Timing Properties of Silicon Drift Detectors for Scintillation Detection

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Abstract—In this work we have evaluated the timing properties offered by silicon drift detectors to be used as scintillation photodetectors in systems for medical imaging. The peculiar drift mechanism of the charge created inside the SDD volume is responsible for a rise time of the signal at the output of the device when this is irradiated over its whole active area. Despite this effect, the rise time is in the order of 200 ns for a 5mm² device, therefore still comparable with the shaping time used for timing measurements. In the paper, the effect on the timing performances of SDDs due to the drift mechanism is first theoretically evaluated. We have then carried out the experimental characterisation of the timing properties of a 5mm² SDD coupled to a GSO crystal, in coincidence with a NaI-PMT detector, using a 511Na source. Despite the low conversion gain of the system (2.5e-/keV), due to the low light output of the crystal and the non-optimized quantum efficiency of the SDD, a timing resolution of 22 ns was measured for 511keV photons. This corresponds to a product resolution times number of collected electrons of about 13.9 x 10^{-3} ns·e⁻ which is comparable to the one achieved with APDs of similar areas. By irradiating the SDD directly with laser pulses, a resolution better than 1 ns was achieved with more than 60,000 electrons, showing no relevant limitations due to possible jitters of the drift time.

I. INTRODUCTION

The use of silicon detectors like conventional photodiodes (PDs), avalanche photodiodes (APDs) and silicon drift detectors (SDDs) in the photodetection of scintillation light is widely increasing in the field of gamma detectors for medical imaging. With respect to PMTs, in fact, they offer the main advantages of a higher quantum efficiency for scintillation light (typically higher than 80%), a better compactness and insensitivity to magnetic fields. In some nuclear medicine applications, like PET and Compton Cameras, the gamma-ray imager has to provide not only good resolution in position and energy but also good timing capabilities. For this purpose, relevant technological improvements achieved in the last years in the APDs development have allowed to reach with these devices good timing resolutions [1-3]. However, APDs still show some intrinsic limitations, like the need of high voltage biasing, a gain sensitivity to temperature drifts and the difficulty to integrate many units with uniform performances in monolithic arrays, although improvements have been recently obtained concerning this last issue.

The silicon drift detector (SDD) appears to be a good photodetector for scintillation detection too. The SDD is a unity-gain device like the conventional PD, but with respect to the last one offers a much lower electronics noise, thanks to the low value of output capacitance (in the order of 0.1 pF) which is independent from the active area of the device. SDDs coupled to scintillators have shown to reach excellent energy resolutions [4], while a monolithic array of several SDDs coupled to a single scintillator in a Anger Camera scheme have allowed to reach a position resolution better than 0.5 mm FWHM [5].

Despite the good electronics noise offered by this device, the SDD has not yet been considered a good candidate for timing measurements in scintillation detection. In fact, the intrinsic drift mechanism of the charge created in the detector bulk towards the collecting anode is responsible for a significant time width of the current impulse at the output of the device. This signal ends when the last electrons (the ones generated in the farthest position with respect to the anode) have reached the anode. This phenomenon is responsible for a rise time of the SDD output signal. To give an idea, in SDDs especially designed for scintillation detection (which have a uniform back-side electrode which acts as entrance window), typical values of the maximum drift time are currently in the order of 200 ns for a 5 mm² device and increase linearly with the area.

The purpose of this work is to determine the timing performances achievable with small-area SDDs. These devices have been successfully used either as single units and as part of monolithic arrays for gamma detection and the additional capability of reaching a moderately good timing resolution could allow to use them in imaging systems like, for instance, Compton Cameras, as second detector [6].

II. CONTRIBUTION OF THE SDD DRIFT TIME ON TIMING PERFORMANCES

The drawback in using SDD for timing application is represented, as mentioned in the previous section, by the relatively long rise time of the detector response. In order to evaluate this effect theoretically, let us consider the common timing technique based on the so-called “Crossover Timing” [7]. As shown in Fig. 1, this technique is based on the
determination of the time of zero-crossing of a bipolar shaping waveform generated by the incoming event. According to the principle shown in Fig.1, the time jitter $\sigma_t$ of the zero-crossing time $T$ can be related to the statistical fluctuation of the signal amplitude $\sigma_{bip}$ and to the pulse derivative at the zero-crossing point $\hat{y}_{bip}|_{_{T}}$ by the following basic relationship:

$$\sigma_t = \frac{\sigma_{bip}}{\hat{y}_{bip}|_{_{T}}} \cdot \frac{1}{y_{MAX}} \cdot \frac{1}{\hat{y}_{bip}|_{_{T}}} \cdot \frac{1}{y_{MAX}} \cdot T = \sigma_{bip} \cdot \frac{1}{\hat{y}_{bip}|_{_{T}}} \cdot T$$

