Application Note No. 18

NEUTRON *Hardness of Photodiodes for use in Passive Rubidium Frequency Standards*

SUMMARY

The photodiode used for optical detection of the atomic resonance in a passive rubidium frequency standard (RFS) is a critical component that can limit the radiation hardness of the standard at high neutron-fluence levels. With the goal of obtaining a more neutron-resistant photodiode than is normally used in an RFS, experiments were carried out to evaluate the neutron hardness of several different types of planar silicon photodiodes. The diodes tested had approximately 1 cm^2 of active area, and were maintained at 100ºC during neutron irradiation and testing. They were exposed to neutron fluences ranging from 7 x 10^{11} to 1.4 x 10^{13} n/cm^2. For each of the diodes, the dc short-circuit current, the ac short-circuit current, and the small-signal ac shunt resistance were measured as a function of neutron fluence.

Of the various types of diodes tested, the n/p types exhibited better performance than the p/n types normally used in RFS's. Superior performance for all of the measured parameters was obtained for n/p diodes fabricated on boron-doped p-p+ epitaxial substrates. Excellent performance was also obtained for conventional n/p diodes having a boron-doped substrate resistivity of 5 oh-cm.

Detailed experimental results are presented, and are compared with previously published data, where possible. The tradeoffs inherent in using the different types of diodes for RFS operation are also discussed.

INTRODUCTION

In recent years there has been an increasing trend toward the use of atomic frequency standards, especially passive rubidium frequency standards (RFS's), in military systems where operation and survival in a nuclear radiation environment is mandatory. As a result, significant effort, most of it unpublished and/or classified, has been directed toward improving the radiation hardness of RFS's. In the past, one area of concern has been the performance degradation of the RFS photodiode produced by neutron irradiation. This is the topic addressed in this paper.

Photodiodes of the p-on-n type have commonly been used as photodetectors in most RFS's. For neutron fluences above about 1 x 10^{11} n/cm^2, the short circuit current (for constant illumination) of this type of photodiode starts to drop rapidly, and although a well-designed RFS is relatively insensitive to even fairly large changes in the short-circuit current, the margin of safety for allowable photocurrent degradation decreases as the fluence level is increased.[1] In the present investigation, six different types of photodiodes were tested by measuring the changes in various parameters of importance for RFS operation as a function of neutron irradiation (fluence). In addition to this application-specific testing, tests of a fundamental nature were also conducted on an additional 40 photodiodes of different types. The results of this latter investigation will be published elsewhere.

TEST DESCRIPTION

Photodiodes

Six different types of planar silicon photodiodes, each having approximately 1 cm^2 of active area, were tested: n-on-p type fabricated on boron-doped p-p+ epitaxial wafers ("epitaxial" type); n-on-p type with boron-doped p-p+ epitaxial wafers ("epitaxial" type); n-on-p type with boron-doped substrate resistivities of 5, 25, and 100 ohm-cm ("n/p" type); and p-on-n type with substrate resistivities of 10 and 400 ohm-cm ("p/n" type). All of the diodes were in the form of squares with sides approximately 1 cm long. Leads were attached with solder to the metal contacts on the top and bottom of each device. Two photodiodes of each type were tested to provide at least a crude measure of reproducibility (time and resources did not permit testing more than two of each type). All of the photodiodes used in these experiments were manufactured by United Detector Technology.

Test Facility

Neutron irradiation and testing were carried out on December 15-16, 1987, at IRT Corporation's new Neutron/Gamma Range Facility[2] located in San Diego. Neutrons are provided by several californium-252 sources having a neutron-to-gamma ratio of 1 x 10^9 neutrons per rad (Si) of gamma radiation. The californium neutron spectrum has been extensively studied, and is well known and documented, thereby allowing 1-MeV (Si) damage-equivalent fluences to be accurately calculated. Comparison tests made between the IRT facility and the Sandia Fast-Burst Reactor confirm the results of these calculations.[2]

For neutron testing using this type of facility, the irradiation times needed to realize the higher fluence levels could be quite long. For the present experiments, irradiation times of several hours were required to attain fluences above 1 x 10^{13} n/cm^2. Because of the long irradiation times and also possibly because of the 100C temperature of the photodiodes during irradiation, annealing effects were not observed in these experiments (any annealing takes place rapidly during the irradiation, not after it).

