INVESTIGATION OF THE USE OF CHARGE COUPLED DEVICES AS HIGH RESOLUTION POSITION SENSITIVE DETECTORS OF IONIZING RADIATION

A. Bross

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Introduction

The use of charge-coupled devices (CCD's) as analog shift registers, optical imagers, and high density memories has been successfully demonstrated during the past ten years. CCD's are capable of very low noise operation (a S/N ratio of 1:1 with 10 electrons per pixel has been demonstrated) and, as imagers, afford high resolution and precise image geometry and stability. The signal charge can be electrically injected into the device via an input structure, can be generated internally by photoelectric processes or, as we shall show, can result from the creation of electron-hole pairs by energetic charged particles.

Basically a CCD is a metal-oxide-semiconductor (MOS) structure forming an array of capacitors. The MOS capacitors are capable of collecting and storing in discrete packets (buckets) charge that has been "injected" into the device by one or more of the mechanisms described above. If the capacitors are packed closely together, charge stored in a particular capacitor (pixel) can be transferred to an adjacent pixel by applying clocking voltages to transfer electrodes. In this fashion charge collected at any one pixel may be moved to an output structure on the CCD device, and an analog signal proportional to the charge stored at that site may be obtained. For a complete discussion of the CCD concept and device implementation we refer the reader to the literature.[2,3]

There are two basic approaches we can take in order to utilize CCD's as particle detectors. The first is to use monolithic CCD area arrays. Commercially available optical CCD imagers are the most common example of this technology. They have been fabricated in formats as large as 800 x 800 elements with cell sizes as small as 15 microns. The sensitive thickness of devices of this type is limited to the depth of the deletion region (5-10 μm) and thus limits the signal that one can obtain to approximately 500-1000 electrons per track. In order to increase the amount of this signal charge, a CCD with a much thicker depletion depth would be required. However, the problems involved in fabricating a monolithic CCD with a thick depletion region (upwards of 100 μm) are quite substantial, and the current level of CCD technological expertise appears to be inadequate to develop such a device.

The second approach circumvents this problem by introducing the use of hybrid CCD detectors. In this scheme the detector (usually a silicon device) and the CCD multiplexer are separate devices. Charge collected in the detector is injected into the CCD via microscopic metallic interconnects (one per CCD pixel). The advantage of this technique is that both the detector and the CCD can be optimized for the desired performance characteristics. In this way the silicon detector can be made relatively thick and still give excellent charge collection efficiency throughout its volume.

Monolithic CCD Area Array Detectors

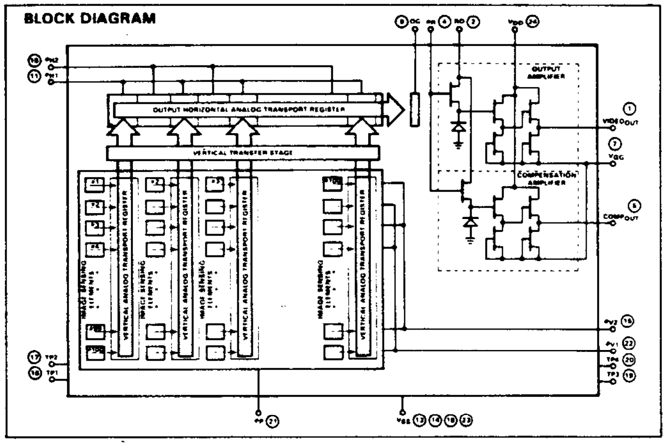
It has already been reported[4-5] that cooled optical CCD's are sensitive to the passage of charged particles. In fact in long exposures for some optical astronomy observations cosmic rays present a significant background problem. If we assume that a minimum ionizing particle penetrates a CCD, the amount of charge deposited within the depletion region (typically 10 microns) is:

$$[2.33\text{g/cm}^3 \times 1.66\ \text{MeV/g/cm}^2 \times 10^{-3}\ \text{cm} \times (3.81\ \text{eV/e}^-)^{-1}] = 1070\ \text{electrons}^6$$

A S/N ratio of 20:1 is therefore obtainable for minimum ionizing events using many commercial CCD's provided that they are cooled.

