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Thin-film silicon detectors for particle detection

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Integrated particle sensors have been developed using thin-film on ASIC technology. For this purpose, hydrogenated amorphous silicon diodes, in various configurations, have been optimized for particle detection. These devices were first deposited on glass substrates to optimize the material properties and the dark current of very thick diodes (with thickness up to 50 μm). Corresponding diodes were later directly deposited on CMOS readout chips. These integrated particle sensors have been characterized using light pulse illumination and beta particle irradiation from ^{63}Ni and ^{90}Sr sources. Direct detection of single low- and high-energy beta particles have been demonstrated. The application of this new integrated particle sensor concept for medical imaging is also discussed.

1 Introduction

Hydrogenated amorphous silicon (a-Si:H) is widely used in various types of large-area electronic devices such as solar cells, flat panel displays, and position detectors, due to the fact that it can be deposited on areas up to 1 m^2 in a cost-effective way. This large-area deposition at low temperatures (around 200 °C) has also generated considerable interest in the use of a-Si:H for large-size X-ray imagers for medical applications [1], using thereby a scintillating layer for the conversion of the X-ray photons into visible light. In the field of high-energy physics, several research groups have demonstrated that a-Si:H can be used for particle detection [2–4]. Moreover, the high radiation hardness of a-Si:H [5–7] is, in this context, an attractive additional feature. However, although the detection of charge particles has been established [3, 8], single particle detection at the minimum ionizing energy (MIP) has not yet been demonstrated. One of the reasons for this lack of success is related to the fact that a MIP generates less than 100 electron-hole pairs per micron of active material thickness. Therefore, very thick diodes are needed to generate, within the semiconductor layer, enough charged carriers while maintaining a fully depleted state condition, in order to allow for their collection. The deposition of such diodes (with thickness of up to 50 μm) remains a technological challenge.

Active pixel sensors (APS) in CMOS technology are widely used for many imaging applications. However, the fact that the pixel readout-electronics shares the die area with the photodiode array limits the imager light sensitivity. A vertical integration of the light sensor, by depositing the photo diode directly over the readout-electronics, may greatly improve the sensitivity [9]. This so-called thin-film on ASIC (TFA) technology – also called thin-film on CMOS (TFC) technology – has an interesting potential for high sensitivity, low level and/or high dynamic imaging [10, 11]; this technology also allows for a geometrical fill-factor (ratio between the active area and the total sensor area) close to 100%.

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It is hence quite attractive to fabricate sensors in TFA technology for particle detection using very thick a-Si:H diodes deposited directly on the CMOS readout electronics. This new concept (a schematic view of such a TFA particle sensor is shown in Fig. 1) offers enhanced sensitivity with low noise, together with the advantages of the radiation hardness of a-Si:H. Compared to the monolithic active pixel sensor approach [12], the TFA approach has the advantage of a detecting layer that can be optimized independently and can be biased at high voltage; it also allows for a minimum dead area between the individual pixels. In contrast to hybrid detector schemes, the TFA technology greatly simplifies the detector construction, and has a large potential for system cost reduction. However, in order to achieve the fabrication of TFA sensors for particle detection, it is necessary to master the deposition of very thick (between 15 and 50 µm) a-Si:H diodes on CMOS chips with sufficiently low defect density and low dark current (at high bias voltages).

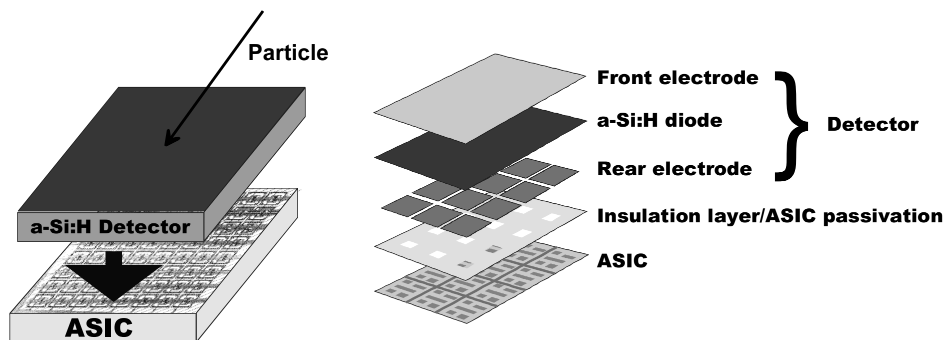

Fig. 1 Schematic view of a particle detector in TFA technology. The interaction of the particle with the intrinsic layer of the a-Si:H diode generates charges that are collected and carried out to the underlying detection circuit (ASIC).

