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A new concept of monolithic silicon pixel detectors: hydrogenated amorphous silicon on ASIC

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Abstract

A new concept of a monolithic pixel radiation detector is presented. It is based on the deposition of a film of hydrogenated amorphous silicon (a-Si:H) on an Application Specific Integrated Circuit (ASIC). For almost 20 years, several research groups tried to demonstrate that a-Si:H material could be used to build radiation detectors for particle physics applications. A novel approach is made by the deposition of a-Si:H directly on the readout ASIC. This technique is similar to the concept of monolithic pixel detectors, but offers considerable advantages. We present first results from tests of a n–i–p a-Si:H diode array deposited on a glass substrate and on the a-Si:H above ASIC prototype detector.

Keywords: Metrology; Solid state detectors

1. Introduction

Progress has been made during the last 20 years in the use of hydrogenated amorphous silicon (a-Si:H) for various sensitive imaging devices including copying machines and flat panel displays with high resolution. Since a-Si:H films can be deposited at low cost onto very large area substrates, it has been an appealing material for photovoltaic solar energy conversion. Meanwhile, several research groups [1–3] have carried out a substantial work in trying to demonstrate that a-Si:H can be used for reliable radiation sensors in high-energy physics. An attractive feature of a-Si:H for collider experiments is its high level of radiation hardness [4,5].

However, although previous works have shown that charged particle detection is feasible [6], single particle detection at the minimum ionizing energy (MIP) turned out to be unrealistic. The problem is the technical difficulty to deposit very thick a-Si:H layers (up to 50 μm), limiting the detector charge signal for a MIP to at most 4000 electron–hole pairs. In the past, the readout of such a low signal level turned out to be the major obstacle for large

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pad detectors. Recently, a radiation sensor for charged particles based on the vertical integration design [7] has been proposed.

The vertical integration technique comprises the deposition of an amorphous Silicon (a-Si) detecting layer on a readout chip [8]. This so-called thin-film on CMOS (TFC) or thin-film on ASIC (TFA) technology has an interesting potential for high sensitivity, low level light detection [9], for both small pixel imaging devices [10] as well as for large area imaging devices for X-ray medical applications [11]. The high integration level of the detecting device and readout electronics allows for a significant reduction of system costs.

Compared to the Monolithic Active Pixel Sensors (MAPS) approach [12,13], TFA technology has the advantage to have an independent detector layer biased at a high electric field, and in contrast to the hybrid pixel detectors approach [14] it greatly simplifies the pixel detector construction.

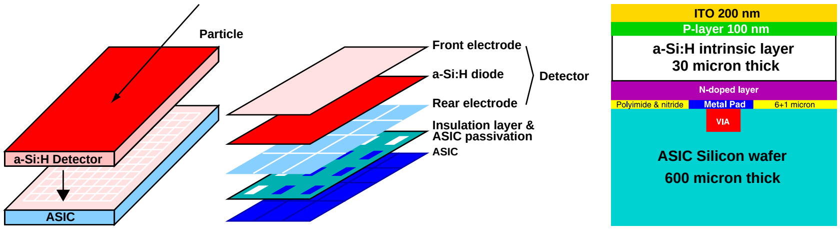
2. Thin film on ASIC technology

The TFA technology is an emerging technology that has first been used for the development of CMOS active pixel sensors (APS). a-Si:H deposition is achieved by a plasma enhanced chemical vapour deposition (PE-CVD) process. This operation is done at a relatively low temperature, 200–250°C, that is compatible with post processing on finished electronic wafers. The PE-CVD deposition of a-Si:H applied for our purpose is the same basic deposition technology used for the manufacturing of a-Si:H photovoltaic solar panels, except for an increased film thickness (up to 30 μm) and keeping a low dangling bond density N_D of the order of 10^{15} cm^{-3}.

Fig. 1(a) shows the basic concept of a vertical integration sensor on ASIC. The 30 μm thick a-Si:H film samples, as it is shown in Fig. 1(b), consist of three layers, the top p-layer that is thin, the intrinsic thick i-layer that is the detecting film and the bottom thin n-layer that is in contact with the ASIC electrodes. The junction where depletion takes place is formed from a p-layer i-layer interface and eventually extends down to the n-layer at full depletion.