Test Fixtures

The 12 photodiodes were placed, in-groups of four each, in three separate test fixtures. Each test fixture consisted of an insulated, cylindrical copper oven that was electrically heated and thermostatically controlled to operate at 100 C during neutron irradiation and electro-optical testing.3 The photodiodes were epoxied to the inside, flat, end surface of the oven. Care was taken to ensure that heat leaks through the electrical leads did not lower the temperature of a photodiode significantly. Each oven had a hole at the far end to admit rubidium light during electro-optical testing, thereby allowing all four photodiodes to be illuminated and tested simultaneously.

Light Source

The light source used for electro-optical testing was a rubidium lamp assembly from an Efratom Model M-100 rubidium frequency standard. The test fixtures were configured for three-point kinematics mounting on top of this light source so as to ensure precise positioning of each fixture before and after each of the four neutron-irradiation levels. Reference measurements of the light intensity of this source that were made several times during the two-day testing period, using an unirradiated reference photodiode, showed a maximum (peak-to-peak) variation of 0.5%. This confirms both the previously documented[4] stability of this type of light source and the effectiveness of the kinematics mount used in these experiments.

The light source was amplitude modulated at 127 Hz for the ac measurements described below. The amplitude was very small compared to the dc level so that the modulation did not affect the dc measurements. Reference measurements of the modulation amplitude, taken at the same time as the dc measurements described in the previous paragraph, showed a maximum variation of 1.3% over the two days of testing.

Electro-optical Measurements

The following electro-optical characteristics of the tested photodiodes were measured before and after each irradiation level for each photodiode: dc short-circuit current, ac short-circuit current, and small-signal ac shunt resistance. All of these quantities were measured in the photovoltaic mode under conditions of constant illumination using the light source described above.

Dc Short-Circuit Current

The dc short-circuit current was measured using a uA739C op amp configured as a current-to-voltage converter. The input of this type of circuit is a virtual short so that the dc output voltage of the op amp is the same as the short-circuit current for the photodiode. Four of these converters were used to provide simultaneous measurements of the dc short-circuit currents of all four photodiodes in a test fixture.

Ac Short-Circuit Current

The 127 Hz intensity modulation of the light source (see above) produces a 127 Hz short-circuit current at the output of the photodiode. This short-circuit current is transformed into an ac voltage by the current-to-voltage converter, and then synchronously demodulated and filtered to produce a dc voltage that is proportional to the amplitude of the ac short-circuit current. Using four identical circuits that perform this function, measurements of the ac short-circuit currents from the four photodiodes in a test fixture were made simultaneously. In an RFS, the servo that locks the frequency of the voltage-controlled crystal oscillator to the rubidium reference frequency uses a low-frequency ac error signal. This signal appears as an intensity modulation of the light beam and is converted by the photodiode to an ac short-circuit current. Any degradation in this conversion process due to neutron bombardment of the photodiode is therefore of concern.

Shunt Resistance

The term "shunt resistance" as used in this paper, unless stated otherwise, refers to small-signal ac shunt resistance. A definition of this quantity can be found in the Appendix. It is of importance for RFS operation because its value, if too small, can increase amplifier noise and significantly degrade the short-term frequency stability of the RFS (see the Appendix for details). A method of measuring it is also given in the Appendix.

Irradiation-Test Sequence

The iterative method of radiation testing was used whereby the component to be tested is first characterized, then exposed to nuclear radiation, then removed and re-characterized. This process is repeated incrementally to obtain data showing how the characteristics of the component vary with the accumulated nuclear-radiation dose. In these experiments, the three test fixtures were not always simultaneously irradiated with neutrons. Consequently, the three fixtures did not receive identical incremental radiation doses, as can be seen from the graphs of the results.

Dosimetry

Sulfur dosimeters were used to determine the incremental neutron fluences. The tolerace2 of such dosimeters is usually taken to be ± 15%, but cross correlation with NBS standards indicate the tolerance of IRT sulfur dosimetry to be less than 10%. The spatial uniformity of the irradiation was within the tolerance of the dosimeters. The fluences quoted in this report are those at the locations of the photodiodes (corrections have been made for attenuation by the test fixture; the correction factor was .73 for all fluences).

