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Pixel detectors using single energetic quantum imaging: Past and future

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The early steps with 2-dimensional semiconductor detectors for particle physics experiments are briefly described. A comparison is made between monolithic devices, especially the CCD, and hybrid detectors, which combine a semiconductor sensor matrix with a separate ASIC in advanced CMOS technology. There is only a fragmentary treatment of the exploitation of the pixelated silicon systems in the LHC experiments, although these have become essential for tracking and vertexing in the high particle density in LHC. Some applications in other fields are mentioned. The difference is pointed out between the single quantum processing in these imagers, and the usual imagers for visible radiation. A few thoughts are developed in view of future pixel detector developments.

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1. Introduction.

The early steps with 2-dimensional semiconductor 'pixel detectors' for particle physics experiments are briefly described. After the 1st Workshop of this series, the author published an earlier article [1], with more details about preceding semiconductor image sensor developments, also in industry, for (near) visible light. These used in-pixel integration of the electrical charge, generated by the light, generally one electron-hole (e-h) pair per converted photon. The innovative feature of the hybrid 'pixel detectors' for particle physics was the implementation of a full classical signal processing chain in each pixel, exploiting the much larger signal charge, >1000 e-h pairs, liberated by a passing ionizing particle or absorbed X-ray. While in 1960 such an electronics chain took the volume of a shoebox, by 1990 it became possible to accomodate the same functions on a silicon surface area, a fraction of a mm^2. The hybrid assemblies combine a relatively straightforward semiconductor sensor matrix, often Si, with an interconnected, complex Application-Specific Integrated Circuit 'ASIC', which can be made with advanced Complementary Metal-Oxide-Silicon 'CMOS' technology. From 2005 such a sensor readout ASIC even could contain more than fifty thousand of these circuits per cm^2.

The early development and characteristics of these sensors with single quantum processing are touched upon in section 3. In sections 2 and 5 comparisons are made between the use of monolithic devices in particle physics, especially the Charge Coupled Devices 'CCD', and the hybrid assemblies. There is only a fragmentary treatment of the pixelated silicon systems in the LHC experiments. These have become essential for tracking and vertexing in the high particle density, and a wealth of details can be found in the large number of publications in litterature. The challenges of the 40MHz beam crossing rate, the overwhelming flood of data and the intense radiation also are not much discussed here. Some applications in other fields for these single quantum imagers are mentioned in section 4. A few thoughts on future developments are presented in section 6.

Unfortunately, thoroughly covering activities in semiconductor pixel detectors exceeds the framework of a conference presentation. The inventions in the beginning were made by only 5-10 people and very few are mentioned here by name. Several more groups soon initiated work on pixel detectors, and the author tries here to illustrate their contributions by at least one or two of their publications, while often they produced tens, and sometimes hundreds of articles and PhD dissertations. It would require a fairly thick book by now. The author asks the reader to tolerate this cursory overview, where some statements originate from personal experience. The slides from the Workshop presentation are accessible for the reader, and therefore only a few figures are reproduced in this article, while many other pictures and graphs can be found on the website [2]:

https://indico.cern.ch/event/829863/contributions/4479398/attachments/2565461/4422706/Heijne-Pixels-11RRpo.pdf

2. 2-D semiconductor imaging detectors: innovation in particle tracking.

In 1980 the introduction of silicon microstrip detectors in elementary particle physics experiments [3] improved by orders of magnitude the precision and rate capability for the measurement of particle trajectories. The main enabling feature was the parallel signal processing for single quanta incident on contiguous microscopic sensor elements. This became possible thanks to miniaturization of components and CMOS semiconductor technology. However, with these linear arrays, simultaneous particles on a small surface area give rise to ambiguities in their position determination, and even with several stacked planes, reconstructing trajectories is not straightforward. Detectors consisting of a true 2-dimensional matrix would obviously be much more capable. Moreover, in the planned particle collider experiments, occupancy and rates would be extreme, and therefore several teams considered 2-D semiconductor detectors for tracking near the vertex region.

