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Investigations on radiation hardness of DEPFET sensors for the Belle II detector

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ABSTRACT

In the upgrade of the Belle detector at KEK (Tsukuba, Japan) the two innermost layers of the vertex detector will be realized by a pixel detector (PXD) consisting of DEPFET (DEpleted P-channel Field Effect Transistor) matrices. As the position of the detector will be very close to the beam pipe, it will suffer from intense radiation levels. The main radiation background is the luminosity related 4-fermion final state radiation, which damages the silicon bulk material and the silicon dioxide from the gate contacts. With the dose expected at Belle II, the DEPFET suffers mainly from additional leakage current and increase in noise. In addition, defects in the silicon dioxide change transistor parameters, e.g. the threshold voltage. We will show results on the hardness factor of electrons after a 10 MeV electron irradiation which was performed in the dose and energy range relevant for the PXD. In addition, we present X-ray irradiations of DEPFET equivalent test structures and compare radiation hardness for different oxide parameters in the prototype production.

1. Introduction

The study of the B-meson decay explored the picture and accuracy of the CKM (Cabibbo-Kobayashi-Maskawa) matrix further and further and may shed some light on fundamental questions like matter dominance in the universe and on new physics. For this exploration, B-factories were built in order to produce very high luminosities and high rates of B-mesons. An upgrade of the KEKB factory to the SuperKEKB facility will be a tool for this exploration. The factory is located at KEK (Tsukuba, Japan) and will deliver electrons with 7 GeV and positrons with 4 GeV to the planned Belle II detector. Running at the center of mass energy of the $\Upsilon(4S)$ resonance, the accelerator will achieve a peak luminosity of $\mathcal{L} = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$. The small difference in the lifetimes of particle and antiparticle is translated via the boost of the system to a difference in the flightpath of $\approx 150\ \mu\mathrm{m}$. In order to reconstruct this small difference in the decay vertices, precise tracking detectors are needed [1].

The device for this purpose is the Belle II detector and there within the vertex detector (VXD). It consists of four layers with double sided silicon strip detectors (SVD) and, for the two innermost layers, the pixel detector (PXD), consisting of DEPFET (DEpleted P-channel Field Effect Transistor) pixels.

2. Pixel detector

2.1. PXD attributes

The PXD is made in a barrel-like shape, by the repetition of units (*modules*) surrounding the beam-pipe, see e.g. Fig. 1 for a technical design drawing of the detector. Each module is made up by two half-ladders glued together with additional reinforcement ceramic inlays. Located along the lateral balcony on one side of the DEPFET sensor are the *Switcher* chips (drawn as red rectangles in Fig. 2), responsible for controlling the gates and clears of the Q3 desired rows (see Section 2.2 for details on the DEPFET Operation). Sitting on each end of the half-ladder the DCD (Drain Current Digitizer, yellow), which digitizes the drain current of the DEPFET. ASICs (Application-Specific Integrated Circuit) are bonded on the all silicon module resulting in an equivalent thickness of $<0.2\%$ of X_0 (for an overview of the readout and control ASICs see Ref. [2]). Following the data path, the next ASIC is the DHP (Data Handling Processor, beige) that processes the data and then transmits it via

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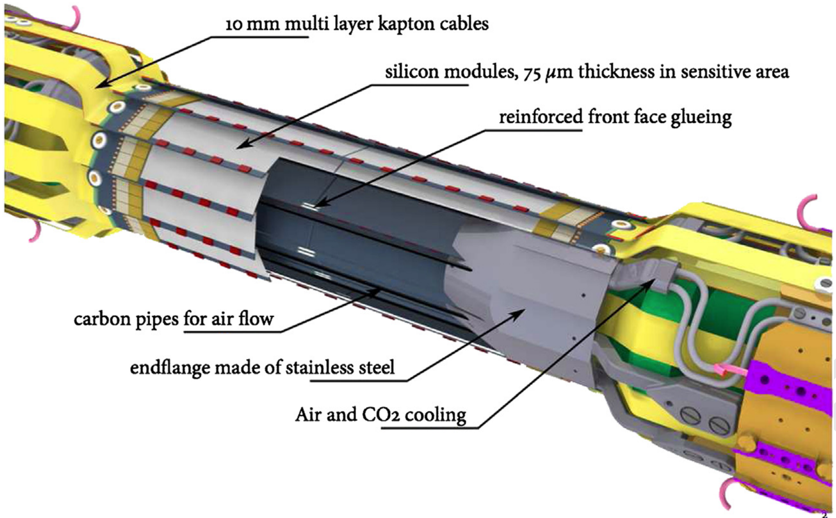

