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⁴¹ **Bibliography** **35**

⁴² Characterization of monolithic CMOS pixel sensors for charged particle detectors and for high
⁴³ intensity dosimetry

44 **Chapter 1**

45 **Introduction**

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

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

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

59 Qual è invece la richiesta per la dosimetria?

60 61 While CCDs pioneered the use of silicon pixels for precision tracking,

62 Chapter 2

63 Pixel detectors

64 2.1 Signal formation

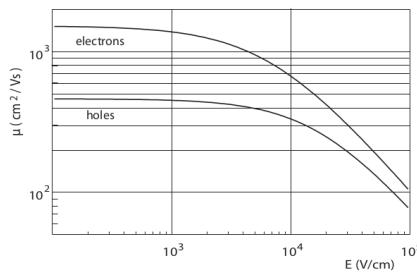
65 When a charge particle passes through a pixel and loses energy by ionization a part of that
 66 energy is used to generate electron-hole pairs (another part is used for other processes, as the
 67 lattice excitation) which are then separated by the electric field and collected at their respectively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

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

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

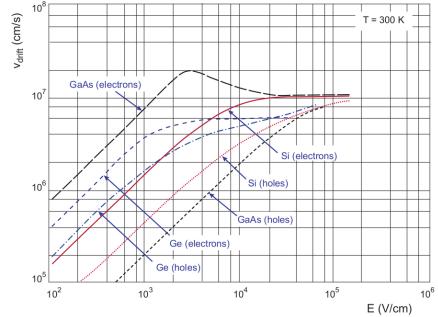
$$v = \mu(E) E \quad (2.2)$$

73 where $\mu(E)$ is a function of the electric field and is linear with E only for small E : at higher values
 74 the probability of interactions with optical phonons increases and the mobility drops and this leads
 75 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

76 The average energy needed to create a pair at 300 K in silicon is $w_i = 3.65 \text{ eV}$, that is more
 77 than the mean ionization energy because of the interactions with phonon, since for a minimum
 78 ionizing particle (MIP) the most probable value (MPV) of charge released in the semiconductor is
 79 0.28 keV/ μ , hence the number of e/h pairs is:

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

¹Even 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

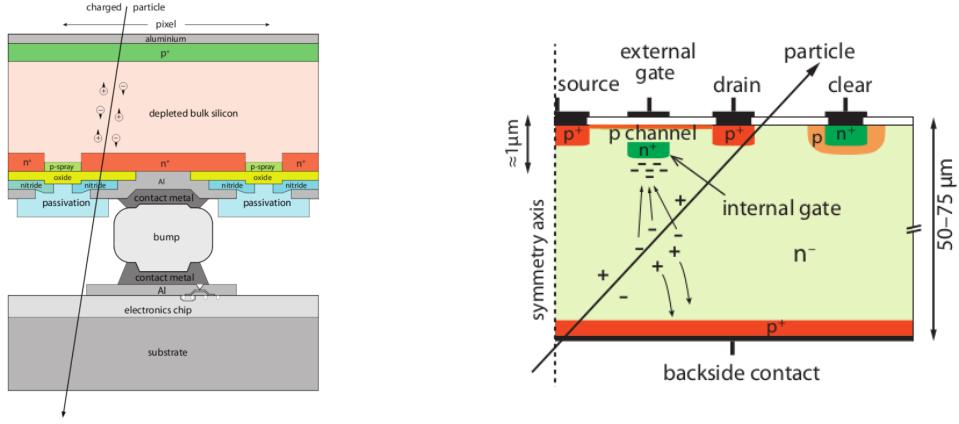


Figure 2.2: Concept cross-section of hybrid pixel (a) and of a DEPFET (b)

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

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

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

93 2.2 CCDs

94 ens of ms due to the need to transfer the charge signals pixel by pixel through a single output
 95 circuit For photon imaging the need of high assorbtion efficiency

96 2.3 Hybrid pixels

97 Hybrid pixels are made of two parts (fig. 2.2a), the sensor and the electronics: for each pixel these
 98 two parts are welded together through microconnection (bump bond).
 99 They provide a practical system where readout and sensor can be optimized separately, although
 100 the testing is less easy-to-do since the sensor and the R/O must be connected together before.
 101 In addition, the particular and sophisticated procedure to bond sensor and ASIC (application spe-
 102 cific integrated circuit) makes them difficult to produce, delicate, especially when exposed to high
 103 levels of radiation, and also expensive.

104 A critical parameter for accelerator experiments is the material budget, which represents the main
 105 limit factor for momentum measurement resolution in a magnetic field; since hybrid pixels are
 106 thicker (\sim hundreds of μm) than monolithic ones (even less than $100 \mu m$), using the latter the
 107 material budget can be down by a third: typical value for hybrid pixels is $1.5 \% X_0$ per layer,
 108 while for monolithic $0.5 \% X_0$.

109 Among other disadvantages of hybrid pixels there is the bigger power consumption that implies,
 110 by the way, a bigger cooling system leading in turn to an increase in material too.

111
 112 DEPFET are the first attempt towards the integration of the front end (FE) on the sensor bulk:
 113 they are typically mounted on a hybrid structure but they also integrate the first amplification

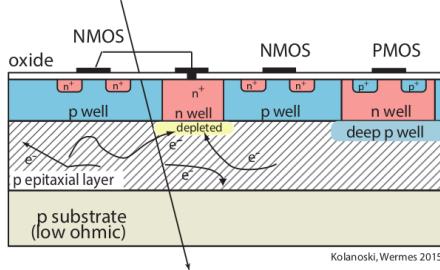


Figure 2.3: Concept cross-section of CMOS MPAS pixel

114 stage.
 115 Each pixel implements a MOSFET (metal-oxide-semiconductor field-effect transistor) transistor
 116 (a p-channel in fig. 2.2b): an hole current flows from source to drain which is controlled by the
 117 external gate and the internal gate together. The internal gate is made by a deep n^+ implant
 118 towards which electrons drift after being created in the depletion region (to know how the signal
 119 is created in a pixel detector look at appendix A); the accumulation of electrons in the region
 120 underneath the n implant changes the gate potential and controls the transistor current.
 121 DEPFET typically have a good S/N ratio: this is principally due the amplification on-pixel and
 122 the large depletion region. But, since they need to be connected with ASIC the limiting factor still
 123 is the material budget.

124 2.4 CMOS MAPS and DMPAS

125 Monolithic active pixels accommodate on the same wafer both the sensor and the front end elec-
 126 tronics, with the second one implanted on top within a depth of about $1\text{ }\mu\text{m}$ below the surface.
 127 MAPS have been first proposed and realized in the 1990s and their usage has been enabled by the
 128 development of the electronic sector which guarantees the decrease in CMOS transistors dimension
 129 at least every two years, as stated by the Moore's law².
 130 As a matter of fact the dimension of components, their organization on the pixel area and logic
 131 density are important issues for the design and for the layout; typically different decisions are taken
 132 for different purposes.

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

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

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

147 2.4.1 DMAPS: large and small fill factor

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

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

²Moore's law states that logic density doubles every two years.

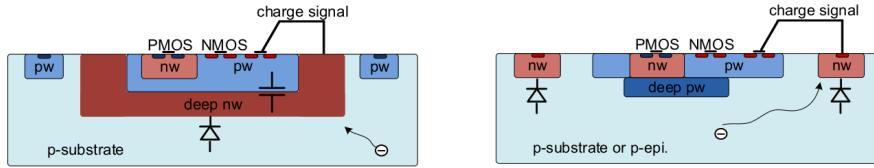


Figure 2.4: Concept cross-section with large and small fill factor

	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

152 To implement a uniform and stronger electric field, DMAPS often uses large electrode design that
 153 requires multiple wells (typically four including deep n and p wells); this layout adds on to the
 154 standard terms of the total capacity of the sensor a new term (fig. 2.5), that contributes to the
 155 total amplifier input capacity. In addition to the capacity between pixels (C_{pp}) and between the
 156 pixel and the backside (C_b), a non-negligible contribution comes from the capacities between wells
 157 (C_{WW} and C_{SW}) needed to shield the embedded electronics. These capacities affect the thermal
 158 and 1/f noise of the charge amplifier and the τ_{CSA} too:

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

160 where g_m is the transconductance, τ_{sh} is the shaping time.
 161 Among the disadvantages coming from this large input capacity could be the coupling between
 162 the sensor and the electronics resulting in cross talk: noise induced by a signal on neighbouring
 163 electrodes; indeed, since digital switching in the FE electronics do a lot of oscillations, this prob-
 lem is especially connected with the intra wells capacities. So, larger charge collection electrode

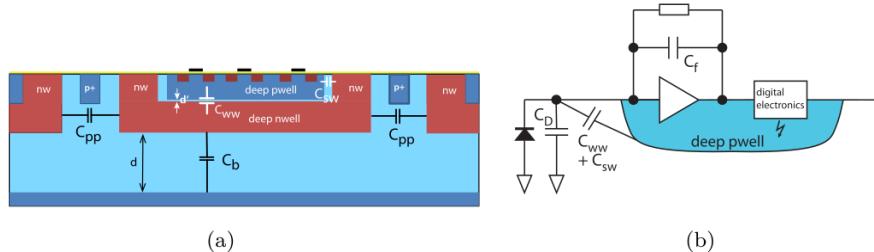


Figure 2.5: C_{pp} , C_b , C_{WW} , C_{SW}

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

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

171 As we'll see these two different types of sensor require different amplifier: the large electrode one is
 172 coupled with the charge sensitive amplifier, while the small one with voltage amplifier (sec 2.5.1).

