

# Summary

2	<b>1</b>	<b>Introduction</b>	<b>3</b>
3	<b>2</b>	<b>Pixel detectors</b>	<b>4</b>
4	2.1	Signal formation . . . . .	4
5	2.2	Hybrid pixels . . . . .	5
6	2.3	CMOS MAPS and DMPAS . . . . .	6
7	2.3.1	DMAPS: large and small fill factor . . . . .	6
8	2.3.2	A modified sensor . . . . .	7
9	2.4	Analog front end . . . . .	8
10	2.4.1	Preamplifier . . . . .	9
11	2.5	Readout logic . . . . .	9
12	<b>3</b>	<b>Use of pixel detectors</b>	<b>12</b>
13	3.1	Tracking in HEP . . . . .	12
14	3.1.1	Hybrid pixels: ATLAS, CMS and LHC-b . . . . .	12
15	3.1.2	CMOS MAPS: ALICE and STAR . . . . .	12
16	3.2	Application in medical imaging . . . . .	12
17	3.2.1	Medipix and Timepix . . . . .	12
18	3.2.2	Applicability to FLASH radiotherapy . . . . .	12
19	<b>4</b>	<b>TJ-Monopix1</b>	<b>13</b>
20	4.1	The sensor . . . . .	14
21	4.2	Front end . . . . .	16
22	4.2.1	ALPIDE-like . . . . .	16
23	4.2.2	Front end parameters . . . . .	17
24	4.3	Readout logic . . . . .	17
25	4.3.1	Dead time measurement . . . . .	20
26	<b>5</b>	<b>Arcadia-MD1</b>	<b>21</b>
27	5.1	The sensor . . . . .	21
28	5.2	Readout logic and data structure . . . . .	21
29	5.2.1	Matrix division and data-packets . . . . .	21
30	<b>6</b>	<b>Threshold and noise characterization</b>	<b>25</b>
31	6.1	Threshold and noise: figure of merit for pixel detectors . . . . .	25
32	6.2	TJ-Monopix1 characterization . . . . .	26
33	6.3	ARCADIA-MD1 characterization . . . . .	26
34	<b>A</b>	<b>Pixels detector: a brief overview</b>	<b>27</b>
35	A.1	Radiation damages . . . . .	27
36	<b>B</b>	<b>FLASH radiotherapy</b>	<b>29</b>
37	B.1	Cell survival curves . . . . .	29
38	B.2	FLASH effect . . . . .	30
39	<b>Bibliography</b>		<b>31</b>
40	Characterization of monolithic CMOS pixel sensors for charged particle detectors and for high intensity dosimetry		

<sup>42</sup> **Chapter 1**

<sup>43</sup> **Introduction**

<sup>44</sup> Pixel detectors, members of the semiconductor detector family, have significantly been used since  
<sup>45</sup> () at the first accelerator experiments for energy and position measurement. Because of their  
<sup>46</sup> dimension (today  $\sim 30 \mu m$  or even better) and their spatial resolution ( $\sim 5\text{-}10 \mu m$ ), with the  
<sup>47</sup> availability of technology in 1980s they proved to be perfectly suitable for vertex detector in the  
<sup>48</sup> inner layer of the detector.

<sup>49</sup> Technological development has been constant from then on and today almost every high energy  
<sup>50</sup> physics (HEP) experiment employs a pixels detector; hybrid pixel currently constitute the state-  
<sup>51</sup> of-art for large scale pixel detector but experiments began to look at the more innovative monolithic  
<sup>52</sup> active pixels (MAPS) as perspective for their future upgrades, as BelleII, or they already have  
<sup>53</sup> installed them, as ALICE.

<sup>54</sup> Requirement imposed by accelerator are stringent and they will be even more with the increase  
<sup>55</sup> of luminosity/intensity, in terms of radiation hardness, efficiency and occupancy, time resolution,  
<sup>56</sup> material budget and power consumption.

<sup>57</sup> Qual è invece la richiesta per la dosimetria?

<sup>58</sup>

<sup>59</sup> **Chapter 2**

<sup>60</sup> **Pixel detectors**

<sup>61</sup> **2.1 Signal formation**

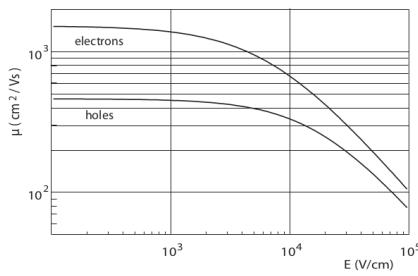
<sup>62</sup> When a charge particle passes through a pixel and loses energy by ionization a part of that  
<sup>63</sup> energy is used to generate electron-hole pairs (another part is used for other processes, as the  
<sup>64</sup> lattice excitation) which are then separated by the electric field and collected at their respectively  
<sup>65</sup> electrodes ( $p$  for holes and  $n$  for electrons)<sup>1</sup>; by the drift of these charges, a signal  $i_e$  is generated  
<sup>66</sup> on the electrode  $e$  as stated by the Shockley–Ramo's theorem:

$$i_e(t) = -q v(t) E_{WF,e} \quad (2.1)$$

<sup>67</sup> where  $v(t)$  is the instantaneous velocity of the charge  $q$  and  $E_{WF}$  is the weighting field, that is the  
<sup>68</sup> field obtained biasing the electrode  $e$  with 1V and all the others with 0V. The drift velocity of the  
<sup>69</sup> charge depends on the electric field and on the mobility of the particle:

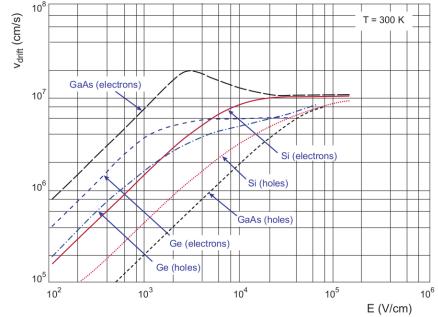
$$v = \mu(E) E \quad (2.2)$$

<sup>70</sup> where  $\mu(E)$  is a function of the electric field and is linear with  $E$  only for small  $E$ : at higher values  
<sup>71</sup> the probability of interactions with optical phonons increases and the mobility drops and this leads  
<sup>72</sup> to an independence of the velocity from the electric field (fig. 2.1b).



(a) Typical values for electrons and holes mobility in

silicon at room temperature are  $\mu_n \sim 1450 \text{ cm}^2/\text{Vs}$ ,  $\mu_h = 500$



(b) Drift velocity at room temperature in different semiconductors

<sup>73</sup> The average energy needed to create a pair at 300 K in silicon is  $w_i = 3.65 \text{ eV}$ , that is more  
<sup>74</sup> than the mean ionization energy because of the interactions with phonon, since for a minimum  
<sup>75</sup> ionizing particle (MIP) the most probable value (MPV) of charge released in the semiconductor is  
<sup>76</sup> 0.28 keV/ $\mu$ , hence the number of e/h pairs is:

$$\langle \frac{dE}{dx} \rangle \frac{1}{w_i} \sim 80 \text{ e}/\text{h} \sim \frac{1.28 \cdot 10^{-2} fC}{\mu m} \quad (2.3)$$

<sup>1</sup>Even if in principle both the electrode can be used to read a signal, for pixel detectors, where the number of channel and the complexity of readout are high, only one is actually used. In strip and pad detectors, instead, is more common a dual-side readout

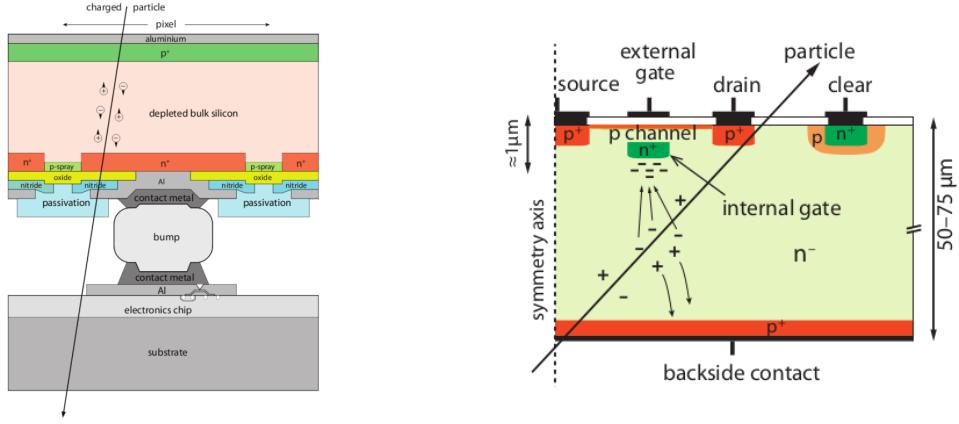


Figure 2.2: Concept cross-section of hybrid pixel (a) and of a DEPFET (b)

77 CON UN'INCERTEZZA CHE È RADICE DI N; ED EVENTUALEMTE SI AGGIUNGE IL  
 78 FATTORE DI FANO NEL CASO DI ASSORBIMENTO TOTALE. IL FATTORE DI FANO È  
 79 0.115 NELL SILICIO. ecc It is fundamental that pairs e/h are produced in the depleted region  
 80 of the semiconductor where the probability of recombination with charge carriers is low to avoid  
 81 loss of signals. Pixel detectors are then commonly reverse biased: a positive bias is given to the  
 82 n electrode and a negative to the p to grow the depletion zone in the epitaxial layer below the  
 83 electrode. The width of the depletion region is related with the external bias  $V_{ext}$ , the resistivity  
 84  $\rho$  and also with the dopant:

$$d_n \sim 0.55 \sqrt{\frac{\rho}{\Omega cm} \frac{V_{ext}}{V}} \mu m \quad (2.4) \quad d_p \sim 0.32 \sqrt{\frac{\rho}{\Omega cm} \frac{V_{ext}}{V}} \mu m \quad (2.5)$$

85

86

87

88 For that reason high resistivity wafers ( $100 \Omega cm - k\Omega cm$ ) are typically preferred because they  
 89 allow bigger depletion zone with smaller voltage bias.

## 90 2.2 Hybrid pixels

91 Hybrid pixels are made of two parts (fig. 2.2a), the sensor and the electronics: for each pixel these  
 92 two parts are welded together through microconnection (bump bond).  
 93 They provide a practical system where readout and sensor can be optimized separately, although  
 94 the testing is less easy-to-do since the sensor and the R/O must be connected together before.  
 95 In addition, the particular and sophisticated procedure to bond sensor and ASIC (application spe-  
 96 cific integrated circuit) makes them difficult to produce, delicate, especially when exposed to high  
 97 levels of radiation, and also expensive.  
 98 A critical parameter for accelerator experiments is the material budget, which represents the main  
 99 limit factor for momentum measurement resolution in a magnetic field; since hybrid pixels are  
 100 thicker ( $\sim$  hundreds of  $\mu m$ ) than monolithic ones (even less than  $100 \mu m$ ), using the latter the  
 101 material budget can be down by a third: typical value for hybrid pixels is 1.5 %  $X_0$  per layer,  
 102 while for monolithic 0.5 %  $X_0$ .  
 103 Among other disadvantages of hybrid pixels there is the bigger power consumption that implies,  
 104 by the way, a bigger cooling system leading in turn to an increase in material too.

105

106 DEPFET are the first attempt towards the integration of the front end (FE) on the sensor bulk:  
 107 they are typically mounted on a hybrid structure but they also integrate the first amplification  
 108 stage.

109 Each pixel implements a MOSFET (metal-oxide-semiconductor field-effect transistor) transistor  
 110 (a p-channel in fig. 2.2b): an hole current flows from source to drain which is controlled by the  
 111 external gate and the internal gate together. The internal gate is made by a deep n+ implant  
 112 towards which electrons drift after being created in the depletion region (to know how the signal

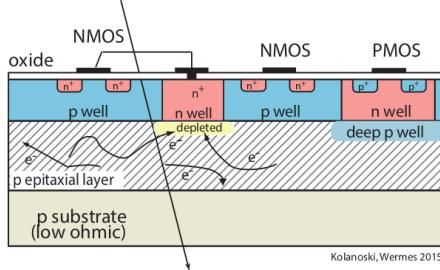


Figure 2.3: Concept cross-section of CMOS MPAS pixel

is created in a pixel detector look at appendix A); the accumulation of electrons in the region underneath the n implant changes the gate potential and controls the transistor current.  
DEPFET typically have a good S/N ratio: this is principally due the amplification on-pixel and the large depletion region. But, since they need to be connected with ASIC the limiting factor still is the material budget.

