The Particle Tracking Silicon Microscope PTSM

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***Abstract*—A novel position- and energy-sensitive particle detector for radiobiological application is described. The aim is to support research in radiation response of biological systems, for example in the induction of mutations in *C. elegans*, where precise knowledge of location and intensity of the radiation is crucial to understand radiation sensitivity of individual cells. The "Particle Tracking Silicon Microscope" (PTSM) consists of a silicon strip detector in direct contact with radiobiological samples (e.g., *C. elegans*), such that the location and intensity of particle radiation can be controlled at the 10 μm scale. The readout is performed with low-noise readout electronics, which allows the determination of the particle's position from the hit strip address and its energy from the specific energy loss. In our implementation, the energy loss is measured through the time-over-threshold (TOT). The noise rate at acceptable thresholds is so low that the single particles can be detected with 100% efficiency. The performance of the front-end ASIC is described, and the results of initial environmental tests are reported. These include placing biological samples and saline solutions in direct contact with the silicon detectors.**

***Index Terms*—Biomedical applications of radiation, silicon radiation detectors.**

I. Introduction

THE 2002 Nobel Prize in Medicine was awarded for work done on a lowly worm [1], *C. elegans*, a hermaphrodite nematode [2]. The adult organizm, which consists of about 850 cells, allows detailed study of control mechanisms like programmed cell death (apoptosis), and long-range cell interactions, which may be responsible for radiation-induced bystander effects [3]–[5]. For this and similar work, it is paramount to know the spatial fluence distribution of ionizing particles at the cell level. Fig. 1 shows a dissecting light microscopic of *C. elegans* showing some body parts and the individual cells [2]. Cells with identical function located 10–100 μm apart show very different cell damage characteristics with respect to radiation [6]. The cell separation of interest is the resolution scale of silicon strip detectors (SSDs), and in the following a novel particle detector, the Particle Tracking Silicon Microscope (PTSM), is described to localize and measure the intensity of radiation deposited in organizms like *C. elegans*.

In Section II, the principle of the PTSM is described, followed by a description of its current implementation. Then, the new ASIC developed for the readout of the silicon detectors is described, including measurements of its performance. Lastly, "environmental" studies are described, which tested whether biological samples in saline solution can be placed directly onto the silicon detector surface.

II. Principle of the PTSM

The aim of the PTSM project is to develop a versatile and inexpensive particle tracking system for protons, α's and heavy ions with energies in the radiobiologically interesting energy range 1–300 MeV. The PTSM should allow *in vitro* and *in vivo* radiobiological studies. It will find applications in research studies for radiation therapy and protection, and will support the low-dose research programs of DOE and NASA. In contrast to conventional radiobiological experiments, where only the average number of particle hits per cell is known, the PTSM will allow to perform radiobiological experiments where the number of particles per cell is exactly known. Both broad beam and micro beam setups will be supported by the PTSM.

The PTSM uses fully depleted silicon strip detectors (SSDs) with an active depth of 300 μm, in proximity focus, as tracking devices, i.e., a worm, immobilized in saline solution, is placed directly on the surface of the SSD. A comparison between the hit position of a particle and the location of the worm determines which cells have been hit. This is true even if the particle undergoes multiple scattering in the worm, because sideways deflection will be limited in the short distance between the worm and detector. The system described here has only a single-sided SSD, giving position measurement in one dimension only; the final system will have a double-sided SSD, to allow a two-dimensional determination of position. SSDs have many advantages for detecting charged particles. They combine measurement of position and energy, or LET, of single particles with high spatial resolution (a few microns) and a wide dynamic energy range. They have a fast charge collection time with self-triggering, allowing for time-resolved measurements and supporting high particle rates, Furthermore, they are radiation hard up to very large fluences [7] and allow simple operation e.g., have low operational voltages, require no consumables, and are relatively compact. They also provide a projective

Manuscript received November 16, 2003; revised June 11, 2004, and July 9, 2004. This work was supported by NASA Cooperative Research Agreement NCC9-149 and Calspace.

