Thin Photodiodes for a Scintillator-Silicon Well Detector

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Abstract

In developing position sensitive radiation sensors, e.g. for medical imaging, low-gain silicon well sensors were made for the detection of scintillation light. The 3x3 arrays include $N^{++}NP$ diodes, processed in the $\sim$12 μm thick membranes that remain after thinning of 530 μm thick (100) silicon wafers by means of a potassium hydroxide (KOH) solution. A comparison is made for the light detection efficiency of these diodes with that of a 500 μm thick PIN photodiode.

I. INTRODUCTION

Several applications of X-ray and gamma ray imaging detectors, e.g. in medical diagnostics [1, 2], require millimeter or sub-millimeter spatial resolution and good energy resolution. In order to achieve such features we propose a new type of camera, which takes advantage of micromachining technology. It consists of an array of scintillator crystals encapsulated in well-type silicon sensors (see fig. 1). The latter can be realised by means of wells etched in a silicon wafer using deep reactive ion etching. Scintillator crystal material can be deposited in the wells, e.g. by evaporation techniques or as a powder with a binder. With 500 μm thick crystals, such as CsI(Tl) or Lu_2S_3(Ce) [3], the absorption efficiency can be 90% at 55 keV and 75 keV respectively.

The light created by the interaction of an X-ray or a gamma ray with the crystal material is confined by the vertical silicon sidewalls and collected onto the photodiode at the bottom of the well. Sub-millimeter spatial resolution can be obtained in the energy range mentioned above.

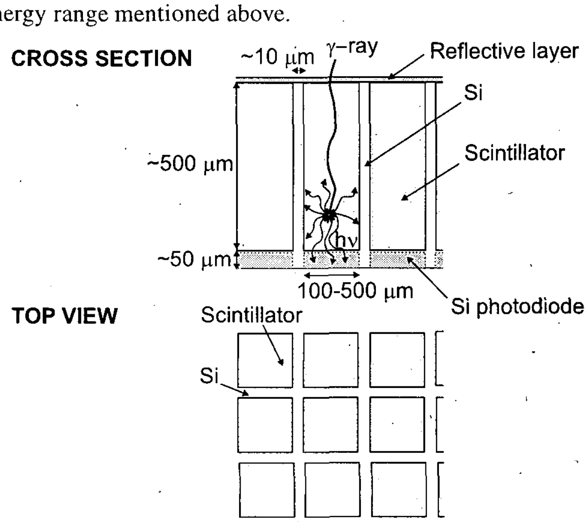

Figure 1: Schematic of the proposed well-type detector (not to scale).

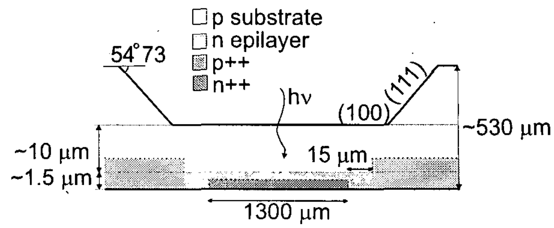

Figure 2: Schematic of the thin test photodiode (not to scale).

Several parameters for the photodiode need to be optimised: uniformity and efficiency of the light detection, gain, leakage current, detector junction capacitance and breakdown voltage. In order to evaluate these parameters we have processed 3x3 arrays of 1.8 mm^2, $\sim$12 μm thick photodiodes (see fig. 2) using (100) wafers etched in a KOH solution. Previous work on thin detectors can be found in [4, 5, 6, 7].

