1. **Solid-state semiconductor diode radiation sensors were first made and used by Pieter Jacobus Van Heerden, a graduate student in the occupied Netherlands during World War II, and have been in use for over 50 years.**

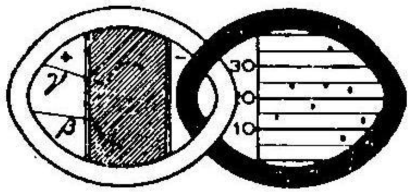
2. **Planar technology was invented by Jean A. Hoerni of Fairchild Semiconductor in 1957- 8, around the time he, Robert Noyce and Gordon Moore left the original (and massively mismanaged) semiconductor company, Shockley Semiconductor, to help form the second one, Fairchild Semiconductor. Within 6 years, planar technology was used for silicon PIN diode sensors** (T. Madden, W. Gibson, *Rev. Sci. Instr*. 34 (1963) 50)**.**

THE CRYSTALCOUNTER

A NEW INSTRUMENT IN NUCLEAR PHYSICS

Erik Heijne → Sherwood Parker
with compliments.

× 7.6 eV / e-h pair in AgCl



× Energy loss of electrons
fig 30 on p. 64

× drawing of AgCl detector crystal
fig 8 p. 23

P. J. VAN HEERDEN

THE CRYSTALCOUNTER

A NEW INSTRUMENT IN NUCLEAR PHYSICS

PROEFSCHRIFT

TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DEN RECTOR MAGNIFICUS, J. BOEKE, HOOGLEERAAR IN DE FACULTEIT DER GENEESKUNDE, VOLGENS BESLUIT VAN DEN SENAAT DER UNIVERSITEIT TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP 30 JULI TE 3 UUR,

DOOR

PIETER JACOBUS VAN HEERDEN
GEBOREN TE UTRECHT

AMSTERDAM
N.V. NOORD-HOLLANDSCHE UITGEVERS MAATSCHAPPIJ
1945

Silicon detectors could solve a problem I had been thinking about, of possible free quarks being lost in a tight jet, but first I wanted to see I wasn't going to be working with a difficult material.

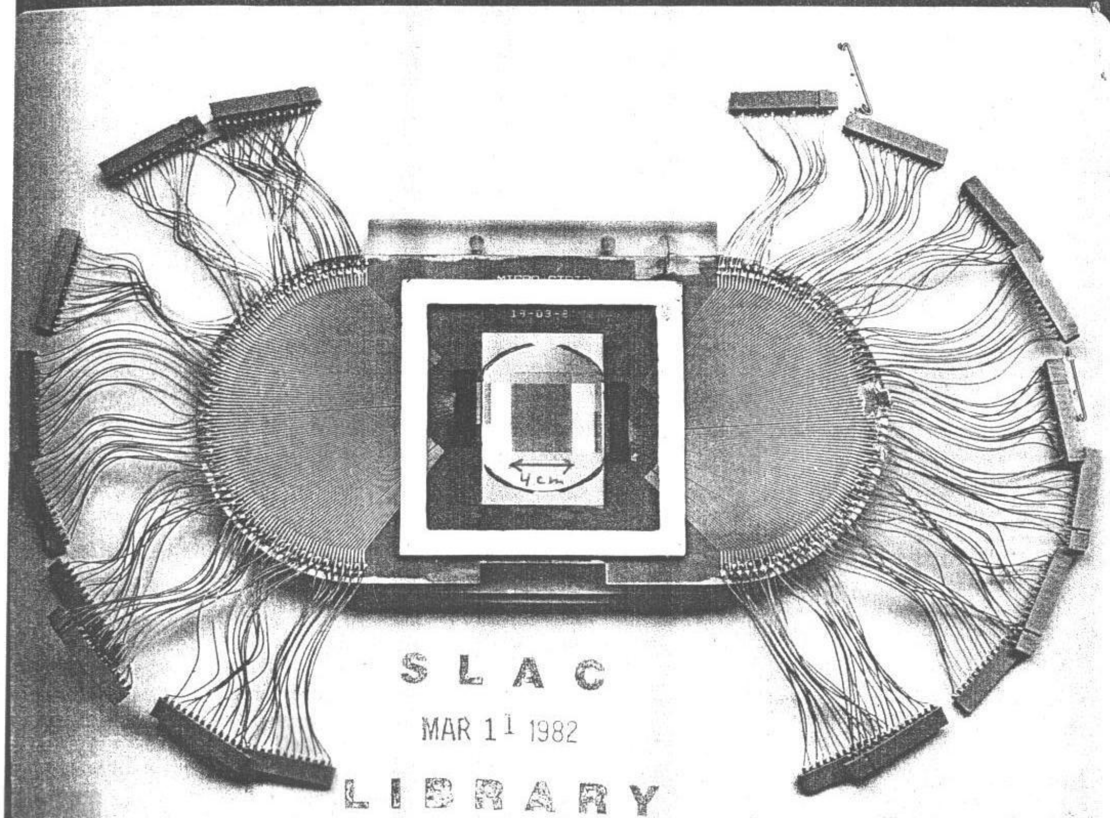
I got a sample from Jack Walton who made silicon detectors for nuclear chemistry, weighted it down, hanging over the edge of my desk, and started hanging weights from it until at more than a 30 degrees bend, I lost courage and gently took them off. I placed the silicon in my desk drawer, calculated its resistance to bending, and found to my surprise, it was the same as stainless steel. So I decided to work with silicon.

(Several weeks later I looked in that drawer and saw hundreds of pieces of shattered silicon, but by then it was too late.)

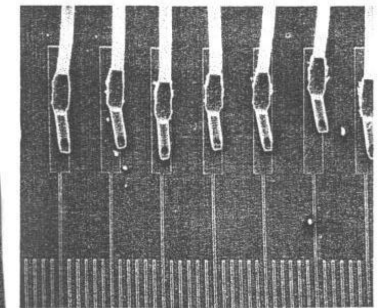
I asked Jack to tell me about the 7 steps described by J. Kemmer, and he did. But every time I went into his lab he was working on something he hadn't mentioned before. (I finally got 98 steps.)

