SILICON RADIATION DETECTORS - PHYSICS AND STRUCTURES

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Abstract: Silicon radiation detectors are used in many fields of application. The development of strip detectors and spectroscopic devices is mainly driven by the research in particle physics and astrophysics. As a result of the progress made in high resolution silicon drift chambers portable spectroscopic systems operating close to room temperature have been developed. They are used for a variety of x-ray analysis methods. In pixel detectors a signal amplification already takes place at the location of signal detection. They have the potential to combine fast signal amplification, high precision and energy resolution with low power consumption.

Silicijevi detektorji sevanja – fizika in strukture

Ključne besede: Si detektorji sevanja silicijevi, Si detektorji silicijevi mikrotrakasti, fizika delcev, astrofizika, naprave spektroskopske, detekcija signalov, X-žarki analiza, ojačenje signalov, ločljivost energijska, ločljivost položajna, detektorji sledilni, naprave sledilne polprevodniške, osnove fizikalne, strukture polprevodniške, DEPMOS strukture silicijeve kovinsko oksidne, DEPFET strukture

Izvleček: Silicijevi detektorji sevanja so našli uporabo na mnogih področjih. Razvoj mikropasovnih detektorjev in spektroskopskih naprav v glavnem spodbujajo raziskave na področju fizike delcev in astrofizike. Kot rezultat napredka pri razvoju visokoločljivih silicijevih drift detektorjev so nastali prenosni spektroskopski sistemi, ki delujejo blizu sobne temperature. Uporabljamo jih pri raznovrstnih analiznih metodah z rentgenskimi žarki. V točkovnih detektorjih signal ojačamo že na samem mestu detekcije signala. Ti detektorji združujejo možnost hitre ojačitve signala, visoke natančnosti in energijske ločljivosti z majhno porabo moči.

1 Introduction

Radiation detectors may be classified according to their use for particle tracking and for spectroscopic applications. Tracking detectors are widely used in the field of particle physics while spectroscopic detectors have their most important applications in material analysis and x-ray astronomy.

At present, the development of tracking detectors is mainly driven by the LHC (Large Hadron Collider) experiments planned to start in 2005 at CERN. Device concepts allowing mass production and providing sufficient radiation hardness are required in this field.

For the category of spectroscopic semiconductor detectors, silicon is the detector material of choice for x-ray detection below 20keV. The focus is put in noise reduction and increase of counting rates in order to minimize the exposure and measurement times.

2 Tracking Detectors

Here the emphasis is on position measurement, although the energy of absorbed (or energy loss of penetrating) particles is sometimes also measured.

The by far most widely used semiconductor tracking devices are strip detectors. These exist in single sided and double sided versions. The readout is either directly or capacitively coupled. Readout of every strip or capacitive charge division readout are possible.

An elegant device, in which the signal charge drifts parallel to the surface to a collecting anode is the semiconductor drift chamber. Here the drift time can be used for determining the position. As these devices provide very small capacitive load to the readout amplifier, the signal charge (or energy) can simultaneously be measured very precisely. For many applications only the energy measurement is used and these devices will (in this presentation) be described in the section of spectroscopic detectors. Similar considerations hold for CCD detectors.

2.1 Strip Detectors

Fast signal readout and good position resolution are the key features of a tracking detector. The typical device being able to fulfill these requirements is a strip detector.

Strip detectors have been developed for the purpose of measuring the position of single particles incident on or traversing the detector. Extremely important progress was made by the development of low-noise, low-power microelectronics which could be directly mounted next to the detectors, connected to it by ultrasonic wire bonding.

The principle of strip detectors at first glance is rather simple. A large area diode is divided into narrow strips, each of them being read out with a separate electronic channel. The position of the ionizing particle incident on or traversing the detector is then given by the location of the strip showing the signal.

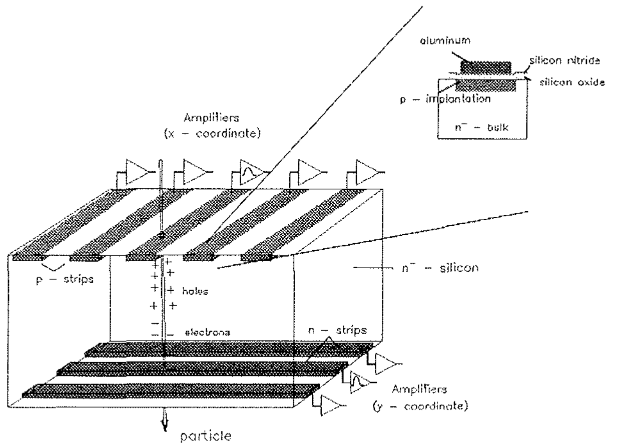

Fig. 1: Schematic drawing of a double sided strip detector. The p-strips on the top side are read out by capacitive coupling (see insert).h The biasing of the p-strips and details on the n-side including the necessary precausions for providing electrical insulation between neighboring n-strips are not shown.