2 Thick a-Si:H diodes

2.1 Experimental details

Thick a-Si:H diodes (with thickness of up to 50 µm) were first optimized on glass substrates in the n–i–p configuration (the n-layer being the first layer to be deposited on the substrate). All devices have been deposited by VHF PE-CVD (very high frequency plasma enhanced chemical vapor deposition) at 70 Mhz and 200 °C with a hydrogen dilution of silane of $R = [H_2]/[SiH_4] = 0.35$; a deposition rate of 15.6 Å/s was here obtained. The deposition conditions were optimized in order to obtain the highest deposition rate while keeping device-quality material properties and the powder formation at an acceptable level. It may be noted that VHF PE-CVD is a very appropriate method for the deposition of thick a-Si:H layers. Compared to standard PE-CVD technique at 13.56 MHz, it allows the deposition of layers at much higher rates with reduced powder formation [13]. The use of an excitation frequency of 70 MHz is also very favorable for internal stress reduction and avoids any problem of peeling off of the layers. Thus, a-Si:H layers with thickness up to 100 µm have been successfully deposited on glass substrates [14]. Note that He dilution of silane has also been proposed for high-rate deposition of thick a-Si:H diodes [8, 15]. This second method has been proven to be quite effective in increasing the deposition rate and reducing the stress; however, its effect on powder formation is less clear.

In order to reduce as much as possible the cross-talk between the pixels, a relatively low conductive n-doped layer was developed. However, this layer was not found to play a major role in device performance; the dark current value was found to be rather insensitive to the optimization state of the n-layer.

Test structures were evaporated on Cr or Al coated glass and the pixel area was defined by a patterned ZnO or ITO top electrode. The patterning was done by a rubber stamping process followed by a wet etch of the transparent conductive oxide. A subsequent partial dry etch of the a-Si:H layer was also carried out to better defined the pixel area. In order to study test devices with a structure similar to the one of

TFA chips, test structures with small size pixels (50 to 200 µm) and a common top electrode were also fabricated by photolithography on glass substrates.

2.2 Depletion conditions

Collection in a thick a-Si:H diode is controlled by the thickness of the depletion region. Ideally, at high bias voltages, the latter should extend from the p-layer down to the n-layer (which will be, in TFA sensors, connected to the CMOS readout electronics). Using a simplified model, the relation between the bias voltage V and the width of the depletion region W_D is given by the Poisson equation

$$\frac{d^2V}{dx^2} = -\frac{qN^*_{DB}}{\varepsilon_0 \varepsilon_{Si}}, \qquad (1)$$

where ε_0 is the dielectric constant in vacuum, ε_{Si} is the relative dielectric constant in silicon, q is the electron charge and N^*_{DB} is the density of ionizable dangling bonds; the latter is assumed to be uniform within the depletion region. In this simple model, the necessary voltage V_D required to deplete a diode of thickness L is then ($W_D = L$)

$$V_D = \frac{qN^*_{DB}L^2}{2\varepsilon_0 \varepsilon_{Si}}. \qquad (2)$$

If we assume a dangling bond density N_{DB} of 2 x 10^{15} cm^{-3} for state-of-the-art a-Si:H material, and that roughly $N^*_{DB} = 0.3N_{DB}$ (only 30% of the dangling bonds are ionized) [16], a field of at least $(0.5 \cdot L)$ V/µm is needed to fully deplete an n–i–p diode. Thus, a voltage $V_D > 1300$ V will be required for a 50 µm thick a-Si:H diode. Even though, this field is far from the value where breakdown can occur, dark current has to be kept small in order to allow the detection of the few thousands of electrons generated by a MIP.

