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The Belle II pixel detector: High precision with low material

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ABSTRACT

An upgrade of the existing Japanese flavor factory (KEKB in Tsukuba, Japan) is under construction, and foreseen for commissioning by the end of 2014. This new e^+e^- machine ("SuperKEKB") will deliver an instantaneous luminosity of 8×10^{35} cm^{-2} s^{-1}, which is 40 times higher than the world record set by KEKB.

In order to be able to fully exploit the increased number of events and provide high precision measurements of the decay vertex of the B meson systems in such a harsh environment, the Belle detector will be upgraded ("Belle II") and a new silicon vertex detector, based on the DEPFET technology, will be designed and constructed. The new pixel detector, close to the interaction point, will consist on two layers of DEPFET active pixel sensors. This technology combines the detection together with the in-pixel amplification by the integration, on every pixel, of a field effect transistor into a fully depleted silicon bulk. In Belle II, DEPFET sensors thinned down to 75 μm with low power consumption and low intrinsic noise will be used.

1. Introduction

A decade ago, PEP-II (SLAC) and KEKB (KEK) started to show that ultrahigh luminosity factories, running at intermediate energies, could complement the direct discoveries of the energy frontier machines by the detailed study of the flavor structure of the Standard Model (SM). Those facilities, that started to produce B mesons in the late nineties, helped to explore the CKM matrix and understand the CP violation mechanism in the SM. The importance of these studies was pointed out in the Nobel Prize awarded to Kobayashi and Maskawa in 2008.

Ten years later, despite the great success achieved by the flavor factories after having collected an integrated luminosity higher than 1000 fb^{-1} in the Belle detector alone, the CKM picture is not fully revealed yet and more data, together with better precision measurements, are required. In order to obtain higher statistics, a new machine will be realized by upgrading the existing KEKB machine in Tsukuba, Japan [1]. The new super flavor factory, SuperKEKB, will be an asymmetric e^+e^- collider (4 GeV and 7 GeV for the positron and electron beams, respectively), working at the center-of-mass energy of the $\Upsilon(4S)$ resonance. The new accelerator will achieve a final peak luminosity 40 times higher than the existing machine, up to $\mathcal{L} = 8 \times 10^{35}$ cm^{-2} s^{-1}, by making collisions with very small spot-size beams (*nano beam*) and slightly higher currents. Under these conditions, an integrated luminosity of 50 ab^{-1} will be collected by 2020.

Despite the beneficial fact of having more physics events at such increased luminosity, there are also critical issues the detector system has to cope with in such a harsh environment. Ultra high luminosity also implies higher backgrounds and event rates, and therefore the detector has to withstand higher radiation levels, larger occupancies and fake hits as well as higher trigger rates. All in all, a significant upgrade of the existing detector (Belle) is pursued by the new Belle II Collaboration.

To fully exploit the huge amount of $B\overline{B}$ pairs that will be created in the new factory, the Belle II Collaboration decided to include a highly pixelated vertex detector very close to the interaction point (IP). As shown in Fig. 1 two layers of DEPFET (**DE**pleted **P**-channel **F**ield **E**ffect **T**ransistor) [2] pixels will be added just 2 mm away of the beam pipe to complement the four layers of DSSD (Double Sided Silicon Strip Detectors) that form the SVD (Silicon Vertex Detector) [3]. With this new configuration the detector will have a more robust tracking system (six layers) and a better vertex resolution (first pixel layer just 14 mm away of the interaction point).

The machine commissioning is planned by 2014, while the machine and detector will be ready by 2015 to start the physics run.

2. The DEPFET pixel detector (PXD)

An overview of the basic requirements for the pixel detector in terms of occupancy, radiation damage, required readout frequency and maximum allowed material budget is shown in Table 1. The

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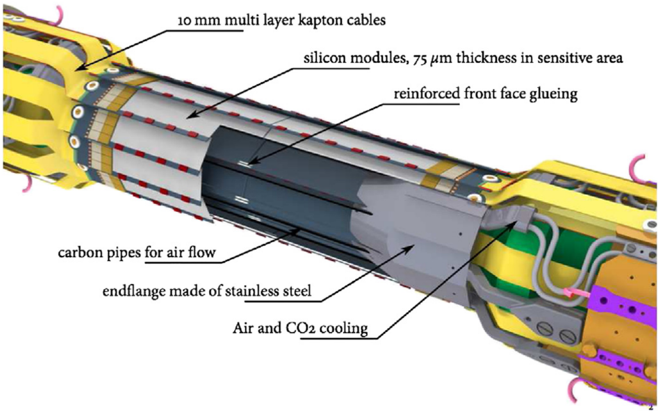

Fig. 1. Schematic view of the Belle II pixel detector (PXD). Two layers of DEPFET pixel sensors will be incorporated as the innermost subsystem. This new sub-detector will lead to a more precise reconstruction of the decay vertices and a more robust tracking system.

Table 1
Belle II PXD detector requirements in terms of occupancy, radiation damage, frame speed and maximum material budget. The combination of all these factors is a substantial challenge for the detector system.

