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Pulsed and Steady-State Radiation Effects on Single Junction Si and Multiple Junction GaAs Photocells

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***Abstract*--Si single junction photocells manufactured by Sandia National Laboratories and commercially available multiple junction GaAs photocells were tested in a pulsed high-dose mixed gamma-neutron environment. The Si photocells were also tested in steady state gamma environment at two different dose rates.**

I. Introduction

PHOTOCELLS have, in recent years, found increasing use in two technologies, optical power transfer and high voltage generation. An optical power transfer system consists of a laser diode to convert electrical power to optical power, a fiber optic cable to transmit the power, and a photovoltaic device to convert the optical power back to electrical power. Such a system provides for isolated electrical power generation and is immune to the effects of electrical interference from outside environments since the power is transmitted optically [1]. High voltage generation using photocells is achieved by connecting multiple devices in series. Since the high voltage is generated directly by the photovoltaic array a transformer and associated components are not needed. Transformers are bulky and eliminating the need for them substantially reduces the overall volume leading to use in applications where space is limited [2]-[4].

Advantages of these two technologies have led to potential roles in applications ranging from systems that experience a low dose rate long term exposure, to applications where survival in a large dose short duration pulsed radiation environment is critical. In this work, an investigation of the photocells was performed examining the susceptibility to pulsed gamma-neutron and steady state gamma radiation environments.

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II. Device Construction

A. Single Junction Si Photocell

The device of interest is a series connected photovoltaic array. When photocells are placed in series the illumination profile becomes a critical parameter [5]. This is due to current limiting caused by the photocell with the weakest illumination. The photocell is illuminated with a multimode fiber. The illumination profile of the multimode fiber is non-uniform and changes spatially as a function of time. Single junction devices of the same construction as those in the series array are tested in order to prevent radiation induced degradation from being convoluted by time-dependent spatial changes in the illumination profile.

Shown in Fig. 1 is a schematic and SEM cross section of a series connected photocell. These devices were manufactured on SOI wafers. The top-Si is 5 µm thick and the thickness of the oxide is 3 µm. Trench isolation is formed by etching through the entire thickness of the top-Si using a dry reactive ion etching technique. The trench is then filled with SiON and the overburden is removed by chemical-mechanical polishing (CMP). A SiO_2 dielectric is used to passivate the top Si layer as well as provide isolation from the metal lines. SiO_2 is also used to passivate the metal lines. Deposition of the SiO_2 is accomplished by standard plasma deposition. The P/N junction is formed by standard lithographically defined ion implantation which is followed by thermal activation. Dopants used in the n and n+ regions are P and As, respectively. The p+ region dopant is B.

B. Multiple Junction GaAs Photocell

Multiple junction GaAs photocells tested were purchased from a commercial vendor. Dimensions of the device measured 2 mm x 2 mm with a circular active area consisting of six wedge shaped series connected photocells. The die is provided by the manufacturer pre-mounted in a receptacle that is compatible with ST type fiber optic cable connectors [6]. Any further information could not be obtained from the vendor due to issues of propriety. Fig. 2 shows the ST receptacle that the photocell is packaged in and the photocell mounted on a TO header.

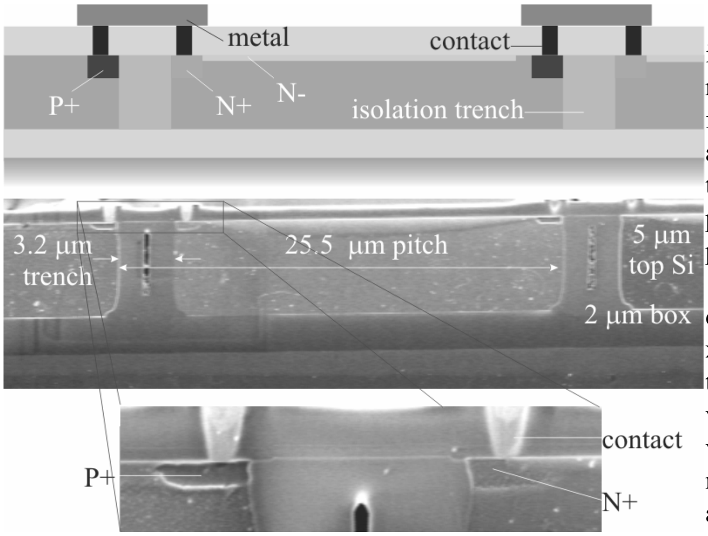

Fig. 1. Schematic (top) and SEM image (bottom) of the photocell construction.