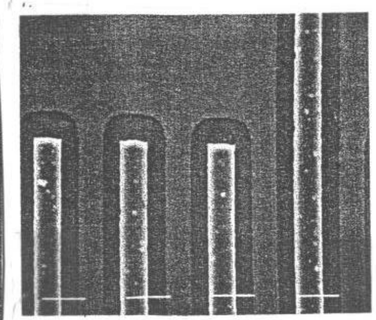
One day, David Leith, a SLAC faculty member suggested I attend an evening talk at his home to be given by Bernard Hyams, who built the first silicon microstrip detector. They were then only used as tiny elements in fixed-target beams, with large fan-out boards to discrete-component amplifiers, and thick bundles of readout cables. It would have been impossible to cram all that closely enough around a collider vertex.

CERN COURIER



Photographs taken with an electron microscope at CERN showing details of the intricate connections which have to be made on the silicon wafer in the semiconductor detector. 1 — wires, about 120 microns apart, are bonded onto the wafer. 2 — an enlarged view of the strip pattern on the wafer. The strips are 20 microns apart.





2.

Paul Karchin in front of a silicon telescope (the rest of the photograph: fanouts and cables).
(Fermilab; 1985, 9 planes, 5 cm x 5 cm)

Bernard had come to Stanford to meet with Terry Walker, a Stanford electrical engineer, to see if he could design and have Stanford fabricate, a custom VLSI readout chip. In his talk he mentioned one unsolved problem: there was no way to connect the planned 128 dense microstrip channels with the equally dense VLSI inputs.

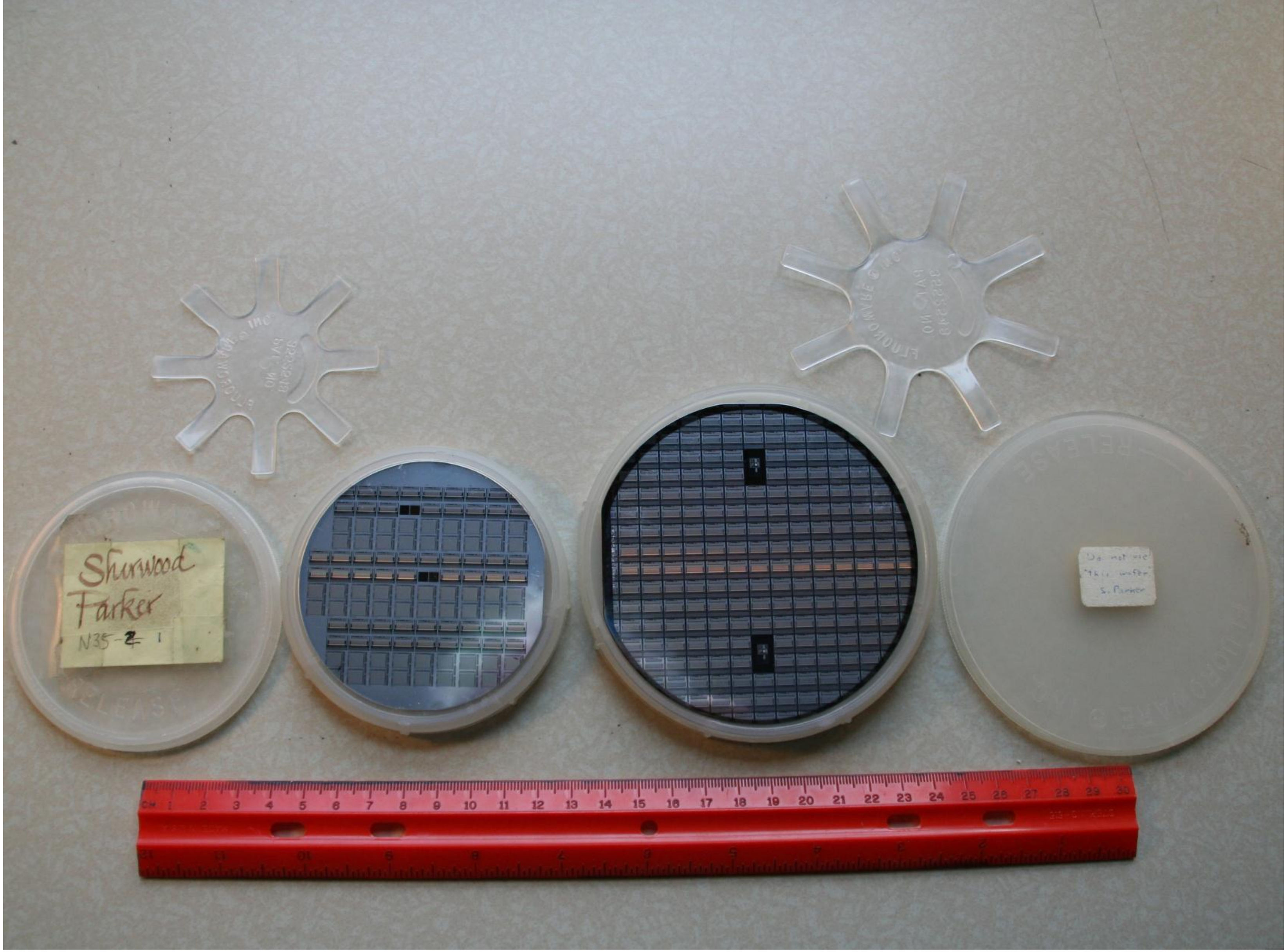
By the question period, I had figured out how, told him so, and discussing it over David's kitchen table afterwards, we decided to work together. My job would be, after Bernard returned to CERN, to meet Terry every week to follow his work.

Vince Peterson, our Hawaii High Energy Physics Group leader, was so enthusiastic he flew to California to attend some of our initial meetings. The first two were in Terry's office in the Applied Electronics Lab. Terry decided it could possibly be built, and then we all went to Jacques Beaudouin's office. As the chief engineer of the integrated circuits lab, he would make the final decision.