## 2.3 CMOS MAPS and DMPAS

Monolithic active pixels accommodate on the same wafer both the sensor and the front end electronics, with the second one implanted on top.

MAPS have been first proposed and realized in the 1990s and their usage has been enabled by the development of the electronic sector which guarantees the decrease in CMOS transistors dimension at least every two years, as stated by the Moore's law<sup>2</sup>.

As a matter of fact the dimension of components, their organization on the pixel area and logic density are important issues for the design and for the layout; typically different decisions are taken for different purposes.

Monolithic active pixel can be distinguished between two main categories: MAPS and depleted MAPS (DMPAS).

MAPS (figure a 2.3) have typically an epitaxial layer in range 1-20  $\mu\text{m}$  and because they are not depleted, the charge is mainly collected by diffusion rather than by drift. This makes the path of charges created in the bulk longer than usual, therefore they are slow (of order of 100 ns) and the collection could be partial especially after the irradiation of the detector (look at A for radiation damages), when the trapping probability become higher.

In figure 2.3 is shown as example of CMOS MAPS: the sensor in the scheme implements an n well as collection diode; to avoid the others n wells (which contain PMOS transistor) of the electronic circuit would compete in charge collection and to shield the CMOS circuit from the substrate, additionally underlying deep p well are needed. DMPAS are instead MAPS depleted with  $d$  typically in  $\sim 25\text{-}150 \mu\text{m}$  (eq. 2.1) which extends from the diode to the deep p-well, and sometimes also to the backside (in this case if one wants to collect the signal also on this electrode, additional process must be done).

### 2.3.1 DMAPS: large and small fill factor

There are two different sensor-design approaches (figure 2.4) to DMAPS:

- large fill factor: a large collection electrode that is a large deep n-well and that host the embedded electronics
- small fill factor: a small n-well is used as charge collection node

To implement a uniform and stronger electric field, DMAPS often uses large electrode design that requires multiple wells (typically four including deep n and p wells); this layout adds on to the standard terms of the total capacity of the sensor a new term (fig. 2.5), that contributes to the total amplifier input capacity. In addition to the capacity between pixels ( $C_{pp}$ ) and between the pixel and the backside ( $C_b$ ), a non-negligible contribution comes from the capacities between wells

<sup>2</sup>Moore's law states that logic density doubles every two years.

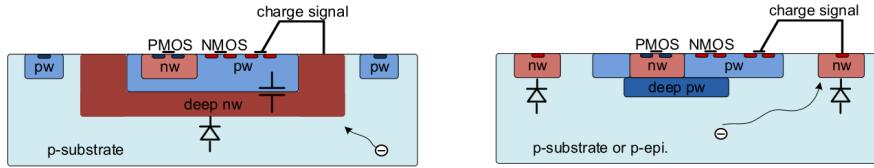


Figure 2.4: Concept cross-section with large and small fill factor

	small fill factor	large fill factor
small sensor C	✓ (< 5 fF)	✗ (~ 100-200 fF)
low noise	✓	✗
low cross talk	✓	✗
velocity performances	✓	✗ (~ 100 ns)
short drift paths	✗	✓
radiation hard	✗	✓

Table 2.1: Small and large fill factor DMAPS characteristics

151 ( $C_{SW}$  and  $C_{WW}$ ) needed to shield the embedded electronics. These capacities affect the thermal  
152 and 1/f noise of the charge amplifier and the  $\tau_{CSA}$  too:

$$ENC_{thermal}^2 \propto \frac{4}{3} \frac{kT}{g_m} \frac{C_D^2}{\tau_{sh}} \quad (2.6) \quad \tau_{CSA} \propto \frac{1}{g_m} \frac{C_D}{C_f} \quad (2.7)$$

154 where  $g_m$  is the transconductance,  $\tau_{sh}$  is the shaping time.  
155 Among the disadvantages coming from this large input capacity could be the coupling between  
156 the sensor and the electronics resulting in cross talk: noise induced by a signal on neighbouring  
157 electrodes; indeed, since digital switching in the FE electronics do a lot of oscillations, this problem  
is especially connected with the intra wells capacities. So, larger charge collection electrode

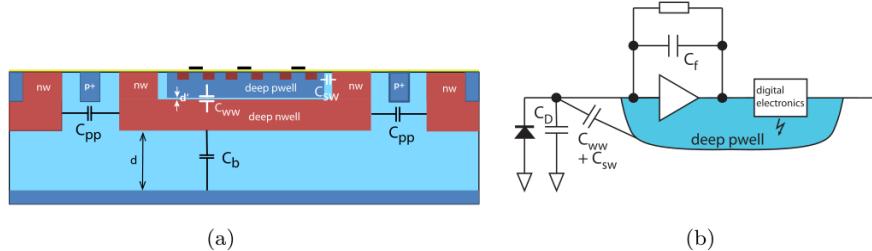


Figure 2.5:  $C_{pp}$ ,  $C_b$ ,  $C_{WW}$ ,  $C_{SW}$

158 sensors provide a uniform electric field in the bulk that results in short drift path and so in good  
159 collection properties, especially after irradiation, when trapping probability can become an issue.  
160 The drawback of a large fill-factor is the large capacity (~100 fF): this contributes to the noise  
161 and to a speed penalty and to a larger possibility of cross talk.

162 The small fill-factor variant, instead, benefits from a small capacity (5-20 fF), but suffers from  
163 a not uniform electric field and from all the issue related to that. **Ho già detto prima parlando dei  
164 MAPS, devo ripetere qui?**

165 As we'll see these two different types of sensor require different amplifier: the large electrode one is  
166 coupled with the charge sensitive amplifier, while the small one with voltage amplifier (sec 2.4.1).  
167

### 168 2.3.2 A modified sensor

169 A process modification developed by CERN in collaboration with the foundries has become the  
170 standard solution to combine the characteristics of a small fill factor sensor (small input amplifier  
171 capacity) and of large fill factor sensor (uniform electric field) is the one carried out for ALICE

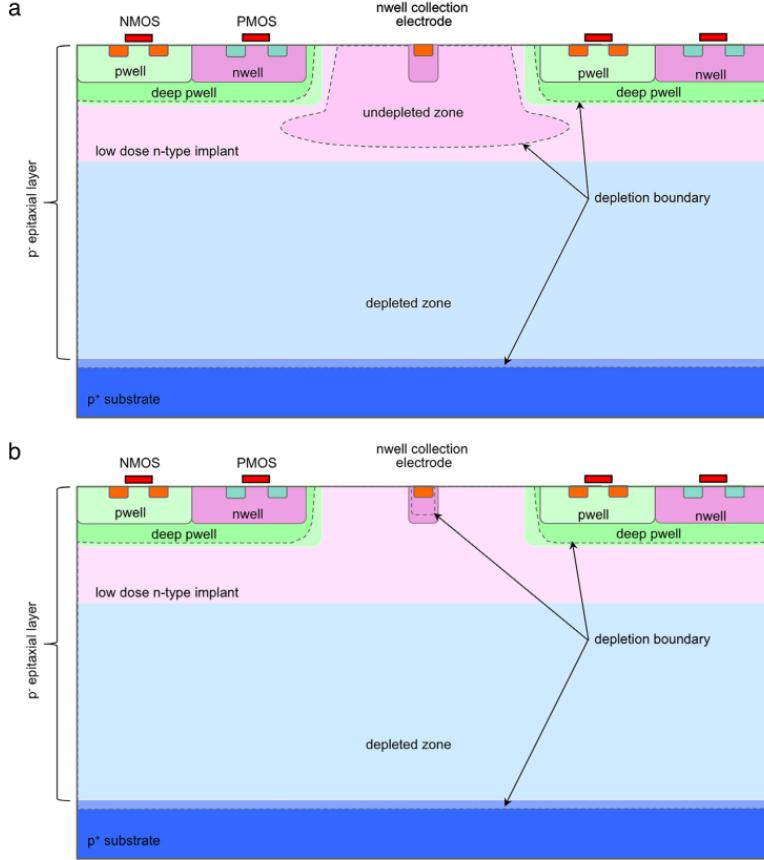


Figure 2.6: A modified process for ALICE tracker detector: a low dose n implant is used to create a planar junction. In (a) the depletion is partial, while in (b) the pixel is fully depleted.

172 upgrade about ten years [1].

173 A compromise between the two sensors could also be making smaller pixels, but this solution  
174 requires reducing the electronic circuit area, so a completely new pixel layout should be though.  
175 The modification consists in inserting a low dose implant under the electrode and one its advantage  
176 lies in its versatility: both standard and modified sensor are often produced for testing in fact.

177 Before the process modification the depletion region extends below the diode towards the sub-  
178 strate, and it doesn't extend laterally so much even if a high bias is applied to the sensor (fig. 2.6).

179 After, two distinct pn junctions are built: one between the deep p well and the  $n^-$  layer, and the  
180 other between the  $n^-$  and the  $p^-$  epitaxial layer, extending to the all area of the sensor.

181 Since deep p well and the p-substrate are separated by the depletion region, the two p electrodes  
182 can be biased separately<sup>3</sup> and this is beneficial to enhance the vertical electric field component.

183 The doping concentration is a trimmer parameter: it must be high enough to be greater than the  
184 epitaxial layer to prevent the punchthrough between p-well and the substrate, but it must also be  
185 lower enough to allow the depletion without reaching too high bias.

## 186 2.4 Analog front end

187 After the creation of a signal on the electrode, the signal enters the front end circuit (fig.2.7), ready  
188 to be molded and transmitted out of chip. Low noise amplification, fast hit discrimination and an  
189 efficient, high-speed readout architecture, consuming as low power as possible must be provided  
190 by the readout integrated electronics (ROIC).

191 Let's take a look to the main steps of the analog front end chain: the preamplifier (that actually  
192 often is the only amplification stage) with a reset to the baseline mechanism and a leakage current

---

<sup>3</sup>This is true in general, but it can be denied if other doping characteristics are implemented, and we'll see that this is the case of TJ-Monopix1

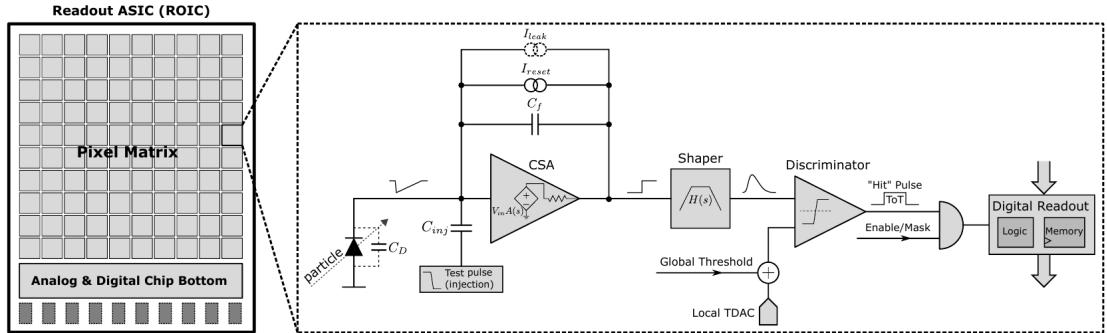


Figure 2.7: Readout FE scheme: in this example the preamplifier is a charge sensitive one (CSA) but changing the capacitive feedback into a resistive one, this can be converted in a voltage or current amplifier.

compensation, a shaper (a band-pass filter) and finally a discriminator. The whole chain must be optimized and tuned to improve the S/N ratio: it is very important both not to have a large noise before the amplification stage in order to not multiply that noise, and chose a reasonable threshold of the discriminator to cut noise-hits much as possible.

