High precision pixel sensor capacitance measurements

M. Havranek, F. Hügging, H. Krüger, N. Wermes

5th Detector Workshop of the Helmholtz Alliance "Physics at the Terascale"

15th March 2012, Bonn

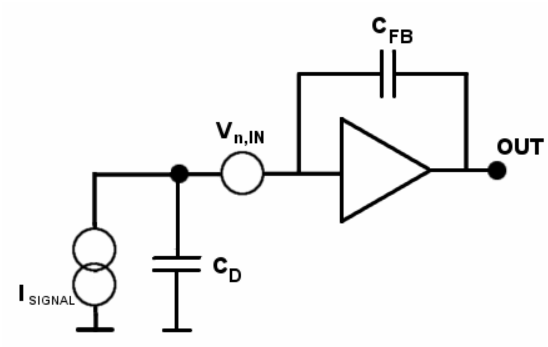
Motivation

- ~ 2020 - LHC luminosity upgrade: $10^{34}\ cm^{-2}\ s^{-1}$ ⟹ $10^{35}\ cm^{-2}\ s^{-1}$
- Detectors need upgrade too
- 3 sensor options for ATLAS Pixel Detector:
  - silicon planar
  - silicon 3D
  - diamond

  } **Which one is the best??**
- FE-I4 read-out chip developed for ATLAS IBL
- Challenges: keep high signal to noise ratio to preserve tracking performance after heavy irradiation

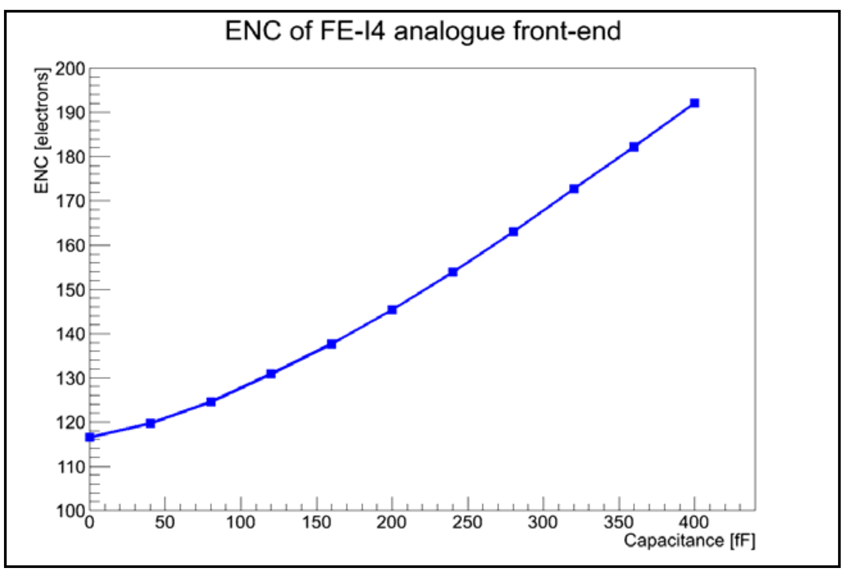
ENC and sensor capacitance

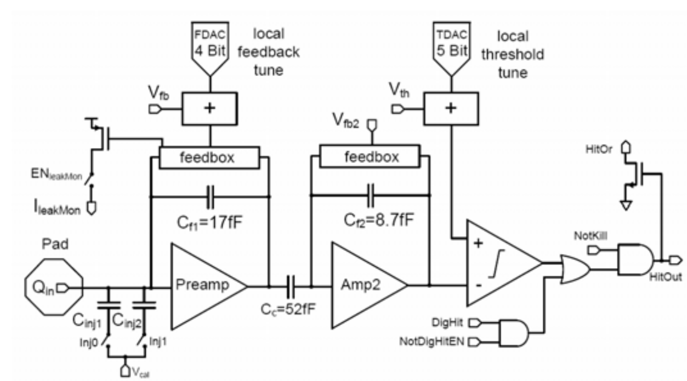
- Equivalent Noise Charge (ENC) depends on the pixel sensor capacitance



$$ENC = V_{n,\,IN} \cdot C_D$$

- Transient noise simulation of FE-I4 analogue front end:

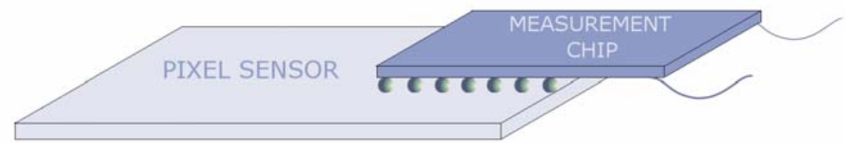


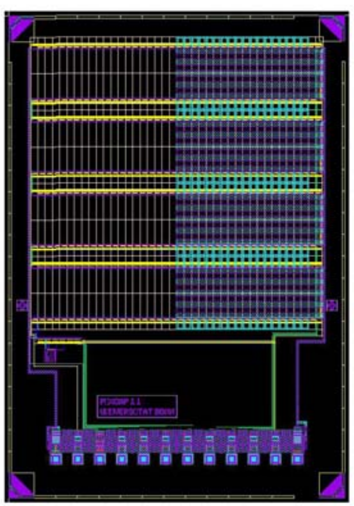


But what is the pixel sensor capacitance???