Fairchild 202

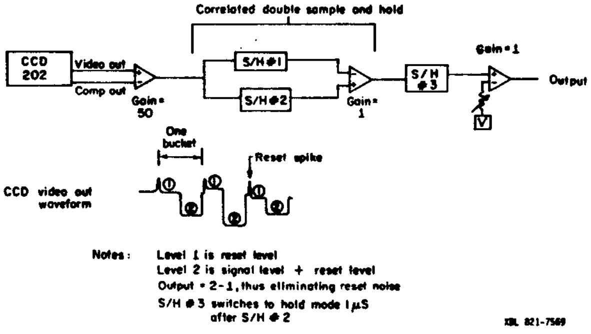
Operational Characteristics. We have recently completed studies involving the Fairchild 202 CCD, a 100 x 100-element interline transfer area imager. (See Figure 1.) The device utilizes two-phase buried channel technology in a 30 μm x 40 μm cell format. The readout is parallel/serial to an on-chip amplifier.



XBL 8112-12948

Fig. 1. Functional Block Diagram for Fairchild 202. (c) 1976. Fairchild Semiconductor Components Group, Fairchild Camera and Instrument Corporation.

The readout rate used for our measurements was 100 kHz. Video processing consisted of a differential amplifier stage with a gain of 50 followed by a double correlated sample and hold (Figure 2). An optical



XBL 821-7569

Fig. 2. CCD output circuit and waveform. The correlated double sample/hold processing function is also shown.

setup projected a standard TV bar pattern resolution chart (Figure 3) onto the CCD and was used for clock driver optimization.

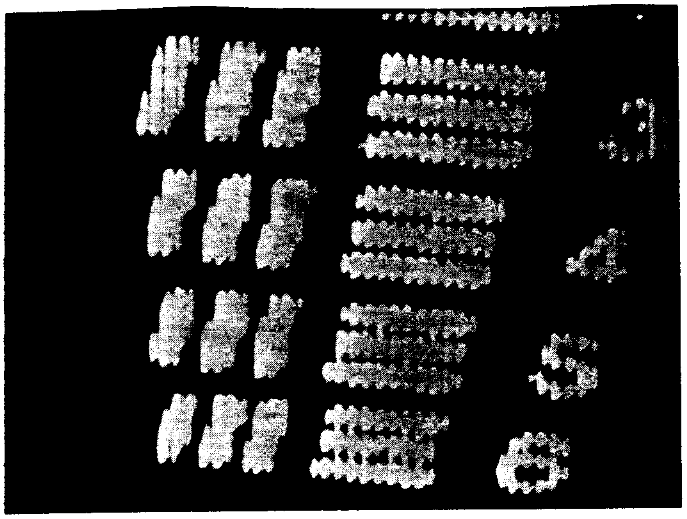


Fig. 3. Optical setup video display. The line-to-line spacing for the smallest set of horizontal lines is approximately 4 pixels.

Sr^{90} Exposure. The CCD was mounted in a cryostat (Figure 4) and operated at temperatures between 145° and 210°K. The 202 was then exposed to a Sr^{90} source and read out continuously at the 100 kHz pixel rate. Figure 5 shows the CCD output displayed on a video monitor showing single hits due to beta's from the Sr source. Each dot in Figure 5 represents a single pixel with a spatial resolution of 30 μm x 40 μm. The CCD output was also sent to a multichannel analyzer in order to obtain the pulse height spectrum from the exposure. The 202 has a depletion depth of 7 μm ± 1 μm; therefore, for a minimum ionizing particle we would expect approximately 700 electrons. From Figure 6 the most probable value for energy loss is approximately 610 electrons. The mean value is channel 280 corresponding to 1050 electrons. The spectrum exhibits a typical Landau tail and has a most probable value agreeing quite well with what we would expect for a 6 μm-8 μm depletion depth. The measured rms noise from the 202/processor system was between 200 and 250 electrons. A threshold cut at channel 120 was used to obtain Figure 6. The detection efficiency for the 202 system averaged over a number of runs was measured to be 50-60%. This measurement was accomplished by