TEST RESULTS & DISCUSSION

Dc Short-Circuit Current

Fig. 1 shows the variation of the normalized dc short-circuit current as a function of cumulative neutron fluence for each of the six different types of photodiodes. The "normalized dc short-circuit current" for a given fluence is defined as the dc short-circuit current of a photodiode at that fluence divided by the value of dc short-circuit current for the same photodiode before any exposure to nuclear radiation. This definition assumes constant illumination of the photodiode during testing which was the case here. Each data point plotted in Fig. 1 is the average of the normalized dc short-circuit currents for the two samples of that type at the indicated fluence. For the epitaxial and n/p photodiodes, the difference between the values for the two samples was less than 3% in all cases. For the p/n, 10 ohm-cm photodiodes the difference were less than 10%, whereas for the p/n, 400 ohm-cm photodiodes the differences were as great as 55% at the highest fluences. Thus, with the exception of the high resistivity p/n devices, the results for each pair of samples exhibit a high degree of consistency, which gives added confidence in the results.

It is clear from Fig. 1 that the epitaxial photodiodes are the most resistant to neutron degradation of the dc short-circuit current. Even at the highest fluences, the dc short-circuit currents were still in excess of 95% of the preirradiation values. The n/p photodiodes also performed very well with the dc short-circuit currents being in excess of 75% of the preirradiation values at the highest fluences. These results for the n/p photodiodes appear to agree quite well with previously published results.[5,6] Fig. 1 also shows that the dc short-circuit current behavior for these latter photodiodes is nearly independent of substrate resistivity. To the best of our knowledge, there are no previous results available for epitaxial devices with which to compare the present results.

The dc short-circuit currents of the p/n photodiodes exhibited a much greater degradation due to neutron bombardment than those of the other photodiodes tested. Clearly, the p/n devices are less suitable for use in a neutron-radiation environment than the other types. Of the two types of p/n devices, those with the higher substrate resistivity showed greater susceptibility to neutron-induced dc short-circuit-current degradation at the higher fluence levels. As regards the low resistivity p/n devices, their performance is consistent with, but somewhat better than, the previously reported performances of large-area, p/n solar cells.[1]

Ac Short-Circuit Current

Fig. 2 shows the results for the normalized ac (127 Hz) short-circuit currents. These results are very similar to those obtained for the dc short-circuit currents except that the neutron-induced degradation is slightly greater for the ac short-circuit currents than for the dc short-circuit currents, with the ac degradation exceeding the dc degradation by about 10-40% at the higher fluence levels. This same effect was observed previously when studying p/n solar cells1. Although it is not known with certainty what is causing this effect, the decrease in small-signal ac shunt resistance with increasing neutron fluence appears to be a contributor. As the ac shunt resistance approaches the smaller values (< several kohms), significant ac photocurrent is shunted through it, thereby reducing the ac short-circuit current by a small amount. If the dc shunt resistance remains large enough that very little dc current is shunted through it, then the ac short-circuit current will decrease somewhat more rapidly than the dc short-circuit current.

Shunt Resistance

A method of measuring the small-signal ac shunt resistance is given in the Appendix. Because of the way this method was implemented in these experiments, the measured shunt resistance values are only approximate, and are expected to be somewhat than the true value.

The small-signal ac shunt resistance results at 100 C is shown in Figs. 3 and 4. In most cases, the ac shunt resistances of the two samples of each type were sufficiently different that they were plotted as separate points. (The ac shunt resistance, like the "beta" of a transistor, is a parameter that is difficult to control tightly). Without exception, the effect of neutron irradiation was to reduce the shunt resistance. The minimum acceptable shunt resistance for satisfactory RFS operation depends on light intensity and also on what type of op amp is used for the photodiode preamplifier; nevertheless.

It is still possible to draw some general conclusions. The high resistivity devices (100 ohm-cm and above) are not suitable for RFS use because the shunt resistance of these devices drips to very low values, even at very low neutron fluences. The epitaxial and low resistivity n/p photodiodes exhibited the highest shunt resistances and would give satisfactory performance in most RFS's even at the highest neutron fluences ($> 10^{13}$ n/cm^2).

Damage Mechanisem

Previous work [5,7] has established that the decrease in photocurrent of solar cells that occurs due to bombardment with nuclear radiation is due to displacement damage within the silicon crystal lattice. This type of damage reduces the diffusion length for minority carriers, thereby lowering the collection efficiency for the photo-generated electron-hole pairs in the substrate (base) material where a significant portion of the electron-hole production occurs at large distances from the p-n junction (depletion region). The photo-produced minority carriers must diffuse from the base to the p-n junction before recombining in order to be collected.