PixCap chip

- PixCap – pixel sensor capacitance measurement chip
- Designed to be bump-bonded on the pixel sensor
- Technology Lfoundry 150 nm CMOS process





Process parameters:

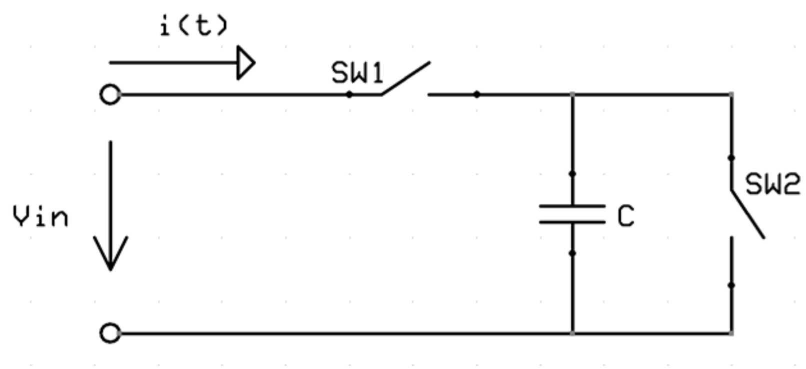
- 6 metal layers
- 1.8 V voltage domain
- low leakage switching transistors

PixCap parameters:

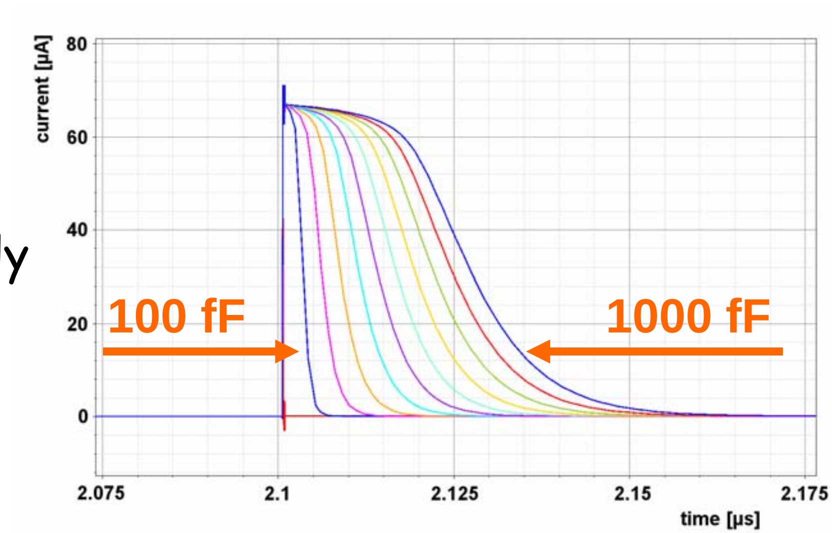
- dimensions 3.2 x 2.2 mm
- 320 (8x40) configurable measurement channels
- half of the chip has metallic shielding
- pixel dimensions 250 x 50 μm (ATLAS PIXEL IBL sensors)

Principle of capacitance measurement

- Charge pump based capacitance measurement

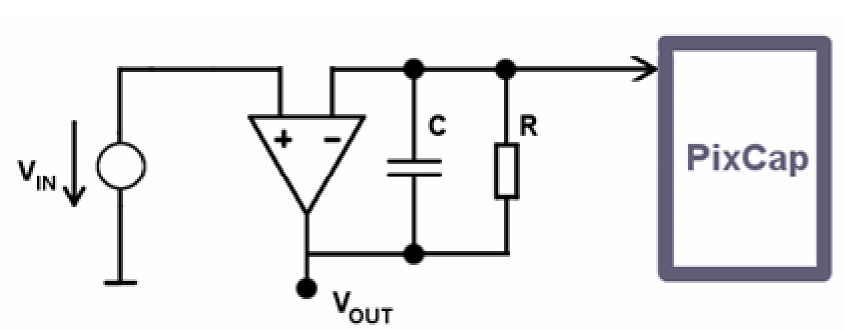


$$C = \frac{Q}{V_{IN}} = \frac{\int i(t)dt}{V_{IN}} = \frac{I_{AV}}{V_{IN} \times f}$$