All devices have been deposited by VHF PE-CVD at 70 MHz and 200°C using hydrogen dilution of silane. The devices tested were deposited at a rate of 15.6 Å/s. Test devices were evaporated on Cr- or Al-coated glass and the pixel areas were defined by a patterned indium tin oxide (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 plasma etch of the a-Si:H layer was also carried out.

Test structures for single-particle detection were developed with n–i–p photodiodes with low dark current at reverse bias voltage lower than 100 V. For this purpose, diodes (in various configurations) have first been optimized on glass substrates. A good compromise between low dark current and high deposition rate was obtained with an a-Si i-layer deposited with a hydrogen dilution of $R = [H_2]/[SiH_4] = 3.5$. In order to avoid the need for patterning the bottom-doped layer in the TFA sensors—the layer that is first deposited on the CMOS chip and that may induce cross-talk



(a) (b)

Fig. 1. (a) Sketch of the technology of vertical integration of a-Si:H films on ASIC. (b) Cross-section of the vertical integration of a n–i–p junction above a pixellized integrated circuit, pads of the pixel circuit determine the a-Si:H detector segmentation.

effects between the pixels—a low conductivity n-doped layer was developed. The same process was then transferred for the fabrication of the a-Si:H photodiodes deposited on ASIC.

3. Experimental aspects

3.1. Test structures

In order to study electrical properties and detection characteristics of thick a-Si:H sensor films, test devices with a structure similar to that of TFA chips, i.e. "chip-like" test structures with small-size pixels (50–200 μm side length) and a common top electrode were fabricated by photolithography on glass substrates. These structures were essentially manufactured to characterize a-Si:H films on glass substrate with well-controlled deposition conditions [15].

Vertical sensor integration of a-Si:H films on CMOS integrated circuit has been achieved by using an available amplifier array "Active Feedback Preamplifier" (AFP) ASIC [16]. The AFP amplifier circuit is a low-noise current amplifier with a very fast peaking time of 5 ns and a noise less than 300 electrons rms for a small pixel capacitance ~1 pF. The AFP amplifier is sufficiently low noise and fast to measure a fast electron transient time τ_D.

The size of pixel pads, used as pixel electrode connected to the a-Si:H film, is 94 μm × 68 μm with a spacing of 26 μm. As it is shown in Fig. 2(a), the pads form a linear 32-pixel array in the middle of the chip. Two TFA 30 μm thick devices have been manufactured, one with a 6 μm polyimide passivation layer on top of the ASIC, and a second with the polyimide passivation removed. We report here results on the TFA with a polyimide passivation (cross-section is shown in Fig. 2(b)).

3.2. Test set-up

The charge collection of a-Si:H films was characterized with a 660 nm laser with a pulse width of 2 ns. The optical power of the laser was adjusted to have a sufficiently low input charge, 1–2 fC, to obtain maximum collected charge efficiency and avoid any saturation effects caused by electron–hole recombination [17].

Sensitivity to charged particles has been measured with low-energy electrons from a ^{63}Ni β source where the electrons are totally absorbed in the a-Si:H 30 μm thick films, and with minimum ionizing electrons from a ^{90}Sr β source with electrons traversing the 30 μm a-Si:H film. Output signal waveforms of the AFP amplifier ASIC were recorded with a digital oscilloscope in self-trigger mode for laser tests. Measurements with electrons were done in self-trigger mode. Signals from laser were directly observed with the digital oscilloscope, signals from β sources were first sent to a timing filter amplifier (ORTEC 474) with an integration time constant of 5 ns.

3.3. a-Si:H detector characteristics

I–V characteristics and charge collection of n–i–p a-Si:H films deposited on ASIC were electrically characterized by applying a negative bias voltage up to 300 V to the ITO electrode,