2.3 Diode dark current

Dark current values I_{dark} as low as 10^{-12} A/cm^2 have already been achieved (at an electric field of 10^4 V/cm) with a-Si:H material deposited at low rates (around 3 Å/s) by VHF PE-CVD for thin (1 µm) diodes (cf. Fig. 2 and Ref. 17). When depositing diodes at more than 15 Å/s, as in the present work, a raise of I_{dark} is observed which can be attributed to an increase in the material defect density. Another increase of I_{dark} occurs as the thickness of the i-layer is enlarged. In Fig. 2, two different regimes may be distinguished: At low electric field, I_{dark} increases almost linearly with the diode thickness since it is mainly controlled by the thermal emission of charge carriers in the volume of the i-layer. However, at higher field, thermal emission is no more the controlling factor of the dark current. This is due to a current injection into the i-layer, which is caused by the very strong field concentration at the p-i interface. In order to avoid this effect at high electrical field and achieve full depletion, the following schemes have been proposed and tested by various research groups: a thick p-layer [18, 19], a buried p-layer [18], a central p-layer [18], a-SiC:H p-layers or buffer layers [20] or He dilution deposition method [8, 15, 21].

During the present optimization of thick diodes, an increase of the p-layer thickness as well as the introduction of a buried p-layer were not successful in reducing further the dark current at high bias fields. However, very promising results were obtained by introducing a thin buffer layer at the p-i interface. As seen in Fig. 3, this buffer layer grown under a hydrogen to silane concentration ratio of 3 is very effective at reducing I_{dark} at the electrical field values, close to those needed to achieve full depletion (field values >1.6x10^5 V/cm for a 32 µm thick diodes).

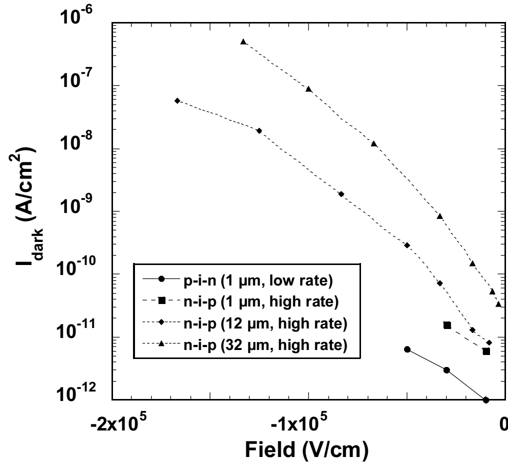

Fig. 2 Dark current I_{dark} as a function of reverse bias field and thickness for materials deposited at low and high rates for diodes without a buffer layer at the p–i interface.

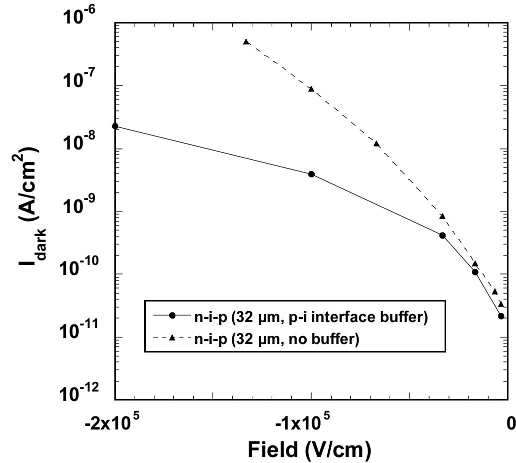

Fig. 3 Dark current I_{dark} as a function of reverse bias field for two 32 µm thick diodes with and without a buffer layer at the p–i interface.

3 Vertical integration of particle sensors on chips

Various a-Si:H diodes with thickness ranging from 12 to 32 µm were deposited on two types of CMOS readout chips designed by CERN and fabricated in IBM 0.25 µm technology. After the deposition of the thick a-Si:H diode, a top ITO or ZnO layer was deposited and patterned. The top electrode was then used as a mask for the dry etching of the a-Si:H layer in order to release the chip bonding pads.

The first chip ("AFP chip") to be tested was a linear array of 32 pixels with a size of 94 µm x 68 µm and a spacing of 26 µm connected to an active feedback preamplifier (AFP). The latter has a very fast peaking time of 5 ns and an rms noise of less than 300 electrons for a small pixel capacitance (≈1 pF). A picture of the processed chip with a 32 µm thick a-Si:H diode is shown in Fig. 4.

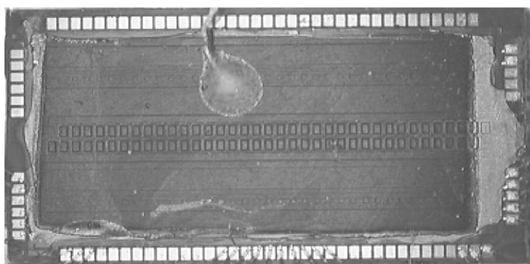

Fig. 4 Processed "AFP chip" with a linear array of 32 pixels (only one row of the central pixels is used) consisting of a 32 µm thick a-Si:H diode connected to an AFP preamplifier. The top ITO electrode is connected with a wire glued with Ag.

