4D tracking – sensors with internal gain

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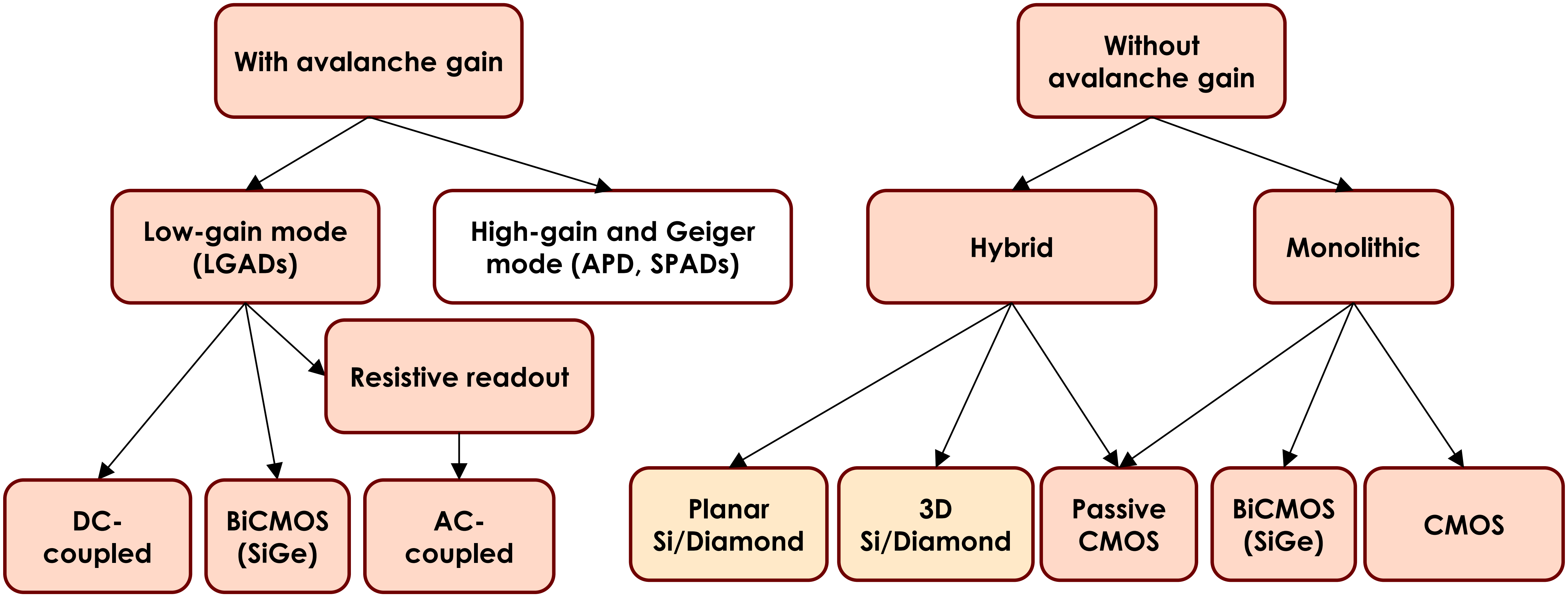
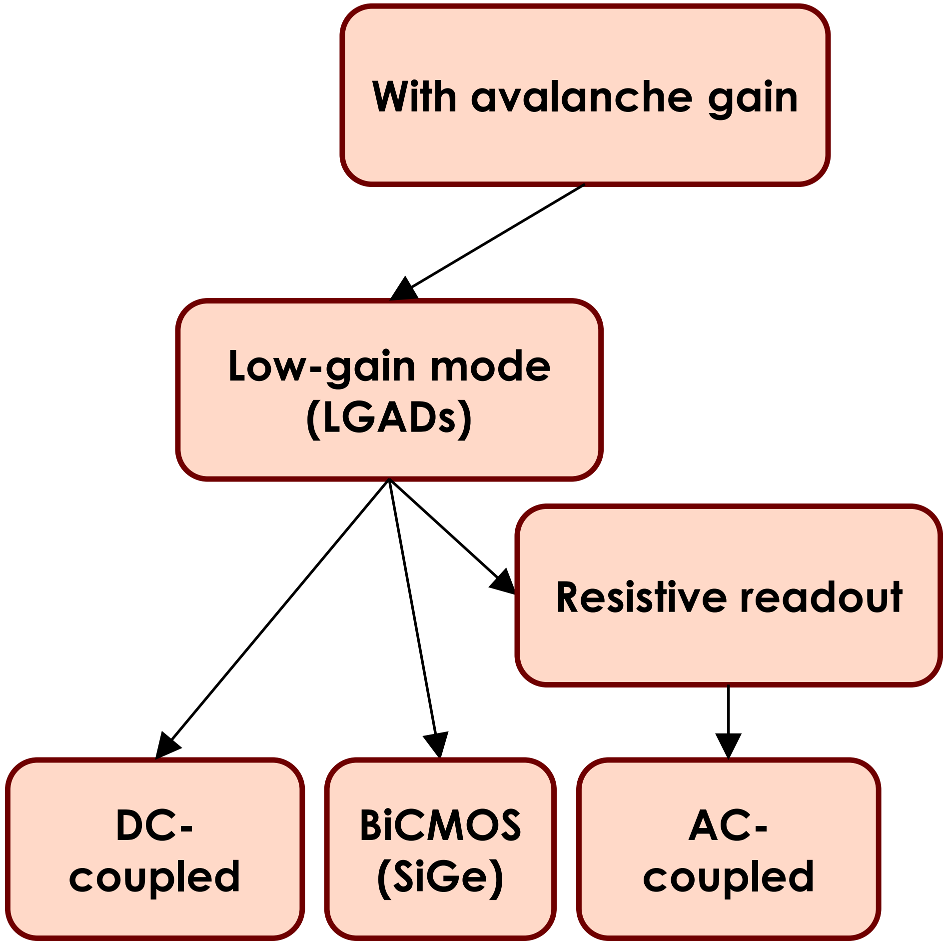
Sensors for future trackers