An immediate possibility was the use of CCD, invented in 1969. These are 1- or 2-dimensional arrays of capacitors on silicon, designated as 'pixels', where charge packets can be pushed from one to the next, and finally to an output node, by variable voltage pulses, with a network of clocking lines. By 1980 CCDs were mostly used for military and scientific imaging with visible, infrared or UV light. Signals are also generated at the passage of ionizing particles, but some drawbacks limit in practice the performance. A demonstration of CCD for vertexing was made by the team of Chris Damerell, in a test beam [4] and then in the CERN NA32 experiment. In 1986 they installed CCD with rolling shutter readout in opposite directions, and could improve the selectivity for interactions involving charm or bottom quarks, characterized by a secondary decay vertex. The experiment found new particles, using a much lower overall beam intensity than had been required with the less precise tracking data from wire chambers and Si microstrips alone. A convincing comparison is shown in fig.1. However, not only had they to refresh continuously the CCD matrix, but also they had to deviate the beam to a dump during the ~15ms serial readout of the CCD, once a positive trigger was received, to avoid many additional, confusing hits. A much larger, tubular CCD system was succesfully employed later in the electron collider experiment SLD at SLAC [5]. A drawback of the CCD was noise from the accumulation of signal-charge from dark current, but this could be reduced by cooling. The CCD have a very thin sensitive layer, resulting in a small signal charge. This still can result in a sufficient signal-to noise S/N ratio if the pixels are small, with a low capacitance. A thicker sensing layer would result in relatively larger signals from minimum ionizing particles (m.i.p.) and eventually, special CCD were designed, using Si with higher resistivity. However, these would increase multiple scattering of the particles, and present a loss of precision in coordinates. Such high-resistivity CCD were produced, for example, by Steve Holland at the Lawrence Berkeley Lab for exposure via the back-side in astronomy applications [6].

In the USA, with the Superconducting Super Collider SSC underway since ~1984, two teams started work on 2D tracking devices. Both reported their plans during the 1988 Workshop on Pixel Detectors, organized by the author, in collaboration with the microelectronics center IMEC in Leuven [7, 8, 9]. Sherwood Parker from Hawaii University, and mostly working at the LBL, proposed a monolithic design on high-resistivity silicon. In a collaboration with the Center for Integrated Systems CIS of Stanford University, a device was manufactured and tested in a beam at Fermilab [10]. Unfortunately, by October 1993 the construction of the SSC was halted, and for a few years in the USA no activities were undertaken towards 2D particle trackers, until teams joined the LHC collaborations.

Also the second effort, initiated by a team at SLAC, was discontinued. They had evaluated hybrid prototypes coming from Hughes Aircraft. Their devices used a pixelated Si sensor chip, bump-bonded to a CMOS readout matrix with addressable pixels, in which signal current was integrated on a capacitive element, during the exposure time [11]. Such a circuit, in this case using four transistors, has been used in many CMOS imager designs over the years. These so-called Monolithic Active Pixel Sensors MAPS started to replace CCD in many imaging systems from ~1990. The designation 'Active' means that in each pixel there is at least one transistor. And several are needed to allow addressing of an individual pixel and transmission of its charge signal towards the output. The circuit is often extended with 'double correlated sampling' in order to compensate for the pixel-specific dark current, measured outside exposure, and the number of transistors per pixel then becomes a few more than 3 or 4.

The planned high-energy, circular particle colliders [12] would have beam crossings of up to 70MHz, and would need fast tracking detectors. In a 200 or 300 μm thick ultrapure Si diode the signal formation is <<10ns if the electric field can approach 50 000 V/cm, or 5V/μm, which gives a saturation carrier velocity towards 10^7 cm/s, or 100μm/ns. Besides the need for 100% fill-factor and fast recovery, pixels need parallel processing, and temporary in-pixel storage of timestamps for hits, until later readout is available.

Besides the three projects mentioned above, in 1987 the most consequential approach was undertaken by the author and his CERN team [13]. They aimed to insert a full, classical signal processing chain in each pixel, eventually even including particle identification via the characteristic pixel cluster patterns. Hence the name 'Micropattern Detector', but the community then adopted 'Pixel Detector'[1]. In these devices, a pixel needed to contain tens, hundreds, or even thousands of transistors, depending on the functions to be implemented. The following section will describe some details of this fourth initiative, and the onset of the developments for the pixel detectors in the LHC experiments. Then spin-off activities towards other applications are mentioned in section 4.

