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A method for real time monitoring of charged particle beam profile and fluence

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ABSTRACT

Detectors planned for use at the Large Hadron Collider will operate in a radiation field produced by beam collisions. To predict the radiation damage to the components of the detectors, prototype devices are irradiated at test beam facilities that reproduce the radiation conditions expected. The profile of the test beam and the fluence applied per unit time must be known. Techniques such as thin metal foil activation and radiographic image analysis have been used to measure these; however, some of these techniques do not operate in real time, have low sensitivity, or have large uncertainties. We have developed a technique to monitor in real time the beam profile and fluence using an array of *p–i–n* semiconductor diodes whose forward voltage is linear with fluence over the fluence regime relevant to, for example, tracking in the LHC Upgrade era. We have demonstrated this technique in the 800 MeV proton beam at the LANSCE facility of Los Alamos National Laboratory.

1. Introduction

Development of instrumentation often requires study of the interaction between high energy charged particles and materials. The energy transferred by charged beams through ionization and lattice displacement can lead to a loss of performance and accelerated aging of structural materials and electronic devices. Devices for the LHC or another future collider are typically tested for this sort of effect by being placed in a charged beam. We have developed a technique for real time measurement of the beam profile and fluence. This is an alternative to other methods such as thin metal foil activation [1], radiographic image analysis [2], flying wire [3], and Faraday cups [4], some of which are either not read concurrently with the beam operation, have larger uncertainties, or have lower sensitivity.

2. Description of the diode array

We construct an array of OSRAM BPW34F *p–i–n* diodes [5] to characterize the charged particle beam. When *p–i–n* diodes with bases manufactured from high resistivity *n*-type silicon are operated under the conditions of low injection, the concentration of carriers in the base region varies such that the resistivity ρ varies as a function of charged particle fluence Φ, as $\rho = \rho_0 e^{\Phi/K_\rho}$. Here ρ_0 is the initial equilibrium resistivity of silicon before irradiation and the coefficient K_ρ has a value between 400 and 3000 cm^{-2} for different silicon materials [6].

The forward voltage across the diode increases linearly with the fluence when supplied with a constant forward current. The diode's forward voltage response at 1 mA, as a function of fluence, is shown in Fig. 1 for exposure to 23 GeV protons and 0.8 MeV neutrons. On this graph, the response of the *p–i–n* diodes to the proton damage is linear in the fluence range from 2×10^{12} to 10^{15} 1 MeV neutron equivalent (neq) per cm^2 before reaching saturation [7]. In the fluence region below 2×10^{12} neq per cm^2 (not studied here), high-sensitivity diodes from CMRP would provide a similar linear characteristic [8]. Advantages of using an array of *p–i–n* diodes to measure the fluence include ease of readout, high spatial resolution, wide range of fluence response, independence of device orientation, dose-rate independence, and commercial availability at very low cost. A disadvantage of the diode is its temperature dependence. We minimize this disadvantage by sourcing the 1 mA current needed to operate them in short (130 ms) pulses.

3. Diode array readout hardware and software

The diodes are soldered to back-to-back metalized pads on the two sides of a G10 board. Four columns of seven diodes each are on one side, and three columns of seven diodes each are interleaved between them on the other side, producing a 7×7 array with nearly complete coverage of a 2.5 cm^2 region when operated

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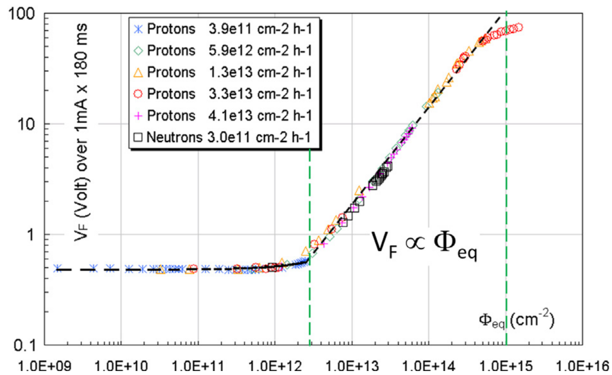

Fig. 1. Forward voltage of a single OSRAM diode as a function of fluence in 1 MeV neutron equivalent per cm^2 [7].

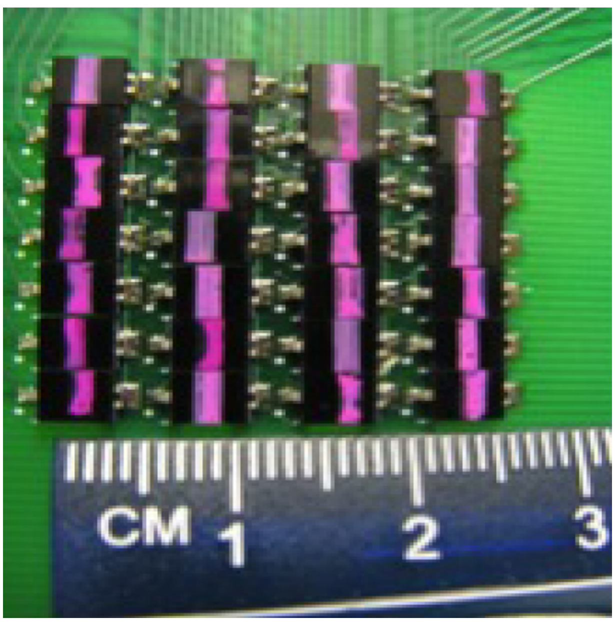

Fig. 2. The front side of the diode array.

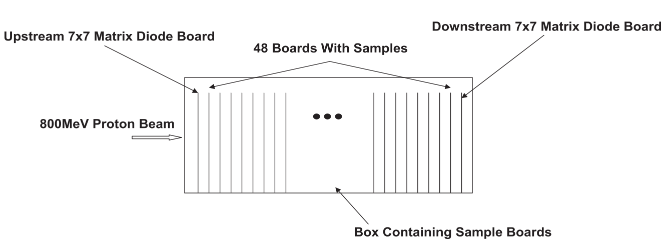

Fig. 3. Setup layout of a stack box.

altogether (see Fig. 2). The active area of each BPW34F diode is 2.65 mm × 2.65 mm, and the pitch between their centers is 3.8 mm. The board can be placed in a stack box (see Fig. 3) with the devices under test (DUT). Custom automated diode scanner software using LabVIEW is capable of scanning 49 channels quickly and remotely without stoppage of the beam. To scan a specific channel, a source measure unit sources a pulse of current and reads out the forward voltage across the *p–n* junction (see Fig. 4). No special environment is required for these measurements.

Our diode array system uses a Keithley 2410 SourceMeter, a Keithley 706 Scanner, and a LabVIEW application. The LabVIEW code controls the setup and functioning of the SourceMeter and Scanner. In general the SourceMeter is set to source a 1 mA constant current while measuring the forward voltage of the selected diode. The Scanner selects each of the diodes as it is pulsed and reads them out one at a time. The total time per diode measurement is approximately 130 ms.

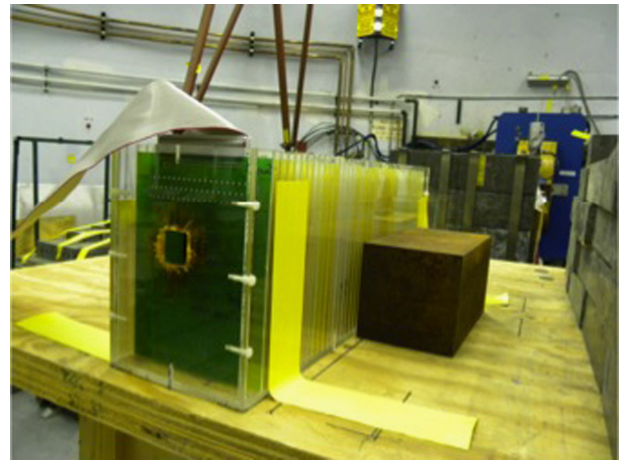

Fig. 4. Stack box along the proton beam. The diode array is attached to cables in the first position.

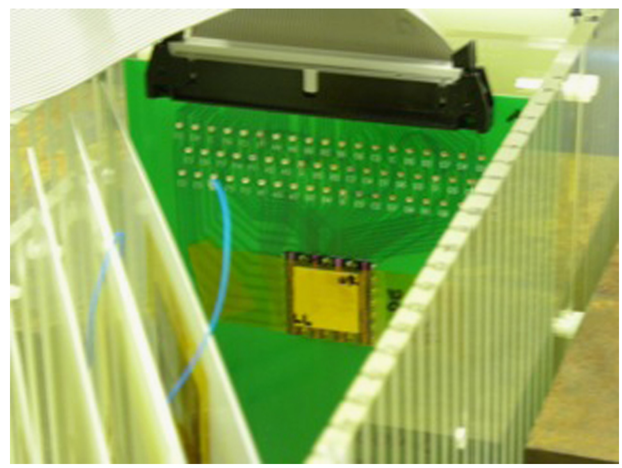

Fig. 5. Aluminum foil matrix attached to the diode array.

4. Calibration and example implementation

Two diode arrays were irradiated at the Los Alamos Neutron Science Center (LANSCE) in September 2012. The accelerator provides bunches of 5×10^{11} protons per macro-pulse at an energy of 800 MeV. The diameter of the proton beam spot is about 2 cm. This proton beam is maintained at a constant current of 80 μA. A useful configuration is to place one array at each end of the stack to monitor beam depletion. Fig. 5 shows the DUT stack box in the beam including one of the diode arrays. The electrical connections used for the beam profile measurement are shown in Fig. 6. The arrays were read out over a 30 m cable after fluences of about 4×10^{13}, 2×10^{14}, 3.2×10^{14}, and 8.2×10^{14} neq per cm^2.

We used aluminum foil activation to calibrate the diode response to fluence from the diode array for the LANSCE 800 MeV proton beam. A foil of size 2×2 cm^2 was attached directly to the diode array as shown in Fig. 5. We then measured the activity of its central 1 cm^2 region and converted this to the