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DEPFET active pixel detectors

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The DEPFET collaboration pursues the development of ultra-thin and precise vertex detectors based on the concept of a depleted field effect transistor. In this contribution the status of several key pieces of the project will be reviewed. Particular emphasis will be given to the results on the performance of DEPFET prototypes that were tested in pion beams at CERN's Super Proton Synchrotron (SPS). The results confirm that the DEPFET concept satisfies the challenging requirements in future colliders.

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1. The Depleted Field Effect Transistor

The concept of the Depleted Field Effect Transistor originated in the 1980s [1]. A schematic view of the concept is shown in figure 1. The DEPFET sensor is made of high-resistivity Silicon, as used in micro-strip and hybrid pixel detectors. The DEPFET sensor retains the favourable properties of such devices. A reverse bias voltage can be applied to deplete the full sensor thickness of charge carriers. The strong electric field throughout the bulk allows the signal from ionizing particles to be collected efficiently and rapidly.

The Field Effect Transistor (FET) is integrated in the sensor material. Free charge carriers generated by the passage of particles are collected on a deep implant underneath the transistor gate. This deep implant acts as a second, internal gate of the FET. Charge collected on the deep implant modulates the source-drain current. Thus, a first amplification of the signal is achieved in the sensor. The gain g_q of this first stage (expressed in units of current per electron) is one of the crucial parameters of the DEPFET.

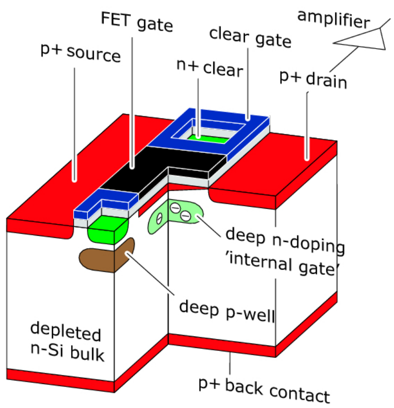

Figure 1: Schematic layout of the depleted Field Effect Transistor.

As stray capacitances due to connections between sensor and amplifier are avoided, a very small input capacitance can be accomplished, resulting in very good noise performance. Thus, the DEPFET concept allows for a competitive MIP Signal-to-Noise on very thin sensors. Read-out of the transistor current is non-destructive: the collected charge remains on the deep implant until it is removed by applying a large voltage on a nearby n-type clear electrode located nearby. In some applications, this feature allows for multiple read-out of the same signal and thus extremely good noise performance.

2. Applications

The unique characteristics of the DEPFET may find applications in a wide range of scientific projects. Currently, DEPFET-based detectors are being developed for the imaging systems of space based X-ray Astronomy missions (IXO, BepiColombo) and for X-ray detection in a free electron laser like XFEL [2]. These applications take advantage, primarily, of the excellent noise performance of the DEPFET and of the large signal from the fully depleted detector thickness.

The in-sensor amplification stage can moreover be taken advantage of to create very thin sensors with an excellent signal/noise ratio for minimum ionizing particles. The DEPFET vertex detector concept was first presented for TESLA [3] and developed further within the the International Linear Collider (ILC [4]) community.

Another application can be found in the future (super) B-factories. An upgrade of the KEKB collider and the Belle [5] experiment have been proposed. DEPFET has been selected as the baseline technology for the Belle-II vertex detector. A second project foresees the construction of a new machine in Italy [6].

*Speaker.

The physics reach of a both types of collider experiments depends strongly on the detector performance. Precise vertex reconstruction is a crucial requirement of the detector concepts. The required performance can only be achieved by a combination of excellent space point resolution and an extremely tight control of multiple scattering contribution. The material budget must be kept to a minimum, severely constraining the sensor thickness, power consumption and the design of detector services.

