Silicon Photodiodes - UVG Series

UVG Operating Principles

When the diode is exposed to photons of energy greater than 1.12 eV (wavelength less than 1100 nm), electron-hole pairs (carriers) are created. These photogenerated carriers are separated by the p-n junction electric field and a current proportional to the number of electron-hole pairs created flows through an external circuit. Ultraviolet photons, with wavelength shorter than about 350 nm, create more than one electron-hole pair [1]. This results in internal quantum efficiencies greater than unity as shown in Figure 1.

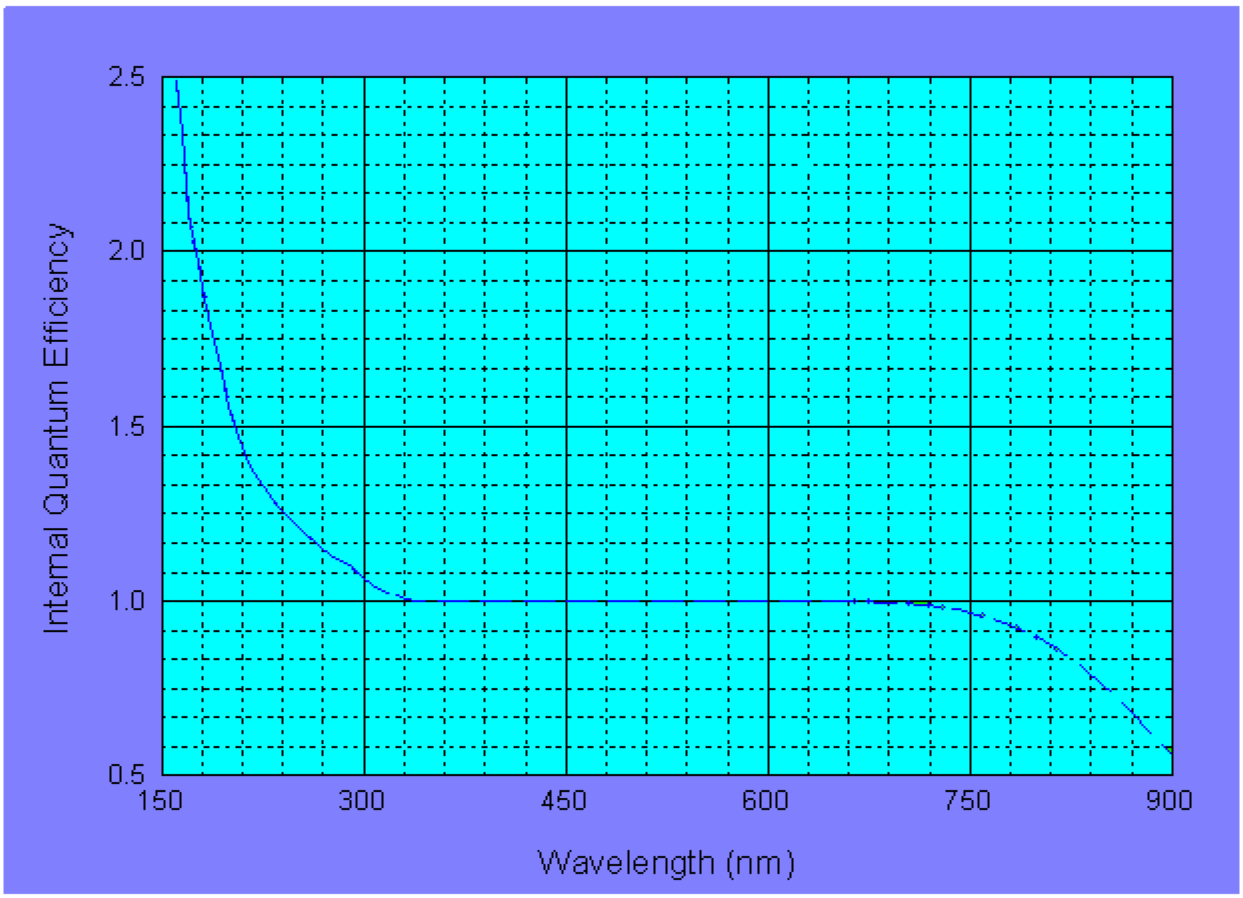


Fig. 1: Internal quantum efficiency of UVG photodiodes

Two unique properties of the UVG photodiodes have resulted in previously unattained stable and 100% collection efficiencies and near theoretical quantum efficiencies.

The first property is the absence of a surface dead region i.e. no photogenerated carrier recombination occurs in the doped n-type region and at the silicon-silicon dioxide interface. As the absorption depths for the majority of UV photons are less than 1 micrometer in silicon, the absence of a dead region yields complete collection of photogenerated carriers by an external circuit resulting into 100% collection efficiency. The flat region from 310 nm to 640 nm in Figure 1 shows that these diodes have 100% collection efficiency.

References:

1] R. Korde and J. Geist, "Quantum Efficiency Stability of Silicon Photodiodes"

Applied Optics, Vol. 26, 5284-5290 (1987).

UVG Radiation Hardness

The second unique property of the UVG diodes is their radiation hard, junction passivating, oxynitride protective entrance window.This super-hard window makes them extremely stable after exposure to intense flux of UV photons. They show less than 2% responsivity degradation after megajoules/cm² of 254 nm and tens of kilojoules/cm2 of 193 nm photon exposure. Because of the oxynitride window, UVG photodiodes did not show any change in uv-visible quantum efficiency after their exposure to 100% relative humidity for several weeks. This unique feature enables their use without the commonly used fused silica protective window. This open face configuration is extremely advantageous in applications where the fused silica window interference effects are problematic.

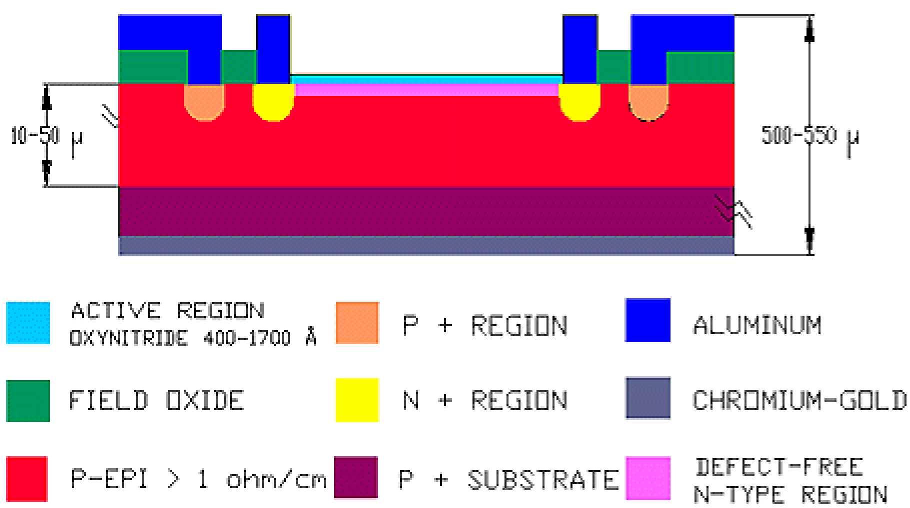
Owing to these outstanding properties, national laboratories like NIST and PTB (Germany) are evaluating UVG photodiodes for use as transfer standards.

