Abstract-- In this work we propose a novel Silicon Drift Detector that can fulfill the demanding requirements of the ideal scatter detector in a high-resolution Compton Camera for medical imaging. The performances of this kind of detector have been assessed in terms of energy and position resolution and maximum event rate and the more relevant results are shown. With respect to a conventional Silicon-Drift Detector back side contacts have been designed and instrumented to pick up the signal induced by the e-h pairs generated by the interaction thus providing the fast coincidence signal between the recoil electron signal and the scattered γ-ray signal at high count rates. Several measurements have been carried out to study the shape of the induced signals and the time resolution. The achieved time resolution on the fast trigger is about 9 ns FWHM measured in a time coincidence setup with the annihilation photons of a $^{22}$Na source. These results show that Silicon-Drift Detectors with fast pick-up on the back electrodes with optimized design as scatter detector allows to develop a Compton telescope working at the Doppler limit ideal for small animal SPECT, for prostate and thyroid cancer monitoring and for cardiac perfusion imaging.

I. INTRODUCTION

Compton imaging is of interest in the fields of astrophysics, homeland security and nuclear medicine as it can improve the detection efficiency without sacrificing position resolution of SPECT imaging. In fact a Compton Camera provides information about the incoming photon direction electronically without limiting the detection solid angle as it is done with mechanical apertures, since Compton scattering preserves information about the direction and energy of incident γ-rays if the scattering by-products can be precisely measured. Fig. 1 shows the scheme of principle of the Compton Camera. The performances of a Compton imager are primarily set by the chosen technology of the scatter detector that must track with high accuracy the primary recoil electron (and any secondary interactions of the scattered photons). Compton kinematics allows then to reconstruct the direction of the incident γ-ray that lies on a cone whose aperture θ can be calculated from the measured quantities. In particular the overall angular uncertainty is set by the following equation:

$$\Delta \theta_{tot}^2 = \Delta \theta_{Doppler}^2 + \Delta \theta_{Geom}^2 + \Delta \theta_{E}^2$$

where $\Delta \theta_{Doppler}$ is due to the Doppler broadening in the scatter detector material, $\Delta \theta_{Geom}$ takes into account the geometrical effects (pixel size and detectors thickness, source-detector and inter-detector distance) and $\Delta \theta_{E}$ is due to the scatter detector energy resolution

$$\Delta \theta_{E} = \frac{m_0 c^2}{\sin \theta (E_{\gamma} - E_e)} \sqrt{(\Delta E_{Fano})^2 + 2.355 \cdot ENC^2}$$

where $m_0 c^2$ is the electron rest energy, $E_{\gamma}$ is the energy of the incident photon and $E_e$ is the recoil electron energy, $\Delta E_{Fano}$ is the intrinsic statistical noise and ENC is the Equivalent Noise

Fig. 1. Principle of operation of a Compton Camera.
Charge of the scatter detector.

Fig. 2 shows the angular uncertainty $\Delta \theta_E$ as a function of the Compton recoil electron energy ($E_e$) for two different ENCs of the scatter detector and for different radionuclides. The absorption detector has been assumed ideal. As it can be noticed the angular resolution improves for increasing $\gamma$-rays energies. At low energies (e.g. 140.5 keV of $^{99}$Tc and 391.7 keV of $^{113}$In) and/or low energies of the recoil electrons (i.e. low scattering angles) the contribution of the detector energy resolution is relevant setting an additional stringent requirement on the scatter detector performances.

In this paper we propose a novel Silicon detector that can fulfill all the demanding requirements of the ideal scatter detector in a high-resolution Compton camera for medical imaging. Section II reviews the characteristics needed for an ideal scatter detector and illustrates the relevant features of the novel detector. Section III presents the achieved performances with the novel detector. Section IV is devoted to the conclusions and future plans.

II. BASIS FOR INNOVATION OF SCATTER DETECTOR

The ideal scatter detector should be a Silicon detector -in order to minimize the Doppler broadening that limits the achievable angular resolution [1]- featuring a position resolution of the order of 150 -200 $\mu$m -to determine the coordinates of the Compton scattering event- and an energy resolution below 30 electrons rms -to measure the energy released by the recoil electron. Moreover it is required to reduce the amount of mass along the photon path to minimize random events. Last but not least the scatter detector should provide a fast trigger with a time resolution of few ns, needed for event coincidence between the scatter detector and the absorption detector. At present an international collaboration is developing a Compton scatter detector based on Silicon pad detectors [2] already employed in high-energy physics experiments. The main drawbacks of this choice are the position resolution -pad side 1mm-, poor energy resolution -260 electrons at room temperature- limited by the high output capacitance of the detector and the number of interconnections and readout channels required by the 2-D array of pads.

The novel detector that we propose is based on the Controlled-Drift principle [3, 4]. In this detector the signal electrons generated by the interaction are transported towards an array of point-like anodes by means of an electrostatic field. The drift time of the electron packet gives one interaction coordinate while the second coordinate is obtained from the granularity of the readout anodes. The energy released in the detector can be measured with spectroscopic resolution thanks to the very low anode capacitance (<100 fF) and the on-chip front-end electronics. The transport mechanism based on electrons’ drift has a two-fold advantage: i) it reduces dramatically the number of channels required for true 2D position sensing (i.e. no. of channels equal to the square root of the pixels) and ii) it allows to optimally connect the front-end electronics aside the detector chip thus minimizing the amount of mass along the incident $\gamma$-ray path. The achievable performances of this kind of detector have been fully assessed in terms of energy resolution, position resolution and maximum event rate [5, 6]. As shown in Fig. 3 the back side contacts have been designed and instrumented to pick up the signal induced by the electrons-holes pairs generated by the interaction to provide the fast coincidence signal.