In table 1 the most important constraints on the vertex detector design are sketched. The numbers are valid for the innermost layer (envisaged to be located at a radius of 10-15 mm in both experiments). The estimates for Belle-II are based on the high current collider design and should be taken as a very rough indication. The expected hit density is similar in both experiments, of the order of a fraction of a hit per μm^2 and per second. To cope with these backgrounds, both vertex detectors require high granularity and a fast read-out architecture. The radiation level in Belle-II, while subject to large uncertainties, is expected to be significantly more severe than that of the ILC. Pulsed powering, taking advantage of the collider duty cycle, potentially yields a very significant reduction of the average power in the ILC. This possibility is excluded in the nearly continuous operation of super KEKB. Therefore, the Belle-II environment poses more severe requirements on many aspects of the detector performance. The Belle-II detector design is, however, greatly facilitated by the much more limited angular acceptance of this experiment. Most of the detector services can be installed outside the tracking volume.

Table 1: Comparison of the current best estimates of the most important constraints on the vertex detector design in Belle-II and ILC. In some cases these numbers are subject to large uncertainties.

	hit density	radiation	duty cycle	acceptance	momentum
ILC	0.1 hits/ $\mu m^2/s$	100 krad/year	1/200	6-174^o	[100 MeV, 100 GeV]
Belle-II	0.4 hits/ $\mu m^2/s$	1 Mrad/year	~ 1	17-150^o	< 1 GeV

The last column of table 1 reveals a difference that is particularly important for the detector design. Particle momenta in the ILC range from 100s of MeV to several 100 GeV. The spectrum of the charged particles from the Υ^{4S} resonance in Belle-II, on the other hand, is very soft. Most charged particles from the decaying B-mesons have transverse momenta of the order of several 100 MeV. The balance of the contribution of detector space point resolution and Multiple Coulomb scattering in the detector material is therefore radically different in both colliders. For Belle-II the resolution of the reconstructed vertices is dominated by multiple Coulomb scattering for any realistic detector design. Therefore, the importance of the material budget is even even more crucial in flavour factories than in high-energy colliders.

3. DEPFET active pixel vertex detectors

An active pixel sensor, with in-sensor signal amplification, is achieved by introducing a matrix of very small DEPFET structures in a large area wafer. The proposal of such a device for application in colliders dates back to 2002 [7, 8]. Devices with several tens of thousands of 20×20 μm^2 have since then been produced and operated successfully.

The matrix of pixels is read out in a rolling shutter architecture. A *column* of the order of 1000 DEPFET pixels is read out by a single channel of a read-out chip located on the edge of the sensor. As the shutter rolls over the matrix, each row of pixels is switched on in turn. The frame time needed to read out the full matrix is then given by the depth of the column times the time required to read out a single pixel.

Several auxiliary chips are required to steer the read-out and process the signal. The CuRO [9, 10] read-out chip has been crucial for the understanding of early DEPFET sensors and is still used intensively for characterization of sensors. A new IC, the Drain Current Digitizer, has been developed. The first performance tests of DCD2 show full functionality at the nominal 600 MHz clock frequency. Importantly, the noise is well below a LSB (corresponding to 100 nA) under a capacitative load of up to 80 pF [1] The power consumption, 6 mA/channel, is as expected.

The IC responsible for addressing the rows, known as the Switcher [11], is located on a balcony along the full length of the sensor. The same device also provides the pulse needed to clear the DEPFETs. The most recent iteration of the Switcher design, Switcher3, allows for a maximum voltage of 10 V. In the next version, Switcher4 in 0.35 μm HV technology with a rad-hard design, this range is extended to 30 V. A third chip, the Data Handling Processor located close to the DCD, is currently under development.

A complete mechanical detector concept known as the all-silicon module [11] has moreover been developed. A module is based on a large (typical wafer of 10 cm $\times$ 1 cm) DEPFET pixel sensor. A large fraction of the sensor area is thinned down to 50 μm using an etching technique. A pattern of thicker Silicon remains to provide mechanical stiffness. This technique to reduce the sensor thickness is described in more detail in references [12] and [13]. Thus, a mechanically robust, self-supporting ladder is created that can be handled without special care.