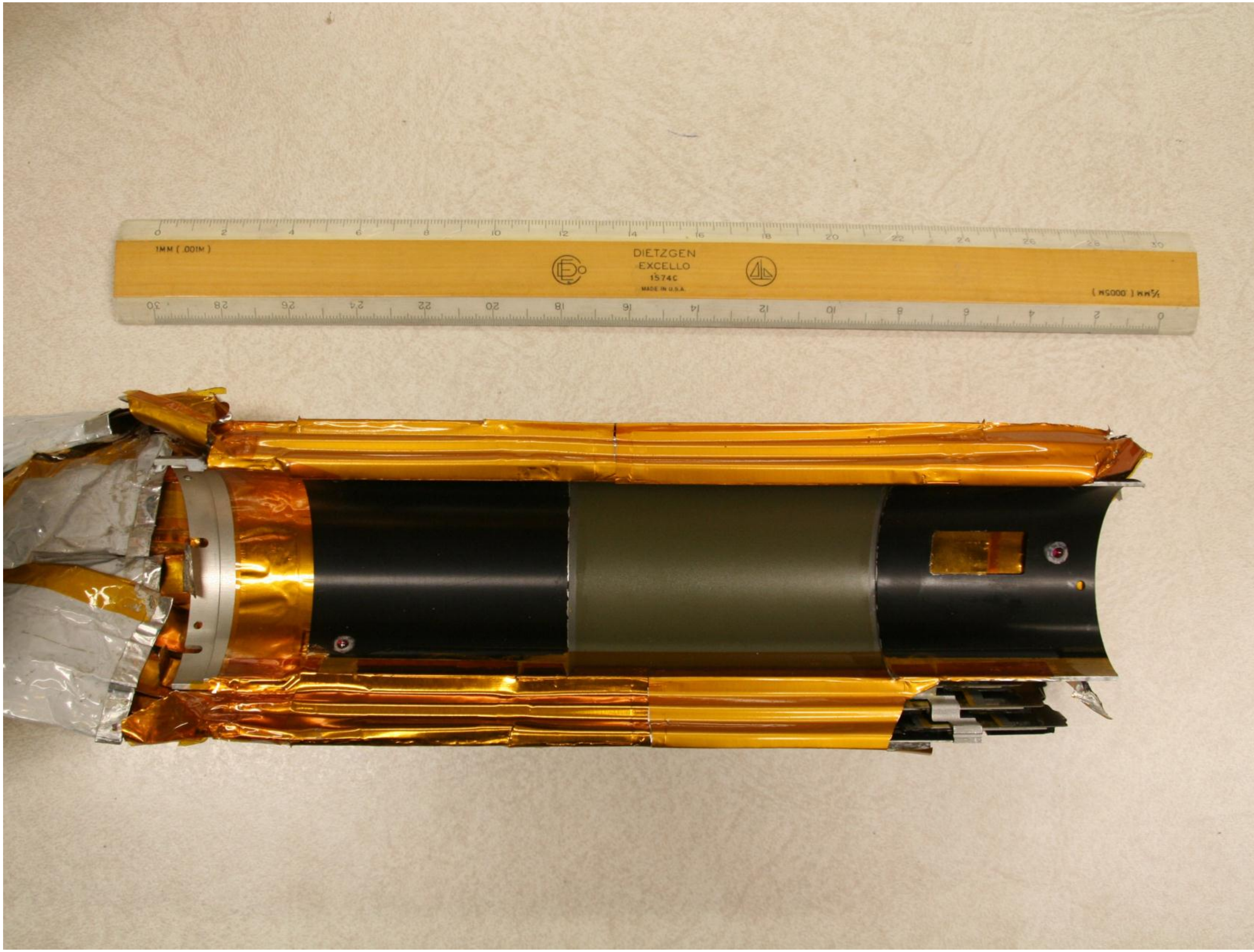
My impression of his attitude was quite clear. I could see an imaginary dotted clock ticking above his head. We had, I think, 15 minutes to make our case. Just as the 15 minutes were up I noticed several pictures of trains on the wall, and as an avid, life-long railroad fan, commented on them. The clock evaporated. We got in a conversation about trains with everyone else impatiently waiting.) But he did decide "yes".

Vince returned to the University of Hawaii, and during a site visit by J. Mandula of the D.O.E., asked him for authority to transfer $20,000 from another project to support the new integrated circuit work. As told to me later by Vince, on Sept.13, 1998, 14:30 after lunch with him and Tess at the Halekulane, Mandula replied: "No, you are not doing that. I'm zeroing it out." Vince replied: "If you zero that out, I'll go over your head and get you reversed."

Mandula backed off, we went ahead, and had the Microplex chip finished over 3 years before any other readout chip, hybridized to a silicon sensor, and then used it in the first-ever silicon microstrip vertex detector at a colliding beam machine, in the Mark II detector at the Stanford Linear Colllider.



The first ever custom VLSI silicon microstrip readout chips. Made at Stanford in 1984). (left, 7.5 cm), then by AMI – (right, 10 cm).



My half of the first silicon vertex detector at a collider - Microplex chips, Hamamatsu diodes - in the Mark II after it is pulled out at the end of the run..

10 years later Vince retired. After Chris Damerell's pioneering work using CCDs that showed the power of pixel detectors, and after Walter built a monolithic pixel detector with 34 x 125 micron pixels, and in January 1992, Walter, Chris, and I tested it at Fermilab with the resolution below:

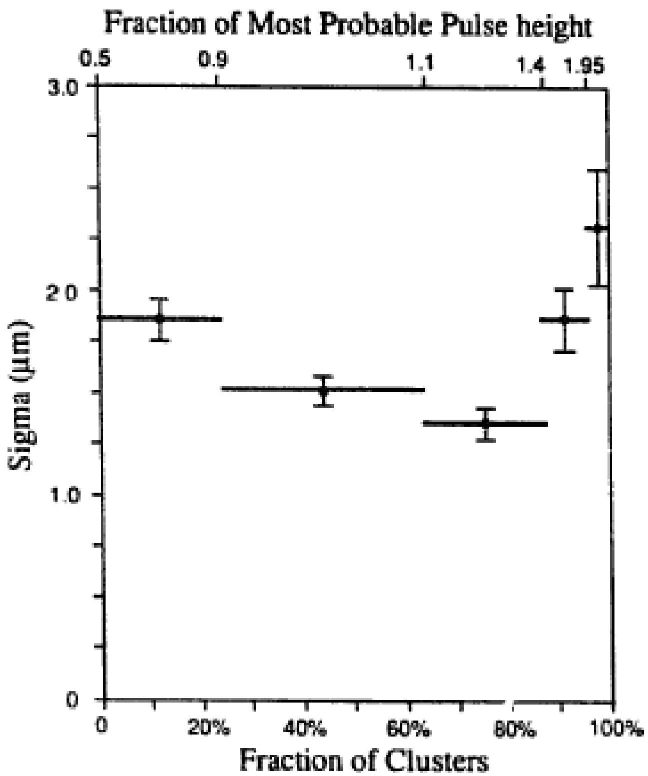


Fig. 13. Intrinsic resolution in direction of 34 µm pitch versus cluster pulse height in terms of the most-probable value for a minimum-ionizing particle (top axis) and fraction of all clusters (bottom axis).