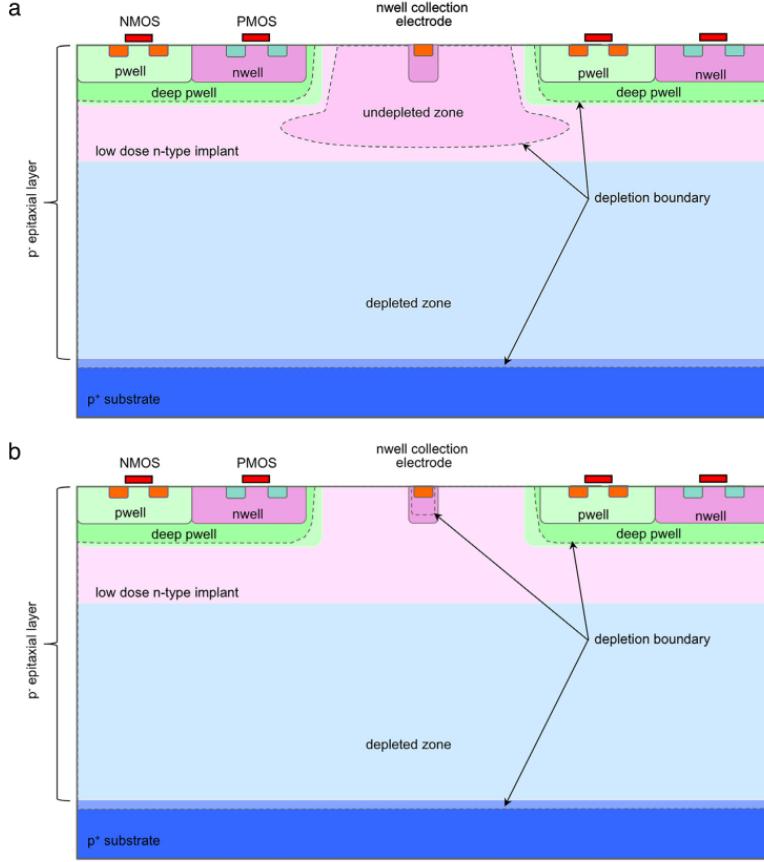


Figure 2.6: A modified process for ALICE tracker detector: a low dose n implant is used to create a planar junction. In (a) the depletion is partial, while in (b) the pixel is fully depleted.

2.4.2 A modified sensor

A process modification developed by CERN in collaboration with the foundries has become the standard solution to combine the characteristics of a small fill factor sensor (small input amplifier capacity) and of large fill factor sensor (uniform electric field) is the one carried out for ALICE upgrade about ten years [1].

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

Before the process modification the depletion region extends below the diode towards the substrate, and it doesn't extend laterally so much even if a high bias is applied to the sensor (fig. 2.6). After, two distinct pn junctions are built: one between the deep p well and the n^- layer, and the other between the n^- and the p^- epitaxial layer, extending to the all area of the sensor.

Since deep p well and the p-substrate are separated by the depletion region, the two p electrodes can be biased separately³ and this is beneficial to enhance the vertical electric field component.

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

2.5 Analog front end

After the creation of a signal on the electrode, the signal enters the front end circuit (fig.2.7), ready to be molded and transmitted out of chip. Low noise amplification, fast hit discrimination and an

³This 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

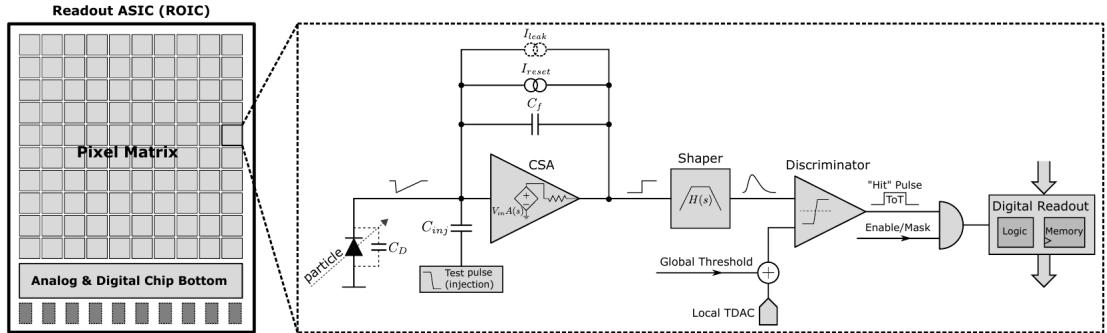


Figure 2.7: Readout FE scheme: in this example the preamplifier is a charge sensitive one (CSA) but changing the capacitive feedback into a resistive one, this can be converted in a voltage or current amplifier.

195 efficient, high-speed readout architecture, consuming as low power as possible must be provided
 196 by the readout integrated electronics (ROIC).

197 Let's take a look to the main steps of the analog front end chain: the preamplifier (that actually
 198 often is the only amplification stage) with a reset to the baseline mechanism and a leakage current
 199 compensation, a shaper (a band-pass filter) and finally a discriminator. The whole chain must be
 200 optimized and tuned to improve the S/N ratio: it is very important both not to have a large noise
 201 before the amplification stage in order to not multiply that noise, and chose a reasonable threshold
 202 of the discriminator to cut noise-hits much as possible.

203 2.5.1 Preamplifier

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

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

207 Depending on whether a capacity or a resistance is used as feedback, respectively a charge or a
 208 voltage amplifier is used: if the voltage input signal is large enough and have a sharp rise time, the
 209 voltage sensitive preamplifier is preferred. Consequently, this flavor doesn't suit to large fill factor
 210 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
 211 for the small fill factor ones: $v_{in} = Q/C_D \approx 3fC/3\text{ pF} = 1\text{ mV}$.

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

216 2.6 Readout logic

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

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

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

230 bunch collisions at LHC; for such reason a reasonable BCID-clock frequency for pixels detector is
 231 40 MHz.
 232 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.

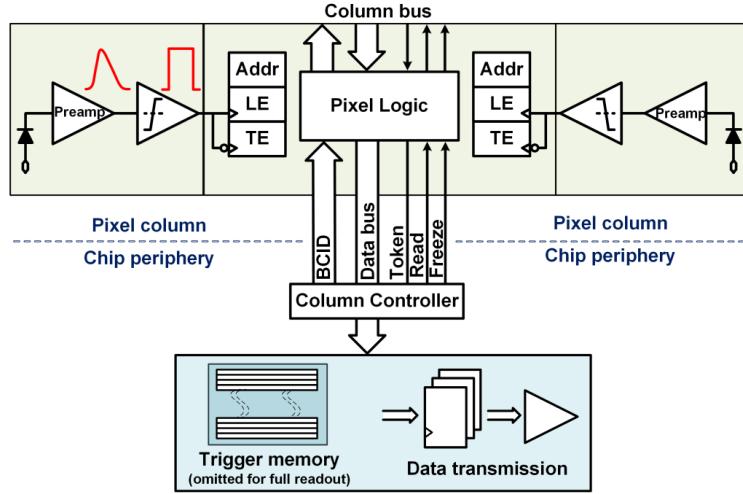


Figure 2.8: Column drain R/O scheme where ToT is saved

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

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

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

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

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

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

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

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

257 To avoid hit loss (let's neglect the contribution to the inefficiency of the dead time τ due to the
 258 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
 259 needed to transfer the hit; since t_t is small, one must have $B_W \gg \mu$, that means a high bandwidth
 260 [4].

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

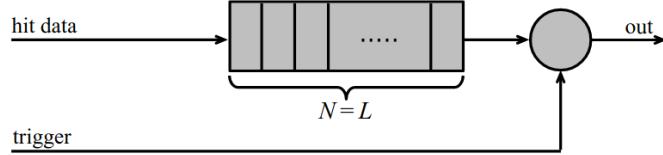


Figure 2.9: Block diagram of a pipeline buffer: N is the dimension of memory buffer and L is the trigger latency expressed in BCID cycles

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

270 In order to reduce the bandwidth a readout with zero suppression on pixel is typically employed;
 271 this means that only information from channels where the signal exceeds the discriminator thresh-
 272 old are stored. Qualcosa sulla zero suppression? La metto qui questa affermazione?

