EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EF 88-14
18 October 1988

DEVELOPMENT OF SILICON PIXEL DETECTORS : AN INTRODUCTION

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ABSTRACT

The concept of the silicon pixel detector is discussed and possibilities for its realization and application are indicated. Emphasis is placed on the use of silicon detectors in elementary particle physics experiments.

Presented at Workshop on Silicon Pixel Detectors
IMEC, Leuven, Belgium, 31 May - 2 June 1988

[Proceedings published by Nucl. Instr. & Methods]

1. APPLICATIONS OF POSITION-SENSITIVE SILICON DETECTORS

In most radiological or radiochemical techniques as well as in particle physics experiments one has to record intensity distributions in space and time of ionizing particles or X-rays. Also, one may be interested in the energy of individual particles or photons. Conventional semiconductor detectors are well-suited to energy measurement and position/time measurement for single particles, but for direct, 2 dimensional X-ray imaging or complicated multi-particle events no adequate semiconductor detectors exist. Photographic film, gas-filled wire chambers or various types of arrays (e.g. optical silicon CCD using phosphors or with scintillator-photomultiplier elements) are mostly used for position-sensitive detection. Very often the energy absorbed in the detector is first converted to light and then only into an electrical signal. Therefore, considerable interest exists in basic science and in selected applications for compact, high spatial resolution, high speed radiation imagers, with direct and efficient conversion of the radiation energy.

In recent years there has been a renewed interest in segmented silicon detectors which prove to be very suitable for high precision localization of elementary particle events [1] and which also could be applied for low energy X-rays, e.g. in synchrotron radiation experiments. The key to the use of multi-element silicon detectors is, however, the availability of electronics circuitry to process a multitude of signals in an economic way. In particular, for large area detection ($> 1 \text{ m}^2$) the number of detecting elements may seem unmanageable. Microelectronics is moving to megaprocessors, and this may help to envisage detectors with over 10^6 elements. On the other hand, one is working on interpolation schemes or sometimes one can reduce the number of output channels by converting position information into the time coordinate, as in the silicon drift detectors [2].

Although sometimes a linear array of detector elements may be sufficient, a true 2-dimensional detector will be necessary in most applications. The information from the detector elements can be in the form of analog signals generated by individual particles or photons, or alternatively it can be the total amount of charge integrated in an element during a time interval. In both cases the signals could be processed through analog-to-digital conversion (ADC) or through a discriminator (threshold comparator or 1-bit ADC). The ultimate justification for the use of semiconductor detectors is the direct link that they provide to digital information processing.

2. DEFINITION OF SILICON PIXEL DETECTOR

The term "picture element" or "pixel" has been introduced in image processing for the smallest discernable element in a given process or device. In silicon Charge Coupled Devices (CCD) used for imaging, "pixel" conveniently indicates the basic cell, which usually has dimensions of the order of 5-50 μm . In the field of silicon particle detectors, the term "pixel detector" is used to distinguish a true 2-dimensional (2-D) structure from the 1-dimensional (microstrip) detector. Earlier the term "checker board detector" [3] has been used, but this referred to a detector with orthogonal linear arrays on front and rear side of a single wafer. Such a structure does not give true 2-D information, because ambiguities arise in the case of multiple coincident particles.

To promote some uniformity in terminology we propose here to reserve "pixel detector" for a true 2-D array of elements with largest element dimension $< 1\text{mm}$. For detectors (1-D or 2-D) with elements between 1 mm and 10 mm the term "pad detector" could be applied and detectors with elements where the smallest element dimension is $> 10\text{ mm}$ could be called "tile detector". Microstrip detectors (1-D) should have a pitch of $< 1\text{ mm}$, otherwise they should be named "pad detector".

It is assumed that the future "pixel detector" is not just an array of passive detecting elements but will include a substantial amount of signal processing circuitry. For a "pixel detector" that incorporates also information processing functions so that event selection or pattern recognition is actually integrated, we propose the name "micropattern detector".