- Average switching current is directly proportional to capacitance

- I->V converter



Sensitivity: **7.2 nA/fF**

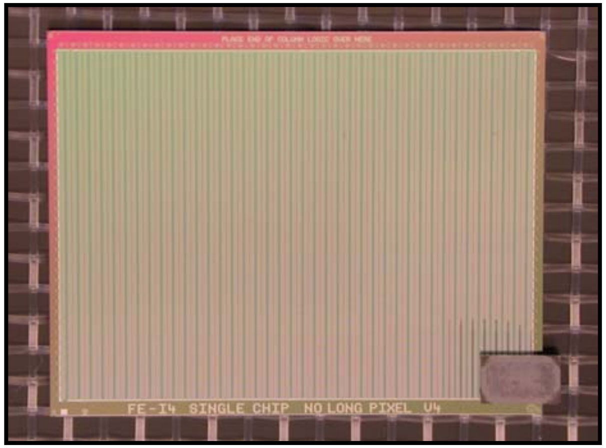
V_{IN} = 1.8 V

f = 4 MHz

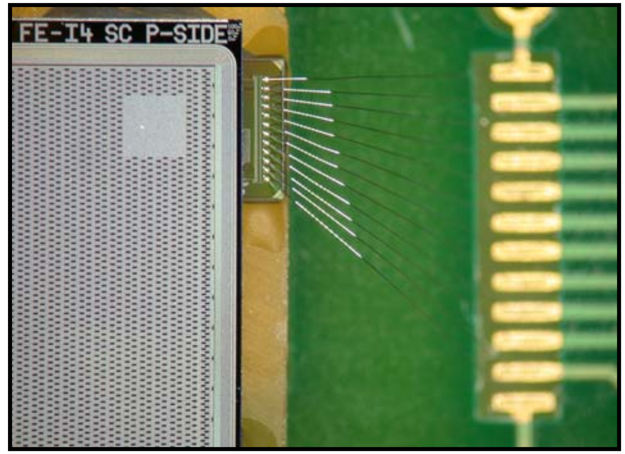
(0.72 mV/fF)

