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Application of p–i–n photodiodes to charged particle fluence measurements beyond 10^{15} 1-MeV-neutron-equivalent/cm^2

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ABSTRACT

Methods are developed for the application of forward biased p–i–n photodiodes to measurements of charged particle fluence beyond 10^{15} 1-MeV-neutron-equivalent/cm^2. An order of magnitude extension of the regime where forward voltage can be used to infer fluence is achieved for OSRAM BPW34F devices.

1. Introduction

At an early point in the operation of the Large Hadron Collider (LHC), the LHC Radiation Monitoring System (RadMon) [1] was developed for the purpose of monitoring and measuring radiation levels in the LHC tunnel, in order to anticipate possible equipment failures caused by radiation. Several device types were characterized and found to be appropriate for use as radiation monitors, and these were compiled into the Sensor Catalogue for Radiation Monitoring [2].

The p–i–n photodiodes of type BPW34F by OSRAM [3] were found to be sensitive to damage produced by fast hadrons ($E > 100$ keV) only. The devices are fabricated with n-type silicon of resistivity approximately 2.5 kΩ-cm with a die thickness of about 210 μm and a cross section of 2.65 mm^2. These devices have been shown to be useful for measurement of charged particle fluences in an operating regime where the forward voltage across the diode increases linearly with fluence when supplied with a constant forward current. They are an appealing choice for the researcher because as a commercial device they are readily available and inexpensive.

At room temperature, using current on the order of 1 mA injected on timescales under 1 s, and for forward voltages in the range of a few volts to tens of volts, the linearity range has been observed [4,5] to extend from about 2×10^{12} to about 2×10^{14} 1-MeV-neutron-equivalent (neq)/cm^2. An assembly of 49 such diodes, arranged as a 7×7 matrix, has been used [6] with those operating conditions for real-time imaging of a charged particle beam in this fluence regime and, equivalently, real-time monitoring of the fluence applied by that beam to a target.

Instrumentation development for detectors that will operate near the interaction points at the High Luminosity Large Hadron Collider (HL-LHC) prompts us to seek fluence monitoring methods with simplicity and economy comparable to that of these diode arrays, but that can be applied for fluences beyond 2×10^{14} neq/cm^2. Ref. [7] has shown that the standard theory for non-irradiated diodes cannot be extended to those in the realm of 10^{15} neq/cm^2; consequently an empirical approach is used here. Ref. [8] examines the applicability of the model of relaxation material theory to these devices and postulates that operation at reduced temperature can extend the upper limit of their useful range.

We have explored the relationship between diode signal and applied fluence for a variety of conditions of applied current amplitude, applied pulse duration, and temperature, for the case of forward bias, at higher fluences. We have developed operating protocols for these diodes for which the diode signal can be used to measure fluence beyond 10^{15} neq/cm^2. For this study, 100 BPW34F diodes were initially characterized, and 98 were used.

2. Irradiation of the diodes

Diodes were exposed at room temperature to a beam of 800 MeV protons at the LANSCE facility, Los Alamos. After radiation exposure, the diodes were placed in a freezer at −20 °C to inhibit annealing. Diodes received fluences ranging from about 8×10^{13} neq/cm^2 to about 3.8×10^{15} neq/cm^2. The fluences received by these diodes are obtained from the diode forward voltage, using a calibration curve we previously produced and reported [6] for these operating conditions. That calibration curve was established during a previous irradiation using an independent set of irradiated diodes, by relating the forward voltage to the fluence measured by gamma spectrometry of thin, high purity aluminum foils that had been stacked atop the diodes in the path of the irradiating beam.

The uncertainty on the actual fluence received is 11% and this number is dominated by the counting time of the calibration foils in the gamma spectrometer.

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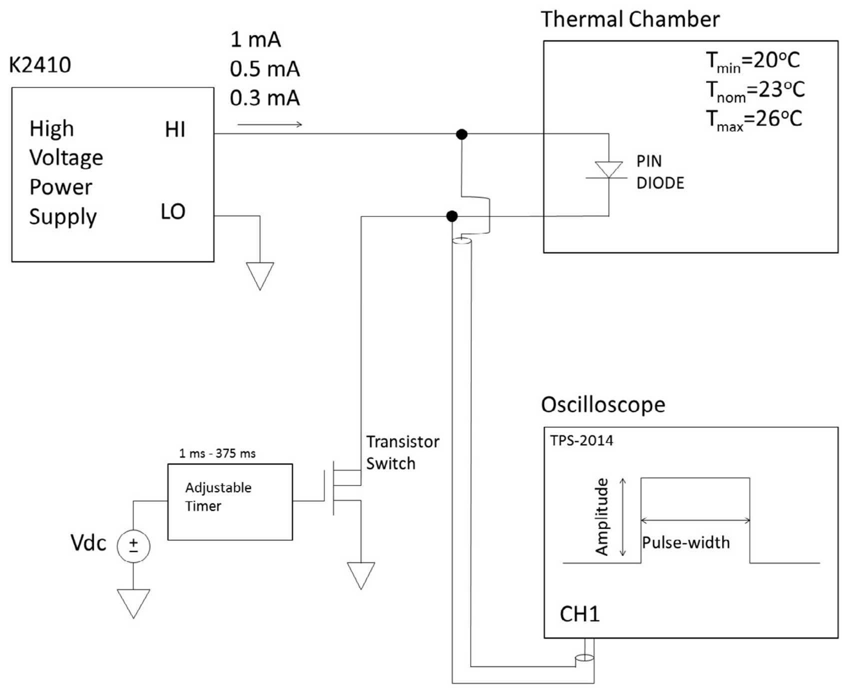

