Capacitance of Silicon Pixels

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Overview

- Goals of the measurements
- Devices and simulation
- Results

Introduction and Goals of the Measurements

The total capacitance of a pixel sensor affects its detector's noise. The ratio,

(Capacitance to neighbors)/(Total capacitance)

affects the cross coupling between channels.

The total capacitive load that a pixel sensor presents to the front end electronics includes

- bump pad
- preamplifier input transistor
- capacitance to neighbors ("inter-pixel contribution")
- backplane contribution

This study examines inter-pixel + backplane capacitance.

For application to LHC + Tevatron experiments, we include the effects of

- radiation damage and
- low temperature operation.

The project:

1. Study a set of test structures whose design is simple enough that the measurement of the capacitance between a pixel and all neighbors is unambiguous.

→“The LBNL Test Structures”

2. Model the capacitance of these test structures to understand systematics and calibrations.

3. Using the same calibration procedure + measurement setup (i.e., systematics), study a set of pixel structures more like those in a physics detector. These sensors use p-stop isolation.

→“Structure 6”

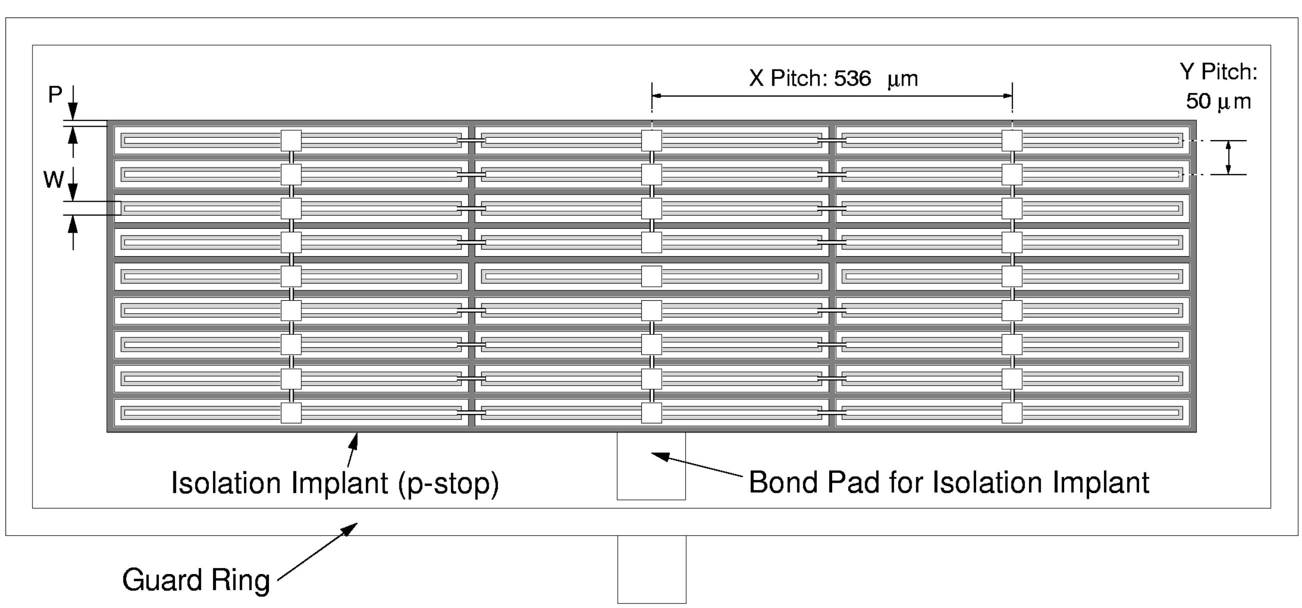
4. Measure the inter-pixel and backplane capacitance of ATLAS prototype (p-spray) sensors.

5. Investigate the dependence of the capacitance on operating temperature.

The LBNL Test Structures

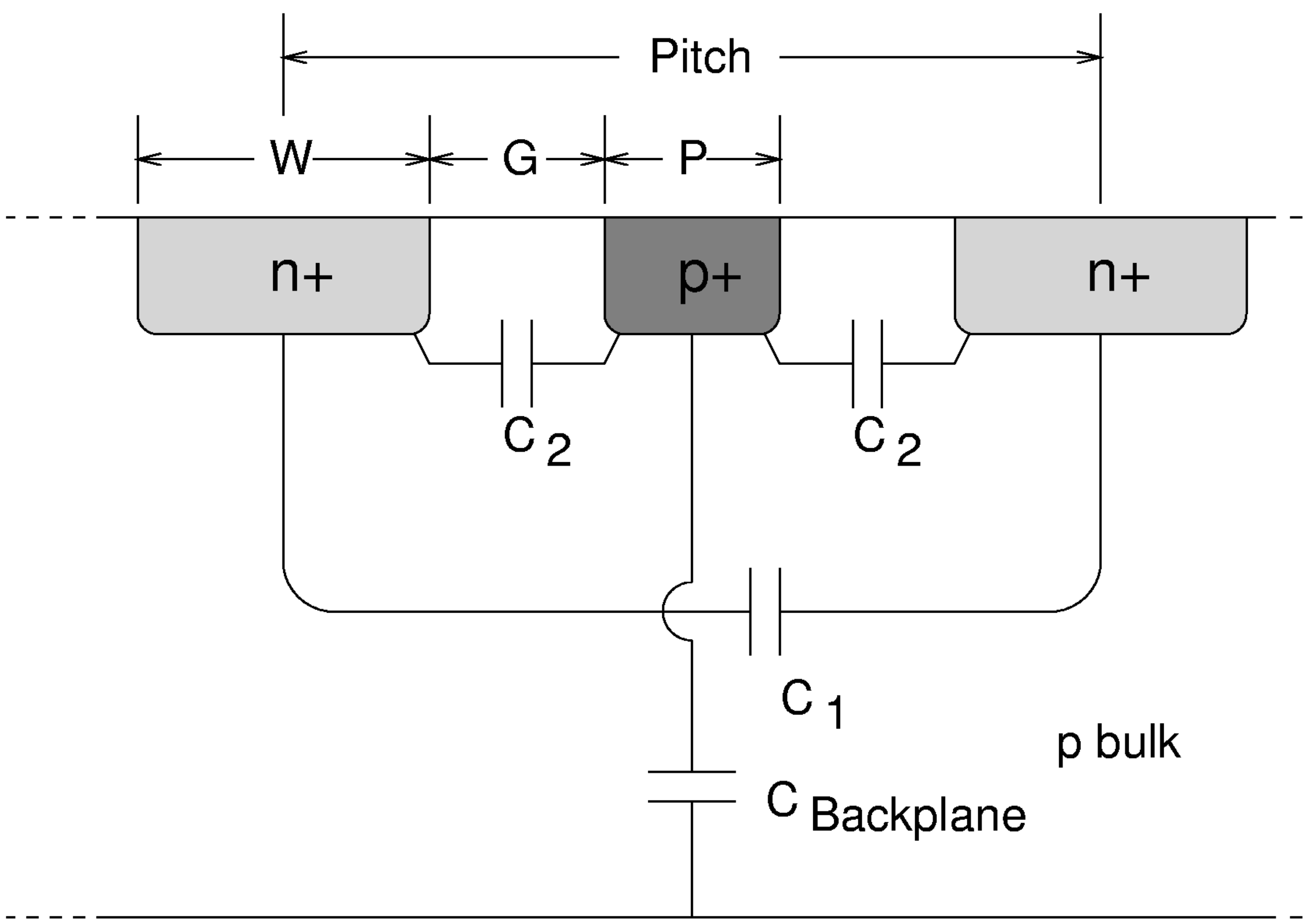
Designed and fabricated by S. Holland, LBNL

- versions in *p*-on-*n* and *n*-on-*p*
- each structure has six 3×9 arrays
- in each array, the center pixel is isolated and the neighbors are ganged. All neighbors can be biased with 1 probe.
- Pitch: 50 μm × 536 μm



•5 *n*-bulk and 5 *p*-bulk were studied

•The *p*-bulk devices examine common p-stops of various widths (“P”) and gaps (“G”).



Feature dimensions of the LBNL Test Structures, in microns. The “g” is the total gap between charge collection implants.