17 years later:

28.7. Semiconductor detectors
Updated September 2009 by H. Spieler (LBNL).
Resolutions of 2–4 μm (rms) have been obtained in beam tests.

It was clear collider trackers should have pixel detectors. At the next DOE review at Hawaii I showed a set of transparencies demonstrating that. With the first transparency, J. Mandula's head went down. He started writing Feynman diagrams and doing calculations. He did not look at a single transparency, and when I finished said: "We're not funding that."

Some time after that, (Sept.13, 1998) Vince told me, after the meeting with Terry and Jacques, he returned to the University of Hawaii, and during the site visit by J. Mandula of the D.O.E., asked him for authority to transfer $20,000 from another project to support the new integrated circuit work. Mandula replied: "No, you are not doing that. I'm zeroing it out." Vince replied: "If you zero that out, I'll go over your head and get you reversed."

The Microplex chip and the Mark II vertex detector were over 3 years ahead of the others in CDF, Delphi, and Aleph, with multiple test results published during that time.

Now to the future. We could cover, besides pure 3D:

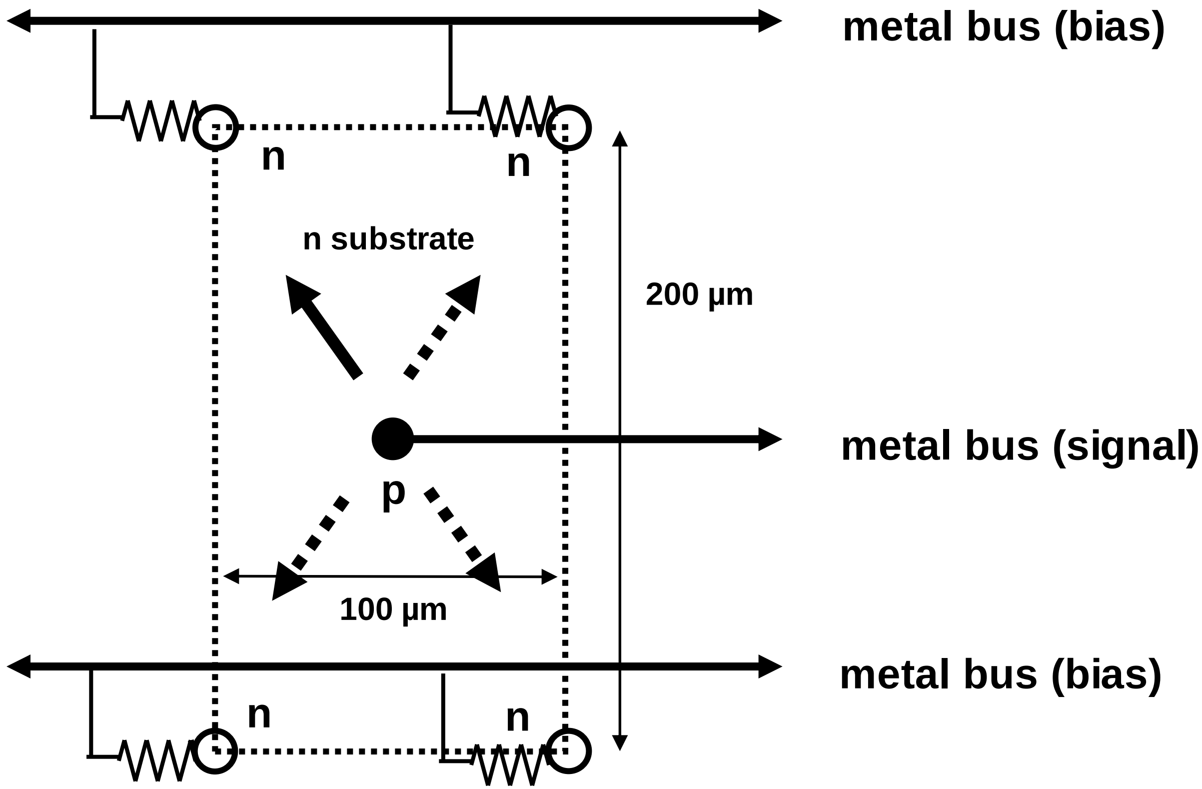
1. Increased resolution with dual readout of induced signals.