3. VARIOUS TYPES OF SILICON PIXEL DEVICES

3.1 Charge coupled devices

At present, the various types of Charge Coupled Devices (CCD) represent the majority of monolithic image sensors, mainly because the charge transfer from cell (pixel) to cell can be made highly efficient (in the best cases inefficiency $\sim 10^{-6}$) and leads to an elegant architecture for TV rates (50 Hz) which allows a single output node for $\sim 10^6$ pixels. Only since 2 or 3 years is economic mass production of color TV camera CCD feasible, after a development period of nearly 15 years. In the end, the problem was not so much to produce working devices, but to manufacture large numbers of these analog devices within reproducible tolerances for given external operating voltages.

The use of a standard, frame-transfer (FT) CCD for particle detection has been pioneered by C. Damerell and his group and will be described in the next article [4]. The CCD structure is not optimized for the detection of ionizing particles or X-rays and the readout architecture is not adapted to the information content and rate of the radiation "images". The trend for optical CCD to go to smaller pixels ($< 10 \mu\text{m}$) is not very useful for X-ray imaging because of the absence of focusing. The smallest relevant dimension in medical X-ray images is $\sim 0.1 \text{ mm}$. On the contrary, it would be of interest to make bigger devices with moderate resolution. The thin sensitive layer ($2\text{--}10 \mu\text{m}$) in the usual CCD makes it not very efficient for X-ray detection. Via the use of phosphors or by employing thicker depletion layers with high-resistivity silicon one tries to increase the efficiency.

For very high "event-image" rates in elementary particle physics (10–50 MHz) silicon CCD even at clock frequencies of 100–500 MHz, seem inadequate as imagers, and their use would require careful adaptation of the experimental set-up.

3.2 Hybrid devices

In a hybrid structure one can optimize the detector elements and the readout circuit separately. The price to pay is a high density interconnection, which often requires advanced technology e.g. indium bump or solder bump connections. For infrared imagers the hybrid approach is often used because of the transparency of Si to infrared light. The readout circuitry can be an addressable matrix of charge storage elements or a CCD shift register. Several papers in this workshop will describe hybrid pixel detectors [5,6], with the detector possibly consisting of high resistivity Si. This gives a reasonable charge signal from minimum ionizing particles ($\sim 10^4$ e-h pairs) or an acceptable efficiency for low-energy (10–20 keV) X-ray photons.

3.3 Monolithic devices

Monolithic radiation sensors with integrated electronics for signal processing appeal certainly to the imagination of users, but their fabrication may pose many more technological problems than hybrid devices. CCDs are in many respects a good example. In all likelihood a totally monolithic system will never exist, but it may be advantageous to integrate certain passive and active components with the detector, inasmuch as the detector technology permits. Several studies in this direction are reported in the workshop [7,8,9].

In a more general way, silicon technology development goes in the direction that is needed for the construction of smart sensors, be it mostly for different reasons. One clear example is the development of 3-dimensional Silicon-On-Insulator (SOI) technology, which is aimed at improvement of speed, suppression of latch-up and shortening of interconnections. It would enable easily a monolithic approach for various types of sensors, particularly because processing temperatures may remain always below $\sim 900^{\circ}\text{C}$ [10]. Another example is the increased use of twin-well processes, which makes the construction of the electronic circuits more independent of the nature of the silicon substrate. Provided the processing is compatible with the high resistivity of the substrate, this can serve as particle detector.

Technology development, especially if it also involves radiation hardening, is costly and time-consuming. Therefore, it is advisable to use existing technology, with minor adaptations, or otherwise go to varying degrees of hybridization.

4. PIXEL DETECTORS FOR X-RAY IMAGING

Medical X-ray imaging is probably still the most important radiological activity, but other applications like airport luggage checking and materials studies are growing fast. At the X-ray energies used (40–80 keV) the efficiency of Si for total photon absorption is falling off rapidly, as illustrated in fig. 1 (the data for this figure are extracted from NBS tables [11,12]). Therefore, alternative semiconducting materials like Ge, HgI_2 or CdTe are more often used as X-ray detectors. These are not easily shaped into pixel arrays. Silicon pixel detectors still may be attractive if the readout architecture can be properly designed for the X-ray imaging applications. But the need to construct fairly complicated arrays may lead to relatively high cost equipment. Only significant advantages like real time information, much lower radiation dose, better contrast through image processing, etc. could justify to replace X-ray film or other X-ray detection media.