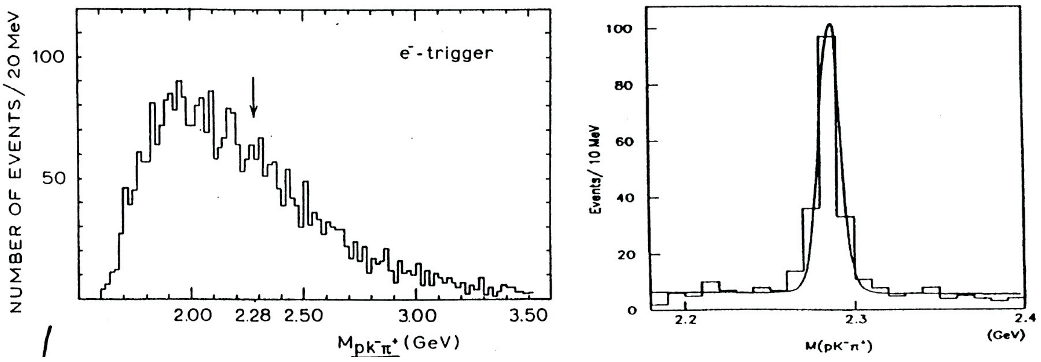

Fig. 1 The impact on particle discovery and mass determination by true 2D position detection with CCD. The selectivity of triggers in the NA32 experiment could be very much improved. Left: reconstructed effective mass for pKπ events triggered by single electrons, hopefully coming from the investigated interaction, and identified with the earlier setup. Right: reconstructed events using triggers based on secondary vertex determination with the data from the additional CCD planes [unpublished].

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[1] The french language avoids the ambiguity in english by 'détecteur à pixels' and 'détecteur de particules' instead of 'pixel detector' and 'particle detector'. The author originally intended: 'détecteur DE patrons'.

3. Convincing performance of hybrid silicon imagers developed by CERN RD19.

In the mid-80s for the inner tracking in the future collider experiments there was no clear solution, while the discovery of charmed particle decay imposed measurements at mm scale, of the decay length and displacement of the secondary vertex. Maybe systems could be built with Si microstrip detectors. This was in fact done in an exploratory approach in the Fermilab CDF experiment, from 1992 until after 2000. This is extensively described in the book by Hartmann [14]. Many layers are needed to resolve the position ambiguities, and multiple scattering in the resulting large thickness degrades the tracking precision. Although CDF obtained nice results, at 286 kHz beam crossings, and discovered the top quark, it would have profited from 2-D tracking detectors. As mentioned earlier, CCD would not be fast enough at this rate, even less at the planned interaction rates of up to 70 MHz.

Among the 4 teams, mentioned above, looking into possible 2-D silicon detectors, the author and his team at CERN envisaged the most disruptive approach, aiming to include a full signal processing chain in each cell of the matrix [13]. This aim was thoroughly discussed at the 1988 Pixel Detector Workshop in Leuven [7], where experienced specialists in microelectronics participated. In a collaboration between CERN and the microelectronics group at the Lausanne EPFL, a first design for a hybrid assembly with 10 MHz synchronous operation in an 8x12 matrix was finished by end 1988. A synchronous circuit was chosen in view of the regular collision frequency at a circular collider [15]. This project initially was part of the Italian LAA detector R&D at CERN. After 1991 this silicon pixel development was approved in the framework of the wider LHC detector research program, as CERN RD19, and then many more groups joined in the effort. Towards the end of RD19 in 1997, there were 29 member institutes and 3 commercial companies participating [16].

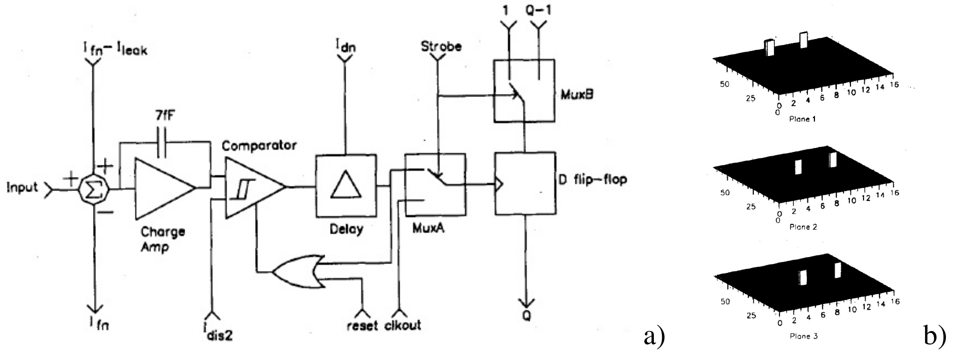

Fig. 2a Block diagram of signal processing circuit in each pixel Fig. 2b The hits from 2 particle traversing the 3 chips, forming a 'telescope'. No noise hits at all.
Matrix of 63 x16 pixels, pixel size was 75μm x 500μm. Drawings CERN [17].