Fig. 4 shows a 3-D simulation of the electron/hole dynamics in the case of an ionization track (similar to the effect of an energetic Compton electron). The potential minimum where electron transport takes place is located at about 10 $\mu$m from the anode side of the detector.

Immediately after the interaction a unipolar current signal is induced on the $p^+$ strip closest to the generation point that collects the holes (i.e. $P2$ in Fig. 4). This current pulse shows a sharp peak, due to the fast electrons’ focusing to the potential

![Fig. 2 Angular uncertainty due to the scatter detector energy resolution as a function of the Compton recoil electron energy for two different Equivalent Noise Charges (ENC). The absorption detector has been assumed ideal.](image)

![Fig. 3 Scheme of principle of a Controlled-Drift Detector instrumented to measure the induced signal on the back side.](image)
minimum, and a slower component, typically lasting less than 10 ns, due to holes’ collection. It should be noted that, after the
initial carrier separation, charge induction on \( P_2 \) is not yet
complete because of electrons’ storage in the drift channel.
The remaining charge fraction (4% in the simulated case)
appears at \( P_2 \) only when the electrons are finally collected at
the anode. For typical drift times, of the order of some µs, this
charge fraction is practically lost as the current signal from
each \( p^+ \) strip on the back side is shaped by a fast amplifier (few
tens of ns) to achieve good timing performance. Therefore it is
critical to design the detector in such a way that the potential
minimum for the electrons lies close to the detector surface
opposite to the sensing electrodes. On the other side, a short
current pulse, corresponding to the full generated charge, is
induced at the collecting anode at the end of the drift because
\( p^+ \) strips screen the signal electrons during their drift towards
the anode. The current pulse induced on \( P_2 \) can provide a
precise timing information by looking at the zero-crossing at
the output of a fast bipolar shaping amplifier. The current
signal induced by the initial carrier separation on the \( p^+ \) strips
not collecting holes (i.e. \( P_1 \) in Fig. 4) has instead a bipolar
shape. After a bipolar shaping these signals will feature a
tripolar shape and can be rejected.

Alternatively the joint analysis of the induced signals on the
electrodes adjacent to \( P_2 \) could be used to derive the depth-of-
interaction information, which will allow to reduce the size of
the voxel of the scatter detector.

The availability of a fast trigger signal allows operating the
detector either in integrate read-out mode -conventional
operating mode for a Controlled-Drift Detector- or in
continuous readout mode -i.e. as a Self-Triggered Multi-Linear
Silicon Drift Detector [7].

III. ACHIEVED PERFORMANCES

A CDD prototype has been instrumented to measure the
signal induction on a \( p^+ \) strip of the back side. The area of the
instrumented \( p^+ \) strip is about 1.6×1.7 mm² and the total
 capacitance of the readout node (\( C_{cap}+C_{stray} \)) is about 10pF.

Several measurements have been carried out – with IR
pulsed laser and radioactive sources - to study the shape of the
induced signals and to evaluate the achievable time resolution.
As the dominant contribution was due to the stray capacitance
(~8pF) the results obtained with this setup can be considered
equivalent to the case of a larger \( p^+ \) strip for signal pickup. A
coincidence measurement setup has been built to measure the
time resolution of the silicon detector prototype using a fast
scintillator-PMT as the time reference and the annihilation
photons of a \(^{22}\text{Na} \) source as schematically shown in Fig. 5. Fig.
6 shows the output waveforms of time coincidence
measurements in the case of a photon that is converted far
away from the anode region as demonstrated by the 600 ns
drift time. Fig. 7 shows the spectrum of the zero-crossing time
measured at the back electrode. The achieved resolution is
about 9 ns FWHM suitable for high rate applications in
Compton Imaging. An improvement of the resolution is
achievable by increasing the voltage difference between the
front and the back side since holes collection time decreases.

IV. CONCLUSIONS AND PERSPECTIVES

The Controlled Drift Detector (either operated in integrate-
readout mode or in continuous readout mode) is probably a

Fig. 4. 3-D simulation of the electron/hole dynamics in the case of an ionization track similar to the one released by an energetic Compton electron. The
insets show the current induced at the back electrodes and at the anode.

0-7803-8701-5/04/$20.00 (C) 2004 IEEE
unique device that combines 2D position sensing with high-resolution energy spectroscopy, microsecond-scale readout and event timing in the nanosecond range. It allows 2D position sensing with low number of channels and about 100µm pixel size, energy resolution below 500 eV FWHM at room temperature and an event time resolution of 9ns FWHM with 511 keV γ-rays. Therefore a better energy and position resolution can be obtained with respect to Si-pad detector, presently used by competing Compton Cameras [2].

Compton Imaging in nuclear medicine should strongly benefit from a scatter detector based on SDDs/CDDs. It is the key to reach Doppler limited performance also for low/medium gamma energies (140 keV, 392 keV). A new 3-cm² CDD prototype has been designed for Compton imaging tests and is currently under production at the Halbleiterlabor of the Max Planck Institut [7].

ACKNOWLEDGMENT

The authors are grateful to P. Holl and the staff of the Halbleiterlabor of the Max Planck Institut for the detector production, to M. Mariani for the PMT setup and to S. Masci for the careful bonding of the detector chip.

REFERENCES