ADVANCED CONCEPTS FOR SEMICONDUCTOR NUCLEAR RADIATION DETECTORS

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By applying the technologies of semiconductor device fabrication, new types of Si radiation detectors have been developed. These include low-noise detectors for energy spectroscopy as well as detectors for precise position measurement of radiation. The activities on smart sensors resulted in detectors with on-chip low-noise signal amplification. One of the most interesting ideas is a random-access pixel detector with charge storage capability.

1. Introduction

The working principle of a semiconductor detector for nuclear radiation as shown in fig. 1 is identical to that of a pin photodiode. In both cases the deep depletion layer of a reverse-biased p⁺n junction diode is used for the absorption and detection of radiation. The energy or intensity of radiation can be determined by measurement of the number of charge carriers produced by the radiation within this layer. As the efficiency for nuclear radiation is increasing with the atomic number of the detector material, semiconductors like Ge, GaAs, CdTe or HgI₂ seem to be superior to Si, the most common semiconductor. Up to now, however, both the fabrication and the operation of these detectors is fairly sophisticated compared to Si detectors. In the last years, modern technologies of semiconductor device manufacturing could be transferred to the fabrication of Si radiation detectors [1,2]. As a result, a variety of new detectors has been realized, which will be overviewed in this paper.

2. Position-sensitive detectors

The work on position-sensitive detectors was very much stimulated by the high-energy physics community, which needs such detectors in large numbers for precise measurement of particle tracks. Depending upon the application, the following principles are in use.

2.1. Principle of charge division

The scheme of a linear position-sensitive detector using the charge division mechanism [3] is shown in fig. 2. In contrast to fig. 1, here the front p layer has a lower doping, resulting in a resistive layer of typically several kΩ resistivity. Metal electrodes are provided only at two strips at opposite ends. If ionizing radiation is absorbed in the detector, the holes drift to the p side and, within the p layer, to the readout electrodes at the left and right. The amount of charge detected by the preamplifiers 1 and 2 depends on the position X of the incoming radiation. By adding both signals, the energy E can be determined and eliminated by

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Fig. 1. Layout of an ion-implanted p⁺nn⁺ Si detector. Under reverse bias a deep depletion layer is formed, which is used for the detection of radiation.

Fig. 2. Position-sensitive detector using charge division within a highly resistive (several kΩ) p layer. The amount of charge detected by the preamplifiers 1 and 2 depends on the position X of the incoming radiation.
2. **Integrated diode arrays**

Integrated diode arrays known as microstrip detectors are used for more precise position measurements of minimum ionizing particles [5–7]. A cross section of such a device is shown in fig. 3. The typical length of the striplike diodes is 30–50 mm, while the pitch is 20–50 μm. When all diodes are polarized together in reverse, the individual depletion layers overlap and the device behaves like a large-area p⁻n⁺ detector having a high number of separated readout electrodes. 

Due to the fairly high capacitance of the detector, a noise level of several tens of keV FWHM is typical. The position resolution for nuclear radiation lies, therefore, near 1% of the detector length L. Readout times are in the microsecond range.

Position sensitivity in two dimensions is easily achieved by using more than two contact electrodes for charge collection. Other structures reported in the literature make use of resistive layers implanted on both sides of the detector [3] or made by epitaxy and diffusion [4].

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To avoid the high number of readout channels and to reduce electronics costs, resistive or capacitive charge division as shown in fig. 2 and discussed above can be used. By capacitive readout of one out of three channels (60 μm spacing) a precision in the position determination of 4 μm could be achieved for minimum ionizing particles. A noise level of 1–2 keV FWHM and readout times of several nanoseconds are obtainable.

Advanced strip detectors have been reported in the literature [8] with integrated bias resistors and readout capacitors. Meanwhile, even double-sided strip detectors with integrated MOS capacitors and bias resistors at both sides have been successfully fabricated and are under test [9].

2.3. **Semiconductor drift chamber (SDC)**

The layout and principle of operation of a SDC device [10,11] are illustrated in fig. 4. Similar to the strip detector of fig. 3, p⁺ strips are implanted at both sides of an n-Si wafer. When both systems of strips are biased simultaneously in reverse, the depletion layers expand into the bulk Si until they touch one another in the middle.

If e⁻-h pairs are generated within the semiconductor volume, the holes drift to the electrodes at the front and rear, while the electrons are collected in a potential minimum in the middle of the device. By superposition of a transverse electric field (up to 1000 V/cm), they can be drifted to a small low-capacitance (less than 1 pF) anode and read out. By measuring the drift time of the electrons, the position of charge creation can be determined very precisely within 3–4 μm. By segmenting the readout anode, position determination in the second dimension was also achieved with an accuracy of approximately 12 μm.

The main advantages of the SDC device are the high position resolution with reduced electronics, the low capacitance (low noise) and the reasonably fast readout time of several microseconds per cm drift length [2].