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Digital Object Identifier 10.1109/TNS.2004.836138

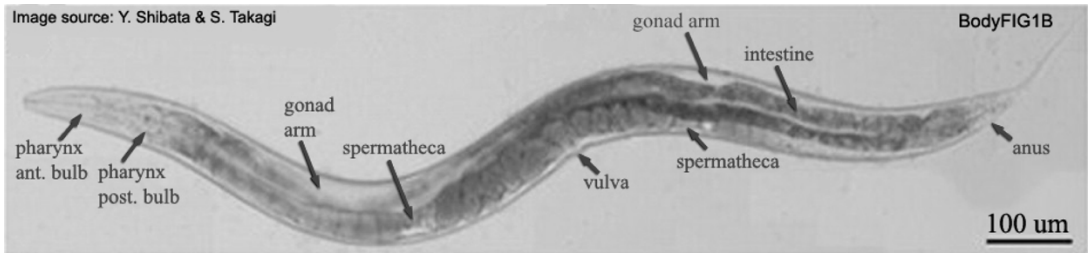

Fig. 1. Transmission light microscopic image of an adult hermaphrodite *C. elegans* [2]. The distance between cells is between 10–100 μm, which can be resolved with a silicon strip detector.

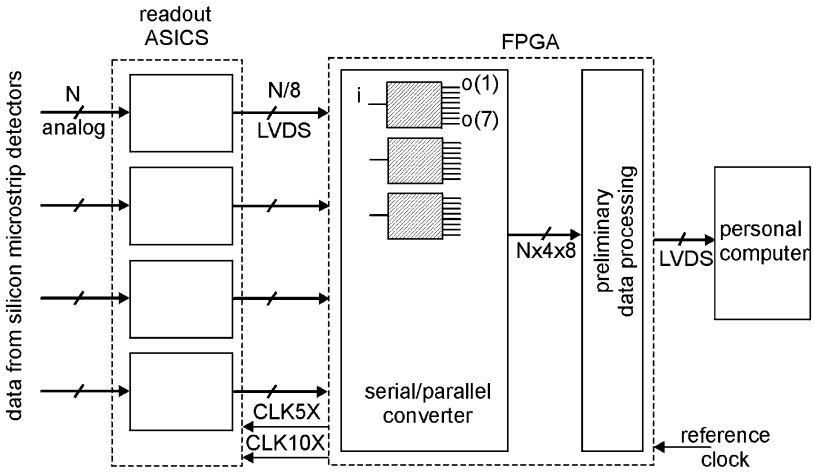

Fig. 2. Schematic diagram of the PTSM electronics readout. The silicon strip detector (SSD) and the readout ASIC (PMFE) reside on the detector board, and the FPGA on another board. The readout into the computer is accomplished with a commercial I/O card. All communications are via LVDS signals for low-noise operation.

geometry and thus are efficient and inexpensive at obtaining the X-Y coordinates in a low flux experiment.

III. Implementation of the PTSM

The conceptual design of the PTSM is as follows: the immobilized biological targets [8] are placed directly onto the surface of a double-sided silicon detector with $\sim 50\mu$m pitch. The readout ASIC, called particle microscope front-end (PMFE), is designed for simultaneous single-particle tracking and energy (or LET) measurements, and the readout controller performs zero suppression and charge determination. The system was designed to have as many commercially available parts as possible.

Our implementation (Fig. 2) uses an ASIC as front-end, and a field programmable gated array (FGPA) as readout controller for parallel data processing. Low noise performance, guaranteeing single-particle tracking, is assured with the low power consumption of the ASIC and the use of low-voltage differential signal (LVDS) drivers throughout the system. Data are serialized 8 channels deep in the PMFE with double data rate at 100 MHz and restored in the FPGA by a serial-to-parallel conversion. The FPGA performs zero suppression of channels without data, and measurement of the pulse length (time-over-threshold, TOT) of the channels hit by particles. The data are read into the computer by a commercial I/O card on the PCI bus.

The front end ASIC presents the TOT signals from the SSD to the FPGA which, after processing the information, presents to the PC I/O card a 64-bit word containing a channel number, timestamp, and a signal transition flag. A schematic of the PTSM test setup is shown in Fig. 2. It should be pointed out that a smaller detector board carrying the SSD and PMFE ASIC can be detached from the FPGA board to permit separate storage and handling of the biological samples.