An important advantage of the all-Silicon module is that the problem of matching thermal expansion coefficients of different materials is effectively avoided as sensor and support are integrated in a single material (and even in a single wafer). The thermal properties of the module are studied in detail by a combination of measurements on thermal mock-ups and mechanical dummies and finite element simulation.

4. DEPFET prototype performance

The PXD5 production of DEPFET sensors includes devices with ILC pixel sizes (32 $\times$ 24 μm^2, 24 $\times$ 24 μm^2 and 20 $\times$ 20 μm^2). The pixels are arranged in a 256 rows $\times$ 64 columns, yielding a total active area of several mm^2. These devices have been integrated in prototype readout modules, where a CuRO reads out 128 channels and two Switchers steer the read-out and provide the clear pulse. Such modules have been submitted to exhaustive characterization in many laboratories in the collaboration. Radioactive source tests, with X-ray and γ sources, allow to relate the output signal (in ADC counts) to the well-known spectra of the these sources. With two further inputs, the ionization potential of Silicon and the gain of the read-out system measured elsewhere, an absolute calibration of the gain of the DEPFET in-pixel amplification stage is obtained. In typical PXD5 devices a quantum gain of up to 350 pA/e^- has been observed.

[1] More exhaustive tests performed since the date of the conference have shown the first, preliminary, results overestimated the noise significantly.

Two design variants have proven to lead to a significantly increase in the performance of the in-pixel amplification stage. DEPFET devices with a capacitatively coupled clear gate have shown a 50 % higher quantum gain compared to devices with the traditional clear gate structure. A second, more straightforward, variation is even more effective. DEPFET devices with a gate length of 5 μm (instead of the 6 μm of most PXD5 devices) have shown an 80 % increase in this crucial parameter.

Over the past five years, the DEPFET collaboration has performed an intense beam test programme to evalute the response of the devices to minimum ionizing particles. These test have provided important feedback to the detector design. They are, moreover, crucial to set up a detailed model of the detector response, to be used as the digitizer in Monte Carlo simulations. Finally, comparison of test beam results to those of source and laser tests have allowed to validate the test setups in the laboratories of the DEPFET collaboration.

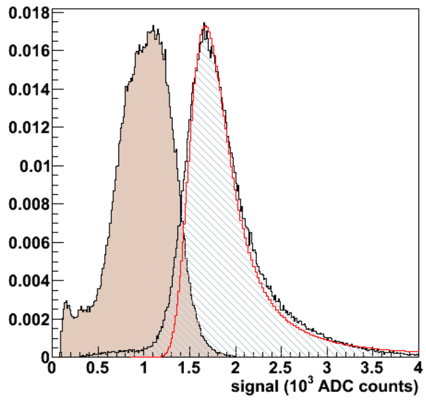

Figure 2: The cluster and seed signal distribution for 120 GeV pions perpendicularly incident on a DEPFET with $24 \times 24\mu m^2$ pixels.

The results of the earliest beam test have been reported in previous publications [14, 15, 16]. In 2008 and 2009 the DEPFET collaboration has continued its test beam programme in the SPS H6 beam line (120 GeV pion beams). Several DEPFET devices have been tested in the EUDET telescope [17] and in a DEPFET based telescope in both periods. A long write-up of the results is being prepared [18]. Here, only a brief summary of the most important findings is given.

The signal distribution for perpendicularly incident MIPs of figure 2 allows a cross-check of the gain measurement. The histogram with the hashed fill colour corresponds to the signal collected in 3×3 pixel clusters. Only pixels with a signal greater than 2.5 times the pixel noise contribute to the cluster. The cluster signal can be related to g_q by comparing to the most probable energy deposition of a minimum ionizing particle in 450 μm. With a value of 131 keV [19] (or 36.500 electron-hole pairs) the observed signal in the test beam is in excellent agreement with the g_q measurements in the laboratory.

