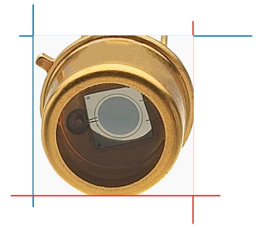

STABILITY

of Silicon Photodiodes for Laser Emission Measurements

The introduction of laser emission safety regulations will necessitate simple instrumentation for user monitoring and regulatory purposes. These instruments must be capable of being accurately calibrated and maintaining their calibrations over long periods and a fairly wide temperature range. This performance must be achieved within the optical transducer. Our objective here is to examine the suitability of silicon photodiodes as the transducer, and to discuss the calibration accuracy, reproducibility and stability that are likely to be achieved from a commercial company.

Device characteristics of Silicon

Within the past year silicon photodiodes have been the dominant sensor in new electro optical instrumentation that has been brought to the market place. This is the result of the determination of the suitability of silicon by a variety of companies and the efforts they have made to improve its stability with time and environmental conditions. The structure of choice for these long-term stable devices has been found to be that depicted in Figure 1. This is a planar passivated structure that incorporates the following features:

A high temperature, planar diffused, P+N junction, a high temperature N plus diffused ohmic contact, an oxide protected junction edge region, a eutectic alloy bonded silicon to metal die attachment, and an ultrasonic aluminum wire bond contact to the front P+ layer. The diffusion processes for creating this structure are carried out at 1,000 C. Boron is the typical P plus acceptor, and Phosphorous, the typical N plus doner. The diffusivities of these impurities in silicon at temperatures below 400ºC are so small as to be immeasurable. The diffused junction parameters, concentration and depth, are thus fixed at high temperature and cannot be changed by operation in low temperature environments below 200ºC. The responsivity of these devices, which is uniquely determined by the junction parameters, similarly cannot change in low temperature operating environments. Long term changes in silicon photodiode responsivity have been observed in the past, arising from nondiffused junction structure, imperfect lead bonding to the junction, and imperfect die bonding of the silicon wafer to the metal header. If the photodiode is operated with an applied reverse bias voltage and a resultant dark leakage current factor which doubles for every 10 degrees centigrade increase in temperature. For this reason, the recommended mode of operation is a photovoltaic, unbiased short circuit collecting mode in which the photodiode signal current is fed to a minimum impedance such as that presented by the inverting input of an operational amplifier. When this mode of operation is used, the silicon photodiode, which is a quantum sensor without gain, exhibits a responsivity (in units of microamps of current out versus microwatts of light power in), that is independent of the absolute value of light power incident on the device. A typical linearity plot for a silicon photodiode is shown in Figure 2. The low limit of this input/output relationship is established by the noise in the photodiode, and has a value between 10^{-12} and 10^{-15} watts depending on the size of the active area, the mode of operation, and the manufacture. The upper limit varies between 10 milliwatts and 500 milliwatts depending on the area of the incident spot of light, and the detailed constructional features of the sensor. A typical planar diffused photodiode, a PIN-10D, with an active area of one centimeter squared and capable of detecting light from 10^{-12} watts to 10^{-2} watts is shown in Figure 3.

