Design of New Photodiode Standards for Use in the MISR In-Flight Calibrator

Carlos R. Jorquera, Raj Korde*, Virginia G. Ford, Valerie G. Duval, Carol J. Bruegge
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive MS 303-210 Pasadena, CA 91109
T: (818) 354-3546 F: (818) 393-6047 EMail: Carlos.R.Jorquera@jpl.nasa.gov

*International Radiation Detectors
2545 W. 237th Street, Suite I Torrance, CA 90505

The Multi-Angle Imaging SpectroRadiometer (MISR) is to be launched in 1998 as part of NASA's Earth Observing System. The 3% (1σ) absolute radiometric calibration requirement for this instrument is considered challenging, particularly since it must be maintained through the five-year mission life. To meet this specification MISR will rely on detector-based calibration techniques, which are primarily founded on High Quantum Efficiency (HQE) detector technology. Filtered HQE photodiodes will be used to characterize solar-reflected light from a diffuse calibration target during the mission. In addition, radiation-hard photodiodes, which have an extended lifetime over the HQE detectors, will be utilized as part of the on-board calibrator. To date, flight photodiodes and filters have been fabricated, along with components of the photodiode flight package, and the photodiodes have undergone performance and stability testing. This paper gives a status report on these new in-flight photodiode standards, with primary emphasis on the photodiode performance measurements taken to date.

INTRODUCTION

Many next generation remote sensing systems plan to use solar reflecting, diffuse standards to calibrate their sensors in-flight. As these diffusers are subject to UV degradation and contamination, they in themselves are not typically used as a radiometric standard. For the Multi-Angle Imaging SpectroRadiometer (MISR) the on-board calibration hardware consists of two Spectralon diffuse panels and a series of silicon photodiodes to monitor the stability and absolute reflectance of the panels. These photodiodes are of three types: a high quantum efficiency (HQE) photodiode which is a shallow junction n-on-p design optimized for an internal quantum efficiency (IQE) of 99.5% or greater when sensing 'blue' wavelength radiance (400 to 700 nm); a 'red' HQE device which is an ion implanted p-on-n device with greater than 99.5% IQE between 600 and 900 nm; and radiation-hard photodiodes which are lower in IQE at the longer wavelengths, but believed to be stable to better than 2% throughout the five year Earth Observing System (EOS) mission.

Each of the HQE photodiodes is in a light-trapped configuration where three photodiodes are arranged optically in series. The light reflected from one diode is collected by the next, such that all the incoming signal is detected, without loss. Each HQE package is filtered to a different spectral band, and four such packages allow panel characterization in each of the four MISR spectral bands. These bands are defined by center wavelengths of 443, 555, 670, and 865 nm, and corresponding gaussian FWHM bandwidths of 25, 15, 15, and 25 nm, respectively.

The radiation-hard diode package consists of four photodiodes, each filtered to one of the four MISR passbands. Thus, only one package is necessary to cover the MISR spectral bands. Several such packages, including one on a goniometric arm, are used within MISR to characterize the panel at multiple spatial and angular points. As a cost saving measure the package can alternatively be used to house the MISR CCD line arrays and corresponding filters. Each package, independent of usage, is hermetically sealed. These photodiode and package designs are unique to MISR, and are being fabricated after solving many design challenges.

The utilization of photodiode standards during flight to characterize diffuse panel radiance allows the MISR instrument to be calibrated without reliance on absolute source irradiance. For this reason stray-light and Earth-shine do not contribute to the calibration uncertainty, provided they are uniform sources across the panel. Also, MISR will calibrate at several radiometric levels, by acquiring data as the sun passes through a varying Earth-atmospheric path during the first minute of calibration. This activity would not be possible if reliance on panel radiance from a solar-irradiance and earth atmosphere-transmittance model were required.

PHOTODIODE DESIGNS

Specifications common to the HQE and PIN photodiodes include a surface reflectance loss <25% and signal-to-noise ratio >500. For the HQE photodiodes further specifications include an IQE >99.5%, linearity to >99.8%, and stability to within ±2% through the first six months of flight. For the radiation-hard photodiodes, the specifications are IQE of >30%, linearity to >99.5%, and stability to within ±2% through the five-year mission. With these photodiode specifications it is estimated that the diffuse panel radiance can be determined to within ±1% uncertainty. Panel illumination non-uniformities, relative bidirectional reflectance factor (BRF) knowledge of the panel, and difference between the photodiode and CCD response functions bring the total estimated error in calibration to ±3%.