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

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

Consider a 50 kHz single pixel hits rate and a trigger latency of 5 μs , the probability of losing

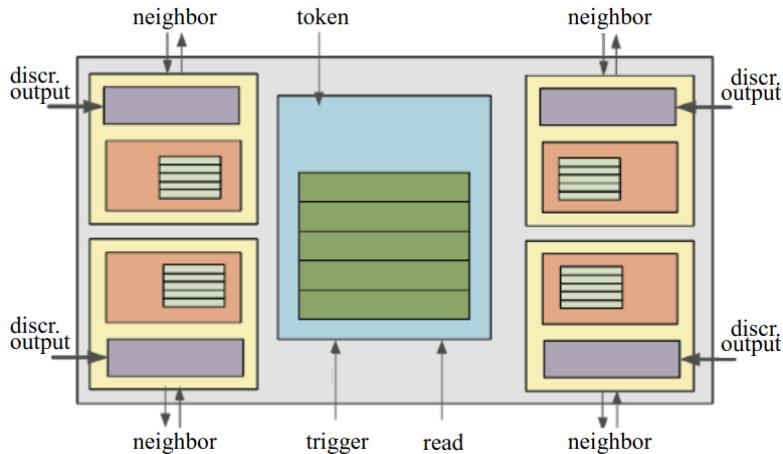


Figure 2.10: Block diagram of the FE-I4 R/O. Read and memory management section is high-
 lighted in light blue; latency counters and trigger management section are highlighted in green; hit
 processing blocks are highlighted in purple; ToT counters and ToT management units are high-
 lighted in orange

283 hits is:
 284

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

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

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

²⁸⁷ Considering the second situation: if the average single pixel rate is still 50 kHz, grouping four
²⁸⁸ pixels the mean number of hits per trigger latency is $\nu = 0.25 \times 4 = 1$. To get an efficiency of
²⁸⁹ 99.9% (eq. 2.11) a buffer depth of 5 hits in the four-pixels region, instead of 3 per pixels, is needed.

²⁹⁰ **Chapter 3**

²⁹¹ **Use of pixel detectors**

²⁹² There always was a tight relation between the development of cameras and pixel detectors since
²⁹³ 1969, when the idea of CCDs, thanks to whom Boyle and Smith were awarded the Nobel Prize in
²⁹⁴ Physics in 2009¹, revolutionized photography allowing light to be captured electronically instead
²⁹⁵ of on film.

²⁹⁶ The charge-coupled device CCD provided the first way for a light-sensitive silicon chip to store
²⁹⁷ an image and then digitize it, opening the door to the creation of digital images. PRemio nobel
²⁹⁸ 2009.

²⁹⁹ A partire dal 2017, i sensori CMOS rappresentano l'89% delle vendite globali di sensori di immagine.
³⁰⁰ Ma praticamente dal 2010 in poi solo CMOSS e non più CCD.

³⁰¹ The principal use cases of pixel detectors are particle tracking and imaging: in the former case
³⁰² individual charged particles have to be identified, in the latter instead an image is obtained by
³⁰³ the usually un-triggered accumulation of the impinging radiation. Also the demands on detectors
³⁰⁴ performance depends on their usage, in particular tracking requires high spatial resolution, fast
³⁰⁵ readout and radiation hardness.

³⁰⁶ Historically, the first pixel detector employed in particle physics was a CCD: it was installed in
³⁰⁷ the spectrometer at the CERN's Super Proton Synchrotron (SPS) by the ACCMOR Collaboration
³⁰⁸ (Amsterdam, CERN, Cracow, Munich, Oxford, RAL) at mid 1980s, with the purpose of studying
³⁰⁹ the recently-discovered charm particles. The second famous usage of CCDs took place at SLAC in
³¹⁰ the Large Detector (SLD) during the two years 1996-98. From that period on particle tracking in
³¹¹ experiments have been transformed radically: it was mandatory for HEP experiments to build a
³¹² inner vertex detector. Today all HEP experiments have a pixel detector: ATLAS, CMS, LHC-b,
³¹³ ALICE and Belle-II are only the more important.

³¹⁴ For scientific imaging, instead, the applications vary from astrophysics and medical imaging
³¹⁵ to studies of protein dynamics, altro? and art authentication, for example. The counting mode
³¹⁶ represents the principal imaging technique, a direct

³¹⁷ **3.1 Tracking in HEP**

³¹⁸ Per gli acceleratori la richieste sono molto stringenti e lo saranno sempre di più con l'aumento dell'
³¹⁹ intensità o della luminosità in termini di radiation hardness (per HL-LHC for example expected
³²⁰ in 5 anni 500 Mrad e NIEL di 10 alla 16), efficiency e occupancy (efficienza alta dopo tanta
³²¹ radiazione e noise occupancy bassa), time resolution (bunch crossing 40 MHz), material budget e
³²² power consumption (material budget below 2 per cento e power consumption 500 mW/cm²)
³²³ Usati come tracciatori per misure di impulso e per misure di energia (per rigettare) ad esempio
³²⁴ dati di fondo (topic fondamentale per BELLE-II).

³²⁵ **3.1.1 Hybrid pixels at LHC: ATLAS, CMS and LHC-b**

³²⁶ From the middle of 2013 a dedicated collaboration, RD 53 ('Development of pixel readout integrated
³²⁷ circuits for extreme rate and radiation'), has been established with the specific goal to find
³²⁸ a pixel detector suitable for phase II future upgrades of the experiments CMS and ATLAS. Even
³²⁹ if the collaboration is specifically focused on design of hybrid pixel readout chips, also monolithic

¹DUE INFO SU QUESTE PERSONE?

330 options have been taken in account for ATLAS ITK outer layers. Tra i chip designed for that
331 purpose there are LF an TJ Monopix.

332 **ATLAS**

333 **CMS**

334 **LHC-b**

335 A noteworthy example of detector originally used in particle physics, and later employed mainly
336 for medical imaging, but also in space and for art authentication, is Medipix, a hybrid system
337 developed at CERN within the Medipix collaboration usato anche da LHC-b (Timepix).

338

339 **3.1.2 A DEPFET example: Belle-II**

340 **3.1.3 CMOS MAPS: ALICE and STAR**

341 Experiments such as ALICE at LHC and STAR at RHIC have already introduced the CMOS
342 MAPS technology in their detectors. ALICE Tracking System (ITS2), upgraded during the LHC
343 long shut down in 2019-20, was the first large-area ($\sim 10 \text{ m}^2$) silicon vertex detector based on
344 CMOS MAPS.

345 **ALICE**

346 ALICE (A Large Ion Collider Experiment) is a detector dedicated to heavy-ion physics at the
347 LHC. **Metti una cosa generale su com'è fatto tutto il detector di ALICE: tpc ecc.**

348 The expected dose is smaller by two order than the one at ATLAS and CMS.(cita libro). The rate
349 of interactions is few MHz, but the number of particles produced in each interaction is really high.
350 The pixel system must cope with high densities as high as $100/\text{cm}^2$, ma ha abbastanza tempo
351 tra un'interazione e l'altra. The challenge is reconstruct very complicated events and relevant is
352 minimize the amount of material since any kind of secondary interaction will complicate further the
353 event topology e diminuisce l'efficacia e la risoluzione delle tracce a più basso momento.

354 **ALICE MAPS: MONOPIX1 COM'è fatto il rivelatore a pixel di ALICE** Thanks to the reduction
355 of the material budget, ITS2, which uses the ALPIDE chip developed by ALICE collaboration,
356 obtained an amazing improvement both in the position measurement and in the momentum resolu-
357 tion, improving the efficiency of track reconstruction for particles with very low transverse momen-
358 tum (by a factor 6 at $pT \sim 0.1 \text{ GeV}/c$). Further advancements in CMOS MAPS technology are
359 being aggressively pursued for the ALICE ITS3 and the Belle II vertex detector upgrades (both
360 foreseen around 2026-27) and other experiments, with the goals of further reducing the sensor
361 thickness and improving the readout speed of the devices, while keeping power consumption at a
362 minimum.

363 **STAR**

364

365 **3.2 Application in medical imaging**

366 **3.2.1 Medipix and Timepix**

367 **3.2.2 Applicability to FLASH radiotherapy**

³⁶⁸ **Chapter 4**

³⁶⁹ **TJ-Monopix1**

³⁷⁰ TJ-Monopix1 is a small electrode DMAPS with fast R/O capability, fabricated by TowerJazz
³⁷¹ foundry in 180 nm CMOS imaging process. It is part, together with prototypes from other series
³⁷² such as TJ-MALTA, of the ongoing R&D efforts aimed at developing DMAPS in commercial CMOS
³⁷³ processes, that could cope with the requirements at accelerator experiments. Both TJ-Monopix
³⁷⁴ and TJ-MALTA series [5], produced with the same technology by TowerJazz (the timeline of the
³⁷⁵ foundry products is shown in figure 4.1), are small electrode demonstrators and principally differ in
³⁷⁶ the readout design: while Monopix implements a column-drain R/O, an asynchronous R/O without
³⁷⁷ 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

³⁷⁸ Another Monopix series, but in 150 nm CMOS technology, has been produced by LFoundry [6].
³⁷⁹ The main differences between the LF-Monopix1 and the TJ-Monopix1 (summarized in table 4.2),
³⁸⁰ lay in the sensor rather than in the readout architecture, as both chips implements a fast col-
³⁸¹ umn drain R/O with ToT capability [7][8]. Concerning the sensors, either are based on a p-type
³⁸² substrate, but with slightly different resistivities; in addition LFoundry pixels are larger, thicker
³⁸³ and have a large fill factor (the very deep n-well covers ~55% of the pixel area). The primary
³⁸⁴ consequence is that LF-Monopix1 pixels have a higher capacity resulting in higher consumption
³⁸⁵ and noise. As I discussed in section 2.4.1, the fact that LF-Monopix has a large fill factor electrode
³⁸⁶ is expected to improve its radiation hardness. Indeed, a comparison of the performance of the
³⁸⁷ two chips showed that TJ-Monopix suffers a comparatively larger degradation of efficiency after
³⁸⁸ irradiation, due to the low electric field in the pixel corner; on the other hand, a drawback of the
³⁸⁹ large fill factor in LF-Monopix is a significant cross-talk.