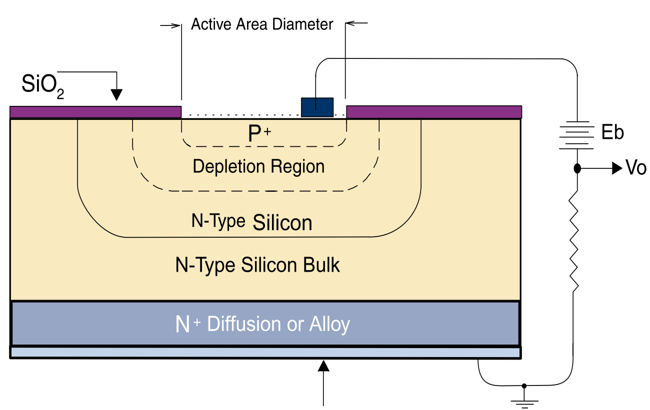

Figure 1 Aluminium Metalization

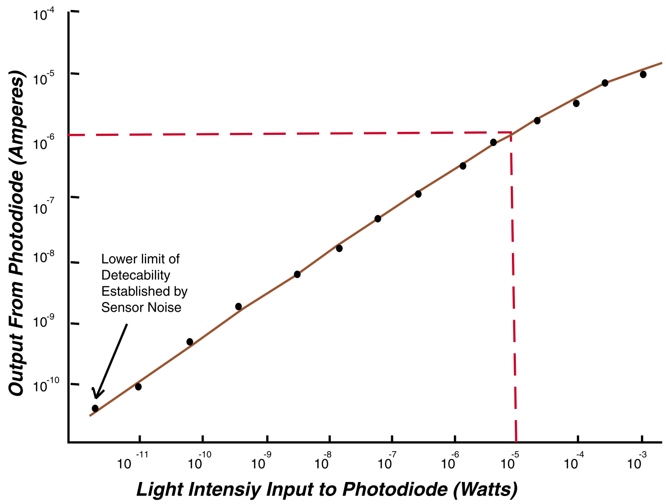

Figure 2. Typical Input/Output Linearity Plot For A Silicon Photodiode.

Figure 3

A 1cm² PLANAR DIFFUSED SILICON PHOTODIODE.

The incident light power level at which the photodiode begins to saturate depends on light power density rather than light power itself. This occurs because the saturation power level is associated with that rate of incoming photon flux per unit area and per unit absorption depth which create a charge density within the PIN junction which exceeds the background doping density of the base silicon wafer. When operated within its linear range, there is no known mechanism for hysteresis or degradation with time for planar diffused silicon photodiodes. The response time of silicon photodiodes can be tailored to be as low as 1 nanosecond and is again a function of active area.

There are, however, four factors, which must be understood when utilizing silicon photodiodes as absolute light sensors.

1.Responsivity changes with temperature.
2.Responsivity non-uniformity over the device active area.
3.Optical properties of coupling the light into the sensor.
4.Saturation flux density.

1) Responsivity changes occur in silicon due to the band gap of the material having a negative temperature coefficient; in other words, as heat is applied, the band gap becomes smaller. This results in an apparent shift of the responsivity curve towards higher wavelengths; the longer wavelengths, beyond room temperature peak, becoming more sensitive, the shorter, less sensitive. The change in responsivity at the higher wavelengths being much more significant due to the larger curve gradient. At 1.06um, the temperature coefficient of responsivity has been measured, for 4000 ohm centimeter N type material, to be on the order of +0.8*/C while in the visible 0.4 - 0.75% um is on the order of - 0.1%/C. Figure 4 shows a typical diffused silicon responsivity curve.

2). Non uniformity of responsivity over the active area of the devices may be caused by a variety of device imperfections, the most significant of which being the junction profile within the photodiode. This is basically a manufacturing problem, however, some manufacturers will now guarantee a uniformity of 3% on instrument rated detectors and better performance can be provided.