The first chip mentioned was manufactured in 1989 by Faselec in Zurich, in their high-density 3μm SACMOS process, which was used mostly for circuits in electronic watches. Measurements were presented at the IEEE Nuclear Science Symposium in October 1989 [15]. However, if the instrument had to be evaluated in fixed target experiments, a random signal processor had to be designed (fig. 2a) instead of the synchronous circuit. An improved, larger design was made, with 1006 active pixels [17]. This ASIC was bump-bonded and already in summer 1991[2] a 3-chip telescope recorded tracks in the ^{32}S heavy ion experiment in the CERN Omega spectrometer (fig.2b).

After additional development, organizing quality test facilities and dealing with various technical issues, a 5x6 cm^2 area could be covered with 6-chip ladders and face-to-face planes. The experiments WA94, WA97 and NA57 ultimately used 7 double planes as a telescope behind their Pb or S targets, and recorded tracks at high density >>100 per event, from the respective beam interactions [18]. An example is shown in fig. 3, where the usual magnetic field intentionally was switched off, because bent tracks are difficult to follow by eye. It is obvious, that such track densities, which were expected in the central region of the colliders, could only be handled by 2D detectors with microscopic elements, and which needed to be fast at the MHz rates.

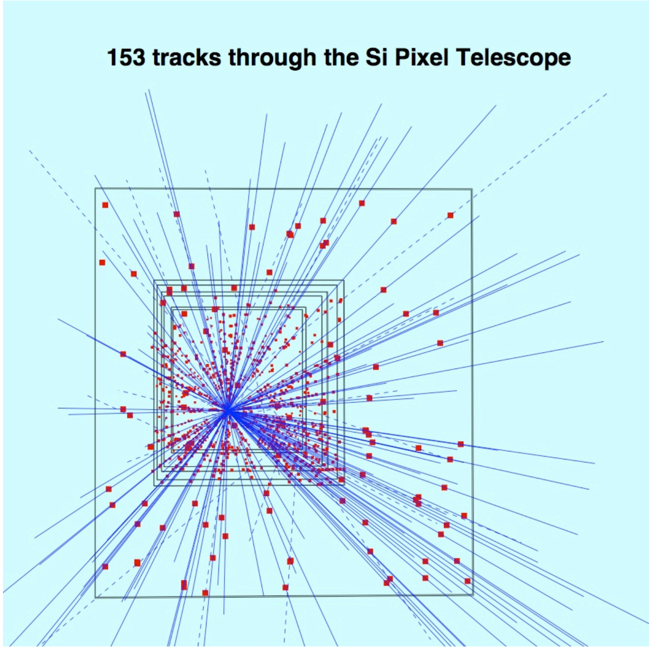

Fig. 3 153 tracks from an interaction of the Pb beam in the Pb target in the Omega WA97 experiment, reconstructed from the hits in 7 identical pixel planes. B-field was here on purpose switched off, so as to recognize the tracks by eye, as straight lines. There are no 'hits' from noise. The reconstruction uses an enhanced perspective view, otherwise tracks would appear too close together.

Some of the teams in the RD19 collaboration participated in the LEP electron-positron experiment DELPHI. They took up the design and installation of pixelated forward tracker systems, using the expertise and facilities in the RD19 framework. Aiming to replace the onerous solder bump bonding, they experimented with screen-printed contacts and other, potentially less expensive contact technologies, for which they implemented larger contact pads in the pixels. However, these degraded the noise performance, and ulimately, the pads were

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[2] Note that the USA team earlier mentioned, with Sherwood Parker, Walter Snoeys and Chris Kenney, only a half year later around Christmas 1991 tested their monolithic pixel detectors in a Fermilab test beam, and obtained quite similar track results.

made smaller again, and solder bumps applied. The systems were operational and succesful from 1997-2000. A detailed and comprehensive report on this pixelated DELPHI Very Forward Tracker VFT is available as the PhD thesis by Johann Heuser [19].