³⁹⁰ The TJ-Monopix1 chip contains, apart from the pixels matrix, all the required support blocks
³⁹¹ used for configuration and testing:

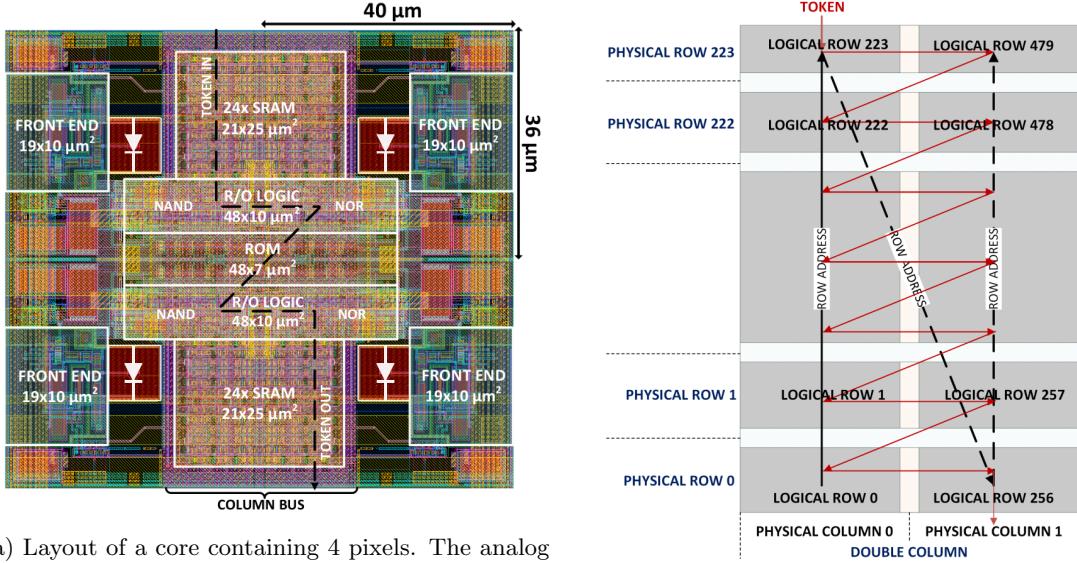
- ³⁹² the whole matrix contains 224×448 pixels, yielding a total active area approximately equal
³⁹³ to 145 mm^2 over a total area of $1 \times 2 \text{ cm}^2$;
- ³⁹⁴ at the chip periphery are placed some 7-bit Digital to Analog Converter (DAC), used to
³⁹⁵ generate the analog bias voltage and current 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 2×2 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 2.4.2 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.

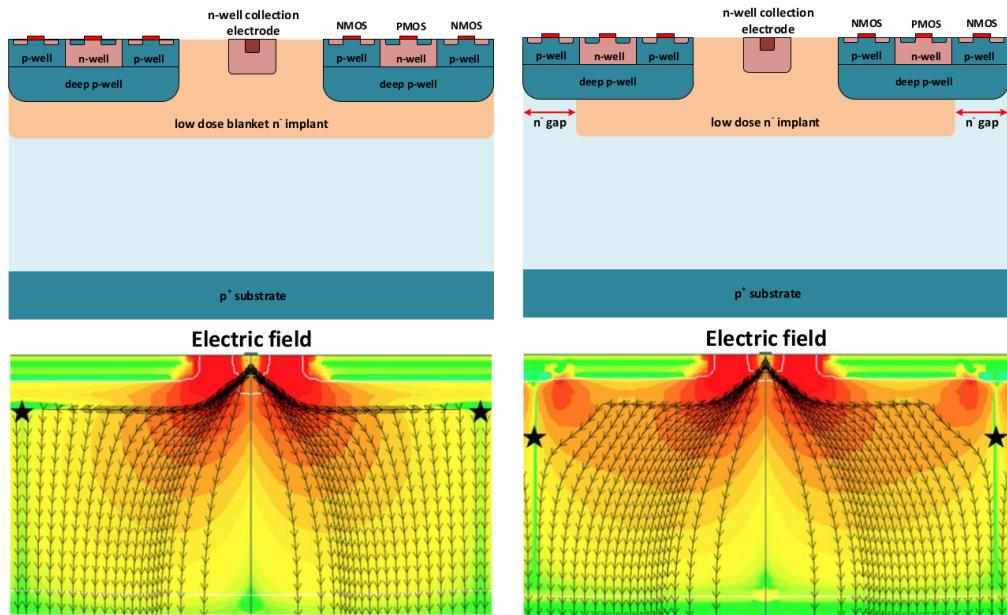


Figure 4.3: (a) The cross-section of a monolithic pixel in the TJ-Monopix with modified process; additionally in (b) a gap in the low dose implant is created to improve the collection of charge due to a bigger lateral component of the electric field. this point in figure is indicated by a star . transversal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

4.2 Front end

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

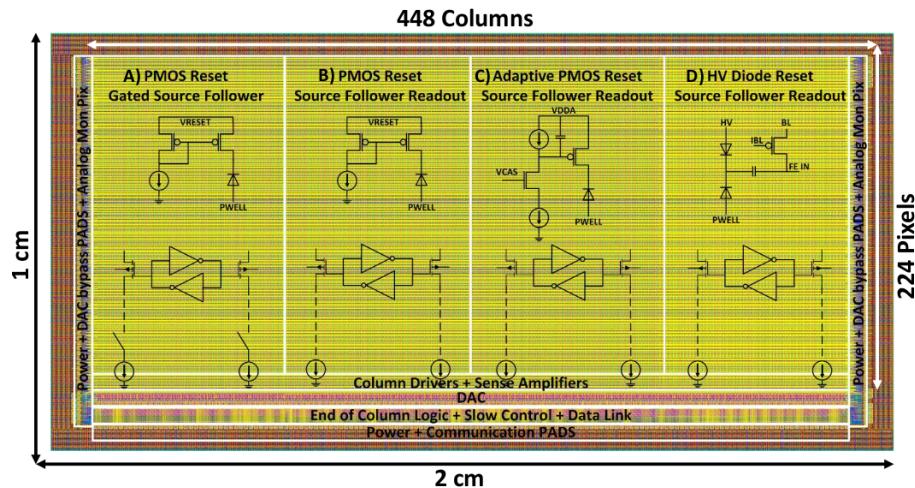


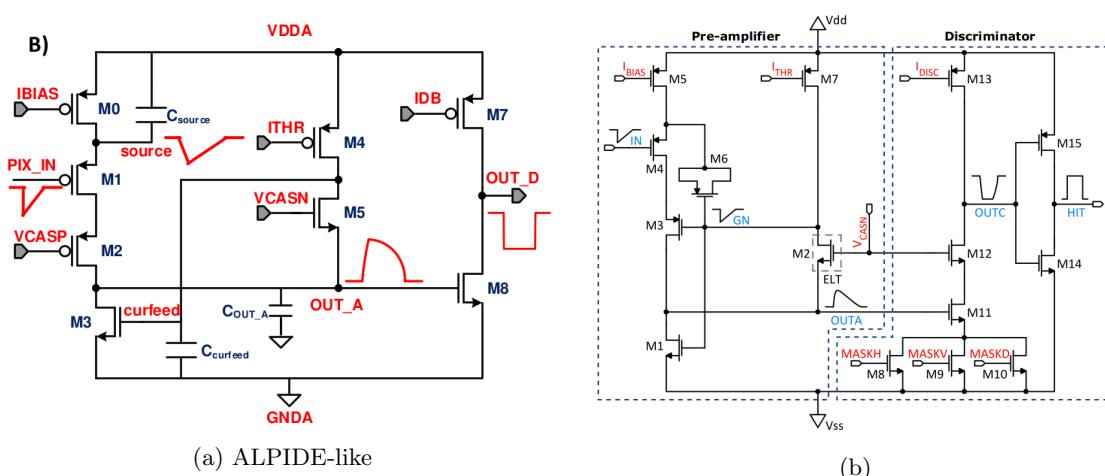
Figure 4.4

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

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

4.2.1 ALPIDE-like

ALPIDE chips, developed by the ALICE collaboration, implemented a standard FE to the point that many CMOS MAPS detectors used a similar FE and are called "ALPIDE-like". Considering 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



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

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

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

$$\Delta V_{OUT_A} = \frac{Q_{source}}{C_{OUT_A}} = \frac{C_{source} \Delta V_{PIX_IN}}{C_{OUT_A}} = \frac{C_{source}}{C_{OUT_A}} \frac{Q_{IN}}{C_{IN}} \quad (4.2)$$

452 A second branch (M4, M5) is used to generate a low frequency feedback, where VCASN and ITHR
 453 set the baseline value of the signal on C_{OUT_A} and the velocity to goes down to the baseline.