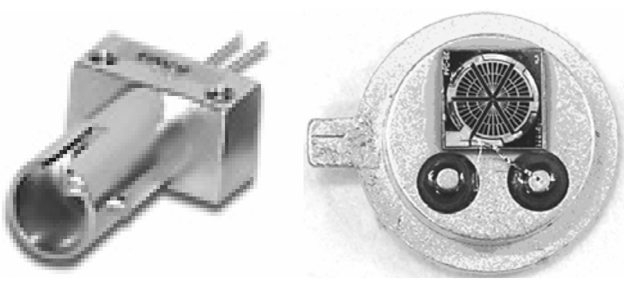

Fig. 2. Photo of a multiple junction GaAs photocell in an ST receptacle (left) and mounted on a TO header (right).

III. Radiation Testing

Single junction Si photocells were tested in different radiation environments. One environment was a pulsed event comprising of both gamma and neutron radiation. The other environment was steady state gamma from a Co-60 array.

Three radiation test facilities at Sandia National Laboratories were utilized as part of this experiment. The annular core research reactor (ACRR) generated the pulsed gamma-neutron environment while the gamma irradiation facility (GIF) was used to generate the steady state gamma environment.

A. *ACRR Passive Tests*

An initial passive test was performed at ACRR to determine if Si and GaAs photocells would survive in a pulsed high neutron fluence environment. ACRR is a research reactor that produces pulsed environment that consists of gamma and neutron radiation. This is the only test in which the GaAs photocells were included.

1) Experiment

The experimental setup in this case involved pre-characterizing the photocells under illumination before exposure, wrapping the devices in aluminum foil and exposing them to the ACRR radiation environment, and post-characterization once the devices have cooled.

Pre-characterization of the Si photocells consisted of illuminating the devices at 154 mW using a fiber coupled 808 nm laser diode was used to illuminate the photocells. The fiber core is 100 µm, has a 0.22 NA, and is terminated with an ST connector. An XYZ translation stage was used to align the photocell to the fiber optic output. Alignment of the GaAs photocells was not required since the devices are prepackaged in an ST receptacle.

A total of 12 Si and 2 GaAs photocells were tested. The Si devices were of different junction areas ranging from 120 µm x 550 µm to 20 µm x 20µm. Two of each junction area was tested. An I-V curve for each photocell was acquired. The value of the short circuit current (I_{SC}) and the open circuit voltage (V_{OC}) is of particular interest and will be used as the metrics by which the photocell degradation is measured against. After irradiation the post-characterization data is taken using the same method.

The radiation environment was measured using eight sulfur pellets and eight CaF2 thermo-luminescent dosimeters (TLD). Based on the activation of the sulfur pellets the photocells experienced a 1 MeV (Si) neutron fluence of 4.1E14 neutrons/cm^2. The CaF2 TLDs were saturated indicating a gamma dose in excess of 100s of krad(Si).

2) Results

The single junction Si experienced a decrease in I_{SC} ranging from 39.3 % to 75.2 % and a decrease in V_{OC} in the range of 21.5 % to 12.6 %. Degradation in I_{SC} is independent of the junction area while V_{OC} is not. Larger junction areas result in a larger decrease in V_{OC}. The multiple junction GaAs I_{SC} degraded ~50 % and the V_{OC} decreased by ~17%. The complete results are shown in Table I.

B. *ACRR Active Tests*

Two active tests were performed at the ACRR with the Si photocells illuminated at 150 mW. The purpose of the active tests was to measure photocell recovery, if any, immediately after the radiation pulse.