Both the early pixel detector operation in the heavy-ion experiments, and the demonstration in DELPHI were essential results, at the right time, to convince the community that the complexity of these new tracking detectors could be mastered, and used for the LHC experiments. Both ATLAS and CMS began to consider them as extensions for tracking towards the inner region [20] .

Highlighted in the 1997 RD19 status report [16], possibilities were discussed for collaboration in the pixel detector development for the LHC experiments. However, ATLAS and CMS then created their own development teams and at that time were not interested in further collaborative efforts. At that point the RD19 collaboration was terminated. Still, the CERN team came up with a new approach for radiation-hard readout ICs in standard CMOS, instead of using special radhard technologies. They implemented the 'radhard-by-design' in a 0.5μm CMOS chip, still in the RD19 framework [21]. A following version of this circuit was made in the 0.25μm CMOS, the technology that afterwards has been used for the majority of the LHC ASICs. These 0.25μm readout chips for the ALICE pixel system have been operating during the full first decade of LHC. Nevertheless, minor bugs were corrected in an iteration, which was not used in ALICE but inserted in the vacuum phototubes for the first Ring-Imaging Cherenkov detector in LHCb [22]. Yet, the LHCb experiment was the only one of the four experiments, not to exploit a silicon pixel detector for their vertexing and tracking. They constructed the VErtex LOcator consisting of microstrip detectors, in vacuum moveable into the beam pipe. Only recently, for their 2021 upgrade they installed the VELOpix detector [23], to replace this earlier, elaborate VELO silicon microstrip system. The VELOpix will operate trigger-less and aims to record all interactions at 40MHz.

During the preparation period 1999 to 2008 both ATLAS and CMS produced several iterations of their pixel readout ICs and the matching Si sensor designs. At first, different CMOS technologies were envisaged, and prototype ASICs manufactured, but eventually, they both used the 0.25μm CMOS technology for their chips. This was shown to be optimally resistant to the expected radiation effects, in part thanks to the inherently thin gate oxide, and thanks to using transistors with 'enclosed' layout [21]. The increase of dark current by radiation defects in the sensors could be limited by operating the systems well below 0°C. However, it can be noted that the micro-segmentation of the sensors already leads to low dark currents at the amplifier inputs, and the overal current and power dissipation is the predominant problem, because pixel current can be compensated even up to ~10 nA in the circuit [24].

It is beyond the aims of this article, to describe the different pixel detector systems constructed for the LHC experiments. The teams were composed of scientists and engineers of different participating institutes, worldwide, some of which had been members of RD19 beforehand. Well after the LHC startup, new R&D activities were initiated ~2015 in view of upgrades, taking into account the practical experience with the first generation of vertexing detector systems. Many aspects of these upgrades are presented in other contributions in this Workshop. In hindsight it has become obvious to the community, that the pixel detectors were an absolute necessity for unraveling the complex tracking environment around the interaction regions in LHC.

With the expertise gained in imaging of single energetic quanta, both particles and photons, it soon became clear that other fields in science and industry could profit from this approach. A few aspects of this spin-off are treated in the next section.

4. Pixelated single quantum detectors beyond elementary particle physics experiments.

In the particle colliders a strong magnetic field is used to curve the particle trajectories, so that their momenta can be determined from precise coordinates. Because precision is most needed perpendicular to the curvature, the pixels in trackers have often a shorter side in that direction. In ATLAS the pixels are 50μmx400μm. For other applications of these unique imagers beyond particle physics, such as X-ray imaging and analysis, it was obvious from the earliest images that square, or possibly hexagonal pixels would be absolutely needed to obtain recognizable images of medical or mechanical objects. An early test by the Pisa team, using a GaAs pixelated sensor attached to an RD19 chip, was a clear illustration [25].

Already in 1996 Fischer at the Bonn University described an efficient photon counter [26], while their group considered medical applications. This team, together with the then just founded institute CPPM in Marseille, started work on a photon counting pixel circuit [27]. They developed the series of XPAD photon detectors, which originally aimed at exploitation in synchrotron X-ray beams, mainly at the ESRF [28, 29].