IL RUOLO DI CURVFEED NON L'HO CAPITO.

455 Finally IDB defines the charge threshold with which the signal OUT_A must be compared: de-
 456 pending on if the signal is higher than the threshold or not, the OUT_D is high or low respectively.

457 The actual circuit implemented in TJ-Monopix1 is shown in figure 4.5b: the principal difference
 458 lays in the addition of disableing pixels' readout. This possibility is uttermost important in order to
 459 reduce the hit rate and to avoid saturating the bandwidth due to the noisy pixels, which typically
 460 are those with manufacturing defects. In the circuit transistors M8, M9 and M10 have the function
 461 of disabling registers with coordinates MASKH, MASKV and MASKD (respectively vertical, ori-
 462 ginal and diagonal) from readout: if all three transistors-signals are low, the pixel's discriminator
 463 is disabled. Compared with a configurable masking register which would allow disableing pixels
 464 individually, to use a triple redundancy reduces the sensistivity to SEU¹ but also gives amount of
 465 intentionally masked ("ghost") pixels. This approach is suitable only for extremely small number
 466 N of pixel has to be masked: if two coordinate projection scheme had been implemented, the
 467 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)

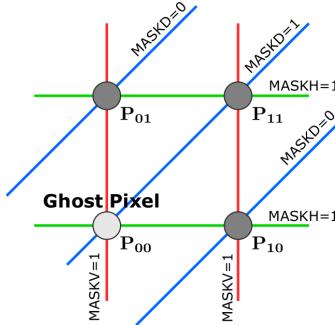


Figure 4.6

468

4.3 Readout logic

470 The simplest readout is "rolling shutter", in which peripheral logic along the chip edge addresses
 471 rows in turn, and analogue signals are transmitted by column lines to peripheral logic at the
 472 bottom of the imaging area. TJ-Monopix1 has a triggerless, fast and with ToT capability R/O
 473 which is based on a column-drain architecture. On the pixel are located two Random Access
 474 Memory (RAM) cells to store the 6-bit LE and 6-bit TE of the pulse, and a Read-Only Memory
 475 (ROM) containing the 9-bit pixel address. Excluded these memories, TJ-Monopix1 hasn't any
 476 other buffer: if a hit arrives while the pixel is already storing a previous one, the new data get lost.

¹Single 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 "fippi" (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	sets the discriminator threshold	yes
IDB	sets the velocity of the return to the baseline	yes
ITHR	sets the baseline of the signal	yes
ICASN	sets the gain of the preamplifier	yes
VRESET	sets the gain of the preamplifier	yes
IRESET	sets the gain of the preamplifier	no

Table 4.3: FE parameters which must be setted through the DAQ. "Function" means that higher parameter implies higher value

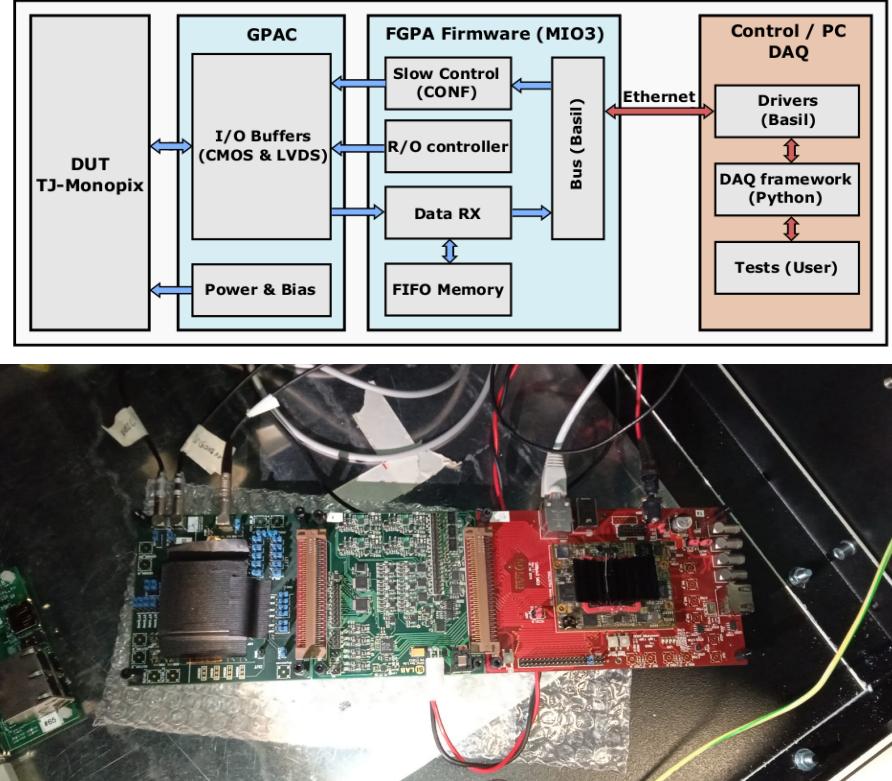
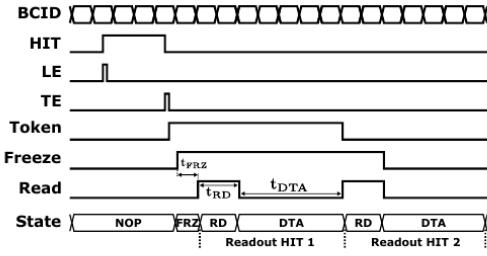


Figure 4.7: Main caption

477 After being read, the data packet is sent to the EoC periphery of the matrix, where a serializer
 478 transfers it off-chip to an FPGA (4.7). There a FIFO is used to temporarily stored the data, which
 479 is transmitted to a computer through an ethernet cable in a later time.

480 The access to the pixels' memory and the transmission of the data to the EoC, following
 481 a priority chain, is managed by control signals and is based on a Finite State Machine (FSM)
 482 composed by four state: no-operation (NOP), freeze (FRZ), read (RD) and data transfer (DTA).
 483 The readout sequence (??) starts with the TE of a pulse: the pixel immediately tries to grab the
 484 column-bus turning up a hit flag signal called *token*. The token is used to control the priority chain
 485 and propagates across the column indicating what pixel that must be read. To start the readout
 486 and avoid that the arrival of new hits disrupt the priority logic, a *freeze* signal is activated, and
 487 then a *read* signal controls the readout and the access to memory. During the freeze, the state of
 488 the token for all pixels on the matrix remains settled: this does not forbid new hits on other pixels
 489 from being recorded, but forbids pixels hit from turning on the token until the freeze is ended. The
 490 freeze stays on until the token covers the whole priority chain and gets the EoC: during that time
 491 new token cannot be turned on, and all hits arrived during a freeze will turn on their token at the
 492 end of the previous freeze. Since the start of the token is used to assign a timestamp to the hit,
 493 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

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

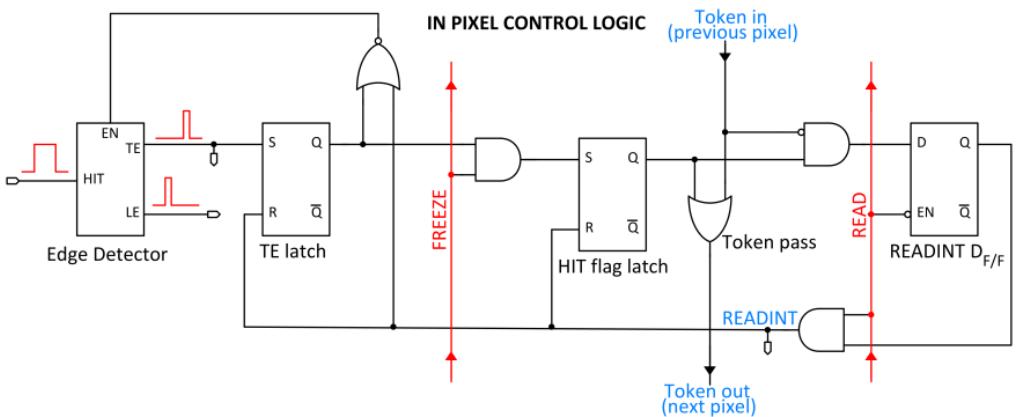


Figure 4.9

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

- **Pixel address:** while the double column address (6-bit) is appended by the EoC circuit, the row address (8-bits for each flavor) and the physical column in the doublet (1-bit) are assigned by the in-pixel logic
- **ToT:** is obtained offline from the difference of 6-bits TE and 6-bits LE, stored by the edge detector in-pixel; since a 40 MHz BCID is distributed across the matrix, the ToT value is range 0-64 clock cycle which corresponds to 0-1.6 μ s
- **Timestamp:** The timestamp of the hit correspond to the time when the pixel set up the token; it is assigned by the FPGA, that uses the LE, TE and a 640 MHz clock to derive it. For all those hits which arrived while the matrix is frozen, the timestamp is no more correlated with the time of arrival of the particle

