

Project name

Development of radiation hard, 3D-electrode array, silicon radiation sensors

Classification (accelerator/detector:subsystem)

Accelerator—L.E.P. (detector for low energy e^+e^- pairs for luminosity optimization) and possible use in the lumi cal or other detectors exposed to high radiation-doses.

Institution and personnel

University of Hawaii, Department of Physics: Sherwood I. Parker (faculty)

Collaborators

Christopher Kenney (Molecular Biology Consortium), Cinzia Da Via, Jasmine Hasi, and Angela Kok (Brunel University.), Hitoshi Yamamoto (Tohoku University). As part of this project involves the fabrication of more than one type of sensor on the silicon wafers, other members of these groups might also join in that part of the work. We are also collaborating, in other aspects of 3D sensor development, with members of the Atlas pixel group, the Totem collaboration, John Morse of ESRF, and other members of the Molecular Biology Consortium.

Project Leader

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Project Overview

We are developing silicon sensors with closely spaced electrodes that penetrate the silicon substrate for uses in which either (1) extreme speed, (2) radiation hardness or (3) the ability to detect particles very close to the beam pipe is important. A beam monitor using the process $\gamma\gamma \rightarrow e^+e^-$ that makes use of these properties will be described. The general technology being developed could also be applied to other detectors needing high resistance to the effects of radiation damage or sensitivity to their physical edges.

Broader Impact

Other than the training of the graduate student Angela Kok (from Hong Kong) and the former student and now post doc on this project, Jasmine Hasi, the main, relatively immediate impact of 3D sensor technology is expected to be in the field of structural molecular biology, and ultimately, medicine. The human genome project has given us information on the sequence of base pairs in DNA, but not on the vitally important shape information for the proteins specified by DNA. That is the object of many tens of dedicated synchrotron x-ray beam lines around the world. Most of them use scintillator – fiber optic – CCD detector systems that their developer, Edwin Westbrook (M.D., Ph. D., Molecular Biology Consortium), with whom we are now working, considers obsolete compared with our 3D active-edge system, now under development. This project,

supported by the National Institutes of Health [1], has successfully developed and tested its initial test detectors. In addition this technology will be broadly applicable to semiconductor radiation detectors, including other experiments in high-energy physics. It is currently being considered for use in two LHC experiments, Totem and the Atlas pixel upgrade.

Results of Prior Research

Working in collaboration with Christopher Kenney of the Molecular Biology Consortium and Cinzia Da Via, Jasmine Hasi, and Angela Kok of Burrell University, we have fabricated and tested sensors that are 120 to 250 microns thick. (See Figure 1.) All recently fabricated sensors have active edges—etched, rather than sawed edges, in which implant and oxidation steps have made the edges into an electrode.

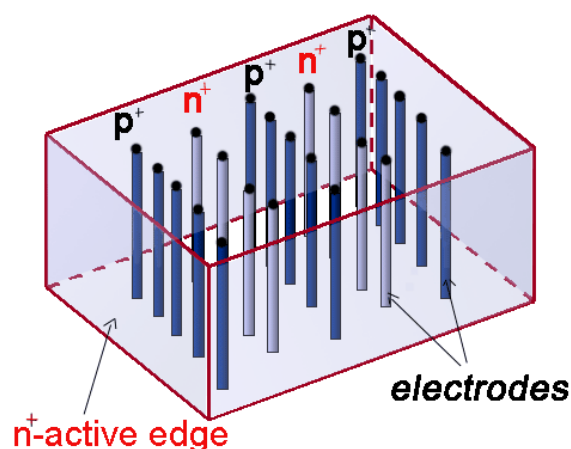


Figure 1: Schematic sketch of a 3D sensor.

Initial calculations indicated it should be possible to have sensors with low depletion voltages and great speed and radiation resistance [2]. Published data now show:

1. depletion voltages as low as 5-10V [3],
2. depletion voltages of only 105V after irradiation by 10^{15} 55 MeV protons/cm² (equivalent to 1.8×10^{15} neutrons/cm²) with a plateau to 150V for sensors without added oxygen and without beneficial annealing [4],
3. room-temperature pulse rise times of only 3.5 ns, and needing only 40V bias, even after irradiation by 10^{15} 24 GeV protons/cm² [5],
4. a Gaussian fit with $\sigma(E)/E$ of 2% to the 14 KeV x-ray line from a ²⁴¹Am source with no excess of points on the left side, from events with partial charge collection [6, Fig. 7].
5. Tests of active electrodes, fabricated from trenches with steps that were similar to those for our new active-edge electrodes, indicated high collection efficiency [7].

