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Pixels detectors and silicon X-rays detectors

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Silicon pixel detectors are beginning to be used in large particle physics experiments. The hybrid technique (detector and electronics on two separate wafers) allows large surfaces to be built. For ATLAS at LHC it is proposed to cover areas of more than 1 m^2 with 5000 to 10000 pixels/cm². Each pixel has a full electronic chain directly connected which means very low input capacitance and no integration of dark current. Furthermore, silicon strip detectors and CCD's have been successfully tested for x-ray detection. Recent results indicate that a spatial resolution in the micron range can be obtained. Building on the CCD developments, the pixel detectors are becoming the best candidate for 2-D X-ray detection, with high speed, high spatial resolution and on-chip smart readout.

1. INTRODUCTION.

Silicon detectors are in widespread use in high energy physics (HEP) experiments. Until now, only strip detectors have been installed but this year two experiments will be equipped with pixels, the CERN-Omega-WA97 and the CERN-LEP-DELPHI experiments. The main advantages of the pixel detectors are photon counting with fast readout capability and on-chip full custom readout systems which can be adapted to the application (selective readout, external trigger or self-trigger, ...). Most of these advantages would be lost with an intermediate light screen. The interest is to convert the photons directly in the detector. To have a reasonable efficiency we need a depletion thickness of 0.3 to 1 mm. Usually, for HEP experiments, the detector thickness is about 0.3 mm. They are implemented in high resistivity silicon which is mandatory for the full depletion of such a thickness. Such detectors have been already tested for medium energy (up to 30 KeV) X-ray but they are mainly strip detectors, which give only a projective readout. The natural evolution is pixel detectors combining the advantages of the fully depleted silicon detectors for direct single photon with those of CCD's which directly give the two coordinates, without ambiguity.

We will first recall briefly the principle of silicon strip detectors, their use in HEP experiments, and some examples of X-ray detection with fully depleted silicon detectors. We will then describe the principle of pixel detectors, applications to HEP experiments and some prospects for X-ray detection with pixel detectors.

2. PRINCIPLE OF SILICON STRIP DETECTORS.

A standard silicon detector is sketched in figure 1. Strip diodes are built with long P⁺ implants on a n-type silicon wafer. Reverse bias voltage on these diodes provides an electric field. If the wafer is of high resistivity, the voltage can be high enough (30 V) to deplete the full substrate (0.3 mm) with a very low leakage current (a few nA). That means that there will be an electric field in the full volume of the

substrate, so that if a charged particle ionises the atoms of the crystal, the electrons and the holes will be pushed to the opposite surfaces where they will be collected. One has then to connect a charge amplifier to produce a pulse height proportional to the deposited charge.

In physics experiments, we are interested in detecting charged particles which leave about 22000 electrons in the silicon. For X-ray detection, the photon is converted in the silicon, mainly by the photoelectric effect if the photon is in the range of 2 to 30 KeV. The number of electrons is equal to the photon energy divided by the average energy of a pair production in the silicon crystal (3.6 eV).

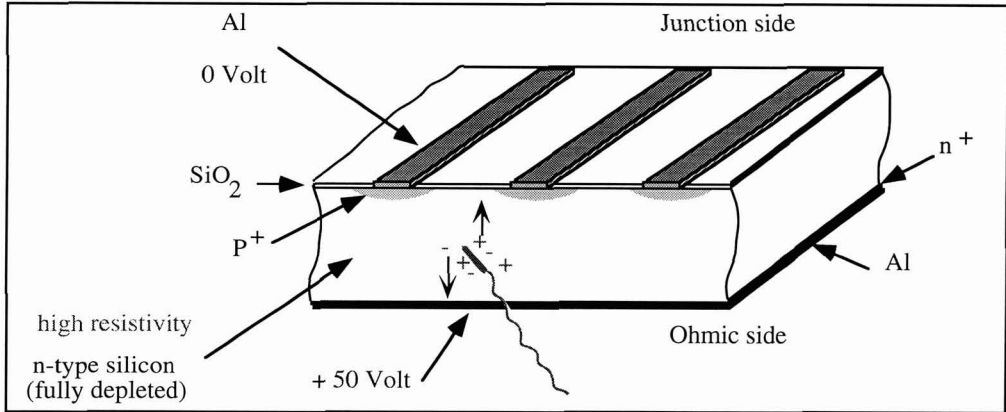


Figure 1 : Principle of silicon strip detectors

Such a detector provides localisation in only one dimension. However, the back plane can be divided in strips along the other dimension. But, since this plane is an ohmic contact the isolation between strips is very poor. There are now different solutions to solve this problem (P⁺ implants in between the strips, field plate to avoid the charge accumulation). Many HEP experiments are, or are being, equipped with double sided strip detectors.