To obtain a two dimensional position information, there is the possibility to glue two strip detectors with different strip directions back to back together. The more natural (elegant) method - reducing simultaneously scattering material - is the use of double sided strip detectors with p-strips on one and n-strips on the other side as schematically indicated in Figure 1. The holes drift to the p-strip while the electrons are collected by the n-strips. Thus both charge carrier types are used for signal formation.

2.1.1 Capacitive coupled readout and bias structures

To decouple the amplifier inputs from the detector leakage current - thereby avoiding channel to channel and time dependent pedestal shifts - capacitively coupled detectors are frequently used. Realization of this readout concept is difficult due to the large values of capacitances and bias resistances needed. The capacitors can be integrated into the detector by inserting insulation layers between the strip implantations and the metal lines. Providing the insulation by the ovelap of two independent layers (as shown in the insert of Figure 1) increases dramatically the strip yield as shorts of the integrated coupling capacitors due to insulator defects are extremely unlikely. In capacitively coupled detectors the strips have to be biassed by additional bias structures which in the simplest case can be resistors located on the ends of the strips. These resistors can be built with poly silicon, by ion implantation in the bulk or by using charge induced layers like the electron accumulation layers that are naturally induced by the always existing positive oxide charges in the transition region of silicon and silicon oxide. However, these methods are either space consuming and/or need additional technological effort. A simple alternative method that needs almost no additional space and no further processing effort is the so called punch through biassing /1/ sometimes also called FOXFET biassing. Here a small gap of about 5 μm between the strip end and a bias line is used to form a potential barrier whose dynamic resistance depends on the leakage current of the individual strip. This leads to a very compact high ohmic bias device which can be implemented for p-strip biassing as well as for n-strip biassing. The only drawback of this structure is its lack on radiation hardness that is caused by the introduction of excess noise /2/ due to the presence of radiation generated bulk traps in the punch through region /3/.

2.1.2 Charge division readout

As the signal charge during collection time will also undergo diffusion, the signal may be spread between neighboring strips. Analog readout of signal charge therefore not only allows simultaneous determination of energy and position but furthermore (by means of interpolation) improves position measurement, provided the strip spacing matches the diffusion width. Charge division may also be used to decrease the number of readout channels. Only a fraction of strips is connected to a readout channel. Charge collected on intermediate (not connected) strips is capacitively coupled to the neighbouring readout strips through the naturally occuring strip to strip capacitances. In order to avoid distortions of the electric field configuration the intermediate strips have to be held at the potential of the readout strips.

2.1.3 Application fields of strip detectors

The development in the field of strip detectors are mainly driven by the LHC (Large Hadron Collider) experiments currently under construction at CERN. The large detection area of more than 150 m^2 leading to about 40000 detectors each of a size of about 40 cm^2 is one of the main challenges in the construction of these experiments. Facing those quantities, robust detector concepts are needed which allow mass production with high yield. For the sake of simplicity of detectors and electronics, single sided p-strip detectors with capacitively coupled readout were chosen as baseline in both multi purpose experiments at LHC (ATLAS as well as CMS). The signal has to read out within two bunch crossings (i.e. 25 ns). This means that the electronics have to operate with a signal peaking time of about 20 ns, a'time that is already in the range of the charge carrier drift time in a 300 μcm thick detector. In this volume a MIP (Medium Ionizing Particle) generates about 24000 electron/hole pairs, a signal that has to be compared with the equivalent noise charge of the system of about 1500 electrons /6/.

The other main challenge is the high radiation environment in which the detectors have to operate over the whole forseen ten years lifetime of the experiments. For example, the innermost barrel layer of the ATLAS SCT (SemiConductor Tracker) has to withstand a radiation dose of 2 x 10^{14} cm^{-2} 1 MeV equivalent neutrons /6/.

2.1.4 Radiation hardness

Radiation does not only interact with the electrons of the semiconductor, thereby providing the transient signals to be detected, but also with the nuclei of the lattice, thereby creating crystal defects which in the following are referred to as bulk damage.

Furthermore ionizing radiation creates electron-hole pairs not only in the semiconductor but also in the insulating layer (SiO_2). While electrons in silicon dioxide have high mobility and escape almost immediately, holes are extremely slow and may be permanently captured in deep level traps of the oxide and in the oxide semiconductor interface /5/. Thus positive charge is produced and accumulated in the oxide and in the oxide-semiconductor interface, leading to threshold shifts of MOS transistors and to local high field regions in detectors. A saturation of the radiation induced oxide charge is observed which may be explained by the limited number of traps. For the commonly used <11.1> oriented detector material oxide charge saturation values of about 1.5 to 3×10^{12} cm^{-2} were measured, with results depending on the technological treatment.

In the silicon the dominant primary induced lattice damage is the displacement of atoms from their regular lattice sites, thus creating simultaneously vacancies and (self) interstitials. Most of these primary defects are not stable. Interstitials and vacancies are mobile at room temperature and will therefore partially anneal if, by chance, an interstitial fills the place of a vacancy. However there are also chances for the formation of other (at room temperature) stable defect complexes. Examples are the well known A-center, a combination of a vacancy and oxygen (a certain concentration of oxygen interstitials is present in the crystal after crystal growing), the E-center, a vacancy phosphor complex and the divacancy (two missing silicon atoms right next to each other).