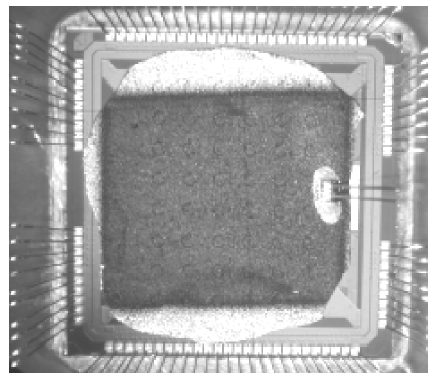

Fig. 5 Processed "macropad chip" with an array of 8x6 pixels consisting of a 32 µm thick a-Si:H diode connected to an AFP preamplifier and shaper.

Another chip ("macropad chip") was tested with an array of 8x6 octagonal pixels with a size of 150 μm and a pitch of 380 μm connected to a charge amplifier (with an active feedback) and a shaper. The circuit was optimized to detect 600 electrons with a much lower (compared to the AFP chip) rms noise of 30 electrons for a pixel capacitance below 0.5 pF and a pixel leakage current up to 10 pA. A picture of a processed chip with a 32 μm thick a-Si:H diode is shown in Fig. 5.

4 Particle sensor performances

4.1 Pulsed light detection

The fabricated particle detectors were first tested under pulsed laser illumination (at 660 nm). Fig. 6 shows the signal output of one channel of an "AFP chip" with a 12 μm thick a-Si:H diode (named below as a 12 μm TFA AFP chip) after the generation of ≈1.5 fC by a light pulse; the noise is roughly 250 electrons rms. Looking at the current transients following much higher light intensity pulses (cf. Fig. 7), one can recognize the short time electron contribution, followed by the longer time hole contribution. From the analysis of the current transient of Fig. 7, we can conclude that, even at 90 V, the full depletion of the a-Si:H device is not attained because the width of the pulse do not decrease (at it should) with increasing bias voltages. As the bias voltage is raised, the width of the depletion region as well as its electrical field increases, which results in an almost constant electron collection time (given by the width of the peaks in Fig, 7). Similar results were obtained with another 32 μm TFA AFP chips.

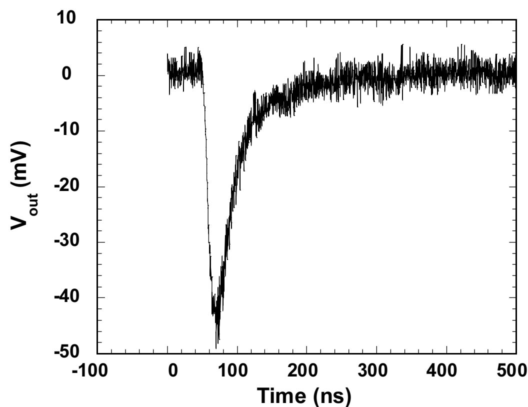

Fig. 6 Signal measured at the pixel output of a 12 μm TFA "AFP chip" following a 2 ns light pulse (at a wavelength of 660 nm). The generated charges induced by the light pulse were here ≈1.5 fC and the bias voltage on the a-Si:H diode –70 V.

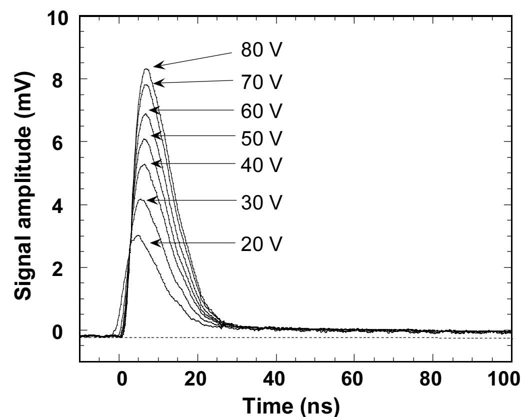

Fig. 7 Current transient for a 2 ns light pulse, as measured for different reverse bias voltage of the TFA photodiode (same as in Fig. 6), and after correction for the active feedback amplifier response. The peaks correspond to the electron drift in the depletion region of the diode, while the slow decaying tails at long time are attributed to hole collection towards the top electrode.