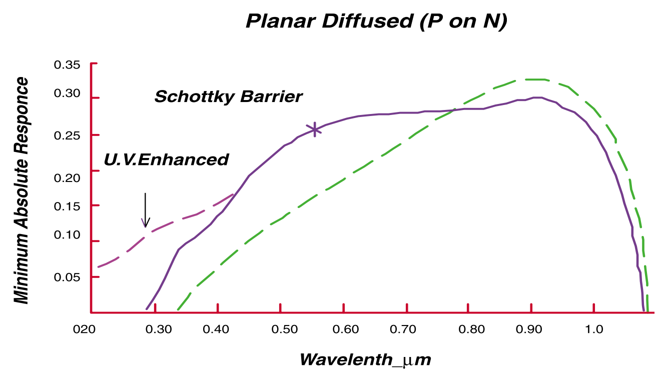

Figure 4. Spectral Responsivity (minimum) for Silicon PIN

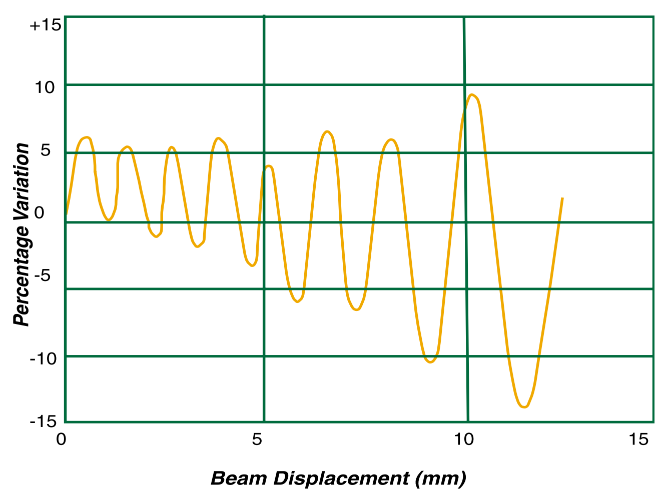

Figure 5. Spatial Variation of Detector output when illuminated

Reference Standard

Standard	Calibration Derivation	Wavelength	Claimed Accuracy
Spectral Irradiance Lamp1000 W Quartz-Halogen Lamp Mfg: General Electric Co.	1973 NBS scale of spectral irradiance Dr. H.J. Kostkowski	450nm 630nm 800nm	1.2% .8% .9%
Light Emitting Diode Assembly Mfg: Calif. Optoelectronic Ind.	1973 NBS scale of spectral irradiance Dr. J.B. Schumaker	666nm	2.5%
Silicon Photodiode Type PIN-10Mfg: United Detector Technology	Physikalisch-Technische Bundesanstalt Thermopile reference Dr. Bischoff	546nmRange -265nm - 1120nm	2% 1% (relative)
Silicon Photodiode Type PIN-10 Mfg: United Detector Technology	National Research Council of Canada Dr. C.X. Dodd	Range - 350nm - 800nm	Not specified
Silicon Photodiode Type PIN-10 openMfg: United Detector Technology	1973 NBS scale of spectral irradiance Boulder, Colorado Transfer calibration Mr. Tom Russel	632.8nm	5%

Detector No.	P.T.B.	Lamp-/Filter	Detector-/N	L.E.D.	Spread
3899	0.325	0.313	0.312	0.316	4%
3593	0.340	0.329	0.326	0.324	5%

Table 2. Comparison of Detector Responsivity At 630 nm

3) The optical coupling of light to silicon photodiodes requires that very special attention be given to all the optical interfaces, especially in the case of a laser where optical attenuation is usually required to prevent flux density saturation. The reflectivity of an uncoated silicon photodiode varies from 47% @ 400nm to 32% @ 900nm; also for protection, a glass window is usually incorporated into the sensor construction. These interfaces can become interference cavities when illuminated with coherent radiation which gives rise to additional spatial non uniformity's of which Figure 5 is a typical example.

4) The cause of flux density saturation was described previously but it is important to be understood: responsivity and stability studies have been carried out by several eminent bodies at levels well into saturation.

Instrumentation can be designed using suitable silicon photodiodes to make power or energy measurement limited in long term stability only by the above constraints. However, the absolute calibration and the repeatability of calibration of the instrument over long periods as ascribed by the manufacturer's calibration laboratory, will introduce additional uncertainty.

Calibration of Silicon Photodiodes

The following discussion examines the results we have achieved in our calibration laboratory as being an example of the type of traceability available from a commercial manufacturer. We currently have four references from which to obtain absolute calibrations; they are: 1) a 1,000 watt spectral irradiance lamp, 2) a light emitting diode 3) P.T.B. calibrated detectors 4) N.B.S. transfer calibrated detectors and 5) N.R.C calibrated detectors. The generic traceability of these references is given in Table 1.

In January of this year we did our first cross correlation between these references @ 630nm and included the LED calibration in March. Table 2 shows a synopsis of the results of this cross correlation in terms of the responsivities determined for the two detectors that had originally been calibrated by P.T.B. The first column values are those given by the German Bureau. The second set was obtained by illuminating the detectors with the spectral irridiance lamp through a narrow bandpass interference filter, from the known characteristics of the lamp and filter determining the responsivity: correction for out of band transmission
(Which amounted to 2%) were made by assuming the P.T.B responsivity values as being correct at other wavelengths. The third column values were obtained by detector responsivity transfer from N.B.S. Colorado calibrated detector by means of a monochromator. The fourth directly from the LED standard and compensating for the wavelength difference (about 4%) by means of the spectral response curve for the detectors.

We have compared the calibration of P.T.B. and the spectral irradiance lamp at two other wavelengths, 450nm and 880nm and find better than 2% agreement between the detectors @ 800nm and an 11% disagreement @ 450nm. We have chosen to calibrate detectors by determining their relative spectral response and ascribing an absolute value @ 630nm. We were aided in reaching this decision by two detectors calibrated in relative spectral response by the National Research Council of Canada and strengthened by the fact that when the N.R.C detectors were compared with the P.T.B. detectors in our laboratory, all four relative spectral responses agreed within 3% at all wavelengths between 450nm and 1,000nm. Below 450nm there is considerable disagreement, which is univestigated at this time.