For the group at the Swiss Paul Scherrer Institute PSI, besides their initiatives for the CMS pixel detector, the main interest also was development of pixelated detectors for their synchrotron radiation experiments [30]. This team was very succesful, and the PILATUS instrument soon became the starting product for the DECTRIS company. Many instruments have now been delivered to synchrotrons worldwide, so that probably at this time the spin-off towards that field has been quantitatively more important than to medical X-ray imaging, where acceptance is growing, but much slower.

With synchrotron beam X-ray facilities becoming available in many places, as important tools for a variety of applications, the need for appropriate detectors has been growing. This challenge is being addressed also by several other groups. Because the X-ray diffraction patterns contain spots with much higher instantaneous intensity, besides single photons, detectors are being developed that can integrate signal charge in a pixel over a large dynamic range, while still capable of detecting a single photon as well. The team at the XFEL accelerator in DESY, also active in the Medipix collaboration, is working on the AGIPD imager family with adaptive gain in each pixel circuit [31]. In the USA, the group of Sol Gruner, first in Princeton and then at the CHESS accelerator in Cornell, initiated work on pixel detectors for synchrotron beam X-ray diffraction [32]. Also at SLAC, when the Linac Coherent Light Source LCLS was constructed, an important detector development effort was started in parallel, in a coordinated effort with Cornell and other institutes. A comprehensive overview of the newly available detector systems at the LCLS was published after some years of operation [33]. At the Spring8 synchrotron in Japan a pixel detector R&D is underway, in a collaboration with the company Rigaku.

Supposing that medical X-ray imaging would become the most fruitful application for single photon analysis, several teams worked towards optimized detectors for the medical high photon rates. A Workshop was held in Trieste, where besides pixel detectors for X-ray imaging [34] also other aspects of medical use of particle physics instruments were studied, including accelerators for cancer treatment. This meeting triggered a collaboration between Pisa and the CERN RD19 team for the design of a dedicated imaging ASIC. A hybrid with a pixelated GaAs sensor was the implicit target, and therefore also the Universities of Glasgow and Freiburg joined, with their expertise in GaAs. This collaboration led to a first hybrid assembly, called PCC and later re-named 'Medipix'. A prototype, but with Si instead of GaAs was tested in 1998 [35]. After the succesful but still rudimentary performance of this first device, it seemed of great interest to continue such a spin-off effort, especially because successive versions in more advanced CMOS could provide the accumulation of technological expertise and practical experience. This appeared necessary in order to remain up-to-date, because of the long cycle times in the LHC operations and expected upgrade periods, which might result in complete loss of ASIC design expertise. From the particle physics viewpoint, this was a major argument for starting the Medipix2 collaboration, by September 1999. An overview of the accomplishments in the first ten years by this worldwide consortium was presented by Michael Campbell in 2009 [36].

Other groups mentioned (and some maybe not mentioned), have continued to progress with ever more powerful pixel imaging instruments for many applications outside elementary particle physics. A number of commercial companies now offer instruments for X-ray materials analysis, environmental dosimetry on earth and in space, and yes, also for medical X-ray imaging.

5. Competition from the monolithic silicon imagers.

Because the demonstrated performance of the first hybrid pixel detectors appeared suitable for their use at LHC, they were the natural choice for vertex determination in the experiments, and ALICE, ATLAS and CMS installed them. However, cost and occasional failure issues made the bump bonding technique a problematic, yet unavoidable part of hybrid pixel detectors. So, monolithic detectors seemed to be desirable for their apparent simplicity and a thinner layer with less deviation on particle trajectories. Fully monolithic devices also might be a better choice in view of the exponential penetration of monolithic imaging chips in cameras and phones. While in 1990 the manufacturing of image sensors was a small segment of microelectronics and restricted to a few factories, after 2000 progressively the silicon-based imagers have become a major part of business, with billions of devices produced yearly. Several teams, proponents of a monolithic approach, started competitive R&D, in order to produce detectors that could be equal to, or outperform the hybrid detectors.

The early use of CCD for vertexing was described in section 2. Those systems needed readout times >10ms. Their readout method, using frame transfer or a rolling shutter, prevented an easy, or even correct representation of the particle hit geometry in successive interactions at 40MHz rate. In was realized that some of these problems could be mitigated with the development of CMOS imagers, where individual pixels or selected areas can be addressed for readout. Later on, by adding more circuitry in or around the pixels, and more layers with signal traces over the chip surface, 'global shutter' architectures were developed in industry.