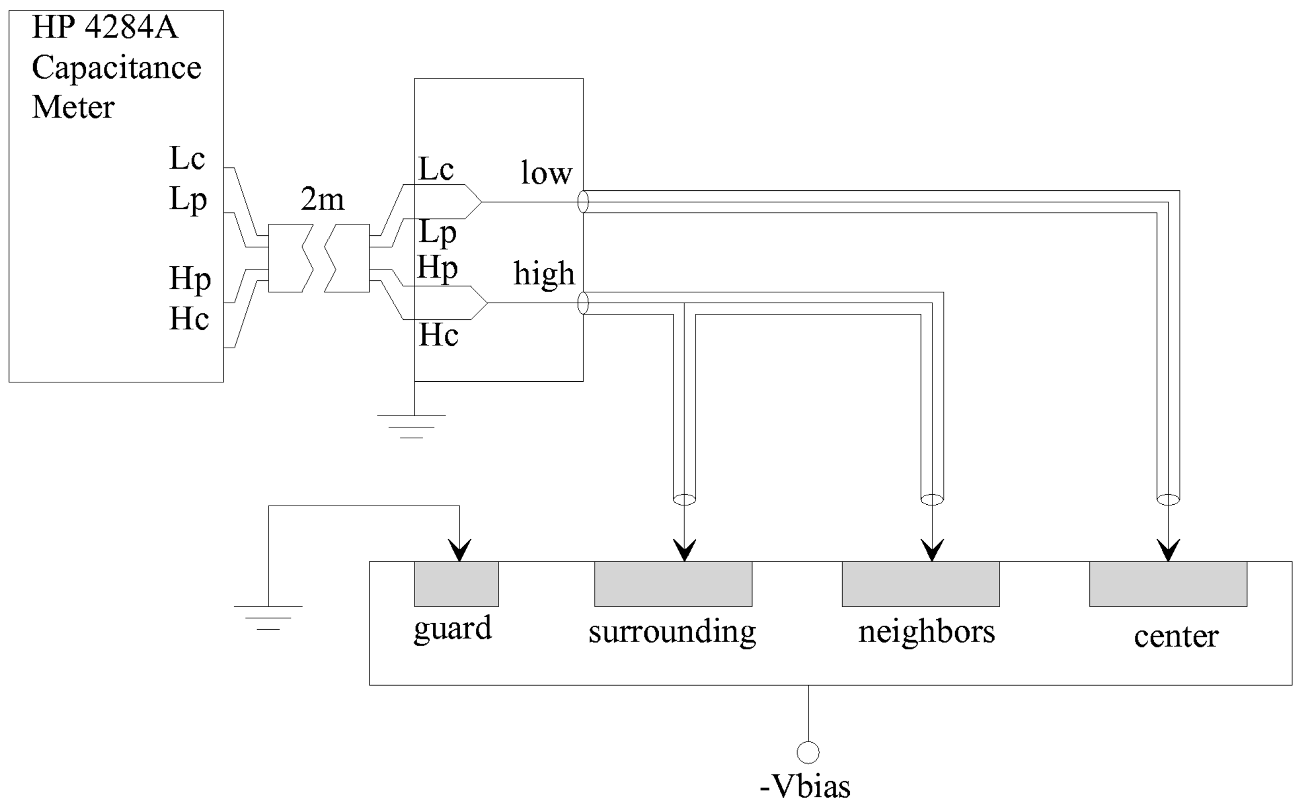
n-bulk:

Array #	*p* Width (W)	Total Gap (g)
2	38	12
3	32	18
4	23	27
5	20	30
6	14	36

p-bulk:

Array #	*n* Width (W)	Total Gap (g)	p-stop Width (P)
2	38	8	4
3	32	12	6
4	23	19	8
5	20	20	10
6	14	24	12

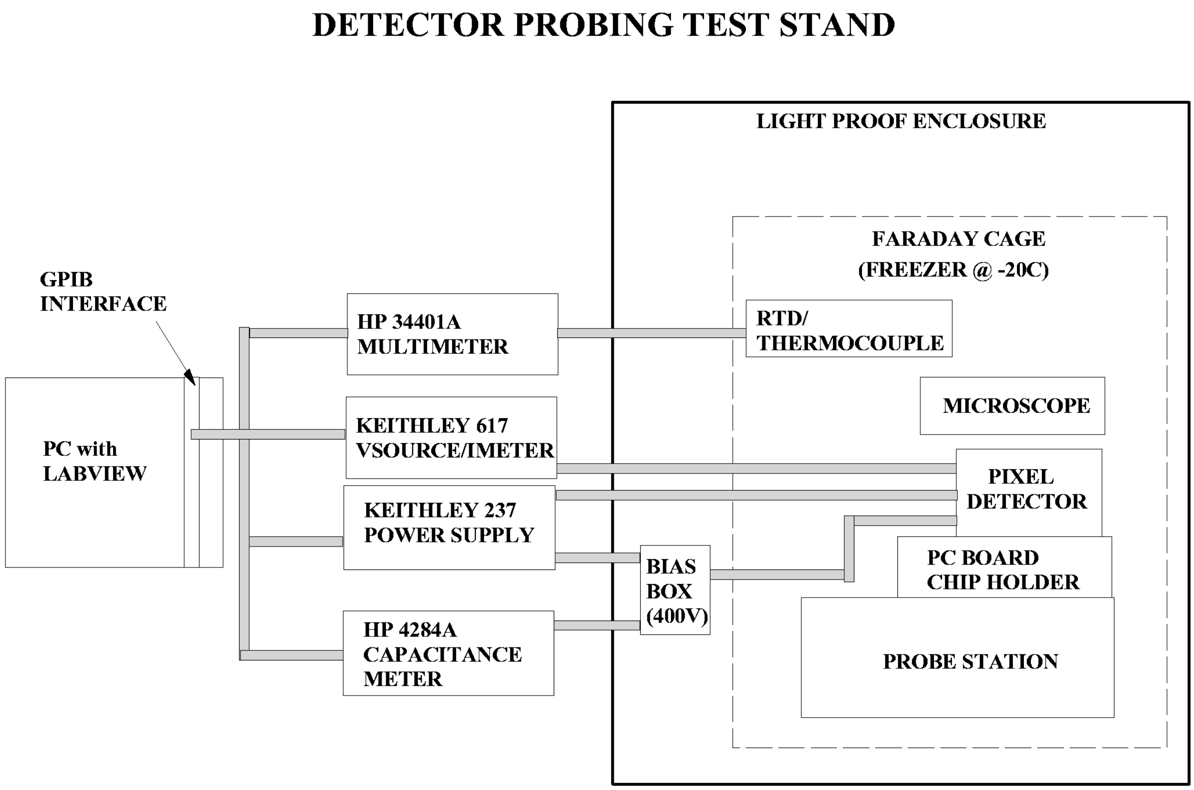
Measurement Setup



•The LCR meter supplies a 250 mV rms signal on HIGH. Amplitude and phase are measured on LOW.

•To measure inter-pixel capacitance, the pixel of interest is connected to LOW, all others to HIGH.

Test stand



•Prior to measurement, the probe attached to LOW is raised a few microns above the pixel, the sensor biased to ~100V (overdepletion), and the meter set to OPEN mode. This procedure measures all parasitic capacitances. The result is stored as a subtractable reference.

•Residual parasitic capacitance after OPEN correction: < 2 fF.

Combined uncertainty per measurement:

- Statistical: 3fF
  - based on the standard deviation of repeated measurements at 1MHz and 200V.
- Systematic: 1fF
  - conservative measure of the voltage dependence of the OPEN correction
- Systematic: 3fF
  - based on the accuracy reported for this meter type (HP 4284A).
- Systematic on irradiated sensors only: 1-13fF
  - in some cases, highly irradiated sensors risked thermal runaway if operated at room temperature at voltages required to plateau their $C_{inter\text{-}pixel}$-V curve. For them, the minimum $C_{inter\text{-}pixel}$ was determined by extrapolation.

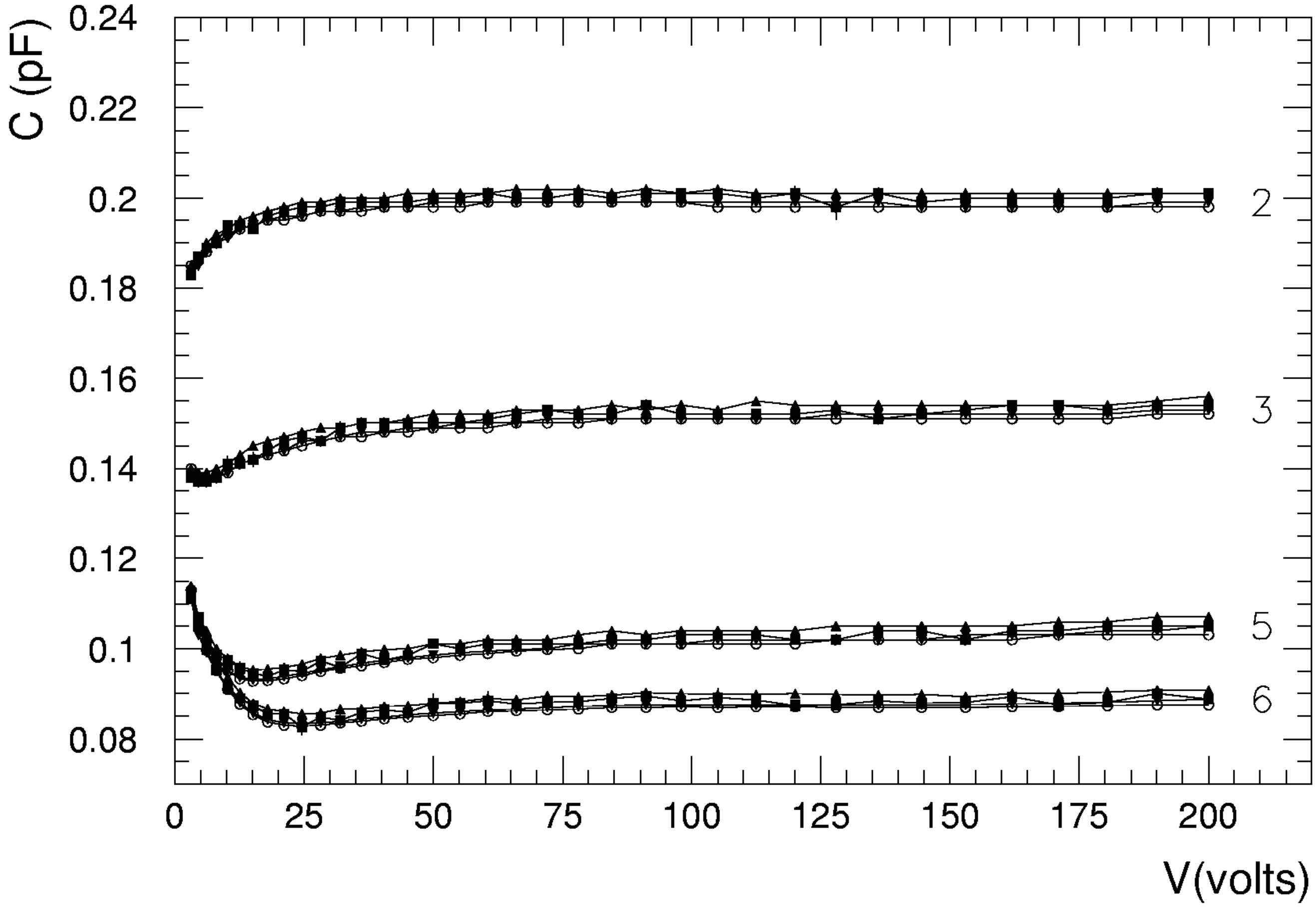
LBNL Test Structure Measurement Results:

•for *p*-on-*n* and *n*-on-*p*

•for frequencies of 3 kHz, 10 kHz, 100 kHz, and 1 MHz

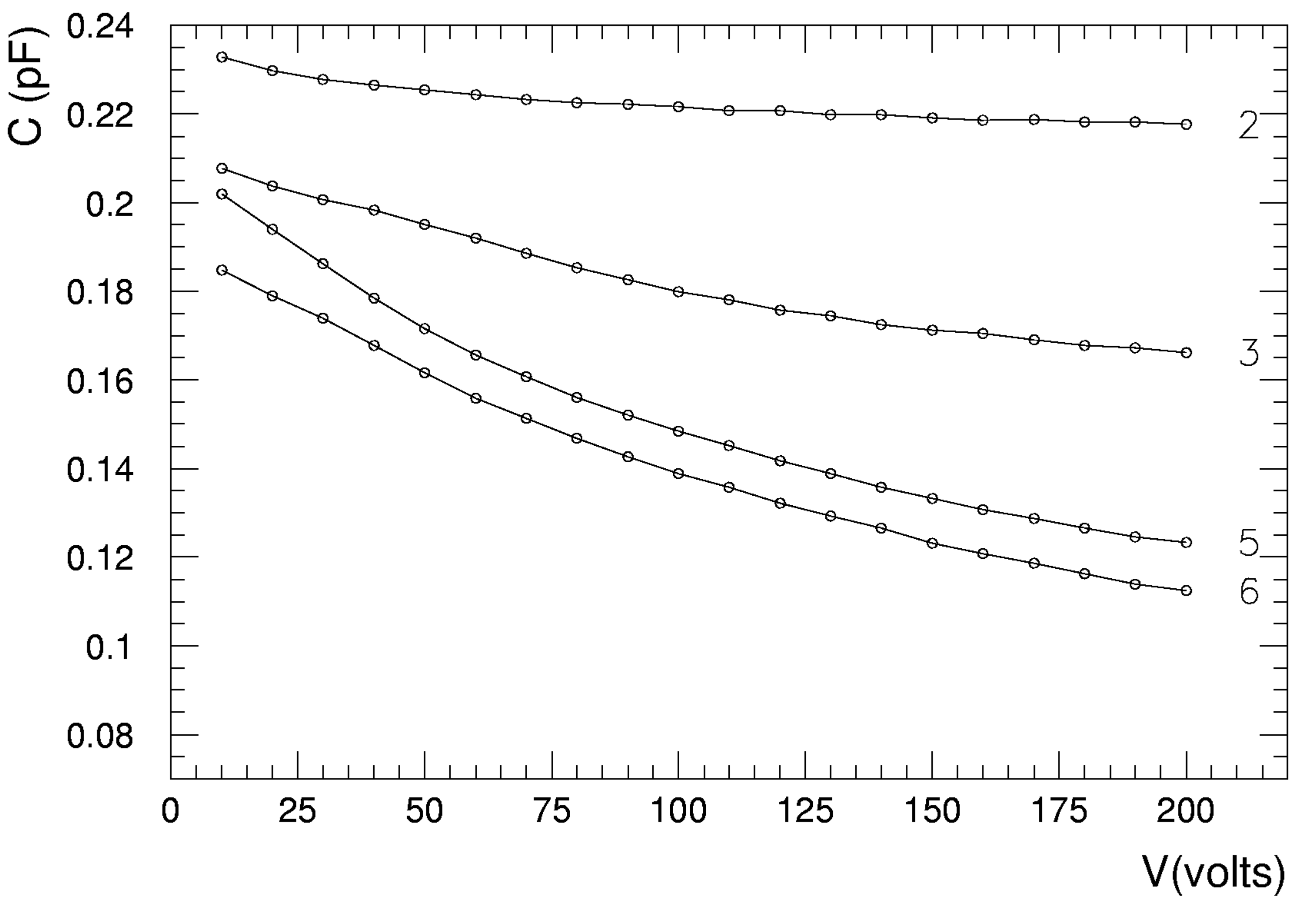
•unirradiated and after 4.8×10^{13} cm^{-2} (1 MeV neutron equivalent) fluence

A typical measurement: the inter-pixel capacitance of unirradiated *p*-type LBNL test structure arrays:



Typical data requiring extrapolation to the minimum $C_{\text{inter-pixel}}$: *p*-type test structures irradiated to fluence 4.8 x 10^{-13} 1-MeV neutron-equivalent/cm^2. The data are well fit by

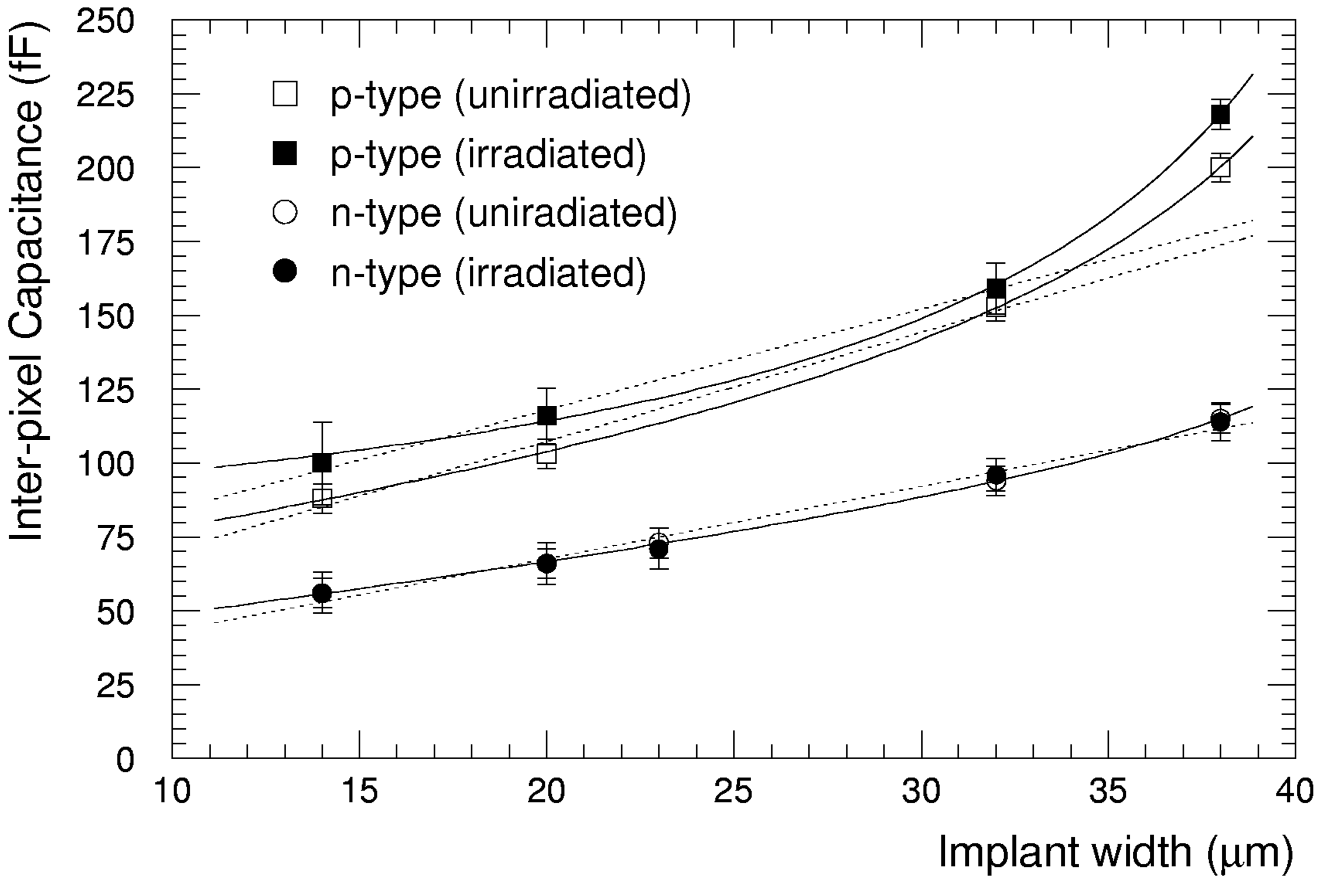
$$C_{\text{inter-pixel}} = A + e^{B-Dx}$$



Summary of inter-pixel capacitance measurements on LBNL test structures :

Array	$C_{unirrad}$ (fF)	C_{irrad}(fF)
	n-type:	
2	115 ± 5	114 ± 7
3	94 ± 5	96 ± 6
4	73 ± 5	71 ± 7
5	66 ± 5	66 ± 7
6	56 ± 5	56 ± 7
	p-type:	
2	200 ± 5	218 ± 5
3	153 ± 5	159 ± 9
5	103 ± 5	116 ± 10
6	88 ± 5	100 ± 14

Inter-pixel capacitance versus implant width:



Dotted line: linear function

Solid line: $C_{\text{inter-pixel}} = A + (BW/\rho) + (D/g)$,

where W = implant width

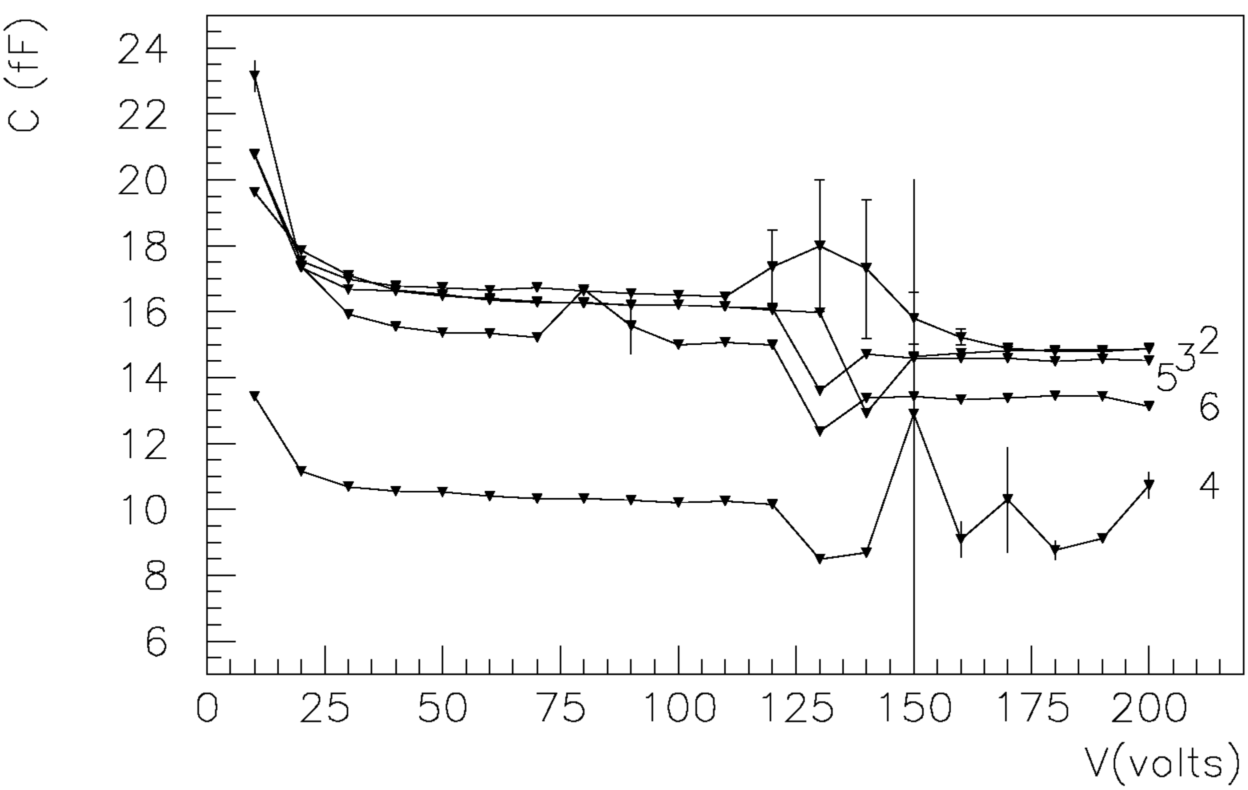
ρ = pitch

g = gap between charge collection implants

Pixel backplane capacitance

•similar to $C_{inter\text{-}pixel}$ measurement, but with LOW connected to the center pixel and HIGH connected to the back side.

•A typical measurement for unirradiated *n*-type:



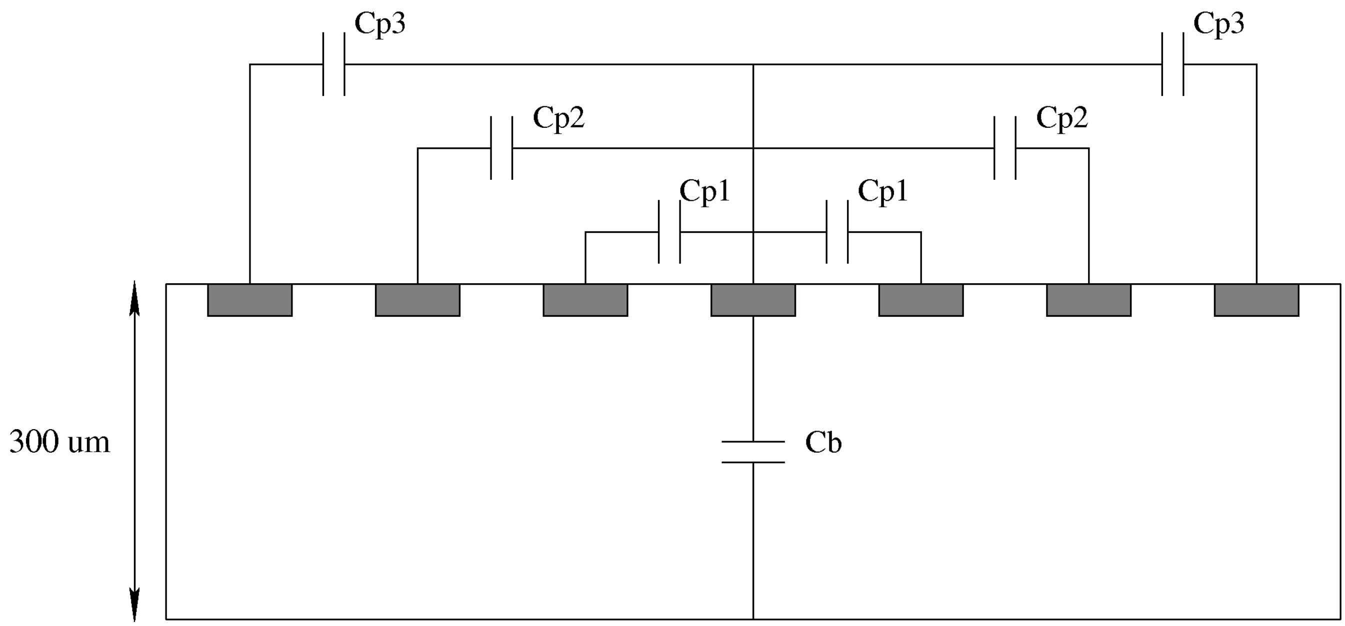
Summary of backplane capacitance measurements on unirradiated LBNL test structures:

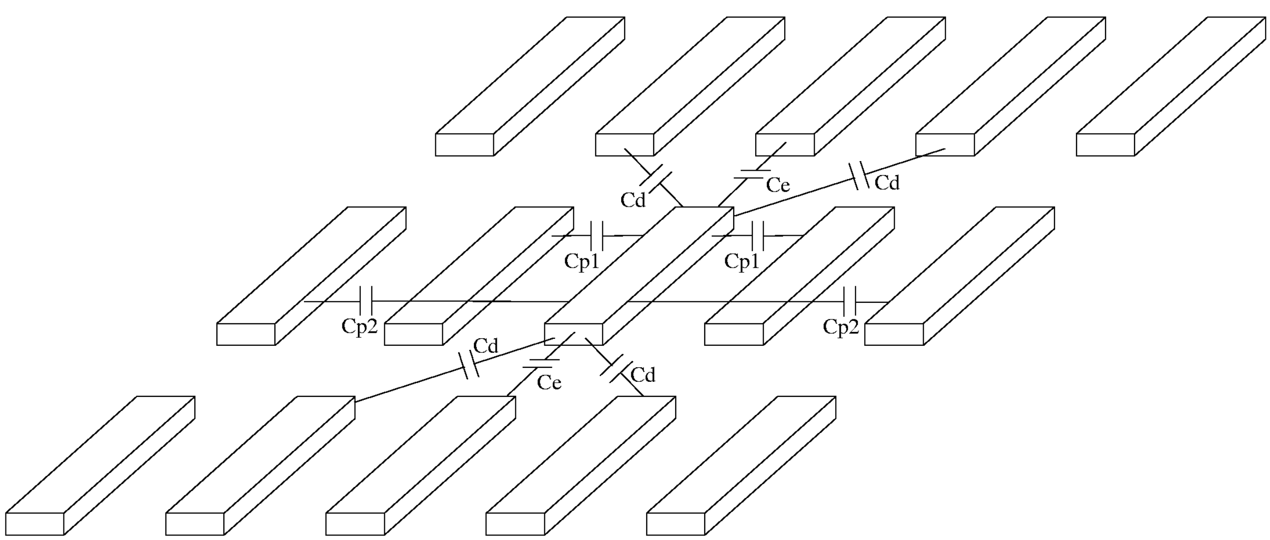
Array	$C_{backplane}$ (fF)
n-type	
2	15 ± 5
3	15 ± 5
4	11 ± 5
5	15 ± 5
6	13 ± 5
p-type	
2	18 ± 5
3	16 ± 5
4	11 ± 5
6	21 ± 5

Simulation of the LBNL Test Structures

- Results of 2-D simulators HSPICE and IES Electro and 3-D simulator IES Coulomb were compared to interpret the measurements, indicate the precision of simulation, and estimate the size of contribution of non-adjacent neighbors.
- The simulators take as input the geometry of the sensor and information about the dielectrics and solve the electrostatic field equations.

Geometries used in the simulation:





Comparison of predictions to measurements:

$C_{backplane}$ of unirradiated n-type sensors:

Array	C_{meas}(fF)	$C_{sim\text{-}IES2D}$(fF)	$C_{sim\text{-}IES3D}$(fF)
2	15 ± 5	10 ± 2	13 ± 3
3	15 ± 5	10 ± 2	13 ± 3
4	11 ± 5	10 ± 2	12 ± 2
5	15 ± 5	10 ± 2	12 ± 2
6	13 ± 5	10 ± 2	12 ± 2

$C_{inter\text{-}pixel}$ of unirradiated n-type sensors:

Array	C_{meas} (fF)	$C_{sim\text{-}HSPICE}$ (fF)	$C_{sim\text{-}IES2D}$ (fF)	$C_{sim\text{-}IES3D}$ (fF)
2	115±5	130±46	109±38	124±43
3	94±5	115±40	91±32	111±39
4	73±5	95±32	78±27	93±33
5	66±5	89±31	72±25	87±30
6	56±5	75±26	66±23	76±27

Implications:

- Agreement between simulations and measurements within 30%
- Contribution of capacitance from next-to-nearest neighbors: ~11%
- Contribution of capacitance from next-to-next-to-nearest neighbors: ~7%

Implications of the LBNL Test Structure studies:

- good agreement between measurement and simulation suggests that the measurement procedure may be used for values in the range 10 fF - a few hundred fF.