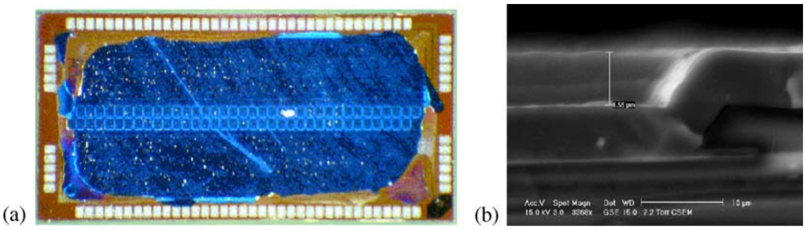


Fig. 2. (a) Microscopic view of a 30 μm n–i–p a-Si:H film deposited on the 32-channel AFP amplifier integrated circuit (2 mm × 4 mm). (b) Cross-section of a 6 μm film above the metal pad of the integrated circuit. At the edge of the pad a a-Si:H step is formed due to the 6 μm polyimide chip passivation.

which is connected to the p-layer, representing the grounding and return of the signal path through the input resistance of the DC coupled amplifier input. Individual leakage of pixels was observed by measuring the DC voltage of the AFP amplifier outputs, whereas the total current was measured in the biasing circuit. Charge collection was measured by stimulating samples with a pulsed laser. Biasing was applied continuously in the same way as crystalline silicon detectors are biased. No attempt has been made to characterize the electron mobility by a pulsed biasing as it is usually done to measure drift mobility in a-Si films [18].

The mean-free path of 660 nm light is about 1 μm in a-Si; therefore electrons have to drift down to the n-layer through the entire thickness of the 30 μm thick i-layer, and holes move up to the p-layer on a short distance as shown in Fig. 3.

When reverse bias is applied, the depletion layer grows from the p-layer and extends down towards the n-layer connected to the ASIC pads. In a simplified calculation, as usually done for c-silicon detectors, with an uniform ionized dangling bond density N_{Di}, the Poisson equation is

$$\frac{\mathrm{d}^2 V}{\mathrm{d}x^2} = -\frac{qN_{\mathrm{Di}}}{\varepsilon_0 \varepsilon_{\mathrm{Si}}}, \tag{1}$$

where V is the electric potential, ε_0 the dielectric constant in vacuum, $\varepsilon_{\mathrm{Si}}$ the relative dielectric constant in silicon and q the electron charge. With the boundary conditions $V(x=0)=0$ and $V(x=W_{\mathrm{D}})=V_{\mathrm{Bias}}$, neglecting the "built-in voltage" of about 0.5 V, the simplified expression for the depletion voltage is given by

$$V_{\mathrm{D}} = \frac{qN_{\mathrm{Di}} W_{\mathrm{D}}^2}{2\varepsilon_0 \varepsilon_{\mathrm{Si}}}. \tag{2}$$

Therefore, the electric field in the depletion layer varies linearly with the depth for not fully depleted films. One important parameter for detector operation is the value of the bias voltage for full depletion. In Eq. (2) $W_{\mathrm{D}} = d$, the thickness of the a-Si:H film, i.e. 30 μm for our sample. The estimated value of N_{D} is $2 \times 10^{15}\ \mathrm{cm}^{-2}$ with an estimated number of ionized states $N_{\mathrm{D}i}$ of 30% [19]. From these values a bias voltage for full depletion is determined to be 415 V. The measured reverse bias characteristic as shown in Fig. 3(b) indicates that above 300 V the leakage current is too large for a reliable detector operation. All measurements have been performed at a reverse bias voltage lower than 300 V because a large noise level is observed at the ASIC outputs, which could be attributed to pixel edge effects or to the p–i interface.

Measurements of the electron and hole collection time are crucial for future collider experiments since all previous measurements of thick a-Si:H films [20] have been done with slow processing time constants, usually with shaping time constants of 0.5–4 μs that do not allow for an understanding of the real collection time. If we assume that the simplified Eqs. (1) and (2) are valid, one can express the transient drift time of an electron at the position x in an electric

