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Power dissipation studies on planar n^+-in-n pixel sensors

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ABSTRACT

Research and development laboratory measurements of non-irradiated and irradiated planar n^+-in-n pixel sensor structures are systematically investigated to determine the power dissipation of those sensors. Measurements were taken at different operation temperatures, sensor bias voltages, bulk thicknesses, sensor areas, and irradiation fluences. For planar n^+-in-n pixel sensors irradiated to HL-LHC fluences of some $10^{16}\ n_{eq}\,cm^{-2}$ a power dissipation area density of (126 ± 8) mW cm^{-2} at a temperature of -25 °C and at an operation voltage of 800 V is derived for small sensors with an area of about 0.7 cm^2. For large sensors as planned for the ATLAS phase-II upgrade a power dissipation of 100 mW cm^{-2} is expected.

1. Introduction

The innermost tracking detector of the ATLAS experiment [1] at CERN-LHC consists of planar n^+-in-n pixel sensors with FE-I3 front-end electronics as hybrids [2]. Also the newly installed phase-0 upgrade insertable b-layer (IBL) [3] consists of pixel sensors with a revised design layout [4] and an improved FE-I4 front-end electronics. The expected radiation fluence in the LHC run-II data taking period of the innermost sensors will be a few 10^{15} Neutrons (1 MeV equivalent) cm^{-2}. The innermost pixel detector layers of the proposed inner tracker (ITk) as part of the ATLAS phase-II upgrade [5,6] at the high luminosity LHC (HL-LHC) [7] are expected to stay operational up to an integrated luminosity of 3000 fb^{-1} which translates to a fluence of above $10^{16}\ n_{eq}cm^{-2}$.

The irradiation impinging on the sensors drives an increase in the leakage current due to non-ionizing bulk radiation damage. Furthermore, the sensor operation voltage during the lifetime of the detector has to be increased to ensure high detection efficiency for particle tracking and tagging purposes. Therefore, the power dissipation will increase during detector operation.

The power dissipation is an important parameter for the design of all detector services like power supplies, cabling and cooling [6]. In a new detector, which has not suffered any radiation damage yet, this power dissipation is dominated by the read-out chip which typically dissipates 160 mW cm^{-2} [3]. However, sensors can gain a sizable fraction of the total increasing power dissipation during operation due to radiation damage.

2. Measurement details

The investigated assemblies consist of oxygenated n-doped float zone sensors which carry n-doped pixel implants with moderated p-spray isolation and a p-doped backside. Some general information about the sensors can be found, e.g. in [2,4,8–10]. Pixels are connected to a front-end chip with the help of a flip-chip process employing tin-lead-bumps. There are two different front-end electronics used. FE-I3 chips [2] are used for the 3-layer pixel detector of the ATLAS experiment. Those chips were produced in a 250 nm feature size bulk CMOS process and each pixel cell consists of an analogue and digital part with a pixel granularity of $400 \times 50\ \mu m^2$. The other front-end chip, called FE-I4 [3], was developed for the Insertable B-Layer at the ATLAS experiment, has a feature size of 130 nm resulting in $250 \times 50\ \mu m^2$ pixel cells. The assemblies used in this study are so-called single-chip assemblies where a sensor matching the size of a single front-end chip is employed. Sensor bulk thicknesses of 150 μm, 200 μm, and 250 μm were studied.

Irradiations of samples took place in three different facilities. At IJS TRIGA Ljubljana reactor neutrons [11,12] were used to reach

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maximum fluences of 2×10^{16} $n_{eq}cm^{-2}$ (HL-LHC-like fluence). The CERN-PS delivers protons at 24 GeV [13] and samples received neutron-equivalent (1 MeV) fluences of up to 1×10^{16} $n_{eq}cm^{-2}$. At Karlsruhe protons at 25 MeV [14,15] were used and FE-I4 assemblies received neutron-equivalent (1 MeV) fluences of 5×10^{15} $n_{eq}cm^{-2}$. This latter value corresponds to expected IBL end-of-lifetime fluences. After irradiation all assemblies and sensors were continuously stored at temperatures around −20 °C to avoid any annealing. The time at room temperature is estimated to be less than one week due to necessary handling steps.

Assemblies were mounted on read-out cards, sensor and front-end pads were wire-bonded to allow tuning and read-out of the assemblies in laboratory set-ups. A copper tape is connected to conduct heat from the assemblies to a metal heat exchanger. With the help of a regulated chiller device-under-test temperatures down to −40 °C were reached. Assemblies are stored in an isolation box which is flooded with nitrogen or dry air. Temperatures of sensors and assemblies are monitored with calibrated PT1000 sensors glued to the sensor and/or to the copper tape, respectively.

Irradiated sensors are biased at reverse voltages up to 1000 V. The front-end electronics is not powered with any operation voltages during these studies. This avoids heat load to the sensor. The bias grid of the sensor is connected to the ground of the front-end electronics.