The improved radiation resistance of n-p photodiodes compared to p-n photodiodes is a direct result of the increased resistance of p-type silicon to displacement damage by neutrons; see Ref. 8 for details.

The additional radiational resistance of the epitaxial photodiodes results from a somewhat different effect. In these diodes, the substrate consists of a layer of very-heavily-doped p-type material (p+ layer) with a layer of "ordinary" p-type material epitaxially grown on the former. The rear metallization of the photodiode is then placed on the p+ layer. Because of the very high doping of the p+ layer (much higher hole density), photo generated minority carriers (electrons) produced in this material are much more likely to recombine there than in the "ordinary" p-type material. Consequently, the effective collection volume of the base region is reduced, and unirradiated photodiodes of this type produce smaller photocurrents than the other types. However, they are also less affected by any reduction in the minority carrier diffusion length due to displacement damage because the rear portion of the effective collection volume is closer to the p-n junction.

At the highest neutron fluences used in this study (> 10^{13} n/cm²), the neutron irradiation is accompanied by a total gamma dose of approximately 10 krad (Si). However, this is not expected to have any significant effect upon the test results because gamma radiation produces very little permanent damage in silicon photodiodes.[9]

CONCLUSIONS & DISCUSSION

The epitaxial photodiodes exhibited the highest neutron hardness in all categories tested. The neutron hardness of the 5 ohm-cm n-p photodiodes was also very good in all respects, and both types offer a considerable hardness improvement, with no major disadvantages, compared to the p-n photodiodes normally used in RFS's.

There are, however, a few minor tradeoffs involved in the use of these diodes. The first is the higher unit cost of manufacturing small quantities of less-commonly-made devices. This amounts to roughly a factor of two for the n-p photodiodes. For the epitaxial photodiodes, the need to use epitaxial wafers as the starting (substrate) material adds roughly an additional 10% to the unit cost. The second minor tradeoff is the somewhat lower responsivity (light sensitivity) of these devices. As an example of the latter for the low-substrate-resistivity devices tested in this investigation, the dc short-circuit currents under conditions of nearly identical illumination prior to neutron irradiation were 57, 70 and 88 μA, respectively, for the epitaxial, the 5 ohm-cm n-p, and the 10 ohm-cm p-n types. Thus, the epitaxial and n-p light sensitivities are about 65% and 80% of "normal", respectively. For most RFS designs this reduced light sensitivity can be compensated for by increasing preamplifier gain at the expense of a small decrease in signal-to-noise ratio.

In closing, it should be noted that use of planar construction produces photodiodes having high shunt resistances. For the applications considered in this paper, this is an essential device feature. In addition, the use of p-type substrate material is essential for the manufacture of photodiodes having improved neutron hardness.

ACKNOWLEDGEMENT

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APPENDIX

In this appendix a noise model of the photodiode and its associated preamplifier is presented. Expressions for the various noise contributions are also presented, and special attention is given to the effect of small signal ac shunt resistance on photodiode-preamplifier noise performance. Finally, the method used to measure photodiode small-signal ac shunt resistance is described.

Noise Model

Fig. 5 shows the photodiode ac equivalent circuit along with a schematic diagram of the associated preamplifier. The shunt capacitance (C) represents the total parallel capacitance of the device, including the capacitance of the p-n junction. It was less than 10 nanofarads for all of the photodiodes tested, and is not of interest here, primarily because the modulation frequencies used in RFS's are typically very low (several hundred Hertz).