4D tracking – sensors with internal gain



First design innovation: low gain avalanche diode (LGAD)

==> ~ 20 gain, thin sensors, large signals, large dV/dt

- Excellent timing resolution (~ 30 ps), not so good spatial resolution (pixel/sqrt(12))

Second design innovation: resistive read-out (joining RPC, GEM..)

==> Spread the signal over many pads while maintaining good efficiency (due to internal gain)

- Excellent position and timing resolutions (<5 um, ~ 30 ps)

4D tracking – options

By "**4D tracking**" we mean the process of assigning a space and a time coordinate to a hit.

Timing can be available at different levels of the event reconstruction:

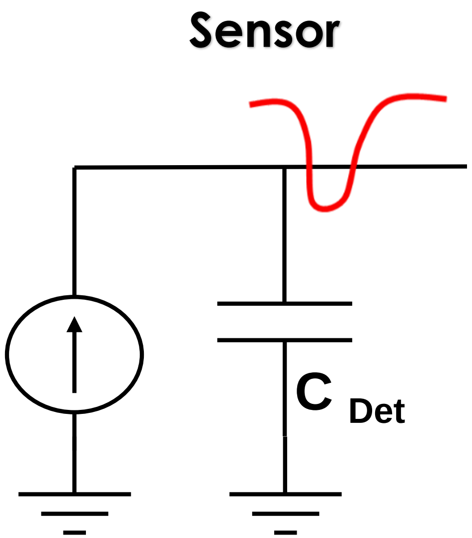
1) Timing in a single point (timing layer ATLAS,CMS)
2) Timing at some points along the track
3) Timing at each point along the track

