
and NEP = 5.1 x 10^{-14} W

Shot noise is the dominant component of the noise current of a reverse biased photodiode. This is particularly true at higher voltages. If devices are operated in a photovoltaic mode with zero bias, the Johnson noise dominates, as the dark current approaches zero. When operating in the zero bias mode the noise current is reduced such that the NEP, and hence the minimum detectable signal, is reduced in spite of some loss of absolute sensitivity.

Risetime (tr)

This is the measure of the photodiode response speed to a stepped light input signal. It is the time required for the photodiode to increase its output from 10% to 90% of final output level (See Response Time).

Maximum Reverse Voltage (Vr Max)

Applying excessive reverse voltage to photodiodes may cause breakdown and severe degradation of device performance. Any reverse voltage applied must be kept lower than the maximum rated value, (Vr max).

Response Time

In many applications the most important parameter is dynamic performance. Photodiode response time is the root mean square sum of the charge collection time and the RC time constant arising from the series plus load resistances and the junction and stray capacitances.

Charge collection time is voltage dependent and is made up of a fast and a slow component. The fast component is the transit time of charge carriers (electrons and holes) through the depletion region, at their respective drift velocities, under the influence of an electric field.

The slow component comes from photon energy absorbed outside the depletion region, producing carriers that are collected by diffusion. The transit time of these carriers will be relatively slow. Figure 6 illustrates the transient response of a photodiode to a square pulse radiation.

When a photodiode is operated in the unbiased mode, the slow diffusion component dominates, giving risetimes of the order of 0.5 μs.

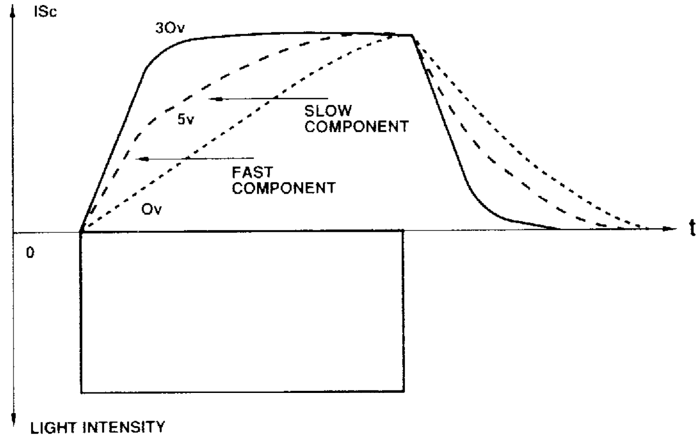

Fig. 6 - Effect of Bias Voltage on Response Time

For a fast response time, silicon resistivity and operating voltage must be chosen to produce a depletion layer within which the majority of the carriers are generated. In this case transit time will be dependent on both electron and hole drift velocities.

The depletion depth necessary for full absorption increases rapidly with operating wavelength. Response times increase correspondingly. This makes it difficult to achieve risetimes faster than 15-20ns at 1064nm, whereas risetimes of less than 2ns are obtainable at or below 900nm.

The Centronic -3T and -4X series take advantage of the increase in drift velocity resulting from a very high electric field. In this structure silicon thickness is reduced to just contain the required depletion depth, and a heavily doped back layer is used to supply the necessary charge to support the depletion region at higher voltage. In this way the operating field, and hence the carrier drift velocities, may be increased without a significant increase in depletion depth.

Further increases in speed may be obtained at the expense of overall sensitivity by using silicon which is not thick enough to allow full absorption of incident radiation.