As n-on-p diodes are more radiation-hard than the more common p-on-n devices [1], UVG diodes are better suited for space missions than conventional silicon photodiodes. UVG photodiodes with 4 mm and 5 mm diameter active area are being used in the Multi-Angle Imaging Spectro Radiometer (MISR) launched in December 1999as part of NASA's Earth observing system [2]. These devices will also be used aboard an Argentinean satellite.

References

R. Korde et. al. "The effect of Neutron Irradiation on Silicon Photodiodes" IEEE Trans. on Nuclear Sciences, Vol. 36, 2169-2175 (1989).

C. Jorquera et. al. "Design of New Photodiode Standards for use in the MISR In-Flight Calibrator" Proc. of IGARSS' 94, IEEE Catalog Number 94CH3378-7, 1998-2000 (1994).



UVG Internal Quantum Efficiency

Recently, 1 cm^2 active area UVG-100 diodes were used to determine quantum yield (number of electron-hole pairs generated per absorbed photon) of silicon in 254 nm to 160 nm spectral region [1]. Quantum yield in this region has been determined for the first time and can be seen in figure1 from 320 nm to 150 nm.

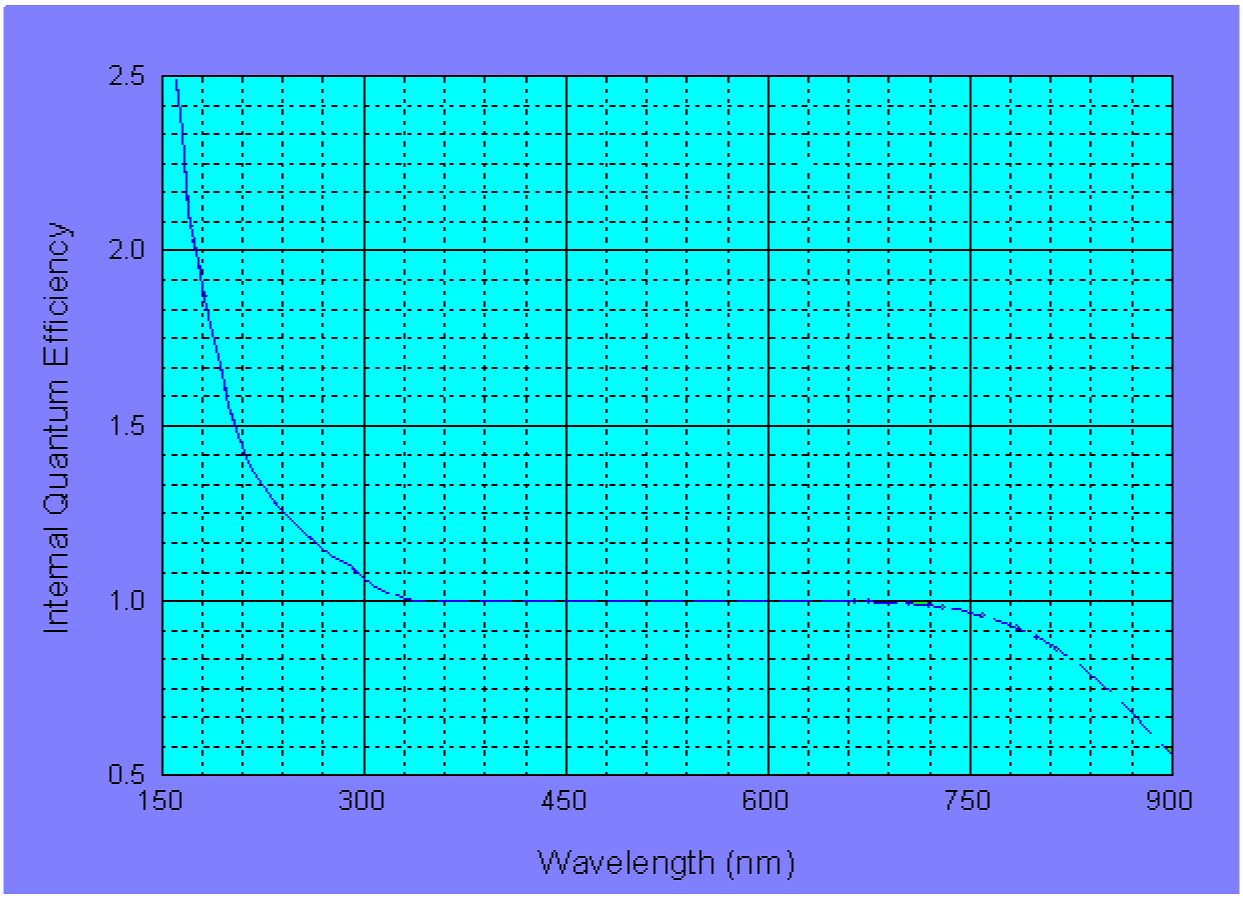


Fig. 1: Internal quantum efficiency of UVG photodiodes

This quantum yield knowledge now makes possible development of trap detectors for absolute flux determination in applications like deep UV lithography, and photorefractive and phototherapeutic keratectomy. Owing to their 100% collection efficiency, the external quantum efficiency of UVG-series photodiodes can be calculated in the UV and short wavelength visible (about 160 nm to 600 nm) as the product of the internal quantum efficiency times one minus the reflectance of the photodiode. The internal quantum efficiency can be taken from figure 1 and the reflectance can be measured or calculated. Figure 2 shows the measured reflectance from 150 nm to 1100 nm for the UVG series photodiodes with 70 nm oxynitride front window.