IV. ASIC PMFE

For the readout of the fast silicon detector signals, a new low-noise, low-power front-end ASIC PMFE was developed. The front end is based on a chip developed for the GLAST space mission [9], but it has several improvements crucial for its use in the PTSM: it can be configured with a simple wire bond to read out either electrons or holes when used with double-sided silicon detectors, it allows time-over-threshold (TOT) measurements on every channel for which it has a large dynamic range up to 300 fC, and it has a short shaping time of 300 ns to permit high data rates. The PMFE is a binary chip of 64 channels with a common threshold for the entire chip.

The performance of the PMFE has been investigated by stimulating the inputs with calibration pulses using the internal calibration capacitors, which were measured to have a value of 55 fF with good matching. The input charge is the product of calibration voltage and calibration capacitance. Performance parameters of interest include the gain, the noise RMS for a given detector load, and the accuracy of the charge measurement using TOT. All parameters were studied as a function of input charge $Q_{\rm in}$.

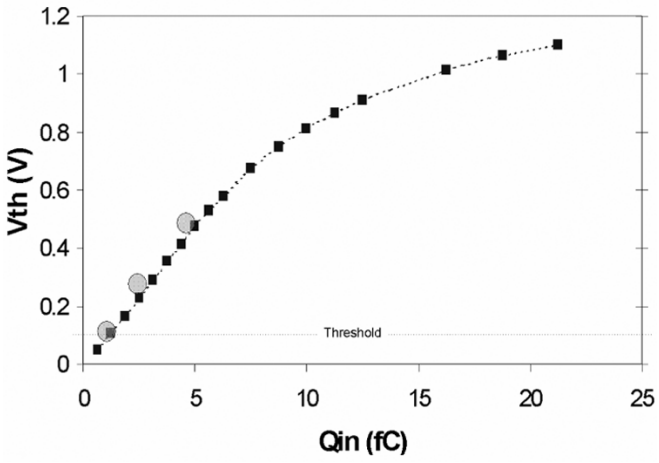

Fig. 3. Gain, i.e., the threshold voltage $V_{\rm th}$ at the comparator corresponding to the input charge $q_{\rm in}$. The round symbols are the results of the SPICE simulation.

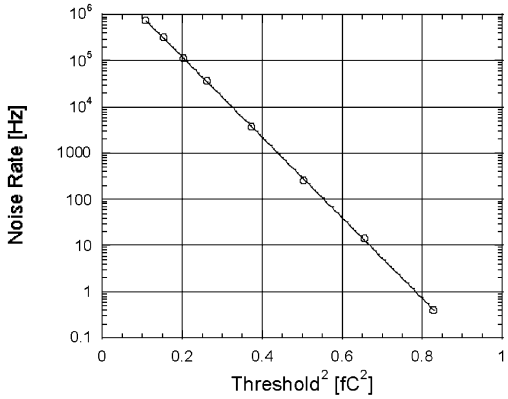

Fig. 4. Noise performance of the full system: noise rate of a group of 8 channels as a function of the square of the input charge in fc, converted from the threshold voltage using Fig. 3. The slope of the curve allows the determination of the noise rms, which is 1000 $\rm e^-$. The charge of a minimum ionizing particle (MIP) in a 300-μm-thick SSD is 23 000 $\rm e^-$.

The measured gain, i.e., threshold voltage at the comparator as a function of input charge is shown in Fig. 3. A fairly linear behavior in the targeted threshold region of one fC is seen, with a gain value of close to 100 mV/fC. The simulated values are in good agreement with the measurements.

Fig. 4 shows the noise performance: the noise rate of a group of 8 channels was measured as a function of the threshold voltage and plotted on a semi-logarithmic scale as a function of the square of the input charge corresponding to that threshold, which was derived from the gain curve in Fig. 3. For white (Gaussian) noise, the relationship is described by an error function, and the inverse of the slope of the line in Fig. 4 is twice the square of the noise rms. From this, a noise rms of close to 1000 $\rm e^-$ was extracted.

The TOT system measures the input charge making use of the fact that the comparator pulse length is proportional to the input charge. Extensive measurements with the GLAST chip in beams have shown how well the energy can be measured with this method [10]. TOT is used because the pulse height can saturate, thereby imposing an upper limit on reading the pulse height directly, but the time for which the signal is above the threshold continues to be proportional to the pulse height.