#### 2.4.1 Preamplifier

Even if circuits on the silicon crystal are only constructed by CMOS, a preamplifier can be modeled as an operational amplifier (OpAmp) where the gain is determined by the input and feedback impedance (first step in figure 2.7):

$$G = \frac{v_{out}}{v_{in}} = \frac{Z_f}{Z_{in}} \quad (2.8)$$

Depending on whether a capacity or a resistance is used as feedback, respectively a charge or a voltage amplifier is used: if the voltage input signal is large enough and have a sharp rise time, the voltage sensitive preamplifier is preferred. Consequently, this flavor doesn't suit to large fill factor MAPS whose signal is already enough high:  $v_{in} = Q/C_D \approx 3fC/100 \text{ pF} = 0.03 \text{ mV}$ , but it's fine for the small fill factor ones:  $v_{in} = Q/C_D \approx 3fC/3 \text{ pF} = 1 \text{ mV}$ .

In the case of a resistor feedback, if the signal duration time is longer than the discharge time ( $\tau = R_S C_D$ ) of the detector the system works as current amplifier, as the signal is immediately transmit to the amplifier; in the complementary case (signal duration longer than the discharge time) the system integrates the current on the  $C_D$  and operates as a voltage amplifier.

## 2.5 Readout logic

Readout logic includes the part of the circuit which takes the FE output signal, processes it and then transmit it out of pixel and/or out of chip; depending on the situation of usage different readout characteristics must be provided.

To store the analogical information (i.e. charge collected, evolution of signal in time, ...) big buffers and a large bandwidth are needed; the problem that doesn't occur, or better occur only with really high rate, if one wants record only digital data (if one pixel is hit 1 is recorded, and if not 0 is recorded).

A common compromise often made is to save the time over threshold (ToT) of the pulse in clock cycle counts; this needs of relatively coarse requirement as ToT could be trimmer to be a dozen bits but, being correlated and hopefully being linear with the deposited charge by the impinging particle in the detector, it provides a sufficient information. The ToT digitalization usually takes advantage of the distribution of a clock (namely BCID, bunch crossing identification) on the pixels' matrix. The required timing precision is at least around 25 ns, that corresponds to the period of bunch collisions at LHC; for such reason a reasonable BCID-clock frequency for pixels detector is 40 MHz.

Leading and trailing edges' timestamp of the pulse are saved on pixel within a RAM until they have been read, and then the ToT is obtained from their difference.

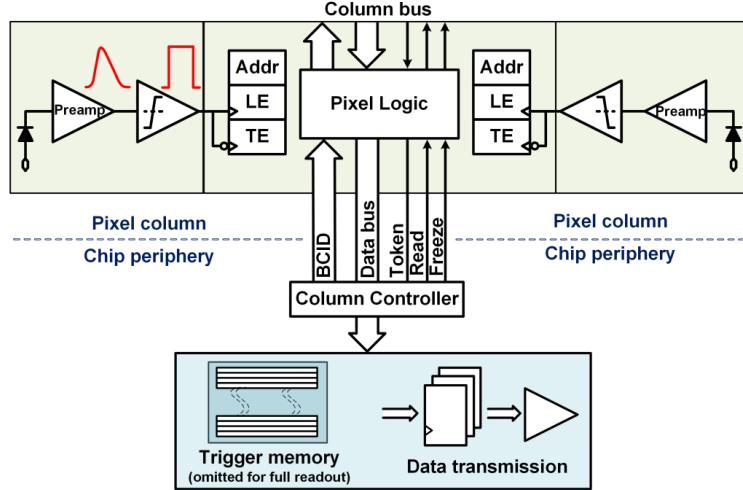


Figure 2.8: Column drain R/O scheme where ToT is saved

Moreover, the readout architecture can be full, if every hit is read, or triggered, if a trigger system decides if the hit must be stored or not. On one hand the triggered-readout needs buffers and storage memories, on the other the full readout, because there is no need to store hit data on chip, needs an high enough bandwidth.

A triggered readout is fundamental in accelerator experiments where the quantity of data to store is too large to be handled, and some selections have to be applied by the trigger: to give an order of growth, at LHC more than 100 TBit/s of data are produced, but the storage limit is about 100 MBit/s [2] (pag. 797).

Typically the trigger signal is processed in a few  $\mu s$ , so the pixel gets it only after a hundred clock cycles from the hit arrival time: the buffer depth must then handle the higher trigger latency.

After having taken out the data from the pixel, it has to be transmitted to the end of column (EoC) where a serializer delivers it out of chip, typically to an FPGA.

There are several ways of transmitting data from pixel to the end of column: one of the most famous is the column-drain read out, developed for CMS and ATLAS experiments [3]. All the pixels in a double-column share a data bus and only one pixel at a time, according to a priority chain, can be read. The reading order circuit is implemented by shift register (SR): when a hit arrives, the corresponding data, which can be made of timestamp and ToT, is temporarily stored on a RAM until the SR does not allow the access to memory by data bus.

Even if many readout architectures are based on the column-drain one, it doesn't suit for large size matrices. The problem is that increasing the pixels on a column would also raise the number of pixels in the priority chain and that would result in a slowdown of the readout.

If there isn't any storage memory, the double-column behaves as a single server queue and the probability for a pixel of waiting a time  $T$  greater than  $t$ , with an input hit rate on the column  $\mu$  and an output bandwidth  $B_W$  is [4]:

$$P(T > t) = \frac{\mu}{B_W} e^{-(B_W - \mu)t} \quad (2.9)$$

To avoid hit loss (let's neglect the contribution to the inefficiency of the dead time  $\tau$  due to the AFE), for example imposing  $P(T > t) \sim 0.001$ , one obtains  $(B_W - \mu) t_t \sim 6$ , where  $t_t$  is the time needed to transfer the hit; since  $t_t$  is small, one must have  $B_W \gg \mu$ , that means a high bandwidth [4].

Actually the previous one is an approximation since each pixel sees a different bandwidth depending on the position on the queue: the first one sees a full bandwidth, but the next sees a smaller one because occasionally it can be blocked by the previous pixel. Then the bandwidth seen by the pixel  $i$  is  $B_i = B - \sum_j \mu_j$ , where  $\mu_j$  is the hit rate of the  $j$ th pixel.

The efficiency requirement on the bandwidth and the hit rate becomes:  $B_{W,i} > \mu_i$ , where the index  $i$  means the constraint is for a single pixel; if all the  $N$  pixels on a column have the same rate  $\mu = N\mu_i$ , the condition reduces to  $B_W > \mu$ . The bandwidth must be chosen such that the mean time between hits of the last pixel in the readout chain is bigger than that.

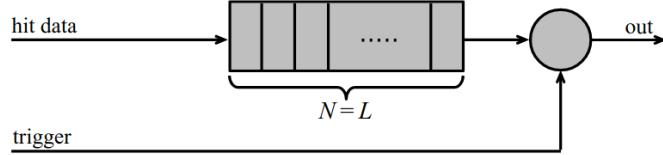


Figure 2.9: Block diagram of a pipeline buffer:  $N$  is the dimension of memory buffer and  $L$  is the trigger latency expressed in BCID cycles

264 In order to reduce the bandwidth a readout with zero suppression on pixel is typically employed;  
 265 this means that only information from channels where the signal exceeds the discriminator thresh-  
 266 old are stored. Qu'è succiso con la zero suppression? La metto qui questa affermazione?

267 If instead there is a local storage until a trigger signal arrives, the input rate to column bus  
 268  $\mu'$  is reduced compared to the hit rate  $\mu$  as:  $\mu' = \mu \times r \times t$ , where  $r$  is the trigger rate and  $t$  is  
 269 the bunch crossing period. In this situation there is a more relaxed constraint on the bandwidth,  
 270 but the limiting factor is the buffer depth: the amount of memory designed depends both on the  
 271 expected rate  $\mu$  and on the trigger latency  $t$  as  $\propto \mu \times t$ , that means that the higher the trigger  
 272 latency and the lower the hit rate to cope with.

273 In order to have an efficient usage of memory on pixels' area it's convenient grouping pixels  
 274 into regions with shared storage. Let's compare two different situations: in the first one a buffer  
 275 is located on each pixel area, while in the second one a core of four pixels share a common buffer  
 276 (this architecture is commonly called FE-I4).

Consider a 50 kHz single pixel hits rate and a trigger latency of 5  $\mu s$ , the probability of losing

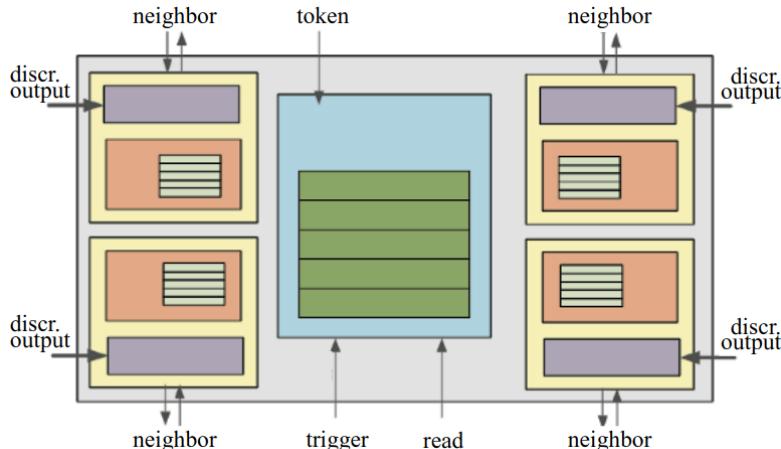


Figure 2.10: Block diagram of the FE-I4 R/O. Read and memory management section is high-  
 lighted in light blue; latency counters and trigger management section are highlighted in green; hit  
 processing blocks are highlighted in purple; ToT counters and ToT management units are high-  
 lighted in orange

277 hits is:  
 278

$$P(N > 1|\nu) = 1 - P(N = 0|\nu) - P(N = 1|\nu) = 1 - e^{-\nu}(1 + \nu) \approx 2.6\% \quad (2.10)$$

279 where I have assumed a Poissonian distribution with mean  $\nu = 0.25$  to describe the counts  $N$ .  
 280 To get an efficiency  $\epsilon$  greater than 99.9 % a 3 hit depth buffer is needed:

$$P(N > 3|\nu) = 1 - \sum_{i=0}^3 P(N = i|\nu) < 0.1\% \quad (2.11)$$

281 Considering the second situation: if the average single pixel rate is still 50 kHz, grouping four  
 282 pixels the mean number of hits per trigger latency is  $\nu = 0.25 \times 4 = 1$ . To get an efficiency of  
 283 99.9% (eq. 2.11) a buffer depth of 5 hits in the four-pixels region, instead of 3 per pixels, is needed.

<sup>284</sup> **Chapter 3**

<sup>285</sup> **Use of pixel detectors**

<sup>286</sup> A partire dal 2017, i sensori CMOS rappresentano l'89% delle vendite globali di sensori di immagine.  
<sup>287</sup> Ma praticamente dal 2010 in poi solo CMOS e non più CCD.

<sup>288</sup>

<sup>289</sup> **3.1 Tracking in HEP**

<sup>290</sup> Per gli acceleratori la richieste sono molto stringenti e lo saranno sempre di più con l'aumento dell'  
<sup>291</sup> intensità o della luminosità in termini di radiation hardness (per HL-LHC for example expected  
<sup>292</sup> in 5 anni 500 Mrad e NIEL di 10 alla 16), efficiency e occupancy (efficienza alta dopo tanta  
<sup>293</sup> radiazione e noise occupancy bassa), time resolution (bunch crossing 40 Mhz), material budget e  
<sup>294</sup> power consumption (material budget below 2 per cento e power consumption 500 mW/cm<sup>2</sup>)  
<sup>295</sup> Usati come tracciatori per misure di impulso e per misure di energia (per rigettare ) ad esempio  
<sup>296</sup> dati di fondo (topic fondamentale per BELLE-II).

<sup>297</sup> **Resolution**

<sup>298</sup> Depending on the type of signal reading the spatial resolution is  $\sigma_x = \frac{p}{\sqrt{12}}$  where p is the pitch  
<sup>299</sup> between pixels, or even better if other analogica information, as the charge, are read and capacitive  
<sup>300</sup> charge division method is applied.

