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3D Detectors on Hydrogenated Amorphous Silicon for particle tracking in high radiation environment

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Abstract

© Published under licence by IOP Publishing Ltd. The vertex detectors for the future hadronic colliders will operate under proton fluencies above 1016 p/cm2. Crystalline Silicon detector technology, up to now, has kept the pace of the increasing fluencies in the LHC era and it is still the prevalent vertex detector material for the present and for the immediate future. Looking ahead in time, an alternative solution for such a detector has to be found because for the future there is no guarantee that Crystalline Silicon will hold this challenge. For this reason the development of hydrogenated amorphous silicon vertex detectors based on 3D-technology have been proposed and the technological solutions in order to build these detectors are described in this paper.

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3D Detectors on Hydrogenated Amorphous Silicon for particle tracking in high radiation environment

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Abstract. The vertex detectors for the future hadronic colliders will operate under proton fluencies above 10^{16} p/cm^2. Crystalline Silicon detector technology, up to now, has kept the pace of the increasing fluencies in the LHC era and it is still the prevalent vertex detector material for the present and for the immediate future. Looking ahead in time, an alternative solution for such a detector has to be found because for the future there is no guarantee that Crystalline Silicon will hold this challenge. For this reason the development of hydrogenated amorphous silicon vertex detectors based on 3D-technology have been proposed and the technological solutions in order to build these detectors are described in this paper.

1. Usage of Hydrogenated Amorphous Silicon in particle detectors

The first study on Hydrogenated Amorphous Silicon (a-Si:H) was reported by Chittik et al. in 1969 [1]. The material was obtained from growth by plasma-enhanced vapor deposition (PECVD) of SiH_4 (Silane). The resulting material had much lower defect density compared to evaporated or sputtered amorphous silicon. Substantial progress of the a-Si:H technology were performed when Spear and Lecomber demonstrated that this material could be substitutionally doped (both in n and p-types) [2]; this led to the development of various types of devices such as transistors [3], solar cells [4] and memories [5].

A-Si:H based particle detectors have been built since mid '80s [6,7] as p-i-n or Schottky diode structures; the thickness of this detectors ranged from 1 to 50 µm, however signal-to-noise ratio, were never fully satisfactory (values of s/n ratio range from 2 to 3) [8,9]. The problems with signal-to-noise ratio are determined by these 3 factors:

1. **High depletion voltage.** A rule of thumb for depletion voltage on a p-i-n diode (unirradiated) is $V_d \approx 0.45\ d^2$ (µm), therefore in order to deplete a 50 µm thick planar detector a 1100 V bias voltage is necessary
2. **Large leakage currents.** The leakage currents of these detectors, when depleted, are in the order of 10^{-7}-10^{-6} A/cm^2.
3. **Relatively low charge collection efficiency.** For detectors of thickness below 50 µm the collection efficiency is around 50% while the energy necessary to create an electron-hole pair is similar to that of crystalline silicon (3.4-4.4 eV).

Another possible drawback of these detectors when used in high rate signal environment is the low mobility of charge carriers (in the order of 1-5 cm^2 V^{-1}s^{-1} for electrons and 0.01 cm^2 V^{-1}s^{-1} for holes). This aspect may limit the capability to operate as vertex detector in high energy physics collider experiments.

Despite these difficulties the intrinsic radiation hardness is definitely remarkable; detectors made of this material can reach the level of 7 x 10^{15} p/cm^2 with only a factor 2 increase in leakage current and this without any special design effort and after 24 hours of annealing at 100 °C resume the original leakage current level [10]. An additional appealing feature of this material is the possibility of deposition, using PECVD, on many materials, in particular on the top of any pixel read-out chip, avoiding expensive bonding techniques (i.e. bump bonding) for pixel detector applications [11].