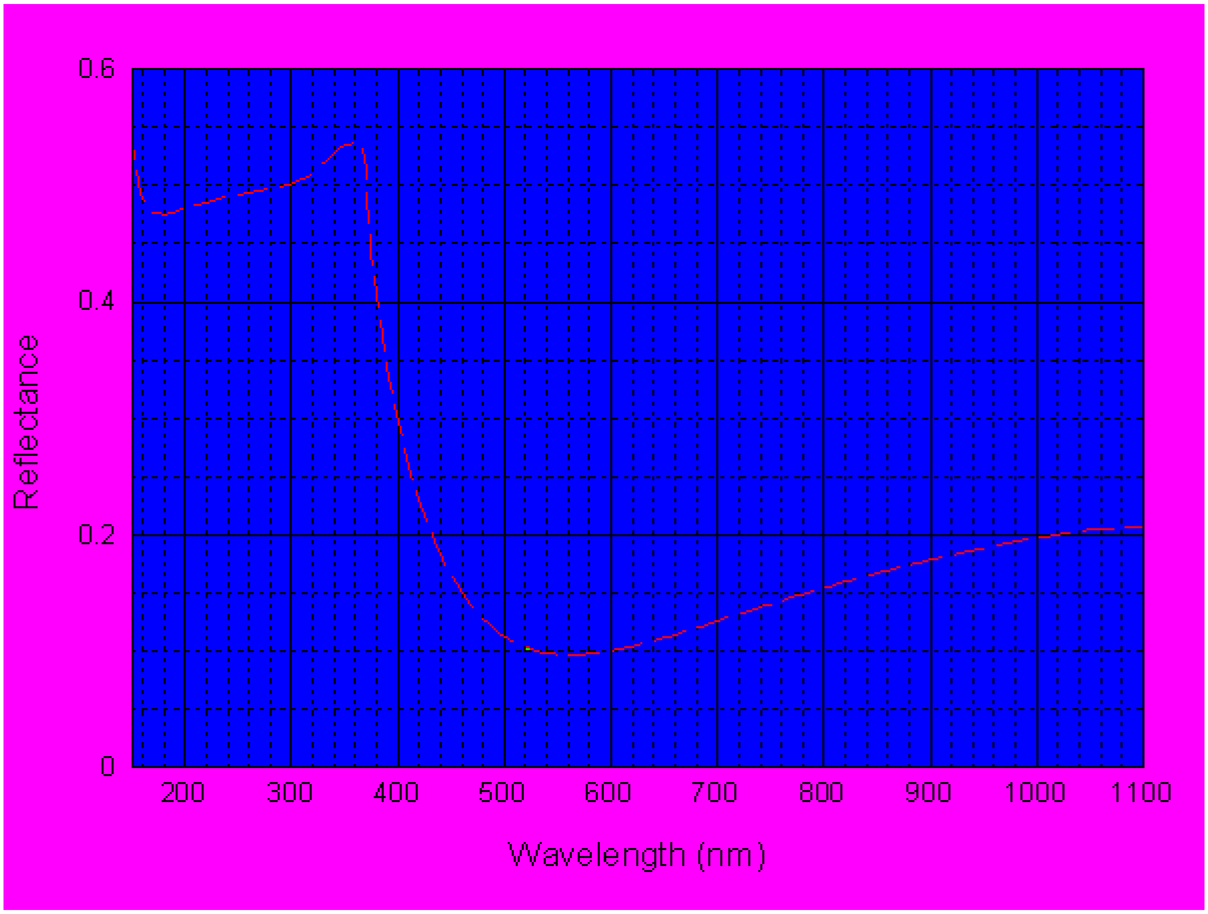


Fig. 2: Typical reflectance of UVG series photodiodes.

References:

1] L.R. Canfield et. al. "Absolute Silicon Photodiodes for 160 nm to 254 nm Photons"

Metrologia, Vol. 35, 329-334 (1998)

UVG-20 Linearity

Figure 1 shows the linearity of the UVG-20 photodiode and a widely used P on N photodiode of equivalent area when exposed to increasing levels of 430 nm radiation. The standard ac-dc method was used to measure linearity. The P on N photodiode showed a noticeable decrease in responsivity at photocurrents greater than 500 µA while the UVG-20 photodiode showed only 0.02% decrease in responsivity at a photocurrent of 3 mA. Application of a reverse bias will extend the linear range of the UVG photodiodes when measuring UV radiation.

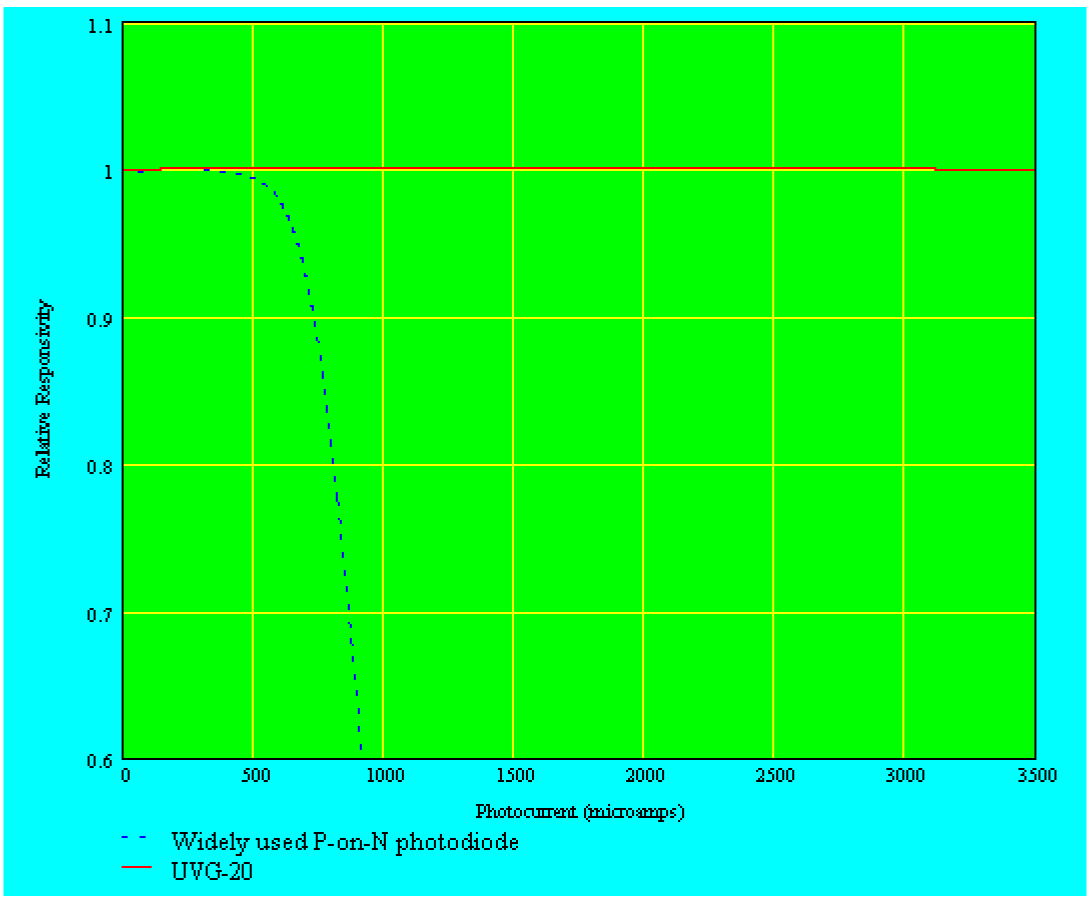


Fig. 1: Linearity of UVG-20 photodiode and a widely used P-on-N photodiode when tested at 430 nm with no reverse bias.

It is believed that the difference in the series resistance of these diodes can explain the large difference in linear range.