On all devices fabricated (so far without a buffer layer at the a-Si:H diode p-i interface), full depletion was not attained, because current leakage strongly limited the bias voltage to much lower voltages than those required for this condition (see also Section 2.2). Even though the measurement of the current leakage in individual pixel was not possible, the value of the total current flowing through all pixels seemed to indicate that the actual I_{dark} values were much higher that the values observed in test structures deposited on glass. This effect is attributed here to a leakage at the pixel periphery due the electric field concentration caused by the sharp edge of the thick chip passivation [17] (see the schematic view of

Fig. 7. Chips used in this study incorporate several passivation layers with a total thickness of roughly 7 µm. A partial removal of the passivation has not yet led to an improvement of I_{dark}.

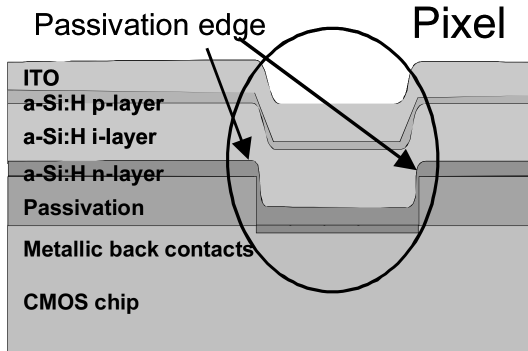

Fig. 8 Schematic view of one pixel of a TFA sensor. The sharp edge of the passivation layer defining the pixel periphery is the cause of large current leakage.

4.2 Particle detection

Figure 9 shows the signal recorded at the pixel output of a 12 µm TFA chip following the absorption of three single β particles from a ^{63}Ni (low energy β) source was also carried out. As demonstrated by Fig. 5, single low energy β can be clearly detected down to a particle energy of 15.6 keV. A clear relationship between the height of the peak and the particle energy is also observed. Here, the fast signal response (with a ≈10 ns peaking time) is due only from electron collection while the slow hole contribution (as seen in Fig. 7) is hidden in the noise. The maximum signal amplitude observed for electrons absorbed in the TFA film corresponds to a β energy of ≈50 keV, which is about the maximum of the β spectrum from ^{63}Ni (minus the energy loss in the air). Similar results were obtained with a 32 µm TFA "AFP chip". The corresponding distribution of amplitudes is plotted in Fig. 10a; the energy loss roughly follows the expected Landau distribution.

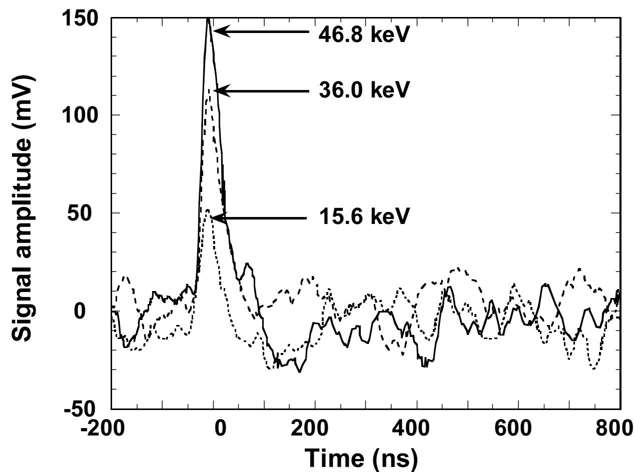

Fig. 9 Signal measured at the pixel output of an "AFP chip" with a 12 µm a-Si:H diode following the absorption of beta particles from the isotope ^{63}Ni. The peak height here depends on the beta particle energy.