Planar a-Si:H detectors have been used also to detect different kind of radiation other than MIPs, namely: x-rays, neutron and ions as well as low energy protons and alphas. Concerning x-rays, as an example, reference [12] describes the detection of 20 keV x-ray using a bare planar p-i-n diode. For x-rays energies of 100 keV a detector based on a deposited CsI layer acting as scintillator has been developed and the resulting light signal is detected by the a-Si:H p-i-n diode with an efficiency better than 70%. In the same article also the detection of low energy protons and alpha is described.

Detection of neutrons requires a conversion layer. Various detector designs have been proposed with, for example, a combination a-Si:H diodes with Gd [13] or with ^{10}B layers [14]. One could also incorporate a ^{10}B–rich semiconductor directly into an a-Si:H-based device. Heavy ion detection (Sulphur) test results are shown in ref. [15].

The best results for MIP detection with a-Si:H sensors have been obtained with a deposition of the p-i-n diode structure on a readout chip [11]. This approach developed by the Siegen University has been called TFA (Thin Film on ASIC). These detectors may find an important application as vertex detector in future collider experiments and in medical x-ray imaging. The performance of this detector deposited on top on an AFP (active feedback preamplifier) has been tested using various sources like: proton, electron and muon beams.

In order to overcome the above mentioned problems we propose to use a 3D detector geometry that allows to keep a small collection distance (the inter-electrode distance that may be kept around 20-30 µm) while having a larger detector space for charge generation since it is possible to grow an a-Si:H layer up to about 100 µm in thickness. The depletion voltage in this case can be kept as low as about 200 V-400 V reducing the leakage current. The radial structure of the electric field may also bring some benefits on the charge collection time. This novel approach, never attempted before, may improve the possibility of using the low-cost and intrinsically radiation hard a-Si:H technology for MIP detection.

2. The fabrication of a 3D Hydrogenated amorphous Silicon detector

As shown in the previous section, 3D detector geometry may be beneficial for MIP detectors based on a-Si:H. However, 3D detector geometry was originally developed for crystalline Silicon (c-Si) that can withstand, during detector manufacturing, temperatures above 1000 °C while a-Si:H starts to lose its hydrogen content (which passivate its defects) when it is warmed up above 300°C. For this reason a careful selection of construction processes should be made.

The starting process of the detector fabrication is PECVD of Silane at 200°C as mentioned in the previous section. As substrate, a low resistivity p-type 6 inches c-Si wafer is chosen. An active layer of at least 100 µm of a-Si:H is deposited but some effort will be made to have a larger thickness since thickness is a key factor to increase signal-to-noise ratio.

Once the thick a-Si:H layer is grown, holes should be made in the a-Si:H layer in order to prepare electrode manufacturing. The technique that will be used for this purpose is DRIE (Deep reactive ion etching). DRIE can fabricate holes with few micron diameter with submicron precision maintaining a process temperature below 250 °C.

Once the holes are drilled, in order to build the basic p-i-n electrode structure of the detector, there is the necessity to dope the a-Si:H material at the surfaces of the holes. Since commonly used techniques for planar structures (i.e. PECVD deposition of doped a-Si:H) are not applicable for this geometry (deep and narrow holes), two options will be considered:

- Option 1- Atomic layer deposition (ALD) of metallic oxides to create selective contacts: Titanium oxide could be used for electron selective contact and Tungsten or Molibdenum oxide for hole selective contacts.
- Option 2- Ion implantation of Phosphor for n-type doping and Boron for p-type doping and subsequent activation (if required) at low temperature (e.g. ≤250°C)