Detector	L.E.D.	Laser	Spectral	Irradiance	Lamp
S/N	1 666.0nm	1 632.8nm	l630nm	l450nm	l800nm
	N.B.S. Cal	N.B.S. det. Cal	Dl11nm	Dl10nm	Dl12nm
4732	0.454	0.438	0.441		
0.436	0.454	0.436	0.439		
0.443	0.457	0.443	0.445		
0.436	0.456	0.436	0.444		
0.435	0.453	0.435	0.441		
0.437	0.457	0.437	0.442		
0.426	0.452	0.426	0.442		
35337	0.45	0.438	0.432		
		0.436	0.442		
PTB 1	0.446	0.310	0.438		
PTB2	0.334	0.309	0.323		
4655	0.327	0.318	0.312		
D4	0.335	0.311			
NBS 1	0.341	0.332			

TABLE 3 DETECTOR RESPONSIVITY mA/mW

Run		L.E.D.	Laser	Lamp		
Date				630nm	450nm	800nm
13/28/74	Mean Standard Deviation	1	1	1	1	1
24/11/74	Mean Standard Deviation	1.00 2.8 x 10fl3	1.01 3.6 x 10fl3	1.00 3.3 x 10fl3	1.05 4.4 x 10fl3	1.06 5.2 x 10fl3
34/24/74	Mean Standard Deviation	0.99 3.6 x 10fl3	1.01 8.5 x 10fl3	1.01 5.7 x 10fl3	1.06 7.4 x 10fl3	1.04 1.0 x 10fl2
45/17/74	Mean Standard Deviation	0.99 6.7 x 10fl3	1.00 2.7 x 10fl3	1.01 3.6 x 10fl3	1.07 8.8 x 10fl3	1.04 4.4 x 10fl3

TABLE 4 COMPARISON OF CALIBRATION MEANS FROM RUN TO RUN

At the end of February, we began a new program in an attempt to monitor our calibration facility. Fifteen PIN-10D detectors were selected, that would be calibrated using: the spectral irradiance lamp; the LED; and a helium neon laser, this group included the P.T.B. detectors and the N.B.S. Colorado calibrated detectors. The PIN-10D, which is a 1cm^2 active area device, was chosen on the grounds of being a widely used general purpose detector that includes all the features of correct construction and design described previously. The "selection" was made only on the basis that an individual device met our "instrument rated" specifications. Table 3 shows a typical result in terms of detector responsivity while Table 4 shows the arithmetic means and standard deviations of the ratio of the responsivities between a particular run and the first run. Table 5 has assumed that the arithmetic mean in Table 4 represents a real change and has divided the detector ratios by the arithmetic mean and presented the percentage variance from units for each detector. This shows that with the exception of one detector, P.T.B. 2, the detector variance in this albeit short time has been negligible. This Table is made more significant by the fact that there has been some noticeable change in the lamp experiments.

The calibration data presented is experimental fact with no great effort taken to examine the uncertainties since this data will be typical and perhaps better than what will have to be worked with in field use.

In conclusion, we feel that silicon photodiodes do, in their own right meet the sensor requirements for regulatory purposes, and within their spectral range only look better by comparison with other alternatives. However, a great deal of care will be required to establish nationwide measurement and define practical tolerances that can withstand litigation.

Detector S/N	Run 2	Run 3	Run 4
4732	0.01	-0.02	0.19
4742	0.15	0.56	0.31
4809	0.02	0.02	0.03
4861	0.06	0.60	0.27
4923	0.11	0.52	0.51
5122	0.06	0.36	0.33
5178	-0.10	0.30	0.25
5214	0.05	0.27	0.05
5293	0.18	0.04	0.03
5337	0.13	-0.06	0.09
PTB1	0.13	-0.51	-0.02
PTB2	-0.62	-1.16	-1.13
4655	0.09	-0.06	-0.01
D 4	-0.1	-0.54	-0.34
NBS	-0.16	-0.30	-0.56

TABLE 5 PERCENTAGE VARIANCE OF DETECTOR RESPONSIVITY MEAN

For applications where little space is available or reduced component count is desired, UDT provides a product line of detector - op-amp combinations called PHOTOPS ™. In some cases feedback elements can be provided to give specified gain, volts/watt. The standard line of PHOTOPS™ consist of 5.1mm^2 diameter photodiode and an op-amp. Specifications are provided to enable the user to calculate system performance exactly as would be done with discrete elements.