3. SILICON STRIP DETECTORS FOR HEP EXPERIMENTS.

The task of silicon detectors is to localise particle tracks with a spatial resolution better than 10 μm. This allows to localise a secondary vertex from the reconstruction of tracks from a short life time particle disintegration. In a collider experiment, silicon detector elements are assembled around a cylinder (barrel), close to the beam.

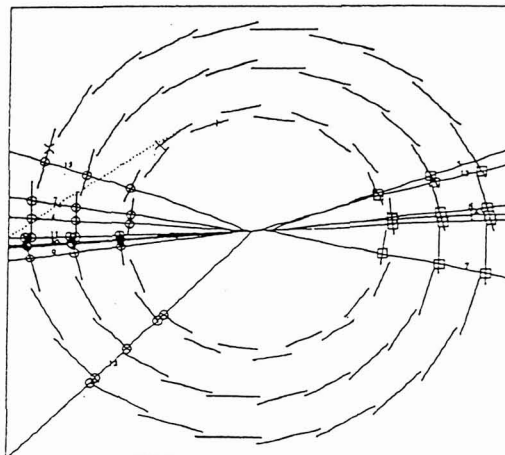


Figure 2 . Event display for a Z⁰ -> b+b-bar from the DELPHI vertex detector.

Detector elements of about 6 cm x 3 cm are glued one to the other to "ladder" of 12 to 24 cm long. At each end a ceramic hybrid is glued. This hybrid contains the front end electronics chips. These include a multi-channel (more than 100 channels) full custom chip containing a low noise charge amplifier, sample and hold circuits and/or comparators. The figure 2 shows a b-event from the DELPHI vertex detector. This detector will be upgraded with pixel detectors, as described later (see session 7.2).

4. X-RAYS DETECTION WITH DEPLETED SILICON DETECTORS.

We will give here some examples of X-ray detection with fully depleted silicon detectors. There are many other experiments, but the aim here is not to give a full inventory of all the existing X-ray silicon detectors, but only to show what we can expect with such detectors in this field.

4.1 SINGLE PHOTON X-RAY DETECTION WITH HIGH SPATIAL RESOLUTION.

Silicon detectors [1] with strips 6 mm long have been assembled to form a large band to measure the radius of diffraction rings (see figure 3). The charge amplifier is of very low noise ($ENC = 100 e^- + 17 \times C - pF$)

The readout is self triggered, which means that as soon as a charge (i.e. from a photon conversion) is detected, the readout (analogue) is activated. A very good linearity of the pulse height versus the photon energy is obtained by calibration using five radioactive sources from 13.4 KeV to 50.7 KeV. The Debye-Scherrer diffraction rings are well separated and their radii are easily measured (see figure 4).

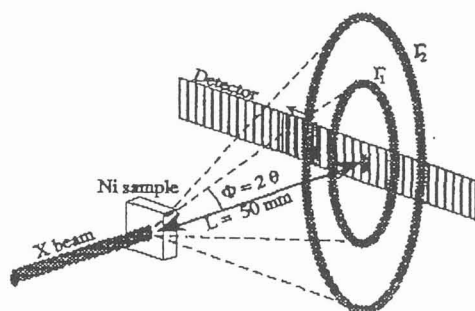


Figure 3 : Geometry for Debye-Scherrer diffraction.