3. Temperature scaling of the reverse bias current

In this section the scaling of the reverse current of the sensor with temperature is characterized. While several measurements of this kind can be found in literature investigating mainly bare and single sensors [16–18], here the investigations of specific bump bonded and irradiated detector assemblies in a specific experimental set-up are carried out. On the one hand, powering of bump bonded assemblies includes biasing through the front-end chip while biasing of single pixel sensors includes the bias grid only. On the other hand, the placement of the temperature sensor includes systematics to monitor the true sensor temperature in different set-ups. For the temperature scaling study FE-I3 pixel sensor assemblies were irradiated to a fluence of 5×10^{15} $n_{eq}cm^{-2}$ using neutrons from the IJS reactor.

The common procedure in these measurements starts with a cooled assembly which is slowly warmed up. A typical measurement cycle takes about one hour. Continuously, temperature, bias voltage and currents are logged. An exemplary measurement is shown in Fig. 1(a). Alternatively, measurements are carried out at fixed temperatures with varying reverse bias voltage. A set of measurements is shown in Fig. 1(b).

3.1. Analysis procedure

The data shown in Fig. 1(a) can be used to extract the scaling function of the sensor current as a function of the temperature. For a numerical analysis an ansatz including a quadratic term of the temperature times a Boltzmann factor including an effective band gap energy $E_{g,\,eff}$ of silicon is used:

$$I(T) = A \cdot T^2 \cdot \exp\left(-\frac{E_{g,\,eff}}{2 \cdot kT}\right), \tag{1}$$

with k= Boltzmann constant, T= absolute temperature, and A= a proportionality factor, specific to each sensor. This depends on the sensor size, doping and defect concentrations including irradiations; A also depends on the bias voltage and contains the volume in which a generation current is collected. With the help of a fit procedure as described in [19] this proportionality factor A can be

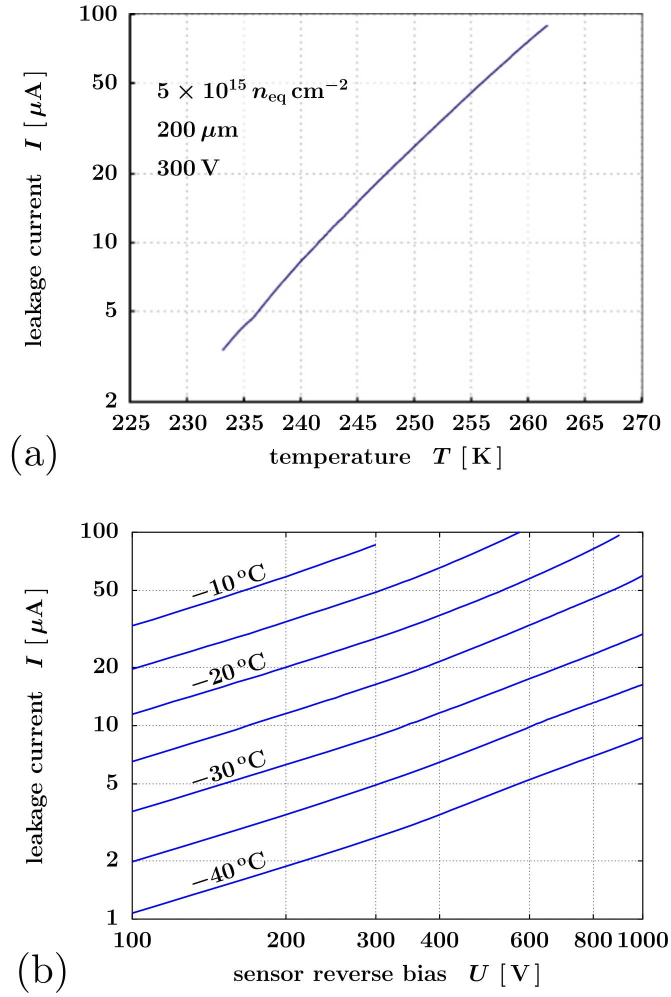

Fig. 1. Leakage current curves of a FE-I3 pixel assembly irradiated to a fluence of 5×10^{15} $n_{eq}cm^{-2}$. (a) Half-logarithmic plot of the leakage current vs. temperature at a fixed bias voltage and (b) double-logarithmic plot of the leakage current vs. sensor bias voltage at fixed temperatures. The line in (a) represents measurements taken in sub-Kelvin temperature steps and in (b) data with voltage steps of about 10 V are used. Here, the fixed temperatures are in steps of 5 K between −10 °C and −40 °C.

determined and allows to derive in a second step the leakage current scaling factor as

$$E_{g,\,eff} = -2 \cdot kT \cdot \ln\left(\frac{I(T)}{A \cdot T^2}\right). \tag{2}$$

A short discussion of errors follows in Section 3.2. Further details of this method and a discussion on systematic uncertainties applied to similar measurements on other but similar pixel single-chip assemblies in the same set-up can be found in [19].

Furthermore, the data allows an analogous procedure applied to leakage current data taken at fixed temperature but varying reverse bias voltage shown in Fig. 1(b). Thus, a voltage dependent leakage current scaling can be extracted.

3.2. Resulting values

Typical results of the leakage current scaling parameter in this specific set of data revealed values of 1.12 eV at 300 V and increases to 1.16 eV (1.19 eV) at 800 V (1000 V), respectively. These values of $E_{g,\,eff}$ are systematically slightly lower than other measurements, e.g. [18]. The difference can be explained by a systematic shift of the absolute sensor temperature in respect to the

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