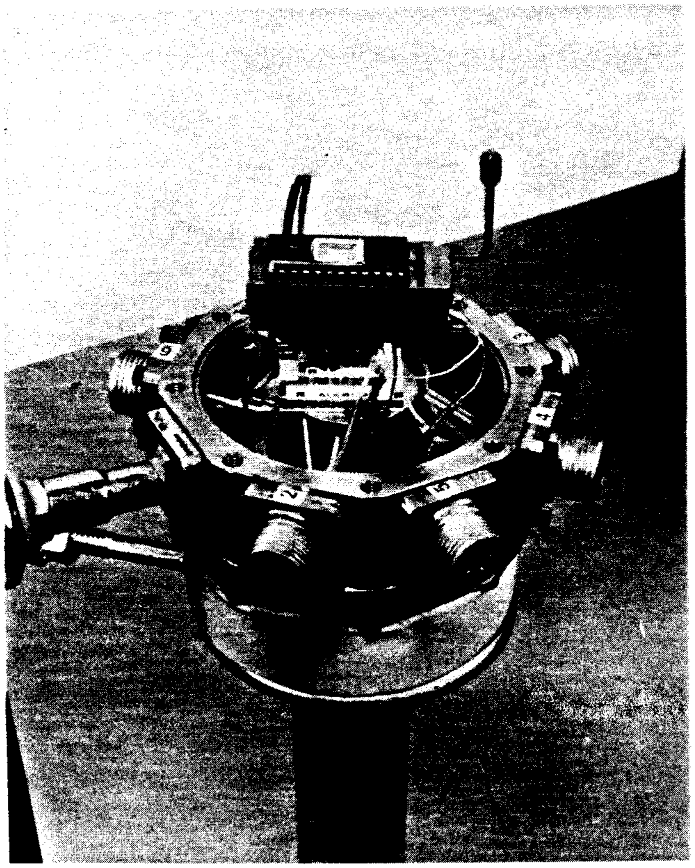


Fig. 4. CCD Cryostat.

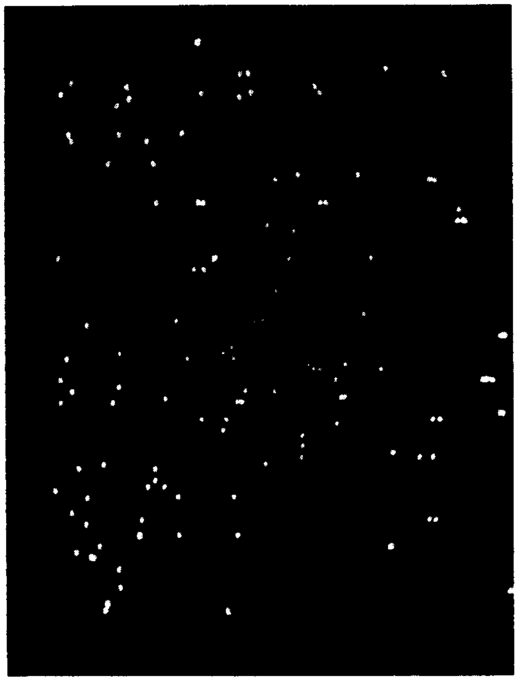


Fig. 5. Single hit Video Display Events from Sr beta's.

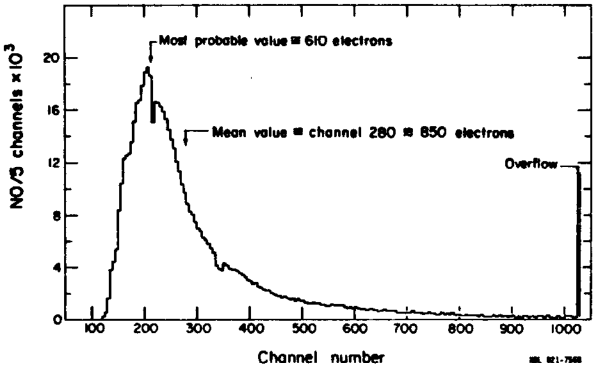
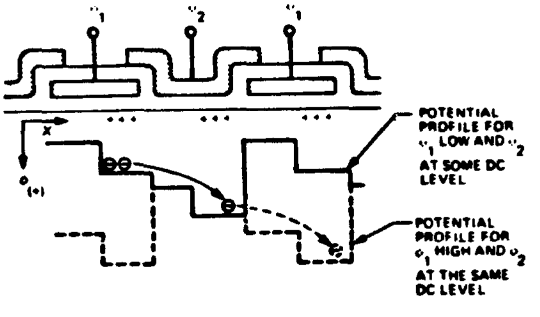


Fig. 6. Pulse height spectrum for Sr^{90} beta's. Effective detector thickness = CCD depletion depth = 7 microns.