1) Experiment

Illuminated and unilluminated photocells of the same junction area were placed side by side. The purpose of the unilluminated photocell was to monitor for radiation generated current within the photocell. Photocell parameters of interest are I_{SC} and V_{OC}. I_{SC} was monitored by measuring the voltage generated across a potentiometer using an oscilloscope. Load resistance was adjusted to ensure that the photocell was biased around 250 mV, well within the linear region of the photocell I-V curve. V_{OC} was determined by recording the I-V curve before and immediately after the radiation pulse. Additional fiber optic cables were placed alongside those used to illuminate the photocells. These fibers are used to account for any reductions in photocell performance due to radiation induced fiber darkening or fluctuations in laser diode output power. High OH content fused silica fibers were used to minimize this effect. Fig. 3 is a schematic of the test setup.

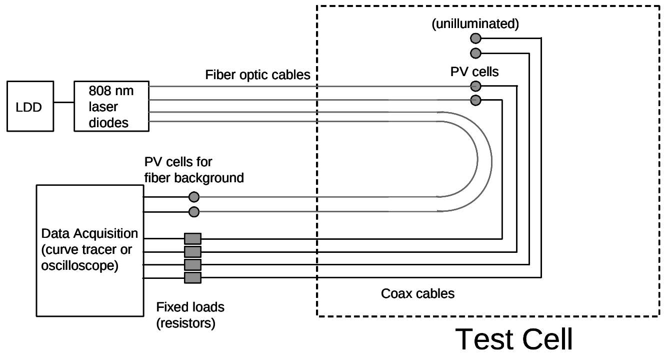

Fig. 3. Schematic of test setup used for active radiation testing of single junction Si photocells.

The first test was performed on photocells with junction areas of 120 µm x 550 µm and 40 µm x 60 µm. Neutron fluence was measured by placing four sulfur pellets and one nickel foil alongside each pair of illuminated and unilluminated photocells. Gamma dose was measured using four TLDs also placed alongside the photocells. The photocells were exposed to a mean 1 MeV (Si) fluence of 2.9E13 neutron/cm^2 and a total gamma dose of 8.8 krad (Si) radiation environment.

Photocells with junction areas of 120 µm x 550 µm and 20 µm x 20 µm were tested next. 1 MeV (Si) neutron fluence and gamma dose was measured to be 4.2E14 neutrons/cm^2 and 170 krad (Si), respectively, using the same method as mentioned above.

2) Results

Photocells that were exposed to the first low energy radiation pulse had a reduced I_{SC} of 30 % and 21% for the large and small junction area photocells, respectively. V_{OC} was reduced by 11% and 4% for the large and small junction area cells, respectively. In Fig. 4 a plot of the response from the two illuminated photocells and the output from the active neutron detector are shown.

The second test exposed the photocells to a high energy radiation pulse and reduced the I_{SC} of both devices by 70%. V_{OC} was decreased by 26% and 14%, respectively, in the large and small junction photocells. Fig. 5 shows the response of the photocells to the high energy radiation pulse.

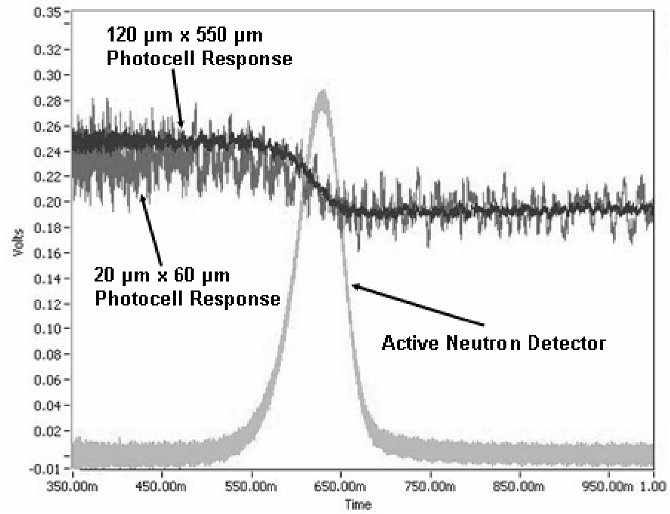

Fig. 4. Plot of photocell response to a low energy radiation pulse during the first active ACRR test.