<sup>301</sup> **3.1.1 Hybrid pixels: ATLAS, CMS and LHC-b**

<sup>302</sup> From the middle of 2013 a dedicated collaboration, RD 53 ('Development of pixel readout integrated  
<sup>303</sup> circuits for extreme rate and radiation'), has been established with the specific goal to find  
<sup>304</sup> a pixel detector suitable for phase II future upgrades of the experiments CMS and ATLAS. Even  
<sup>305</sup> if the collaboration is specifically focused on design of hybrid pixel readout chips, also monolithic  
<sup>306</sup> options have been taken in account for ATLAS ITK outer layers. Tra i chip designed for that  
<sup>307</sup> purpose there are LF an TJ Monopix.

<sup>308</sup> **3.1.2 CMOS MAPS: ALICE and STAR**

<sup>309</sup> For years ALICE have been pioneering MAPS detectors and its sensors are currently state-of-the  
<sup>310</sup> art in this sector, to the point that most of today's CMOS MAPS chips implement the same FE  
<sup>311</sup> of ALICE Pixel Detector, and in fact they are commonly called "ALPIDE-like" sensors<sup>1</sup>.

<sup>312</sup> **3.2 Application in medical imaging**

<sup>313</sup> **3.2.1 Medipix and Timepix**

<sup>314</sup> **3.2.2 Applicability to FLASH radiotherapy**

---

<sup>1</sup>As we'll see TJ-Monopix1 and ARCADIA have an ALPIDE-like front end.

<sup>315</sup> **Chapter 4**

<sup>316</sup> **TJ-Monopix1**

<sup>317</sup> TJ-Monopix1 is a small electrode DMAPS with fast R/O capability, fabricated by TowerJazz  
<sup>318</sup> foundry in 180 nm CMOS imaging process. It is part, together with prototypes from other series  
<sup>319</sup> such as TJ-MALTA, of the ongoing R&D efforts aimed at developing DMAPS in commercial CMOS  
<sup>320</sup> processes, that could cope with the requirements at accelerator experiments. Both TJ-Monopix  
<sup>321</sup> and TJ-MALTA series [5], produced with the same technology by TowerJazz (the timeline of the  
<sup>322</sup> foundry products is shown in figure 4.1), are small electrode demonstrators and principally differ in  
<sup>323</sup> the readout design: while Monopix implements a column-drain R/O, an asynchronous R/O without  
<sup>324</sup> any distribution of BCID has been used by TJ-Malta in order to reduce power consumption.



Figure 4.1: Timeline in TowerJazz productions in 180 nm CMOS imaging process

<sup>325</sup> Another Monopix series, but in 150 nm CMOS technology, has been produced by LFoundry [6].  
<sup>326</sup> The main differences between the LF-Monopix1 and the TJ-Monopix1 (summarized in table 4.2),  
<sup>327</sup> lay in the sensor rather than in the readout architecture, as both chips implements a fast col-  
<sup>328</sup> umn drain R/O with ToT capability [7][8]. Concerning the sensors, either are based on a p-type  
<sup>329</sup> substrate, but with slightly different resistivities; in addition LFoundry pixels are larger, thicker  
<sup>330</sup> and have a large fill factor (the very deep n-well covers ~55% of the pixel area). The primary  
<sup>331</sup> consequence is that LF-Monopix1 pixels have a higher capacity resulting in higher consumption  
<sup>332</sup> and noise. As I discussed in section 2.3.1, the fact that LF-Monopix has a large fill factor electrode  
<sup>333</sup> is expected to improve its radiation hardness. Indeed, a comparison of the performance of the  
<sup>334</sup> two chips showed that TJ-Monopix suffers a comparatively larger degradation of efficiency after  
<sup>335</sup> irradiation, due to the low electric field in the pixel corner; on the other hand, a drawback of the  
<sup>336</sup> large fill factor in LF-Monopix is a significant cross-talk.

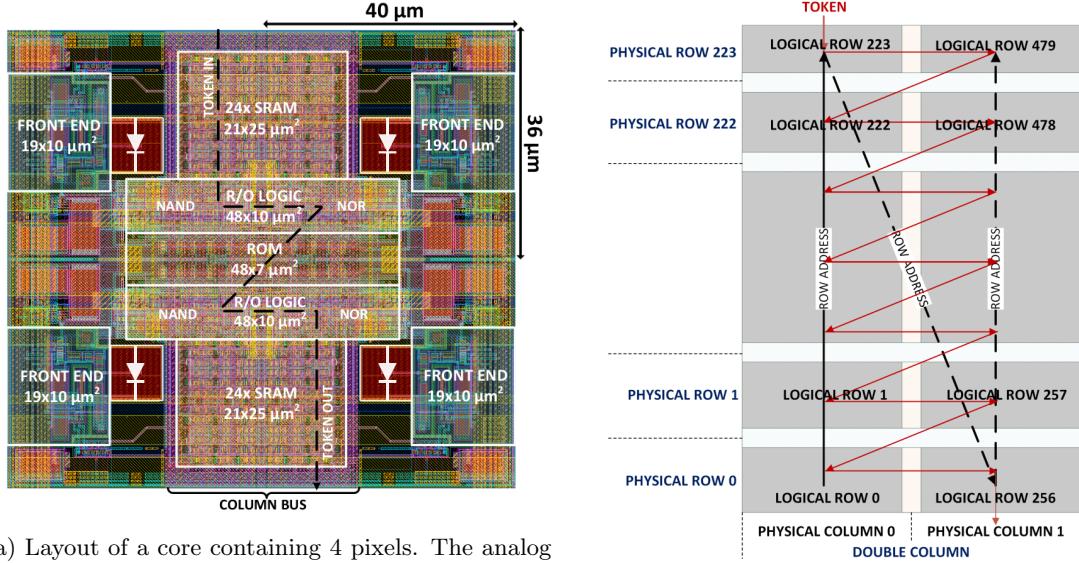
<sup>337</sup> The TJ-Monopix1 chip contains, apart from the pixels matrix, all the required support blocks  
<sup>338</sup> used for configuration and testing:

- <sup>339</sup> the whole matrix contains  $224 \times 448$  pixels, yielding a total active area approximately equal  
<sup>340</sup> to  $145 \text{ mm}^2$  over a total area of  $1 \times 2 \text{ cm}^2$ ;
- <sup>341</sup> at the chip periphery are placed some 7-bit Digital to Analog Converter (DAC), used to  
<sup>342</sup> generate the analog bias voltage and current levels and to configure the FE;

	LF-Monopix1	TJ-Monopix1
Resistivity	$>2\text{ k}\Omega\text{cm}$	$>1\text{ k}\Omega\text{cm}$
Pixel size	$50 \times 250\mu\text{m}^2$	$36 \times 40\mu\text{m}^2$
Depth	$100\text{-}750\mu\text{m}$	$25\mu\text{m}$
Capacity	$\sim 400\text{ fF}$	$\sim 3\text{ fF}$
Preamplifier	charge	voltage
Threshold trimming	on pixel (4-bit DAC)	global threshold
ToT	8 bits	6 bits
Consumption	$\sim 300\text{ mW/cm}^2$	$\sim 120\text{ mW/cm}^2$
Threshold	$1500 e^-$	$\sim 270 e^-$
ENC	$100 e^-$	$\sim 30 e^-$

Table 4.1: Main characteristics of Monopix1 produced by TowerJazz and LFoundry [7][8]

- at the EoC is placed a serializer to transferred datas immediately, indeed no trigger memory is implemented in this prototypes;
  - the matrix power pads are distributed at the sides
  - four pixels which have analog output and which can be monitored with an oscilloscope, and therefore used for testing
- Pixels are grouped in  $2 \times 2$  cores (fig. 4.2a): this layout allows to separate the analog and the digital electronics area in order to reduce the possible interference between the two parts. In addition it simplifies the routing of data as pixels on double column share the same column-bus to EoC. Therefore pixels can be addressed through the physical column/row or through the logical column/row, as shown in fig. 4.2b: in figure is also highlighted the token propagation path, whose I will discuss later.



(a) Layout of a core containing 4 pixels. The analog FE and the digital part are separated in order to reduce cross-talk be

(b)

## 4.1 The sensor

As already anticipated, TJ-Monopix1 has a p-type epitaxial layer and a n doped small collection electrode ( $2\mu\text{m}$  in diameter); to avoid the n-wells housing the PMOS transistors competing for the charge collection, a deep p-well substrate, common to all the pixel FE area, is used. TJ-Monopix1 adopts the modification described in section 2.3.2 that allows to achieve a planar depletion region

Parameter	Value
Matrix size	$1 \times 2 \text{ cm}^2$
Pixel size	$36 \times 40 \mu\text{m}^2$
Depth	$25 \mu\text{m}$
Electrode size	$2 \mu\text{m}$
BCID	40 MHz
ToT-bit	6
Power consumption	$\sim 120 \text{ mW/cm}^2$

Table 4.2

near the electrode applying a relatively small reverse bias voltage. This modification improves the efficiency of the detector, especially after irradiation, however a simulation of the electric field in the sensor, made with the software TCAD (Technology Computer Aided Design), shows that a nonuniform field is still produced in the lateral regions of the pixel compromising the efficiency at the corner. Two variations to the process have been proposed in order to further enhance the transversal component of electric field at the pixel borders: on a sample of chip, which includes the one in Pisa, a portion of low dose implant has been removed, creating a step discontinuity in the deep p-well corner (fig. 4.3); the second solution proposed[MOUSTAKAS THESYS, PAG 58] consists in adding an extra deep p-well near the pixel edge. A side effect of the alteration in the low dose implant is that the separation between the deep p-well and the p-substrate becomes weak to the point that they cannot be biased separately to prevent the punchthrough.

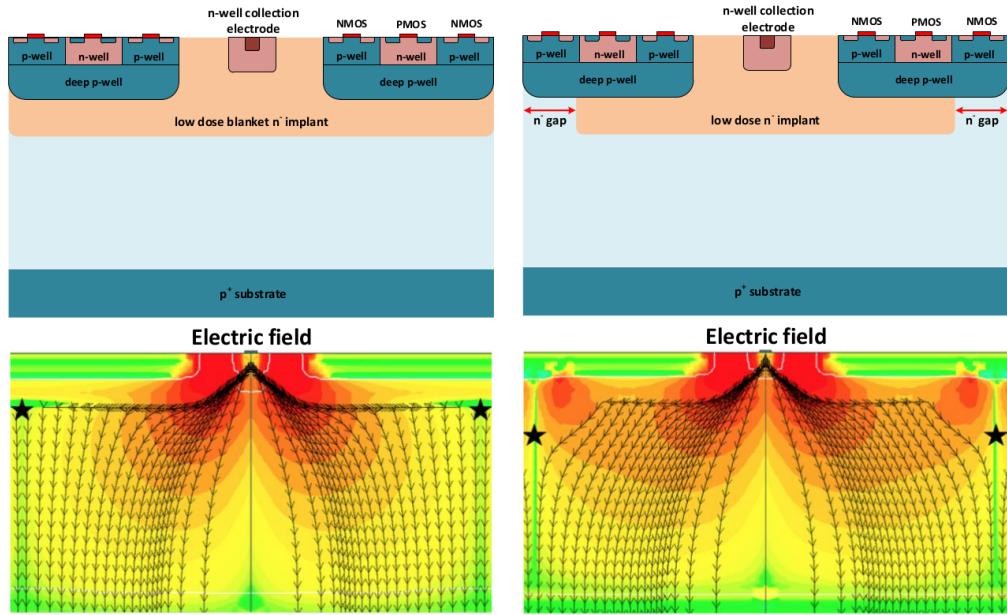


Figure 4.3: (a) The cross-section of a monolithic pixel in the TJ-Monopix with modified process; additionally in (b) a gap in the low dose implant is created to improve the collection of charge due to a bigger lateral component of the electric field. this point in figure is indicated by a star . transversal component of the electric field drops at the pixel corner

Moreover, to investigate the charge collection properties, pixels within the matrix are split between bottom top half and bottom half and feature a variation in the coverage of the deep p-well: the electronics area can be fully covered or not. In particular the pixels belonging to rows from 0 to 111 are fully covered (FDPW) and pixels belonging to rows from 112 to 223 have a reduced p-well (RDPW), resulting in a enhancement of the lateral component of the electric field.

## 375 4.2 Front end

376 The matrix is split in four sections, each one corresponding to a different flavor of the FE. The  
 377 four variation have been implemented in order to test the data-bus readout circuits and the input  
 reset modes.