II. PROCESSING

We used double-sided polished (100) p-type wafers of 4 in. diameter, 530 μm thick, with a resistivity of 2-5 Ω.cm. The arrays consist of 3x3, 1.8 mm^2 photodiodes at a pitch of 2 mm. The p-n junction is made from the remaining p-substrate and a 1.5 μm thick n-epilayer (see fig. 2). The low-ohmic contacts are obtained by ion implantation. Our process can be considered as a single-sided process. On the opposite side of the wafer only a 300 nm silicon-rich nitride layer was deposited and patterned. It was used as the mask during the etching of silicon. The etching was the last step of the process. It was carried out in a 33 wt% KOH solution at a controlled temperature of 80$\pm$1 °C. The etch-rate was determined experimentally with a precision of only 2%. However, a two-step etching process with timed-etch stop allowed us to obtain $\sim$12 μm thick membranes. We measured the membrane thickness mechanically. It varies $\pm$3 μm over the wafer area. This large variation is due to measurements errors and does not reflect the wafer thickness variation nor the non-uniformity of the wet etching. A thickness of 12$\pm$3 μm is a good compromise between a relatively low bias voltage and a good light absorption. Already 10 μm silicon is enough to absorb 90 % of the light up to a wavelength of 700 nm.

III. EXPERIMENTAL RESULTS

A. Noise and Gain Measurement

In the readout of the silicon photodiode, the dominant contributions to the electronic noise come from the total leakage current and the input transistor noise which is

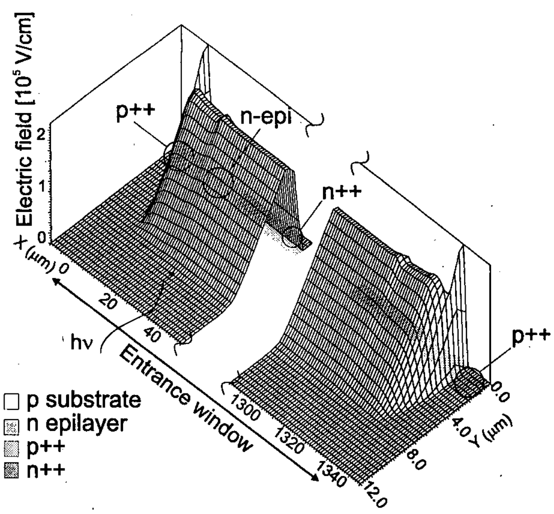

Figure 3: MEDICI simulation of the electric field in a 12 μm thick photodiode (see fig. 2) at a bias voltage of 67 V. The bulked resistivity is 5 Ω.cm.

proportional to the total capacitance parallel to the detector. The best photodiodes have a relatively low leakage current. Close to the breakdown voltage at 65 V we could measure leakage currents of 0.4 nA. However all the diodes show a high junction capacitance of $\sim$50 pF due to the thin depletion region. The use of low-resistivity wafers allows the depletion of a very thin region with a relatively high bias voltage. This results in a high electric field region where amplification may take place. According to simulations made using MEDICI, at a bias voltage of $\sim$70V the electrical field in the diode may be in the order of 10^5 V/cm (see fig. 3). This is high enough for amplification. Close to the breakdown voltage we measured for 5.89 keV X-rays using a calibrated charge sensitive amplifier an amplification factor of $\sim$3 (see fig. 4). The gain and the leakage current grow exponentially with the bias voltage. A compromise between the noise and the gain is found at a bias voltage of 66 V. We measured an rms noise of $\sim$310 electrons and a FWHM of 1.5 keV at the 5.89 keV Kα peak of ^{55}Fe decay (see fig. 5). X-rays absorbed in the high field region, which is a few micrometers wide, generate pulses which are partially amplified. This results into a large tail on

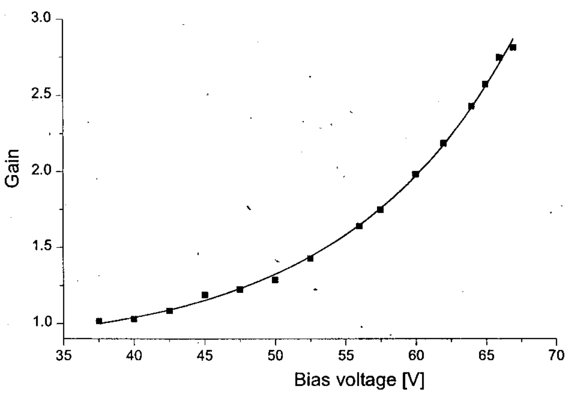

Figure 4: Gain as a function of the bias voltage.