Parameter	Value [DAC]	Value [μs]
START_FREEZE	64	1.6
STOP_FREEZE	100	2.5
START_READ	66	1.65
STOP_READ	68	1.7

Table 4.4: Default configuration of the R/O parameters

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

521 4.3.1 Dead time measurements

522 The hit loss is due to analog and digital pile up: the first one occurs when a new hit arrives during
 523 the pre-amplifier response, the second instead, which is the more relevant contribution, while the
 524 information of the previous hit has not yet been transferred to the periphery. As only one hit at
 525 a time can be stored on the pixel's RAM, until the data have completed the path to get out, the
 526 pixel is paralyzed and the dead time τ almost corresponds with the time needed to transmit the
 527 data-packets off-chip. Since the exportation of data from pixel to the EoC occurs via a 21-bits
 528 data bus, only one clock cycle is needed to transfer the data to the end of column and the dead time
 529 bottleneck is given by the bandwidth of the serializer at the EoC. In our setup it operates at 40
 530 MHz, thus to transmit a data packet (27-bit) at least 675 ns are needed. For what we have said so
 531 far, the R/O is completely sequential and therefore is expected a linear dependence of the reading
 532 time on the number of pixels to read:

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

533 where α and β are parameters dependent on the readout chain setting.

534 To measure and test the linearity of the reading time with the number of pixels firing, I have
 535 used the injection mode available on the chip. Indeed, the injection mode allows fixing not only
 536 the amplitude of the pulse, which corresponds to the charge in DAC units, but also the period and
 537 the width. I have injected a fix number of pulses (100) and looked for the rate when the efficiency
 538 decreases. Moreover to test that there is no dependence of the digital readout time from the charge
 539 of the pulse, I have tried to change the amplitude of the pulse injected, but the parameters found
 540 were consistent with the default configuration ones.

541 **Un esempio se leggo un singolo pixel: LA SLOPE CON CUI L'EFFICIENZA SCENDE È
 542 ABBSTANZA UNIFORME? perché satura a 50?**

543 While the single pixel reading time and the dead time do not depend on the position on the
 544 pixel matrix and are equal to 106 (46+60) clock counts within 1 clock count, on the other hand the
 545 τ depends on the pixel position on the matrix when more than one pixel are firing. In particular
 546 the priority chain goes from row 224 to row 0, and from col 0 to 112, that means the last pixels to
 547 be read is the one on the bottom right corner of the matrix.

548 In figure 4.11 is reported the reading time versus the number of pixels injected; the R/O
 549 parameters that control the reading time and their default values are reported on table ??.

550 The factor α , referring to eq. 4.3 is proportional to the difference (STOP_FREEZE - START_READ),
 551 while the offset β lies between 5 and 15 clock counts. Since through the injection a random hit rate
 552 on the matrix can't be simulated, as the coordinates of the pixels to inject must be specified, for
 553 convenience I used the pixels on the same column/row. No difference in the α and β coefficients
 554 has been observed between the two cases.

555 **A tutte le hit di una iniezione che arrivano contemporaneamente viene assegnato lo stesso
 556 timestamp; Risoluzione temporale??**

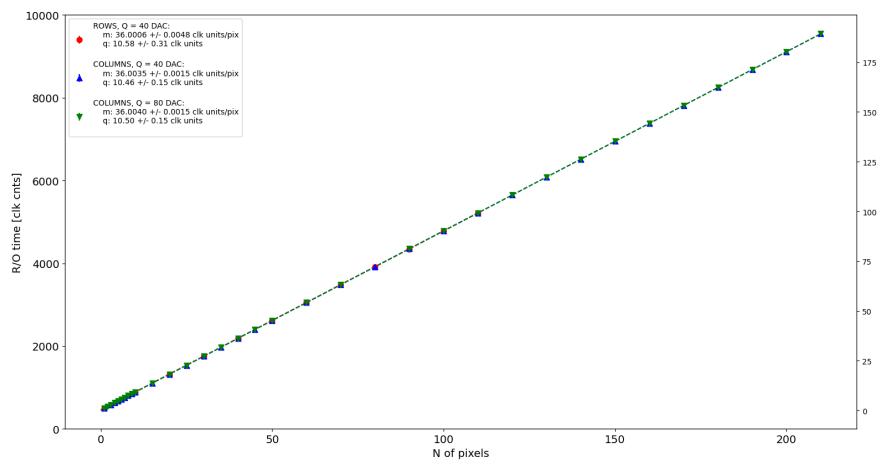


Figure 4.10

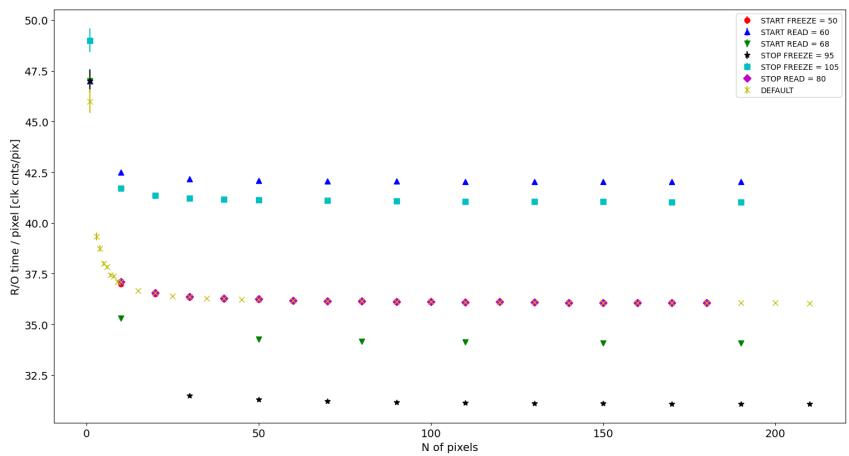


Figure 4.11

557 Chapter 5

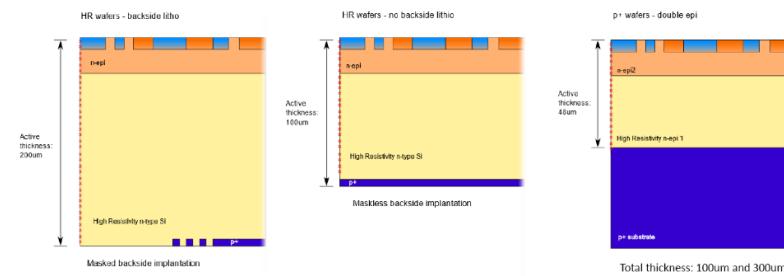
558 Arcadia-MD1

559 [10] [11]