The evolving silicon-based technology for imagers enables new approaches for science as long as the user can accomodate the inherent boundary conditions. Manufacturing imagers is not quite identical to CMOS technology for usual microelectronics. For example, imagers now most often use back-side light incidence, which implies the use of highly thinned Si wafers and also excludes using the bulk Si for purposes such as crystal defect elimination. It is often impossible to know the precise processing steps and their effects on ASIC performance. For designers, only the confidential simulation and layout instructions are available. The RD19 collaboration, mentioned in section 3, tried in the early 90s to produce monolithic tracking devices in a Silicon-on-Insulator SOI technology, in parallel to their work on hybrid detectors. Unfortunately, unforeseen incompatibility between succesive processing steps at different contractors made the device inoperative. An MeV deep-implanted layer, intended for shielding of cross-talk between the signal amplifiers in the top layer and the sensing volume in the 'handle wafer' was destroyed by too high a temperature later in the processing.

The teams who took up again development work for monolithic imaging particle tracking, now used either improved SOI, or more advanced CMOS as offered by Si imager manufacturers. The SOI technology gained renewed interest after the introduction by SOITEC (Grenoble) of their 'Smart-Cut' SOI wafers. The Japanese SOIpix collaboration has produced detectors already for two decades, in collaboration with the company OKI [37], since ~2015 named Lapis. Also a Polish group works since quite some time on this approach [38]. An advantage of the SOI structure is the possibility to use a fairly thick, high resistivity substrate that can deliver a larger signal than other monolithic imaging chips, where the sensing layer is usually at most ~30μm thick. Also 'double-SOI' wafers are now available, where the transistor threshold shift after irradiation can to some extent be compensated by applying a voltage on the intermediate layer.

Working with regular CMOS imaging technologies, a long-term effort in development of monolithic pixel detectors was made by the team in the University of Strasbourg, soon joined by scientists from Fermilab. They published measurements with their first 'MIMOSA' detector in 2000 [39], including data from a beamtest at CERN. After a few years, also at the Rutherford Appleton Laboratory RAL a parallel effort was initiated [40]. Quite a nmber of iterations have followed, later including an epitaxial layer with a higher resistivity, in order to enhance the signal from a passing m.i.p. [41]. Eventually, a full vertexing system based on monolithic sensors has been installed in the STAR experiment at RHIC, the Brookhaven heavy ion collider [42]. The relatively low ion-beam event trigger frequency in RHIC, mostly < 100kHz, allows to accomodate the still long readout time of this type of pixel detector. The same is true for the most recent installation: the new pixel detector in ALICE at the LHC, where the beam crossing frequency is 50kHz. This system uses the ALPIDE imaging chip, designed in a collaboration between CERN and several teams around the world [43, 44]. In the final ALPIDE ASIC a large effort is made in collaboration with the foundry, to tailor the doping densities in the sensing layer underneath the electronics, in order to improve the charge collection efficiency. The ion implantations are executed so that signal charge is optimally directed towards the amplifier input contacts, also from the corner areas [45]. Previously a fraction of the signal charge carriers was lost, leading to a tracking inefficiency. The ALICE inner tracking system has been installed for the LHC upgraded running, and is operating from 2022 onward.

R&D is ongoing, to develop methods to increase rate capability and reduce readout time for monolithic pixel detectors. The speed performance has to be improved in two respects. First, in the pixels the charge collection often is partially by diffusion and not completely by drift, depending on electric field, as in hybrid sensors. For the 40MHz running, collection time and timestamping must be <25ns. Further, the imaging MOS technologies do not automatically offer all the features which make the ASICs for hybrids so fast. Examples are the stack of metal connections on top of the chip, which in 65nm CMOS already may offer as many as 10-15 layers, or the Through-Si-Vias TSV which now make tiling possible with the hybrid assemblies. For the recent, most advanced industrial imagers it appears that one moves towards devices in hybrid mode, in order to integrate more on-chip functionality. Another reason is the desire for a global shutter, which can eliminate motion artefacts. For fully monolithic devices in physics, it remains a question , if it will be possible to achieve on a single chip all the functions that are needed for vertexing operation in the experiments, at the required rates and intensities. The performance has to be competitive with that of the hybrid assemblies. For example, at this moment the timing precision, data transmission rate and area coverage available with the Timepix4 ASIC [46] are not yet achieved in a monolithic device.