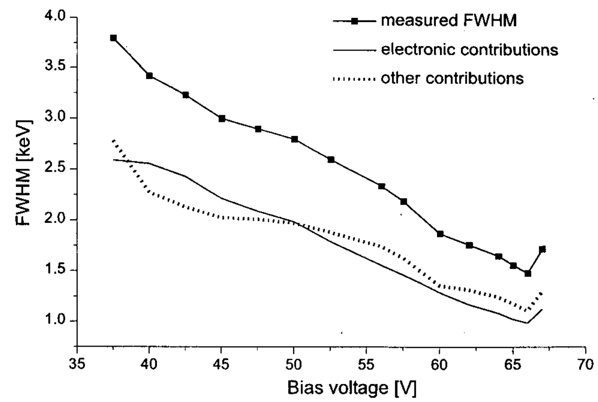

Figure 5: FWHM as a function of the bias voltage measured at the 5.89 keV Kα peak of ^{55}Fe decay with a shaping time of 6 μs.

the low energy side and fitting was thus performed on the high energy side of the peak. Taking into account the internal gain M and the statistical fluctuation of the gain reflected by the excess noise factor F, the energy resolution of the diode can be expressed as [8]:

$$\frac{\Delta E}{E} = 2.35\sqrt{\left(\frac{N_e}{NM}\right)^2 + \frac{(F-1)}{N} + \frac{F_f}{N}} \qquad (1)$$

where N_e is the electronic noise expressed in rms electrons, N the mean number of primary electrons and F_f the Fano factor. Subtracting the electronic noise (first term in Eq. 1) from the measured energy resolution shows that the statistical gain fluctuations and other contributions not reflected in Eq. 1, are comparable to the electronic noise contribution (see fig. 5). Obviously the gain dependence on the X-ray interaction depth degrades the energy resolution.

B. Light Detection

Measurements on light detection were performed with a pulsed laser. The laser can be positioned with an accuracy of one micrometer. The spot has an aerial spread of $\sigma \approx 75$ μm and each pulse deposits in the detector an equivalent radiation energy of $\sim$350 keV. Fig. 6 presents the relative optical response of a low leakage current photodiode at a bias voltage of 67 V. Normalisation has been performed using two 0.81 cm^2 PIN photodiodes from which the optical response is equal to the absolute light detection efficiency: 60$\pm$5% at 675 nm. It is shown that the light is collected over the whole active area. However, the response is non-uniform and peculiar edge effects are present. The relative optical response varies between 85-100% on a plateau corresponding to 62% of the active area, and $\sim$125% on the edges. This results in a mean value of 97% relative to the PIN photodiodes.

The gain at 675 nm differs from what has been measured with X-rays. The light is distributed in the high field region and experiences a mean amplification lower than the maximum amplification that is measured with low-energy X-rays. The optical response can be defined as the QE multiplied by an effective gain. However the latter can not be calculated or deduced from measurements since neither the depletion

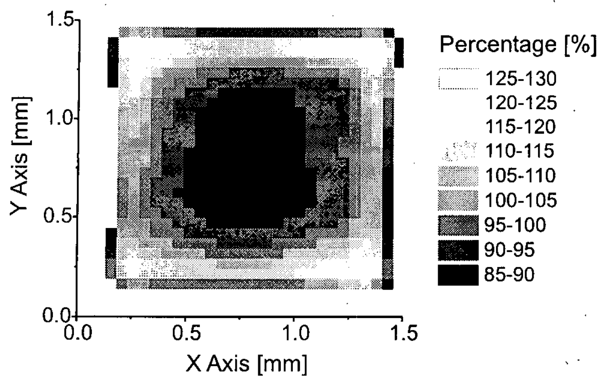

Figure 6: Optical response to a 675 nm pulsed laser normalised with the response of PIN photodiodes.