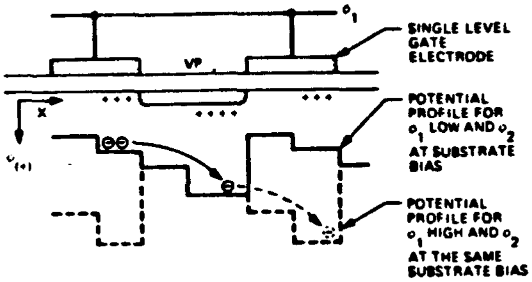
masking off a thick scintillator to give a 3 mm x 4 mm window corresponding to the active (sensitive) area of the 202. We then placed the scintillator in the same geometric relationship to the source as was done with the 202 and measured the count rate (window open) - count rate (window closed). This number was defined as the 100% efficient count rate to which the CCD rate was compared. The CCD efficiency number was limited by the relatively high noise value we obtained for this chip which was due in part to our clock driver electronics and in part to a relatively high noise value for the particular 202 chip we were using. An optical system using a 202 CCD has reported[7] a noise figure of 30 electrons, and we believe this number is more indicative of the noise characteristics that are obtainable with the 202.

Virtual Phase CCD

We are also beginning work using a Texas Instruments 200 x 200 element area array based on the virtual phase-buried channel technology. Virtual phase devices function in a manner similar to a two-phase operation where one of the phases is kept at a constant D.C. potential and the other phase clocked above and below this level. Thus in this way only a single clock is needed to drive the CCD. See Figure 7 (Ref. 8). In the virtual phase device the "D.C. clock" electrode is not placed over the oxide layer but is built into the surface of the silicon by an ion implant. This biases this "D.C. phase" of the device at the substrate potential. The directionality of the transfer is defined by the doping profile used to define the clocked and virtual sections in the silicon. The advantages of the "virtual phase" technology are: 1.Simplified fabrication procedures giving the possibility for much higher yields and the ability to build very large devices, 2. High reliability, 3. Low dark current, and 4. High resistance to radiation damage. Virtual phase devices have exhibited dark current values an order of magnitude better than other buried channel CCD's. It is the fabrication procedure used for VP CCD's that yields oxide layers that have much better radiation hardness than those obtained in multiple phase technologies. Virtual phase CCD's given an exposure of 10^5 RAD have shown no measureable increase in dark current (versus a 20-fold increase for a 3-phase device at an exposure level of 10^4 RAD).[9] A group at the Jet Propulsion Laboratory working with a Texas Instruments 800 x 800 VP CCD imager has measured the dark current for the device to be 0.4 nA/cm^2(25 C) with a noise floor of 18 e's/pixel. This device was exposed to a Sr^{90} beta source and gave a most probable energy loss corresponding to approximately 700 electrons.



Two-phase operation.



Virtual Phase electrode.

Fig. 7. Two-phase CCD operation vs. Virtual-phase operation.

Our current plans at LBL involving the TI VP CCD's include device studies and characterization of dark current, min noise floor, maximum operable clock frequency and studies of possible readout problems encountered when operating the devices in high magnetic fields. Beam studies involving a three-plane CCD spectrometer are also envisioned for the near future. These studies are needed to accurately measure CCD tracking resolution and efficiency. In addition, we can study the one dimensional mode of CCD operation in this environment. Normal CCD readout requires that one row at a time be loaded into the output register and then read out, thus retaining X-Y information (Figure 8). Alternatively, the information from all the rows in the CCD can be summed in the output register, and then this register need only be read out once instead of many times per CCD read. Only one-dimensional information is retained, but the readout time is substantially reduced. This scheme increases the usefulness of monolithic CCD systems for fixed target accelerator experiments, since readout time for this mode of operation can be as short as 50 μS. CCD's operated in this manner are functionally equivalent to a microstrip detector with a built-in readout structure.

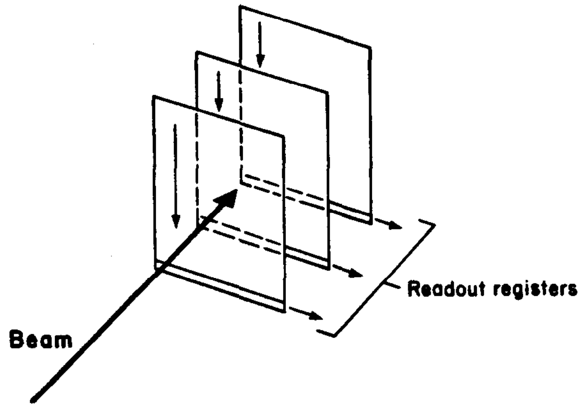


Fig. 8. CCD Planar spectrometer, operable in either one- or two-dimensional modes.