With extremely fast electronic comparators integrated in the pixels, one could envisage to count single X-ray photons rather than to integrate charge. By using very thin metal films in a silicon sandwich structure (like in the calorimeters used in particle physics) one might improve the conversion efficiency.

More realistic applications in the near future will be for synchrotron radiation experiments (~ 10 keV) once multichannel, low noise (≤ 3 keV FWHM) signal processors are built. A discussion of synchrotron radiation applications is presented by N. Allinson [13].

5. THE SILICON MICROPATTERN DETECTOR FOR ELEMENTARY PARTICLE PHYSICS

New hadron colliders for elementary particle physics are under design (SSC, LHC) or already under construction (HERA). Experiments at these machines have to deal with event "frame" rates approaching 100 MHz and with typically ~ 100 particles per event. This means that ambiguities in space or time will be difficult to resolve. Tracking detectors should have fast response (ns) and true 2-D resolution with precision in the micron region. No such devices exist at present, but silicon microstrip detectors are closest in characteristics, except for being one-dimensional. The pitch of the usual microstrip detectors varies from $10\ \mu\text{m}$ to $50\ \mu\text{m}$, and there is no technical problem in making mosaic arrays rather than linear. But the number of elements per detector increases from 10^3 to 10^6 , placing severe constraints on the signal processing electronics, on the interconnect technology and on the information treatment.

A particularity in these particle physics experiments is that only few of the "frames" are of interest for the experiment: maybe 10-1000 out of 10^7 . Moreover, the events sparsely occupy, but in a random way, the multitude of detecting elements: maybe 100 segments out of 10^7 have non-zero signal. A hierarchical organization of detecting elements will enable to reduce the record of useful information to small dimensions. The information has to be stored in a pipeline until a decision about the interest of the frame has been taken. This first-level trigger may arrive $\sim 500\ \text{ns}$ after the event, so that a pipeline with a depth of up to 50 frames is minimally required. Further pipelining is needed while awaiting second or higher level trigger decisions, and this should at the same time serve to de-randomize the information, so that optimal use is made of the time-consuming readout to the off-line medium (magnetic tape, optical disc, etc.).

Intensely debated remains the question of complete analog or 1-bit digitized information readout. Analog data enable interpolation and various off-line treatments. Digitized data alleviate the readout architecture, reduce cabling cost and speed up the off-line analysis. Trade-offs will have to be made, taking into account all aspects of a given experiment.

The essential feature of the silicon micropattern detector would be that it has on-board information processing, so that it only delivers data that are useful at some level. Tentative characteristics are summarized in table 1. It is assumed that the trend in future experiments will be towards increase of on-line data processing, to

improve the feedback on the actual trigger set-up and to reduce the burden of off-line processing which progressively becomes unrealistic in the light of the available on-line computing power.

6. CONCLUSION

Several approaches exist towards the concept of a silicon pixel detector. There is a delicate matching to be made between the detection function and the electronic signal processing. A smart design is needed to keep the amount of information within manageable limits. The power consumption will be an ever-present limitation. For an efficient solution one also has to take into account the overall system requirements, so that real-time data processing is matched to off-line information handling.

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TABLE 1

Tentative characteristics of silicon micropattern detector

- 2-dimensional array of detecting elements,
- granularity of 20 μm to 100 μm ,
- no insensitive regions between segments,
- in situ signal processing by front-end amplifier, comparator and position encoder,
- memory function for information until external trigger/clear is received,
- pipeline structure for information, for frame rates approaching 100 MHz,
- hierarchical information structure, enabling zero suppression, adapted to mosaic of devices,
- recognition of useful data or patterns,
- active area per device $\gtrsim 100 \mu\text{m}^2$ so that $1 \text{ m}^2 \approx 10^4$ devices,
- power dissipation per device $\lesssim .1 \text{ W/cm}^2$,
- radiation tolerance: $10^4 - 10^5 \text{ Gy}$ (1 - 10 Mrad),
 $10^{14} \text{ neutrons/cm}^2$.