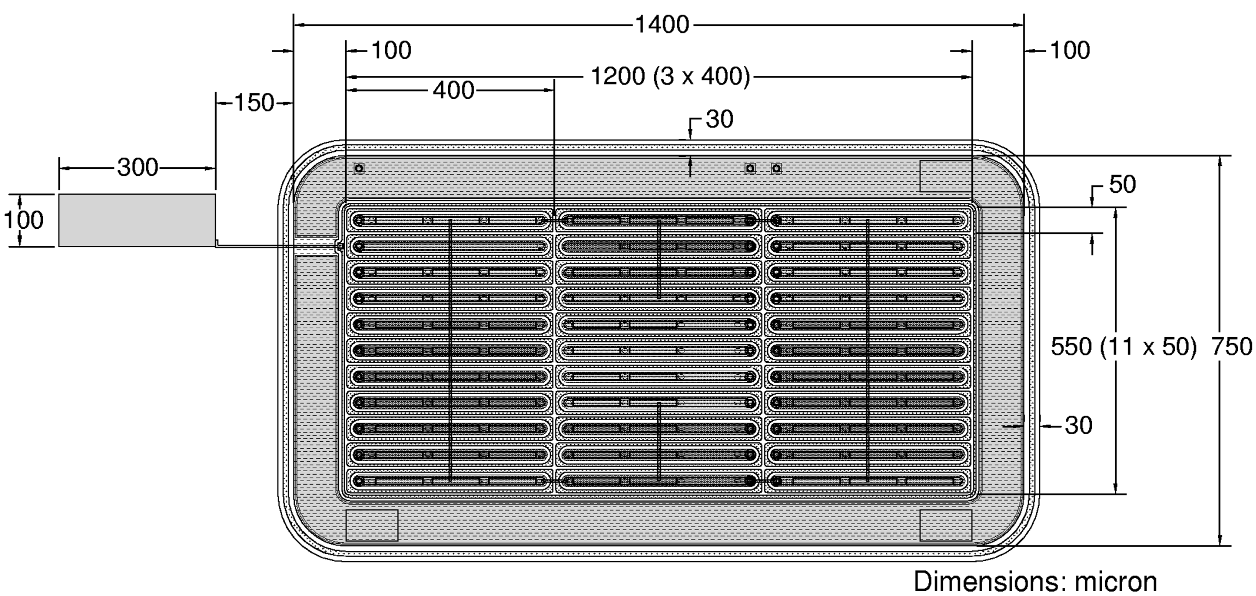
- For sensors with 50 μm pitch, 300μm thickness, typical ratio $C_{backplane}/C_{inter\text{-}pixel}$ is 10-25%.

We next apply the procedure to a set of more realistic pixel arrays, Structure 6...

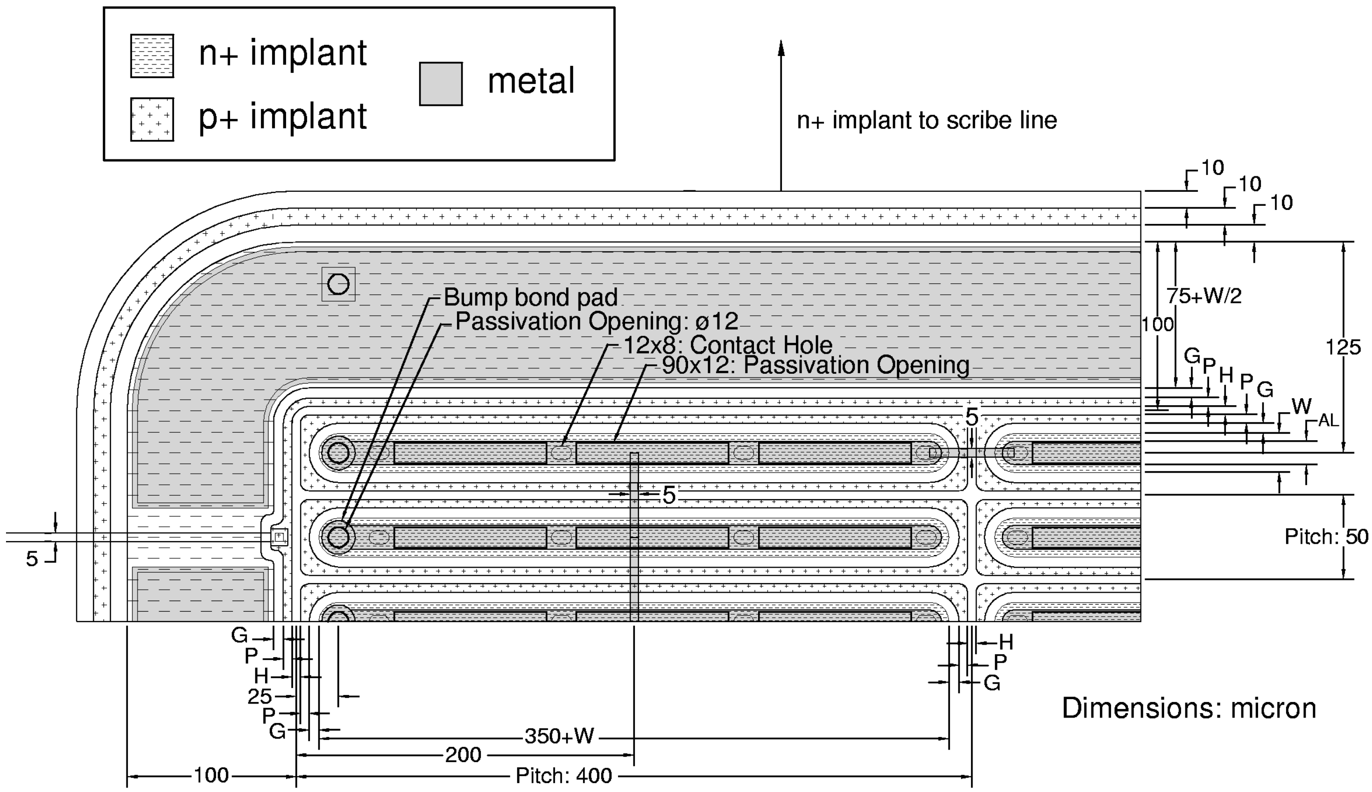
Structure 6

Designed by G. Gorfine at Univ. of New Mexico, fabricated at CiS and Seiko

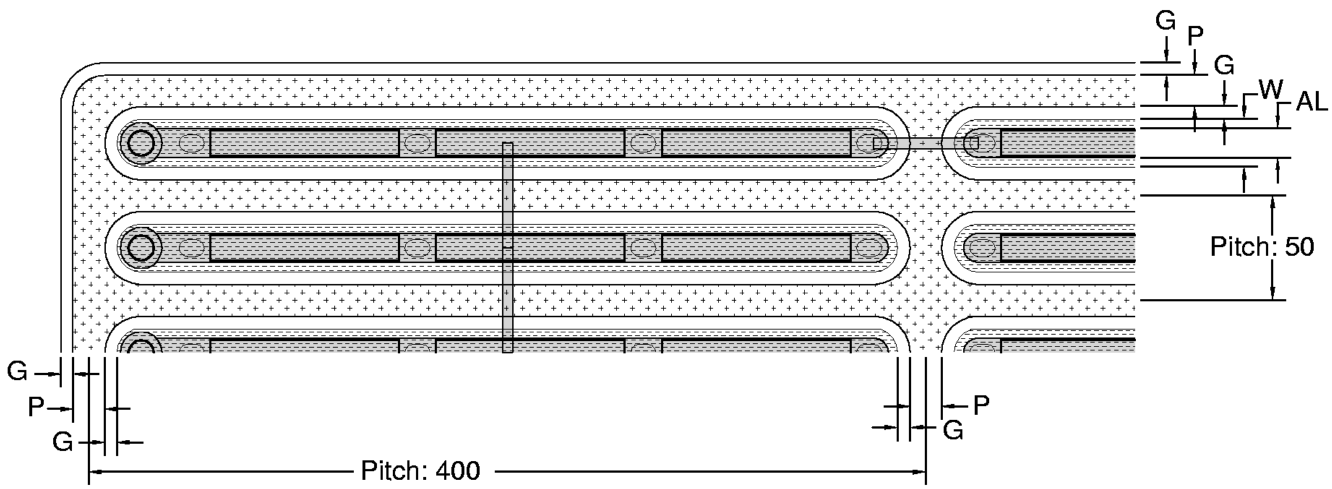
- n-on-n, 300 μm thick
- eleven 3 × 11 arrays, each with the center 3 pixels isolated and neighbors connected