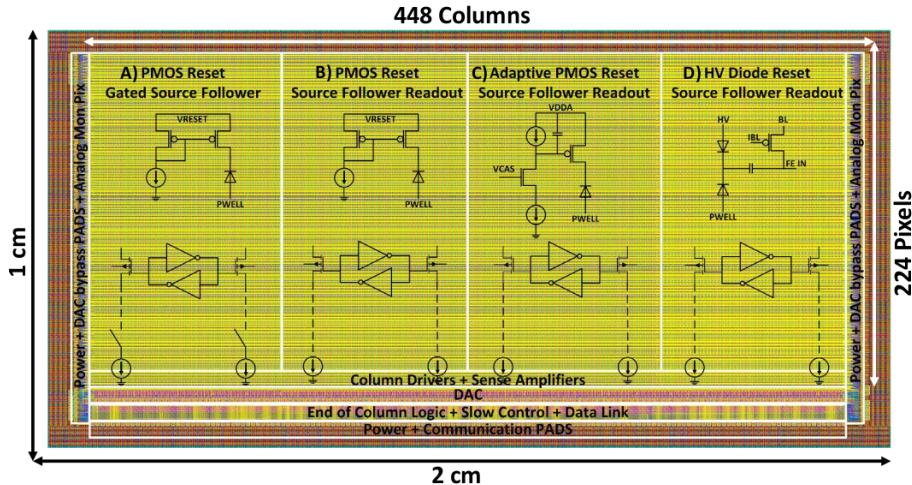


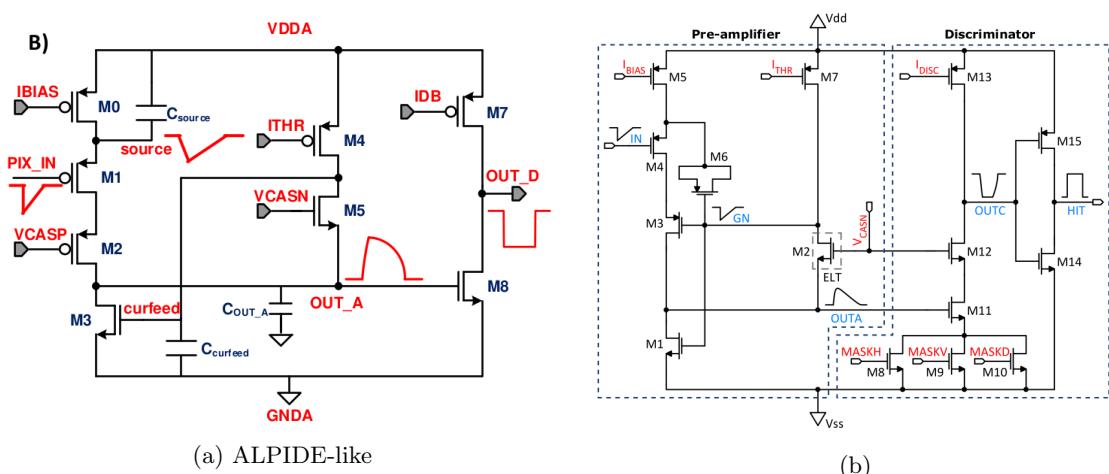
Figure 4.4

378 All the flavors implement a source-follower double-column bus readout: the standard variation  
 379 is the flavor B, that features a PMOS input reset (referred as "PMOS reset"). Flavor A is identical  
 380 to flavor B except for the realization of the source follower (it is a gated one) that aim to reduce  
 381 the power consumption. cosa significa? C instead implements a novel leakage compensation circuit.  
 382 Moreover the collection electrode in flavors A, B, C is DC-coupled to the front-end input, while  
 383 in D is AC-coupled, providing to apply a high bias voltage; for this reason flavor D is called "HV  
 384 flavor".

385 R resistenza di reset deve essere abbastanza grande in modo da far sì che il ritorno allo zero  
 386 è abbastanza lento (non devi "interferire" con la tot slope e non devi più corto del tempo del  
 387 preamplificatore, sennò hai perdita di segnale). Baseline reset: all'input solitamente hai un PMOSS  
 388 o un diodo; R reset; Voltage amplifier

### 390 4.2.1 ALPIDE-like

391 ALPIDE chips, developed by the ALICE collaboration, implemented a standard FE to the point  
 392 that many CMOS MAPS detectors used a similar FE and are called "ALPIDE-like". Considering  
 393 that both TJ-Monopix1 and ARCADIA-MD1 have an ALPIDE-like FE, I am going to explain the  
 broad principles of the early FE stage. The general idea is of the amplification to transfer the



395 charge from a bigger capacity[9],  $C_{source}$ , to a smaller one,  $C_{out}$ : the input transistor M1 with  
 396 current source IBIAS acts as a source follower and this forces the source of M1 to be equal to the  
 397 gate input  $\Delta V_{PIX\_IN} = Q_{IN}/C_{IN}$ .

$$Q_{source} = C_{source} \Delta V_{PIX\_IN} \quad (4.1)$$

398 The current in M2 and the charge accumulates on  $C_{out}$  is fixed by the one on  $C_{source}$ :

$$\Delta V_{OUT\_A} = \frac{Q_{source}}{C_{OUT\_A}} = \frac{C_{source} \Delta V_{PIX\_IN}}{C_{OUT\_A}} = \frac{C_{source}}{C_{OUT\_A}} \frac{Q_{IN}}{C_{IN}} \quad (4.2)$$

399 A second branch (M4, M5) is used to generate a low frequency feedback, where VCASN and ITHR  
 400 set the baseline value of the signal on  $C_{OUT\_A}$  and the velocity to goes down to the baseline.

#### 401 IL RUOLO DI CURVFEED NON L'HO CAPITO.

402 Finally IDB defines the charge threshold with which the signal  $OUT\_A$  must be compared: de-  
 403 pending on if the signal is higher than the threshold or not, the  $OUT\_D$  is high or low respectively.

404 The actual circuit implemented in TJ-Monopix1 is shown in figure 4.5b: the principal difference  
 405 lays in the addition of disableing pixels' readout. This possibility is uttermost important in order to  
 406 reduce the hit rate and to avoid saturating the bandwidth due to the noisy pixels, which typically  
 407 are those with manufacturing defects. In the circuit transistors M8, M9 and M10 have the function  
 408 of disabling registers with coordinates MASKH, MASKV and MASKD (respectively vertical, ori-  
 409 zontal and diagonal) from readout: if all three transistors-signals are low, the pixel's discriminator  
 410 is disabled. Compared with a configurable masking register which would allow disableing pixels  
 411 individually, to use a triple redundancy reduces the sensistivity to SEU<sup>1</sup> but also gives amount of  
 412 intentionally masked ("ghost") pixels. This approach is suitable only for extremely small number  
 413 N of pixel has to be masked: if two coordinate projection scheme had been implemented, the  
 414 number of ghost pixels would have scale with  $N^2$ , if instead three coordinates are used, the N's  
 exponential is lower than 2 (fig. 4.6)

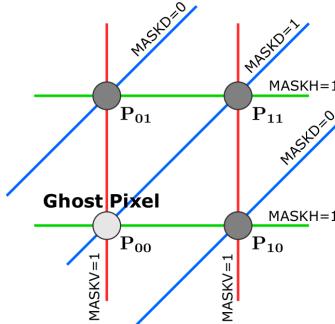


Figure 4.6

415

#### 416 4.2.2 Front end parameters

417 Descrivo un po' le misure fatte sul fe e sul significato dei vari parametri.  
 418 it allows injecting pixels with a known charge in DAC units. the front-end analog output of  
 419 four special pixels at each side, placed next to the matrix, is buffered and can be monitored for  
 420 characterization and debugging purposes.

### 421 4.3 Readout logic

422 TJ-Monopix1 has a triggerless, fast and with ToT capability R/O which is based on a column-drain  
 423 architecture. On the pixel are located two Random Access Memory (RAM) cells to store the 6-bit

<sup>1</sup>Single Event Upset, in sostanza è quando un bit ti cambia valore (da 0 a 1 o viceversa) perché una particella deposita carica nell'elettronica che fa da memoria registro/RAM/.... Questo tipo di elettronica ha bisogno di un sacco di carica prima che il bit si "flippi" (cambi valore), infatti tipicamente per avere un SEU non basta una MIP che attraversa esattamente quel pezzo di chip in cui è implementata la memoria, ma un adrone che faccia interazione nucleare producendo più carica di quanto farebbe una MIP. Questo metodo pur essendo più comodo richiede less amount of area ha però come drawback che il registro può essere soggetto a SEU problema non trascurabile in acceleratori come HL-LHC adronici

Parameter	Meaning
IBIAS	
IDB	
ITHR	
VCASN	
VREF	
IREF	

Table 4.3

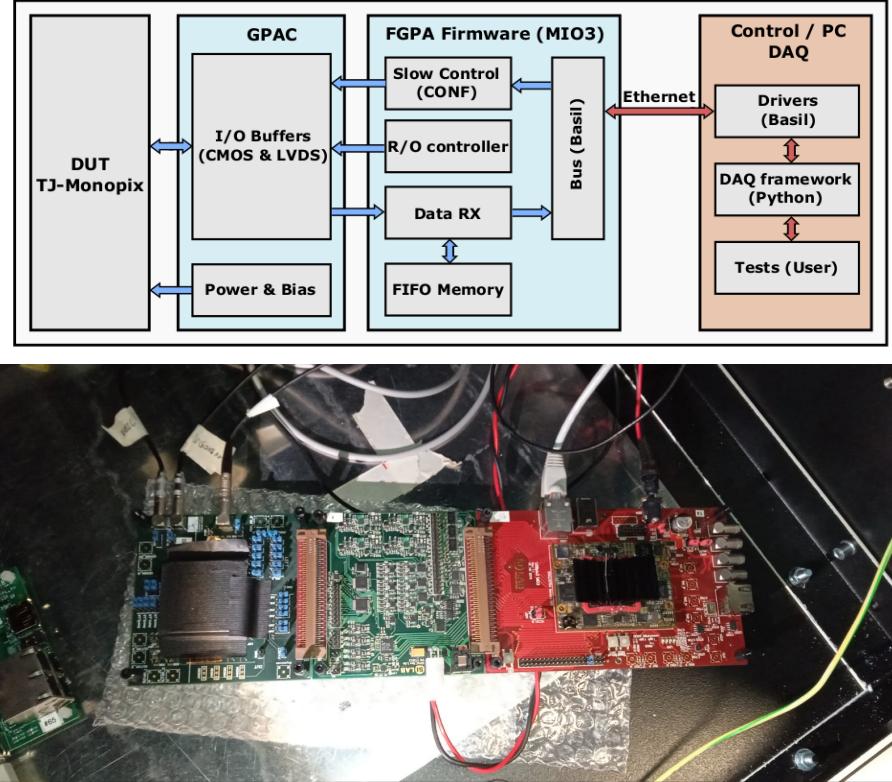
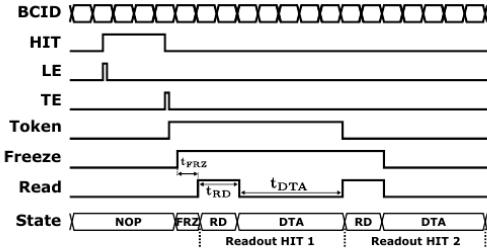


Figure 4.7: Main caption

424 LE and 6-bit TE of the pulse, and a Read-Only Memory (ROM) containing the 9-bit pixel address.  
 425 Excluded these memories, TJ-Monopix1 hasn't any other buffer: if a hit arrives while the pixel is  
 426 already storing a previous one, the new data get lost. After being read, the data packet is sent to  
 427 the EoC periphery of the matrix, where a serializer transfers it off-chip to an FPGA (4.7). There  
 428 a FIFO is used to temporarily stored the data, which is transmitted to a computer through an  
 429 ethernet cable in a later time.