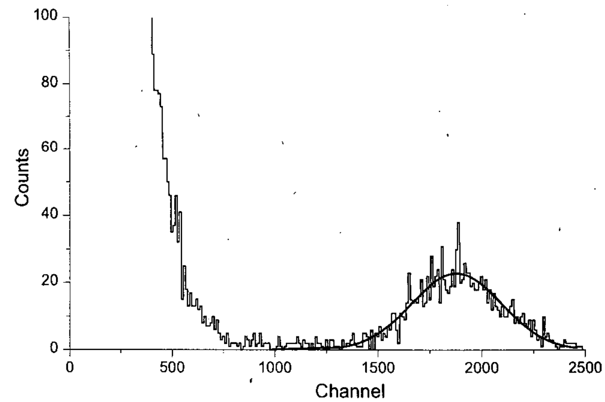

Figure 7: Pulse height spectrum of ^{244}Cm 5.8 MeV α (1 count per 10 seconds).

thickness nor the gain depth dependence are well defined. One can thus only conclude that at 675 nm the thin photodiode combine an effective gain lower than 3 with a QE higher than 20% which make their optical response nevertheless comparable to that of ~60% QE PIN photodiodes.

An explanation of the non-uniform optical response is the 'trenching effect' observed when (100) wafers are etched in a KOH solution [7]. The etch-rate is faster near the slowly etched (111)-planes than in the middle of the membranes. This results in gutters at the (111)/(100) intersections (see fig. 2) which can be few microns deep. SEM membrane profiles measured close to the tested diode give thicknesses of 10 μm and 7 μm for respectively the middle and the edge of the membrane. A 'breakdown' occurs when the depletion region is close to the deeper gutter where a large number of defects generates a high leakage current. The first few micrometers of the entrance window remain undepleted. The light detection efficiency depends then on the thickness variation of this dead layer. The edge effects are more pronounced along the Y-axis than along the X-axis. The asymmetry can be explained by the vertical position of the wafer during the etching process. The etching may be influenced differently along the Y-axis and the X-axis by rising of hydrogen bubbles.

C. Readout of CsI(Tl) Scintillation Light

A 200 μm thick film of structured CsI(Tl) has been deposited on top of the thin photodiodes using a vapor deposition technique. A first attempt to read out scintillation light has been performed using an alpha source. Fig. 7 shows a pulse height spectrum of 5.8 MeV alpha's from a ^{244}Cm source measured with a shaping time of 6 μs at a bias voltage of 60 V. The source was set 1.8 cm away from the detector, so each alpha deposits ~4 MeV in the scintillator. Assuming a light yield of ~30000 ph/MeV α [9], each event generates thus ~120000 photons. From the channel number, we calculated the number of electrons collected to be 10600. Considering a gain at 60 V lower than the factor 2 measured with X-rays (see fig. 4), this results in a photon detection efficiency between 5 and 10%. This is a rather low value, mainly because of the silicon dead layer. Also we did not use a reflective layer on top of the scintillator. Moreover the alphas are absorbed in the top layer of the crystal while the surface quality is rather poor. The low energy resolution of 27% reflects the light collection variation and the non-uniform optical response of the photodiode. The latter should be however balanced by the spreading of the scintillation light on the active area over the detector. The relative standard deviation of the number of photoelectrons is lower than 3.5% FWHM. The measured noise contribution of 270 rms electrons at 60 V bias voltage results in a spread of 6%. The large noise tail is due to the very low count rate.

IV. Conclusion

The performance of 1.8 mm^2 thin photodiodes is limited by the high junction capacitance. However smaller pixels, e.g. of 0.25 mm^2, would exhibit an electronic noise around 100 electrons because of the smaller capacitance. This electronic noise should not be the limiting factor for the energy resolution of a future imaging camera. More important parameters are the light yield and the intrinsic resolution of the crystal and the light collection in the well sensor. Concerning the light detection, the thin photodiodes combine a rather low quantum efficiency balanced by an amplification process which makes their optical response comparable to that of normal PIN photodiodes. We are now investigating deep reactive ion etching to obtain vertical wells, better entrance window profiles and thicker diodes.

Acknowledgments

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V. References

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