These stable defects locally distort the symmetry of the crystal. They in general may assume two or more charge states corresponding to different types of chemical binding respectively lattice distortion. Change of the defect charge state is accomplished by electron and hole capture or emission. The minimum energy necessary to emit an electron to the conduction band or a hole to the valence band determines the energy level of the particular defect charge state within the band gap.

Depending on the charge states and energy levels of the defects, some of the following effects will be dominant in the space charge region of a detector:

- Generation of leakage current by alternative emission of electrons and holes. This mechanism is dominant for defects with the energy level close to the band gap center.
- Trapping: capture and later reemission of electrons or holes. This process dominates if the defect level is not very close to either band.
- Defects assuming an (on average) non-zero charge state. This effect results in a change of space charge and the required operating voltage for the detector.

The stability of defects is temperature dependent. Heating may make them movable or break up defect complexes. Removing defects this way is termed annealing. Some of it occurs already at room temperature. New types of defect complexes may however be generated in the process.

As the physics of radiation damage is rather complicated and only partially understood, involving many types of defects, one usually restricts oneself to a parameterization of measured changes in material parameters like the generation lifetime (determining the leakage current), the charge trapping probability and the effective doping change (determining the operating voltage). Irradiation of silicon changes the effective doping in the direction of increased p-doping, as found by observing the space charge density. N-type silicon will first change to intrinsic and then to effective p-doping. After ending the irradiation the effective doping will decrease on short time scales but then it will rise again on time scales of months or years. This unpleasant and not satisfactorily understood effect, leading to high required operating voltages has been termed reverse annealing. It can be suppressed by cooling the devices to roughly 0°C.

Some data taken from the ATLAS TDR (Technical Design Report) /6/ should demonstrate the practical relevance of this effect. The operation (and maintenance) temperature scenario of ATLAS leads to depletion voltages of about 220 V for the innermost barrel layer after ten years operation not taking into account the safety margins /6/. The maximum operation voltage is assumed to be 350 V at which the detectors has to run still stable in order to avoid any self heating effects by increased power consumptions. Keeping in mind that commonly used detectors usually operate at voltages below 100 V this implies a new quality of requirements to the detector design and technology[1].

2.1.5 Double sided detectors for high radiation applications

A radiation hard double sided capacitively coupled strip detector developed and produced by the MPI Semiconductor Lab for the HERA-B experiment at DESY Hamburg /8/ is shown in Figure 2. The radiation level in HERA-B is even an order of magnitude higher than in the LHC experiments. This means that the detectors have to be replaced after they reach a damage level which makes a reasonable data analysis impossible. However, although the number of 64 detectors installed in HERA-B is rather small compared with the LHC experiments, it is an important physical and economic issue to provide components which survive at least an operation period of one year. In order to reduce the scattering of the tracks on the detector material, double sided detectors were chosen, thus halving the amount of silicon material seen by the incident particles compared to two single sided detectors. Several features are implemented with the focus to prolonge the survival time of the device in the harsh radiation environment.

1 Very recent results of the ROSE collaboration suggest that intrinsic radiation hardening of silicon can be achieved by the increase of oxygen concentration within the bulk silicon /7/.

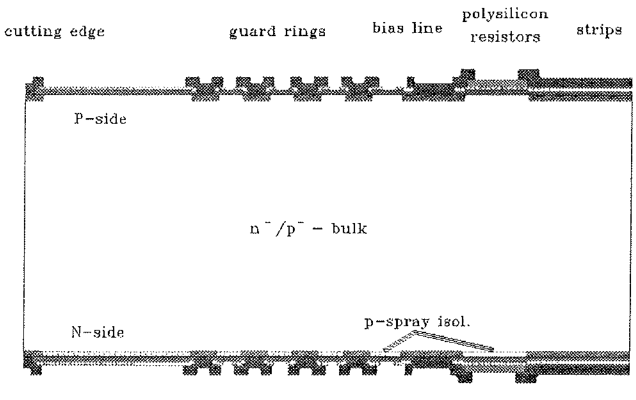

Fig. 2: Schematic cross section through a double sided strip detector designed and produced for HERA-B. For the sake of clearness the real guard ring number of 16 is reduced in the figure.

The detector is designed to operate at bias voltages above 500 V after an exposure to 2 x 10^{14} cm^{-2} 1 MeV equivalent neutrons. On both sides high voltage protection structures provide for a smooth drop of the bias voltage from the rim of the active area towards the cutting edge. The operation of this multi-guard ring structures bases on moderated potential drops between neighboring guard rings that are adjusted by the punch through voltages between the rings /4/. Large gaps between neighboring implantations are avoided in the whole detector area. This measure reduces lateral electric field peaks and increases the break down voltage /10/. The positive oxide charge at the Si/SiO_2 interface usually generates an electron accumulation layer that shorts neighboring implantations. Additional p-stops are usually implanted to interrupt or suppress this electron layer. In the HERA-B detectors an overall p implantation (that does not need a further mask) is used /9/ to provide this isolation. Besides the obvious process simplification this technique implies the feature that the critical lateral electric fields between the n-implants and the p-isolation layer decrease with increasing oxide charges leading to the desired situation of decreasing field maxima after irradiation /10/. An examples for this behavior will be shown in chapter 4. (Pixel detectors). The biassing of the capacitively coupled implanted strips is done by poly silicon in order to avoid the above mentioned excess noise generation.