430 The access to the pixels' memory and the transmission of the data to the EoC, following  
 431 a priority chain, is managed by control signals and is based on a Finite State Machine (FSM)  
 432 composed by four state: no-operation (NOP), freeze (FRZ), read (RD) and data transfer (DTA).  
 433 The readout sequence (??) starts with the TE of a pulse: the pixel immediately tries to grab the  
 434 column-bus turning up a hit flag signal called *token*. The token is used to control the priority chain  
 435 and propagates across the column indicating what pixel that must be read. To start the readout  
 436 and avoid that the arrival of new hits disrupt the priority logic, a *freeze* signal is activated, and  
 437 then a *read* signal controls the readout and the access to memory. During the freeze, the state of  
 438 the token for all pixels on the matrix remains settled: this does not forbid new hits on other pixels  
 439 from being recorded, but forbids pixels hit from turning on the token until the freeze is ended. The  
 440 freeze stays on until the token covers the whole priority chain and gets the EoC: during that time  
 441 new token cannot be turned on, and all hits arrived during a freeze will turn on their token at the

442 end of the previous freeze. Since the start of the token is used to assign a timestamp to the hit,  
 443 the token time has a direct impact on the time resolution measurement; this could be a problem  
 coping with high hits rate.



(b) Readout sequence timing diagram. In this example two hits are being processed.

Figure 4.8: Readout timing diagram: in this example two hits are being processed

444  
 445 The analog FE circuit and the pixel control logic are connected by an edge detector which is  
 446 used to determine the LE and the TE of the hit pulse (fig. 4.9): when the TE is stored in the first  
 447 latch the edge detector is disabled and, if the FREEZE signal is not set yet, the readout starts. At  
 448 this point the HIT flag is set in a second latch and a token signal is produced and depending on  
 449 the value of Token in the pixel can be read or must wait until the Token in is off. In figure an OR  
 450 is used to manage the token propagation, but since a native OR logic port cannot be implemented  
 451 with CMOS logic, a sum of a NOR and of an inverter is actually used; this construct significantly  
 452 increases the propagation delay (the timing dispersion along a column of 0.1-0.2 ns) of the token  
 453 and to speed up the circuit optimized solution are often implemented. When the pixel become the  
 454 next to be read in the queue, and at the rising edge of the READ signal, the state of the pixel is  
 455 stored in a D-latch and the pixel is allowed to use the data bus; the TE and the HIT flag latches  
 456 are reset and a READINT signal that enable access of the RAM and ROM cells is produced.

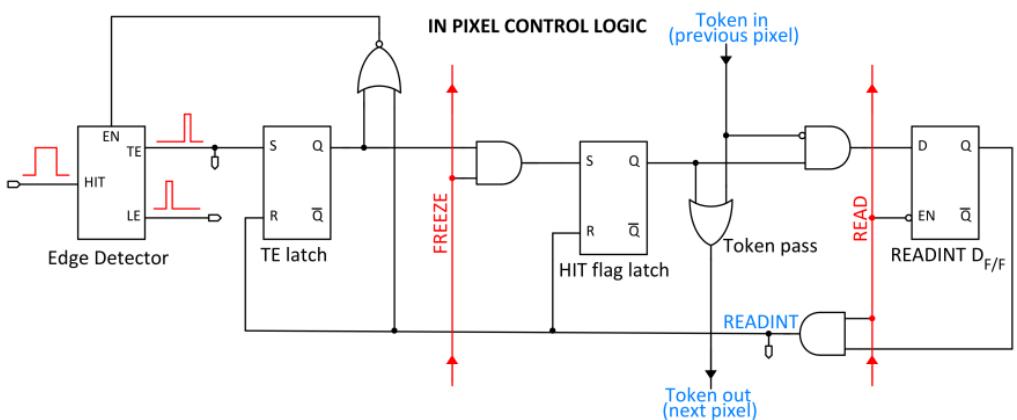


Figure 4.9

457  
 458 The final data must provide all the hits' information: the pixel address, the ToT and the  
 459 timestamp. All those parts are assigned and appended at different time during the R/O chain:

- 460 • **Pixel address:** while the double column address (6-bit) is appended by the EoC circuit,  
 461 the row address (8-bits for each flavor) and the physical column in the doublet (1-bit) are  
 462 assigned by the in-pixel logic
- 463 • **ToT:** is obtained offline from the difference of 6-bits TE and 6-bits LE, stored by the edge  
 464 detector in-pixel; since a 40 MHz BCID is distributed across the matrix, the ToT value is  
 465 range 0-64 clock cycle which corresponds to 0-1.6  $\mu$ s
- 466 • **Timestamp:** The timestamp of the hit correspond to the time when the pixel set up the  
 467 token; it is assigned by the FPGA, that uses the LE, TE and a 640 MHz clock to derive

468 it. For all those hits which arrived while the matrix is frozen, the timestamp is no more  
 469 correlated with the time of arrival of the particle

470 When the bits are joined up together the complete hit data packet is 27-bit.

#### 471 4.3.1 Dead time measurement

472 The hit loss can be due to both analog and digital pile up: the first one occurs when a new hit  
 473 arrives during the pre-amplifier response, the second instead occurs when a new hit arrives while  
 474 the information of the previous hit has not yet been transferred to the periphery. The digital  
 475 pile-up contribution is the more relevant and the dead time is almost entirely determined by that;  
 476 as only one hit at a time can be stored on the pixel's RAM, until the data have completed the path  
 477 to get out, the pixel readout is paralyzed and the  $\tau$  corresponds with the time needed to export  
 478 the data-packets. Since the transmission of data from pixel to the EoC occurs via a ?-bits data  
 479 bus (this means that only one clock cycle is need to transfer the data to the end of column), the  
 480 dead time bottleneck is given by the bandwidth of the serializer at the EoC: typically it operates  
 481 at 40 MHz, and to transmit a data packet (27-bit) at least 675 ns are needed. For what we have  
 482 said so far, the R/O is completely sequential and therefore is expected a linear dependence of the  
 483 reading time on the number of pixels to read:

$$\tau = 25 \text{ ns} \times (\alpha N + \beta) \quad (4.3)$$

484 where  $\alpha$  and  $\beta$  are parameters dependent on the readout chain. In particular, looking at fig. 4.8,  $\alpha$   
 485 is the time with  $\alpha$  (CONF STOP FREEZE-CONF START READ), and  $\beta$  ToT + CONF START  
 486 FREEZE.

487 To measure and to test the linearity of the reading time with the number of pixels firing, I have  
 488 used the injection mode available on the chip, that allows fixing not only the amplitude of the pulse  
 489 (charge in DAC, as already seen in the previous section) but also the period and width. I have  
 490 injected one hundred of pulses Reducing each time the distance between two consecutive pulses,  
 491 I have injected until the number of hits counted were less than the injected ones. **Un esempio se**  
 492 leggo un singolo pixel: l'efficienza satura al 50%

493 Per definire meglio il  $\tau$  faccio riferimento alla fig ??: se una hit arriva su un pixel mentre ha  
 494 il token alto allora la hit viene persa. Se una hit arriva su un pixel che non ha il token alto  
 495 ma ha il freeze alto, allora non viene persa ma le viene assegnato un timestamp errato. PARLO  
 ANCHE DELLA "RISOLUZIONE TEMPORALE?" A tutte le hit di una iniezione che arrivano

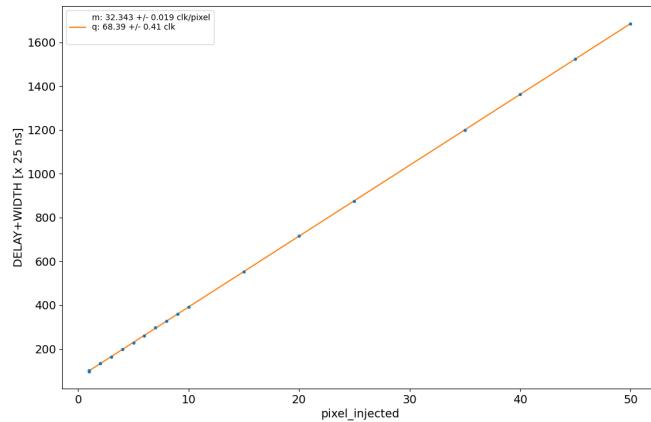


Figure 4.10

496 contemporaneamente viene assegnato lo stesso timestamp; quando le hit iniziano ad essere meno  
 497 di quelle che mi aspetti. Mappa in funzione delle iniezioni di quali pixel hai letto. NON DIPENDE  
 498 DALLA CARICA

## 500 Chapter 5

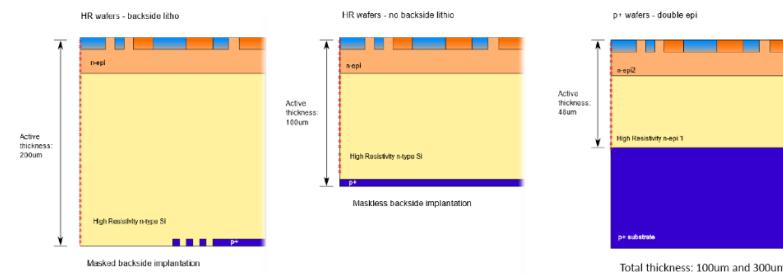
### 501 Arcadia-MD1

502 [10] [11]

503 Breve introduzione analoga a Monopix1 in cui descrivo brevemente la "timeline" da SEED  
504 Matisse a Md1 e Md2

#### 505 5.1 The sensor

506 ARCADIA-MD1 is an LFoundry chip which implements the technology 110 nm CMOSS node  
507 with six metal layer ???. The standard p-type substrate was replaced with an n-type floating zone  
508 material, that is a tecnique to produce purified silicon crystal. (pag 299 K.W.).



509 Figure 5.1

510 Wafer thinning and backside litography were necessary to introduce a junction at the bottom  
511 surface, used to bias the substrate to full depletion while maintaining a low voltage at the front side.  
512 C'è un deep pwell per - priority chainseparare l'elettronica dal sensore; per controllare il punchthrough  
513 è stato aggiunto un n doped epitaxial layer having a resistivity lower than the substrate.

514 RILEGGI SUL KOLANOSKY COS'È IL PUNCHTHROUGHT, FLOAT ZONE MATERIAL,  
515 COME VENGONO FATTI I MAPS COME FAI LE GIUNZIONI

516 It is part of the cathegory of DMAPS Small electrode to enhance the signal to noise ratio.  
517 It is operated in full depletion with fast charge collection by drift.

518 Prima SEED si occupa di studiare le prestazioni: oncept study with small-scale test struc-  
519 ture (SEED), dopo arcadia: technology demonstration with large area sensors Small scale demo  
520 SEED(sensor with embedded electronic developement) Quanto spazio dato all'elettronica sopra il  
521 pwell e quanto al diodo. ..