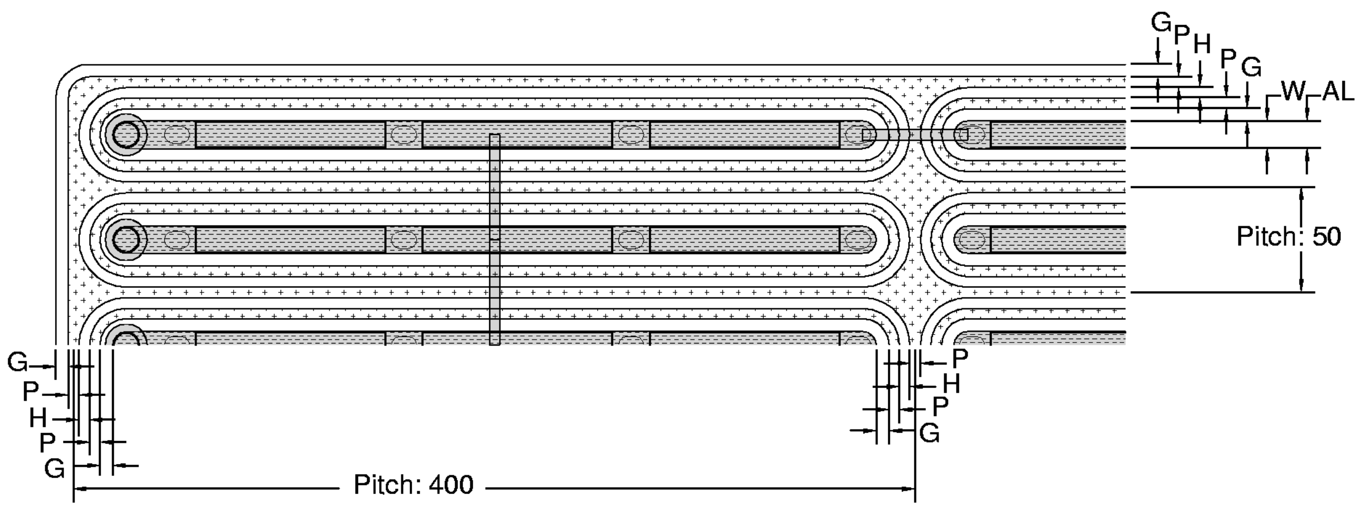
- 3 p-stop designs were studied:
  - atoll:



  - common:



• combined:



Geometries tested:

Array	p-stop Design	W	P	G	H	g
1	Atoll	23	5	6	5	17
2	Atoll	23	5	6	5	17
3	Atoll	16	5	6	12	24
4	Atoll	15	5	10	5	25
5	Atoll	19	5	8	5	21
6	Combined	13	5	6	5	22
7	Common	33	5	6	x	12
8	Common	28	10	6	x	12
9	Common	23	15	6	x	12
10	Common	24	10	8	x	16
11	Common	20	10	10	x	20

W = *n*-implant width

P = p-stop width

G = gap between *n*- and *p*-implants

H = gap between neighboring *p*-implants

g = total gap between charge collection implants

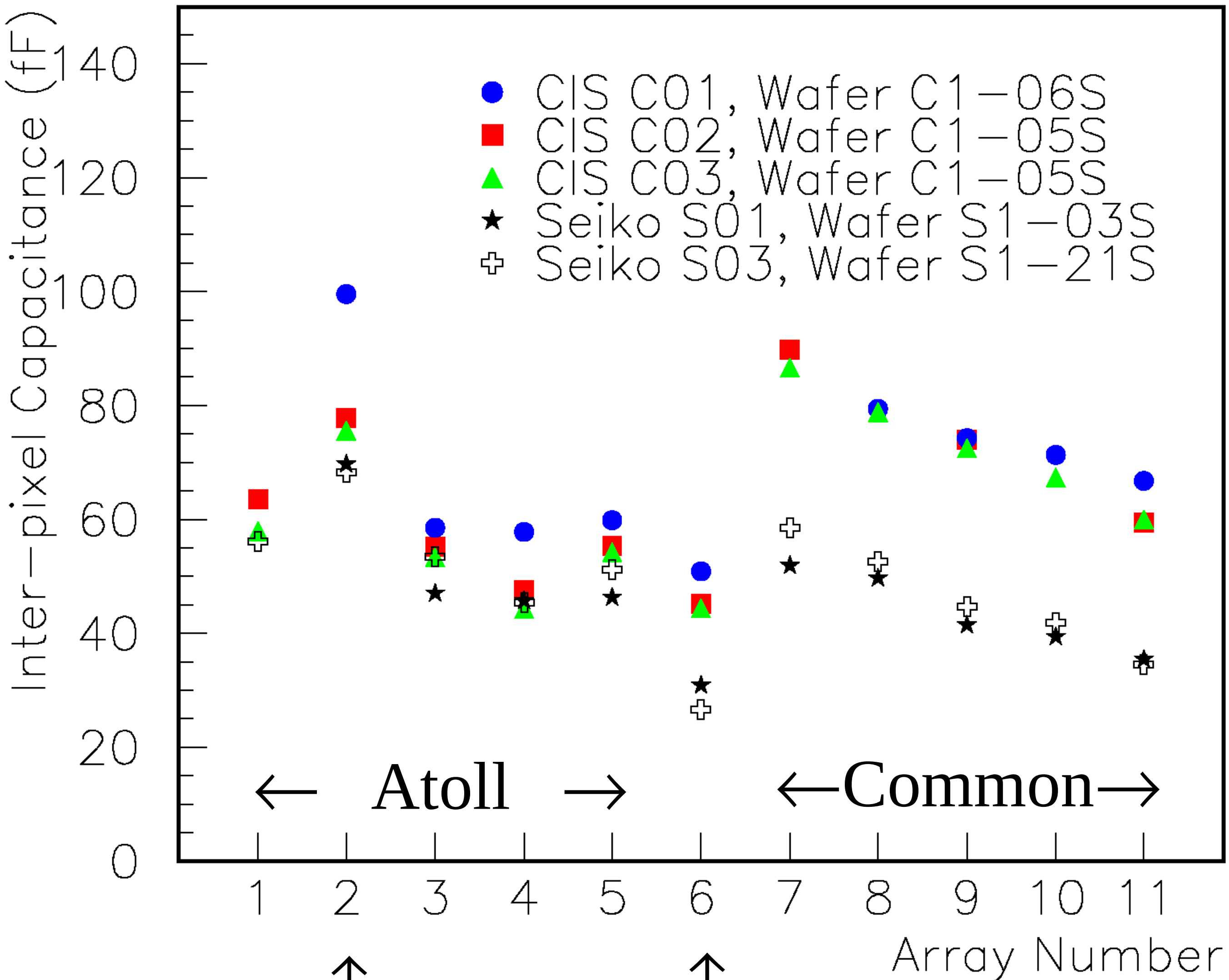
All arrays except #2 have metal narrower than implant.

We did not simulate Structure 6. However, Array 1 of Structure 6 has the same geometry as Tile 1, a design using p-stops that was examined in the First ATLAS Pixel Sensor Prototypes. The p-stop design was studied in a device simulation whose results are published in T. Rohe, et al., NIM A 409, 224 (1998).

From T. Rohe et al., Table 1:

Capacitance (fF)	p-spray Option (d)	p-stop Design
Total	128	86.4
1st neighbor	54.0	33.0
2nd neighbor	3.96	3.6
Backplane	7.35	7.4

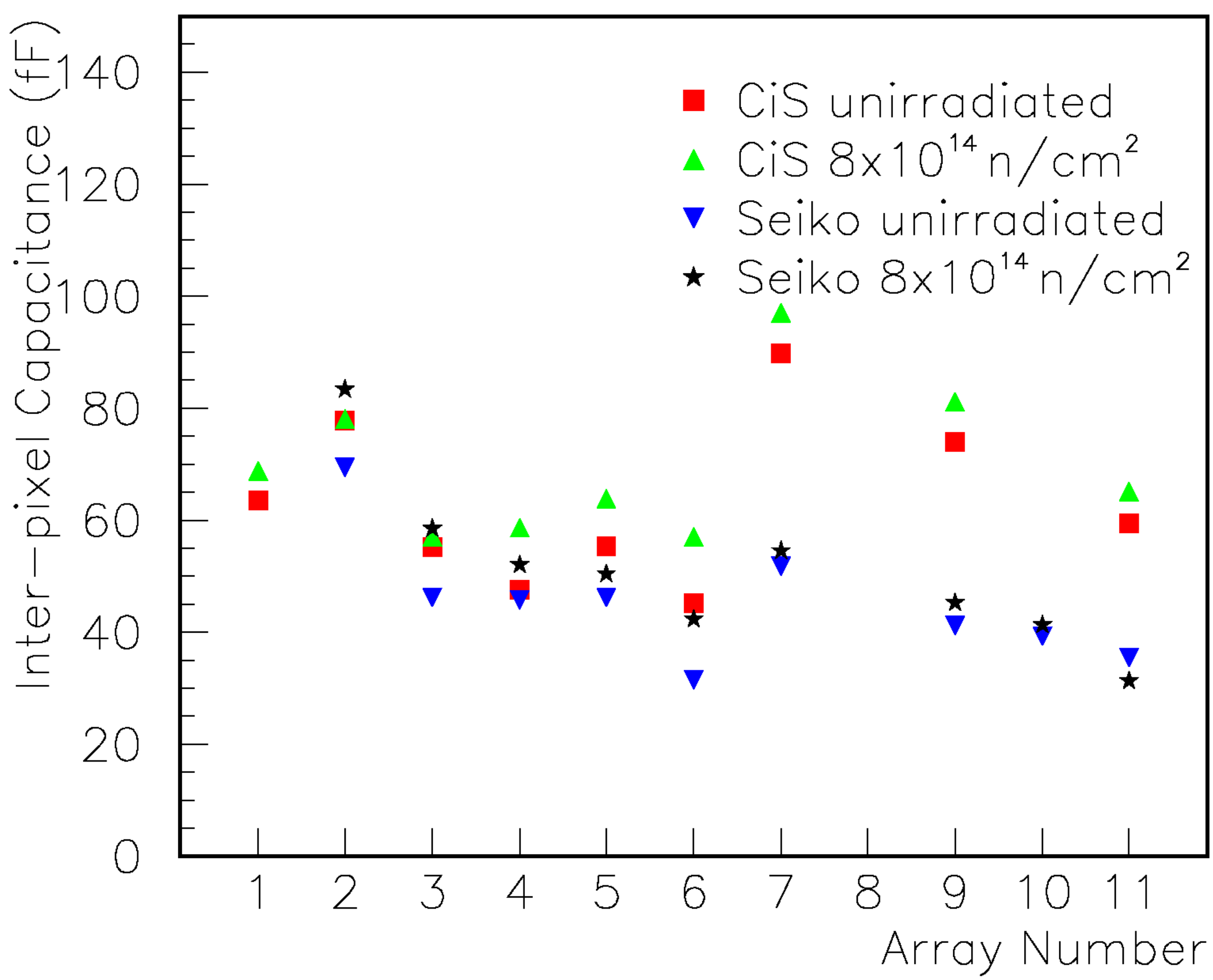
Inter-pixel capacitance of unirradiated Structure 6 arrays for different p-stop designs:



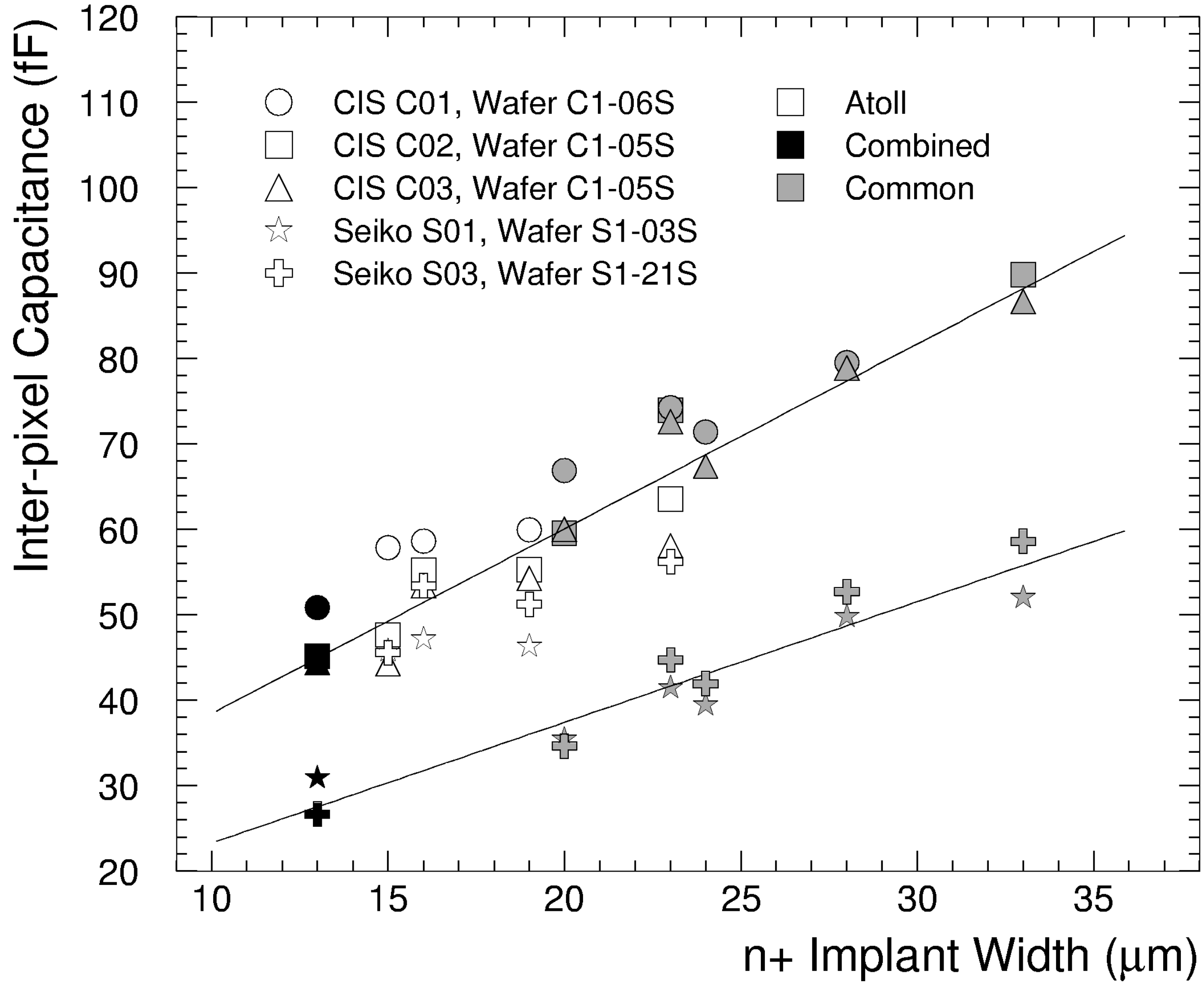
↑ Metal wider than implant

↑ Combined

Inter-pixel capacitance of Structure 6 arrays for different p-stop designs, before and immediately after irradiation:



Inter-pixel capacitance versus implant width for unirradiated Structure 6 sensors of pitch 50μm:

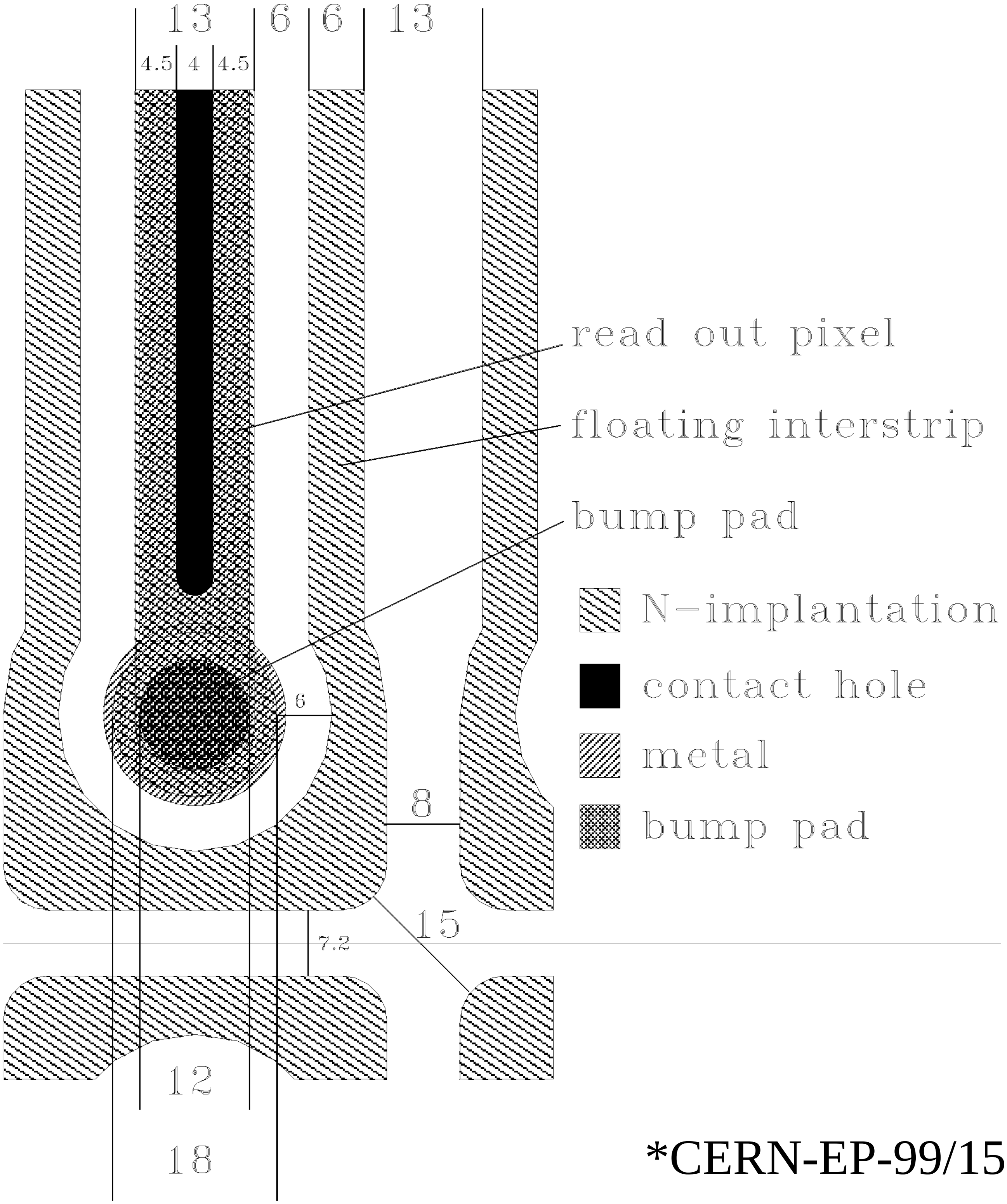


We next apply the procedure to the ATLAS prototype pixel sensors with p-spray* isolation…

*R. H. Richter et al., NIM A 377, 412 (1996).