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

562 5.1 The sensor

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



566 Figure 5.1

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

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

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

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

579 5.2 Readout logic and data structure

580 5.2.1 Matrix division and data-packets

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

583 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

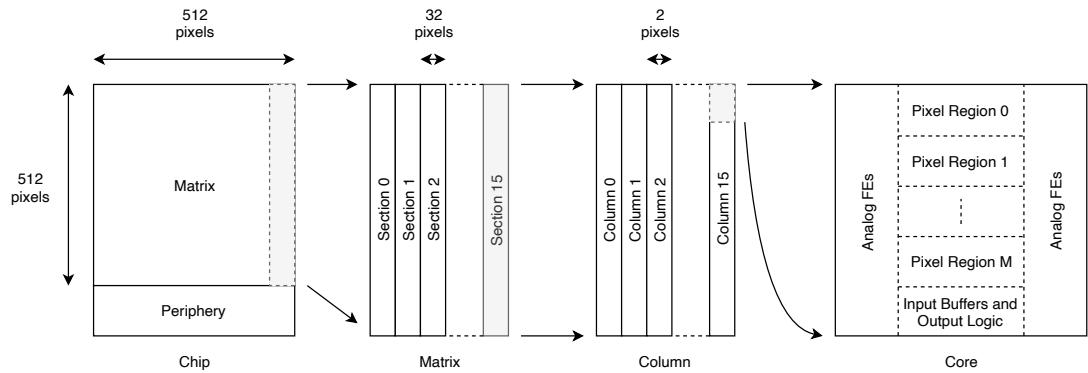


Figure 5.2

584

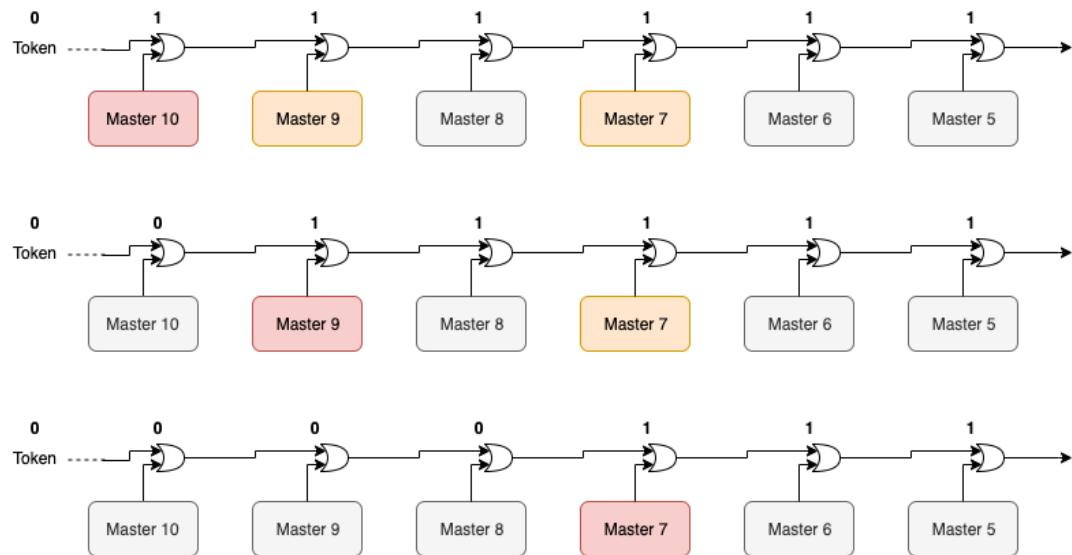


Figure 5.3

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

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

592

593 TABELLA: con la gerarchia del chip Matrix (512x512 pixels) Section (512x32 pixels) Column
594 (512x2) Core (32x2) Region (4x2)

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

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

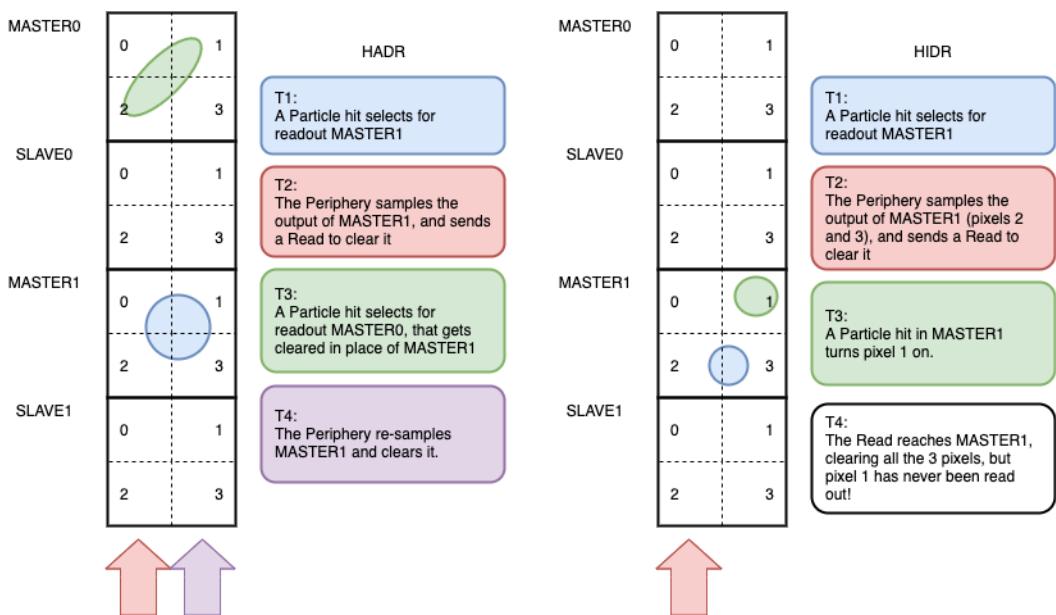


Figure 5.4

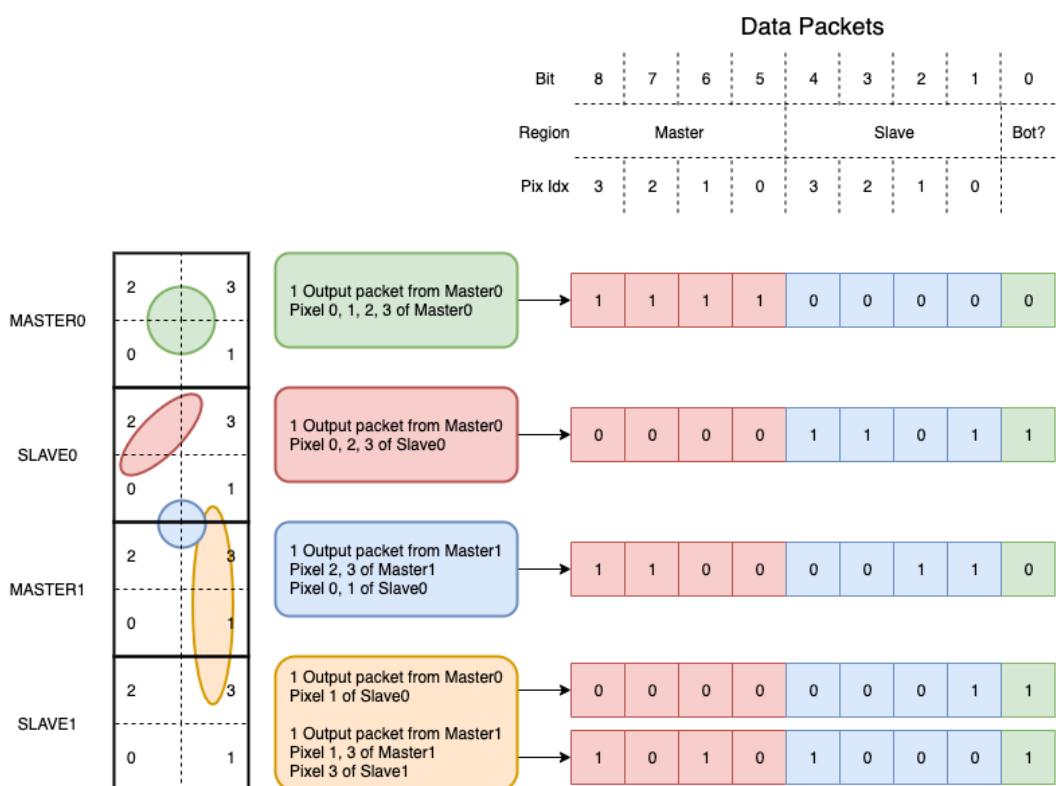


Figure 5.5

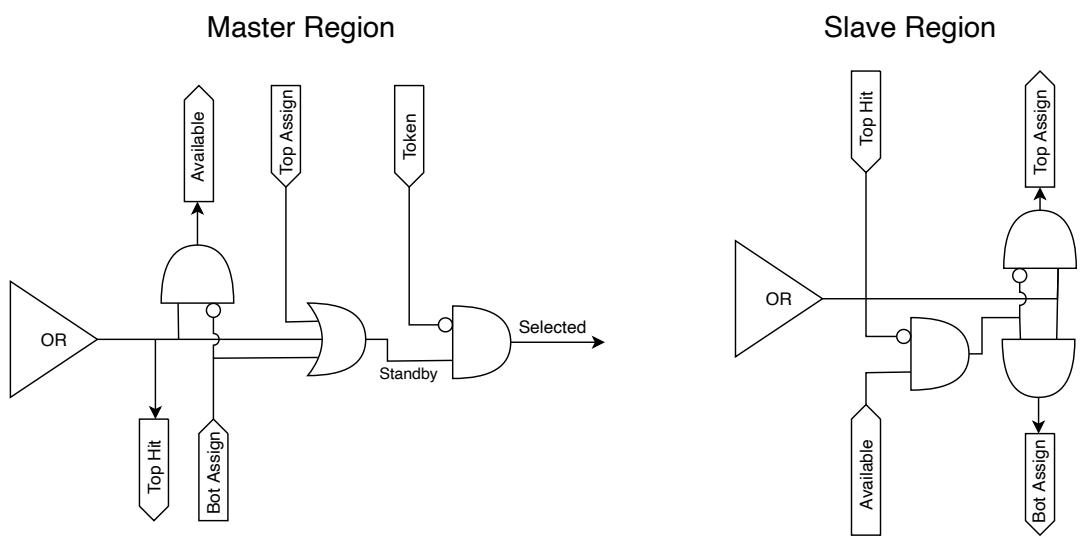


Figure 5.6

598 **Chapter 6**

599 **Threshold and noise
600 characterization**

601 **6.1 Threshold and noise: figure of merit for pixel detectors**

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

603
604 la soglia deve essere abb alta da tagliare il rumore ma abb bassa da non perdere efficienza.
605 Invece di prendere il rapporto segnale rumore prendi il rapporto segnale soglia. Perchè? la soglia
606 è collegato al rumore, nel senso che: supponiamo di volere un occupancy di 10-4 allora sceglierò la
607 soglia in base a questo. (plot su quaderno) Da questo conto trovo la minima soglia mettibile
608 In realtà quello che faccio è mettere una soglia un po' più grande perchè il rate di rumore dipende
609 da molti fattori quali la temperatura, l annealing ecc, e non voglio che cambiando leggermente uno
610 di questi parametri vedo alzarsi molto il rate di rumore. In realtà non è solo il rumore sensibile a
611 diversi fattori, ma anche la soglia: ad esempio la cosa classica è la variabilità della soglia da pixel
612 a pixel.