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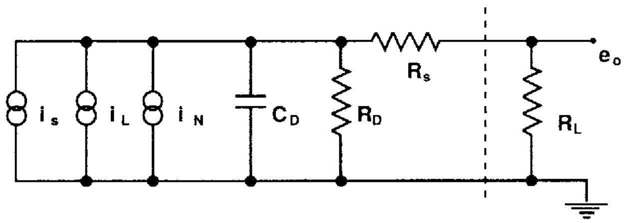
Equivalent Operating Circuits



i_s = signal current
i_L = leakage current
i_N = noise current
C_D = diode junction capacity

R_o = diode parallel shunt resistance
R_s = diode series resistance
R_L = load resistance
$e_o = \frac{(i_S + i_L + i_N)\ (R_L R_D)}{(R_L + R_D + R_S)}$

Fig. 7 - Photodiode Equivalent Circuit

The equivalent circuit of a photodiode is shown (Fig. 7). Fundamentally a photodiode is a current generator. The junction capacitance of the diode depends on the depletion layer depth and hence bias voltage. The value of the shunt resistance is usually high (megohms). The series resistance is low. The effect of the load resistor value on the current/ voltage characteristics is discussed below (Fig. 8).

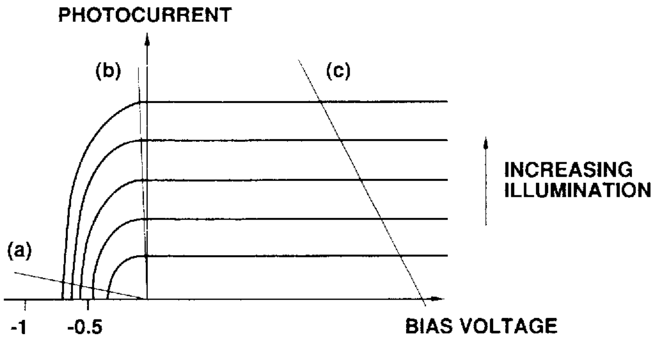


Fig. 8 - Effect of Load Resistor

Photovoltaic Operation

$R_L >> R_D$ (load line (a))

The generated photocurrent flows through R_D (Fig. 7) causing a voltage across the diode. This voltage opposes the band gap potential of the photodiode junction, forward biasing it. The value of R_D drops exponentially as the illumination increases. Thus the photo-generated voltage is a logarithmic function of incident light intensity. The major disadvantage of this circuit is that the signal depends on R_D which typically has a wide spread of values over different production batches. The basic circuit is shown in Fig. 9.

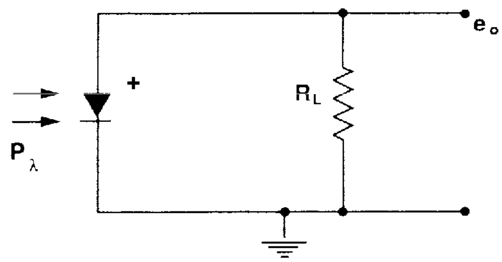


Fig. 9 - Basic Photovoltaic Circuit

Zero Bias Operation

$R_L << R_D$ (load line (b))

The generated photocurrent flows through R_L which is fixed. The resultant voltage is therefore linearly dependent on the incident radiation level. One way to achieve sufficiently low load resistance, and an amplified output voltage, is by feeding the photocurrent to an operational amplifier virtual ground as shown (Fig. 10). This circuit has a linear response and has low noise due to the almost complete elimination of leakage current.

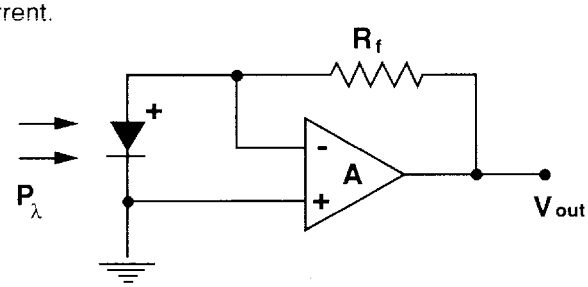


Fig. 10 - Recommended Zero Bias Circuit

Photoconductive Operation

(load line (c))

In the photoconductive mode, the generated photocurrent produces a voltage across a load resistor (see load line (c) Fig. 8), in parallel with the shunt resistance. Since, in the reverse biased mode R_D is substantially constant, large values of R_L may be used still giving a linear response between output voltage and applied radiation intensity. This form of circuit is required for high speed of response. The main disadvantage of this mode of operation is the increased leakage current due to the bias voltage, giving higher noise than the other circuit modes already described. Practical photoconductive mode circuits are shown in Figs. 11 and 12. (Note: In both circuits the photodiode is reverse biased.)