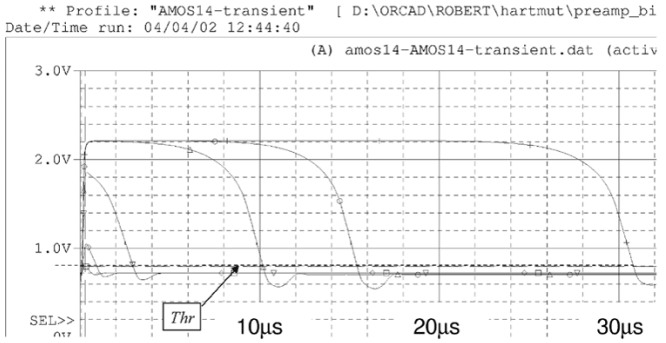

Fig. 5. Simulated pulse shapes at the comparator for input charges of 1, 4, 16, 64, 100, and 300 fC, respectively. As the pulse height saturates, the pulse length still increases with increasing input charge. The TOT saturates at about 30 μs.

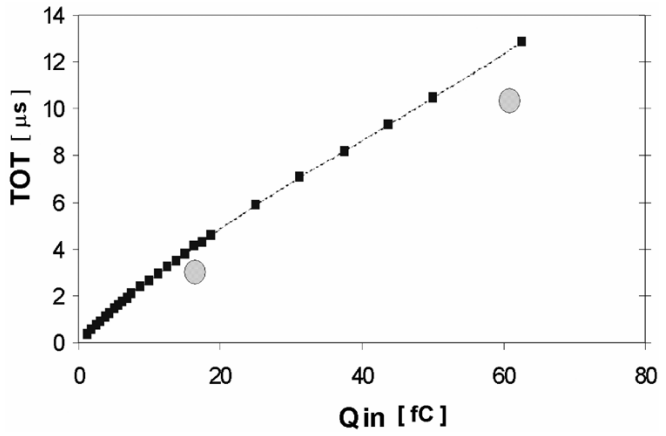

Fig. 6. Measured TOT in μs vs. input charge Q in fC. The two round symbols indicate the values from the initial SPICE simulation shown in Fig. 5.

TOT thus has a greater dynamic range. Fig. 5 shows that for input charge greater than 16 fC pulse height saturation occurs, whereas a useful TOT signal is still achieved. When pulse height does not saturate, the two approaches are equivalent as shown in Fig. 6.

The electronic calibration yielding the TOT vs. input charge, exhibits a linear dependence of the TOT on the charge input up to a duration of 13 μs, as shown in Fig. 6. This figure uses the full range of the internal calibration capacitors that are not able to extend to the saturation region. Saturation is expected to begin with a charge of about 300 fC, corresponding to an energy loss of about 6 MeV. The calibration of each strip allows the TOT measurements to be normalized, thereby compensating for the single threshold value used in all the comparators.

The threshold is set to 1 fC. A higher threshold reduces noise but reduces the efficiency from 100% especially when the charge is shared between two strips. However, the incident radiation is expected to produce a large signal with respect to the threshold such that no significant loss in efficiency is encountered.

PMFE currently samples the silicon strips at a rate of 10 MHz, with the option to increase. Providing that the rate of incident particles is small in comparison, it is unlikely that two or more events will hit a detector strip during the same read operation. The expected rate required for the biological application is in the few MHz range.

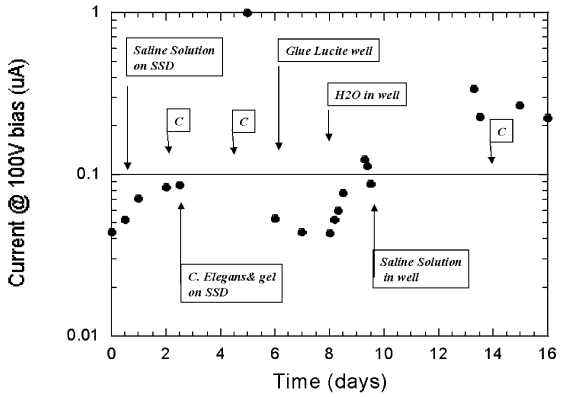

Fig. 7. Detector leakage current versus time. The different environmental tests are indicated, as are the times of cleaning ("C"). The leakage current increase seen at the end of the tests was correlated with deep gouges in the detectors caused by the manipulation of *C. elegans* with metal probes between days 12 and 13.