Pulses from 3D sensors can be shorter because collection distances are shorter, for any given maximum field, average fields can be higher, and for perpendicular tracks, the signals are concentrated in time as the track arrives, rather than spread out in time as is the case with planar sensors. (Most of the signal is induced when the charge is close to the electrode where the Ramo weighting field and electrode solid angle are large.)

We have measured pulses from a 3D sensor exposed to betas from a ^{90}Sr source, in which only (1) and (2) apply. Figure 2 shows both prior [5] and, in (c) recent results. Figure 2a and 2b use an amplifier described in [8]. With the selection of the cold technology collider and its 337 ns collision spacing, this speed no longer is so important.

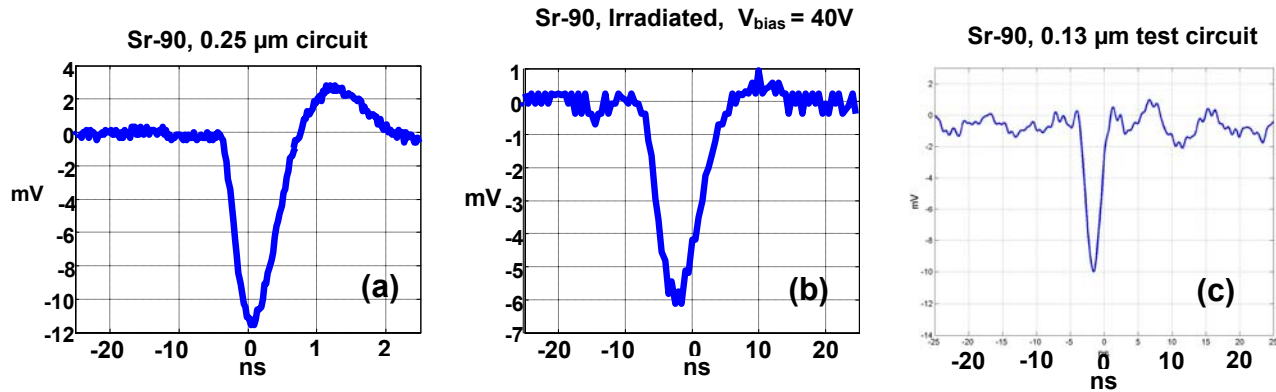


Figure 2. (a) Beta pulse from an un-irradiated, $100\ \mu\text{m} \times 200\ \mu\text{m}$ -cell size, 3D sensor. The overshoot can be reduced, but with longer rise times. (b) Pulse from a room temperature sensor without added oxygen, collecting holes, and irradiated with 10^{15} 24 GeV protons/ cm^2 . (c) Pulse from a room-temperature sensor read out with an early version of an experimental $0.13\ \mu\text{m}$ circuit. The full width at the base is 4 ns.

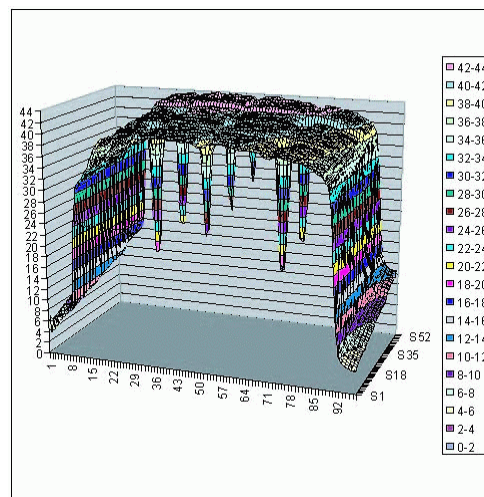


Figure 3. Signal from a scanned full 3D (center and edges) sensor showing both active edge sensitivity, and reduced sensitivity in central electrode regions.