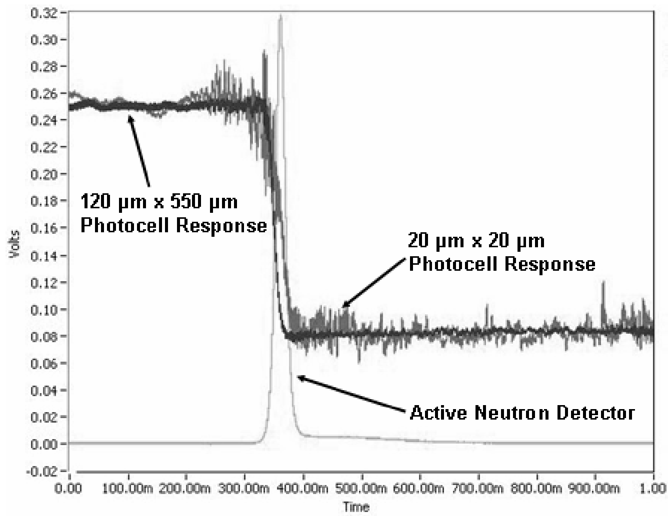

Fig. 5. Plot of photocell response to a high energy radiation pulse during the first active ACRR test.

Neither radiation generated current within the photocell nor fiber darkening was observed. Data was recorded for a length of twenty minutes after the radiation pulse in order to observe any recovery in device performance. None was evident.

TABLE I
TEST RESULTS FROM PASSIVE ACRR TESTING

Manufacturer	P/N	S/N	Illumination (mW)	Pre I_{sc} (A)	Post I_{sc} (A)	I_{sc} Reduction (%)	Pre V_{oc} (V)	Post V_{oc} (V)	V_{oc} Reduction (%)
Photonic Power	PPC-6E	CN176	10.0	6.30E-02	3.00E-02	62.3	6.42	6.32	17.1
Photonic Power	PPC-6E	CN177	10.0	6.64E-02	3.02E-02	63.6	6.64	6.44	16.8
Sandia MDL	120X550	1	164	3.67E-03	1.10E-03	70.0	0.76	0.80	21.6
Sandia MDL	120X550	2	164	2.64E-03	1.00E-03	60.6	0.75	0.80	20.7
Sandia MDL	120X250	3	164	1.18E-03	3.05E-04	74.2	0.75	0.69	21.8
Sandia MDL	120X250	4	164	1.30E-03	4.95E-04	61.9	0.78	0.80	20.4
Sandia MDL	40X100	6	164	1.93E-04	6.00E-05	68.9	0.72	0.80	17.4
Sandia MDL	40X100	5	164	1.63E-04	6.90E-05	61.4	0.70	0.80	16.1
Sandia MDL	40X60	7	164	8.60E-05	3.60E-05	68.6	0.70	0.80	14.6
Sandia MDL	40X60	8	164	8.00E-05	2.80E-05	65.0	0.70	0.69	16.7
Sandia MDL	20X40	9	164	2.68E-05	1.16E-05	65.1	0.68	0.69	12.9
Sandia MDL	20X40	10	164	2.90E-05	1.18E-05	69.3	0.69	0.80	12.8
Sandia MDL	20X20	11	164	1.46E-05	9.80E-06	30.3	0.67	0.69	13.1
Sandia MDL	20X20	12	164	1.87E-05	6.30E-06	66.3	0.68	0.80	12.6

C. *GIF Tests*

Testing of Si single junction photocells was also performed at GIF in order to determine susceptibility to steady state gamma radiation. The gamma source is a Co-60 array.

1) *Experiment*

The experimental setup used at GIF was identical to that used at ACRR (Fig. 3) with the exception of the data acquisition system. A multi-channel curve tracer was used to simultaneously record the I-V curves of all of the photocells. Data was recorded over a period of 18 hours. After four hours of exposure the alignment of the test setup inside of the Co-60 array began to change thereby invalidating any data that was taken after that point. Change in alignment was due to the degradation of previously unknown plastic components that were present inside of the alignment fixture.