#### 522 5.2 Readout logic and data structure

##### 523 5.2.1 Matrix division and data-packets

524 The matrix is divided into an internal physical and logical hierarchy: The 512 columns are divided  
525 in 16 section: each section has different voltage-bias + serializzatori. Each section is devided in

526 cores () in modo che in ogni doppia colonna ci siano 1Pacchetto dei dati 6 cores. ricordati dei serializzatori: sono 16 ma possono essere ridotti ad uno in modalità spazio

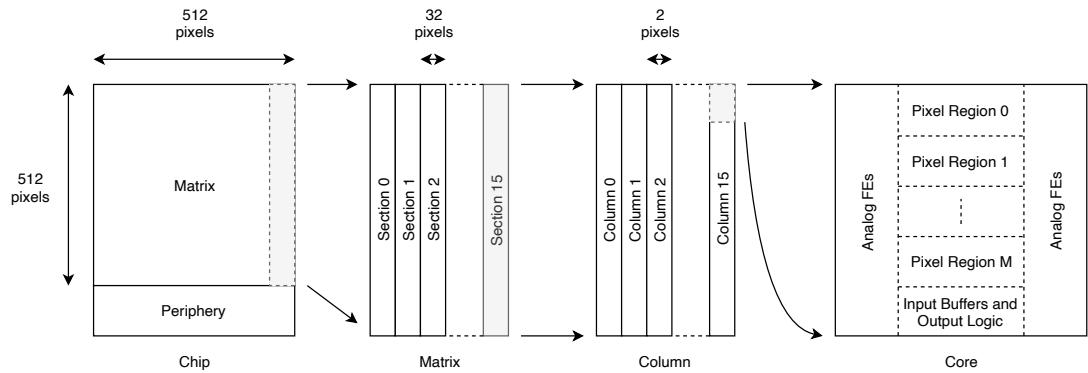


Figure 5.2

527

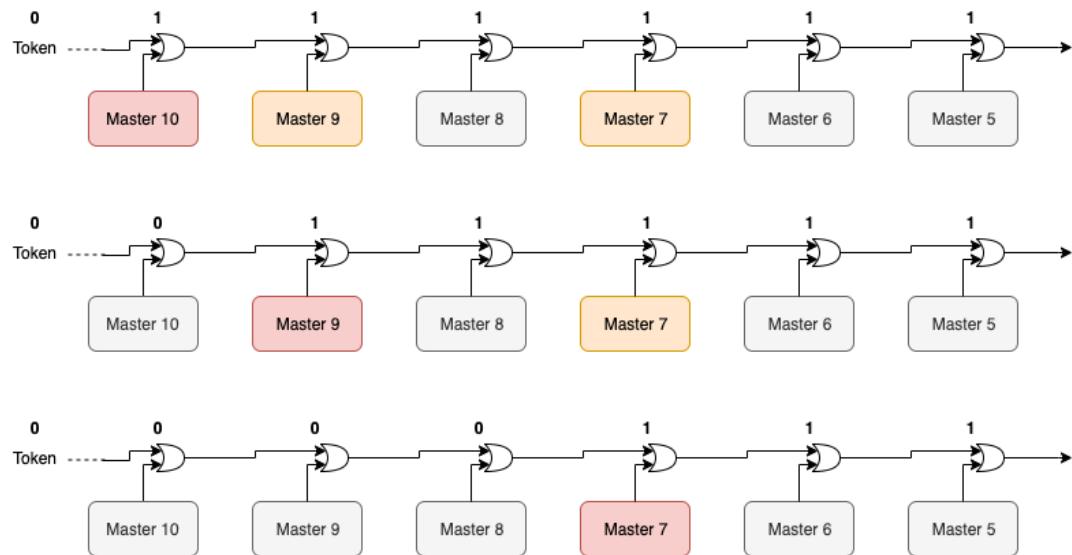


Figure 5.3

528 Questa divisione si rispecchia in come sono fatti i dati: scrivi da quanti bit un dato è fatto e le  
529 varie coordinate che ci si trovano dentro; devi dire che c'è un pixel hot e spieghi dopo a cosa serve,  
530 e devi accennare al timestamp

531 "A core is simply the smallest stepped and repeated instance of digital circuitry. A relatively  
532 large core allows one to take full advantage of digital synthesis tools to implement complex func-  
533 tionality in the pixel matrix, sharing resources among many pixels as needed.". pagina 28 della  
534 review.

535

536 TABELLA: con la gerarchia del chip Matrix (512x512 pixels) Section (512x32 pixels) Column  
537 (512x2) Core (32x2) Region (4x2)

538 Nel chip trovi diverse padframe: cosa c'è nelle padframe e End of section.

539 "DC-balance avoids low frequencies by guaranteeing at least one transition every n bits; for  
540 example 8b10b encoding n =5"

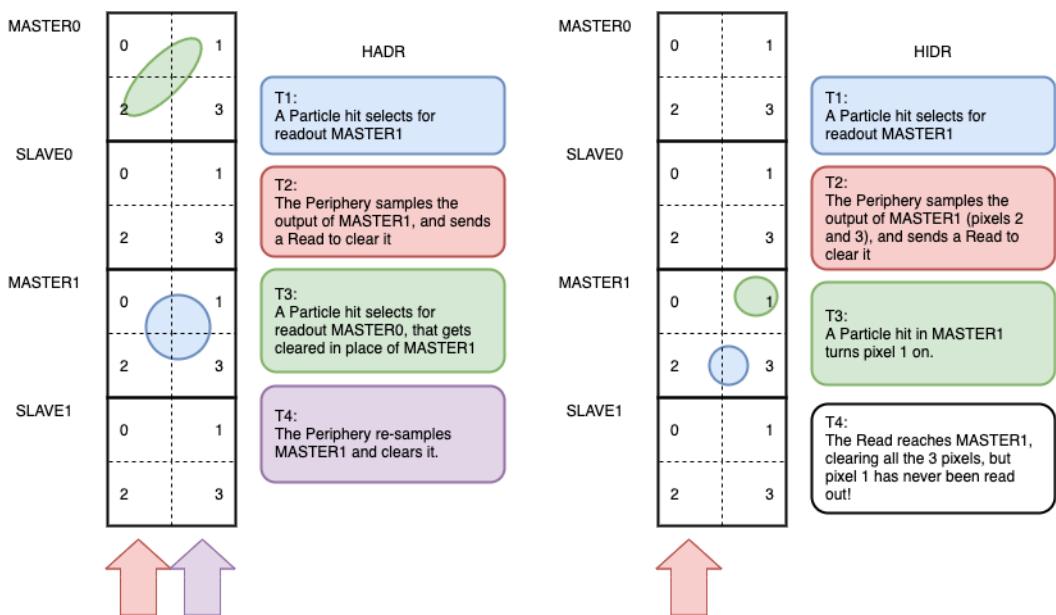


Figure 5.4

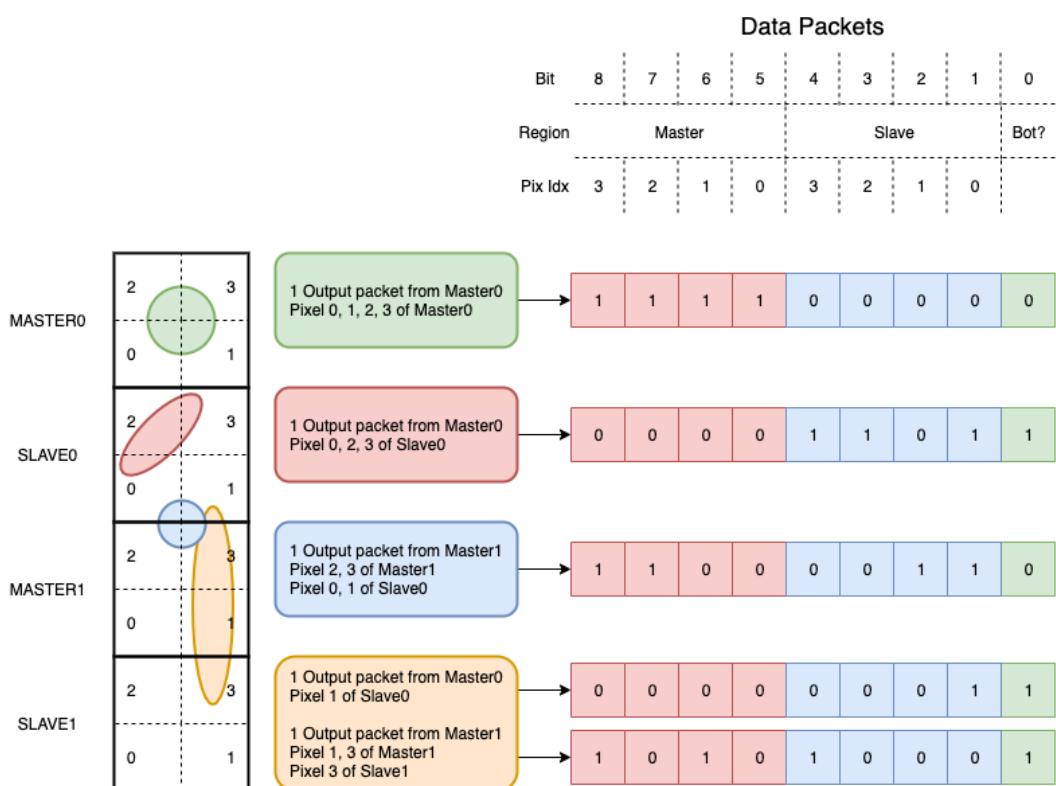


Figure 5.5

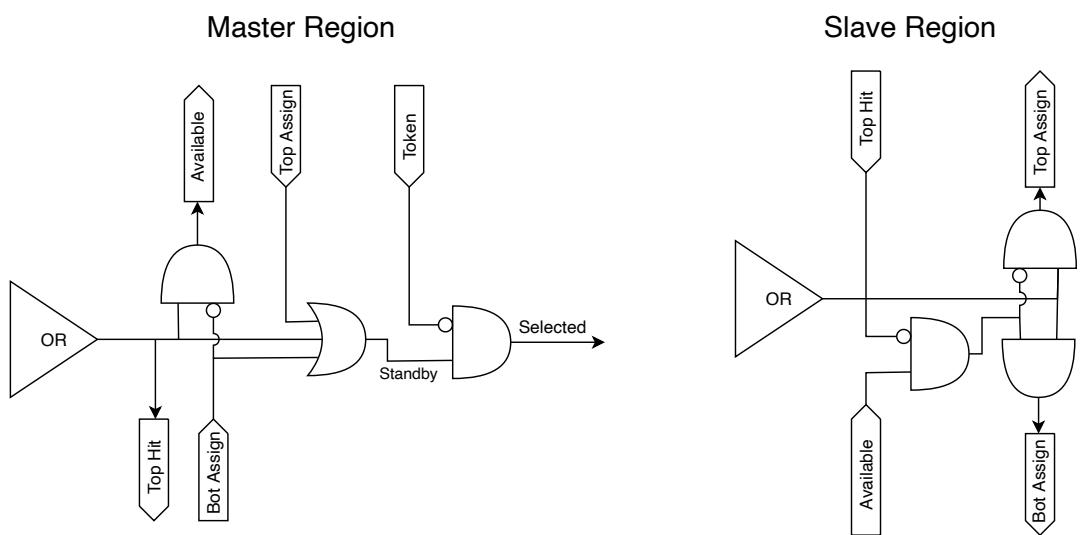


Figure 5.6

541    **Chapter 6**

542    **Threshold and noise  
543    characterization**

544    **6.1 Threshold and noise: figure of merit for pixel detectors**

545    The signal to threshold ratio is the figure of merit for pixel detectors.

546  
547    la soglia deve essere abb alta da tagliare il rumore ma abb bassa da non perdere efficienza.  
548    Invece di prendere il rapporto segnale rumore prendi il rapporto segnale soglia. Perchè? la soglia  
549    è collegato al rumore, nel senso che: supponiamo di volere un occupancy di 10-4 allora sceglierò la  
550    soglia in base a questo. (plot su quaderno) Da questo conto trovo la minima soglia mettibile  
551    In realtà quello che faccio è mettere una soglia un po' più grande perchè il rate di rumore dipende  
552    da molti fattori quali la temperatura, l annealing ecc, e non voglio che cambiando leggermente uno  
553    di questi parametri vedo alzarsi molto il rate di rumore. In realtà non è solo il rumore sensibile a  
554    diversi fattori, ma anche la soglia: ad esempio la cosa classica è la variabilità della soglia da pixel  
555    a pixel.

556    In questo modo rumore e soglia diventano parenti.

557    Review pag 26.

558    The noise requirement can be expressed as:

559    Questo implica tra le altre cose che voglio poter assegnare delle soglie diverse a diversi pixel:  
560    Drawback è dare spazio per registri e quantaltro.  
561    Questo lascia però ancora aperto il problema temporale delle variazioni del rumore: problema per  
562    cui diventano necessarie le misure dei sensori dopo l'irraggiamento.