Fig. 1. Technical drawing of the PXD. The overall volume defined by the detector is roughly ($L \times \varnothing$) 123 $\times$ 22 mm^2 for the active area. The services are delivered at both ends of the detector, outside of the acceptance. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

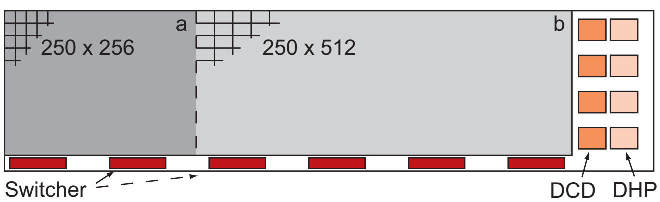

Fig. 2. Schematic drawing of a PXD half-ladder. The region *a* (closer to the interaction point) has a finer pixel granularity than the outermost region *b*. Along one side are the Switcher located controlling 32 channels each. At the end of the Q4 module are four DCDs with 250 channels each and the DHPs for data processing.

flexible PCBs (Printed Circuit Board) outside the Belle II experiment.

For a closer look on the design of the PXD, please see e.g. Refs. [1,3,4].

2.2. DEPFET mode of operation

The DEPFET was invented in 1987 by Kemmer and Lutz [5]. Since then, the technology evolved and the DEPFET can be designed to fit several applications like astronomy experiments or as a tracker element in particle physics.

It consists of a field effect transistor integrated on a medium to high resistivity bulk, which can be depleted via sidewards depletion from front and backside. For a typical DEPFET pixel, see e.g. Fig. 3.

The depletion ensures a fast charge collection process. While the holes are removed via the negative potential on the backside, the electrons are transported to the minimum of potential, a $n+$ implantation beneath the transistor channel, called *internal gate*.

The stored charge in the internal gate increases the drain-source current by $g_q = \partial I_{DS}/\partial Q_{sig} \approx 400\ \mathrm{pA/e^-}$. Higher amplifications have been achieved with thicker dielectrics [1].

The internal gate may eventually get filled up with signal electrons or leakage current and therefore a charge reset mechanism to avoid saturation becomes necessary. For this purpose an additional $n+$ implantation *clear* is implemented on the periphery of each pixel. By applying a high positive voltage in the clear contact, a punch-through to the internal gate is established and the electrons collected therein are removed. A deep p implantation surrounds and shields the clear in order to prevent the signal electrons to drift to the clear region during the charge collection phase.

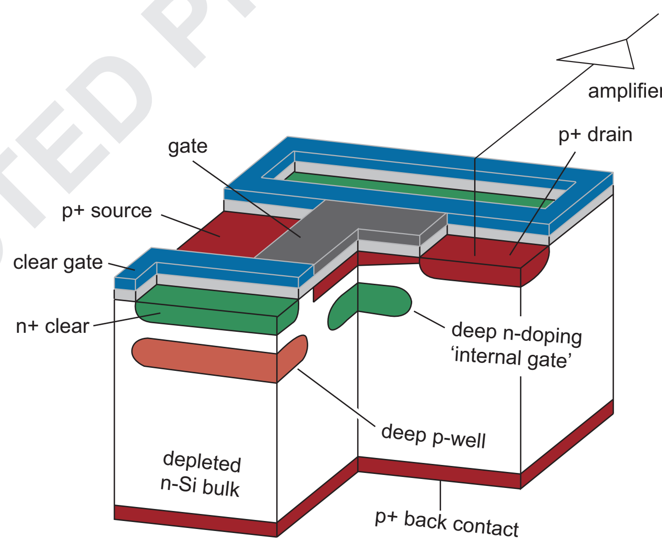

Fig. 3. Sketch of a typical DEPFET pixel cell.

The read-out consists of two steps[1]: first the drain current is sampled and then a clear process takes place. Due to the fast timing conditions in Belle II, the determination of the baseline current is done later electronically in the digital domain.

3. Radiation damage

3.1. Origin of radiation damage

The PXD gets irradiated during its lifetime by several processes like synchrotron radiation, beam–gas Coulomb interactions and Touschek scattering in both beams. However, the main background which is crucial for the assessment of the radiation hardness of the DEPFET is the 4-fermion final state radiation $e^+e^- \rightarrow e^+e^- + f^+f^-$.

As a quantum electrodynamic process it is luminosity dependent and simulations give a cross-section of $\sigma_{th} = 4.56 \times 10^7$ pb for this process [6]. This will result in dose rate of ≈20 kGy/smy

[1] Called single sampling.