Option 1 has been used in solar panel construction [16] but never demonstrated for detectors. Important device characteristics for the particular application such as the carrier collection efficiency and the leakage current as a function of applied electric field have never been studied. Option 2 has been demonstrated for the fabrication of state-of-the-art doped layers used in detectors in ref. [17]. Since these processes are not very common, a prototyping phase, where these two techniques will be used in the construction of planar p-i-n diodes, is foreseen. Concerning the other technological steps, Chromium will be used as conducting metal for contacts since it can be deposited at low temperature and also because it does not diffuse into a-Si:H; such a material has already been used in detector fabrication. In order to improve soldering capability Aluminium will be deposited over Chromium by sputtering or thermal evaporation. Silicon Nitride will be deposited for passivation using PECVD at low temperature (e.g. ≤250°C). Fig. 1 and 2 shows two possible configurations for the construction of the detectors. P-type electrodes will be connected together to the bias voltage while n-type electrodes will be individually (or in small groups) connected to the readout electronics. In Fig. 1 the p-type electrodes are connected to a metallic grid-shaped contact under the passivation layer while n-type electrodes are connected to pads. In Fig. 2 the p-type electrode are connected to the common silicon p-type substrate (low resistivity) on the opposite side where the passivation is deposited while n-type electrodes have the same connection as in Fig. 1

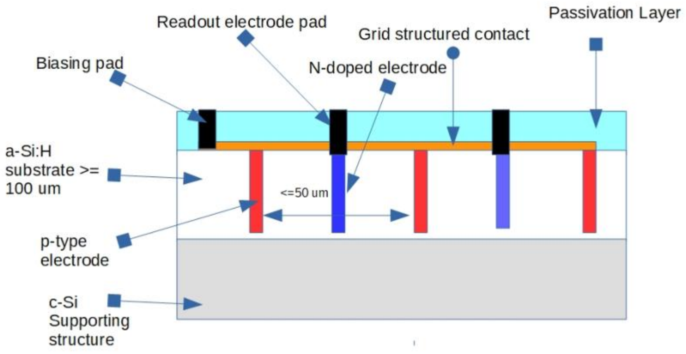

Fig. 1 Detector configuration with grid structured contact under the passivation layer in order to connect P-type electrodes.

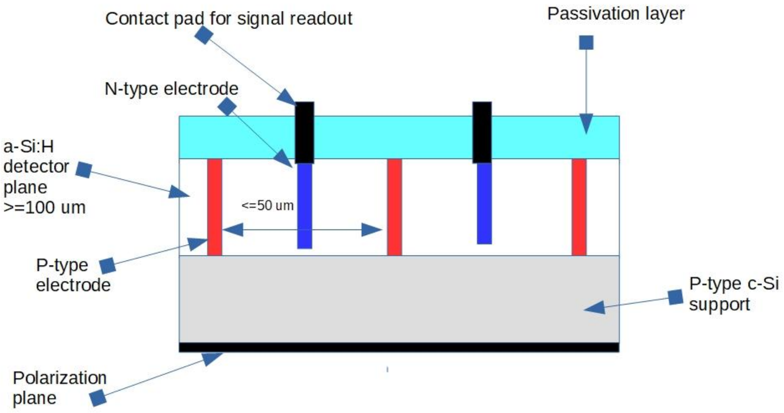

Fig. 2 Detector configuration with c-Si support used as a contact for p-type electrodes.

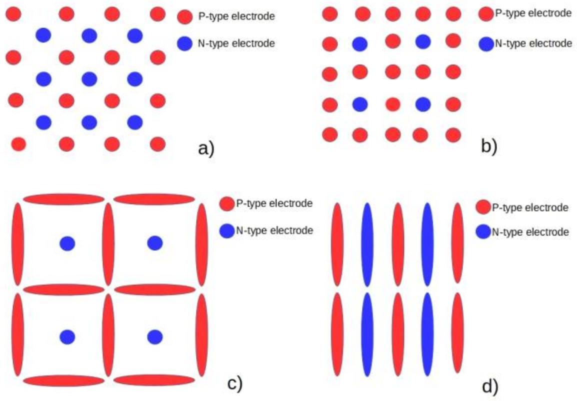

Fig.3 Four possible electrode configurations: a) baseline structure with n-type electrode (signal collecting electrode) surrounded by 4 p-type electrodes b) n-type electrode surrounded by 8 p-type electrodes. c) n-type electrodes surrounded by p-type trenches. d) p-type and n-type trenches

Fig. 3 show possible arrangements and shapes for the electrode structures: Fig. 3a shows a configuration where the signal collecting electrode (n-type, finger shaped) is surrounded by 4 p-type finger shaped electrodes placed on the vertexes of a square, while Fig. 3b shows the configuration where the signal collecting electrode (n-type, finger shaped) is surrounded by 8 p-type finger shaped electrodes. Fig. 3c shows the configuration where the n-type electrode is surrounded by 4 p-type trenches forming a square and Fig. 3d has p-type and n-type trenches.