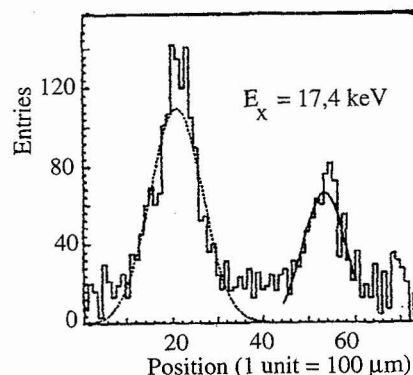


Figure 4 : Ring separation

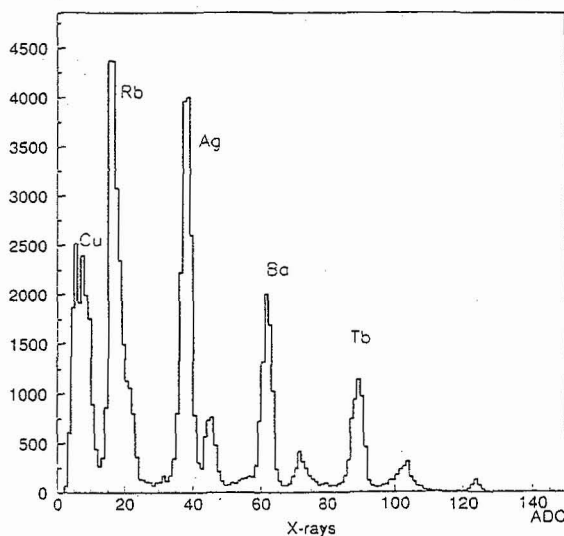


Figure 5 : Energy spectrum for radioactive sources down to 8 keV.

Using the same electronics, but on a 2 x 2 mm diode, an energy resolution of about 1.6 % has been obtained [2]. The low noise allows photon detection down to 8 KeV (see figure 5).

4.2 HIGH RATE, LOW NOISE, X-RAYS SILICON DETECTOR.

An even lower noise amplifier ($ENC = 29 e^- + 26 \times C$ (pF) at $T = 5^\circ C$) with very low leakage current (15 pA) detectors has been realised [3]. When connected to the detector, the total noise is $48 e^-$ at $22^\circ C$ for 1 μs peaking time. The measured energy resolution is 350 eV at FWHM (at $5^\circ C$) for Fe^{55} (5.89 and 6.49 KeV).

4.3 FULLY DEPLETED CCD FOR X-RAY DETECTOR.

Full depletion of a CCD substrate is a real challenge, since in this device, the charges have to travel along the surface and not across the volume. This has been done [4] on 280 μm wafers by a P^+ implant on both sides and lateral polarisation on N^+ anode. This device works like a silicon drift chamber. The size of one element is 1 x 3 cm for 200 x 64 pixels of $150 \times 150 \mu m^2$. Twelve elements have been assembled to form a surface of 6 x 6 cm. The readout of the full matrix is done in 24 μs but a windowing mode is possible which can reduce the readout time to 0.7 μs . That is very nice performance, however it should be much easier to build this kind of detector by using the hybrid pixel detector technique.

5. PRINCIPLE OF HYBRID PIXEL DETECTORS.

A silicon pixel detector is an array of very small diodes (less than $100 \mu m \times 100 \mu m$) with their associated electronics. The problems are two fold ; to concentrate the electronics in the pixel area and to make a contact point for each pixel input. The second problem does not exist in the case of monolithic detectors in which the electronics and the diodes are in the same substrate. However there are still many problems to be solved in this case and in particular, we have no good solutions to build large surfaces. We prefer for now to direct our efforts toward the hybrid technique, in which the detector and the diodes are on different substrates. This is much easier to build since the diodes have to be in high resistivity silicon while the electronics has not. Figure 6 illustrate the principle of hybrid detectors.

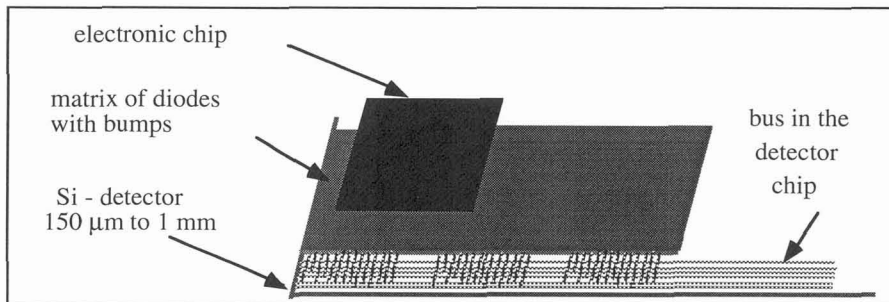


Fig 6 : Hybrid pixel detector

Also, since the detector substrate is of simple design, it can be of large size with a still reasonable yield, whereas the electronic part cannot. Large surfaces can be obtained by assembling large detector substrates (6 to 8 cm long) onto which 10 to 16 electronic chips of about $1 cm^2$ are bump bonded. The signals are transmitted from chip to chip by busses integrated into the detector substrate. The electronic chain includes in general an amplifier, a shaper, a comparator, memories and switches for a smart readout (of only the hit pixels).