2.4. **Fully depleted junction charge-coupled devices (JCCDs)**

As the depletion layers of standard CCDs expand only several μm into the Si, such devices are suitable for nuclear radiation in special applications only [13]. However, by applying the SDC principle [10], JCCDs have been fabricated with a thickness of several 100 μm, as shown in fig. 5.
This new experimental device [14] consists of an array of p⁺n diodes at the front and a large-area p⁺n junction at the rear. By applying a high reverse bias at the rear, the bulk can be totally depleted. If the front diodes are also biased in reverse, potential wells of several μm thickness are formed, which can be used as charge stores for majority carriers (electrons) collected within the whole volume of the detector. Using the methods of standard CCDs, the charge can be transferred from one well to the next until it reaches the readout electrode. Since the device behaves like a buried channel CCD, high transfer efficiency and high operating frequencies (100 MHz) are expected. The position accuracy is 4–5 μm. The first devices fabricated do not yet show this optimum behaviour, but demonstrate the operation principle.

A comparison of the data for the different types of position-sensitive detectors shows similar position resolution (several μm) and noise behaviour (approximately 1 keV FWHM) for strip detectors, SDC devices and fully depleted JCCDs. Considering the electronics required, SDCs and fully depleted JCCDs are preferable. With respect to readout speed, strip detectors (ns) and SDCs (μs) are superior to the CCDs (ms). Detectors using resistive layers for position determination are even worse in their physical properties, but simpler to fabricate.

3. Special developments

On the basis of the semiconductor drift chamber (SDC) device, a number of new detectors has been proposed [15] and already realized. In the following some of the most interesting devices will be discussed.

3.1. Low-capacity diodes

One of the most characteristic properties of SDC devices is the low capacitance, which makes them very attractive for the construction of low-noise radiation detectors. A detailed description of such a diode is given in ref. [16]. It contains a large-area (1.5 cm²) highly doped p⁺ layer at the front, while the drift field is maintained by a spiral configuration at the rear. The electrons are collected at a low-capacity (0.1 pF) anode in the center. The energy resolution achieved at room temperature is approximately 1.5 keV FWHM for 241Am X-rays.

3.2. DEPMOS device

A very interesting device fabricated lately is a detector with a special type of MOS transistor integrated. As can be seen from fig. 6, this depleted PMOS transistor (DEPMOS) is built into the surface of the detector opposite to the p⁺n junction. Under working conditions the detector is totally depleted and a potential minimum for electrons is formed at a small distance underneath the channel of the transistor. Electrons generated by radiation are collected there and change the conductance behaviour of the channel. The potential minimum can thus be considered as an additional internal gate. A clearing electrode is provided for removing the charge stored in the internal gate after measurement. With such a device a FWHM of 250 eV was achieved at room temperature for 56Fe X-rays [17]. An improvement by a factor of 2 seems to be possible after optimizing the transistor parameters. Thus, this detector may become very useful for high-resolution X-ray fluorescence and PIXE analysis.

3.3. Random-access PIXEL detector

By integration of a high number of DEPMOS transistors a matrix PIXEL detector is feasible, characterized by the following outstanding features:

- low-noise signal amplification,
- short-time charge storage capability in each PIXEL,
- individual repeated readout of each PIXEL without losing the charge signal in it,
- individual clearing of each PIXEL.
3.4. Multievent-storage random-access PIXEL device

A device that is able to perform simultaneously as a detector and as a storage device for several charge images has been proposed in ref. [9]. It is developed from the PIXEL device by adding buried grids into the bulk of the detector, underneath the top readout structure. As shown in fig. 7 a three-dimensional grid of electron potential minima is formed and signal charges produced in the bottom detector region of the device will be collected in the minima close to the lowest gating grid.

By proper biasing of the consecutive grids, the charge image can be transferred upwards in a similar manner to that used in CCDs, until it reaches the readout part at the top. The device therefore can be considered as a combination of a radiation detector and a three-dimensional CCD. The CCD part allows storage and simultaneous movement of several charge images taken from the detector part.

Alternatively, it should also be possible to inject charges into the internal gates immediately below the top surface and move them downward into the bulk. Thus one may use the device as a purely electronic memory. Finally, one may use the storage register itself as detector, thus obtaining three-dimensional images of strongly ionizing corpuscular or electromagnetic radiation.

4. Integration of front-end electronics

Due to the high complexity of detector systems planned for future applications, miniaturization of the front-end electronics is unavoidable. One way to solve this problem is by direct bonding of individual detector elements to integrated circuits. For this purpose MOS electronics have been developed in several laboratories [18,19], containing up to 256 analog channels per chip.

Besides the previously mentioned DEPMOS transistor, direct integration of electronic components into the detector chip is under way, too [20]. Meanwhile, a complete low-noise charge-sensitive preamplifier was realized in detector-grade silicon by using the same technological steps applied for detector fabrication [21]. All transistors and resistors are fabricated by ion implantation. The preamplifiers are under test now and show the expected behaviour.

5. Conclusions

After a description of the working principles of Si radiation detectors, the different methods used for position measurement of radiation have been discussed. These are: the charge-division mechanism, the integration of diode arrays, the measurement of the drift time of charge in the semiconductor drift chamber and the charge transfer in JCCDs. The special developments on detectors include the low-capacity spiral diode, the detector with integrated DEPMOS transistor for low-noise amplification, the random-access PIXEL detector and the multievent-storage random-access PIXEL device. The research on integration of electronic components into high-purity Si resulted in the design of a charge-sensitive preamplifier compatible with the detector process.

References


III. EQUIPMENT