Blue HQE Photodiode Design- MISR Bands 1 - 2

The detector design implemented for MISR spectral bands 1 and 2 (443 and 555 nm) consists of a shallow-junction n-on-p photodiode fabricated on 4" diameter P-P+ epitaxial (epi) silicon wafers. The epi silicon layer for these wafers has a thickness of approximately 25 μm and possesses a resistivity of greater than 1 Ω·cm. Phosphorus diffusion is carried out to obtain a shallow junction 0.1 to 0.25 μm deep (see Fig. 1). Through careful processing this design is capable of achieving dynamic resistances of upwards of 1 GΩ, resulting in detectors with very low noise performance. Additionally, in order to minimize signal losses due to front-surface reflections, the silicon dioxide anti-reflection coating is optimized for MISR bands 1 and 2. This is accomplished by thinning the coating down to about 80 nm following completion of the diffusion.

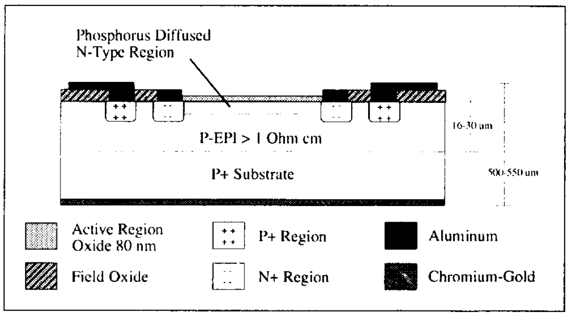

Figure 1. Blue HQE photodiode design.

0-7803-1497-2/94 $4.00 © 1994 IEEE

This design offers several advantages over other earlier proposals, in particular, a more stable and lower noise performance that does not require biasing for high QE operation. This is a very significant improvement over the inversion-layer photodiode (Hansen, 1978), which is the more traditional choice for this particular spectral range, and which until not long ago (Korde, 1987) was the only detector type that could achieve IQEs large enough which allowed it to be used in the fabrication of absolute radiometric standards (Zalewski, 1983).

Red HQE Photodiode Design- MISR Bands 3 and 4

The Red HQE detectors intended for MISR bands 3 and 4 (670 and 865 nm) are p-on-n photodiodes fabricated on 4" float zone silicon wafers, again with a resistivity greater than 1 Ω·cm (Fig. 2). The p-n junction was created by a specific boron ion implantation process which minimizes the front surface dead region of the photodiode, thereby achieving very high IQE, even at the shorter wavelengths (Korde, 1989). As was the case for the blue HQE diodes, dynamic resistances greater than 1 GΩ were also obtained for the red HQE diodes. The optimal SiO_2 anti-reflection coating thickness used for these wavelengths was 128 nm.

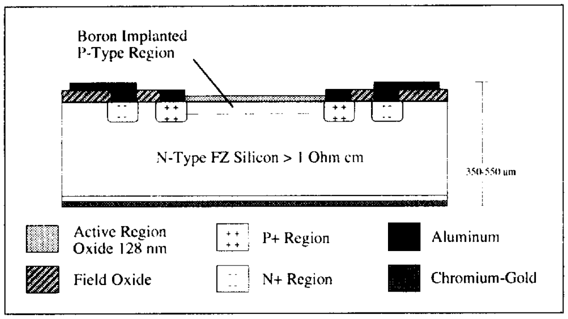

Figure 2. Red HQE photodiode design.

Radiation-Hard Photodiode Design

In order to achieve the radiation-hardness required, and at the same time obtain highest possible external QE, six different types of radiation-hard photodiodes were fabricated to attain the optimal trade-off. Three types of these detectors were built on p-p+ epitaxial wafers, each type having one of three possible epi layer thicknesses of 5, 15, or 25 μm (same structure as Fig. 1 except for the epi thickness). The remaining three diode types were fabricated on Silicon Oxide Insulator (SOI) wafers (with a buried oxide thickness in the range of 250 to 1000 nm), and similarly, each type had one of three possible active Silicon thicknesses: 5, 10, or 18 μm. Because the active Silicon thickness for the radiation-hard detectors was limited to a maximum of 25 μm, IQE was expected to be lowest for MISR band 4. Hence, the anti-reflection coating was optimized for this spectral region in the same way as for the Red HQEs. In addition, as with the HQE diodes, a dynamic resistance of greater than 1 GΩ was also another goal of this design.