We are just at the beginning of this path

4D tracking: Sensor – ASIC interaction

- **Sensors produce a current pulse**
- **ASICs measure the time of arrival**

==> Sensors and ASICs are two parts of a single object



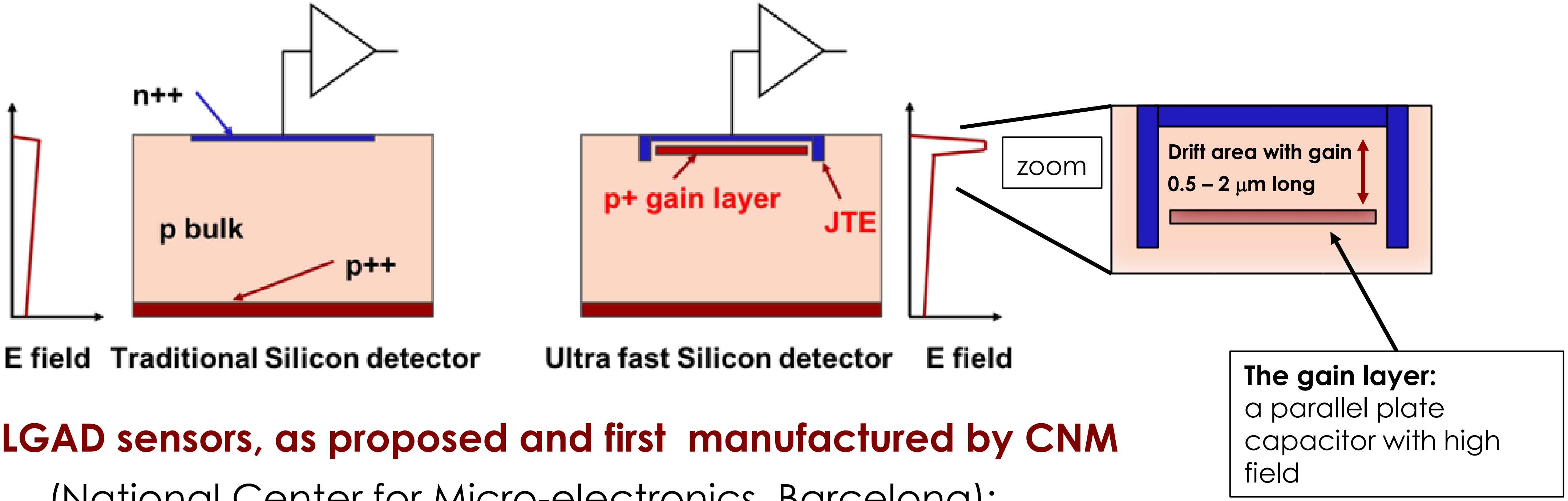
Optimization of 4D tracking can only happen with a very strong collaboration between the two community.

Future developments need to be done by desiging the sensors and the ASIC together

In timing circuits "things can go wrong very rapidly" (quote from a wise ASIC designer),

==> this is not a simple evolution of what we know how to do.

First design innovation: low gain avalanche diode



The LGAD sensors, as proposed and first manufactured by CNM

(National Center for Micro-electronics, Barcelona):

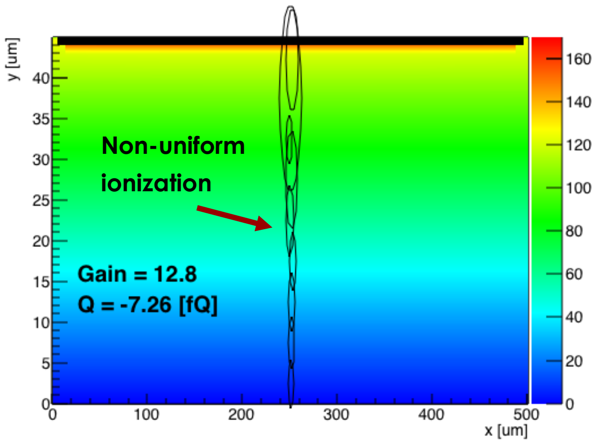
High field obtained by adding an extra doping layer

E ~ 300 kV/cm, closed to breakdown voltage

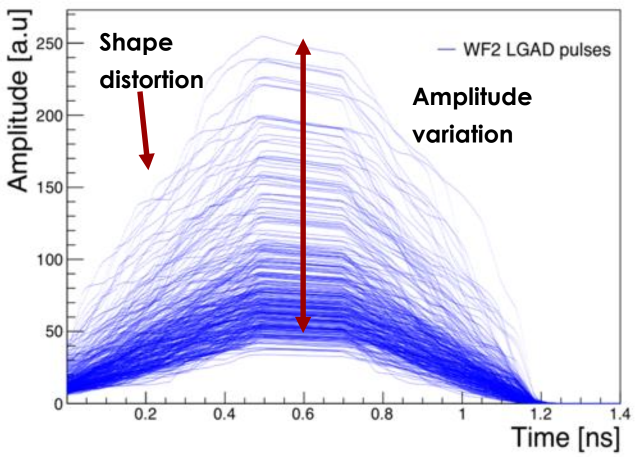
The low-gain mechanism, obtained with a moderately doped p-implant, is the defining feature of the design.