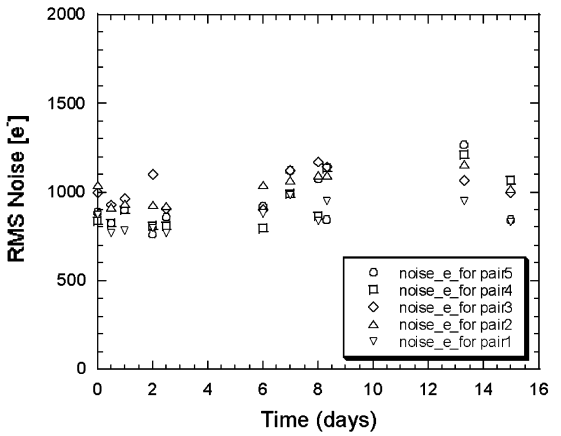

Fig. 8. Detector noise vs. time during the environmental tests indicated in Fig. 7. The noise rms was calculated from the noise occupancy as the average of groups of eight channels (Fig. 4). No systematic change in noise was seen during the different tests.

V. Environmental Tests

The use of silicon detectors in biological applications is fairly new and only limited experience on the compatibility of SSD with the environment in which biological samples are kept exists. In the PTSM, the detector board is physically separated from the read out system to allow biological samples to be prepared, handled, and stored in their proper environment without compromising the readout system. In our studies, the silicon strip detector was operated in direct contact with biological samples in order to determine if a insulating sheet (e.g., from Kapton or Mylar) is needed for the proper functioning of the PTSM under these conditions. As indicated in Fig. 9, the following tests of leakage current were done in sequence:

- saline solution;
- worms on detector surface (Fig. 9);
- worms in gel;
- plexi well glued onto SSD;
- water in well;
- saline solution in well.

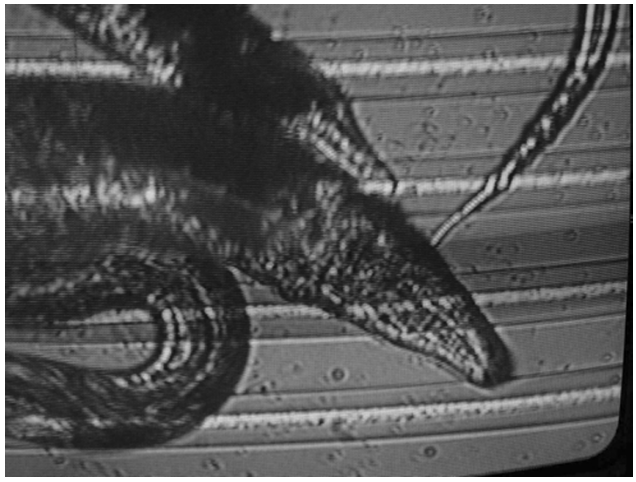

Fig. 9. *C. elegans* placed directly on the silicon strip detector with strip pitch of 50 μm, corresponding to a particle tracking resolution of approximately 15 μm (pitch/sqrt(12)).

In each case, the entire detector area was not covered. The saline solution was dropped on and held in place by surface tension; the gel was viscous enough that it did not spread. Care was taken to only cover part of the detector, the wire bonds for example were not affected in these tests. Between experiments, the SSD was cleaned using water and alcohol, as indicated by "C" in Fig. 7. The leakage current increased somewhat toward the end of these studies, which was likely associated with the use of metal probes to locate the worms in the gel, causing deep gouges in the detector surface. It is of interest that during the environmental tests the detector noise did not change, as shown in Fig. 8. We will repeat these environmental tests with more care to avoid mechanical damage to the passivation layer of the SSD, consisting of silicon oxide and nitrite. The fact that SSDs can work in contact with saline solutions had already been shown in an earlier UCSC Senior thesis [11]; our results confirm this conclusion and suggest that directly placing a worm, immobilized in gel on the surface of an SSD will not adversely effect the detector operation.

VI. Conclusion

A novel particle-tracking silicon microscope based on silicon strip detectors for application in radiobiology has been constructed, including a new ASIC for readout of double-sided silicon detectors. The use of an FPGA as a readout controller affords flexibility and speed in data reduction. Low noise rates have been achieved allowing single particle tracking. Environmental tests with biological samples indicate that the silicon detectors can be operated with the samples in direct contact with the detector (Fig. 9).

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