One Application - A CCD Vertex Detector for the Stanford Linear Collider.

Assuming the viability of the VP CCD for HEP experiments, we can visualize a vertex detector for the SLC based on 120 CCD's. The SLC is an ideal accelerator for this system, since the proposed beam pipe for the machine is only 1 cm in diameter, and the repetition rate of 180 pulses per second allows for a relatively long readout time. The basic detector in this system would be a commercial optical CCD. The most probable format would be 500 x 400 elements with a cell size of 15-30 μm. Using a 20 μm cell size, the system in Figure 9 uses 120 CCD's with overlapping concentric planes in order to get efficient solid angle coverage. This detector would cover 45° with respect to the beam. Solid angle coverage could be increased, of course, by adding additional CCD's. (60° coverage would require

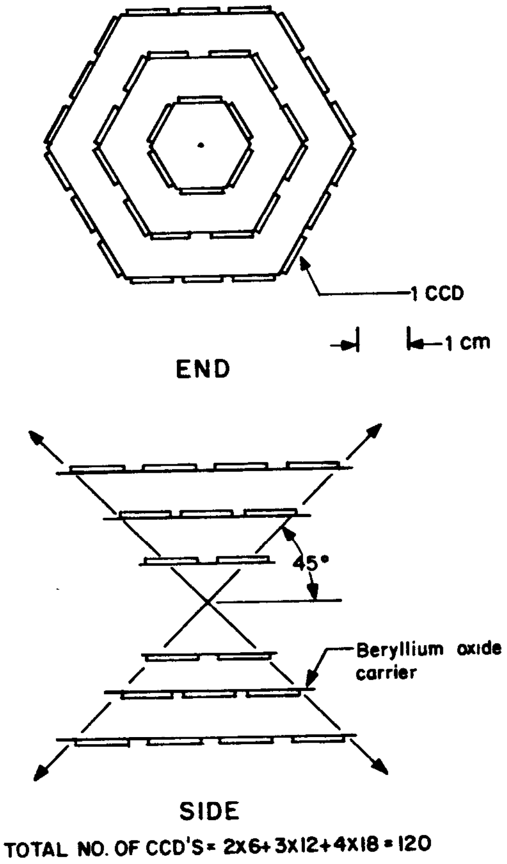


Fig. 9. End and side views of CCD vertex detector system for the SLC.

approximately 220 CCD's.) The total number of elements is 2.4 x 10^7, but there are only 120 output channels. Readout time for the system would be on the order of 10-15 mS. Also, due to the x-y nature of the CCD's, the tracking is unambiguous, each plane giving both x and y coordinates. Beryllium oxide that was copper clad and then etched could be used as the chip carrier, thus providing input and output lines and a cooling substrate. Rough estimates on the cost of such a system are

CCD's	120 x \$500 = \$60k
Electronics	120 x \$800 = \$96k (including FLASH ADC's)
Carrier/Fixturing	\$150k?

Our general conclusion concerning monolithic CCD's is that emerging commercial CCD technology is producing devices that will be able to detect minimum ionizing particles with nearly 100% efficiency (within the chip's active area) with pixel sizes as small as 15 μm x 15 μm and formats as large as 800 x 800 elements. In addition, the radiation hardness of some of these devices appears to make them useful as detectors for High Energy Physics Experiments. These devices present great promise as high resolution vertex detectors in experiments where the cross sectional area of the CCD system does not have to be excessively large.

Hybrid CCD's

As we mentioned above, in this approach the detector and the CCD multiplexer are separate devices. This allows for great flexibility in designing the detector, since we are not restricted by the CCD parameters.

Rockwell 30311

Our current hybrid work involves studies of the Rockwell International 30311 CCD multiplexer using a general purpose CCD driving system and low-noise correlated double sample and hold processor. The CCD is a 32 x 32 element area array with 88 μm x 88 μm cell size using a 4-phase surface channel structure. A diagram of the injection scheme is shown in Figure 10. Charge collected from the detector is injected into the CCD via the input diffusion and stored under the storage gate. Readout is accomplished by transferring the charge under the storage gate to the CCD shift registers (array mux gate) to be read out in typical parallel/serial fashion. Data rates for this device are a maximum of approximately 1 MHz. The connection between the detector and the CCD is accomplished via microscopic indium bumps. The bump pattern applied to the detector corresponds to the CCD input node geometry. The CCD and the detector are then aligned in a microscope and cold-weld bonded together. With the use of a number of CCD multiplexers to read out a single detector, a bulk CCD can be fabricated. A detector designed in this fashion and used as an active target in a fixed target experiment is depicted in Figure 11.

