SCIPP 94/31
October 1994

CHARGE COLLECTION IN SILICON STRIP DETECTORS WITH A LARGE STRIP PITCH

K. Ing, T. Kurosky, R. Johnson, R. Rennels,
Santa Cruz Institute for Particle Physics,
University of California, Santa Cruz, CA 95064

Abstract

We present a study of charge collection in silicon strip detectors for which the readout pitch is equal to the thickness of the silicon wafer and is much larger than the strip width. The charge collection efficiency and signal characteristics are measured as a function of the lateral distance of the initial ionization from the strip, for various bias voltages. We find that the charge collection efficiency is significantly degraded in the region midway between strips. A simple simulation supports the hypothesis that the effect is due to interaction of drifting holes with the silicon surface. The situation could be rectified, at the expense of greater capacitance, by greatly increasing the strip width or decreasing the pitch.

I. Introduction

Silicon strip detectors have been proposed for use in a next-generation orbiting gamma-ray pair-conversion telescope [1] that would yield more than an order of magnitude improvement in sensitivity over the EGRET experiment currently operating on the Compton Gamma-Ray Observatory. Such an instrument would contain a large area of silicon detectors (nearly 80 square meters). Due to power and cooling limitations, the number of channels must be no larger than necessary, prohibiting the use of the 50 micron readout pitch that is typical in particle physics applications. In fact, due to multiple scattering of the electrons in the radiators, nearly optimal angular resolution can be achieved with a readout pitch as large as 300 microns. The channel count is also minimized by ganging several detectors in series, to give total strip lengths of up to 24 cm.

Long strips can result in large capacitance and, therefore, a poor signal-to-noise ratio. To minimize the interstrip capacitance, one would like to make the strips as narrow as possible, within the constraints imposed by strip resistance and the size of the AC coupling capacitors. Our measurements show, however, that making the strips very narrow with respect to the pitch results in poor collection of ionization from the region between strips. By observing the signals produced by an infrared laser beam scanned across the interstrip region, we have studied the time structure and efficiency of the charge collection as a function of the distance of the beam from the strip.

*This work was supported in part by a grant from the California Space Institute of the University of California, award #CS-44-94

II. The Detectors

For these measurements we used three single-sided, 300 μm thick, AC-coupled silicon strip detectors, designated Z1, Z2, and R1, which were purchased from Hamamatsu Photonics through a NASA grant to Stanford University (NAGW-3489, P.I. Peter Michelson). R1 had been irradiated with a dose of 21 krad in earlier studies of radiation damage. Each detector has an active area of 6 cm by 6 cm and is divided into six regions. Each region has p^+ implant strips of 10, 30, or 60 μm width, with alternate regions having the strips spaced at 150 μm pitch or 300 μm pitch. The implants are biased through 1 MΩ polysilicon resistors from a p^+ guard ring. Each strip implant is AC coupled to an aluminum strip separated from the implant by a layer of SiO_2 and of the same width as the implant, except for on R1, where all of the aluminum strips are 60 microns wide. The readout strips have bare aluminum pads at both ends for wire bonding. However, in the 150 μm pitch regions, only every other strip has bonding pads.

III. Experimental Apparatus

The infrared laser pulses were provided by a Berkeley Nucleonics Corporation 6040 Universal Pulse Generator model 106H. The pulse length was about 4 ns with the "width" set to its lowest value. The 1064 nm wavelength corresponds to a photon energy below the absorption edge of silicon, resulting in a long attenuation length of more than 6 times the 300 micron detector thickness. A fiber optic cable transported the laser pulse to an Alessi microscope station equipped with Mitutoyo optics and an Alessi stage and stage controller. The detector bias voltage was supplied by a Keithley 237 High Voltage Source Measurement Unit.

