CERN/EF 87-8
27 October 1987

THE SILICON MICROPATTERN DETECTOR: A DREAM ?

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ABSTRACT

The present use of silicon microstrip detectors in elementary particle physics experiments is described and future needs are evaluated. Possibilities and problems to be encountered in the development of a true two-dimensional detector with intelligent data collection are discussed. This paper serves as an introduction to various other contributions to the conference proceedings, either dealing with futuristic device designs or with cautious steps on the road of technology development.

Presented at the London Conference on Position-Sensitive Detectors
London, 7-11 September 1987

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1. INTRODUCTION

For the study of matter in physics, astronomy or biology the development of microscopic imaging techniques has proved to be of crucial importance. Given the potential of digital data processing, there is a growing need to replace the human eye (or the photographic film) by devices which can produce electronic images, ready for digitization. While significant progress is made in some respects (e.g. CCD for colour TV, image intensifiers, infrared sensors, use of synchrotron radiation sources) bottle-necks appear in other respects (e.g. suitable detector for UV radiation, data processors capable to deal with digital TV). So far some areas seem to be little affected at all, like medical X-ray imaging.

In nuclear and elementary particle physics the "objects" to be imaged are the interactions (events) between incoming particles, which result in other outgoing particles. The ionization created by these swift particles in a suitable medium makes their tracks visible, like in a bubble chamber or a nuclear emulsion (fig. 1). Both the large number of interactions required to study rare phenomena and the necessity of computer-aided reconstruction of these interactions in space and time have led to the development of various types of electronic particle detectors. Silicon particle detectors which can measure the track coordinates with a few μm precision have become feasible in recent years [1,2] by the use of silicon planar technology.

In this introductory paper we will briefly describe present characteristics of such "silicon microstrip detectors", and discuss the possibilities for further development of fast, two-dimensional particle imaging devices. Ultimately, following the trend in optical "smart sensors", the detector system should incorporate some level of intelligence, which enables it to distinguish between useless data and interesting events with a characteristic pattern. It is for this intelligent, two-dimensional microscopic radiation imager that we propose the name "micropattern detector".

2. SILICON MICROSTRIP DETECTORS IN ELEMENTARY PARTICLE PHYSICS EXPERIMENTS

A silicon microstrip detector is a contiguous array of linear diode elements on a high resistivity silicon substrate. If sufficient reverse bias voltage is applied to all diodes, the substrate becomes totally depleted of free charge carriers, a high impedance is created between neighbouring elements and excess charge created by

the traversal of an ionizing particle is collected in a short time (≈ 10 ns) at the electrodes of the particular diode traversed. In the simplest approach each diode is connected to a low impedance preamplifier, as shown in fig. 2. This preamplifier should have low noise, e.g. between 500–1000 e^- r.m.s., for a signal shaping time of 40 ns – 200 ns, with input charge signals that are typically 2×10^4 e-h pairs, from a 300 μ m thick Si detector. In view of the large number of amplifiers needed, their power dissipation should be small and their price low.

Due to the relatively simple manufacturing process and the availability of microelectronics technology, clean rooms, and high quality silicon wafers, it proved possible to make large devices (up to $\approx 65 \times 65$ mm²) with acceptable yields [3]. The pitch of the diode elements can be 10 μ m, but usually it is 20 μ m or 50 μ m, leading to 500, 1000 or 2500 elements on one detector. The accuracy on the position of a particle is in first approximation determined only by the size of the detecting element, e.g. 20 μ m in one coordinate and several centimeters in the other coordinate. Sometimes, a particle causes signals in two adjacent diodes (double hit). For perpendicular incidence it is found that in this case the particle passes practically on the geometrical separation between the elements and the spreading of the signal reflects the diffusion (≈ 5 μ m) of the initial ionized carriers [4]. If all strips of the detector are connected, it may be sufficient to retain only single-bit information, after comparing the signals with an appropriate threshold (discrimination). To obtain a three-dimensional determination of the track direction, information from several detector planes has to be combined. Once combinatorial ambiguities can be lifted, a track fitting algorithm yields a precision on the track coordinates that is somewhat better than the pitch, notwithstanding possible deviation by multiple scattering.

In more sophisticated schemes only a subset of diode elements is connected to preamplifiers with superior noise performance, and the analog values of the signals are compared, to find the particle position by interpolation. Both capacitive [5] and resistive charge division have been employed, and the best accuracies (≈ 2 μ m) have been obtained with these methods [5]. One has to pay a price in reduced multiple particle capability. Also, the electronics is more complicated (high speed analog signal processing, ADC) and the data reduction is more time consuming than in the case of the single strip/single bit scheme [6].

The silicon microstrip detector has quickly gained acceptance in particle physics experiments because its precision is much better than that of previously existing wire chambers, it is directly providing an electronic image (albeit in one dimension only) and it has a repetition rate and timing performance comparable to that of a scintillator/photomultiplier tube. Therefore, it can be placed directly in the particle beam (however, ionization phenomena in the oxide passivation layers sometimes may cause degradation problems in high intensity beams).