2. Speed. From ns to ps.

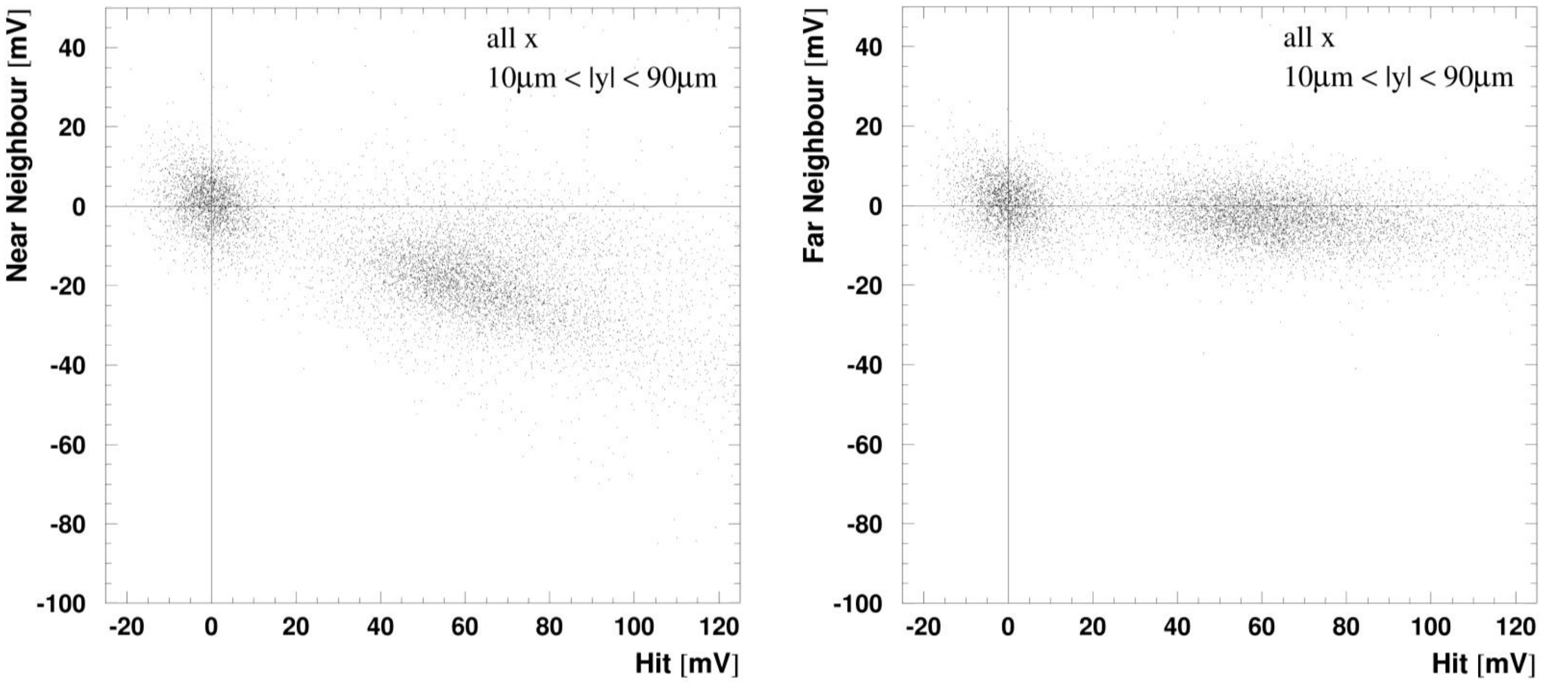
3. Proposed Triple-wall, Voltage-isolating Electrodes for Multiple-bias-voltage 3D Sensors

Sherwood Parker, N.V. Mokhov, I.L. Rakhno, I.S. Tropin, Cinzia DaVia, S. Seideld, M. Hoeferkamp, J. Metcalfe, Rui Wang, C. Kenney, Jasmine Hasi, Philippe Grenier

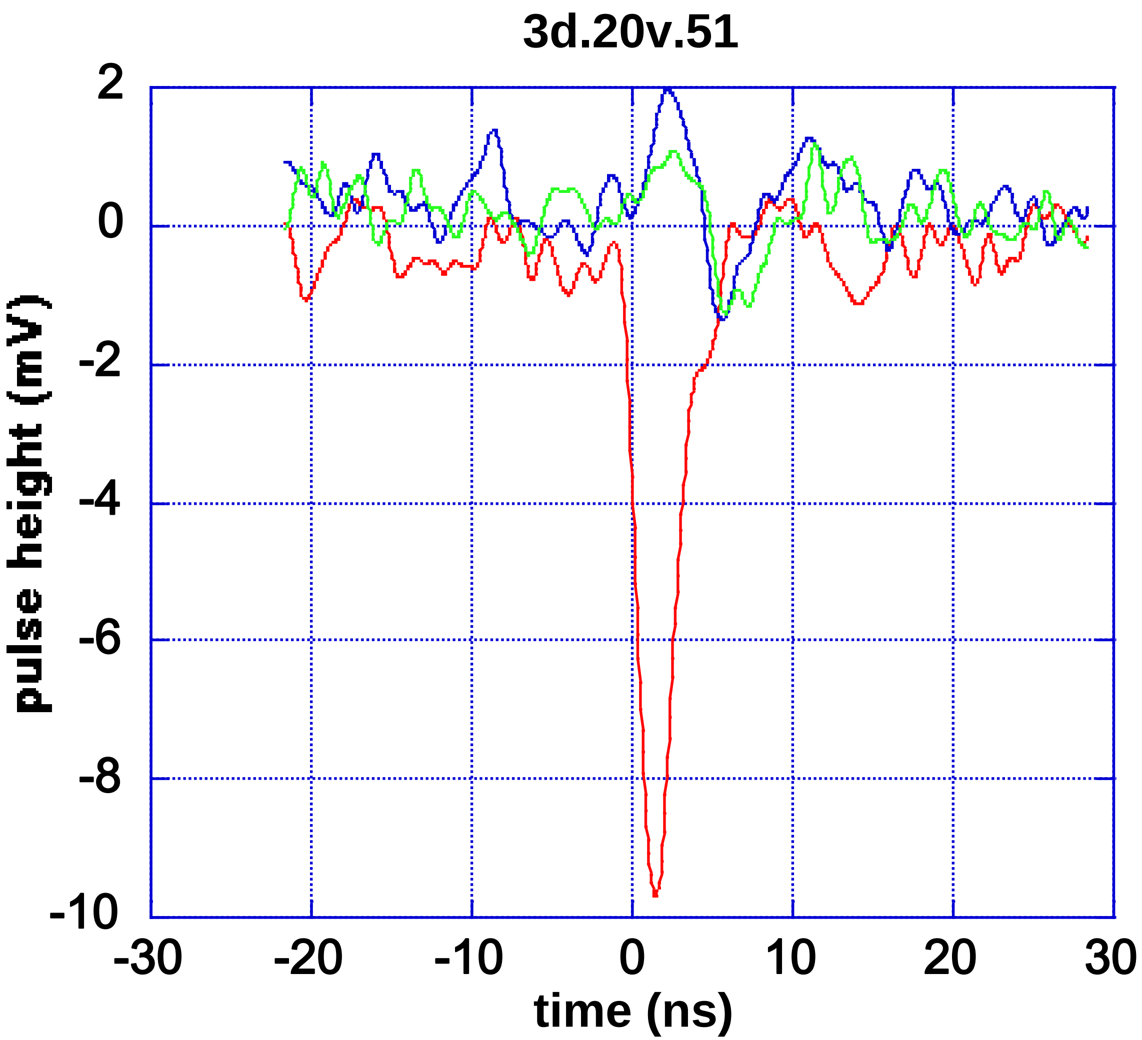
Sensors in the proposed 214 m, far forward detectors, now starting fabrication, may have a new form of radiation damage failure. One possible solution involves a new type of sensor.



One pixel showing the addition of series resistors in the bias supply network to the 3D n^+ electrodes that will prevent rapid voltage changes, lowering the effective capacitance of the p^+ signal electrode and inducing a negative signal on the closest neighboring signal electrodes.