Two sets of tests, using photocells with junction areas of 120 µm x 550 µm and 20 µm x 20 µm, were run simultaneously at different dose rates. Different dose rates were achieved by placing one setup in the center of the Co-60 array and the other setup inside of a box shielded with 1/8" thick lead at the back of the test cell. Dose rate was determined by exposing four TLDs, placed at the same location as that of the photocells, for 5 minutes and dividing the total dose by the total time of exposure. The TLDs measured a dose rate of 800 rad (Si)/s and 5.33 rad (Si)/s in the center of the Co-60 array and inside of the lead shielded box, respectively.

2) *Results*

Fig. 6 shows the normalized photocell I_{SC} as a function of dose for both tests. Device degradation appears to be a function of photocell junction area, dose rate and total dose. The high dose rate environment shows that photocell I_{SC} degrades by 20 % and 50% for the large and small photocells, respectively at a total dose of 12 Mrad (Si). Large and small junction area photocells exposed at the low dose rate had I_{SC} reductions of 20 % and 60 %, respectively, at a total dose of 350 krad(Si). Even though the total dose, at the lower dose rate, was two orders of magnitude lower the devices suffered comparable degradation. These results suggest that the photocells are susceptible to enhanced low dose rate effects (ELDRS). When the test results are plotted as a function of time in (fig. 7) there appears to be a strong time dependent degradation in I_{SC}. Data was recorder for 30 min after the gamma exposure had ended. There was no device recovery.

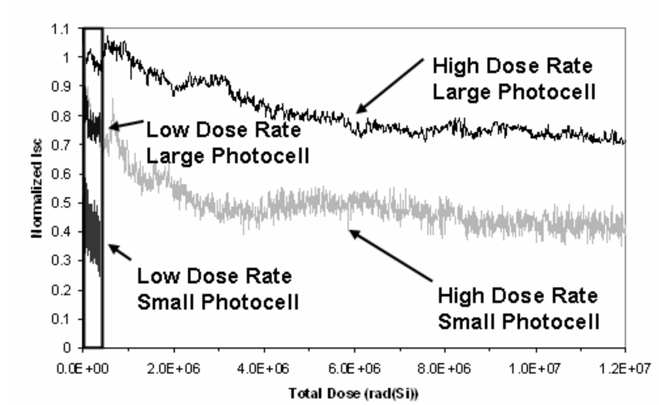

Fig. 6. Plot of normalized photocell I_{SC} as a function of total dose (Si.)

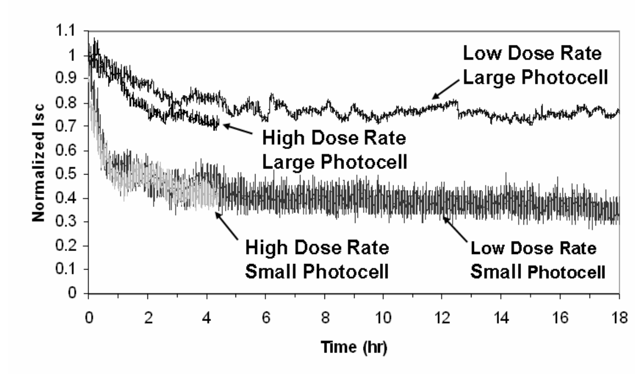

Fig. 7. Plot of normalized photocell I_{SC} as a function of time.

IV. SUMMARY

Single junction Si and multiple junction GaAs photocells were tested in a pulsed high-dose mixed gamma-neutron at ACRR and a steady gamma environment at GIF.

Testing in a mixed gamma-neutron pulsed environment has shown that a 1 MeV (Si) neutron fluence of on the order of 4E14 neutrons/cm^2 and a total gamma dose of 170 krad (Si) that the I_{SC} in Si photocells degrades ~70 % independent of the junction area. Reduction in V_{OC} ranges from ~20 % to ~10 % with larger junction area devices suffering the greater degradation. GaAs photocells had a reduction of `50 % and ~20 in I_{SC} and V_{OC} respectively.

Testing at GIF shows that Si photocell I_{SC} degradation is a function of dose rate, junction area, and total dose. I_{SC} degradation of 60 % occurred in a 5.33 rad (Si)/s dose rate with a total dose of 300 krad (Si).

V. ACKNOWLEDGMENT

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VI. REFERENCES

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