Figure 2 shows the linearity of a UVG-20 diode and a P-on-N photodiode with an internal quantum efficiency of 80% at 430 nm. This 80% IQE is a result of photogenerated carrier recombination in the front region. The supralinearity (increased responsivity) in the low IQE device is caused by the filling of trap centers with increasing flux [1]. As the trap centers are filled the minority carrier lifetime increases reducing the photogenerated carrier recombination resulting in increased responsivity. The UVG series photodiodes have 100% internal quantum efficiency (no photogenerated carrier recombination) at 430 nm so they show no supralinearity. Because it is difficult to correct for non-linearity errors, high accuracy applications require linear photodiodes like the UVG series diodes.

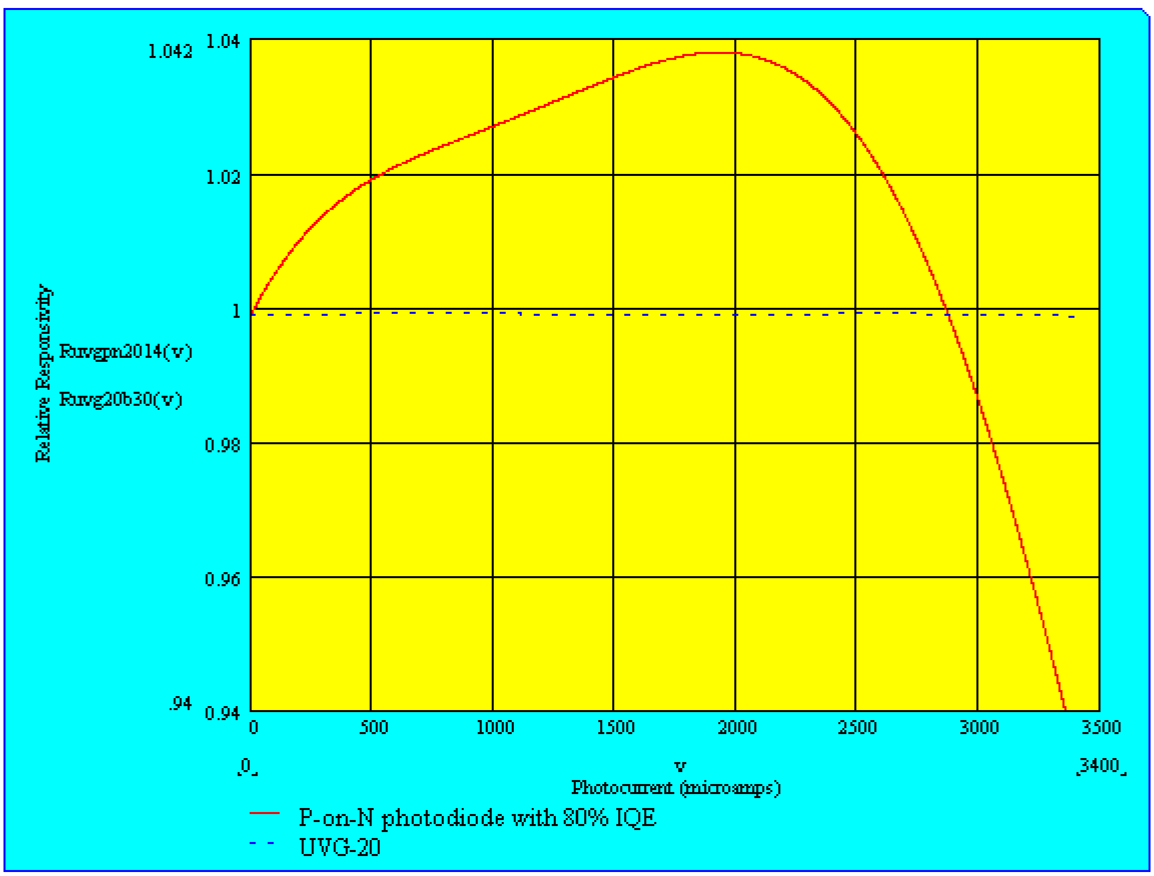


Fig. 2: Linearity of P-on-N photodiode with 80% internal quantum efficiency and UVG-20 photodiode with 100% internal quantum efficiency.

Figure 3 compares the linearity of the UVG-20 photodiode and a widely used P on N photodiode with equivalent area when exposed to increasing levels of 980 nm radiation. The P on N photodiode showed noticeable supralinear behavior for photocurrents above 20 µA while no noticeable supralinearity was observed in the UVG-20 diode. At high irradiance levels, the P-on-N photodiode was found to lose responsivity much more rapidly than the UVG series diode.

As the UVG series diode internal quantum efficiency drops rapidly after 700 nm owing to the limited silicon thickness, IRD also provides P-on-N photodiodes (for example: UVG-PN100, UVG-PN20, etc.) which have shown over 97% internal quantum efficiency at 950 nm.