(1)

where $y_{MAX}$ is the maximum pulse amplitude, $\sigma_{bip}$ is the statistical fluctuation normalized to the pulse maximum amplitude and $\hat{y}_{bip}|_{_{T}}$ is the zero-crossing derivative normalized both to pulse amplitude and zero-crossing time $T$. Considering now that the statistical fluctuations of the pulse maximum amplitude due to the intrinsic fluctuation of the created charge do not affect the time jitter $\sigma_t$ when using a bipolar pulse, the only effect on $\sigma_{bip}$ and therefore on $\sigma_t$ is due to the electronics noise:

$$\sigma_t = \frac{ENC}{Q_s} \cdot \frac{1}{\hat{y}_{bip}|_{_{T}}} \cdot T$$

(2)

where ENC is the Equivalent Noise Charge and $Q_s$ is maximum pulse amplitude expressed in charge.

Eq. (2) basically summarizes that the timing resolution is inversely proportional to the signal-to-noise ratio of the detector-preamplifier system and to the crossover derivative normalized in time and amplitude, while it is proportional to the zero-crossing time $T$. From this equation it can be supposed that reducing $T$ as much as possible will result in an indefinite improvement of the time jitter. However, the reduction of $T$ will affect both the ENC, as described later, and the normalized derivative.

The normalized derivative is influenced, at short $T$, mainly by three effects: (a) the rise time of the preamplifier, (b) the decay time of the scintillator and (c) the drift time in the SDD. The first effect is due to the fact that the preamplifier has a finite bandwidth and therefore the output pulse, which is the input of the bipolar shaping amplifier, has a non-zero rise time. In our specific case, the rise time is dominated by the input JFET, integrated on the SDD itself (Fig. 2), which is operated in a Source Follower configuration [8]. The scintillator contribution is represented by the exponential decay time of the scintillation emission and varies according to the specific crystal used. The third contribution is specifically due to the SDD and it will be considered in more detail.

For the sake of simplicity, let us suppose that the first two effects just described are not present. In this hypothesis all the scintillation photons arrive simultaneously on the detector and the rise time of the preamplifier is zero. If we consider a cylindrical SDD, as the one shown in Fig. 2, it can be easily evaluated that, in the hypothesis of an uniform illumination of the whole entrance window by the scintillation light, the output current signal from the anode is represented by a ramp which starts at the interaction of the radiation in the scintillator and ends after a time equal to the maximum drift time of the charges inside the detector (the time needed for the charges created in the outermost regions of the SDD to reach the anode). A typical ramp of the anode current is shown in Fig. 3, where the current starts from a non-zero value, supposing that the charge created in the region underneath the anode is collected immediately.

The bipolar pulse which results from this effect on the anode current, can be determined as the convolution of the anode current signal and the pulse response of the bipolar shaping amplifier. In Fig. 4, the resulting bipolar waveform is shown with respect to different values of the drift time. For simplicity, the bipolar shaper pulse response has been considered as the derivative of a gaussian unipolar waveform with $\sigma = 1$, which presents a time width between the maximum amplitude and the zero-crossing time $T$ equal to 1. The drift time is considered normalized to this unitary width. As shown in figure, the drift time affects the resulting waveform by reducing the peak amplitude (ballistic deficit) and shifting the zero-crossing time, with respect to its nominal value. Both these effects reduce the absolute value of the derivative at the zero crossing time. The consequent increase of $\sigma_t$ can still be evaluated from eq. (2) by using the same value of the nominal S/N ratio, $\sigma_{bip}$, leaving $T$ equal to the nominal zero crossing time of the bipolar shaper, and substituting $\hat{y}_{bip}|_{_{T}}$ with a value modified by the presence of the drift time, to be considered still normalized both to nominal amplitude $Q_s$ and nominal zero crossing time $T$. In Fig. 5, the reduction of the derivative as well as the ballistic deficit on the pulse amplitude are shown for different ratios between zero-crossing time and drift time. It has to be noticed that in SDD with homogenous entrance window, the drift time increases almost linearly with the detector active area. In a typical SDD on 450 $\mu$m thick silicon wafer, a drift time of about 1.5 $\mu$s/cm$^2$ can be estimated. From this value, from eq.(2) and from plots like the one shown in Fig. 5, it is possible to estimate the maximum area that could be allowed for the detector in order to achieve a required timing resolution.

As well known [9], the time width of the shaping pulse also affects the ENC. Therefore the choice of the optimum ‘shaping time’ $T$, hereafter considered in this paper equal to the zero-crossing time of our bipolar shaper, has to be a compromise between the derivative contribution and the electronics noise contribution.