Tested devices

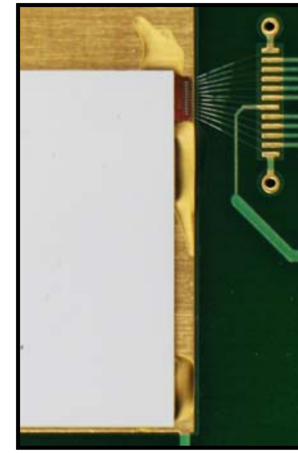
silicon planar sensor – bottom side



silicon planar sensor – top side

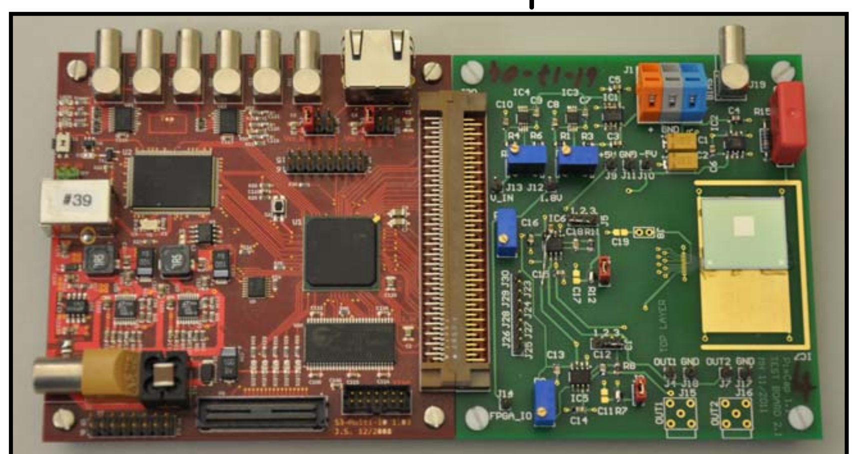


silicon 3D sensor

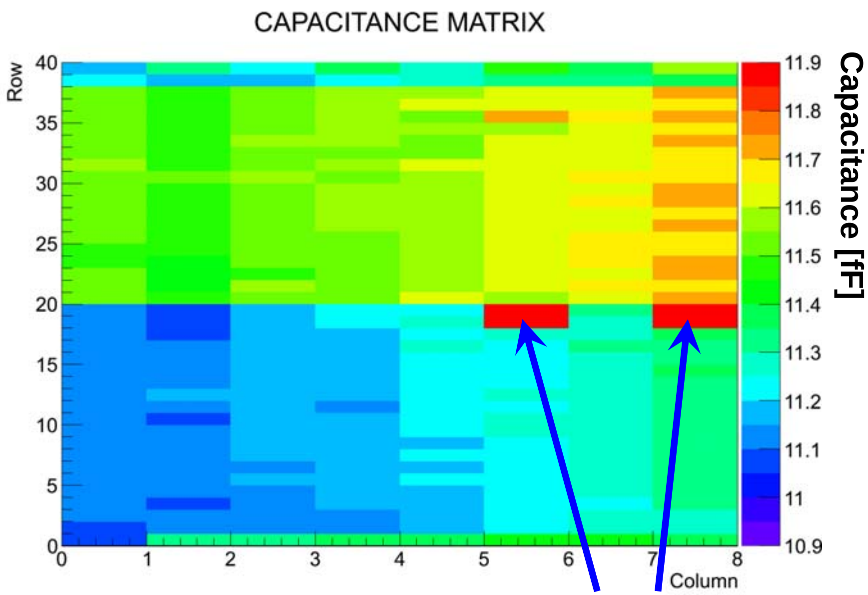


single crystal diamond sensor

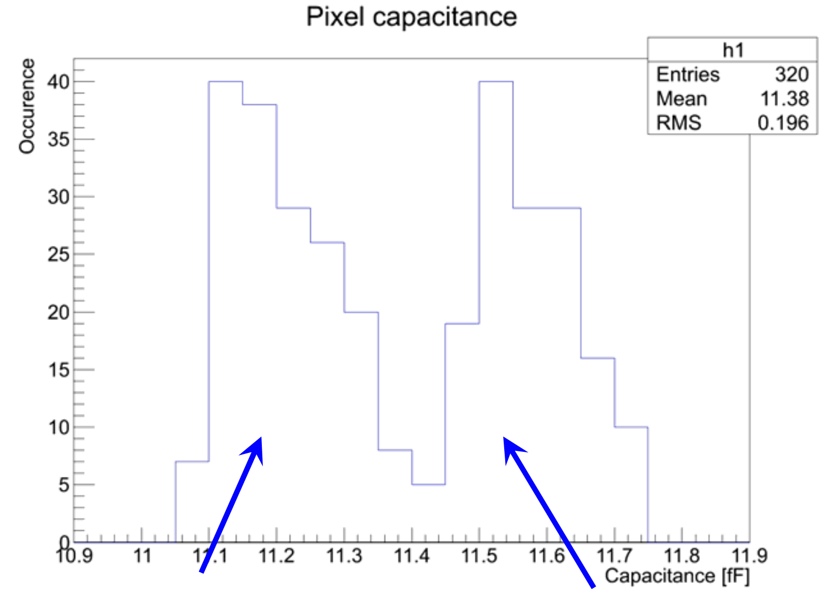
test setup



PixCap without sensor



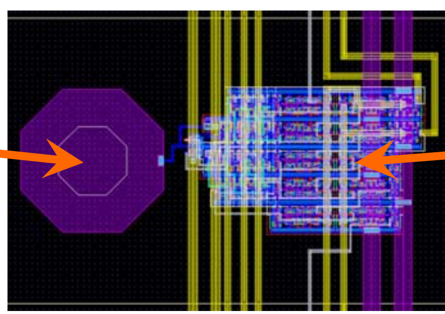
test pixels



pixels without shielding

pixels with shielding

bond pad



charge pump
+config. logic

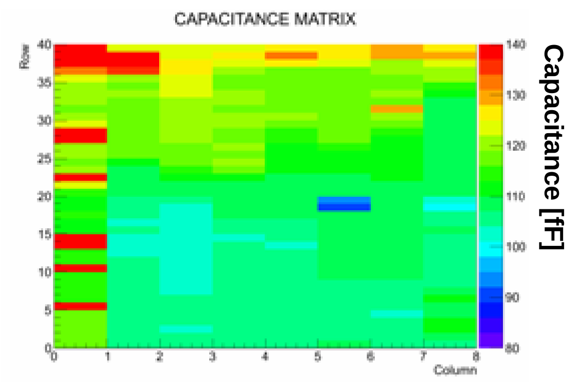
Bare PixCap chip:

C_{no_shield} = 11.22 fF
C_{shield} = 11.57 fF

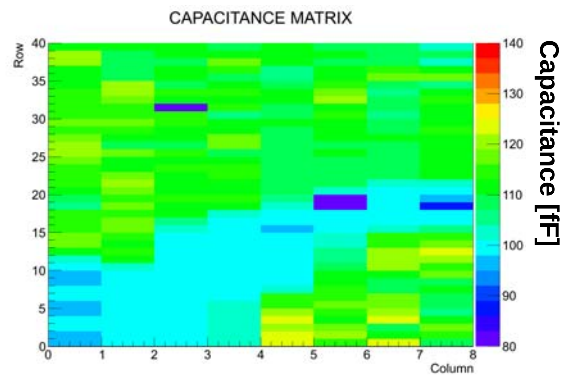
- Effect of metallic shielding is apparent
- PixCap capacitance is dominated by bond-pad

Silicon planar sensors (N on N)