The schematic of Fig. 5 also includes all known noise sources. In this diagram, $i_{pn} = \sqrt{(2eI_p)}$ is the shot noise associated with the dc photocurrent Ip, $i_{sn} = \sqrt{(4kT/R_{sh})}$ is the Johnson noise associated with the small-signal ac shunt resistance, $e_{fn} = \sqrt{(4kTR_f)}$ is the Johnson noise associated with the feedback resistance R_f, e_n is the op amp input-equivalent voltage noise source, i_n is the op amp input-equivalent current noise source, A is the op amp open loop voltage gain, e is the magnitude of the electronic charge (1.60 x 10^{-19} C), k is Boltzmann's constant (1.38 x 10^{-23} J/K), and T is the absolute temperature in degrees Kelvin. As long as the noise fluctuations are small compared to the quiescent values, which is the case for a good op amp, the noise contribution of each noise source to the output voltage of the op amp may be found by using the principle of superposition, considering each noise source to be acting alone. The various noise contributions obtained in this way are summarized in Table 1. For a well-designed RFS, the contribution due to the shot noise of the dc photocurrent is the dominant contributor. However, as can be seen from the table, if the photodiode shunt resistance is too small, [10] the contribution from the op amp input-equivalent voltage noise source can become important and even swamp the shot-noise contribution. The other noise contributions are normally small by comparison, and can usually be neglected.

Shunt Resistance Measurement

The overall I-V characteristic of a photodiode is a nonlinear function. As in other nonlinear electronic devices, the parameters that are useful for the description of small signal and noise behavior are differential, or "small-signal ac" parameters. Parameters defined in this way are themselves nonlinear functions of the operating ("quiescent") conditions of the device (e.g., light intensity).

The test configuration used to measure the small-signal ac shunt resistance is shown in Fig. 6. The box labeled “shunt” represents all shunt current paths internal to the photodiode, and includes the p-n junction and any leakage resistances. This box is assumed to have an unknown, nonlinear I-V characteristic. The input resistance of the current-to-voltage converter is estimated from R_f (< 100 kohm) and A (20/10 k) to have been about 5 ohms, and can be taken as a short in what follows. The shunt resistance was measured operationally by taking readings of the op amp output voltage with the switch closed (short-circuit condition), and with the switch open (load condition) under conditions of constant illumination (I_p = constant).

The small-signal ac shunt resistance R_{sh} can be computed from the above readings by starting with the definition, $R_{sh} = dV_{sh}/dI_{sh}$. The derivative can be approximated by finite differences, $DI_{sh} = -DI = I_{sc} - I_L$ and $DV_{sh} = I_{sc}R_s - I_L (R_s + R_L)$ to obtain $(R_{sh} + R_s) = \text{limit } (I_L R_L / DI)$ as DI —> 0. Since what is actually measured are the op amp output voltages, $V_{sc} = I_{sc}R_f$ and $V_L = I_L R_f$, with $DV = V_{sc} - V_L$, the final result is that $(R_{sh} + R_s) = V_L R_L/DV$, valid for small DV. Although this expression involves the series resistance, it is the expression of interest since the same quantity also appears in the noise equation for the e_n contribution (Table 1).

The values of R_L used in these experiments were different for each photodiode tested, but once selected were kept constant throughout the experiments. The values were selected to produce a DV before irradiation of approximately 50 mV. The corresponding R_L values were in the range of 15-500 ohms, depending on the value of R_{sh} for the diode. As the shunt resistances dropped with neutron irradiation, the DV’s increased, typically being around 200 mV after irradiation at the highest levels. It has been our experience that as DV is made smaller, the measured shunt resistance tends to increase, approaching the true value, which is higher than the measured value.

Ideally, the DV values should have been kept on the order of 10 mV or less for all shunt resistance measurements, but this would have meant changing RL for each photodiode after each irradiation, and this was not practical.