As an example, we have numerically evaluated all of the three mentioned effects for a SDD detector of 5mm$^2$, whose experimental characterization is presented later in the paper. In Fig. 6a, the calculated ENC is plotted with respect to the shaping time. The bipolar shaper has been considered as the
derivative of a semigaussian shaper of different orders, \( n \). From the plot it can be observed that also for the ENC the shaping time can not be reduced indefinitely due to the increase of the series noise contribution. In Fig. 6b, the derivative of the bipolar pulse at the zero-crossing time versus shaping time is shown. In the calculation of the derivative, all three effects have been taken into account: a SDD drift time of 200ns, a preamplifier rise time of 80ns and a scintillator decay time of 60ns (GSO). Finally, in Fig. 6c, the timing resolution, calculated in correspondence of a signal of 1000e- and on the basis of the ENC and derivative behavior is shown. The timing resolution reaches a minimum at an optimum shaping time \( \tau_{opt} \) and this minimum changes with the order of the filter. In our specific example, the theoretical minimum is equal, for a 7th order filter, to 13.8 ns FWHM (for 1000 e-signal).

III. TIMING PERFORMANCES OF THE SDD IRRADIATED WITH LASER PULSES

In order to experimentally verify the timing performances offered by the SDD, we have first characterized at room temperature a SDD with an on-chip front-end JFET with 5mm² of active area and 0.3 mm of thickness. We have irradiated the whole area of the detector with a pulsed IR laser source (\( \lambda = 830\)nm, picosecond pulse width). In order to decrease to a minimum value the front-end rise time, a second source follower has been introduced after the first one. A rise time of about 80ns have been achieved in this configuration (Fig. 7).

During the timing measurements, the signal from the second source follower was fed into a voltage preamplifier, followed by a bipolar shaping amplifier (Tennelec TC244) set to 0.25 \( \mu \)s shaping time (corresponding to approximately 600ns zero-crossing time). The output bipolar signal from the shaper was fed into a zero-crossing discriminator whose output was connected at the ‘stop’ input of a TAC (Time to Amplitude Converter, Ortec OR566). The laser trigger signal was connected to the ‘start’ of the TAC.

When irradiating the SDD with picosecond laser pulses, only the effects of the drift time and of the preamplifier rise time are present. In these conditions we have measured the waveform shown in Fig. 8a which is in agreement with the one theoretically expected considering the detector current pulse shown in Fig. 1 and a drift time value of 200ns, of the same order of the value calculated from just geometrical considerations. For comparison, in Fig. 8b, the waveform made slower only by the source follower rise time is also reported, to show the different shape with respect to the one where the drift time plays a role.

Measurements carried out at room temperature with the laser at different intensities have allowed to trace the plot shown in Fig. 9. The agreement of the experimental points plotted in this figure with respect to the I/X slope shows the expected inverse proportionality of the timing resolution with respect to the signal charge [eq. (2)]. From the fitting, a resolution of 19.7 ns (1000e-) can be determined, in good agreement with the value of 18.6 ns (1000e-) theoretically calculated. Moreover, it has to be pointed out that in correspondence of a large signal charge, 67,000 e-, a resolution of 0.8 ns has been achieved (Fig. 10). This results is useful to highlight that all the limitations introduced up to now are sufficient to explain the timing performances of the SDD down to a resolution better than 1ns and that other possible effects, like for instance limitations arising from possible jitters of the drift time over the whole SDD area do not play a significant role.

IV. TIMING PERFORMANCES OF THE SDD COUPLED TO A SCINTILLATOR

With the device described in the previous paragraph, we have carried out timing measurements by using a coincidence chain composed, on one line, by the SDD (cooled at -10°C) coupled to a GSO crystal [Gd_2SiO_5(Ce), decay time of 60ns] and, on the other line, by a NaI scintillator coupled to a PMT. Although the GSO is not the best scintillation crystal to be chosen for this measurements, basically due to its low emission output (9000Ph/MeV), it was already available from previous tests [10]. The scintillator has a cross section of 2.5\times2.5 \text{ mm}^2 and a thickness of 10mm. It was wrapped by Millipore filter paper and coupled to the SDD entrance window by optical grease (Fig. 11).

The scheme of the electronic chain is schematically shown in Fig. 12. The SDD-GSO detector signal was filtered with the TC244 bipolar shaping (600ns zero-crossing time) and the timing signal was obtained by the zero-crossing discriminator, as in the previous measurements with the laser. The NaI scintillator + PMT signal was sent to a constant fraction discriminator (Ortec OR583). The timing signals from the two chains were fed into the inputs of the TAC. The 511keV gamma rays from a \(^{22}\)Na source was used for the coincidence measurements. A lower amplitude threshold of 400 keV was used as gating to the ADC in order to select pulses around 511 keV.