Fig. 1. The setup for the measurement of diode forward voltage.

3. Approaches to the problem

Figure 8 of Ref. [5] demonstrates a linear relationship between applied fluence and measured forward voltage in a limited range. Under the conditions applied in [4,5], the linear characteristic is lost above about 2×10^{14} neq/cm^2, and diodes studied in [4,5] had essentially no resolution for fluence measurements above 10^{15} neq/cm^2. The goal of the present study is to extend the upper bound of the fluence range to which the diodes may be applied. A model [9] that may describe the linearity has the forward voltage as a sum of the voltage drops at the p–i and i–n junctions together with the voltage drop over the intrinsic base. When the diffusion length approaches the width of the base, the overall voltage sensitivity to particles becomes positive, and at high fluences, the rise of the base resistance itself becomes increasingly important [10].

We seek an operating regime in which the diode voltage provides information about the fluence received, for fluences higher than those studied previously, while maintaining low joule heating and low risk of electrical breakdown. We have explored approaches to extending the high end of the linear region by modifying current pulse width and amplitude relative to those in the procedure of [4,5].

Although the diodes will be used for fluence measurements in real time in an active particle beam, the optimization procedure was carried out on proton beam-irradiated diodes studied in the controlled conditions of the laboratory. Fig. 1 shows the setup for the measurements on the laboratory bench of previously-irradiated diodes. Diodes are connected to a Keithley 2410 source/voltage-measure unit set up to source a constant current. A circuit is used to modulate the pulse-width of the source current. That modulation, along with a thermal chamber, allow selection of a variety of combinations of measurement conditions. The diode voltage is displayed and measured on the oscilloscope screen.

4. Pulse width optimization

The method of [4,5] involves reading the diode forward voltage while pulsing a 1 mA current for a duration of several hundred milliseconds. Prior to the irradiation, measurements were performed with a 1 mA current pulse of 372 ms duration applied to each diode in the forward bias direction; the forward voltage response was measured for each sample. At diode temperature (23 ± 0.5) °C, the average observed forward voltage of the unirradiated samples was $V_F = 0.563$ V $\pm$ 1%.

Noting that joule heating depresses diode forward voltage and could lead to non-linear response by the irradiated diodes of the type apparent in Figure 8 of [5], we studied the effect of the joule heating correlated with pulse width, examining the waveform of the pulse for widths of 372 ms, 50 ms, and 5 ms. Those measurements are shown in Fig. 2(a), (b), and (c), respectively. One observes a decrease in amplitude as pulsewidth increases, compromising the accuracy of the measurement. On this basis we revise the measurement procedure down from hundreds of milliseconds to values in the range 5–50 ms. This minimizes the uncertainty on the measurement of the forward voltage pulse of the p–i–n diode, which is especially important for very high fluences.

5. Systematic uncertainties

Measurements carried out in situ at a radiation facility will typically be made at the ambient temperature of the experimental hall which may vary, especially in response to local activation. Additionally the temperature of the diode itself rises transiently upon impact of radiation species. Using the temperature chamber on the laboratory bench, we studied the effect of reading out the diode at temperatures 20°, 23°, and 26 °C. The variation in diode forward voltage due to temperature variation from 20° to 26 °C is represented in Fig. 3 by vertical error bars associated with this ±3 °C variation around the central value of 23 °C. This range of temperature variation propagates to an uncertainty below 10% on fluences below 5×10^{14} neq/cm^2, rising to uncertainty of 16% at 10^{15} neq/cm^2 and 30% above 2×10^{15} neq/cm^2.

The current pulse width contribution to the uncertainty is minimized by reducing the width to a value for which the diode voltage amplitude as displayed on the oscilloscope approaches constancy and the uncertainty is less than or equal to 1.25% of the maximum.

The Keithley 2410 sourcemeter sources currents to a precision of 0.054%. For measurements reported here, the effect of the cable from the diode to the readout system is negligible. The total uncertainty on the measurement is determined by summing in quadrature the individual components.