6. THE BUMP BONDING.

One technique is to deposit a wet conditioning on the contact pads (using standard micro-electronics techniques) and to grow a thick layer of solder on the whole surface. After heating, the

solder erupts into small balls located on the contact pads only. The chips are then aligned and assembled by a flip-chip machine. The bump-bonding technique is already offered by many companies (GEC Marconi, IBM, Letti,....). Within the framework of the CERN RD19 collaboration this technique has been applied to pixels [5]. Similar techniques can also be used, including indium bumps (Thomson, Hughes Aircraft, Micron) or gold chips (ESD, CSEM). These methods are suitable for small contact pads (8 to 60 μm) but are expensive.

In the case of relatively large pixels (for example 300 μm , like in DELPHI), there is enough space for larger pads and one can try cheaper techniques including anisotropic conductive film and screen printing. The anisotropic conductive film is a plastic film in which conductive balls are randomly distributed. The film is deposited in between the detector and the electronic chips. when heated and pressed, the film fuses and the conductive balls make a contact perpendicular to the surface (between the detector and the electronic chip pads) but not along the film. Screen printing of conductive glue spots is based on printing technology but applied with micro techniques. A screen is built by laser drilling of holes at the places of the contact pads. Then a conductive glue is spread on it in such a way that the glue is deposited through the holes, on the contact pads only. Both methods are under test for the DELPHI experiment (anisotropic film at CPPM, Marseille and screen printing at INFN-Milano).

7. PIXELS DETECTORS FOR PARTICLE PHYSICS EXPERIMENTS.

7.1 THE CERN OMEGA WA97 PIXEL DETECTOR.

A pixel detector is being build at CERN in the framework of the RD 19 collaboration [5]. The aim is to build four 5 cm x 5 cm planes, of 75 μm x 500 μm pixels. In addition to the standard items (amplifier, comparator) the electronics includes a 500 ns delay and a coincidence with an external strobe. There are 16 x 64 pixels per chip. The bump bonding is done by the solder ball method by GEC Marconi (UK). Detector ladders of 5 cm long are produced and six chips are bonded on each. Six such ladders are then glued and wire bonded on a ceramic plate on which the input/output busses are deposited. Two such plates are assembled to constitute a fully active plane. A complete plane of 5 x 5 cm^2 (72000 pixels) is already built and installed in the heavy ion experiment WA97 at CERN.

7.2 THE DELPHI PIXELS DETECTOR.

DELPHI (Detector for Electrons, Photons and Hadrons Identification) is a physics experiment installed at the CERN LEP (Large Electron Positron collider). The innermost detector is a barrel of three layers of silicon strip detectors (see figure 2). This "micro vertex detector" is being upgraded by

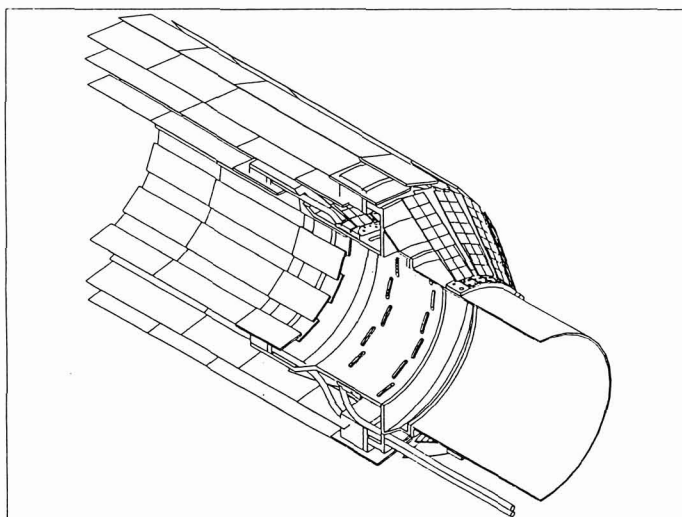


Figure 7 : DELPHI vertex detector upgrade 1995 with the pixel detectors.

lengthening the barrel and adding, on each end, two crowns of pixel layers followed by two crowns of silicon strips. Each crown of pixels will be built with 38 modules (see figure 7). The modules are 7 cm x 1.6 cm and has 8000 pixels of 330 μm x 330 μm . Sixteen chips are to be bonded on each detector substrate by a cheap technique, either anisotropic conductive film or screen printing.