Active edge sensors have been made and tested in x-ray micro-beams at the Advanced Light Source at the Lawrence Berkeley Lab, at ESRF, and with 100 GeV muons at

CERN. Figure 3 shows results of the x-ray micro-beam test. In all tests, sensitivity was shown to extend as close to the physical edge as could be measured, usually about ± 4 or 5 microns. It is expected the dead region will be at least as thick as the oxide side wall, which is a bit less than 1 μm . The ability to make sensors of arbitrary shape could be helpful in beam monitors. It is vital for the molecular biology project and very important for the Totem experiment Roman-pot detectors. The 3D feature that is vital for the linear collider is radiation hardness. This will be discussed under project activities.

Reference [5] gives a summary of recent work for high energy physics as well as additional topics on radiation hardening. Figure 1, showing capture distances in irradiated silicon is particularly important, as capture will be a dominant limitation, even if the silicon can be depleted at high voltages. Close spacing of electrodes is likely to be a necessity. A first draft of a detailed description of the molecular biology project has been completed, and is available if desired.

The beam shape monitor

This sensor technology should be ideal for the small angle detectors of a beam shape monitor. At linear colliders, a large number of electron-positron pairs are created from $\gamma\gamma \rightarrow e^+e^-$, where one or both photons can come from beamstrahlung or from the Coulomb fields of individual beam particles. The secondary e^+e^- pairs that can escape the beam pipe and be detected have energies, E , typically in the few-hundred MeV range and are created at small angles to the beamline of around $m_{\text{electron}}c^2/E$. They then acquire a P_t kick from the electromagnetic field of the rest of the on-coming bunch. If the charges of the created electron or positron and of the bunch are of opposite sign, the particle oscillates around the beam plane and the net acquired P_t is small. If the particle and the on-coming bunch have the same charge sign, P_t may be larger, giving a $P_t c/E$ large enough to produce a substantial angular deflection, with the particle escaping before much beam disruption has occurred. It was found that these large deflection can be used to study σ_x and σ_y of the on-coming bunch [9].

With as many as 10^5 pairs created per bunch crossing, the resultant high occupancy suggests that silicon strip detectors are not suited for this application while CCDs, good candidates in terms of occupancy, would not give the timing information necessary to study possible structures within a train unless some external gating is applied.

Simulation work and the development of electronics with sufficient data rate, and time and spatial resolution, for a pixel detector using 3D sensors are now under development by a KEK—Tohoku (Hitoshi Yamamoto) group [10]. A timing resolution of 19 ns has now been demonstrated. Additional work has started using the changed conditions with a cold-technology collider [11].

Facilities, Equipment and Other Resources

At the Stanford Linear Accelerator, we have a lab with 185 sq. ft. of space. It primarily contains equipment for the testing of integrated circuits and silicon sensors, including an Alessi REL 4100A probe station with a 5-objective 20X—2000X Mitutoyo microscope with an infrared micro-beam, a CCD camera-computer system, three-axis micron-scale

position measurement, probe cards, and 12C and 18B Picoprobes for probing internal nodes of circuits and sensors. Additional equipment includes Tektronix TDS 540 digital and 2465 analog oscilloscopes, NIM modular electronics, power supplies, pulse generators, multi-meters, and a refrigerator for the storage of irradiated sensors.

We are qualified to work at the Stanford Nanofabrication Facility. Located on the Stanford campus, it contains a 10,000 sq. ft. class-100 clean room with all the equipment needed to fabricate silicon sensors, silicon micro-machined devices, and integrated circuits in the 1 – 2 micron range. These include:

1. mask-making equipment including an electron beam system and a laser writer,
2. optical photolithography equipment including 3 resist coaters, a resist developer, 2 full-wafer aligners, and 4 steppers,
3. 9 chemical vapor deposition systems for such materials as oxides, nitrides, polycrystalline silicon, single-crystal silicon, and SiGe,
4. metallization systems including 3 sputtering systems, an evaporator, and a low-pressure chemical vapor deposition system,
5. many annealing, oxidation and doping furnaces,
6. wet benches (for wet etching, pre-furnace cleaning, etc.),
7. in-line process characterization systems including a line width measuring system, a layer thickness measuring system, a surface profilometer, a resistivity mapping system, an optical spectrophotometer, etc.,
8. 8 plasma etching systems including two STS deep reactive ion etchers that we use to make the holes and trenches for 3D sensors,
9. a wafer bonder,
10. a wafer saw,
11. a scanning electron microscope (which was used for Figure 2).