For the prototyping phase the two different detector fabrication options, as described above, will be explored in terms of processing and testing. In parallel, an appropriate simulation of the detector layout will allow to obtain a well defined detector design in terms of electrode layout and grouping. The prototyping phase will be structured as follows:

1. Construction and validation test for p-i-n diodes and planar test structures in order to test option 1 (diodes with selective electrodes built using ALD technique) and option 2 (diodes with electrodes built using ion implantation).
2. Construction and validation test for 3D structures in order to test option 1 and option 2
3. Construction and validation of complete 3D detectors built with the techniques above described both in option 1 and 2.

During this manufacturing process an appropriate simulation study will be performed using SYNOPSYS TCAD; however since a-Si:H is not in the material library of this program a appropriated model has been developed and the results of this development are shown in ref. [18].

3. Test plans and applications

Prototypes and final detector structures, once built, need to be tested. A certain number of parameters will be determined via electrical parameter measurement on diodes and test structures. These measurements includes I/V curves at various temperatures in the range -30÷25°C to evaluate the leakage current and C-V curves for depletion voltage determination. Van der Pauw, cross-bridge and TLM test structures will be used to measure sheet resistance, carrier concentration, Hall coefficient and contact resistance.

These I-V and C-V measurements should be performed also after and possibly during irradiation tests in order to evaluate the radiation resistance of the diodes and detector prototypes; irradiation test should be performed with protons and/or neutrons with reference doses up to 10^{15}-10^{16} (1 MeV) n_{eq}/cm^2 . Concerning total dose, the reference doses with gamma or X-rays should be in the order of 100 Mrad- 1 Grad.

Charge collection efficiency and energy spectra measurements should be also performed using laser pulses, X rays, beta rays from Strontium and other sources. Electron, protons and ion tests using accelerators should also be performed in order to evaluate the particle detection capabilities, and also the capability of these detectors to be used for beam dosimetry for radiotherapy particle beams. X and gamma ray beams tests will be performed in order to evaluate the usage of 3D detectors and p-i-n diodes in dosimetry and x-ray imaging.

Another important measurement will be the charge collection efficiency map measurement using the IBIC microbeam (protons and light ions) available at the Wollongong University (AUS).

Concerning the applications of these detector technology, the most obvious is the use as vertex detector in the future LHC experiments and above, where such detectors may benefit of the high radiation resistance necessary for the application. Since we would like also to evaluate the radiation damage due to total ionizing dose, also irradiation with gamma rays will be performed and this test can be used to make assessment on the capability to operate in highly intensive electron beams and/or electron colliders. As a byproduct of this assessment, also the capability to be used as a beam flux measuring device will be evaluated. Other application of these detectors can be in the field of X-ray imaging for medical or structural analysis purposes.

4. Conclusions and outlook.

We have a 3 years program funded by INFN to build and test 3D a-Si:H detectors. At the end of this program we should have built and evaluated the response of a detector to MIPs ions and x-ray before and after relevant irradiation tests. We do not expect to have an optimized position detector at the end of this 3-years program because, in order to have that, we would need to make a successful integration with readout electronics for pixel detectors. In order to accomplish these goals we should build a detector suitable for bump bonding, as a first step, and evaluate its space resolution and other relevant parameters which are important for a pixel detector. As a second step, deposition of a-Si:H should be attempted directly on chip and a planar detector should be manufactured on this a-Si:H layer. As a third final step the fabrication of a 3D detector will be attempted on a a-Si:H layer deposited on a pixel readout chip in order to build a compact monolithic device with all the related advantages.

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