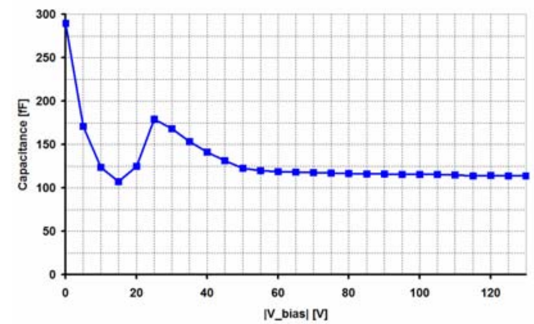
First prototype

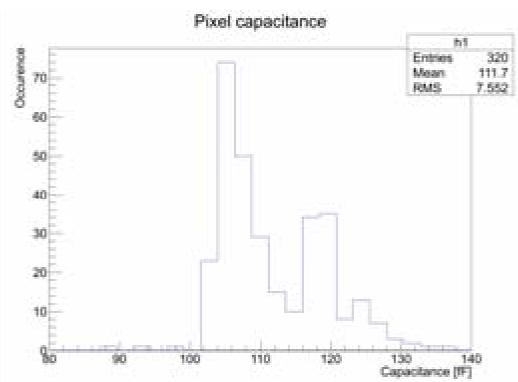


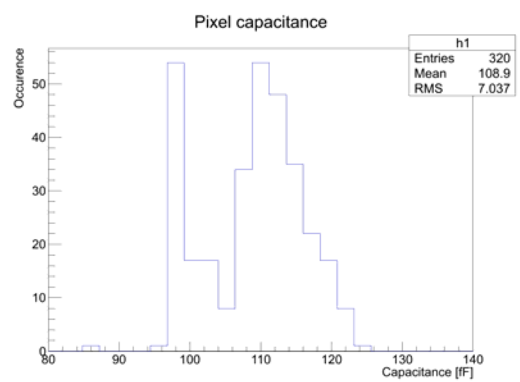
Second prototype



C-V characteristic







Values are corrected by:
- bare PixCap capacitance
- sensor's leakage current

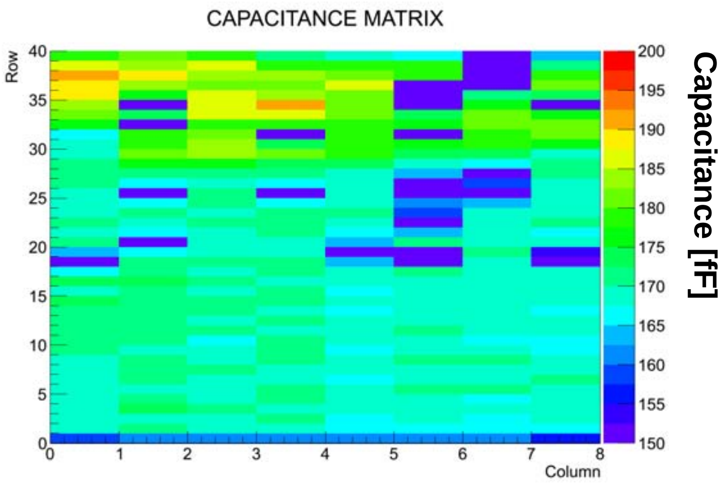
Silicon planar sensor:

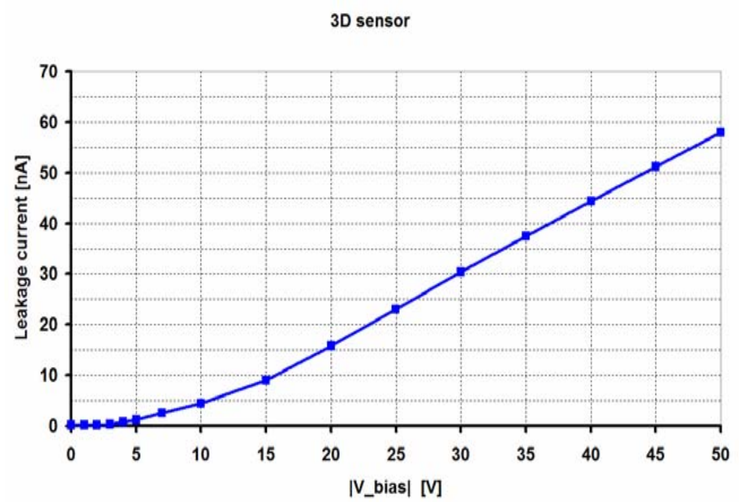
C_{MEAN1} ~ 111.7 fF

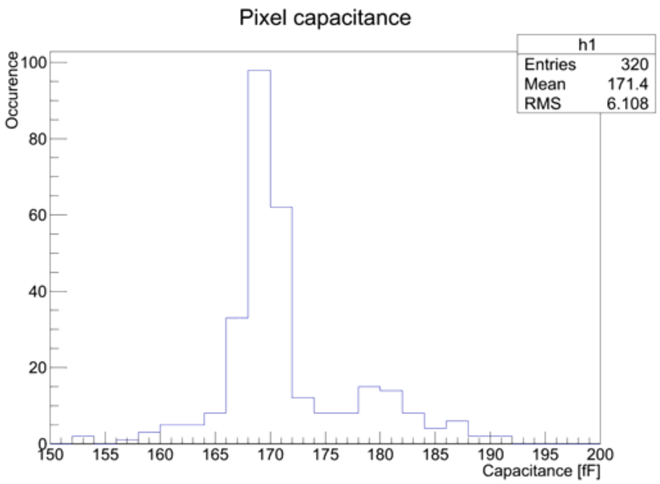
C_{MEAN2} ~ 108.9 fF

Capacitance variations are probably due to sensor process variations

Silicon 3D sensor





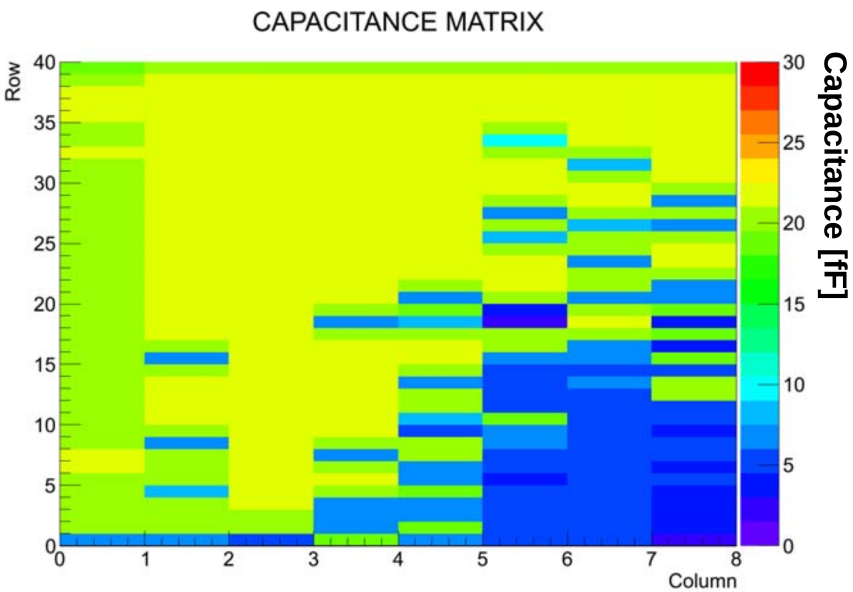


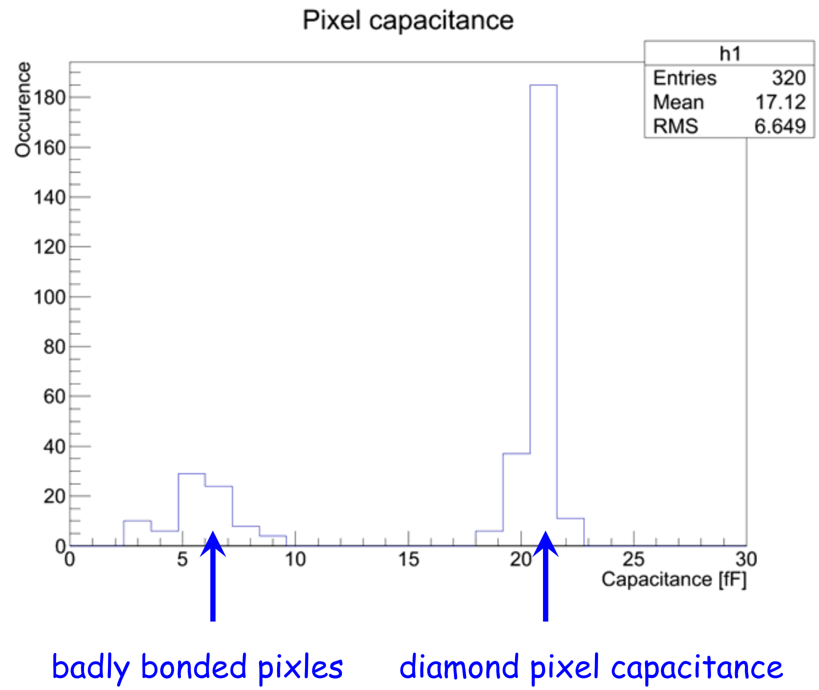
Tested 3D sensor suffers with large leakage current => measurement at low V_{BIAS}= -5 V

3D silicon sensor:
C_{MEAN} ~ 171.4 fF

Diamond

- Single crystal diamond – nearly perfect insulator => no leakage current
- Capacitance is independent of sensor bias potential

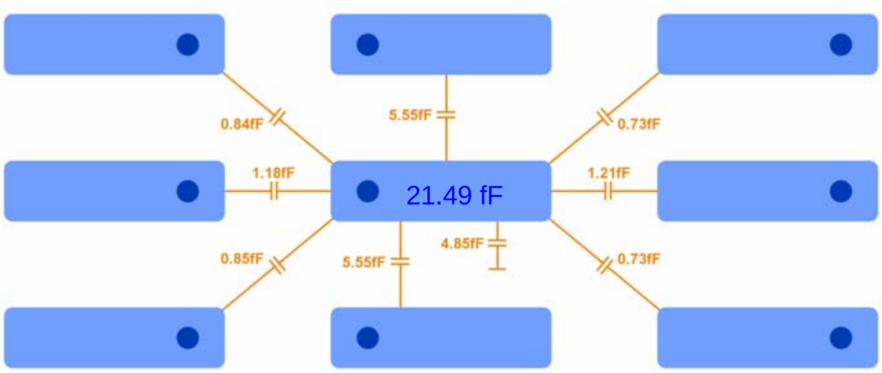




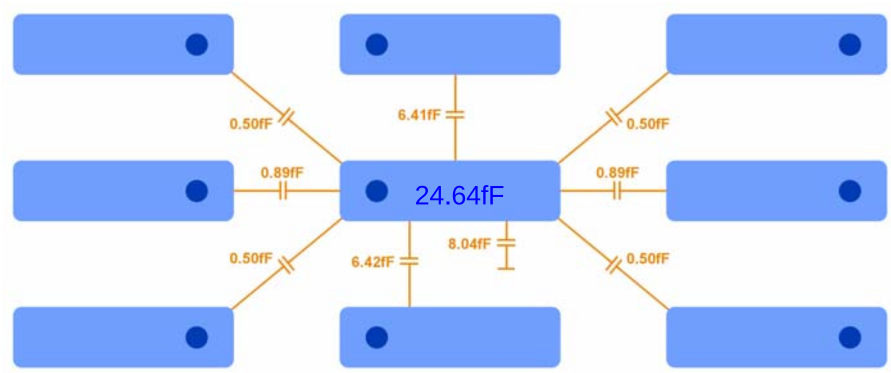
Diamond sensor:
C_{MEAN} ~ 20.81 fF
C_{BB} ~ 5.79 fF