3. DESIGN CONSIDERATIONS FOR INTEGRATED SILICON DETECTOR SYSTEMS

Particle physics experiments have high event rates, $\approx 1\text{MHz}$, and this will be even more severe in future colliders, with beam crossings every 20 or 100 ns. Superposition of interactions in the same beam crossing or in following ones may be unavoidable, and therefore a true two-dimensional detection is primordial to keep the ambiguity problem solvable. The size of the detection elements may be from $20 \times 20 \mu\text{m}^2$ to $100 \times 100 \mu\text{m}^2$, although bigger elements might prove useful also, for example, to provide a high precision two-dimensional hodoscope inside a collider-calorimeter.

The shape of the system is to be cylindrical around the beam intersection region, a few centimeters in diameter for the innermost plane, and probably more than 1 m long. It might look like the silicon arrays described by Goessling et al. in this conference [7], apart from the much larger number of elements: 10^8 instead of $10^3/\text{m}^2$.

As it is nearly impossible to read out so many elements in 20-100 ns, it appears that the organization of the information stream is a more critical issue than the design of the detectors themselves. One is tempted to build some of the read-out and signal processing functions into the detector itself. In the case of optical imaging with CCD the elegant solution of parallel-serial shift registers with serialization through a single output structure is inherent to the device structure and needs relatively little power ($\approx 1\text{ W}$ for 10^6 pixels). A few micro-seconds are needed to read out all pixels, which is short compared to the "observation time" in television, but which is very long for particle physics.

There seem to be two approaches to solve this problem for particle detectors. The first one is to use fully parallel storage (pipelines) of all data during a certain period, e.g. $\approx 1 \mu\text{s}$. Once a trigger decision has been taken, data are discarded, or multiplexed and read out, which indeed may take a longer time. A choice has to be made if the pipe lines store data in analog or already digitized form. Obviously, one needs a subset of detectors with direct fast read-out to establish the trigger. In this approach it is supposed that using this subset one is able to recognize the few interesting events among the many which are continuously flooding the detector.

In the second approach one uses directly the fact that each event is a very sparse matrix, having only $\approx 10^2$ significant pixels out of $\approx 10^9$. No pipe lines are employed, but the signals are kept on or near the detector elements until a reset signal is issued. Active circuitry indicates the occurrence of a signal in a certain detector region, and via a hierarchical structure; a pattern for the event may be determined in a very short time ($\leq 100 \text{ ns}$). A global or regional clear can be issued, or the decision for read-out be taken. Then the active circuitry is used in addressable mode and precise coordinates as well as signal height could be determined, probably again taking a considerable time. In this approach virtually the whole detector can be employed for the trigger decision.

Some of the contributions in this conference discuss these approaches in quite some detail, the CCD structure by Kemmer and Lutz [8] is an example of the "pipe line" approach, whereas the device discussed by Parker [9] is an example of the "local storage" approach.

It is clear that circuit development and new detector technology will be needed to create a device that has the desired performance in the future experiments. The intelligence of the device is not a luxury but is badly needed to limit the otherwise unmanageable amount of mostly useless data.

4. CIRCUIT DEVELOPMENT FOR A MICROPATTERN DETECTOR

A block diagram of a typical detector and its read out is shown in fig. 3. In recent years the blocks have been implemented separately, using standard modular electronics or specially designed circuits with discrete components. Now that the fabrication in small series of Application Specific Integrated Circuits (ASIC) is becoming economical, various parts of the read out can be customized and a higher level of integration comes in sight.

It is certainly worthwhile to develop integrated circuit versions of separate functions, like the comparator, the delay line or the ADC, because detailed experience can be gained in this work, and the functional units almost certainly will find quick acceptance in experiments already under preparation.

Because the front-end or pre-amplifier is nearly always special-made, it has attracted most interest so far. Buttler, Lutz et al. [10] report in this conference on the performance of a multiplexed 128 channel chip, which uses a number of switched capacitors, and on which they have been working since 1981. P. Seller et al. from RAL report [11] on a CMOS version of Microplex chip, which also uses capacitor switching. A third similar circuit is developed at LBL by Spieler and Kleinfelder, as part of a project aiming at the construction of a silicon pixel detector [12]. At CERN we have chosen to go a different way, and use a continuous feedback loop like in the classical charge-sensitive preamplifier. This enables true asynchronous use of the amplifier, eliminating the need of resetting all amplifiers every ≈ 20 ns. At the same time a better noise performance is obtained [13].

The development of a small, fast, low-power comparator is essential for the micropattern detector. It should eliminate the need for interpolation, and maybe, for analog signals altogether. The trade-off is to have small detection elements, each with a simple amplifier-comparator, or larger elements necessitating drivers/ADC for obtaining the required precision by interpolation, on-line or off-line.

However, as in some detector systems (notably the calorimeter-related detectors) analog information is tantamount, ADC that can be simply integrated with the detector should also be designed.