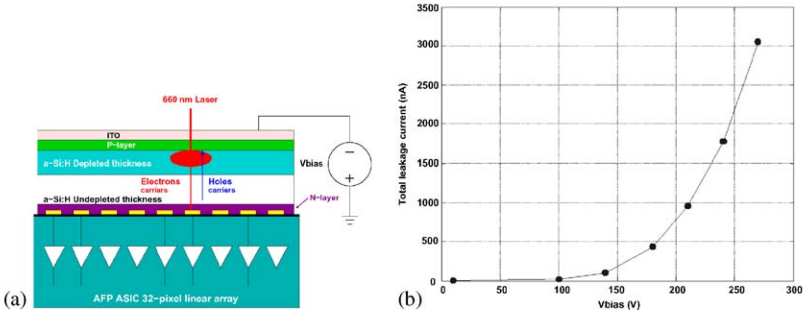


Fig. 3. (a) Schematic of the test circuit used to characterize the TFA detector sample. Depletion works like in crystalline silicon except that the undepleted layer behaves like an insulator coupling the depleted layer to the collecting ASIC electrodes. (b) I–V characteristic of the entire TFA chip. The total leakage current is in the nA range for a bias voltage lower than 100 V.

field $E(x) = 2V_B/W_D(W_D - x)/W_D$ by

$$t(x) = \int_0^x \frac{1}{\mu_e E(x)}\,\mathrm{d}x = -\tau_C \ln\left(\frac{W_D - x}{W_D}\right), \qquad (3)$$

where $\tau_C = \varepsilon_0\varepsilon_{Si}/q\mu_e N_{Di}$ is the transient or collection time constant that defines the electron motion:

$$x(t) = W_D(1 - \mathrm{e}^{-t/\tau_C}). \qquad (4)$$

For a film which is not fully depleted, the collection time constant τ_C does not depend on the electric field and for our sample it is in the range of 2–20 ns for an electron mobility μ_e in the range of 10–1 cm^2/Vs.

The characteristics of n–i–p a-Si:H films calculated with Eqs. (1)–(4) simplifying the complex electronic transport in hydrogenated amorphous silicon [21,22] are sufficiently precise for the electron non-dispersive transport for which the mean-free path is much larger than the film thickness. However, this is not true for the dispersive hole transport which is subject to trapping in deep states that turns hole mobility into a time-dependent parameter.

4. Results

All results presented are based on the measurement of one TFA sample, however, comparable results have been obtained with another 30 μm thick sample without the polyimide layer, and with a 13 μm TFA sample [7].

4.1. *Results from pulsed laser tests*

The results from the laser test are summarized, details are reported elsewhere [23]. The charge collection has been measured for bias voltages ranging from 50 to 260 V, and as shown in Fig. 4(a) signal amplitudes do not saturate, indicating that the 30 μm thick film is not fully depleted as expected from calculation. One can also note that the signal shape (Fig. 4(b)), corrected by the amplifier pulse response, has a constant peaking time, thus a constant collection time as expected for a not fully depleted film.

The electron transient time extracted from the signal deconvolution of the measured signal is about 4.5 ns. Thus the electron mobility of 5 cm^2/Vs is estimated. The signal from the holes (visible after electron transport) is slower by about two orders of magnitude, depending on the bias as shown in Fig. 4(b), but in contrast to the electron signal, the signal shape varies with the electric field.

4.2. *Measurement with ^{63}Ni and ^{90}Sr sources*

Results from the test with β sources confirm that the detector time response of the n–i–p a-Si:H films deposited on ASIC is fast. Fig. 5(a) shows three signals recorded in a single shot of the 30 μm TFA film exposed to a ^{63}Ni β source (energy max 67 keV). The signal shape induced by electron transport follows the fast processing time of the

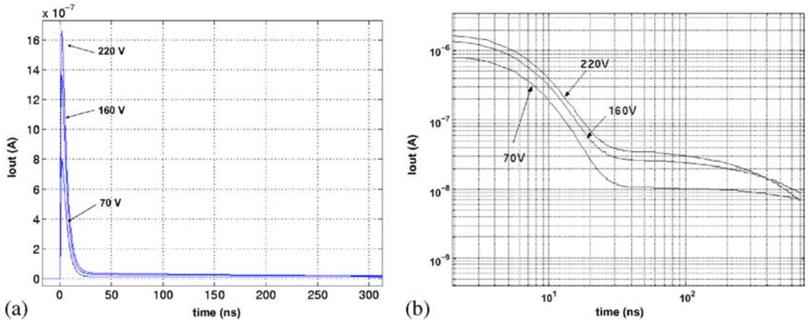


Fig. 4. (a) The signal response of one pixel of the 30 μm TFA film exposed to a pulsed laser beam for 3 bias voltages, the fast signal induced by electron transport has a constant peaking time of 6 ns. (b) The slow signal induced by hole transport extends to 1 μs and has a signal amplitude two orders of magnitude smaller than the electron signal.