Due to the low emission yield of the GSO crystal and the non optimized quantum efficiency of the SDD detector to the scintillations spectrum centered at 440nm (anti-reflecting coatings are not implemented at the moment on the SDDs), the achieved conversion gain of the detector was at its best equal to about 2.5 e-/keV.

The timing resolution measured at 0°C was of 13.8 ns FWHM (Fig. 13). Considering for this measurement that the 511 keV signal has given 1257 e-, the resulting resolution normalized to 1000 e- is of 17.3 e- FWHM. The SDD-GSO detector was then cooled to -10°C. Unfortunately, due to a deterioration of the wrapping, the conversion gain had decreased to 633e- for 511keV photons. The electronic noise of the SDD was of 16.6 e- rms using unipolar shaping and of 27 e- rms using the bipolar shaping for the timing measurements. The timing resolution in this conditions was of 22 ns FWHM which, normalized to 1000e-, corresponded to 13.9ns FWHM. This normalized resolution, improved with respect to the measurement at 0°C because of the reduction of the electronics noise, is well matching the value theoretically expected of 13.8ns (§II).

Despite the low gain, the energy resolution measured at –
10°C (using unipolar semigaussian shaping with 0.25 µs shaping time) was of 8.9 % FWHM at 511 keV (Fig. 14).

V. DISCUSSION

In this work we have evaluated the performances that can be achieved using SDDs coupled to scintillators for timing measurements. Although the SDD drift time could affect significantly the timing resolution, with an effect increasing with the active area of the device, SDDs of small areas (up to a few tens of mm²) can still be considered for detection system where a moderate timing resolution (5-10 ns) can be still of interest. With respect to other photodetectors, the SDDs could offer better performances in the energy detection.

With a 5 mm² SDD used in this work, we have demonstrated that a resolution down to less than 1 ns can be achieved for large charge signal, showing not relevant limitations deriving from the drift mechanism.

When coupled to a GSO crystal, a timing resolution of 13.8 ns was obtained at 0°C for 1257 e- signal and at –10°C a resolution of 22 ns was obtained for 633 e- signal. These resolutions are rather poor as absolute values because of the small signal collected by the SDD. The reasons for this significant signal deficit are mainly due to the low scintillation emission from the GSO crystal and to the non optimized quantum efficiency of the SDD at the GSO scintillation wavelengths.

However, if we normalize the obtained resolution to 1000 e- electrons, the product resolution × number of collected electrons is of 13.9 x 10³ ns·e-h at –10°C which is comparable to the one achieved with APDs of similar areas [2].

Because of the basic inverse proportionality of the timing resolution with respect to the signal amplitude, the results obtained in this work let us suppose that for higher conversion gains, to be achieved by using other crystals (like LSO or RGB) and optimized SDD entrance windows, a resolution in the order of few ns can be achieved.

VI. REFERENCES

Fig. 1. Example of bipolar shaping pulse used for Crossover Timing. The cause of uncertainty on the timing measurement is the presence of noise and, at the first level of approximation, it is possible to suppose a linear relation between amplitude and time fluctuations.

Fig. 2. Drawing of a circular SDD, like the one used for the timing measurements, showing the active area and the integrated J-Fet, which is the first stage of the preamplifier.
Fig. 3. SDD pulse response to the scintillation light, taking into account of the internal drift time.

Fig. 4. Waveforms of a bipolar pulse with respect to different drift time of the signal charge inside the SDD. Drift times are indicated in the same arbitrary units of the horizontal axis.

Fig. 5. Normalized derivative versus the ratio between drift time and shaping time.
Fig. 6. (a) ENC versus shaping time, for different orders of the shaping filter. The parameters of the system are: 60ns of scintillation time constant; 200ns of drift time and 80 ns of rise time for the preamplifier itself (10-90%). In fig (6.b) appears the derivative at the zero crossing time and in (6.c) the timing resolution.
Fig. 7. Rise time of the preamplifier during x-ray detection, without the effects of the drift mechanism and of the scintillator.

Fig. 8a. Measured rise time, compared with the theoretical one, at the output of a SDD followed by a voltage preamplifier, in correspondence of a laser pulse illuminating the whole photodetector area.
Fig. 9. Measured timing resolution with respect to signal charge created inside the SDD by laser pulses. The fitting of the data is also shown.

Fig. 10. Timing resolution in correspondence of a signal in the SDD of about 65,000 electrons.

Fig. 11. Wrapping of the Scintillator, which is placed at the top of one detector of an array of 6 SDDs.
Fig. 12. Schematic of the chain used for the timing coincidence measurements

Fig. 6. Timing resolution measured with the GSO-SDD detector with a $^{22}$Na source. The measured signal charge for the 511 keV line is of 633 electrons.