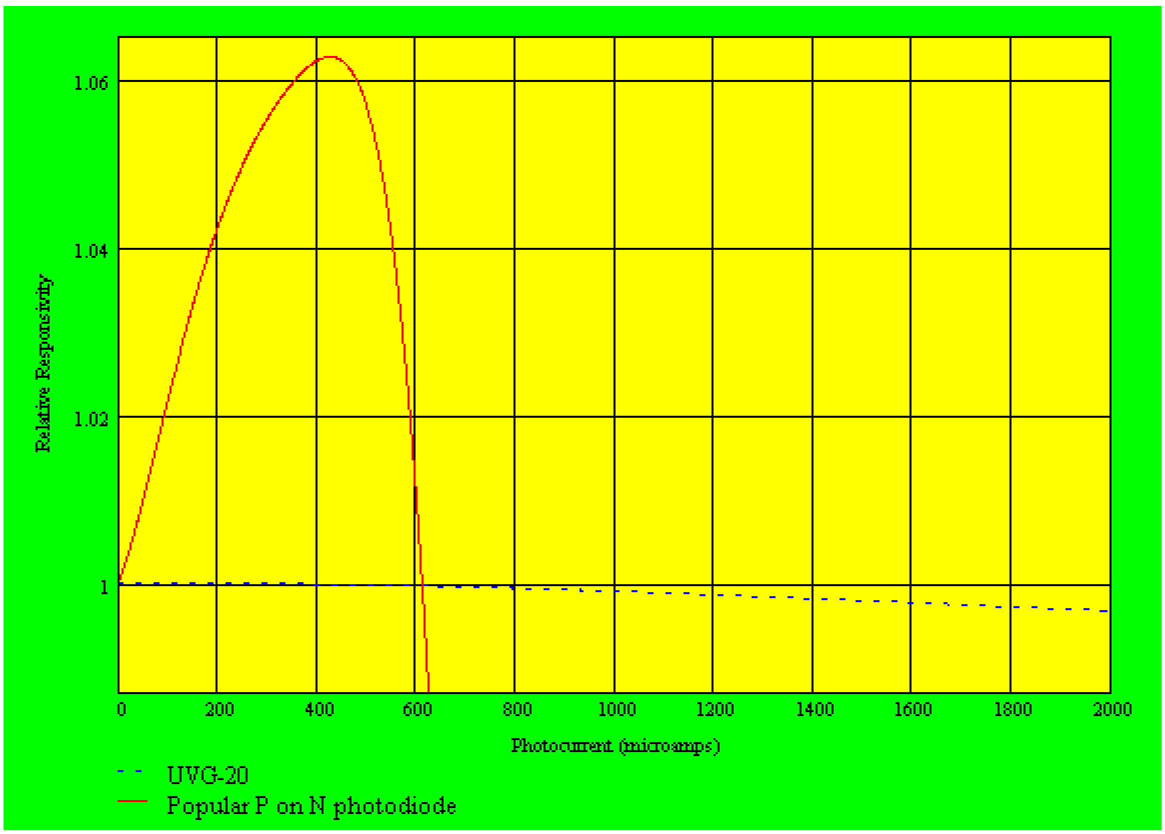


Fig. 3: Linearity of UVG-20 photodiode and widely used P-on-N photodiode when tested at 980 nm with no reverse bias

Interestingly, the linearity of the IRD P-on-N diodes (IRD model # UVG-PN20) was exactly the same as that of the standard UVG-20 diode depicted in Figure 3. Also, the internal quantum efficiencies of the IRD P-on-N and the widely used P-on-N photodiodes are nearly equivalent at 980 nm indicating they will have the same minority carrier lifetime. This suggests that the minority carrier lifetime (diffusion length) is not the only factor which determines the supralinearity as was previously believed [1].

The substrate doping concentration of the UVG-PN20 diode is 2 x $10^{13}/cm^3$ and that of the widely used P-on-N diode is 5 x $10^{12}/cm^3$. Computer modeling has shown that this difference in the starting materials can qualitatively explain why these photodiodes exhibit such different levels of supralinearity.

Figure 4 shows the structure of the UVG-PN20 photodiode that was investigated.

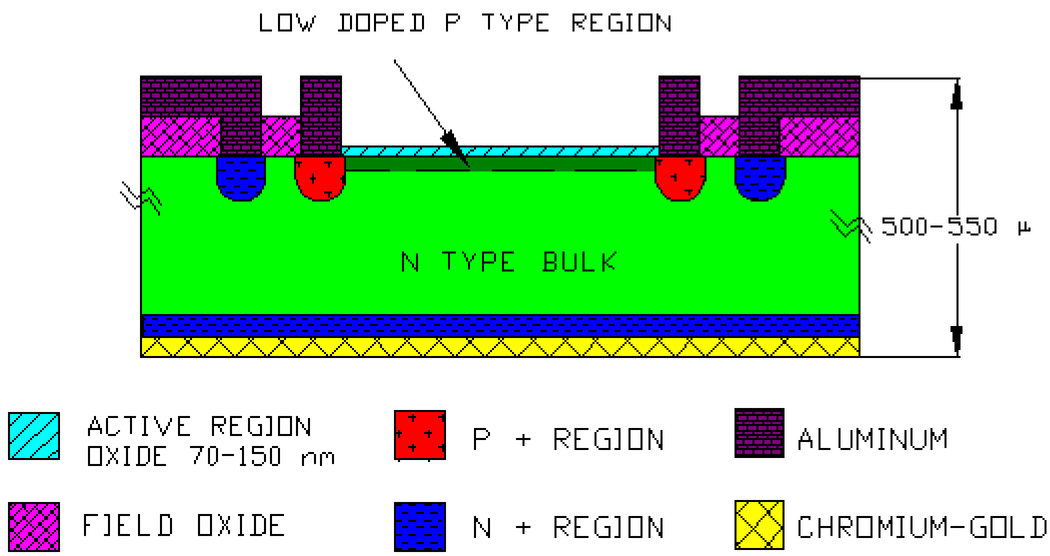


Fig. 4: Structure of the UVG-PN20 photodiode

References:

1] A.R. Schaefer, E.F. Zalewski, and Jon Geist "Silicon detector nonlinearity and related effects"

Applied Optics, Vol. 22, 1232-1235 (1983)

UVG Uniformity / Spectral Response

Response uniformity of a 10 mm X 10 mm active area IRD photodiode used by NIST as a transfer standard in the 5 nm to 254 nm spectral region is shown in Figure 1. The response uniformity was within ± 0.5% when scanned with a 254 nm photon beam of 1 mm dia. For comparison, Figure 2 shows the uniformity of the UV enhanced diode which NIST currently uses as a transfer standard in the 200 nm to 400 nm spectral range [1]. As seen in Figure 2, the response uniformity of this device was within ± 2%.

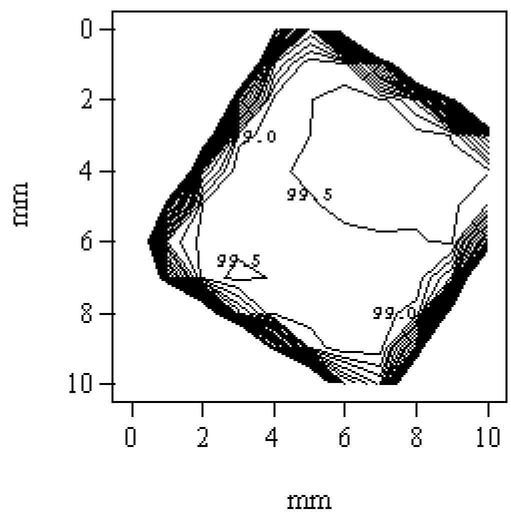


Fig. 1: Uniformity of IRD photodiode at 240 nm [1].

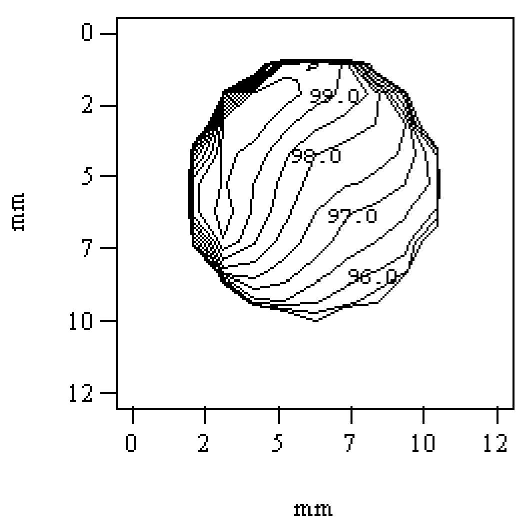


Fig. 2: Uniformity tested at 240nm of UV enhanced photodiode used by NIST as a transfer standard for 200nm to 400[1]

The excellent spatial response uniformity of IRD photodiodes will provide better reproducibility than other commercially manufactured photodiodes and therefore exhibit a lower overall measurement uncertainty.

References:

1] Ping-Shine Shaw et. al. "The new ultraviolet spectral responsivity scale based on cryogenic radiometry at Synchrotron Ultraviolet Radiation Facility III"

Rev. of Sci. Instruments, Vol. 72, 2242-2247 (2001)

UVG Responsivity Stability

Responsivity Stability

It has been known for a number of years that silicon photodiodes show degradation in responsivity or linearity when exposed to intense UV flux [1,2].

The major UV induced instability arises because of inferior quality of the silicon-silicon dioxide (Si-SiO_2) interface [1]. Passivating layers other than silicon dioxide have been investigated recently to improve the interface quality of silicon devices. Among the many alternative passivating coatings reported, silicon oxynitrides (nitrided oxides) look promising. Oxynitrides have been shown to have higher resistance to ionizing radiation and impurity diffusion compared to pure oxides [3]. It has been postulated that the energy required to break a Si-N bond is much greater than that required to break Si-H or Si-OH bonds. Thus, less interface states are created in a nitrided device after exposure to UV radiation.

The above point was verified by us recently when diodes with 1 G-rad (SiO_2) hardness [4] were fabricated by incorporating nitrogen in the passivating oxide. It may be noticed here that this hardness is about 10,000 times the hardness of commonly used p-on-n photodiodes, and is the highest hardness ever reported or is known to exist in any silicon device.

Two other causes may be pointed out for quantum efficiency instability of silicon photodiodes. The first cause is formation of latent recombination centers by metallic impurities like silver [5]. These recombination centers become active over a period of several years causing a long term loss in quantum efficiency.

The other cause for quantum efficiency degradation is moisture penetration into the device over a long period of time. Moisture is suspected of causing recombination centers near the oxide-silicon interface leading to the quantum efficiency loss [6].

To minimize the effects of the above quantum efficiency instability mechanisms, UVG photodiodes were fabricated in an extremely clean environment to have negligible latent recombination centers and a trap-free, moisture insensitive Si-SiO_2 interface. Nitrogen incorporation in the Si-SiO_2 interface is known to make it insensitive to impurity penetration. Fig. 1 shows a quantum efficiency plot of our UV-enhanced diodes before and after exposure to 100% relative humidity. These diodes were fabricated by nitrogen incorporation at the interface and hence have exhibited no change in the 50 to 250 nm quantum efficiency even after 4 weeks of 100% relative humidity exposure at room temperature [4].

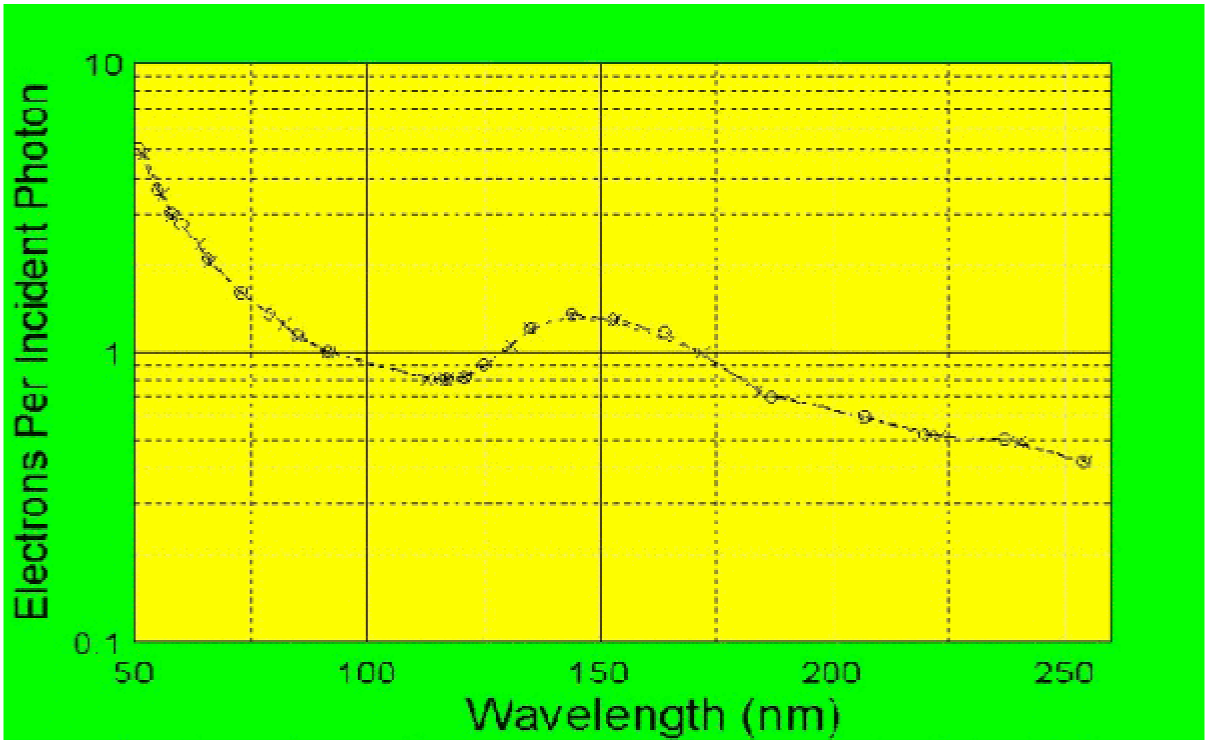


Fig. 1: Quantum efficiency of UV-enhanced photodiodes with 60 Å oxynitride passivating front window. O Before exposure, X after exposure to 100% relative humidity for 4 weeks.

Figures 2 and 3 show the responsivity stability of the UVG series diodes after exposure to intense radiation at 254 nm and 193 nm respectively. The 254 nm exposure was performed by a 20 mW/cm^2 low pressure mercury lamp. A Lambda Physik ArF excimer laser with 100 Hz pulse repetition rate and an energy density of 200 mJ/cm^2 (3.9 W at 100 Hz) was used to carry out the 193 nm stability test.