6. Thoughts on further possibilities.

It is relevant to note that between 1960-2010, the business turnover and corresponding capital investment needed for a silicon manufacturing facility, usually called 'foundry', has grown from ~1 million $ by a factor ~10^4 to >10B$ and the driver is the explosive use of silicon in society for customer devices. Over this timespan the cost for an accelerator plus experiments with their label of 'Big Science' has grown also, but by a much smaller factor of <100 . This by now reduces science, as well as space or the military, to users with miniature volumes of ASICs. The only way to be an acceptable client for this industry is to adapt precisely to their production methods and rules. This has to be taken into account in the thinking about future electronic instruments for particle physics. But after all there is an area of convergence between our physics world and society: exponentially more data. Either we have to follow the mainstream industrial possibilities, and which involves significant money, or alternatively we can implement various good ideas about pixel detectors (or other ASICs) using specialized, but much less advanced manufacturing facilities. Maybe some are available, or otherwise these have to be created. Ultimately this might involve even more money than the first approach.

Looking through the windows of industry, a mainstream trend since ~6 years in silicon imagers is stacking of the sensing layer with a signal processing layer, using Cu-Cu connections, even for each pixel, and even at very small pitch. For computer or server processors, a similar trend is also 3D stacking, using 'chiplets' which can be a memory matrix, or a segmented processor unit or a photonics circuit. Multi-core can be fully integrated on a single layer, or divided on segments. It may be obvious that the complete manufacturing sequence has to be adapted to these new architectures, including simulation tools, lithography, fabrication tools and testing. For science, observing these realities in the industry, however, may inspire new ideas for instrumentation in physics, as it was the case in the mid-80s with the introduction of designing our own ASICs. Also the achievement of excellent radiation hardness was largely based on serendipitous information, that thin gate oxides would not charge up thanks to tunneling.

The guiding principle for the particle physics pixel detectors has been, to have parallelism as far as possible through the signal processing chain, up to numerous fast electrical or optical output ports. This approach is based on the new reality of billions of extremely small, and cheap transistors, together on a small area. This is quite contrary to the classical architectures where it was considered to be sophisticated if channel numbers could be minimal. Another aspect is the signal/noise performance, which also often may be better with small pixels and small capacitances. It will all the time be needed, to carefully consider the power requirements for each scheme, but ultra-segmentation may often use less power than large sensing elements over the same area.

Another point where future physics converges with trends in nanoelectronics is fast, precise timing. Often not the speed of the circuits themselves is pushed, because this would need lots of power, but better precision can be obtained using the 'vernier' approach, a clever use of interference between separate, slower clocks.

A final thought about the ever-shrinking pixels is, that these could eventually approach capacitance values in the atto-domain. Then a single electron on such a small capacitor changes the external voltage by ~100mV. Single-electron transistors are being studied in industry. Now electronics eventually is approaching the world of elementary particles from the low-energy side. Maybe there could be discoveries, as well as in our own future work at ever higher energy.

Acknowledgements.

This introductory presentation and review could definitely not cover the wide range of activities in pixel detectors for experiments with energetic particles and photons, let alone details about silicon detectors in general. Among the many achievements left in the dark, it has skipped over nearly all the work in the LHC experiments. The books by Rossi, Fischer, Rohe and Wermes from 2005 [47] and Hartmann, 2nd ed. from 2017 [14] fill in a lot of this information. A very recent book by Stefanov describes the CMOS Image Sensors in general [48]. And even then there is still much more. The author would welcome readers who like to mention anything in this field, which they consider under-represented.

It is a pleasure to acknowledge and thank the microelectronics team at CERN for their constructive, inspiring and long collaboration, over many decades. Colleagues from around the world have made it possible to operate the large experiments in particle physics, at CERN and elsewhere, in which the pixel detector systems play a critical role. Progressively these efforts also lead to much wider applications, useful for mankind.

The author thanks the organizers of the Workshop, especially Prof. S. Seidel, for the opportunity to present this overview.

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