Silicon Sensors for the Electron Tagger at a Gamma-Ray Beam Line in ALBA

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1 Silicon sensors

Semiconductor sensors are widely used in Particle Physics experiments as tracking devices. Charged particles lose energy by ionization processes while crossing the sensor bulk. That energy is used to generate pairs of electron and holes inside the semiconductor, which are separated by an electric field which accelerates them. That produces an electrical current which can be detected and produces the detector's signal.

There exists several semiconductors materials which can be used in particle detectors as silicon, diamond and GaAs. Silicon sensors are the most in use by far, because of their good sensing properties, well known and developed technology and affordability. The current particle physics experiments are equipped with hundreds of squared meters of silicon sensors, while the very first experiments (in the 80's) had just a few squared centimeters. This gives an idea of the large development of the sensor technique using silicon and that its technology is well known.

Silicon sensors have a very good spatial resolution. Of course, spatial resolution depends on the geometric configuration of the sensors. There exists designs where the active areas are strips and designs with active areas in pixels. For microstrips sensors the resolution depends directly on the strip pitch, but it can be better than 20 microns. The spatial resolution of individual sensors can be further improved on a tracking system by combining several layers of sensors.

Silicon sensors are manufactured as plates of several centimeters wide and large but just of the order of 300 microns thick. The charge collecting time is of the order of few nanoseconds. Therefore silicons sensors are an appropriate type of sensors to be used in experiments with a very large trigger rate and read out rate. In fact the sensors developed many years ago for the CERN's Large Hadron Collider do work at a 40 MHz readout rate with a typical signal to noise ratio of 12-15. One can obtain much better signal to noise ratio when using these sensors in an environment where the readout rate is lower.

One of the advantages of using thin sensor layers (as it is for silicon) is a minimization of the multiple scattering effects. Of course it also depends on the incident particle type and on its energy but using layers of 300 micron-thick detectors has the benefit of having a small radiation length.

In the recent years there has been also a large development of radiation hard silicon sensors. This development has been motivated specially because of the LHC experiments, where the silicon sensor will operate under extreme radiation levels. The radiation damage causes a signal lose and an increase of the noise. Nowadays there exists silicon sensors able to operate providing a signal to noise of 10 even after been irradiated with a dose of 10^{15} protons/cm^2.

All these aspects concerning the properties and operation of the silicon sensors are developed in the following sections.

1.1 Detector design and spatial resolution

As already stated, there are available several designs of silicon sensors. They can be grouped in two main categories: pixels and strips.

Pixels allow to measure the crossing points of charged particle with a good 3D space point spatial resolution, while microstrips just provide a good 2D space point. 3D resolution must be gained by combining several layers of microstrip sensors oriented at different angles. The option of using double sided microstrip detectors has to be discarded because of the problems induced by the radiation damage.

In principle the spatial resolution of microstrip sensors is just the strip pitch divided by $\sqrt{12}$. So for a typical sensor with a strip pitch of 75 microns on just gets a resolution of 20 microns. It can be improved by using an analogue readout. With an analogue readout it is possible to give a relative weight to all channels giving signal according to the height of the pulse, and then compute the gravity center, thus producing a more accurate spatial point.

It is possible to use microstrip detectors with a pitch strip down to 50 microns. Detectors with a thiner pitch strip are also possible, but some problems arise as for instance, the electric field among strips increases and so does the probability of micro-discharges. This problem can be circumvented by using some specific design and manufacturing process. A thiner pitch strip increases considerably the number of readout channels, which in his turn requires more electronics, more power consumption and heat dissipation. Of course all this effects have an impact in the final cost.

A disadvantage of the pixel system is that the electronics must be located on top of the active sensor. This means that the electronics will receive the same radiation dose as the sensors. Besides, the ASICs will introduce some material which introducing multiple scattering.

The sensor design for the LHCb experiment consists in two types of geometries, and the sensors have a half-disk shape. There are sensors that are devoted to measure the azimuthal angle, therefore have strips in a radial configuration, while the second type of sensors are meant to measure the radial distance, therefore the strips are segments of circle. Both configurations include also a varying strip pitch in order to achieve a better granularity in the region where the density of particles is supposed to be higher. So complicated strips geometry that matches the physics requirements are possible.

In brief, one must say that 20 microns spatial resolution can be achieved without too much hassle. Better space point resolution can be also achieved at a some cost in the detector design, but also considering the electrical insulation among strips.

One can foresee a system with multiple layers of silicon sensors, which may improve the tracking if the distance among them is not to short. This of course will have an impact in the momentum determination of the scattered electrons and helping tremendously to the physics goals of the experiment. Besides it will provide a redundancy in the system. This redundancy will be much appreciated in case of accident or problems in one of the layers, as the system could be still operated and the detection of the scattered electrons will not be perturbed. Therefore at system with four layers separated few centimeters among them can provide a very good and realible tracking system.

In conclusion a multilayer system of single sided microstrip detectors (of variable pitch if needed) with the electronics located in the outermost part is a very good option for the tracking system.

1.2 Read Out

Another important aspect is the readout electronics. This requires to use a hybrid board with multipurpose functions. The first is to connect the sensor to the bias voltage, the second to support the front end electronics and the connection with the data acquisition system, plus some mechanical support, cooling system and pitch adapter.

In what concerns the readout electronics, the sensors have to be AC coupled to the ASICs, which count with a front end amplifier plus pulse analyzer. The late can be performed in many ways depending on the event rate and on the available time to integrate the signal. As stated above the LHC systems can operate up to 40MHz. This gives enough time between events to collect all the signal but the noise due to the large sampling rate is also quite important. A lower sampling rate will reduce the noise, keep all the signal, leading to a better spatial resolution, reduced noise occupancy and fake hits.