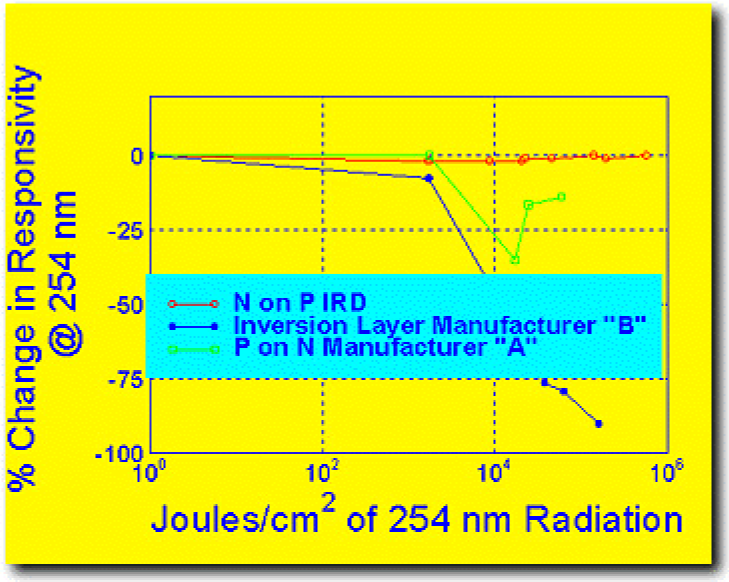


Fig. 2: Stability of a UVG series diode compared to other types of diodes after exposure to 254 nm radiation

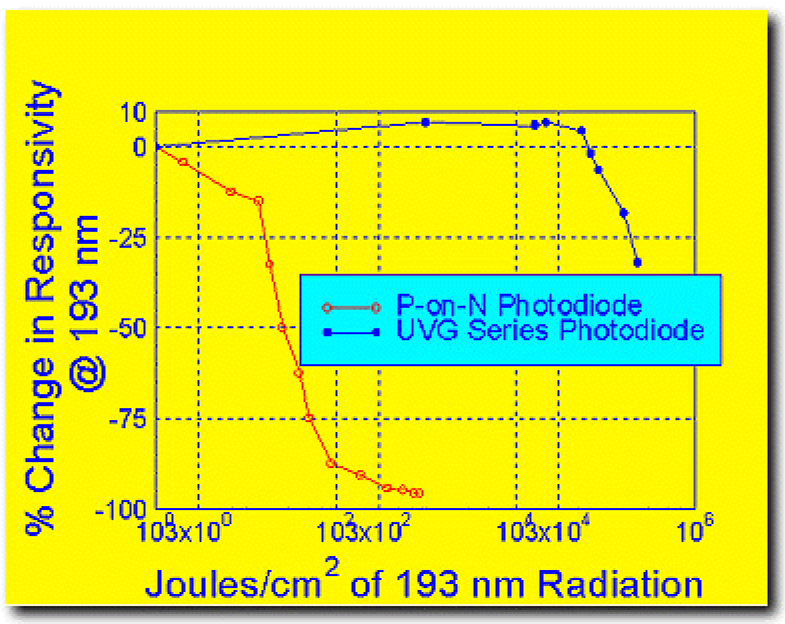


Fig. 3: Stability of a UVG series diode compared to p-on-n diode when exposed to 193 nm radiation.

Fig. 4 shows the response of three types of silicon photodiodes used to test the stability of Nichia 378 nm LED. Current through the photodiodes was about 61 nA. It is interesting to note that the p-on-n and the inversion layer diodes indicate that the long term stability of Nichia UV LED is questionable!

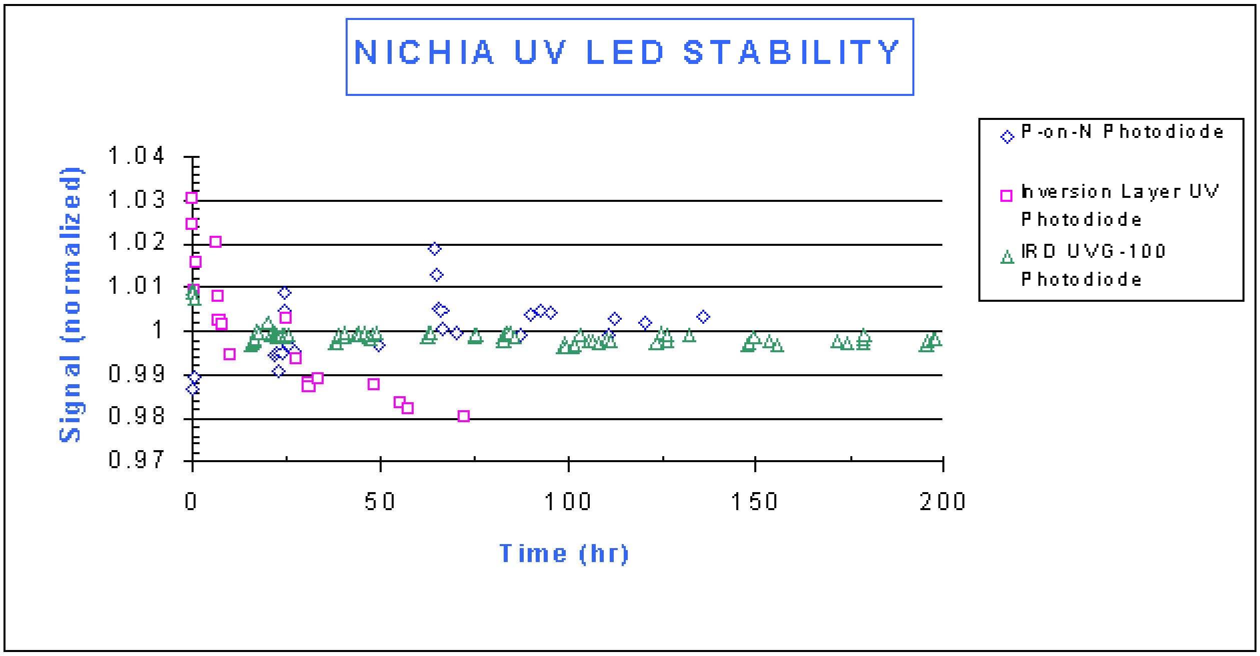


Fig. 4: Nichia 378 nm LED stability measured with p-on-n, inversion layer, and the UVG-100 photodiodes [7].

References:

1] R. Korde and J. Geist, "Quantum Efficiency Stability of Silicon Photodiodes", Applied Optics, Vol. 26, 5284-5290 (1987).

2] K. D. Stock, "Regeneration of the Internal Quantum Efficiency of Silicon Photodiodes," Inst. Phys. Conf. Ser. No. 92, 167-171 (1988).

3] For example, see : "Ultra-thin Dielectrics for Semiconductor Applications - Growth and Characteristics" H. R. Harrison and S. Dimitrijev, Microelectronics Journal, Vol. 22, 3-38 (1991).

4] R. Korde, J. Cable and R. Canfield, "100% Internal Quantum Efficiency Silicon Photodiodes with One G-rad Passivating Silicon Dioxide" IEEE Trans. on Nuclear Sciences, Vol. 40, no. 6, 1655-1659 (1993).

5] V.G. Weizer et al., "Photon Degradation Effects in Terrestrial Silicon Solar Cells," J. Appl. Phys. Vol. 50, 4443 (1979).

6] L. Manchandra, "Hot Electron Trapping Generic Reliability of p+ Polysilicon/SiO2 /Silicon Structures for Fine Line CMOS Technology," in 24th Annual Proceedings, Twenty-Fourth Annual Conference on Reliability Physics IEEE, 183-186 (1986).