The ATLAS ST2 Prototype Sensor*

Designed by R. Richter, T. Rohe, et al.;
fabricated at CiS and Seiko

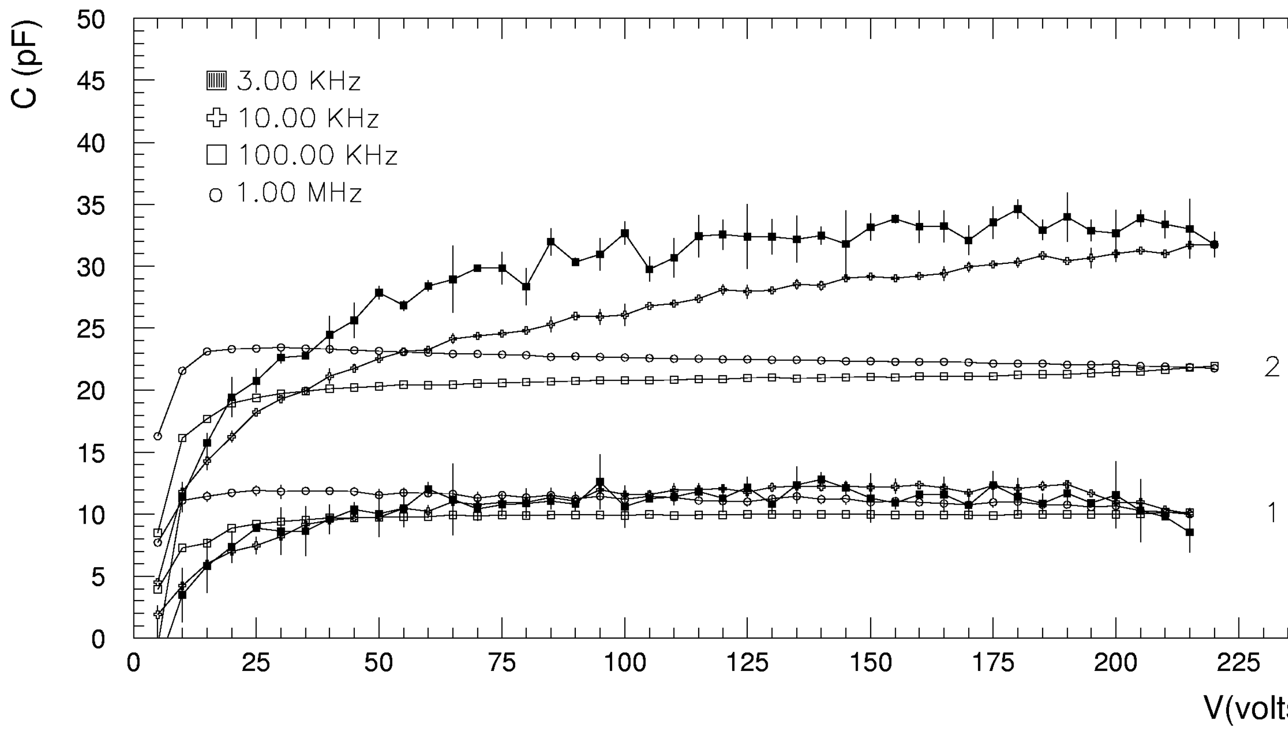


*CERN-EP-99/152

Inter-pixel capacitance of a p-spray ST2 sensor irradiated with 1.3 x 10^{14} (55 MeV p)/cm^2:

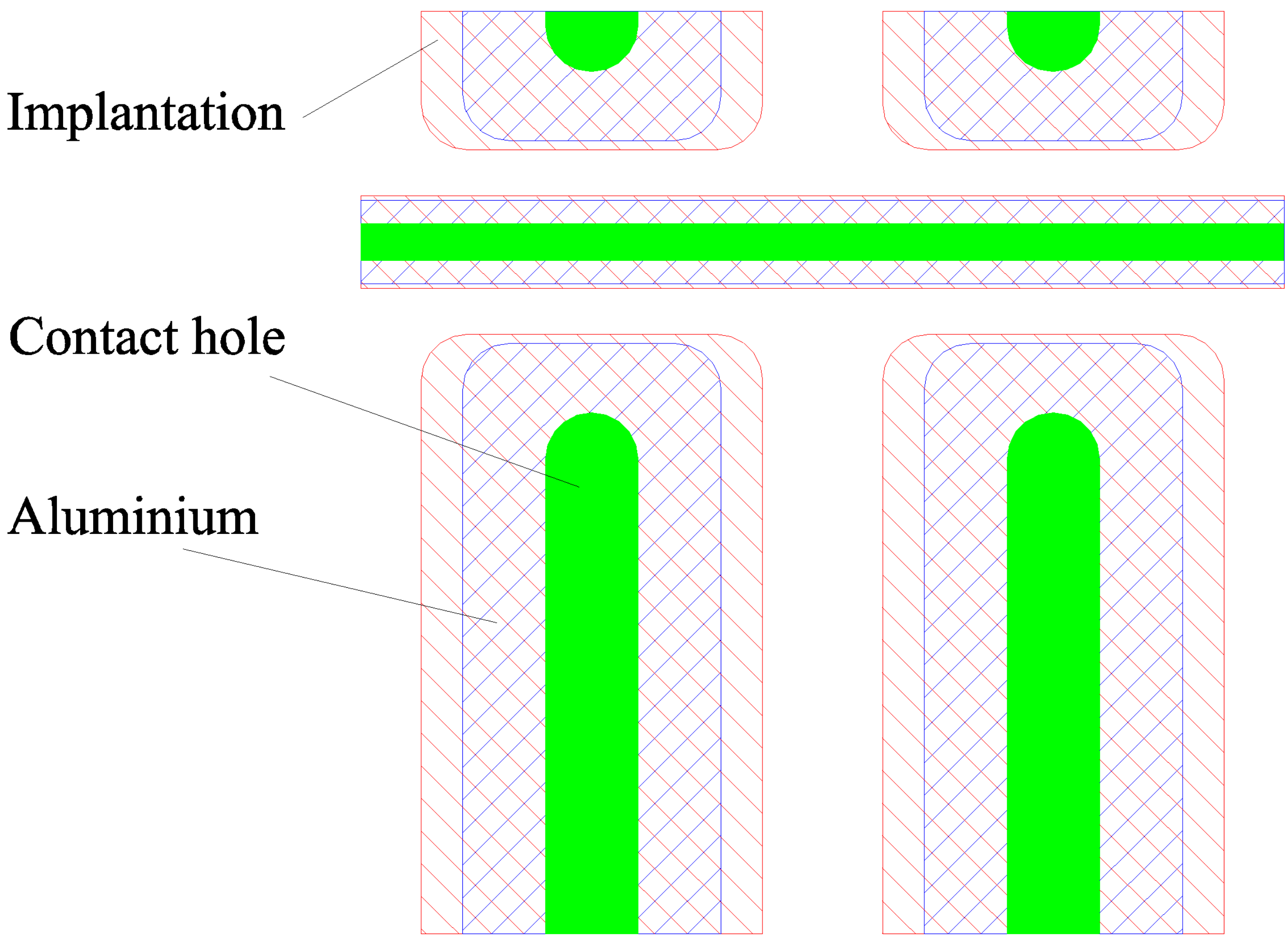
Lower curve: 1 nearest neighbor

Upper curve: both nearest neighbors



The ATLAS SSG Prototype Sensor*

Designed by R. Richter, T. Rohe, et al.;
fabricated at CiS and Seiko

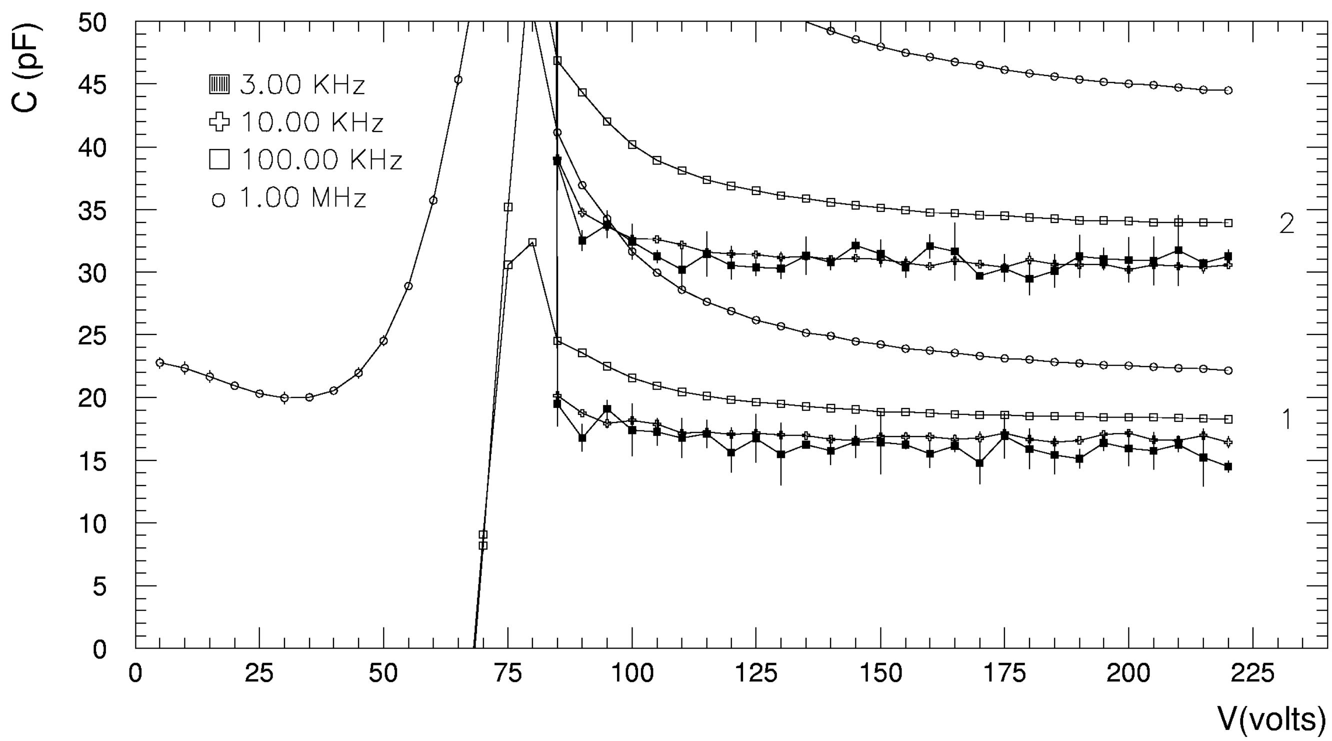


*CERN-EP-99/152

Inter-pixel capacitance of an unirradiated p-spray SSG sensor

Lower curve: 1 nearest neighbor

Upper curve: both nearest neighbors



Temperature dependence of inter-pixel capacitance of irradiated pixel sensors: