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Hadron damage investigation of low gain avalanche detectors

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The High Luminosity Large Hadron Collider upgrade will increase the luminosity of the LHC by a factor of 10. Low gain avalanche detectors (LGADs) promise excellent timing resolution, which can facilitate pileup mitigation associated with high luminosity. The most highly irradiated LGADs will be subject to $2.5 \times 10^{15} \mathrm{n_{eq}}\ \mathrm{cm}^{-2}$ of hadron fluence during the HL-LHC operation; their timing performance must tolerate this. Hamamatsu Photonics K.K. (HPK) and Fondazione Bruno Kessler (FBK) LGADs have been irradiated with 400 and 500 MeV protons respectively up to the to the max. equivalent fluence of $1.5 \times 10^{15} \mathrm{n_{eq}}\ \mathrm{cm}^{-2}$. Preliminary characterizations of the FBK gain layer depletion voltage and timing resolution are presented here.

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1. Introduction

The High Luminosity LHC (HL-LHC) upgrade is expected to come online in 2029 and will increase the number of interactions per collision by an order of magnitude, up to about 200 interactions per bunch crossing. This increases the pileup and complicates the track reconstruction. The temporal distribution of p-p hits within colliding bunches is ~180 ps. In order to alleviate track assignment to the wrong collision vertex, experiments at the HL-LHC must have timing resolution significantly smaller than 180 ps. ATLAS is installing the High Granularity Timing Detector (HGTD) [1] in the forward region which will provide a timing resolution of ~30 ps at the start of the HL-LHC run and ~50 ps after receiving a fluence of 2.5×15 $\mathrm{n_{eq}/cm^2}$. CMS is installing the Endcap Timing Layer (ETL) with similar timing goals [2].

Both the ETL and HGTD will be made of low gain avalanche detectors (LGADs). LGADs have excellent timing resolution. Improvement of their radiation hardness is the goal of this study. An irradiation campaign was carried out this year on LGADs produced by Hamamatsu Photonics K.K. (HPK) and Fondazione Bruno Kessler (FBK), with 400 and 500 MeV protons respectively. Preliminary results on the FBK LGADs are reported here. Their fluence was applied at the Los Alamos Neutron Science Center (LANSCE) primary proton beam.

LGADs are thin sensors that have an $n^{++} - p^{+} - p - p^{++}$ structure. The sensors are operated under reverse bias with their bulk fully depleted at voltage V_{fd}. The p^{+} layer is referred to as the gain layer or charge multiplication layer. When fully depleted, the electric field across the gain layer can exceed 4×10^5 V/cm [3]. Charged particles from LHC collisions passing through the sensor will produce electron-hole pairs. The electrons undergo charge multiplication via impact ionization in the gain layer. The voltage required to deplete the gain implant, V_{gi}, is related to the dopant concentration in the gain layer, N_A, by

$$V_{\mathrm{gi}} = \frac{qN_A w^2}{2\epsilon}. \tag{1}$$

Here q is the electron charge, w is the width of the gain implant, and ϵ is the permittivity of silicon. The size of the gap between the gain implant and the n^{++} electrode is the gain layer depth, d. The voltage required to deplete the gain implant and the gap between the gain implant and the n^{++} electrode is called the gain layer depletion voltage, V_{gl}. V_{gl} is related to gain layer depth and the gain implant depletion voltage by

$$V_{\mathrm{gl}} \approx V_{\mathrm{gi}} + V_{\mathrm{gap}} \approx V_{\mathrm{gi}} \left(1 + 2\frac{d}{w}\right). \tag{2}$$

The electric field in the gain layer, and therefore the gain, are related to the gain layer depletion voltage. Fluence from collisions at the LHC will reduce the active dopant concentration via transformation of the boron acceptors into defect complexes no longer acting as acceptors [4]. This phenomenon is called acceptor removal and is the primary mechanism by which the gain and consequently the timing performance of LGADs is reduced [5].