7] Courtesy of Donald F. Heath, Research Support Instruments, Boulder Co.

UVG Performance Characteristics

A less than 1% change in the 254 nm responsivity was observed when UVG photodiodes were subjected to the following accelerated testing.

1. Exposure to 100% relative humidity at room temperature for a week
2. Exposure to 20 mW/cm^2 254 nm radiation for two weeks and
3. Baking at 100° C for four weeks.

Thus, it is clear that UVG-series diodes possess excellent long term stability as well as radiation hardness.

Reponse uniformity of UVG diodes over 10 mm x 10 mm active area was within +/- 0.5% when scanned with a 254 nm photon beam of 1 mm diameter and is shown in Figure 1.

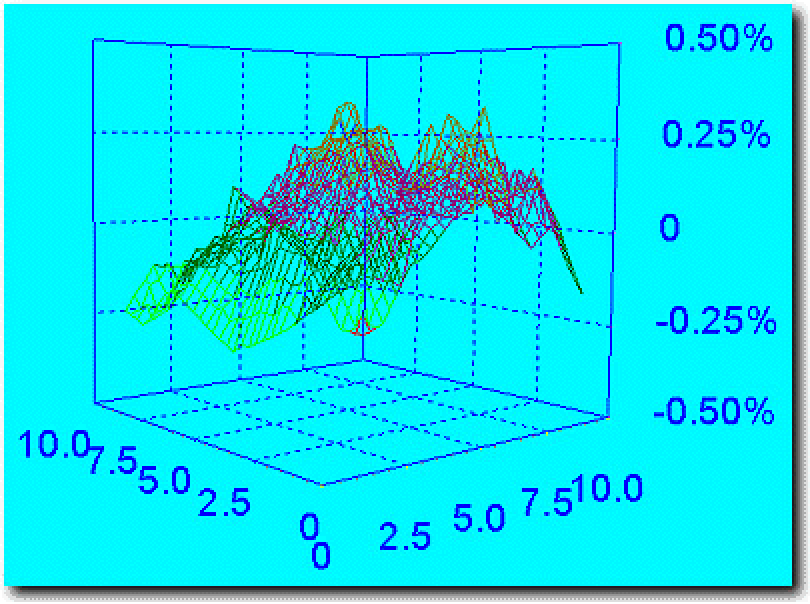


Fig. 1: Uniformity of UVG-100 photodiode at 254 nm.

Fig. 2 shows the temperature dependence of the diode responsivity at 254 nm. Typically the responsivity was found to increase by 0.045% per degree celsius. Note that this responsivity dependence on temperature is less than that reported by other manufacturers of UV-enhanced photodiodes. As the diode does have 100% internal collection efficiency, we believe that the temperature dependence of the responsivity is caused by an increase in the quantum yield with higher temperatures and also partly by the change in surface reflectance.

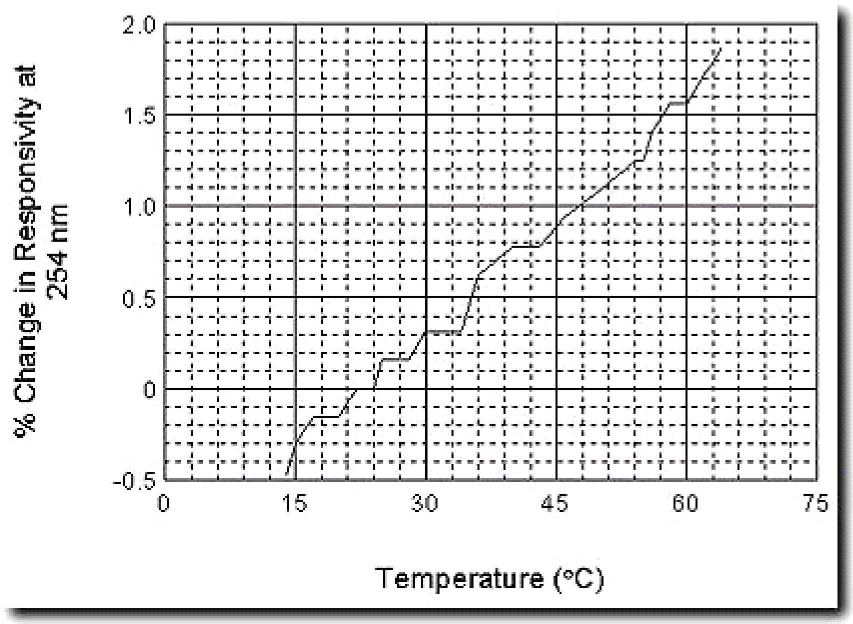


Fig. 2: Change in 254 nm responsivity of UVG photodiodes with temperature.

Fig. 3 shows temperature dependence of the shunt resistance. The shunt resistance was found to decrease by a factor of 2 for every 7.5°C rise in temperature.

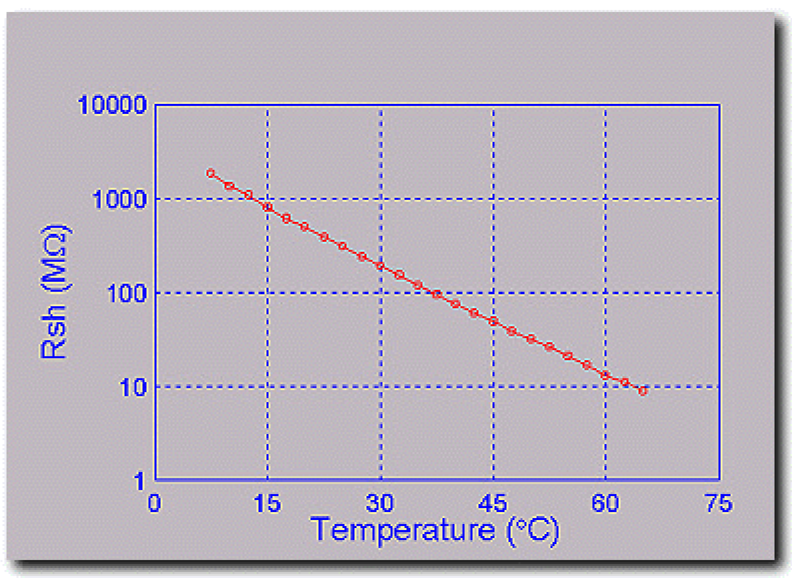


Fig. 3: Change in shunt resistance of UVG photodiodes with temperature.

As UVG diodes are windowless devices, they are supplied with protective epoxy on their wire bonds. Hence, these devices need to be operated near room temperature, i.e., one can not heat these devices for out gassing purpose nor cool them to reduce the noise. This is necessary to avoid generation of stress on the wires because of difference in the Thermal Coefficient of Expansion (TCE) between the wire and the epoxy.

If necessary, UVG series diodes can be provided without epoxy on the wire bonds or with a UV transmitting window like fused silica or magnesium fluoride.