In each electronic chip, selective readout allows only the hit pixels to be read at the rate of 100 ns per hit. It works as an associated memory: each pixel, as soon as it is hit, asks to be read by setting internal switches itself. The detectors are expected to be built and installed for the beginning of 1995.

7.3 PIXELS DETECTORS FOR ATLAS.

ATLAS is a detector to be installed at the future CERN 14 TeV proton collider (LHC) in the year 2002. The conditions around this collider will be very difficult: high crossing rate (25 ns) and very high luminosity (more than 10^{34} p/s.cm²). Two layers are proposed at 11 and 14 cm from the beam, containing about 120 millions of pixels of 50 μm x 200 μm with a total area of 1.2 square meters.

The integrated rate is calculated to be of about $6 \cdot 10^{13}$ particles/cm².year. This is to be multiplied by 10 since the experiment is built for at least 10 years. After such a radiation dose a conventional silicon strip detector substrate will have a large number of defects which will cause an increase of leakage current by a factor of 100 to 1000, while the voltage bias necessary to deplete the detector could be higher than the breakdown voltage. Also the electronic chips will be damaged. The main consequence for the electronics is charges trapped at the insulating oxide and/or at the boundary of the oxide and the silicon. These charges will change the regime of the transistors, or even destroy them. The effect of high leakage current is an increase in noise. After about 10^{14} particles/cm² the ratio signal/noise of a strip detector is becoming very bad. For a pixel detector the ratio signal/noise is 10 times better (more than 100) and this allows the thickness of the detector to be reduced by a factor of 2. This in turn decreases the depletion voltage by a factor of 4. But the main advantage of the pixel detectors regarding the radiation effect is the very small leakage current per amplifier, due to the very small element size. We are testing pixel detectors equipped with radiation hard electronics and we expect them to remain operational after $6 \cdot 10^{14}$ particles/cm².

Because of the very high beam crossing rate, the readout system has to include a time stamping. That means that it has to select not only the hit pixels but those hit at the same beam crossing as the trigger, and their readout has to be done without stopping the data taking. We are studying four different readout systems with this capability.

8. PROSPECTS FOR X-RAYS DETECTION WITH PIXELS.

We will give examples which demonstrate the high spatial resolution and the good energy resolution already obtained with pixel detectors. We will also make some remarks on the efficiency limitation of silicon detectors for x-rays and some points of comparison of pixels with CCD's.

8.1 SPATIAL RESOLUTION WITH PIXELS DETECTORS.

From our knowledge, the best spatial resolution obtained with hybrid pixel detectors is from S. Shapiro et al. [6]. This was a prototype of 256 x 256 pixels of 30 μm x 30 μm . The electronic chips

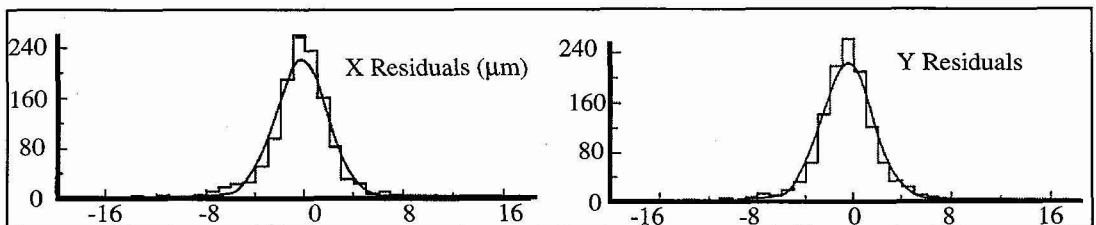


Figure 8 : Spatial resolution with 30 μm x 30 μm pixels ($\sigma_x = \sigma_y = 2.6 \mu\text{m}$).

were bump bonded with indium bumps (at Hughes Aircraft, USA). Figure 8 shows the residual plot for straight tracks traversing three detector hybrids at normal incidence that demonstrate $2.6 \mu\text{m}$ (σ) spatial resolution in both transverse dimensions.