613 In questo modo rumore e soglia diventano parenti.

614 Review pag 26.

615 The noise requirement can be expressed as:

616 Questo implica tra le altre cose che voglio poter assegnare delle soglie diverse a diversi pixel:
617 Drawback è dare spazio per registri e quantaltro.

618 Questo lascia però ancora aperto il problema temporale delle variazioni del rumore: problema per
619 cui diventano necessarie le misure dei sensori dopo l'irraggiamento.

620
621 Per arcadia i registri (c'è un DAC) per la soglia (VCASN) si trovano in periferia. Non fare
622 trimming sulla soglia è uno dei problemi che si sono sempre incontrati: a casusa dei mismatch dei
623 transistor le soglie efficaci pixel per pixel cambiano tanto. La larghezza della s curve è il noise se se
624 assumi che il noise è gaussiano

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

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

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

628
629 Each ROIC is different in this respect, but in general the minimum stable threshold was around
630 2500 electrons (e) in 1st generation ROICs, whereas it will be around 500 e for the 3rd generation.
631 This reduction has been deliberate: required by decreasing input signal values. Large pixels (2 104
632 um²), thick sensors (maggiore di 200 um), and moderate sensor radiation damage for 1st generation
633 detectors translated into expected signals of order 10 ke, while small pixels (0.25 104 um²), thinner
634 sensors (100 um), and heavier sensor radiation damage will lead to signals as low as 2 ke at the
635 HL-LHC

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

₆₃₈ **6.2 TJ-Monopix1 characterization**

₆₃₉ **6.3 ARCADIA-MD1 characterization**

640 Chapter 7

641 **Test beam measurements**

642 Epitaxial layer thickness: più grande è e più carica viene depositata da una MIP, però devi fare
643 attenzione alla forma della zona svuotata perchè può portare ad un aumento della charge sharing
644 tra pixel vicini. Se il diodo è molto piccolo rischi che l'efficienza di collection è diminuita perchè
645 l'intensità del campo elettrico è più bassa intorno al diodo, e hai più charge sharing.

646 Possibilità di integrare carica sul pixel: due elettroni consecutivi su un pixel ogni quanto ar-
647 rivano? Fai il conto del tempo medio

649 Vogliamo sfruttare l'analog pile up, per fare questo dobbiamo fare attenzione a non finire nel
650 digital pile up Devi avere che il tot dell'elettrone (cioè MIP) è maggiore del deltat medio; in questo
651 caso potresti riuscire ad integrare carica.

652 Appendix A

653 Pixels detector: a brief overview

654 A.1 Radiation damages

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

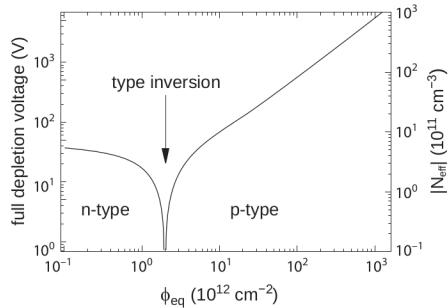
660 The first one has a principal non ionizing nature, due to a non ionizing energy loss (NIEL), but
 661 it is related with the dislocation of the lattice caused by the collision with nuclei; by this fact the
 662 NIEL hypothesis states that the substrate damage is normalized to the damage caused by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

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

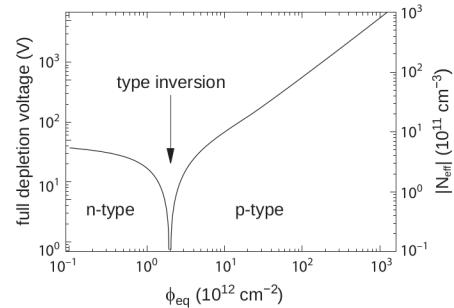
670 Let's spend instead two more other words on the more-relevant substrate damages: the general
 671 result of high radiation level is the creation of new energy levels within the silicon band gap and
 672 depending on their energy-location their effect can be different, as described in the Shockely-Read-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

675 **Changing of the effective doping concentration:** is associated with the creation/removal
 676 of donors and acceptors center which trap respectively electrons/holes from the conduction band
 677 and cause a change in effective space charge density. Even an inversion (p-type becomes n-type¹)
 678 can happen: indeed it is quite common at not too high fluences ($\phi_{eq} 10^{12-13} n_{eq} cm^{-2}$). A changing
 679 in the doping concentration requires an adjustment of the biasing of the sensor during its lifetime
 680 (eq.2.1) and sometimes can be difficult keeping to fully deplete the bulk.

¹L'INVERSIONE OPPOSTA NON CE L'HA PERCHÈ?



(a) 1a



(b) 1b

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

684 **Increase of trapping probability:** since the trapping probability is constant in the depleted
685 region, the collected charge decreases exponentially with the drift path. The exponential coefficient,
686 that is the mean trapping path, decreases after irradiation and typical values are 125-250 μm and
687 must be compared with the thickness of the depleted region which () corresponds to the mean drift
688 path.

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

697 Appendix B

698 FLASH radiotherapy

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

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

705 Un problema dei fotoni ad esempio è che il loro rilascio di dose è lineare, per cui danneggia
706 anche i tessuti sani. Il problema dei protoni invece è che hanno un picco troppo stretto per cui non
707 puoi coprire grosse zone e soprattutto se sbagli rischi davvero di danneggiare molto i tessuti sani.
708

710 B.1 Cell survival curves

711 Curva di efficacia del trattamento in funzione della dose:

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

712 dove $F(D)$

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

713 dove α e β 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.

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

721 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)

724 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:

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

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

726 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
727 Una scelta bilanciata si applica guardando a questi due fattori; si usa il therapeutic index definito
728 come TCP/NTCP.

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

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

733 Nell Intra operative radiation therapy (IORT), where they reach values respectively about 20 and
734 100 times greater than those of conventional radiation therapy.

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

737

739 **B.2 FLASH effect**

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

741

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

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

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

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

748

⁷⁴⁹ Bibliography

- 750 [1] W. Snoeys et al. “A process modification for CMOS monolithic active pixel sensors for
751 enhanced depletion, timing performance and radiation tolerance”. In: (2017). DOI: <https://doi.org/10.1016/j.nima.2017.07.046>.
- 753 [2] H. Kolanoski and N. Wermes. *Particle Detectors: Fundamentals and Applications*. OXFORD
754 University Press, 2020. ISBN: 9780198520115.
- 755 [3] E. Mandelli. “Digital Column Readout Architecture for the ATLAS Pixel 0.25 um Front End
756 IC”. In: (2002).
- 757 [4] M. Garcia-Sciveres and N. Wermes. “A review of advances in pixel detectors for experiments
758 with high rate and radiation”. In: (2018). DOI: <https://doi.org/10.1088/1361-6633/aab064>.
- 760 [5] M. Dyndal et al. “Mini-MALTA: Radiation hard pixel designs for small-electrode monolithic
761 CMOS sensors for the High Luminosity LHC”. In: (2019). DOI: <https://doi.org/10.1088/1748-0221/15/02/p02005>.
- 763 [6] M. Barbero. “Radiation hard DMAPS pixel sensors in 150 nm CMOS technology for opera-
764 tion at LHC”. In: (2020). DOI: <https://doi.org/10.1088/1748-0221/15/05/p05013>.
- 765 [7] K. Moustakas et al. “CMOS Monolithic Pixel Sensors based on the Column-Drain Architec-
766 ture for the HL-LHC Upgrade”. In: (2018). DOI: <https://doi.org/10.1016/j.nima.2018.09.100>.
- 768 [8] I. Caicedo et al. “The Monopix chips: depleted monolithic active pixel sensors with a column-
769 drain read-out architecture for the ATLAS Inner Tracker upgrade”. In: (2019). DOI: <https://doi.org/10.1088/1748-0221/14/06/C06006>.
- 771 [9] D. Kim et al. “Front end optimization for the monolithic active pixel sensor of the ALICE
772 Inner Tracking System upgrade”. In: *JINST* (2016). DOI: doi:10.1088/1748-0221/11/02/
773 C02042.
- 774 [10] L. Pancheri et al. “A 110 nm CMOS process for fully-depleted pixel sensors”. In: (2019). DOI:
775 <https://doi.org/10.1088/1748-0221/14/06/c06016>.
- 776 [11] L. Pancheri et al. “Fully Depleted MAPS in 110-nm CMOS Process With 100–300-um Active
777 Substrate”. In: (2020). DOI: 10.1109/TED.2020.2985639.