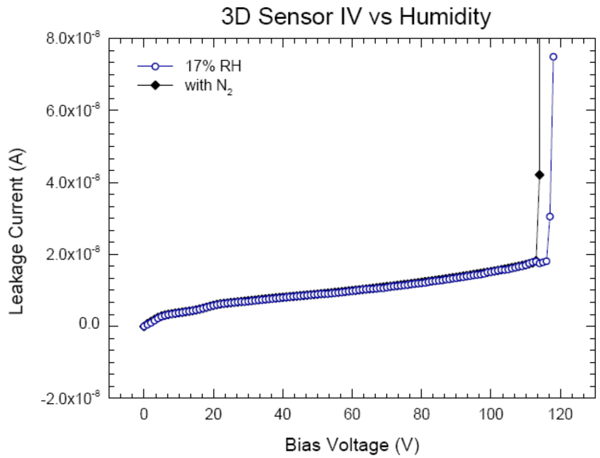


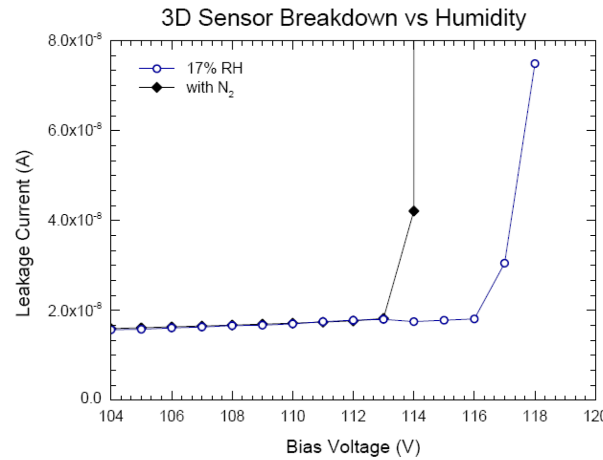
Scatter plot of the direct signal pulse height (horizontal) and the induced signal pulse heights (vertical) from the near neighbor, S3, (top), and the far neighbor, S1 (bottom). A beam telescope predicts the location of the track impact point. The events in these two plots are limited to the shaded regions of slide 3 (10 μm < |y| < 90 μm) where there is no significant charge-sharing from diffusion.

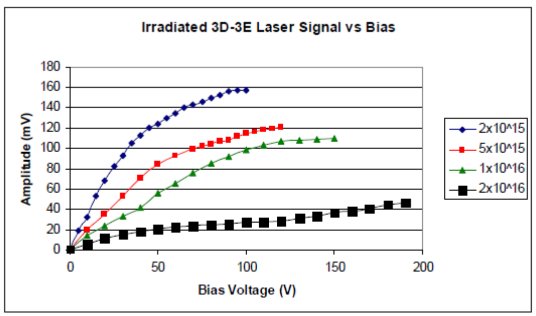


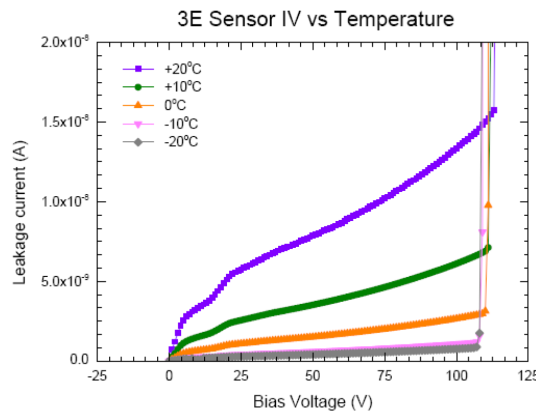
The middle event

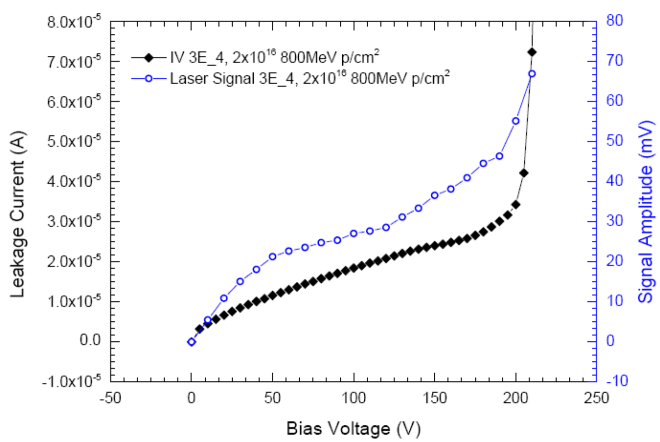
horizontal		1	3	5	7	9	11	13	15	17	19	21	23
vertical													
24		4	5	4	3	6	6	6	6	8	18	29	24
		4	6	3	6	6	10	6	13	16	34	34	35
20		4	5	6	8	12	7	9	15	17	37	16	31
		3	7	8	7	12	32	18	19	13	15	15	16
		7	5	8	15	17	19	32	38	19	24	18	13
		9	50	14	40	26	22	28	24	15	16	15	27
		18	14	28	22	51	38	50	40	31	18	52	45
10		20	20	34	55	58	38	24	22	24	22	28	26
		14	33	18	42	45	50	31	43	57	51	40	54
		14	61	31	38	65	74	70	60	38	33	34	37
		26	58	81	122	110	68	53	35	38	38	50	53
		22	61	145	222	223	255	97	88	112	68	171	842
0		11	21	77	204	303	519	201	203	930	**1310**	**2000**	**4750**
		19	43	125	328	256	226	119	56	128	83	180	865
		33	49	60	150	86	69	40	33	35	36	39	60
		20	34	50	103	77	50	37	38	25	31	25	28
		11	36	52	59	35	28	49	48	34	39	23	17
-10		19	13	47	53	48	26	45	39	24	29	19	26
		15	17	84	72	48	50	53	43	23	24	17	29
		16	11	23	21	31	47	71	78	35	43	18	13
		8	7	12	19	16	34	53	35	37	19	21	15
		5	8	6	8	15	37	24	29	25	36	14	20
-20		4	9	8	8	7	8	16	16	10	18	12	38
		4	5	10	11	6	6	6	20	14	26	24	34
-24		7	4	5	3	4	4	4	7	7	10	10	16
horizontal		1	3	5	7	9	11	13	15	17	19	21	23