3 Spectroscopic Silicon Devices

Energy measurement of x-rays is accomlished by determination of the amount of charge that is generated by the converted x-ray. In order to obtain highly precise charge measurements dedicated devices were developed. Here we have to answer the question of the achievable noise minimum. Independent from the optimization of the detector and electronics there exists an minimum noise level wich cannot be lowered (as long as the basic detector material is not changed). This noise is attributed to the charge generation process itself. The energy conversion of an x-ray takes place in a cascade process. Starting with a small number of energetic electrons consecutive impact process leads to a generation of electron/hole pairs, which generates further electron/hole pairs (Figure 3). This process continues until the energy of the charge carriers is lower than the threshold level (E_{th}). In the cascade process not all of the energy is transfered to newly generated charge carriers, a large fraction is transmitted to phonons. This energy splitting undergoes statistical fluctuations resulting in the Fano noise /11/. The Fano noise depends on the x-ray energy

$$\sigma_F = \sqrt{wFE}$$

With the pair creation energy w (3.7 eV for silicon), the Fano factor F (F = 0.12 for Si) and the photon energy E. For example in silicon a Fe^{55} x-ray signal (5.895 keV) is generated with a Fano noise contribution of 118 eV at room temperature.

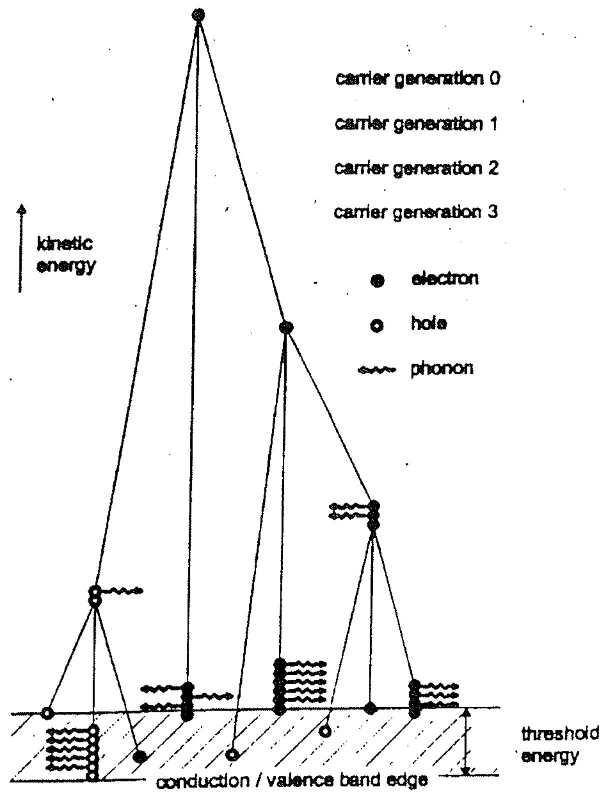

Fig. 3: Ionization casdade after a x-ray conversion. Electron/hole pairs can be generated only above the threshold energy (Courtesy of P. Lechner)

While the Fano noise drops with decreasing energy, other noise contributions remain constant. A usually dominant noise source is the serial noise that is generated by noise sources within the (charge sensitive) amplifier and that increases linearly with the capacitive load at the amplifier input. Reducing the detector capacitance therfore is imperative for low noise spectroscopic detectors. With the silicon drift detector this can be accomplished while keeping large detection volumes.

3.1 Drift Detectors

The working principle bases on the eflect of sidward depletion which may be explained by starting from the diode.

The backside N^+ contact does not have to extend over the full area, but can instead be put at any place of the undepleted conducting bulk (Figure 4a). Then there is space to put diodes on both sides of the wafer. At small voltages applied to the N^+ electrode we have two detectors separated by the conducting undepleted bulk region (hatched in the figure). At high enough voltages (Figure 4b) the two space charge regions touch each other and the conducting bulk region retract towards the vicinity of the N^+ electrode. At this point the capacitance between N^+ electrode the P^+ electrodes drops dramatically and becomes moreover independent on the detector area. A potential valley for electrons is obtained in which thermally or otherwise generated electrons assemble until they (slowly) diffuse towards the N^+ electrode (anode) while holes are drifting (fast) in the electric field towards the P^+ electrodes. Increasing of the voltage leads to an overdepletion and to the isolation of the N+ electrode which now can act as anode in a detector system (Figure 4c).