Analog or digital pipelines may be needed to build an adequate micropattern detector. A study on the feasibility of fast CCD for this purpose has been done already some time ago [14], whereas a chip with addressable capacitor storage (AMU, Analog Memory Unit) has also been recently developed [15].

The information from detector elements is usually fed into programmed microprocessors, which then construct a higher-level trigger. Recently a special ASIC gate array, the contiguity processor for the DELPHI TPC, has been made [16]. It is one of the first examples of dedicated processor chips which help on-line in data selection and pattern recognition. In spite of the increasing capabilities of the

microprocessors, it may often be advantageous to use full-custom or semi-custom chips for increased speed or lower power consumption. Using recently available CAD tools the programming effort for the chip may be comparable or less than that needed to program the microprocessor. One may also keep in mind that intelligent on-line processing of information can significantly reduce the amount of data produced as well as off-line analysis time.

In practice, to obtain a micropattern detector several of the functions mentioned above must be combined into a single device. Where at present from several circuit technologies (n-MOS, CMOS, bipolar, etc.) the best can be chosen to match the desired performance of a particular circuit, in the full integration one has to adapt the circuit design to the restrictions of the process technology.

5. TECHNOLOGY DEVELOPMENT FOR A MICROPATTERN DETECTOR

The process technology for a silicon micropattern detector should probably derive from some standard 1 μm CMOS technology, because particle physics is not ready at short term to invest sufficient funds to develop a totally new process. The most important question to be answered is, if the device will be a monolithic or a hybrid. The former will certainly need much more process development, whereas the latter poses the problem of interconnection between at least two wafers. For various types of sensors "bumping" interconnection techniques have been developed, often between a composite detector material (e.g. Cd Hg Te for infra-red detection) and a CCD multiplexer chip. In the near future the hybrid solution may therefore be favoured, but still, in view of the complexity, one may wish to accomodate at least some functions on the detector substrate. Vanstraelen et al. [17] discuss results obtained in building transistors either directly on the high resistivity silicon, or in a deep ion-implanted p-well. Much more work in this respect will have to be done.

A more futuristic technology holding promise for the micropattern detector is the deep implantation of O^+ or N^+ , resulting in buried isolating layers. In this way one might eventually come to "three-dimensional" electronics but for the moment the goal is limited to creating locally a thin silicon top layer that is well isolated from the bulk: Silicon On Insulator (SOI). Smaller dimensions and higher speed are the benefits, as well as immunity from latch-up. For detectors, this technology would enable the construction of electronics in the top layer of the otherwise high

resistivity wafer, with good separation. The complete re-crystallization of the damaged surface after the heavy implantation is still a big problem. Circuit design for a three-dimensional technology has not seriously been considered yet.

One may also raise the question if the detector substrate has to be necessarily high resistivity Si. The depletion layer needed to detect minimum ionizing particles is a function of the signal to noise ratio, and related to the element capacitance. For X-ray applications one might wish to use altogether different detector materials.

Another subject which needs to be addressed is the radiation damage. The world effort to improve radiation resistance of silicon microelectronics is already quite considerable, and one might to some extent profit from existing knowledge. But in the specific case of high-resistivity devices only little seems to be done. The radiation tolerance of the newer CMOS technologies is found to be generally better (up to ≈ 500 krad) than that of older ones. In part this is attributed to the thinner oxide layers.

6. CONCLUSION

The marvellous development of microelectronics easily leads to enthusiastic projections into sensor applications. More often than not the problems turn out to be unsurmountable because the boundary conditions of the application are rigid, contrary to the more fluid requirements in information processing. In recent years, silicon microstrip detectors have been successful, especially in elementary particle physics, because precision and speed coincided with needs in that field of research. The linear organization of the detectors did not prove a great disadvantage at this stage, but it seems to be unacceptable in future experiments. The development of a true two-dimensional detector with similar properties in speed and precision is quite a different enterprise. It requires new developments in silicon technology, interconnection technology and circuit design.

It seems possible to build devices that meet some of the expectations, but one should not underestimate the effort needed. Flexibility is needed in the overall detector system approach, and the management of the large amount of information has to be given special attention.

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FIGURE CAPTIONS

- Fig. 1 Interaction (event) of a high-energy photon (incoming from the left, invisible because neutral and not ionizing) in a nuclear emulsion. Two charmed particles, one neutral, the other charged may be seen to decay after 120, resp. 50 μm (CERN Experiment WA58).
- Fig. 2 A silicon microstrip detector (512 elements, pitch 50 μm) of which each diode element is connected to a separate amplifier. The connection is made via a metallic pattern on a ceramic support plate and a flexible kapton foil. There can be 128 amplifiers in the box, 4 on each small ceramic plate.
- Fig. 3 Block diagram of the various functions in one channel of a usual detector system.

Fig. 1

Fig. 2

TYPICAL PARTICLE DETECTOR SYSTEM

Fig. 3