Drs. Kenney and Hasi also have desks there, and a computer that is used for the design of photolithography masks.

Description of first year project activities

The major initial activity will be the fabrication of test sensors for the pair monitor and further development of radiation hardening technology. The later will involve optimization of the deep etching process to produce narrow holes for electrode fabrication. We will also investigate the observed sensitivity of the outer regions of the 3D electrodes, evident in Figure 3 and in many other measurements, which was not expected. In addition, increasing the temperature-time profile after polysilicon deposition should increase the grain size and carrier lifetime, allowing charge carriers to diffuse out to the single-crystal collection volume, thus also increasing sensitivity. All of these items will allow closer placement of electrodes without loss of sensitive volume, decreasing the depletion voltage, collection times, and capture losses. A limitation to this line of attack, is the increased inter-electrode capacitance which could lower the signal to noise ratio.

Deliverables will be sensors to H. Yamamoto's group in Japan (and knowledge). The exact design and schedule depends on the design of the readout chip progress, now underway in Japan. Their suggested pixel size has been set: 0.3 mm x 0.3 mm. Each

fabrication run would be followed by lab and beam tests. The start time would be shortly after funding is available, as we could probably agree quickly on an initial overall size.

Description of second and third year project activities

It is expected that additional sensors will be needed and will be fabricated by us. We expect further developments in radiation hardening. In particular, the large RD50 collaboration is working in this field, particularly with material science, to improve the resistance to silicon to the effects of radiation damage. One example of this type of activity was the earlier use of diffused oxygen to decrease the depletion voltage in radiation-damaged silicon. (However, that specific method may not help at all, when capture becomes the dominant factor.) If they succeed, the improvement factor provided would multiply our factor, which originates in geometry. Given the uncertainties in this field, it is now not possible to put an upper limit on the possible hardness of silicon sensors.

These developments may also be applicable to the LumiCal, which will be heavily irradiated. The exact extent of the radiation damage to the sensors will depend on detailed calculations of the showers, as the damage is energy-dependent up to about 100 MeV. (Fortunately, electrons are not as damaging as hadrons. [12])

Budget

Fabrication runs take from two to four months, depending on equipment availability, batch sizes, and the details of the run steps. The table below lists the main costs of a typical fabrication run. With salary support, it is clear that two or even one run per year would exceed the typical budget for a proposal under this program, so we would do what we have been doing up to now: have shared-wafer runs.

	Funds
Items for each fabrication run (2)	
Stanford Nanofabrication Facility charges – 4 months	4 x \$2,500 = \$ 10,000
Wafers (float zone, test, support, etc.)	1,700
Wafer thinning, polishing	1,000
Implants	1,100
Photolithography masks	5,200
Polycrystalline silicon deposition runs	4,000
Fabrication engineer, technicians	<u>23,000</u>
Sum	46,000
One-time items	
Sputter targets	2,000
DAQ computer (to use at existing probe station)	3,000
DAQ software, hardware	<u>1,700</u>
Sum	6,700

The proposed budget assumes about one quarter of each of the processed 10 cm diameter wafers would be devoted to this project (with our already funded work for the Atlas pixel

upgrade), that there would be two runs per year, and that the costs would be shared with other ongoing projects. There is also the possibility of sharing personnel time, with work on the thin wafers taking place while the NIH x-ray wafers are undergoing processes not needing continuous supervision, such as furnace runs, and vice-versa. It is assumed read out electronics development, testing, and assembly continue in Japan. The D.O.E. Hawaii program officer is now requiring projects other than the ongoing Manoa-based ones provide salary support. (He intends this to include Atlas, which did not have that item in its budget.) Just how this will be resolved is not clear, but I have put down \$20,000 for that item. Given the size of this budget, I have not included travel to any linear collider meetings.

Item	Year 1	Year 2	Year 3
Fabrication runs (0.25 x 2 x \$46,000)	\$23,000	\$23,000	\$23,000
One-time items (0.25 x \$6,700)	\$ 1,675		
Salary support	\$20,000	\$20,000	\$20,000
Indirect costs (20.6%)	\$ 9,203	\$ 8,858	\$ 8,858
Hawaii total	\$53,878	\$51,858	\$51,858

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