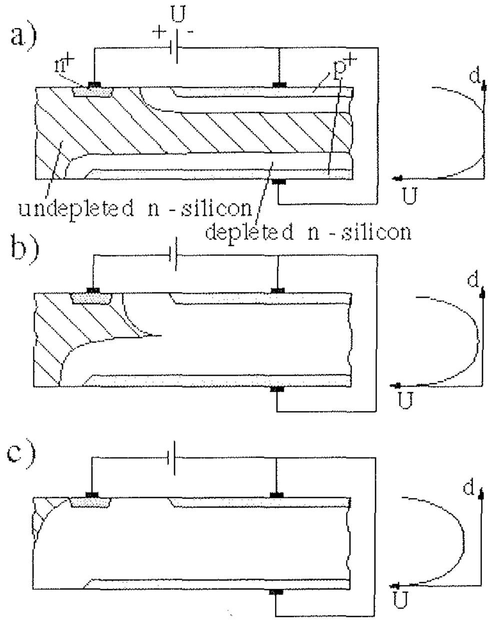

Fig. 4: Basic structures leading towards the drift detector: diode partially depleted from both sides (a); diode just depleted (b); diode overdepleted (c)

In the Silicon Drift Detector (SDD), in its basic form proposed by E. Gatti and P. Rehak /1/) in 1984, an additional electric field component parallel to the surface of the wafer is added so as to provide for a drift of electrons in the valley towards the anode. This is accomplished by dividing the diodes into strips and applying a graded potential to these strips on both sides of the wafer. Drift chambers may be used as position and/or energy sensitive detectors. The position can be obtained from the time between incidence of ionizing particle and formation of the signal on the readout electrode (drift time of signal electrons). Its importance as energy sensitive device is due to the fact that signal charges from a large area device are collected on a small area and therefore small capacitance electrode, thus reducing noise in the readout electronics.

Other drift field configurations (e.g. radial drift) can be obtained by suitable shaping of the electrodes. Drifting towards a central collecting electrode is especially interesting for energy measurement (Figure 5) as the capacitance of the readout electrode may be reduced to the 100 f F range. Drifting outwards towards a segmented ring anode has also been done for a special application /12/. As an example of what can be achieved by combining various features described before a x-ray spectrum measured with a novel drift device is presented. The single sided structured device with the electron potential valley running from the outside bottom to the inside top collecting anode provides a homogeneous entrance window. Cylindrical geometry with radial drift provides small capacitance and low noise.

Integration of a first (Single Sided JFET) transistor /13/ avoids stray capacitances leading to low noise and fast signal shaping in order to take full advantage of the minimized anode capacitance. Further properties are the integration of a voltage divider for the field shaping electrodes and the draining of surface generated leakage currents.

The device is very well suited for (near) room temperature spectroscopy as demonstrated in figure (Figure 6) where the Fe^{55} spectra at 25°C and -13°C obtained with 0.25 respectively 1 μs shaping time constant are shown. An energy resolution of 178 eV respectively 144 eV has been achieved /14/.

These high resolution spectra qualify the silicon drift chamber for applications different x-ray analysis techniques where good spectroscopic features together with high counting rates are required, for instance x-ray flourescence (XRF), electron microprobe analysis

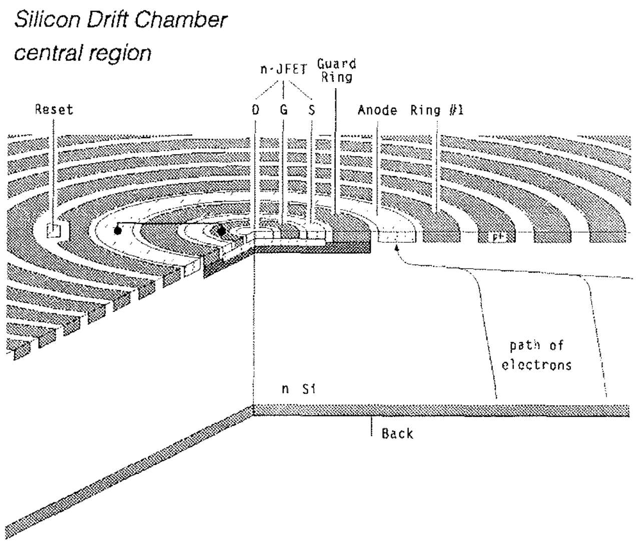

Fig. 5: Drift diode with integrated Single Sided JFET and non structured homogeneous backside entrance window

(EDX) or particle induced x-ray emission (PIXE). An example for a working detector system is the portable XRF spectrometer for non-destructive analysis in archeometry /15/ developed in collaboration of Politecnico di Milano, MPI Semiconductor Lab and Ketek GmbH.