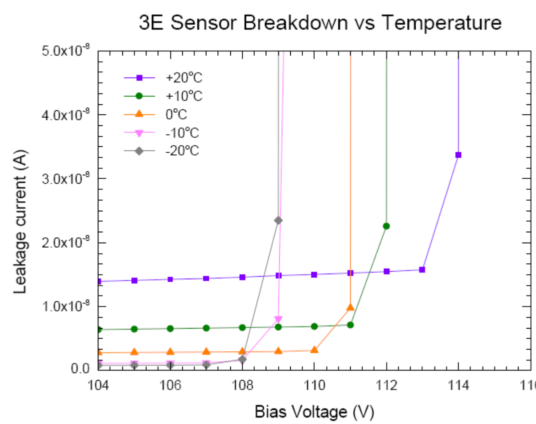

3D Sensor IV vs Humidity
Leakage Current (A)
Bias Voltage (V)
17% RH
with N_2

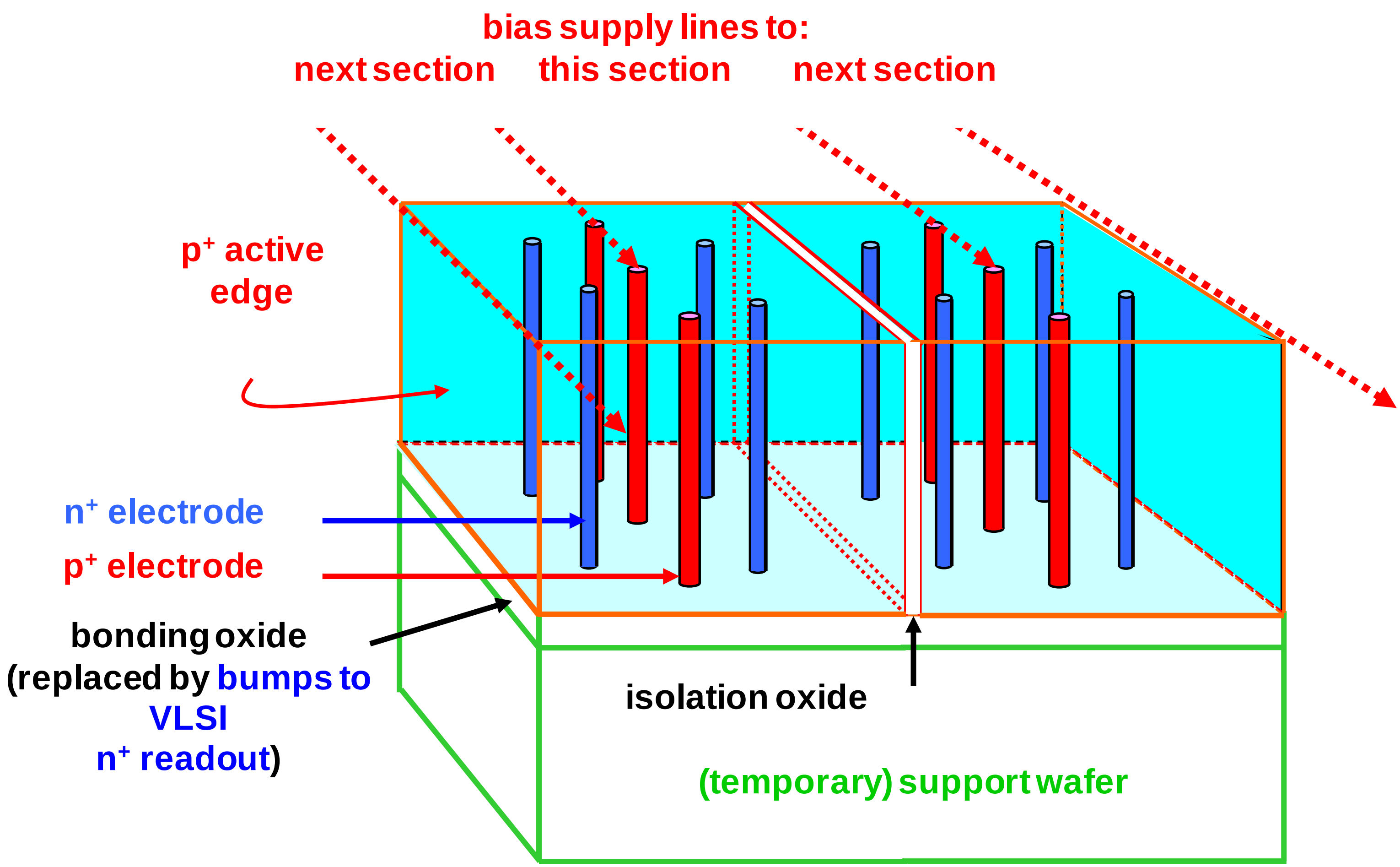

3D Sensor Breakdown vs Humidity
Leakage Current (A)
Bias Voltage (V)
17% RH
with N_2