The shaded histogram in figure 2 represents the *seed* pixel, the pixel with the largest signal. On average approximately two thirds of the signal is collected on a single pixel. This fraction depends strongly on the in-pixel position. A detailed high-statistics study is performed and will be reported in the near future [18, 20]. The DEPFET single pixel signal is found to saturate for a signal corresponding to approximately 60.000 electrons. This effect is attributed to the finite capacity of the internal gate. The measured value agrees within the device-to-device variation with a measurement of this effect using the leakage current [21].

In the device under test the pixel pitch (24 μm) is very small in comparison with the sensor thickness (450 μm). Therefore, for relatively small angles the particle trajectory projects onto a large distance on the read-out plane. For a particle incident under a 3^o angle, the length of this projection is 24 μm, equal to the pixel size. The effect of the non-perpendicular incidence on

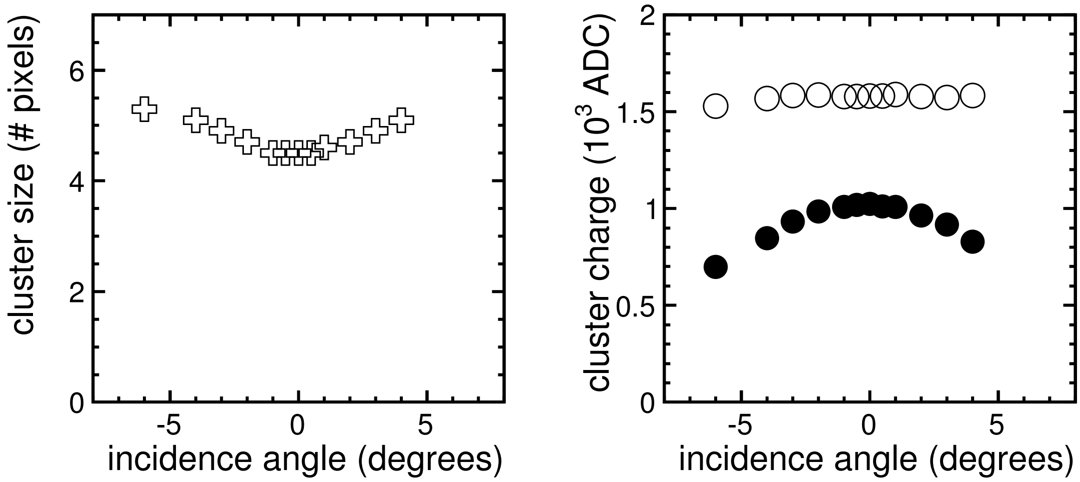

Figure 3: Variation of the cluster properties with incidence angle of the beam particles. Leftmost figure: average cluster size. Rightmost figure: seed (filled markers) and cluster charge (open markers).