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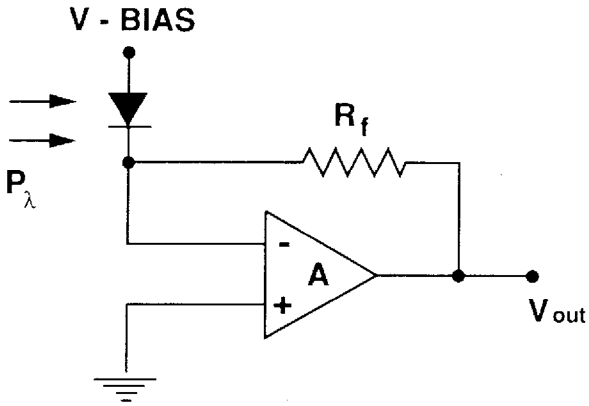


Fig. 11 - Basic Negative Bias Circuit

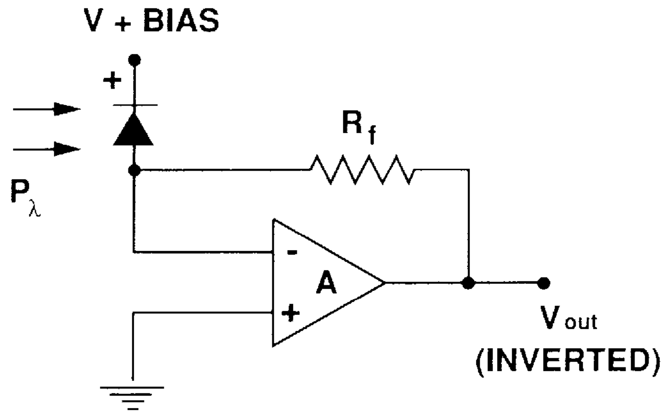
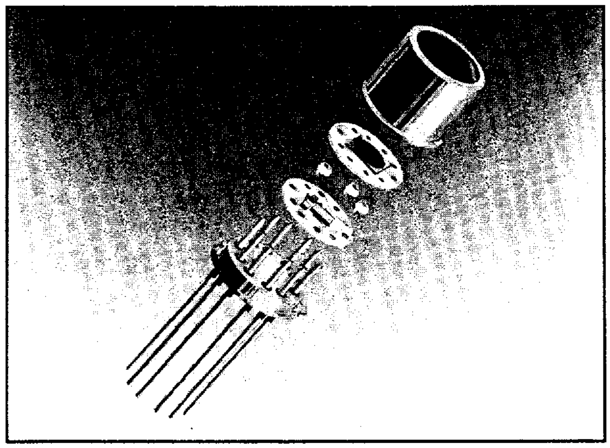


Fig. 12 - Basic Positive Bias Circuit

Hybrid Amplifiers

It is now possible to produce a miniature hybrid photodiode and transimpedance amplifier in a package little different from the basic photodiode. This reduces lead lengths and stray capacitances at the small signal, high impedance amplifier input points. Noise pick up and amplifier generated noise are therefore both kept to the absolute minimum using this technique. Hence, for low noise, high frequency, and user convenience, a hybrid circuit is the optimum device to choose. Centronic has several standard photodiode/op-amp hybrids. Please see our OSI Series on page 30.



Abbreviations

μA	=	Microamps	PC	=	Photoconductive
A/W	=	Amps per Watt	pF	=	Picofarads
Hz	=	Hertz	PV	=	Photovoltaic
I_D	=	Dark Current	R_D	=	Shunt Resistance
Isc	=	Short Circuit Current	R_L	=	Load Resistance
mA	=	Milliamps	R_s	=	Series Resistance
nA	=	Nanoamps	tr	=	Rise Time
NEP	=	Noise Equivalent Power	Vr	=	Reverse Bias Voltage
nm	=	Nanometers	W	=	Watts
ns	=	Nanoseconds	λ	=	Wavelength
pA	=	Picoamps			

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