8.2 ENERGY RESOLUTION.

Until now, few efforts have been made to optimise the energy resolution. Figure 9, shows an X-ray energy spectrum of a cadmium source measured with the CERN-RD19 - Omega chip [5]. This chip has no analogue readout but, from the derivative of the threshold curve, an energy resolution of 1.4 keV (FWHM) is measured.

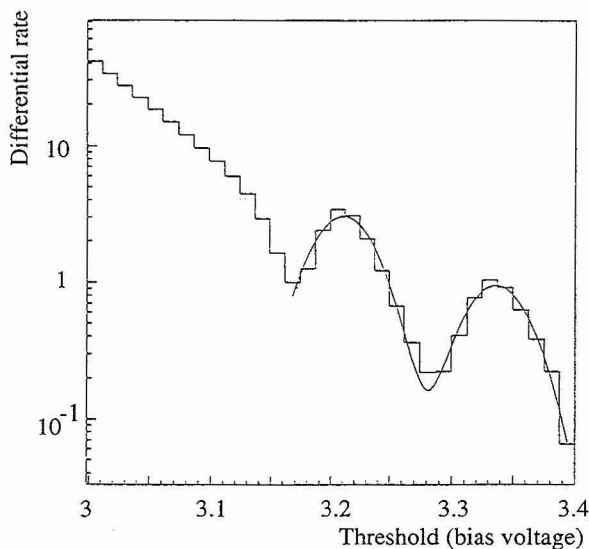


Figure 9 : Derivative of the threshold curve for the Cd source (22 keV and 25 keV).

If, for a given application, the measurement of the energy is needed, an electronic chip can be designed with an analogue output. We have several such designs. Since the charge collection in pixel detectors is very close to 100% and the noise is lower than strip detectors (because of the small capacitance at the input of the amplifier), the energy resolution for an optimised pixel electronics should be better than for a strip detector.

8.3 EFFICIENCY OF SILICON DETECTORS FOR X-RAYS.

Up to 50 keV, the production of charges in the detector by a photon is mainly due to the photoelectric effect. One can then compute the detection efficiency as a function of the photon energy from the photoelectric cross section. This is done for $300 \mu\text{m}$ and 1 mm of silicon [4]. For the standard thickness of $300 \mu\text{m}$, the efficiency is better than 98% for photons of less than 10 keV, while it is down to 7% for 30 keV. For high energy synchrotron radiation, we need 1 mm of thickness to have 60% at 20 keV and 5% at 50 keV.

8.4 COMPARISON OF PIXEL DETECTORS WITH CCD.

Since we are looking at the direct detection of photons, the pixel detectors could be compared only with fully depleted CCD of the same thickness. Some points of comparison are in table 1.

This table is not exhaustive; for each application the advantages/disadvantages of each technique have to be compared. For example, each time one needs full information on each photon (energy, position in space and time), pixels are preferred. If the photon flux is to be integrated, the CCD could be worthwhile.

Table 1 : Comparison of pixel detectors with fully depleted CCD.

CCD (Fully depleted)	PIXELS
open input	can be gated or self-triggered (photon counting)
large dynamic range needed (charge integration)	the dynamic range is not a relevant parameter (charge readout photon by photon)
maximum 100 full readout /sec	100 ns/charged pixel/cm ² , 10 ⁷ ph/cm ² 100 ns/pixel counter (10 bit)/cm ² , ≤ 10 ¹⁰ ph/cm ²
30 μm x 30 μm	ext. readout --> 30 μm x 30 μm int. readout --> 30 μm x 200 μm
difficult to fully deplete	easy to deplete until 1 mm
serial readout	flexible readout adaptation to specific applications (VLSI)

9. CONCLUSION.

Silicon strip detectors are in widespread use in particle physics experiments. They are essential for the precise localisation of interaction points.

Silicon detectors can have a very good spatial resolution (2.5 μm) and energy resolution (FWHM = 350 eV). The efficiency is better than 30% for photons between 2 to 30 keV (wafer thickness = 1 mm).

Pixel detectors are the natural evolution of silicon strip detectors, and can provide a two dimension localisation of a charged particle or a photon in less than 100 ns. This very fast readout is possible because a full electronic chain is directly connected to each pixel. This reduces the input capacitance and the noise to a minimum and allows the readout to be adapted to each application.

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