Presented at the IEEE Nuclear Science Symposium, Norfolk, VA, October 30–November 5, 1994

To measure the effective spot size of the ionization produced by the laser, we scanned the beam across the edge of a strip in 3 micron steps, measuring the ionization collected on the strip at each step. Since the aluminum strip completely blocks the light incident upon it, the resulting plot of ionization versus position is approximately an error function. By differentiating it and fitting the result to a gaussian, we extracted a width for the waist of the beam of $\sigma = 4.6\,\mu$m. By repeating the measurement with the focus shifted by $20\,\mu$m, we deduced an effective angle of divergence for the beam of 140 mrad. That would result in the beam never being greater than about $40\,\mu$m in r.m.s. effective width. The measurements that we report were made with the waist near the surface. If the ionization were not linearly dependent on the laser intensity, then the divergence would result in a substantial nonuniformity of ionization with depth, in spite of the long attenuation length. However, we found that the signal did vary linearly with the laser power, at least for power variations as large as a factor of two. Nonetheless, we checked that the results did not change substantially when the waist was moved $100\,\mu$m into the silicon.

Detector Z1 was mounted on a hybrid built for the Leading Proton Spectrometer of the Zeus HERA experiment at DESY. That allowed us to make use of the Zeus readout electronics, consisting of a bipolar amplifier-discriminator, followed by a CMOS digital readout chip [2]. A Macintosh computer controlled the microscope stage, the laser triggering, and the data acquisition system [3]. The laser power was set to 38 mW, and the "width" was set to 1, which resulted in about half the ionization that would be deposited by a minimum-ionizing particle. To obtain pulse size measurements from this binary readout system, at each position of the beam on the detector we scanned the comparator threshold over a wide range. At each comparator setting 100 laser pulses were measured, and a plot was made of the fraction of times that the comparator fired versus threshold. The resulting "threshold curve" was fit to extract the signal level. A similar method was used in conjunction with the amplifier calibration inputs to calibrate the gain and pedestal of each channel.

Detectors Z2 and R1 were mounted on copper clad G-10 boards, allowing two adjacent readout strips to be wire bonded to large pads from which short $50\,\Omega$ cables from an external amplifier could be connected. A Hewlett-Packard 8447D Amplifier with a 1.3 GHz bandwidth, $50\,\Omega$ input impedance, and 26 dB gain was used in order to preserve the time structure of the signal. The amplified signals were viewed on a Tektronix TDS 540 Digitizing Oscilloscope by averaging 1000 pulses. For each measurement a baseline was obtained by pulsing the laser with zero power and was subtracted from the signal measurement.

Detector R1 was irradiated twice with a Co^{60} source at UCSC [4], although not originally for the purpose of this study. The dose rate was 15 krad/hr in silicon, for a total dose of 21 krad. The detector was reverse biased at 50 V at all times during exposure. A period of two months passed between the exposure and the first measurements.

IV. Experimental Results

A plot of the collected charge from Z1 as a function of position transverse to the strips is given in Fig. 1. When

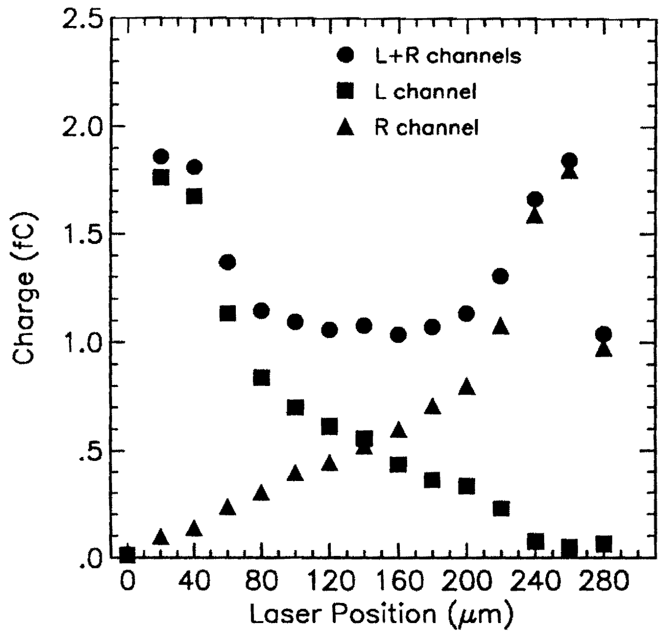

Figure 1: The collected charge as a function of interstrip position for detector Z1, in the $300\,\mu$m pitch, $30\,\mu$m width region. The detector bias voltage was 100 V.

the beam is directly over a strip it is blocked by the aluminum. However, the full signal can be seen about $20\,\mu$m from the strip edge. Further from the edge the signal becomes shared between the two strips, but the sum of the two strip measurements falls off by nearly a factor of two in the center, with respect to the measurements made near the strips.

To check that the effect is not due to insufficient depletion of the detector, we repeated the measurements at several bias voltages. The results are shown in Fig 2. It is evident that the detector does not fully deplete until a bias voltage of about 100 V is reached. However, the ratio of the signal collected midway between strips to that collected adjacent to a strip is almost independent of bias voltage, even when it is raised far above the depletion voltage.

To further investigate this affect, we made detailed measurements of the pulse shapes from detectors Z2 and R1 with the fast HP amplifier and the digitizing oscilloscope. The loss of signal in the interstrip region was also observed by this method, in which the signal size was taken to be the integral of the pulse observed on the oscilloscope (which

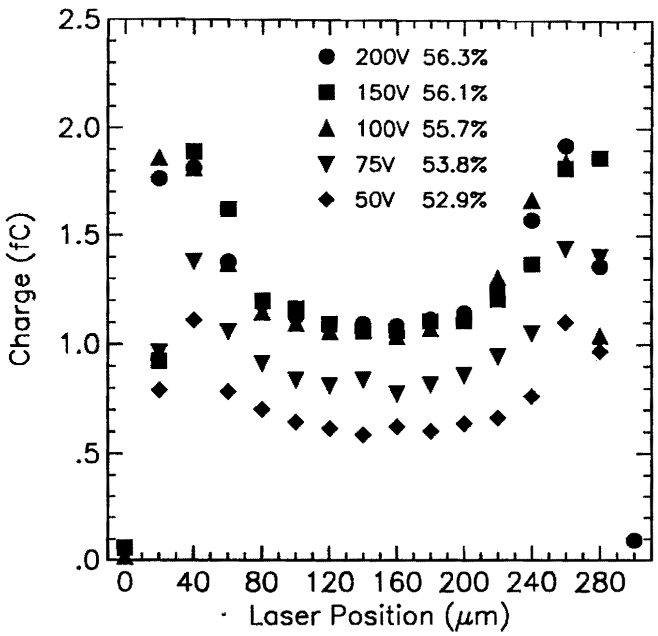

Figure 2: The collected charge as a function of interstrip position and bias voltage for the 300 μm pitch, 30 μm width region of detector Z1. The percentage values indicate the ratio of charge collected in the center to that collected near a strip. Only the sum of signals from the two adjacent strips is shown.

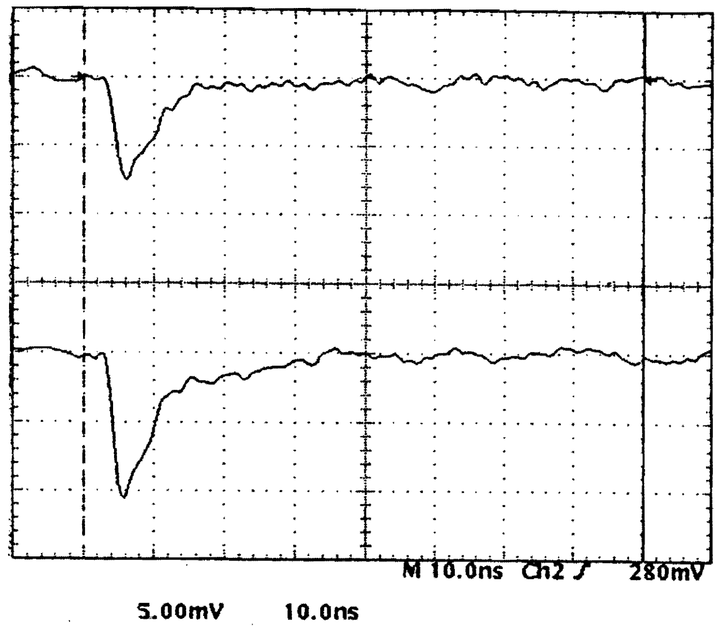

Figure 3: Oscilloscope traces from detector Z2, in the 300 μm pitch, 30 μm width region. The amplifier output was averaged over 1000 pulses to remove random noise. The laser power was set to 45 mW with the "width" equal to 1. The lower trace is from a laser pulse 20 μm from the edge of a strip, while the upper trace is from a pulse centered between the strips. The ratio of areas of the two pulses is 0.72.

because of the short ($\approx$ 35 ns) integration time of the Zeus electronics is not necessarily equivalent to the discrimination method used for detector Z1). Figure 3 shows an oscilloscope trace of a signal produced near a strip and one produced halfway between strips. The pulse from halfway between strips is about 30% smaller in area than the other, and there is some evidence that the loss at large times is greater than the loss at short times. Since the late signal is largely due to movement of holes, this suggests that the hole current is affected more than the electron current.

We also checked that there is no dependence of the results on the position of the laser along the strip direction. The irradiated detector, R1, shows the same behavior as Z2. Because the intermediate strips in the regions with 150 μm strip pitch are covered with glass and have no bonding pads, we were not able to repeat the measurements with a smaller pitch. We did look at the region of Z1 with 60 μm wide strips and 300 μm pitch and found no significant improvement over the region with 30 μm wide strips. Finally, there are some indications that the effect decreases as the laser power is increased.

V. Simulations

In order to understand the effects that we observed in the laboratory, we have attempted to simulate the charge collection in wide-pitch, narrow strip detectors. Our simulation is based on a program used in previous work [5], except that we replaced the electric field calculation. Whether or not the effects that we have observed can be reproduced in the simulation depends on what is assumed for the characteristics of the silicon surface region between the strips. In Ref. 5 the component of the field perpendicular to that boundary was assumed to be zero, which resulted in all of the field lines converging on the strips from within the silicon. To produce such a field, however, would require potential differences as high as the full bias voltage along the interstrip surface. Such potentials would not be sustainable. Alternatively, since the accumulation layer resulting from fixed positive charge in the surface oxide results in some surface conductivity, one could impose the condition that the potential be constant along the interstrip boundary. That would result in a parallel-plate configuration with field lines perpendicular to the surface everywhere, such that holes produced by minimum ionizing particles would drift straight to the surface.

We hypothesize that the signal loss between strips is due to the lack of signal from holes which drift to the surface instead of toward the strips. What happens to them after they reach the surface is not so clear. They might be trapped or otherwise have a sufficiently reduced mobility that they are not able to move to the strips fast enough to contribute to the signal. To simulate this, we assumed that the holes simply vanish upon reaching the surface, and we assumed the surface region not covered by aluminum to be a simple dielectric interface between silicon and air. Therefore, we included the region exterior to the silicon when we calculated the electric fields, and we ignored any conductivity or fixed charges at the surface. An artificial boundary at zero potential was placed about 2 mm above the detector, while periodic boundary conditions were used at the sides. Figure 4a shows equipotential lines for the resulting field configuration. Evidently, holes produced in most of the interstrip region would drift into the silicon-air interface rather than to a strip.

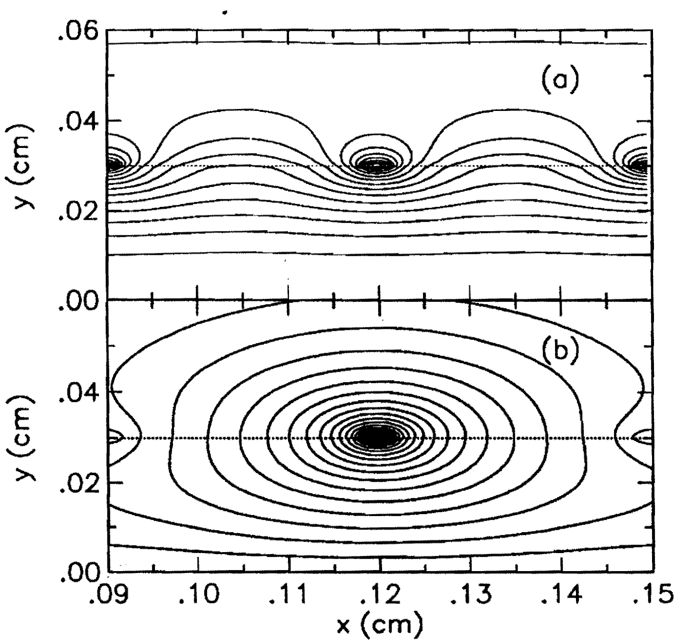

Figure 4: Equipotential lines for the drift field $\vec{E}_d$ (a) and the weighting field $\vec{E}_w$ (b) calculated for a detector with a pitch of 300 μm and a strip width of 30 μm. The surface area between strips is assumed to be nonconducting and free of charge (except for the dielectric's polarization charge). The current on the strip due to a charge q drifting with velocity $\vec{v}$ is given by $I = q\vec{E}_w \cdot \vec{v}$, with $\vec{v}$ proportional to $\vec{E}_d$.

To calculate the current resulting from drifting holes, we used a "weighting field" in the same way as Ref. 5, which was calculated by putting a 1-volt potential on a single strip and grounding all other conducting surfaces (8 strips were used in the calculation, with periodic boundary conditions at the sides). That field is shown in Fig. 4b. By comparing it with Fig. 4a, it is evident that drifting holes in the interstrip region tend to move parallel to equipotential lines of the weighting field and therefore contribute negligibly to the current signal. Only if after reaching the surface they subsequently moved along it toward a strip would they contribute substantially to the signal. In all cases the electrons liberated by ionizing particles drift nearly directly to the backplane and contribute fully to the signal, regardless of position.

The detailed simulation of drifting ionization follows our expectations, when it is assumed that drifting holes stop upon reaching the dielectric surface. Figure 5 shows that when the particle passes through midway between strips the current signal from drifting holes is reduced by about a factor of 5 with respect to particles passing near a strip. The electron signal is unaffected, except that it is slightly delayed when the particle passes midway between strips. Figure 6 shows a plot of the integrated pulse as a function of the distance from the strips. When the currents on the two adjacent strips are summed, the resulting signal is a full factor of two less for a particle midway between strips, compared with a particle only 20 μm from the strip center. The situation midway between strips is similar for geometries with narrow pitch. However, in that case the region in which the signal loss is severe becomes relatively small and insignificant.

The simulation does predict a significant loss of signal from the interstrip region, but it oversimplifies the surface properties of the silicon and the issue of what happens to drifting holes after they reach the surface. We also have not included properties of the laser beam, such as its attenuation length, spot-size, and divergence, all of which would have to be done to make a quantitative comparison with our measurements. Nonetheless, our results support the hypothesis that interaction of the drifting charge with the surface results in the poor charge collection that we observe in the interstrip region. Whether or not the surface is assumed to be conductive or a simple dielectric results in either case to the holes drifting into the surface. Therefore, one must consider the effect of the surface itself on the motion of the holes. It may be that for time scales of at least the order of tens of nanoseconds the holes stop moving once they encounter the surface.

VI. Conclusions

Our measurements have shown that, although silicon strip detectors with strips that are very narrow with respect to the pitch are attractive from the point of view of low capacitance, in the case where the pitch approaches the detector thickness, the signal collection from the region between strips is degraded with respect to the region under

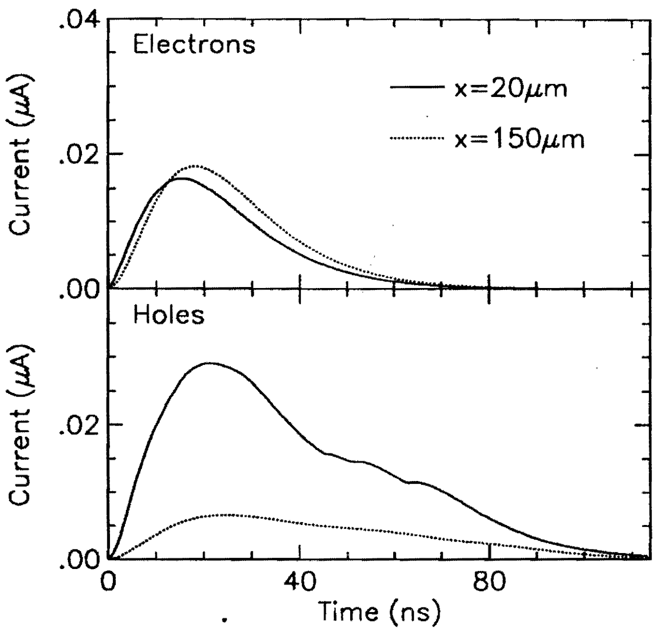

Figure 5: The simulated strip current, summed over two adjacent strips, due to a minimum ionizing particle passed perpendicularly through a 300 μm pitch silicon strip detector. The electron and hole contributions are shown separately for each of two distances from one of the 30 μm wide strips. Since more holes than electrons drift through the region of large weighting field, they dominate the signal on the p-strips. RC/CR shaping of the signal is simulated, with a time constant of 10 ns.

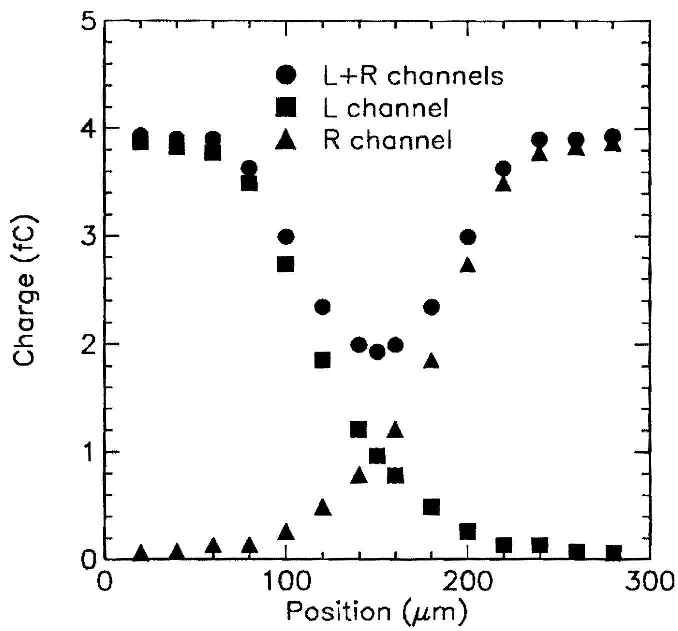

Figure 6: Simulation of the charge collected on two adjacent strips as a function of the distance of the minimum ionizing particle from one of the strips.

the strips. A simple model has been found that reproduces the effect, but we still have a poor understanding of the interaction of the drifting holes with the silicon surface.

The problem with the charge collection can be avoided, at the risk of a substantial increase in capacitance and equivalent noise charge (ENC), by reducing the strip pitch or by increasing the strip width. If the pitch is reduced, for example to 150 μm, while retaining narrow strips, then it is important that all of the strips be connected to the readout, either individually or ganged. At a pitch of 150 μm with 30 μm width or less, the interstrip capacitance is not sufficiently large compared with the capacitance to the back plane to ensure adequate charge collection by capacitive coupling. For a given pitch, the problem can also be alleviated, without a capacitance penalty, by going to thicker detectors. The increased multiple scattering would not be significant for a pair-conversion telescope. In general, in order to optimize the system, the poor charge collection that results from narrow strips must be balanced against the increased ENC that would result from decreasing the pitch or increasing the strip width.

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