563  
564    Per arcadia i registri (c'è un DAC) per la soglia (VCASN) si trovano in periferia. Non fare  
565    trimming sulla soglia è uno dei problemi che si sono sempre incontrati: a casusa dei mismatch dei  
566    transistor le soglie efficaci pixel per pixel cambiano tanto. La larghezza della s curve è il noise se se  
567    assumi che il noise è gaussiano

568    Il trimming della soglia avviene con dei DAC: la dispersione della soglia dopo al tuning e dovuta  
569    al dac è:

$$\sigma_{THR,tuned} = \frac{\sigma_{THR}}{2^{nbit}} \quad (6.1)$$

570    dove il numero di bit cambia varia tra 3-7 tipicamente. Monopix è 7 Arcadia 6

571  
572    Each ROIC is different in this respect, but in general the minimum stable threshold was around  
573    2500 electrons (e) in 1st generation ROICs, whereas it will be around 500 e for the 3rd generation.  
574    This reduction has been deliberate: required by decreasing input signal values. Large pixels (2 104  
575    um<sup>2</sup>), thick sensors (maggiore di 200 um), and moderate sensor radiation damage for 1st generation  
576    detectors translated into expected signals of order 10 ke, while small pixels (0.25 104 um<sup>2</sup>), thinner  
577    sensors (100 um), and heavier sensor radiation damage will lead to signals as low as 2 ke at the  
578    HL-LHC

579    The ENC can be directly calculated by the Cumulative Distribution Function (CDF) (scurve)  
580    obtained from the discriminator "hit" pulse response to multiple charge injections

<sup>581</sup> **6.2 TJ-Monopix1 characterization**

<sup>582</sup> **6.3 ARCADIA-MD1 characterization**

583 **Appendix A**

584 **Pixels detector: a brief overview**

585 **A.1 Radiation damages**

586 Radiation hardness is a fundamental requirement for pixels detector especially in HEP since they  
 587 are almost always installed near the interaction point where there is a high energy level of radiation.  
 588 At LHC the  $\phi_{eq}$  per year in the innermost pixel detector is  $10^{14} n_{eq}/cm^2$ ; this number reduces by  
 589 an order passing to the outer tracker layer [2] pag 341 Wermes. Here the high fluence of particles  
 590 can cause a damage both in the substrate of the detector and in the superficial electronics.

591 The first one has a principal non ionizing nature, due to a non ionizing energy loss (NIEL), but  
 592 it is related with the dislocation of the lattice caused by the collision with nuclei; by this fact the  
 593 NIEL hypothesis states that the substrate damage is normalized to the damage caused by 1 MeV  
 594 neutrons. Differently, surface damages are principally due to ionizing energy loss.

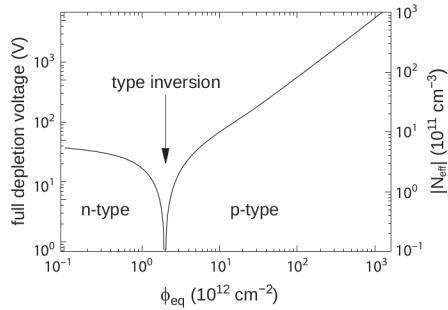
595 **DUE PAROLE IN PIÙ SUL SURFACE DAMAGE** A charge accumulation in oxide ( $S_iO_2$ ) can  
 596 cause the generation of parasitic current with an obvious increase of the 1/f noise. Surface damages  
 597 are mostly less relevant than the previous one, since with the development of microelectronics and  
 598 with the miniaturization of components (in electronic industry 6-7 nm transistors are already used,  
 599 while for MAPS the dimensions of components is around 180 nm) the quantity of oxide in circuit  
 600 is reduced.

601 Let's spend instead two more other words on the more-relevant substrate damages: the general  
 602 result of high radiation level is the creation of new energy levels within the silicon band gap and  
 603 depending on their energy-location their effect can be different, as described in the Shockely-Read-  
 604 Hall (SRH) statistical model. The three main consequence of radiation damages are the changing  
 605 of the effect doping concentration, the leakage current and the increasing of trapping probability.

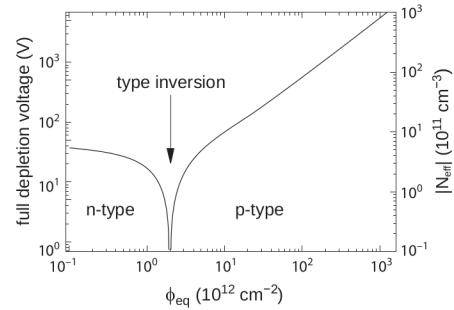
606 **Changing of the effective doping concentration:** is associated with the creation/removal  
 607 of donors and acceptors center which trap respectively electrons/holes from the conduction band  
 608 and cause a change in effective space charge density. Even an inversion (p-type becomes n-type<sup>1</sup>)  
 609 can happen: indeed it is quite common at not too high fluences ( $\phi_{eq} 10^{12-13} n_{eq} cm^{-2}$ ). A changing  
 610 in the doping concentration requires an adjustment of the biasing of the sensor during its lifetime  
 611 (eq.2.1) and sometimes can be difficult keeping to fully deplete the bulk.

---

<sup>1</sup>L'INVERSIONE OPPOSTA NON CE L'HAI PERCHÈ?



(a) 1a



(b) 1b

612       **Leakage current:** is associated with the generation-recombination centers. It has a strong  
613 dependence with the temperature ( $I_{leak} \propto T^2$ ), whose solution is therefore to operate at lower  
614 temperature.

615       **Increase of trapping probability:** since the trapping probability is constant in the depleted  
616 region, the collected charge decreases exponentially with the drift path. The exponential coefficient,  
617 that is the mean trapping path, decreases after irradiation and typical values are 125-250  $\mu m$  and  
618 must be compared with the thickness of the depleted region which () corresponds to the mean drift  
619 path.

620       Different choices for substrate resistivity, for junctions type and for detector design are typically  
621 made to fight radiation issues. Some material with high oxygen concentration (as crystal produced  
622 using Czochralki (Cz) or float-zone (Fz) process (**CONTROLLA LA DIFFERENZA TRA I DUE**))  
623 for example, show a compensation effect for radiation damage; another example is the usage of  
624 n+ -in-p/n sensors (even if p+ -in-n sensors are easier and cheaper to obtain) to get advantage  
625 of inversion/to have not the inversion (since they are already p-type). After inversion the n+p  
626 boundary, coming from n+ in-n, but to keep using the sensor the depletion zone still must be  
627 placed near the diode.

628 **Appendix B**

629 **FLASH radiotherapy**

630 La radioterapia si usa nel 60 per cento dei pazienti, sia come cura che come trattamento palliativo.  
631 Si associa spesso ad altre cure e si può fare prima/durante/dopo un intervento.

632  
633 Si può fare in modi diversi: da dentro (brachytherapy) oppure da fuori (quella standard). Un  
634 requisito importante è la delinazione del target (non vuoi rischiare di beccare i tessuti sani), per  
635 cui prima tipicamente si fanno esami di imaginig del tumore. Tipicamente anche gli acceleratori  
636 stessi per la terapia sono provvisti di radiografia.

637 Un problema dei fotoni ad esempio è che il loro rilascio di dose è lineare, per cui danneggia  
638 anche i tessuti sani. Il problema dei protoni invece è che hanno un picco troppo stretto per cui non  
639 puoi coprire grosse zone e soprattutto se sbagli rischi davvero di danneggiare molto i tessuti sani.

640

641 **B.1 Cell survival curves**

642 Curva di efficacia del trattamento in funzione della dose:

$$\frac{S(D)}{S(0)} = e^{-F(D)} \quad (\text{B.1})$$

643 dove  $F(D)$

$$F(D) = \alpha D + \beta D^2 \quad (\text{B.2})$$

644 dove  $\alpha$  e  $\beta$  rappresentano due tipi di danno diversi: coefficients, experimentally determined, characterizing the radiation response of cells. In particular, alpha represents the rate of cell killing by single ionizing events, while beta indicates the maximal rate of cell killing by double hits observed when the repair mechanisms do not activate during the radiation exposure. Si ottiene una curva di sopravvivenza dove si vede la possibilità delle cellule di autoripararsi. A basse dosi infatti le cellule possono ripararsi.

650

651 Per introdurre l'effetto FLASH introduco prima la therapeutic window.

652

653 TCP è la tumor control Probability che indica la probabilità delle cellule del tumore di essere uccise dopo una certa dose (con in riferimento a dose in acqua)

654 Se una media di  $\mu(D)$  di cellule di tumore are killed con una dose D, la probabilità che n cellule sopravvivono è data da  $P(n|\mu)$  poisson:

$$P(n|\mu) = \frac{\mu(D)^n e^{-\mu(D)}}{n!} \quad (\text{B.3})$$

$$TCP(D) = P(n=0|\mu(D)) = e^{-\mu(D)} \quad (\text{B.4})$$

655 D'altra parte hai una probabilità di fare danno su normal tissue NTCP Normal Tissue Complication Probability, che rappresenta il problema principale e che limita la massima radiazione erogabile  
656 Una scelta bilanciata si applica guardando a questi due fattori; si usa il therapeutic index definito  
657 come TCP/NTCP.

661 La cosa ottimale è ampliare la finestra del therapeutic ratio.

662  
663 CONV-RT 0.01-5 Gy/min. A typical RT regime today consists of daily fractions of 1.5 to 3  
664 Gy given over several weeks.

665 Nell Intra operative radiation therapy (IORT), where they reach values respectively about 20 and  
666 100 times greater than those of conventional radiation therapy.

667 FLASH vuole ultrahigh mean dose-rate (maggioranza di 40 Gy/s) in modo da ridurre anche il  
668 trattamento a meno di un secondo.

669

## 670 **B.2 FLASH effect**

671 Ci sono due effetti che affrontano il flash effect e la sua applicabilità: Dose rate effect e oxygen

672  
673 Cellule che esibiscono hypoxia (cioè cellule che non hanno ossigeno sono radioresistenti); al  
674 contrario normoxia e physoxia non lo sono. La presenza di ossigeno rende la curva steeper indicando  
675 che lo stesso danno si raggiunge a livelli di dose più bassi rispetto al caso senza ossigeno.

676 FIGURA con una curva a confronto con e senza ossigeno.

677 Typically, the OER is in the order of 2.5–3.5 for most cellular systems

678 Quindi si vogliono sfruttare questi effetti per diminuire la tossicità sui tessuti sani

679

# 680 Bibliography

- 681 [1] W. Snoeys et al. “A process modification for CMOS monolithic active pixel sensors for  
682 enhanced depletion, timing performance and radiation tolerance”. In: (2017). DOI: <https://doi.org/10.1016/j.nima.2017.07.046>.
- 684 [2] H. Kolanoski and N. Wermes. *Particle Detectors: Fundamentals and Applications*. OXFORD  
685 University Press, 2020. ISBN: 9780198520115.
- 686 [3] E. Mandelli. “Digital Column Readout Architecture for the ATLAS Pixel 0.25 um Front End  
687 IC”. In: (2002).
- 688 [4] M. Garcia-Sciveres and N. Wermes. “A review of advances in pixel detectors for experiments  
689 with high rate and radiation”. In: (2018). DOI: <https://doi.org/10.1088/1361-6633/aab064>.
- 691 [5] M. Dyndal et al. “Mini-MALTA: Radiation hard pixel designs for small-electrode monolithic  
692 CMOS sensors for the High Luminosity LHC”. In: (2019). DOI: <https://doi.org/10.1088/1748-0221/15/02/p02005>.
- 694 [6] M. Barbero. “Radiation hard DMAPS pixel sensors in 150 nm CMOS technology for opera-  
695 tion at LHC”. In: (2020). DOI: <https://doi.org/10.1088/1748-0221/15/05/p05013>.
- 696 [7] K. Moustakas et al. “CMOS Monolithic Pixel Sensors based on the Column-Drain Architec-  
697 ture for the HL-LHC Upgrade”. In: (2018). DOI: <https://doi.org/10.1016/j.nima.2018.09.100>.
- 699 [8] I. Caicedo et al. “The Monopix chips: depleted monolithic active pixel sensors with a column-  
700 drain read-out architecture for the ATLAS Inner Tracker upgrade”. In: (2019). DOI: <https://doi.org/10.1088/1748-0221/14/06/C06006>.
- 702 [9] D. Kim et al. “Front end optimization for the monolithic active pixel sensor of the ALICE  
703 Inner Tracking System upgrade”. In: *JINST* (2016). DOI: doi:10.1088/1748-0221/11/02/  
704 C02042.
- 705 [10] L. Pancheri et al. “A 110 nm CMOS process for fully-depleted pixel sensors”. In: (2019). DOI:  
706 <https://doi.org/10.1088/1748-0221/14/06/c06016>.
- 707 [11] L. Pancheri et al. “Fully Depleted MAPS in 110-nm CMOS Process With 100–300-um Active  
708 Substrate”. In: (2020). DOI: 10.1109/TED.2020.2985639.