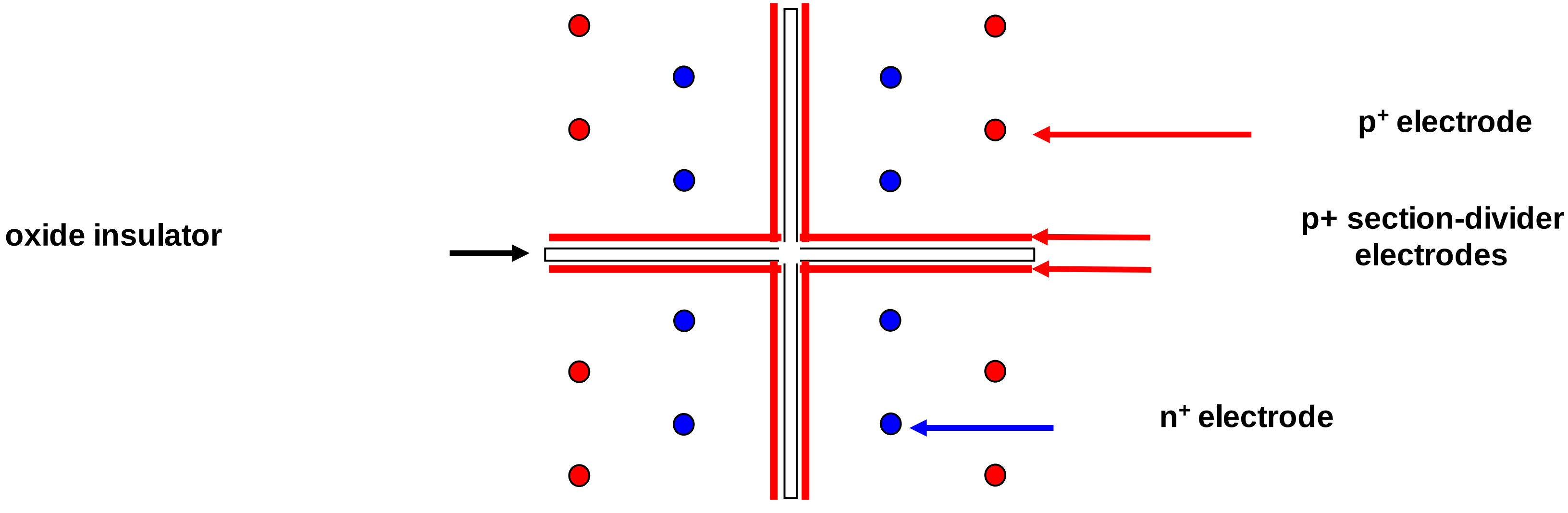

Irradiated 3D-3E Laser Signal vs Bias
Amplitude (mV)
Bias Voltage (V)
2x10^15
5x10^15
1x10^16
2x10^16

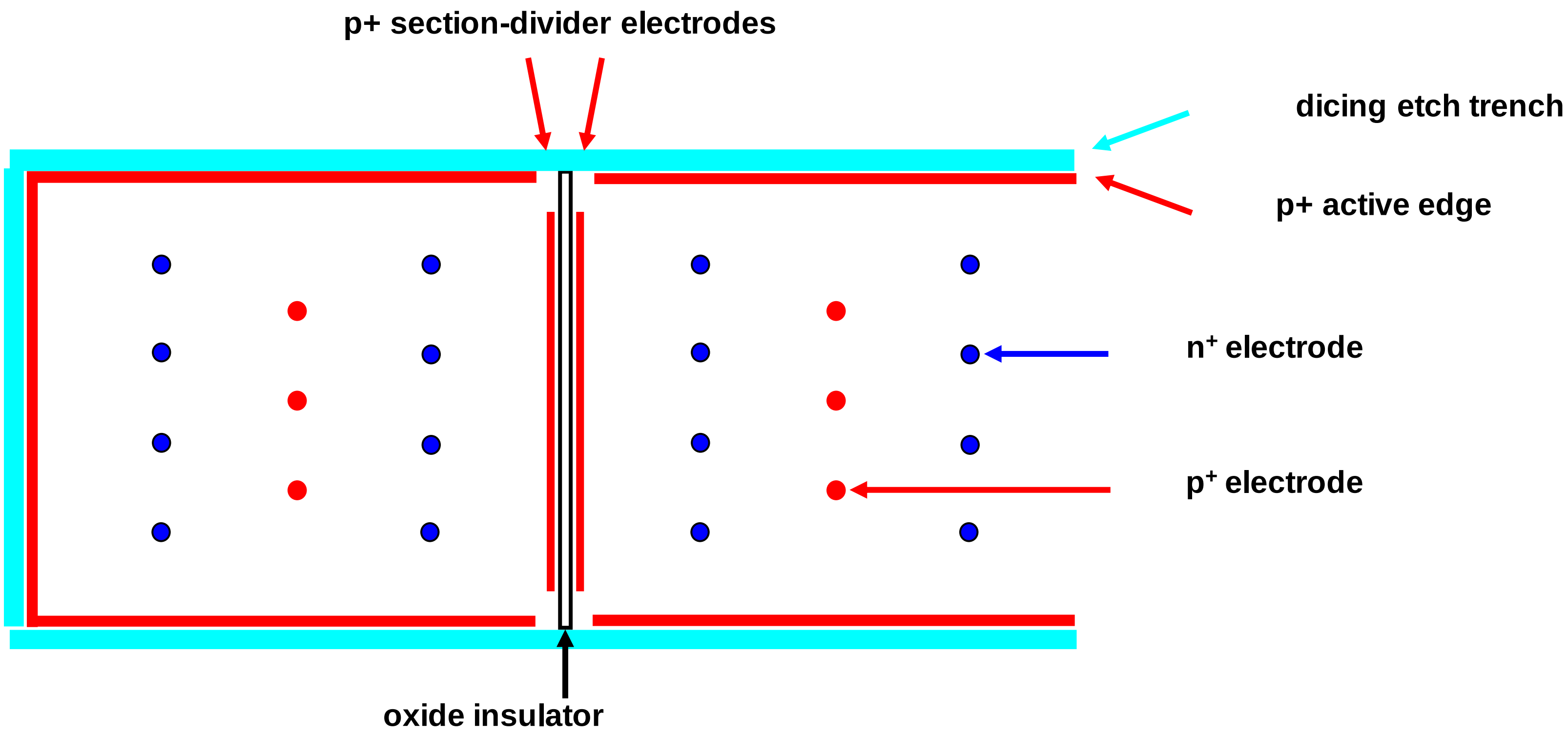

3E Sensor IV vs Temperature
Leakage current (A)
Bias Voltage (V)
+20°C
+10°C
0°C
-10°C
-20°C


IV 3E_4, $2x10^{16}$ 800MeV p/cm^2
Laser Signal 3E_4, $2x10^{16}$ 800MeV p/cm^2
Leakage Current (A)
Signal Amplitude (mV)
Bias Voltage (V)


3E Sensor Breakdown vs Temperature
Leakage current (A)
Bias Voltage (V)
+20°C
+10°C
0°C
-10°C
-20°C


bias supply lines to:
next section
this section
next section
p+ active edge
n+ electrode
p+ electrode
bonding oxide (replaced by bumps to VLSI n+ readout)
isolation oxide
(temporary) support wafer


oxide insulator
p^+ electrode
p+ section-divider electrodes
n^+ electrode


p+ section-divider electrodes
dicing etch trench
p+ active edge
n+ electrode
p+ electrode
oxide insulator

And the last – for now – very important, very incomplete slide, but one to be followed, I hope, by many more.

Vera Luth

Jasmine Hasi

Vince, Fred, Jan

Alan, Terry, ...