For tracking systems with large number of channels it is convenient to use a binary readout system. That means, after the front end amplifier and the pulse shaper the ASICs can integrate a digital part where a threshold can be set in order to transfer only the channel identification of those channels providing signal. However for systems with small number of channels it is convenient to use an analogue system. That means, that what it is transfer to the data acquisition system the pulse height of all channels. The event size can further be reduced by including some means of zero suppression or DPS (Dynamic Pedestal Subtraction). But keeping the analogue information may help tremendously in an offline analysis. It may help to determine the center of gravity when a cluster of channels is formed, those improving the spatial resolution. Matters as common noise are rather better threated offline than on-line. Masking noisy or dead channels can be done either way, on-line or offline. Gain recalibration can be easily monitored in an offline system and the channel-by-channel effects be taken into account.

Nowadays sumbicron chip technology provides at affordable prices a radiation hard technology. Although in this system the readout chips can be located further away from the beams thus keeping radiation damage as low as possible.

In what concerns the data transmission, optical link provides nowadays a realible means of data transmission, at a low cost and with very small impact in the material budget.

1.3 Radiation hardness

Silicon sensors operating in a high radiation environment suffer from radiation damage. The basic effects of the radiation is a change in the effective doping concentration, which in its turn affects the bias voltage, an increase in the leakage current and therefore the noise, the power consumption and the heat dissipation, and the introduction of charge trapping centers, thus reducing the signal.

The above are the macroscopic manifestations of the microscopic effects of the radiation damage. The radiation damage appears when an incident particle transfers to a silicon atom enough energy in order to vacate its position in the silicon lattice. The binding energy of a silicon atom is 25 eV. So for a fixed energy, heavier particles as protons and neutrons create more radiation damage than light particle as electrons. The studies of the radiation damage are based in the NIEL hypothesis (Non Ionizing Energy Loss). That means that the damage to the silicon lattice is due to the non ionizing energy lost by incident particles that does not induces signal but moves silicon atoms form its lattice location.

As mentioned above when a silicon atom is removed from its position in the silicon lattice it leaves a vacant position behind. As that vacant can be filled by a neighbouring atom just by thermal excitation, the vacant moves and therefore the defects in the lattice are mobile. As defects move around, they can meet and generate more complex defects. The vacants can react with interstitials, impurity atoms and other vacants. A particularly harmful state is a divacant, formed when two vacants meet. The divacant or V_2 state is quite stable. As V_2 act as acceptor states, the Fermi level is the moved toward the lower side of the band gap modifying the effective doping concentration and therefore affecting the bias voltage needed to operate the detector. It is also possible to invert the bulk type, from an initial majority of donors (n-type) to a majority of acceptor states (p-type).

Not only V_2 states are formed. The phenomenology of defects is quite complex. There is also the possibility of the vacants to react with impurities and create more complex structures, as for instance oxygen atoms and create VO or V_2O. It appears also regions where the lattice structure is severely damaged.. All these defects may act as effective doping centers, either trapping centers.

The radiation damage has been a matter of concern for the silicon tracking detectors of the LHC experiments (namely ATLAS, CMS, LHCb and ALICE). Therefore during the past recent years there has been a large development in this area. It has been seen that the diffusion of oxygen in the silicon bulk improves the radiation tolerance, and that other silicon materials, like Czoralski silicon are also more radiation hard. The LHC experiments have studied mainly the effect of the proton and neutron irradiation, inside what was called the ROSE collaboration, an specific R&D CERN project, which nowadays has its continuation in RD50.

Studies of the radiation damage due to electrons have been carried out inside RD50. The irradiation have been performed using low (15 MeV) and high energy (900 MeV, from the LINAC injector at Elettrra in Trieste) electrons. Those studies performed with radiation doses up to

10^{15} e/cm^2 show that the charge collection efficiency is reduced just by a 1-2% for Czoralski and epitaxial silicon and somewhat higher for FZ (Float Zone) and DOFZ (Diffusion of Oxygen in Float Zone).

The annealing of the irradiated samples, either at room or at high temperature shows a slight improvement of the macroscopic properties of the irradiated samples. This is seen in a reduction of the effective doping concentration, thus the depletion voltage, a decrease of the leakage current and a slight increase of the charge collection efficiency.

It remains to be studied the defects in the surface of the silicon detectors. Although what it has been seen they are less important than the bulk defects. However the presence of a charge accumulation layer in the interface between silicon and the passivated layer has to be taken in to account in the design.

A last word must be said on what sort of bulk (n-type or p-type) may be used. It is known that the n-type-bulk detectors are more radiation tolerant. This is due to the fact that in n-on-n silicon the signal is carried by electrons, which have a larger mobility rather than the holes (the signal producers in the p-on-n type sensors). On the other hand, single sided n-on-n detectors need a double side processing in order to prevent short circuits in the back side when the bulk type inversion occurs, therefore they are more expensive than p-on-n detectors. The ATLAS studies have shown that irradiated p-on-n type detectors can be used in the real experiment. Moreover the CNM (Centro Nacional de Microelectronica) in Barcelona has recently produced silicon sensors form a p-type bulk. This presents some operational advantages as the bulk type will not invert during irradiation. Irradiation studies with this sort of sensors are currently being performed.

It must be also said, that if the radiation damage is to large one can consider to replace the tracking system. This is the solution adopted by the LHCb experiment for its VELO (VErtex LOcator) system. During the detector phase design of the LHCb VELO, it has been always assumed that the radiation damage will be so important that the system will last just a couple of years. The VELO system will be located just a couple of centimeters away from the LHC beam axis, therefore the expected dose is to reach 10^{16} protons/cm^2 in a couple of years. The VELO system has the readout chips located in the outermost part of the sensors, just where the radiation dose will be smaller.