DETECTOR PERFORMANCE

IQE and Reflectance Measurements

These measurements were performed by following the technique used in a previous study (Jorquera, 1992). Essentially, two types of light-trapping 100% QE detectors were used as absolute standards: an inversion-layer QED-200 trap made by United Detector Technologies; and a Graseby Optronics QED-150 trap composed of Hamamatsu photodiodes. The QED-200 was the reference for MISR bands 1 and 2, while the QED-150 was best suited for bands 3 and 4. A light-tight fixture was fabricated to place the photodiode under test at 45º from the opening to the QED-200, and readings were acquired for the reflected signal, the photodiode signal, and the total incoming signal measured by an additional QED-200 and the QED-150. From these measurements it was then possible to directly calculate both the front surface reflectance (at 45º) and the IQE for the photodiodes.

The results presented some surprises. First of all, the Red HQE diode response showed to be extremely high (> 99%) for wavelengths below 600 nm, which is generally not expected from p-n photodiode architectures. This indicates that the Red HQE photodiodes lack the front dead region normally found in p-n diodes. Unfortunately this performance was short lived. In a span of little over a month following fabrication, the IQE for these devices dropped down to 90% at 420 nm, and down to 97.7% at 552 nm (Fig. 3), indicating that there are still serious issues of stability to resolve. It is of importance to note that this IQE degradation was not due to humidity effects since all photodiodes were kept within a dry nitrogen purge.

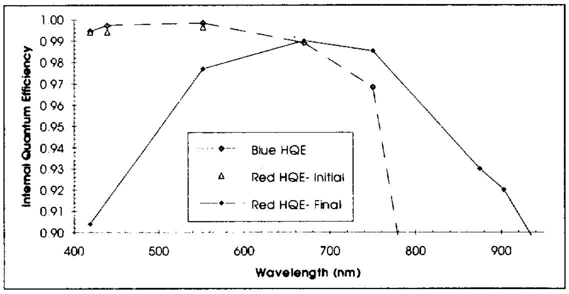

Figure 3. Typical Blue and Red HQE photodiode IQE.

Another unexpected result pertaining to the Red HQE sensors was that the IQE at the longer wavelengths showed not to be as high as required, only about 92% at 875 nm. This may be attributed in part to the fact that the foundry used for building these photodiodes is primarily dedicated to IC fabrication, and therefore their processing is not particularly tailored for obtaining long minority carrier life times, as is critical for these detectors. Currently, additional foundries which specialize on detectors are being involved in further photodiode fabrication runs in the hopes of solving this problem.

The Blue HQE detectors generally showed acceptable performance, although their IQEs at 420 nm were approximately 99.4%, which was not quite as high as desired (Fig. 3).

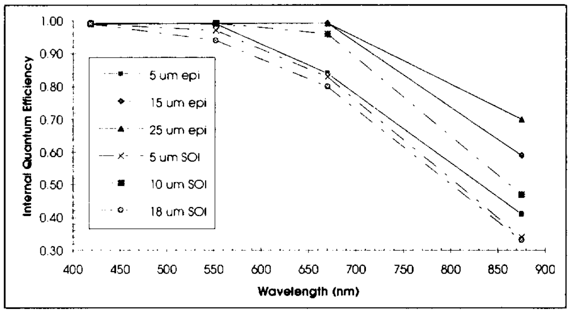

Figure 4. Typical IQE for all Radiation-Hard photodiode types.

The radiation-hard photodiode IQE results met more closely with expectations. First of all, the detectors fabricated on epi wafers showed very comparable performance to the Blue HQE diodes in MISR bands 1 and 2. This was as expected since the only difference between the rad-hard designs on epi wafers and the Blue HQE design was the epi thickness involved. Towards the longer wavelengths, their IQEs were strong functions of the active silicon thickness of each rad-hard diode, also as expected (Fig. 4). The one exception to this were the SOI diodes with an active silicon thickness of 18 μm, which had the lowest IQE in all bands. This was due to the fact that this particular wafer was of a different type than the other SOI wafers, and additionally, was of lower quality.

Front surface reflectance for all photodiode types was found to be at worst 20%, for spectral regions not targeted by anti-reflection coating optimization, and at best 10%, for those regions which were optimized.

IV Characterization, Shunt Resistance, and Shunt Capacitance Measurements

Current vs. bias voltage (IV) curves were obtained for all photodiodes. From these, the dynamic resistance at zero bias (shunt resistance) was calculated for each diode using data points near zero volts. In a separate step, shunt capacitance was also obtained. All three measurements were performed at ambient temperature, which was generally about 26º Celsius. The shunt resistance for all photodiodes was determined to be very nearly 1 GΩ, with the exception of the Red HQE diodes, for which it was approximately 10 GΩ. It is of importance to point out that the operating temperature for all these detectors, once in flight, is expected to be approximately 10º C. Taking into account the shunt resistance temperature coefficient for these diodes, which was measured approximately to be a 10% decrease per degree C increase, it is expected that the shunt resistance for all photodiodes will be about three times as large in-flight as has been measured at room temperature. Therefore, these sensors are expected to have excellent signal-to-noise ratios.