Capacitance between pixels (diamond)

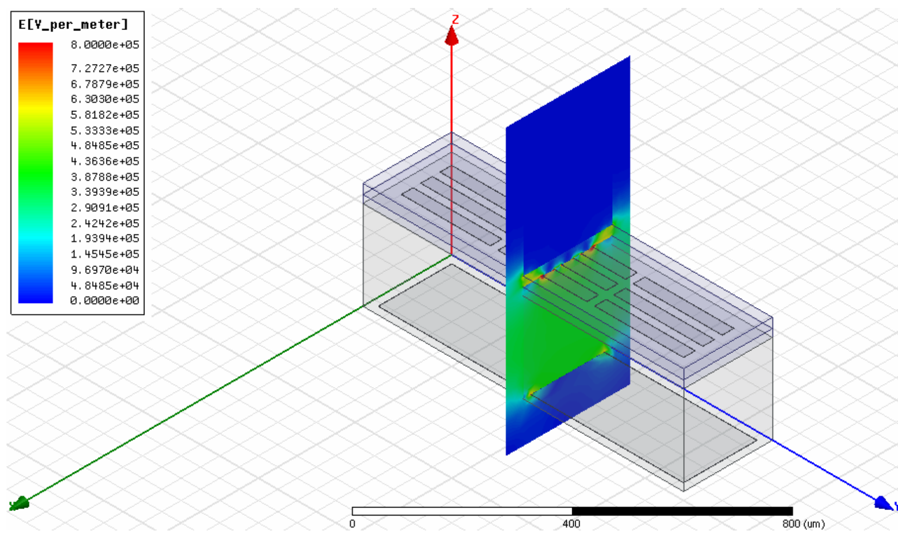
PixCap measurement



Simulation (Ansys Maxwell)



- ❑ Capacitance between pixels -> major contributor to the total pixel capacitance
- ❑ PixCap measurement was cross-checked by simulation
  => good agreement
- ❑ Similar measurement made with silicon sensor but results are not yet well understood



Summary

- Pixel sensor capacitance impacts detector noise performance
- PixCap – chip for capacitance measurement
- Several sensor types has been measured with PixCap:

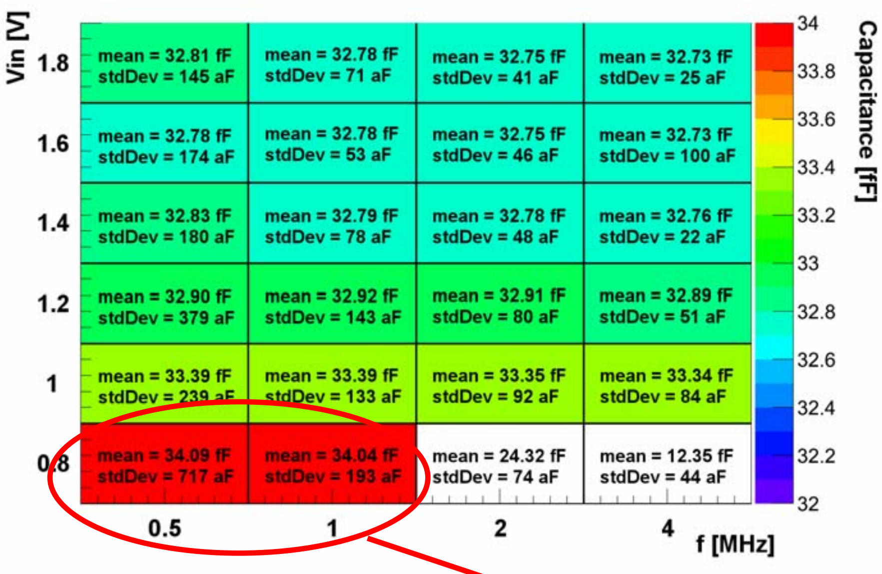
silicon planar:	C ~ 110 fF
silicon 3D:	C ~ 170 fF
diamond:	C ~ 20.8 fF

Back-up slides

Sensitivity to input signals

Sensitivity of capacitance to Vin voltage and switching frequency
- capacitance not corrected by leakage current and parasitic capacitance of PixCap