2. Sensors, Irradiations, and Measurements

The FBK LGADS explore a range of parameters. They have 55 μm active thickness, multiple guard rings, shallow and deep gain layer depths, and carbon co-implantation in the gain layer. The carbon co-implantation has shown improved radiation hardness to neutrons [6] but has not yet been studied with charged hadrons. In addition to single LGADs, sensors without a gain layer and sensors in a 2x2 grid were fabricated to investigate the gain and inter-pad characteristics respectively. The FBK LGADs were irradiated at 2×10^{14}, 5×10^{14}, 1×10^{15}, and 1.5×10^{15} n_{eq}/cm^2. A sensor from each wafer was irradiated at each fluence. The devices were irradiated at room temperature ~ 23°C. All devices were stored at −25°C to inhibit annealing approximately 25 hours after the irradiation.

Three measurement techniques are used in this study: current versus voltage (IV), capacitance versus voltage (CV), and a measurement of timing resolution using a beta source. The IV measurement is used to infer the leakage current and breakdown voltage. The CV measurements are used to infer the V_{gl} and V_{fd} since the capacitance is inversely proportional to the depletion width. For IV and CV measurements, the LGAD sensor is held at 20.0 ± 0.5°C with a Peltier thermal chuck inside of a dark box. Bias is applied and current is read with a Keithley 237 HV Source Meter. For the CV measurement, a HP4284A LCR meter is used. The timing resolution is measured with a collimated ^{90}Sr source. The device under test (DUT) is measured in triple coincidence with a reference LGAD (REF) above and a SiPM coupled to a scintillator below. Both LGADs are bonded to dedicated pre-amplifier boards [7]. The output of those is further amplified by a Particulars AM-02B (35 dB) amplifier before being read out on a Tektronix DPO7254 2.5 GHz 40 GS/s oscilloscope. The measurement is done with the boards in an environmental chamber at −30 ± 1.5°C. The time-over-threshold values from the DUT and REF are extracted with a 25% constant fraction discriminator. The difference between the time-over-threshold values for the two LGADs is a constant that depends on the setup, with width determined by the timing resolution of the LGADs. This width is extracted with a gaussian fit to the difference between the REF and DUT time-over-threshold. The measured width (σ_{MEAS}) is related to the timing resolutions of the REF (σ_{REF}) and DUT (σ_{DUT}) by

$$\sigma^2_{\mathrm{MEAS}} = \sigma^2_{\mathrm{REF}} + \sigma^2_{\mathrm{DUT}}. \tag{3}$$

The reference is calibrated by a measurement of two identical sensors. In this case $\sigma_{\mathrm{MEAS}} = \sqrt{2}\sigma_{\mathrm{REF}}$, so a single measurement gives the resolution of both LGADs. For the reference, an unirradiated HPK-2 W43 LGAD biased at -160 V, which has a timing resolution of 33.4 ± 0.6 ps, was used.

Measurements are performed before and after annealing the sensors at 60°C for 80 minutes. After annealing, the leakage current decreased by ~30%, and the breakdown voltage increased by ~20 V. There was no significant change in V_{fd} or V_{gl} due to the annealing, likely because the beneficial annealing [8] occurred during the room temperature irradiation. While studies of annealing in neutron-irradiated sensors have been performed, similar studies for proton irradiated devices are not extensively reported in the literature [8, 9]. Accordingly, some irradiated wafers from both HPK and FBK have been set aside unannealed, and a comprehensive study of annealing after proton irradiations is underway.

3. Results

The CV and IV measurements were used to extract V_{gl} for FBK4 W18 sensors that received different doses. These measurements are shown in Figure 1. A decaying exponential,

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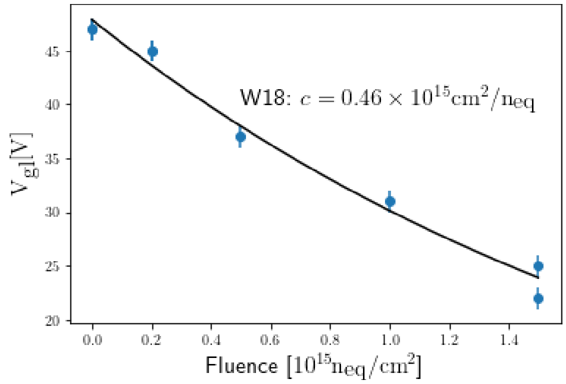

Figure 1: Measured V_{gl} for FBK4 W18 versus the proton fluence. The curve represents the function $V_{gl}(\Phi) = V_{gl,0}e^{-c\Phi}$. The acceptor removal constant, c, is $(0.46 \pm 0.02) \times 10^{15}$ cm^2/n$_{eq}$, and $V_{gl,0} = 47.8 \pm 0.7$ V.

$V_{gl}(\Phi) = V_{gl,0}e^{-c\Phi}$, is fit to the gain layer depletion voltage versus fluence to extract the acceptor removal constant, c. Preliminary measurements suggest that the acceptor removal constant is 0.46×10^{15} cm^2/n$_{eq}$ in this wafer. This is about three times greater than the acceptor removal constant in similar sensors after neutron irradiations [10].

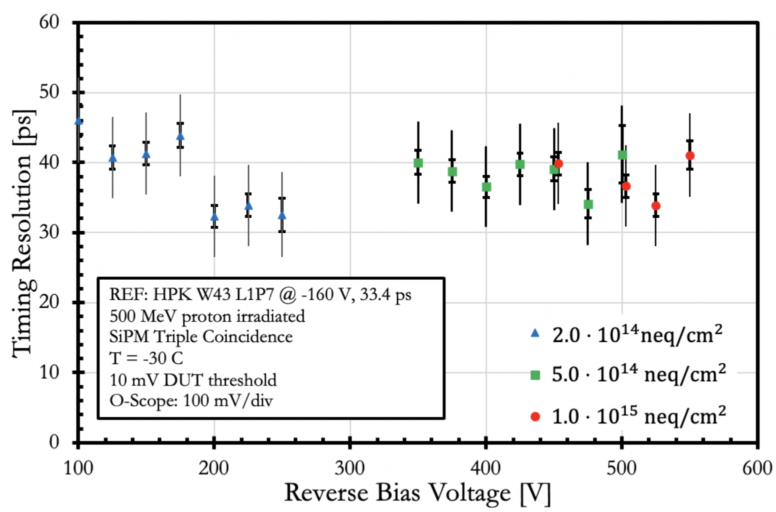

Figure 2: Timing resolution of FBK W9 versus bias voltage for various applied proton fluences. The capped errors bars represent the statistical uncertainty, and the un-capped error bars represent the statistical and systematic uncertainties added in quadrature.

Beta source timing measurements of FBK W9 were performed with sensors that received up to 10^{15} n$_{eq}$/cm^2. A 10 mV threshold ($\sim$ 0.5 fC) was chosen for the measurements. If the most probable value of the signal's Landau power spectrum fell below this threshold or if the electronic noise gaussian's tail exceeded the most probable value of the signal's Landau power spectrum, the data were discarded. These measurements are shown in Figure 2. Preliminary measurements indicate that the timing resolution does not exceed 50 ps after 10^{15} n$_{eq}$/cm^2. The bias voltage required for optimal resolution changes from ~300 V to ~550 V.

The systematic uncertainties on the timing resolution measurements were evaluated as follows. For all measurements, the oscilloscope was set to 100 mV/div (~ 4 mV/bin). By comparing otherwise identical measurements with 200 mV/div and 70 mV/div, it was determined that the choice of vertical digitization has a systematic error of 5 ps. The horizontal digitization was investigated by measuring at 5, 10, and 20 GSamples/s; from this study it was determined that the choice of horizontal bin width has a 2 ps uncertainty. The slope from a linear fit on timing resolution measurements at temperatures 7°C above and 7°C below the nominal temperature of -30°C was multiplied by the environmental chamber's 1.5°C uncertainty, to infer a 2 ps uncertainty associated with temperature instability.

There is statistical uncertainty from the gaussian fit to the difference between the REF and DUT time-over-threshold, and this is reflected in Figure 2 with capped error bars. The sources of systematic uncertainty are added in quadrature with the statistical error, and that total error is shown in Figure 2.

Measurements of the remaining irradiated FBK and HPK wafers are in progress and will further illuminate the effect upon LGADs of proton radiation.

4. Acknowledgments

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