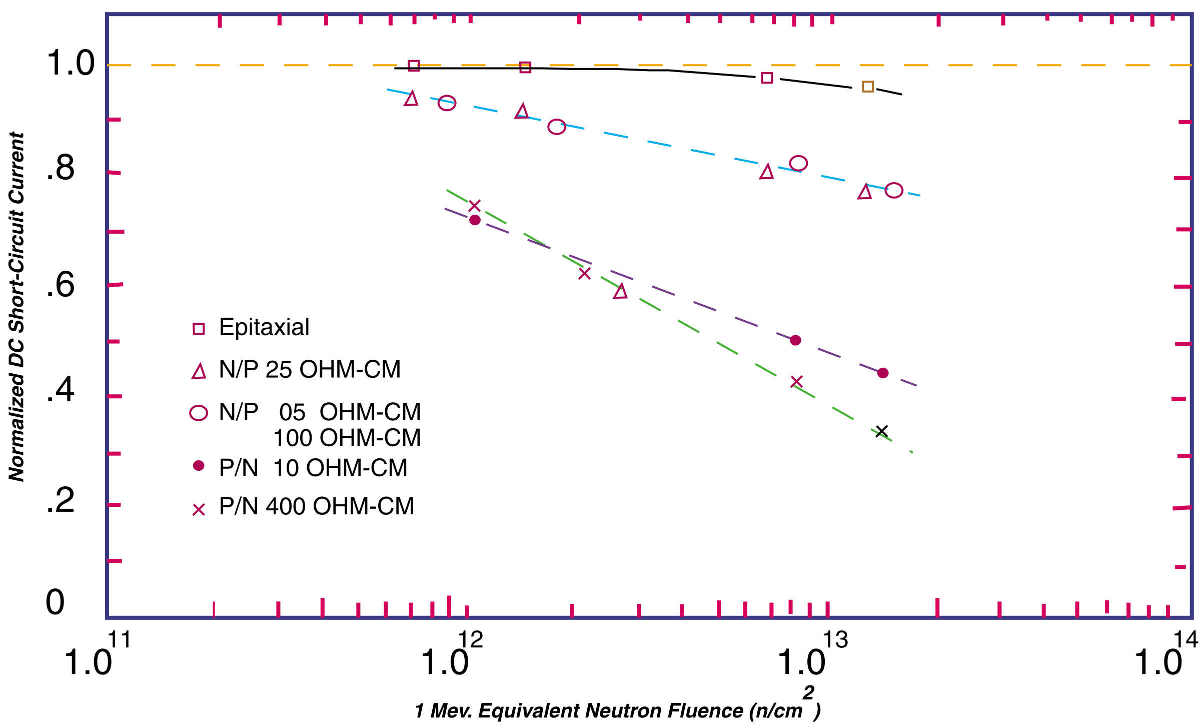

FIGURE 1. Photodiode DC short_Circuit Current Versus Neutrone Fluence

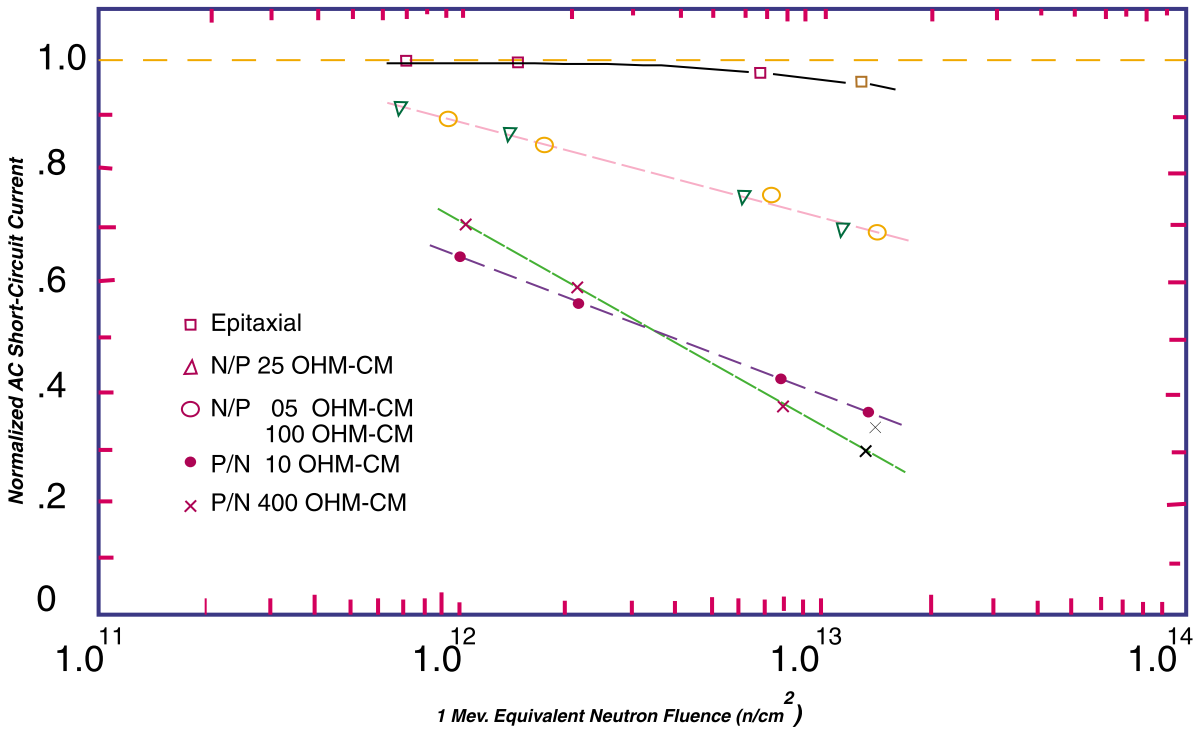

FIGURE 2.Photodiode AC short_Circuit Current Versus Neutrone Fluence