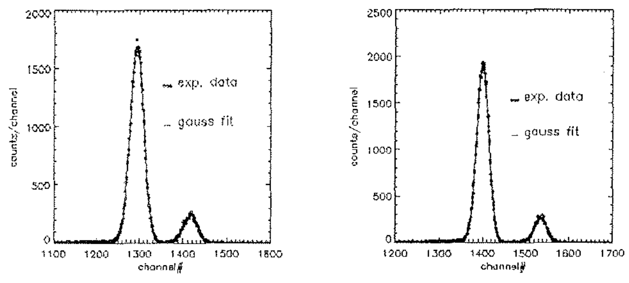

Fig. 6: Drift diode with integrated electronics: Manganese spectrum from an Fe^{55} source recorded at 25°C Shaping time = 0.25 µs, FWHM = 178 eV (left); Manganese spectrum recorded at -13°C Shaping time =1 µs, FWHM =144 eV (right)

3.2 Fully depleted p-n CCD for x-ray applications

The p-n CCD (Figure 7) is based also on the sideward depletion principle. Putting non equal potentials on front and backside diode junctions one moves the electron potential valley close to the top surface. Instead of applying a linearly rising potential to the field shaping electrodes on the top side a periodic potential is used thus creating electron potential minima in which the signal electrons are confined. The backside of the device is a single large area diode, thus providing a homogeneous radiation entrance window for the completely depleted and therefore fully sensitive detector volume. Signal charge is moved towards the N^+ doped collecting anode by a cyclic change of the (three phase) register potentials.

The development of x-ray CCDs is clearly driven by the requirements of the astrophysics. 6 x 6 cm^2 large monolythic devices with a pixel size of 150 x 150 μm^2 will be used as focal instruments in space based X-ray telescopes developed for astronomical observations /19, 20/. The flight models are already qualificated for the launches of the ABRIXAS and XMM satellites scheduled in spring 1999 and 2000, respectively.

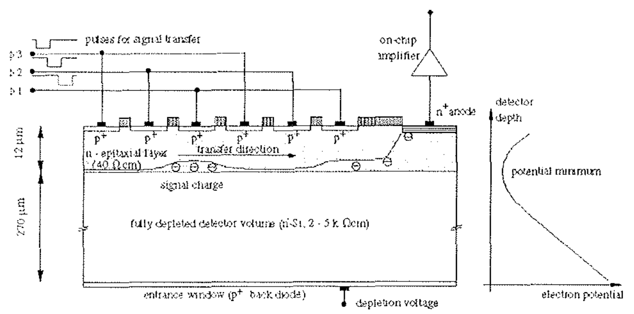

Fig. 7: Schematic cross section of a three phase p-n CCD with integrated JFET amplifier. The register consists of p-n diodes and the charge transfer depth is in the range of 10 µm allowing larger pixel sizes as used in conventional MOS-CCDs.

4 New Detector Structures - Pixel Detectors

An inherent problem of strip detectors is that in the case of multiple hits occouring in one read out time slot the two dimensional local resolution becomes ambigous. The very high luminosity occuring in the LHC experiments leads to large amount of vertices to be detected especially in the very inner parts of the detectors. Therefore in this regions higher segmented detectors, so called pixel detectors, will be installed. These detectors contain basically diode arrays where the attached electronic channels are mounted on top of the diodes using flip chip bump bond technique /16/. Comparing strip detectors with pixel detectors the advantages of the latter are the definite relation between a small sensor diode and the attached frontend electronics and the reduced input capacitance seen by each input amplifier. The principle is illustrated by the schematic cross section (Figure 8) showing a single diode bumped to its attached electronic channel. The drawback consists in the much more complex technology required.

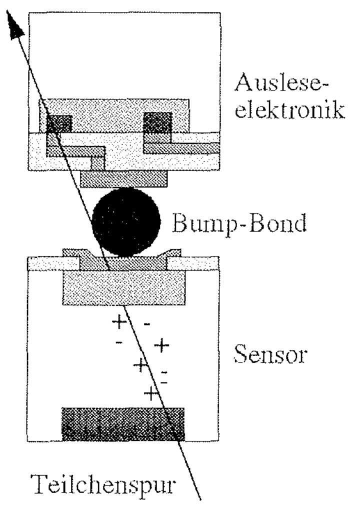

Fig. 8: Principle of sensor diode and amplifier connection via bump bonding used for ATLAS pixel detectors.

To avoid these complications an alternative concept was proposed. The idea bases on a field effect transistor (MOS or JFET) integrated on the surface of a fully depleted silicon detector. A potential minimum for generated charge carriers is located directly beneath the transistor channel forming an floating internal transistor gate. Charge carrier generated by particles or photons in the detector bulk drift into the potential minimum and control the transistor current /22/. Thus a signal amplification directly at position of detection is achieved. In contrast to the bump bonded device, sensor and related transistor are fabricated within the same technological process.

4.1 Diode Arrays bump bonded to Electronics

The inner detectors of LHC experiments will contain hybrid pixel detectors as described in /6/.

Pixel detectors for LHC experiments are heavily affected by the requirement of extreme radiation hardness (for instance up to 10^{15} hadrons/cm^2 during 10 years operation in the ATLAS-inner region). Here, the emphasis is put on the sensor design and operation while the electronic concept is discussed in detail in /6/.