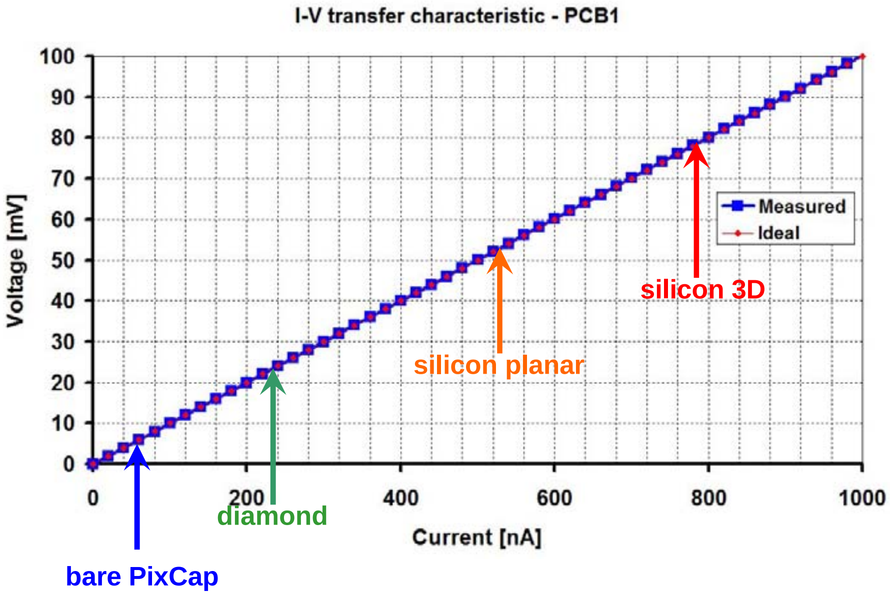
One channel of diamond sensor

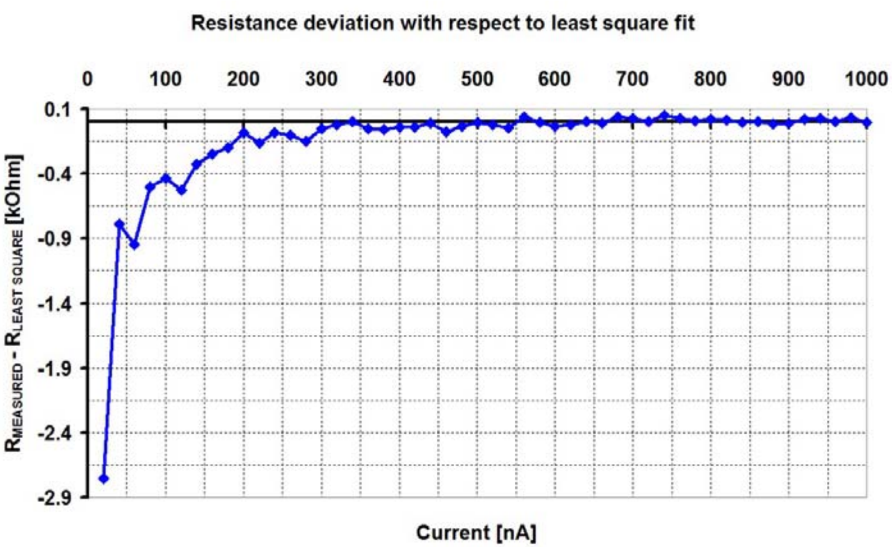


One channel of silicon planar sensor

not exactly known

Determination of conversion constant





- I-V converters work as expected
- Resistor values for each PCB were determined from transfer function (least square fit)

	Unsoldered resistors		determined from transfer function		
PCB	R_{VIN} [kOhm]	R_{MEAS} [kOhm]	R_{VIN} [kOhm]	R_{MEAS} [kOhm]	Note
1	100.115	100.025	100.179	100.076	Bare PixCap
2	99.778	99.605	99.743	99.532	Silicon planar
3	100.085	100.256	100.080	100.227	Diamond
4	99.905	99.920	99.941	100.066	Silicon planar
5	99.565	99.575	99.602	99.694	Silicon 3D

Measurement uncertainty

$$C = \frac{V_{CAP} - V_{REF}}{V_{IN} \cdot R \cdot f} - \frac{V_{CAP\_B} - V_{REF\_B}}{V_{IN\_B} \cdot R_B \cdot f} - \frac{V_L - V_{REF\_L}}{V_{IN} \cdot R \cdot f} \cdot DutyCycle$$

total capacitance seen by PixCap — bare PixCap correction — leakage current correction

Measurement uncertainty:

$$U = \sqrt{\sum_i \left(\frac{\partial C}{\partial x_i} \Delta x_i \right)^2} \quad , \quad C(x_1, x_2, x_3, \ldots)$$

Most of the terms are negligible. Typical values:

$$\frac{\partial C}{\partial V_{CAP}} \Delta V_{CAP} = 17 \text{ aF}$$

$$\frac{\partial C}{\partial V_{REF}} \Delta V_{REF} = 8 \text{ aF}$$

$$\frac{\partial C}{\partial f} \Delta f = 4.5 \text{ aF}$$

-
-
-

The largest source of uncertainty comes from current to voltage conversion constant (R) !!

Uncertainty of capacitance measurement

Taking into account all parameters for capacitance determination the uncertainty of capacitance measurement for each sensor types are following:

Bare PixCap:

$$U_C = 114 \text{ aF}$$

Silicon planar sensor:

$$U_C = 272 \text{ aF}$$

Diamond sensor:

$$U_C = 131 \text{ aF}$$

Silicon 3D sensor:

$$U_C = 266 \text{ aF}$$