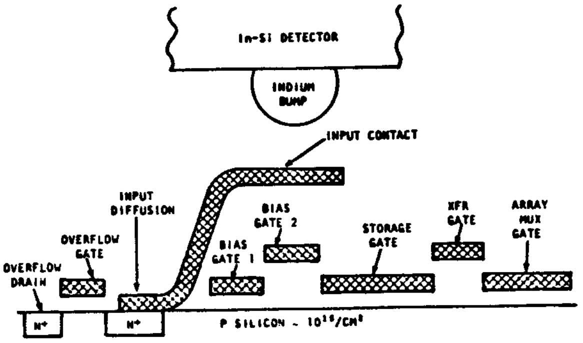


Fig. 10. Cell structure and injection scheme for Rockwell 30311.

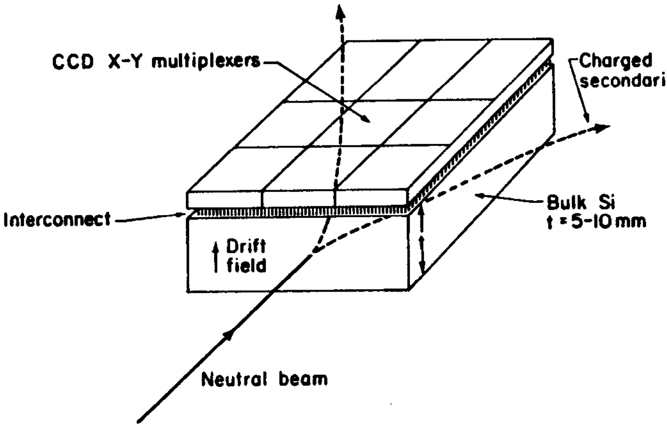


Fig. 11. Bulk CCD Detector.

Due to the flexibility of the hybrid design, this target system can be configured to suit the requirements of a particular experiment (segmented target etc.). In addition, readout rates of 10 mHz are possible with some hybrid devices, so a detector using fast CCD's with a 32 x 32-element format would have a system readout time of approximately 100 μS. This active target would thus be fast enough to provide secondary level trigger decisions in addition to particle tracking data.

Micro Needle Detector

Another possible (but somewhat speculative) application of hybrid CCD arrays would be their use as the readout structure for what we have called the micro needle detector. The operation of the needle detector has been demonstrated;[11] but their widespread application has been limited due to their relatively poor resolution and by the lack of a simplified readout scheme to be used in conjunction with the needles. What we envision is an integrated approach to the "needle" design. With the use of standard MOS integrated circuit fabrication techniques the structure in Figure 12 could be produced. The "needle" detector could be fabricated on a silicon substrate with aluminum needles grown into etched holes. Silicon dioxide would be used as an insulator and the metallic focussing electrode is aluminum. This structure is very simple by IC standards, and a 50-100 μm needle spacing makes the dimensions large compared to those typical in IC fabrication practices. The coupling to the CCD (shown below the needle detector in Figure 12) would be accomplished using the indium bump technique, as we have discussed above. Figure 13 shows an electrostatic field calculation using the needle structure shown in Figure 11. With the proper voltage applied to the metallic electrode, the correct field shaping can be achieved for getting good field mapping of the active volume onto the needle and sufficient field strength near the needle in order to start an avalanche. There are obvious advantages to such a gas/silicon hybrid. Since the "active" volume is gaseous it can be made very large compared to what could be done with a solid state device. Of course, what is obtained is a two-dimensional projection of the event onto the needle plane with the charge collected by the needle injected into the CCD. The needle plane would be limited in size by the CCD structure. The signal strength (upwards of 10^6 electrons) would make CCD signal processing extremely simple, and the problem of reading many needle channels is, of course, solved by the CCD.

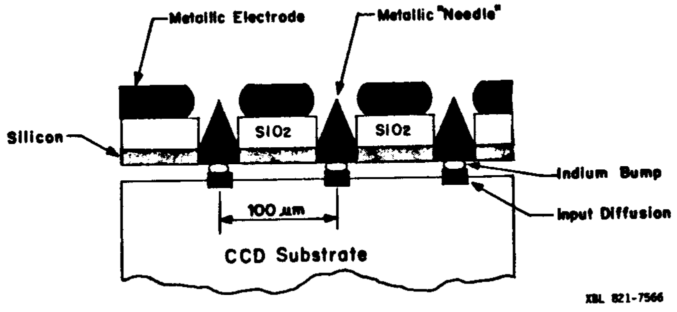


Fig. 12. Micro needle structure "bumped" to CCD multiplexer

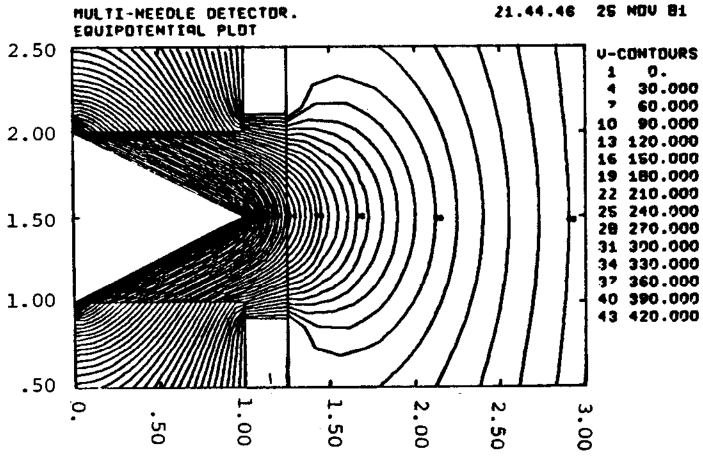


Fig. 13. Electrostatic equipotential plot for a single cell of the micro needle detector.

The main questions concern electrostatic stability and CCD survivability. The electrostatic stability of the needle structure would depend heavily on the fabrication steps involved in the production of the needle devices. The simplicity of the design, however, would help to minimize variations in the final product. CCD survivability in this environment is an open question and can only be determined accurately once a suitable needle structure has been developed.

Conclusion

We believe that 100% detection efficiency for minimum ionizing particles is possible with a number of commercially available optical CCD's (within their active area). The VP CCD technology seems to be able to produce devices that have the resolution, low noise and radiation hardness qualities that will be needed to be useful as high resolution detectors for HEP.

Hybrid CCD detectors, using a much more sophisticated technology, present the possibility of producing CCD detectors with a much thicker active volume with a very small dead region. These detectors could be used as "active" targets at fixed-target accelerators. "Thick" CCD detectors, if used to track particles normal to their surface, as we have done with optical CCD's, could be operated without cooling and would have very little dead area, since bonding pad structures are on the backside of the detector.

Charge Coupled Devices present great promise as high resolution vertex detectors in experiments where the cross sectional area of the CCD system is not excessively large.

References

1. Wen, D. D., "Low Light Level Performance of CCD Image Sensors," Proc. 175 Int. Conf. Solid-State Circuits, Vol. SC-9, pp. 410-414, 1974.
2. Sequin, C. H. and Tompsett, M. F., Charge-Transfer Devices, Academic Press Inc., 1975.
3. Barbe, P. F., "Imaging Devices Using the Charge-Coupled Concept," Proc. of IEEE, Vol. 63, No. 1, January, 1975.
4. Marcus, S., Nelson, R., and Lynds, R., "Preliminary Evaluation of a Fairchild CCD 221 and a New Camera System," SPIE, - Proc., Vol. 172, 1979.
5. Meyer, S. S., "Astronomical Spectrometer Using a Charge Coupled Device Detector," Rev. Sci. Instrum., 51 (5), May 1980, p. 638.
6. Bertolini, G., and Coche, A., Semiconductor Detectors, John Wiley and Sons, Inc., 1968.
7. Op. cit., Meyer, p. 638.
8. Janesick, J. R., Hynecek, J., and Blouke, M. M., "A Virtual Phase Imager for Galileo," SPIE Proc. Vol. 290, p. 165.
9. Op. cit., Janesick, p. 168.
10. Janesick, J. R., Private communication.
11. Grunberg, C., and LeDevehat, J., "The Needle Chamber: A New Highly Versatile Detector," Nucl. Inst. and Methods, 118, 1974, p. 457-463.