The pixel cells consist of n-implants placed on n-bulk material (n on n device) /17/ while the junction is situated on the back side of the sensor surrounded by a multi guard ring structure. This choice which in comparison to the standard p^+n detectors requires a more difficult and expensive sensor fabrication technology (due to the needs of double sided processing and n-side inter-pixel isolation) is motivated by two reasons. During operation the radiation damage will increase the full depletion voltage of the pixel sensors to values well above the maximum forseen bias voltage of 600 V. Because of the effective p-doping of the bulk after irradiation the depletion region then extends from the n-pixels into the bulk. Because the electronics does not need the whole signal of the fully depleted detector, the detector can be operated partially depleted as a trade off between a reduced operation voltage and a smaller signal. Furthermore the n on n concept allows to use pside guard structure only. That keeps the whole n-side of the sensor on ground potential. Thus the danger of disruptive discharges between the sensor and the very closely spaced front-end chip /17/ is avoided. For n-side interpixel isolation, the already mentioned p-spray technique was used. Figure 9 shows the IV-curves of 1 cm^2 large test detectors before and after irradiation /18/. The irradiation was done with 1.1 x 10^{15} pions/cm^2.

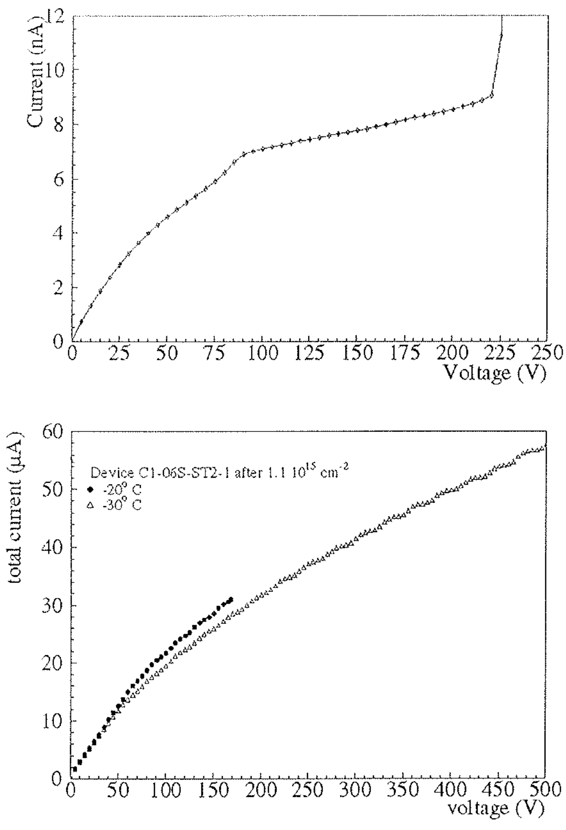

Fig. 9: IV-curves of 1 cm^2 n on n ATLAS-Pixel test detectors before and after an irradiation of 1.1 x 10^{15} pions/cm^2. The devices were fabricated by CiS (Germany).

The break down voltage of the unirradiated device is about 200V. Breakdown occurs at the electric field maxima located at the n pixel - p-spray junction. After irradiation, much higher operating voltages be used as a result of the reduced electric fields /10/. A further publication, especially of source measurements of irradiated sensors with flip-chip bonded ATLAS pixel electronics is in preparation /21/.

4.2 DEPMOS, DEPFET as detectors

The DEPleted Field Effect Transistor structure simultaneously has the functions of detector and amplifier. Its working principle is most easily explained by comparing it to a standard field effect transistor (Figure 10). Out of the various types of FET structures which can be used for this new device we have chosen the p-channel MOS enhancement transistor. The standard transistor shown on the top part of the figure is located on an undepleted n-doped bulk kept at substrate potential V_{bias}. The p-doped source and drain are connected through an inversion layer, the transistor channel. The transistor current is steered by the potential of the metal gate on top of the insulating gate oxide. It is worth noting that this current may also be modulated by varying the substrate potential. This usually unwanted feature is called bulk effect.

Adding a large area diode on the back, one may deplete the bulk from the backside, similarily as was done with the structure shown in Figure 4 which lead us to the drift

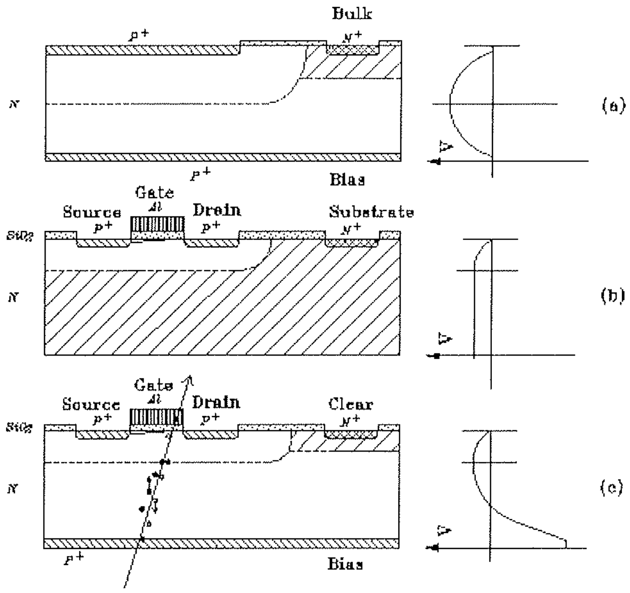

Fig. 10: Operation principle of a DEPMOS detector. The structure is arranged on a fully depleted high ohmic bulk acting as conversion volume for incident irradiation. The generated electrons drift to the potential minimum beneath the transistor channel steering its current.

chamber concept. Once a sufficiently negative voltage has been applied on the back the bulk underneath the transistor structure will be fully depleted of charge carriers and a potential energy minimum will be present underneath the transistor. Obviously for functioning of the transistor only the potential at the valley is important independent of the depletion status in the region below it.