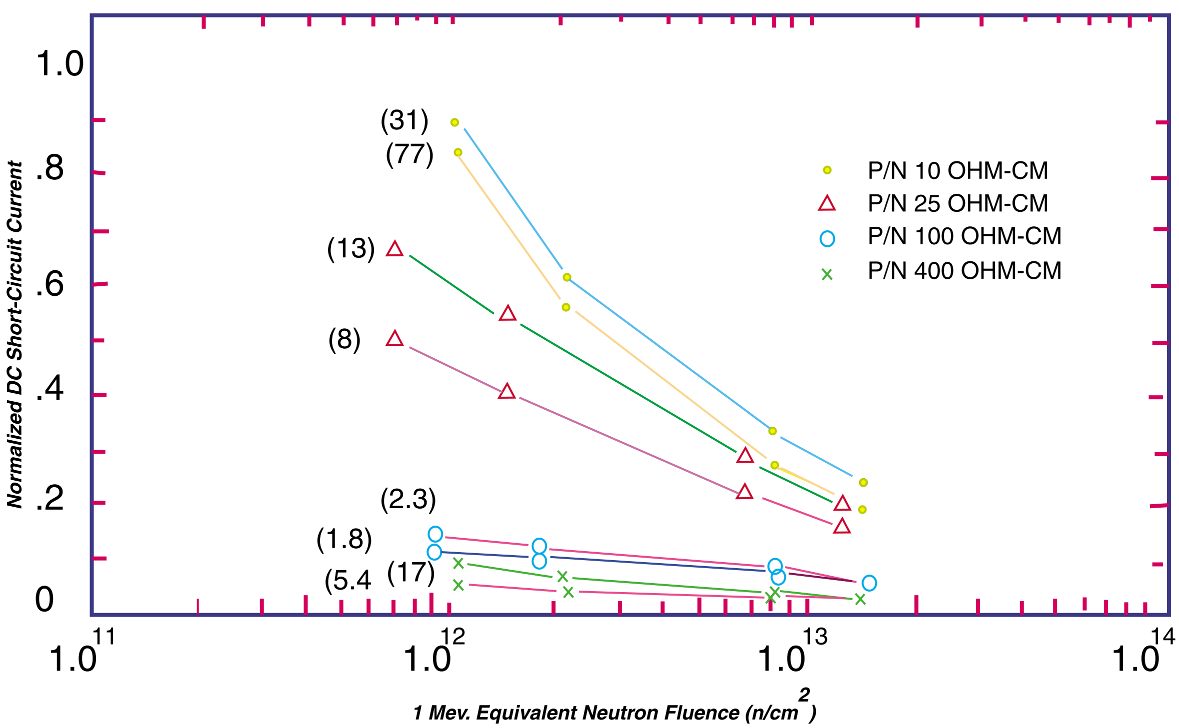

FIGURE 3. Small-Signal AC Resistance Versus Neutron Fluence.
(The Numbers in parantheses are the shunt resistance in Kohms befor Netrune irradition.)