Main characteristics	Belle II pixel detector
Occupancy	0.1 hits/μm^2/s
Radiation damage	15 kGy/year
Frame time	20 μs (continuous readout mode)
Material budget	$<0.2\%$ X_0 per layer

crucial consideration for the detector design is given by the fact that Belle II is dominated by low momentum tracks (<1 GeV). The resolution of the pixel detector is dominated intrinsically by multiple Coulomb scattering, so with a moderate pixel size ($50 \times 50\ \mu m^2$ for the innermost layer), the required spatial resolution (∼10 μm) can be achieved. For the same reason, the material budget has to be the lowest possible, below 0.2% X_0[1] per layer, including support structures, services, bump bonding and all the metal layers. The detector is read out continuously with a frame time of 20 μs (50 kHz frame rate) which, together with a small pixel pitch, keeps the occupancy lower than 3%. The combination of resolution, mass and power dissipation is a substantial challenge and, although the DEPFET technology can cope with these challenging requirements, the Collaboration faces a tight schedule to develop a complete detector system by 2015.

2.1. The DEPFET technology

A sketch of one DEPFET pixel is shown in Fig. 2. Each DEPFET pixel consists of a p-channel field effect transistor (FET) integrated on a completely depleted bulk. The substrate is a high resistivity (∼500 Ω-cm) n-type silicon with a p^+ backside contact. The charge in this device is fast collected by a drift process due to the fully depleted bulk. A deep n-doping implantation creates a minimum of potential for the electrons under the transistor's gate, in a region called *internal gate*. The signal electrons created in the substrate by the impinging particles, move towards and are accumulated in the internal gate. The transistor's current therefore is modulated proportionally to the collected charge. The accumulated charge in the internal gate can eventually screen its potential, resulting in an insensitive detector. To avoid such screening effect, after the readout, the charges are removed from the internal gate by applying a positive pulse to an n^+-contact (called *clear*) [4], placed on the periphery of each pixel. The figure of merit in this technology is the g_q factor, that is the internal amplification of the device. The internal gain expected for the final Belle II PXD sensors is on the order of 500 pA/e^-, although values 50% higher were achieved with thicker sensors and dielectrics in previous DEPFET productions [5].

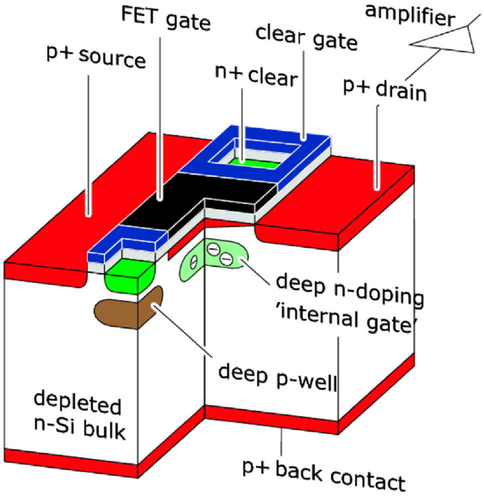

Fig. 2. Schematic view of a DEPFET pixel. The internal gate represents the minimum of potential for the electrons created in the substrate, where they are collected. The DEPFET technology provides detection and internal amplification at the same time.

A DEPFET sensor provides detection, fast charge collection and internal amplification at the same time. Due to the small capacitance of the collection node, the DEPFET has a low intrinsic noise while a large signal is achieved due to the fully depleted bulk, resulting in a device with a high signal-to-noise ratio (SNR).

This technology allows the design and operation of thin sensors (down to 50 μm) [6] with very small pixel sizes ($20 \times 20\ \mu m^2$), if required by the nature of the application [7].

2.2. Mode of operation

A DEPFET sensor is a combination of a certain number of individual DEPFET pixels arranged in a rectangular shape and operated together. In a DEPFET sensor, all the pixels lying on the same row have the gate and clear contacts connected to a steering chip (*Switcher-B*) [8], while the pixels on the same column have the drain contacts connected to the front-end electronics (*DCDB* or Drain Current Digitizer) [9] (Fig. 3). Such a DEPFET configuration is operated in *rolling-shutter* mode (row-wise readout). The drain current of all the pixels lying on the same row is sampled once per cycle before the clearing; once a row is read out and cleared, the next row is processed. The pedestal subtraction is done in the digital domain in a processor chip (*DHP* or Data Handling Processor) [10]. It has been measured [11] that, with a ∼6 cm long DEPFET sensor, a read-clear cycle can be done in 92 ns, without compromising the signal settling and reaching the target speed of 100 ns for the Belle II PXD. Because only the pixels to be read during the readout cycle have to be active, the sensor has a low power consumption although, even in the off state, all the pixels can collect charge at any time.

2.3. Auxiliary ASICs

In Fig. 1 it is clearly visible that the PXD is made by the repetition, in a cylindrical arrangement around the beam pipe, of a basic unit called all-silicon ladder (Fig. 4). In the silicon ladder, the

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[1] Radiation length.