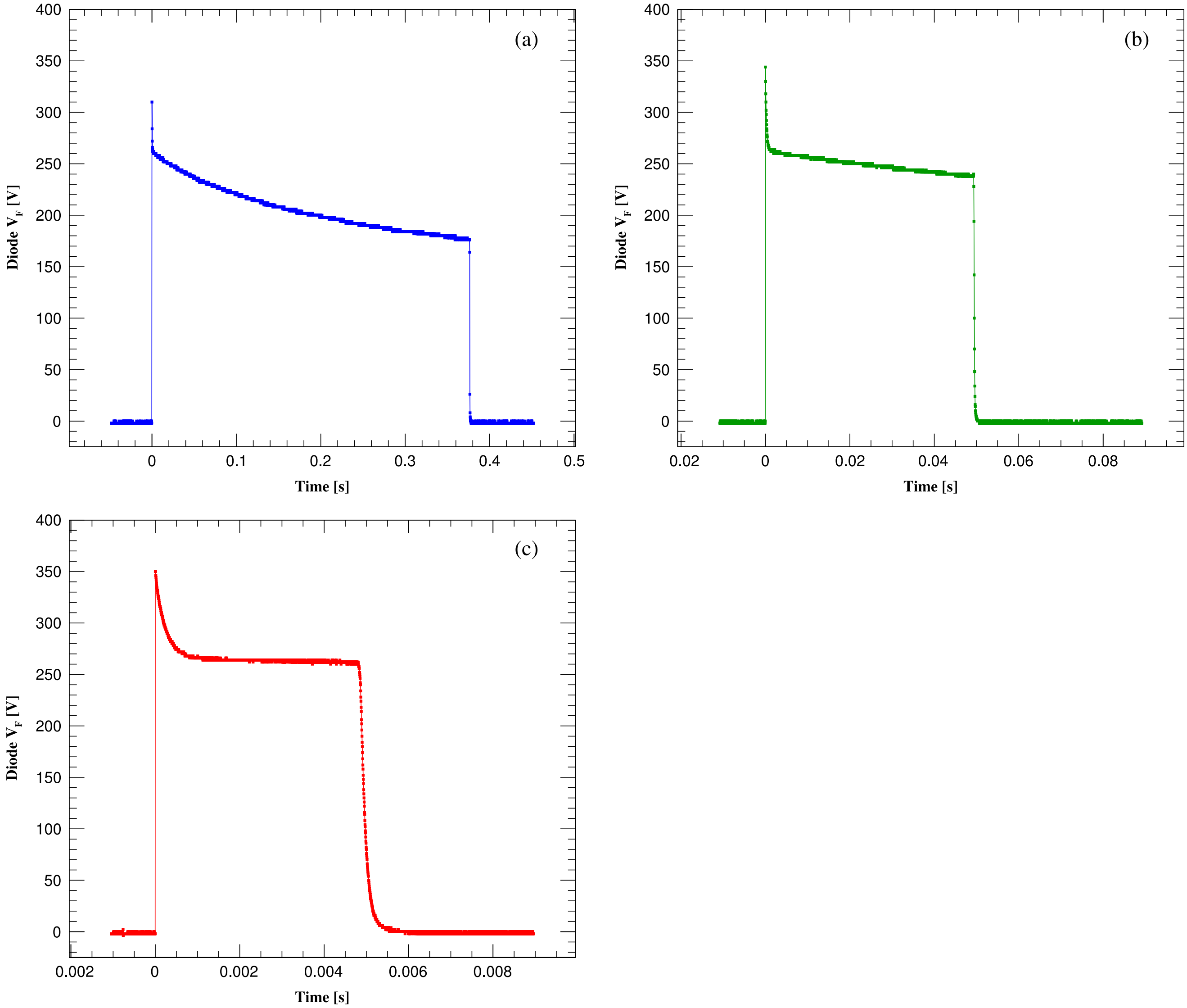

Fig. 2. Diode forward voltage versus time, for a p–i–n diode irradiated to a fluence of 2.1×10^{15} neq/cm^2 at 20 °C, observed for pulse widths of 372 ms (a), 50 ms (b), and 5 ms (c). Reducing the pulse width to a value for which the amplitude is constant is important for minimizing the diode heating and measurement uncertainty.

Table 1
Coefficients in the fit of analytical functions to the data in Fig. 3. Diode forward voltage V_F in volts is determined as a function of fluence Φ_{neq} given in units of 1-MeV-neutron-equivalent/cm^2.