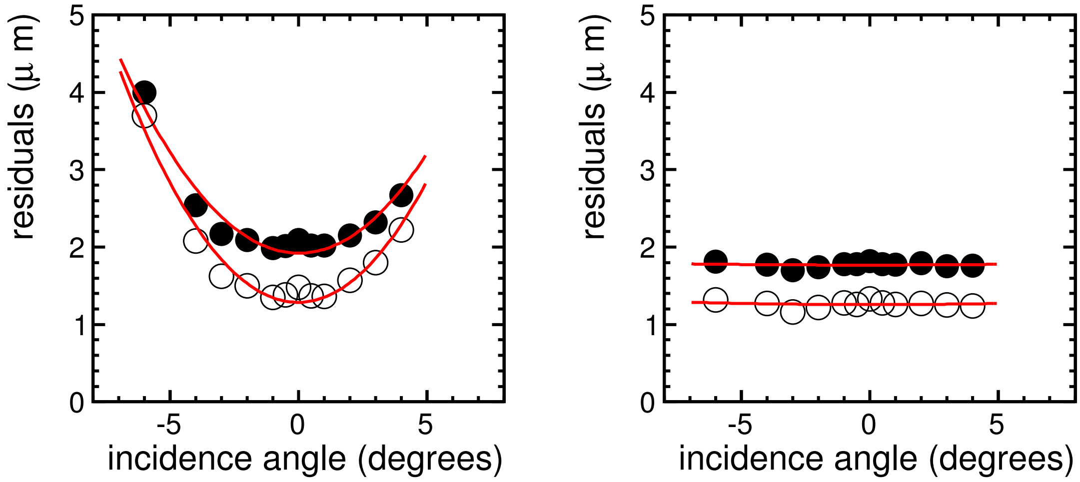

Figure 4: Residual width (filled markers) and resolution (open markers) of the small-pixel module versus incidence angle.

cluster properties like the number of pixels above threshold and the fraction of signal in the seed pixel is shown in figure 3. The increased charge sharing at larger angles is clearly visible in both plots.

The measurement of the resolution of the devices under test is not straightforward. The measurement of the resolution of the devices under test is not straightforward. The width of the unbiased residual distribution on the DUT receives signficant contributions from the finite telescope resolution and multiple scattering in the setup. A sophisticated method to extract the DEPFET resolution from the unbiased residual distribution has been developed. The correct functioning of the method has been verified using Monte Carlo simulations of the test beam. The details of this method have been discussed in a previous paper [14].

The resolution extracted from the 2008 data ranges from 1.6 μm to 2.6 μm for the X-coordinate measurement of the telescope devices, and between 1.3 μm and 1.8 μm for the Y-coordinate. The better resolution in this second coordinate is a result of the rectangular pixel design (the telescope modules have 32 $\times$ 24 μm^2 pixels). On the device under test, with square 24 $\times$ 24 μm^2 pixels, a resolution of 1.3 $\pm$ 0.2 μm and 1.2 $\pm$ 0.2 μm has been observed in the X and Y coordinate, respectively.

The increase in charge sharing at non-perpendicular incidence affects the resolution of the device, as shown in figure 4. For very small angles of $\pm 1^o$ or $\pm 2^o$ the resolution improves slightly. As soon as the projection of the particle trajectory on the read-out plane exceeds the pixel size the resolution is rapidly degraded.

Thus, beam tests confirm the exceptional performance of highly granular DEPFET devices with in-pixel amplification. The high quantum gain of the in-pixel amplification stage is a crucial step to achieve the material budget required for good vertex reconstruction performance in future linear colliders or B-factories. DEPFET is therefore among the few mature proposals that are able to meet the very challenging performance requirements these experiments.

A detailed comparison is performed of the latest test beam data with the results of a Monte Carlo simulation using GEANT4 [22, 23] of the test beam setup. This study is crucial to validate the detailed detector model used to predict the DEPFET vertex detector performance in the experimental environment of Belle-II and the ILC experiments. The results of this study are being prepared for a future publication [24].

5. Outlook

The DEPFET collaboration is developing active pixel sensors for applications in future collider experiments. A Field Effect Transistor integrated in every pixel yields a first amplification of the signal, resulting in excellent signal to noise ratio even for very thin sensors. The reduced material budget is a crucial asset in applications in the vertex detectors of a future linear collider or the upgrades of the B-factories.

Over the last five years considerable progress has been made in the sensor design, in the thinning technology, in the electronics for read-out and control of the DEPFET matrices and in the overall detector design, including concepts for cooling and services.

Small-scale, un-thinned, prototype DEPFET sensors have been tested in the H6 beam line of the CERN SPS. The beam tests validate measurements performed in the laboratory. Importantly, they confirm the significant increase in quantum gain observed for devices with shorter gate length and a novel clear structure. The DEPFET devices have proven to offer an excellent spatial resolution of slightly over 1 μm. Test beam data under different incidence angles are being used to validate the a detailed model of the DEPFET response to MIPs. An accurate digitizer is crucial predict the performance of DEPFET vertex detectors in a realistic experimental environment.

6. Acknowledgements

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