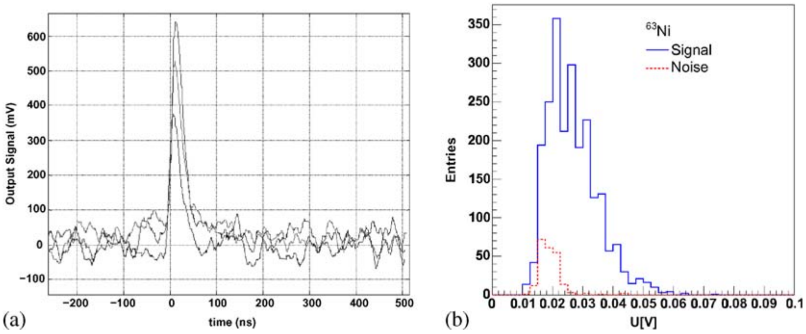


Fig. 5. (a) Signal response of one pixel of the 30 µm TFA film exposed to a ^{63}Ni β source recorded for three events. Only the signal from electron transport is visible, the signal from holes is hidden in the noise. (b) Amplitude distribution (solid line) from the measurement with the source. The noise distribution, recorded without source, is also shown (dashed line).

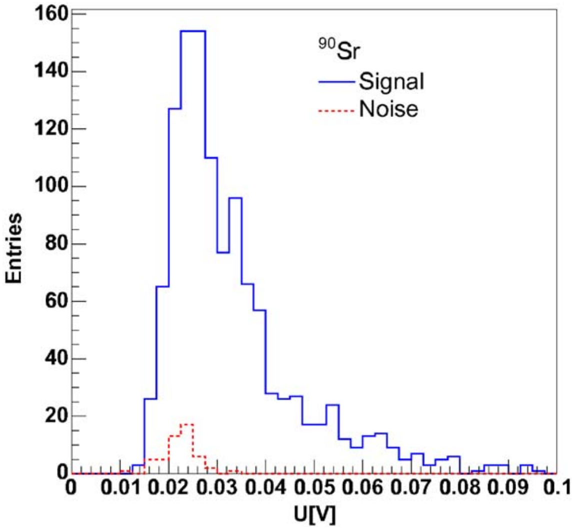


Fig. 6. Distribution of amplitudes (solid line) obtained using a ^{90}Sr β source, the small peak (dashed line) indicates the noise measured.

electronic channel (10 ns peaking time). The maximum signal amplitude observed for electrons which are completely absorbed in the 30 µm TFA film is about 50 keV, which is the maximum energy of the β spectrum minus the energy loss in the air.

The distribution of amplitudes obtained from a ^{90}Sr β source (energy max 546 keV) is shown in Fig. 6. The distribution was recorded with a digital oscilloscope in a "self-trigger" mode. The most probable energy deposition is estimated to about 8 keV for the 30 µm silicon layer, which corresponds to ~1200 electrons, about four sigma above noise (300 electrons rms), assuming that only electrons contribute to the fast signal.

5. Summary

A TFA technology has been developed for the deposition of thick film a-Si:H on ASIC. The measurement of the detector signal response shows two components; a fast signal with a few ns time constant induced by electron transport and a slow signal of a few 100 ns time constant induced by hole transport. The results demonstrate that a pixel detector based on this approach is feasible and offers attractive features compared to crystalline Silicon hybrid pixel detectors.

The measurement of the 30 µm thick a-Si:H on ASIC sample, partially depleted, demonstrates that electrons from ^{63}Ni and ^{90}Sr sources can be detected with a 5–10 ns fast signal shaping. However, MIP detection is not yet fully proven since the noise of the AFP amplifier, not optimized for the small capacitance of the pixel detector, has a signal-to-noise ratio (SNR) of four, too low to detect a charge of 1200 electrons expected from a MIP.

It is believed that with an optimized pixellized ASIC design, MIP detection with a sufficient SNR is feasible. Precise measurements of the energy deposition and energy creation of one electron–hole pair have to be done with fully depleted thick a-Si:H films.

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