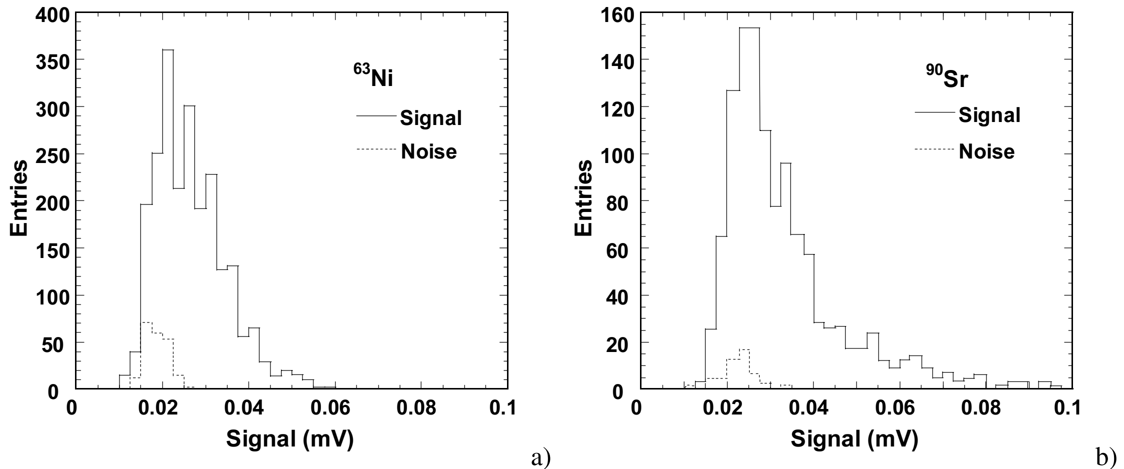

Fig. 10 Distribution of amplitudes (solid line) obtained from a ^{63}Ni (a) and from a ^{90}Sr (b) source with a 32 µm TFA "AFP chip". The small peaks (dashed line) indicate the measured noise.

The distribution of amplitudes obtained from a ^{90}Sr (high energy) β source with a 32 µm TFA "AFP chip" is shown in Fig. 10b. The probable energy deposition per β (MIP) particle is estimated to 8 keV in the case of the 32 µm thick a-Si:H intrinsic layer; this energy corresponds to ≈1200 electrons, a value which is about 4 times the noise level. Note here that only electrons generated in the bulk of the a-Si:H diode intrinsic layer are considered. The holes collected at much longer times do not contribute to the signal and are hidden in the noise. The latter is mainly due to the fact that the "AFP chip" was not optimized for the low capacitance of the a-Si:H pixel detector. The signal-to-noise ratio (SNR) is here too low to confirm the detection of single MIPs.

In order to improve this relatively low SNR, TFA sensors using the very low noise (≈30 electrons) "macropad chip" have also been tested with 32 µm thick a-Si:H diodes. However, the pixel leakage current that is acceptable for this chip (around 10 pA) has so far limited the bias voltage to values around 70 V. This value is thus far too low to obtain large depletion width W_D, and thus also limits the charges to be collected. The reason why the TFA sensors were more leaky when deposited on the "macropad chip" than when deposited on the "AFP chip" is not yet fully understood. At the present stage, due to the fact than only partial depletion was so far obtained, TFA sensors on "macropad chips" were not able to demonstrate MIP detection from a ^{90}Sr source. On the other hand, measurements with a 32 µm thick TFA "macropad chip" using a ^{63}Ni source (low-energy β source) delivered results similar to those obtained with the 32 µm TFA "AFP chip".

5 Conclusions

Several particle sensors have been fabricated comprising up to 32 µm thick a-Si:H diodes deposited on low noise readout chips. Detection of β particles from ^{63}Ni and ^{90}Sr sources has been achieved with very fast (≈ a few ns) signal response. This fast signal component is here almost entirely due to electron collection; the much slower hole collection is hidden in the noise.

The partial depletion state of the thick a-Si:H diodes (in the TFA sensors) and the resulting low SNR have not yet permitted to demonstrate the detection of single MIP. However, with a better control of the chip surface morphology (in order to avoid peripheral current leakage), one should indeed be able to fabricate thick diodes with considerably lower leakage currents. This will allow for a considerable increase of the bias voltage and enable an almost complete depletion state of the diode. A much higher SNR is thereby expected, which should permit an easy detection of MIPs. With a total depletion state,

precise measurements of the energy deposited by a MIP and the energy creation of one electron-hole pair will also be possible.

The results obtained so far show that TFA technology based on thick a-Si:H diode is a promising concept for particle detection. For collider experiments in high-energy physics, it offers many attractive features compared to crystalline silicon pixel detectors.

The same technology may also apply to medical imaging. The high (geometrical) fill factor of a TFA sensor improves the sensitivity and could help reduce X-ray exposure in radiography or tomography. It is also certainly a very attractive technology for positron emission tomography (PET) because of the fast response and very limited dead area between the individual pixels.

The possibility of depositing a-Si:H diodes on large areas and the high degree of integration of TFA sensors, are additional beneficial aspects for collider experiments or PET. Large areas of detectors can be build up with potentially lower system costs.

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