If we now have an ionizing particle incident e.g. from the bottom side, the signal holes will move towards the large area diode while the electrons are caught in the potential minimum below the transistor (with suitable doping in the region below the gate). They will by influence induce opposite charge in the channel and thus increase the transistor current.

The DEPFET structure has some extraordinary properties which make it extremely interesting for detector applications:

- As it is simultaneously detector and amplifier, the problem of matching the amplifier to the detector does not arise and parasitic capacitances due to connections between detector and amplifier are absent. This gives at least a factor of two improvement in noise performance.
- The signal size is proportional to the ratio of the transconductance over the (external) gate capacitance, the thermal (output) noise proportional to the square root of the transconductance. Thus a very high signal to noise ratio may be obtained by shortening the gate length and width and increasing the oxide thickness.
- The signal charge located in the energy minimum underneath the gate can be completely cleared by a short pulse on a nearby clearing electrode. Thus clearing does not contribute to noise.
- As the measurement of signal charge is based on a change of the transistor current by means of influence, the signal charge is not destroyed and repeated readout is possible.

The detector principle has been experimentally confirmed /23, 24/ and provided immediately very good noise performance. Here a p-channel JFET was used as basic device in order to reduce the inherent channel noise. Equivalent noise values of about 20 electrons have been achieved at room temperature.

Due to the special properties of the DEPFET structure a variety of applications is possible ranging from readout devices for drift detectors and CCDs to completely new devices. For instance, a pixel detector can be composed by an array arrangement of DEPFET transistors. Such a device has already been proposed in the original paper /22/ and the proper functioning of a 8 x 8 pixel prototype has been demonstrated in /23/.

5 Technological Challenges

In the radiation detectors discussed so far, the whole silicon bulk acts as conversion volume for incident radiation or particles. For a fast charge loss free signal detection the bulk has to be completely depleted and this requires the use of rather high ohmic silicon substrates produced by flow zone technique.

The relationship between the depletion voltage and the detector thickness is simply given by the dependence of the depletion width versus applied reverse bias voltage for an asymmetric abrupt pn-junction. For instance, to deplete a 280 μm thick detector with a bulk doping of 10^{12} cm^{-3} a bias voltage of about 60 V is needed.

A major breakthrough in the field of semiconductor detectors was the first implementation of the planar technology /25/ which allows to take full advantage of the technological progress made in microelectronics. Especially the use of photolithography and ion implantation as doping technique leads to much more advanced detector devices. However, there are still many special processing steps required that forbid detector processing on standard microelectronics production lines. The detector backside has to be protected against scratches and other mishandling. More than this, many device concepts need photolithographic steps on both wafer sides. The large generation volumes and the in most circumstances not allowed implementation of classical gettering techniques require a very clean processing in order to achieve leakage currents below 1 nA/cm^2 for a full depleted device at room temperature. In the meantime the detector sizes start to extend an area of 35 cm^2 and more. This means that there is only one device at a 4 inch wafer. For such situations the yield problem has to be addressed in a new way. One serious defect systematically introduced at a critical position may not only cause malfunctioning of devices on many wafers but can even ruin a whole production run. To produce even larger devices the entry into the 6 inch technology is expected rather soon.

6 Summary - Outlook

We wanted to give an overview about the current status of silicon detectors. In the field of tracking detectors silicon detectors are very established due to their fast response time and high position resolution. They are able to cover a large detection area requiring a moderate number of electronic read out channels. The main challenges to strip detectors mainly driven by the LHC experiments at CERN are the improvement of radiation hardness and the reduction of production costs. To avoid ambiguities in vertex detection the very inner regions of high luminosity detectors will be equipped with pixel diode arrays bump bonded to electronics. For highly irradiated double sided strip detectors and n on n devices like the ATLAS pixel sensors the p-spray isolation technique is a good method to provide excellent high voltage operation capapility without producing excess noise induced by impact ionization.

In the last decade there was significant progress in the field of spectroscopic detectors. The silicon drift chamber has been elaborated in a way that an on chip amplification transistor and a voltage devider were integrated. These devices achieve energy resolutions at moderate temperatures provided by Peltier cooling. Simultaneously the signal rate capabilities have been increased by order(s) of magnitude. The avoidance of bulky nitrogen cooled apparatuses which were needed earlier allow the building of portable measurement systems for a variety of x-ray analysis techniques. Detectors based on the DEPMOS/DEPFET principle have the potential to cover both fields of application, tracking as well as spectroscopy providing fast signal amplification together with high energy and position resolution.

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