SPACE RADIATION EFFECTS

Fully characterized photodiode samples of each type were selected for proton radiation damage testing. The fluences for all other charged particles during the mission are expected to be negligible. The photodiodes were irradiated at four proton energies: 0.1, 0.5, 1.0, and 5.0 MeV. Different photodiodes of each type were exposed to each of the four energies, and an additional set were exposed to all four energies. The fluence for each proton energy level was chosen according to what is expected for the five year flight mission times a factor of three as an error margin: 4.8 x 10^7, 3.2 x 10^7, 1.2 x 10^8, and 6.0 x 10^8 $\frac{PROTONS}{cm^2}$. Following irradiation, characterization measurements were repeated to determine the amount of induced performance degradation.

The results were a great deal more favorable than originally expected. All radiation-hard and Blue HQE photodiodes showed no noticeable IQE changes at any of the exposed proton energies, even at 875 nm. The radiation-hard photodiodes built on epi wafers (and the Blue HQE devices for that matter) were expected to be extremely radiation insensitive at the shorter wavelengths (Korde, 1993). Similar results were also expected for the detectors fabricated on SOI wafers, although no data was available on these. At the longer wavelengths IQE variations were expected to be a function of the detector's active Silicon thickness. It was very encouraging to see that the predicted fluences were too low to produce noticeable changes even at the longer wavelengths for the rad-hard and Blue HQE sensors.

Data obtained from the Red HQE devices matched more closely what was expected. No IQE changes were detected in the first two MISR bands (420 nm and 552 nm), while for bands 3 and 4 (670 nm and 875 nm) IQE drops of 2% and 11%, respectively, were observed. Additionally, this degradation was only measured at the proton energy of 5.0 MeV, indicating that only the damage towards the rear volume of the photodiodes was significant.

PACKAGING

Following detailed characterization of the radiation-hard and HQE photodiodes, a selection will be made for the engineering model, flight, and flight spare devices. The radiation-hard photodiodes will next be packaged in clusters of four, each diode in the cluster filtered to a MISR spectral band. Each radiation-hard package will be approximately 4.5 cm in diameter, with diodes apertured to 3 mm in receiving area. The package itself is made from a black ceramic fabricated at Coors. It will be back-filled with argon. The hermetic package provides a stable environment, and eliminates the potential for damage due to humidity or contaminants. As both the diodes and CCDs will be hermetically sealed in their packages, it is expected that filter shifts, although predicted to be small, will be of the same magnitude and direction for the calibration and camera systems alike. Finally, a light-baffle tube is added to define the fields-of-view to approximately 8º. The apertures used within this assembly are precision made using photolithography techniques and manufactured to a diameter uncertainty of 2 mm. This yields an uncertainty in the AΩ product to less than 0.5%. The HQE packages are of a different layout, and include a ceramic triangle wedge with which the three HQE photodiodes are mounted. These four packages, one for each MISR wavelength, are also hermetically sealed and utilize precision apertures.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

REFERENCES

Hansen, T. "Silicon UV Photodiode Using Natural Inversion Layers," *Phy. Scripta*, vol. 18 (1978): p. 471.

Jorquera, C.R., Bruegge, C., Duval, V. "Evaluation of high quantum efficiency silicon photodiodes for calibration in the 400 nm to 900 nm spectral region," in SPIE Vol. 1762 Infrared Technology XVIII, 1992, pp. 135-144.

Korde, R., Geist, J. "Stable, High Quantum Efficiency UV-Enhanced Silicon Photodiodes by Arsenic Diffusion," *Solid State Electronics* vol. 30 (1987): pp. 89-92.

Korde, R., Geist, J. "Quantum Efficiency Stability of Silicon Photodiodes," *Applied Optics* vol. 26 (1989): pp. 5284-5290.

Korde, R., Cable, J.S., Canfield, L.R. "100% Internal Quantum Efficiency Silicon Photodiodes with One Gigarad Passivating Silicon Dioxide," *IEEE Trans. in Nuclear Science* vol. 40 no. 6 (1993): pp. 1655-1659.

Zalewski, E.F., Duda, C.R. "Silicon photodiode device with 100% external quantum efficiency," *Applied Optics* vol. 22 (1983): pp. 2867-2873.-