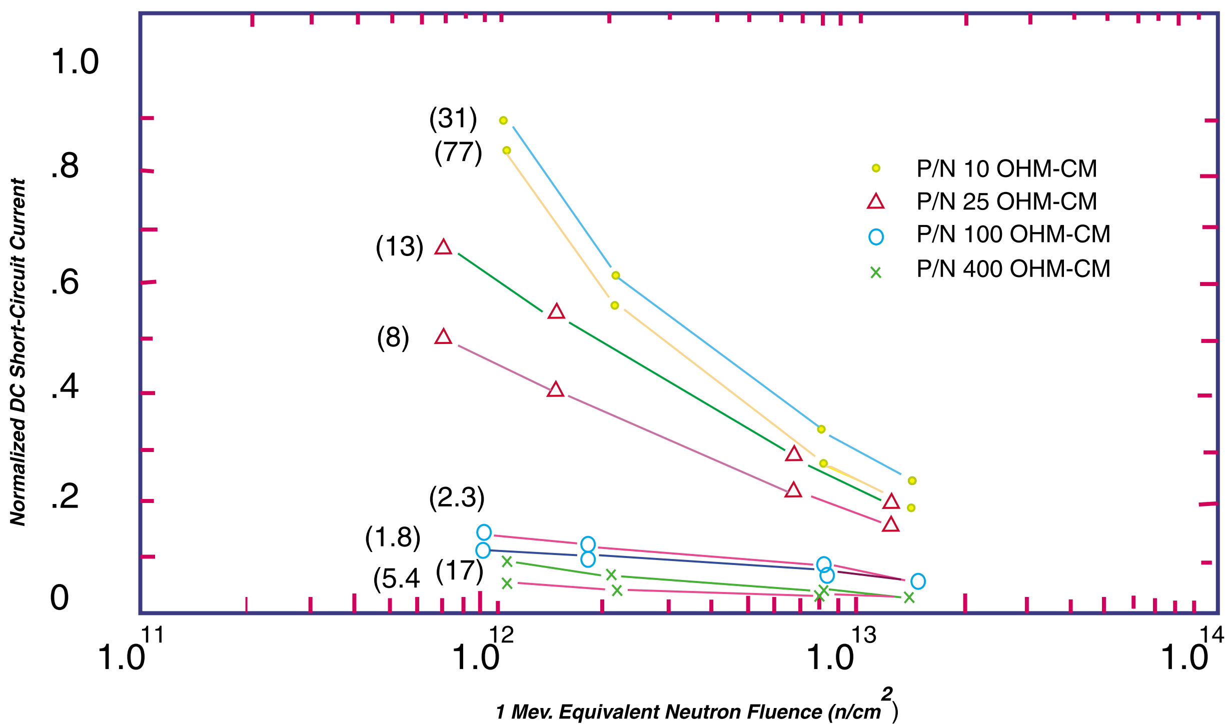

FIGURE 4. Small-Signal AC Shunt Resistance Versus Neutron Fluence.
(The Numbers in parantheses are the shunt resistance in Kohms befor Netrune irradition.)

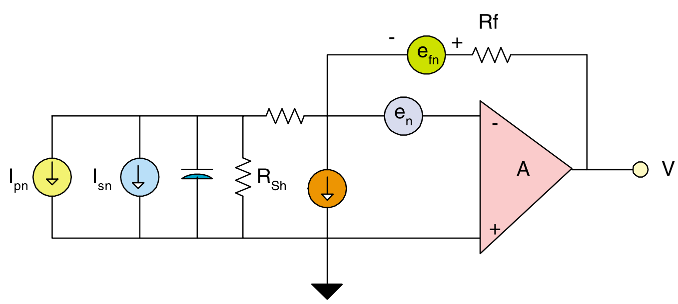

Figure 5. Photodiode and Photodiode Preamplifier AC Equivalent Circuit With noise Source

Noise Source	Output Voltage Contribution
I_{pn}	$I_{pn} R_f (1+R_s/R_{sh})$
I_{sn}	$I_{sn} R_f (1+R_s/R_{sh})$
I_n	$I_n R_f$
e_n	$[1+R_f/(R_{sh}+R_s)]e_n$
e_{nf}	e_{nf}

Table 1. Noise Contributions to output Voltage of Photodiode Preamplifier

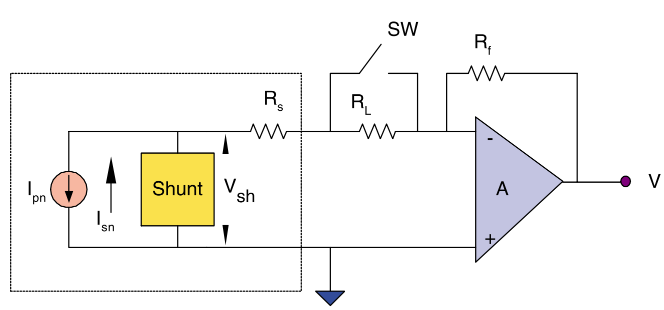

Figure 6. Test configuration Used For Measurement of Photodiode AC Shunt Resistance