Applied current (mA)	Functional form, $V_F(\Phi_{neq})$, volts	χ^2 on the fit to the data in Fig. 3
0.3	$-21. + 1.3 \times 10^{-3} \cdot (\Phi_{neq})^{0.3}$	8.8954
0.5	$-7.5 + 4.6 \times 10^{-8} \cdot (\Phi_{neq})^{0.6}$	7.0246
1.0	$0.0059 + 9.5 \times 10^{-14} \cdot \Phi_{neq}$	0.00598

6. Amplitude of the pulsed current

Fig. 3 also compares the voltage response to currents of magnitude 1 mA, 0.5 mA, and 0.3 mA. (The pulse widths are 5 ms, 25 ms, and 25 ms, respectively.) As expected the forward voltage decreases with lowered current, but the 0.3 mA and 0.5 mA curves become non-linear above about 5×10^{14} neq/cm^2. The 1 mA characteristic remains linear up to the highest fluence studied, 3.8×10^{15} neq/cm^2. The curves resulting from the 0.3 mA and 0.5 mA stimulus have the advantage that the maximum measured voltage remains below 110 V. Those curves are fit by the analytical functions shown in Table 1 so with application of the appropriate function they are comparable to the linear curve in providing fluence information in situations where voltage compliance is at issue.

7. Conclusions

A linear characteristic in forward voltage versus fluence can be obtained with OSRAM BPW34F pin diodes for fluences up to approximately 4×10^{15} neq/cm^2 using applied current amplitude 1.0 mA and pulse width 5 ms at temperature 23 °C. This represents a twenty-fold extension of the linear region of applicability of these diodes relative to previous operational guidelines.

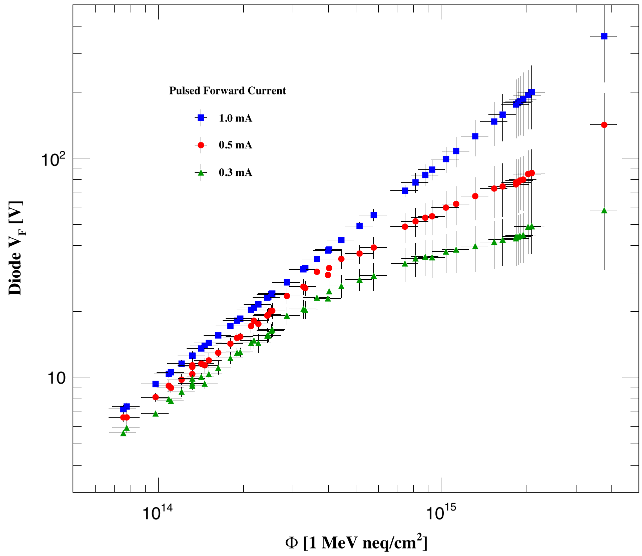

Fig. 3. Diode forward voltage as a function of applied fluence, for three choices of applied current amplitude. The vertical error bars indicate the combined uncertainties related to temperature variation during the irradiation process, current pulse width, and sourcemeter precision. The horizontal error bars indicate the uncertainty deriving from counting statistics on calibration foils in the gamma spectrometer.

Reducing the instantaneous measurement temperature down to 20 °C, and/or decreasing the applied current as low as 0.3 mA, increases the voltage-fluence regime over which measurements can be made. Functional forms for the voltage-fluence characteristic curves are provided for several combinations of current and temperature.

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References

[1] G. Spiezia, et al., The LHC Radiation Monitoring System - RadMon, PoS RD11, 2011, p. 024.
[2] https://ep-dep-dt.web.cern.ch/irradiation-facilities/radmon.
[3] OSRAM Opto-Semiconductors. BPW34F photodiode datasheet. www.osram-os.com.
[4] F. Ravotti, Development and Characterization of Radiation Monitoring Sensors for the High Energy Physics Experiments of the CERN LHC Accelerator (Ph.D. dissertation), Université Montpellier II, 2006.
[5] F. Ravotti, et al., Commercial p-i-n diodes for high-level 1-MeV neutron equivalent fluence monitoring, IEEE Trans. Nucl. Sci. 55 (4) (2008) 2133–2140.
[6] P. Palni, et al., A method for real time monitoring of charged particle beam profile and fluence, Nucl. Instrum. Methods A 735 (2014) 213–217.
[7] L. Beattie, et al., Forward bias I-V characteristics for heavily irradiated silicon diodes, Nucl. Instrum. Methods A 439 (2000) 293–302.
[8] J. Mekki, et al., Prediction of the response of the commercial BPW34FS silicon p-i-n diode used for radiation monitoring sensors up to very high fluence, IEEE Trans. Nucl. Sci. 57 (4) (2010) 2066–2073.
[9] M. Swartz, M. Thurston, Analysis of effect of fast-neutron bombardment on the current–voltage characteristic of conductivity modulated p-i-n diodes, J. Appl. Phys. 37 (2) (1966) 745–755.
[10] A. Rosenfeld, P-I-N diodes with a wide measurement range of fast neutron dose, Radiat. Prot. Dosim. 33 (1–4) (1990) 175–178.