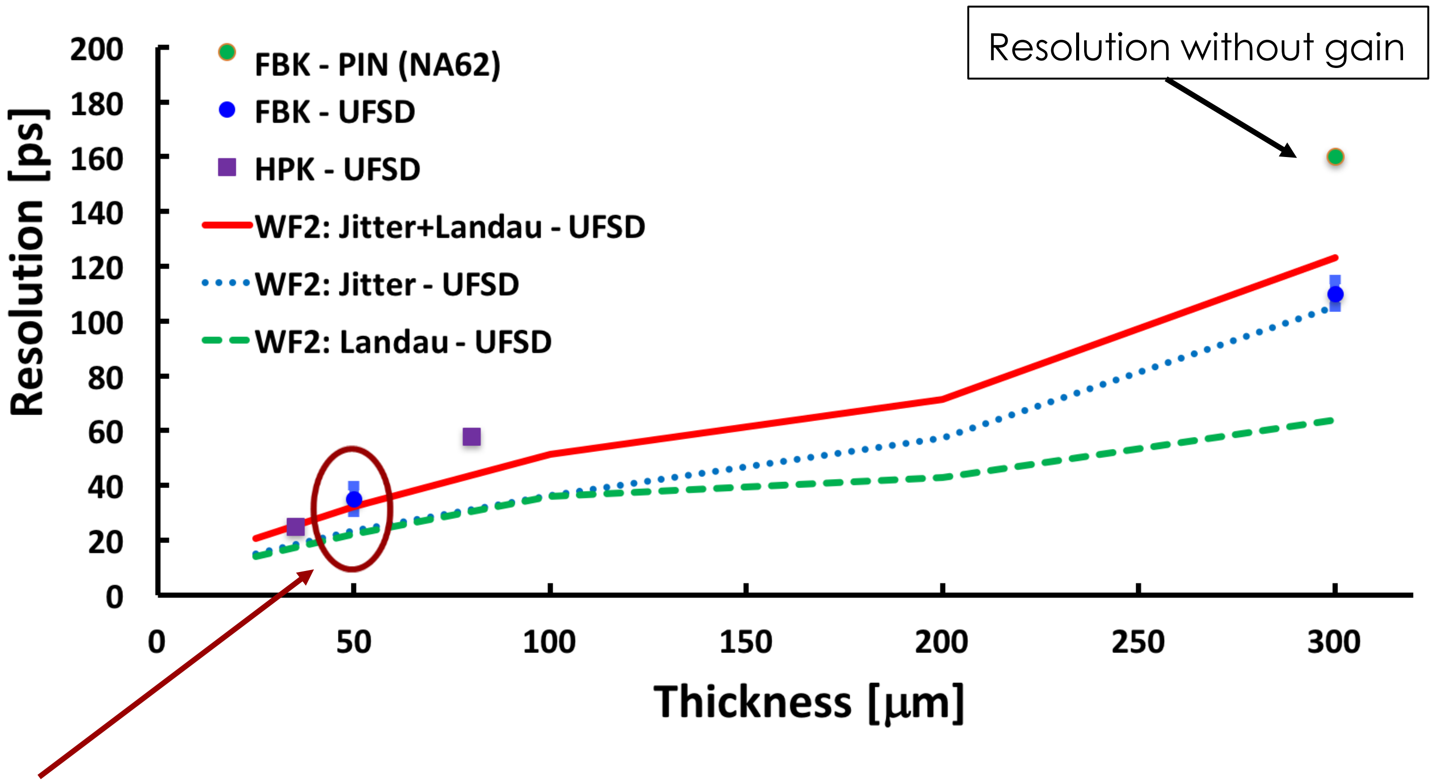
Summary of LGAD temporal resolution

Physical limit:
non uniform signal shape



Simulation of signals in 50-um RSD





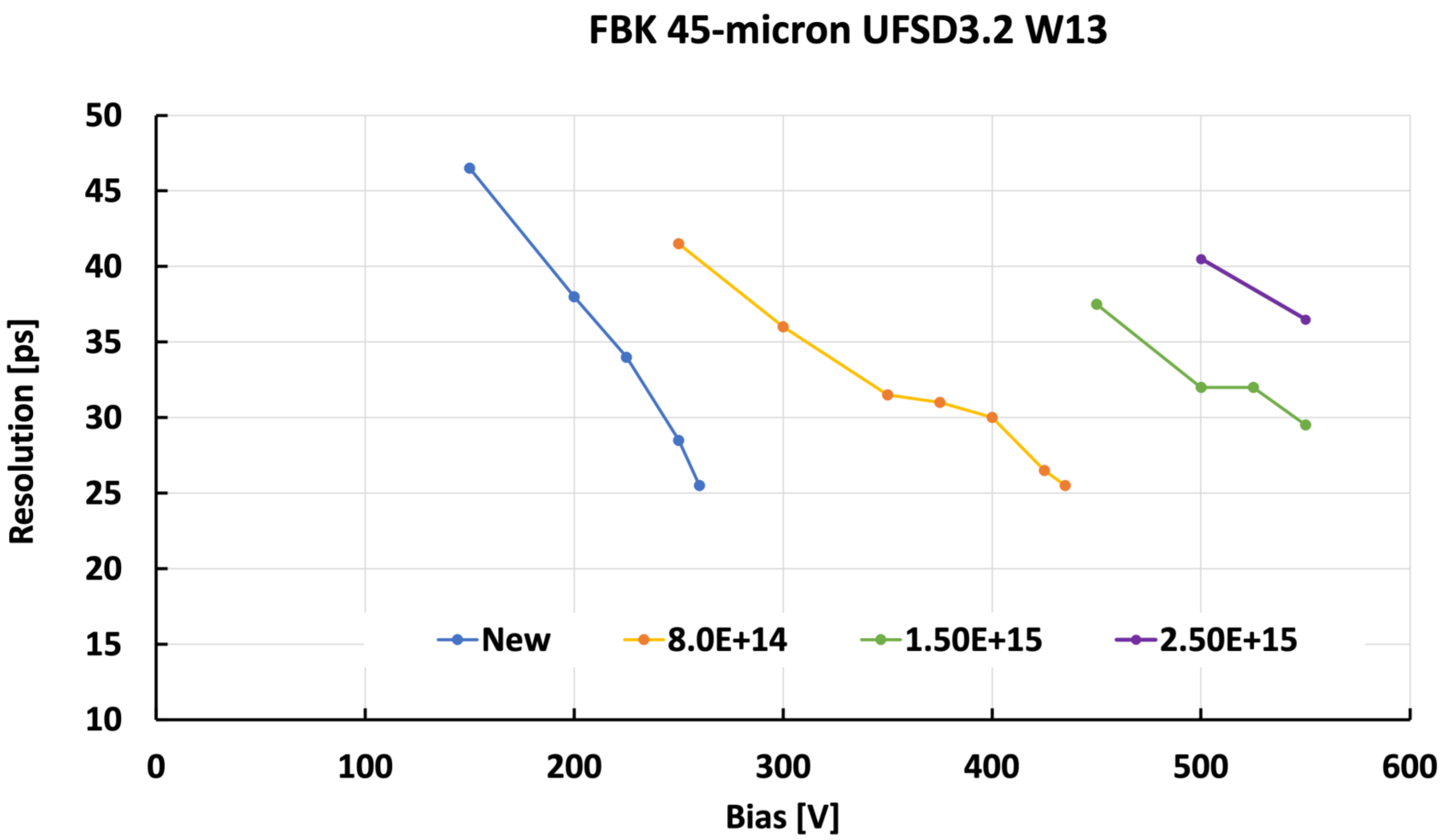
There are now hundreds of measurements on 45-55 μm-thick UFSDs

➔ Current sensor choice for the ATLAS and CMS timing layers

LGAD radiation hardness

Evolution with radiation of the biasing working point for a 45-micron thick LGAD with a carbonated gain layer

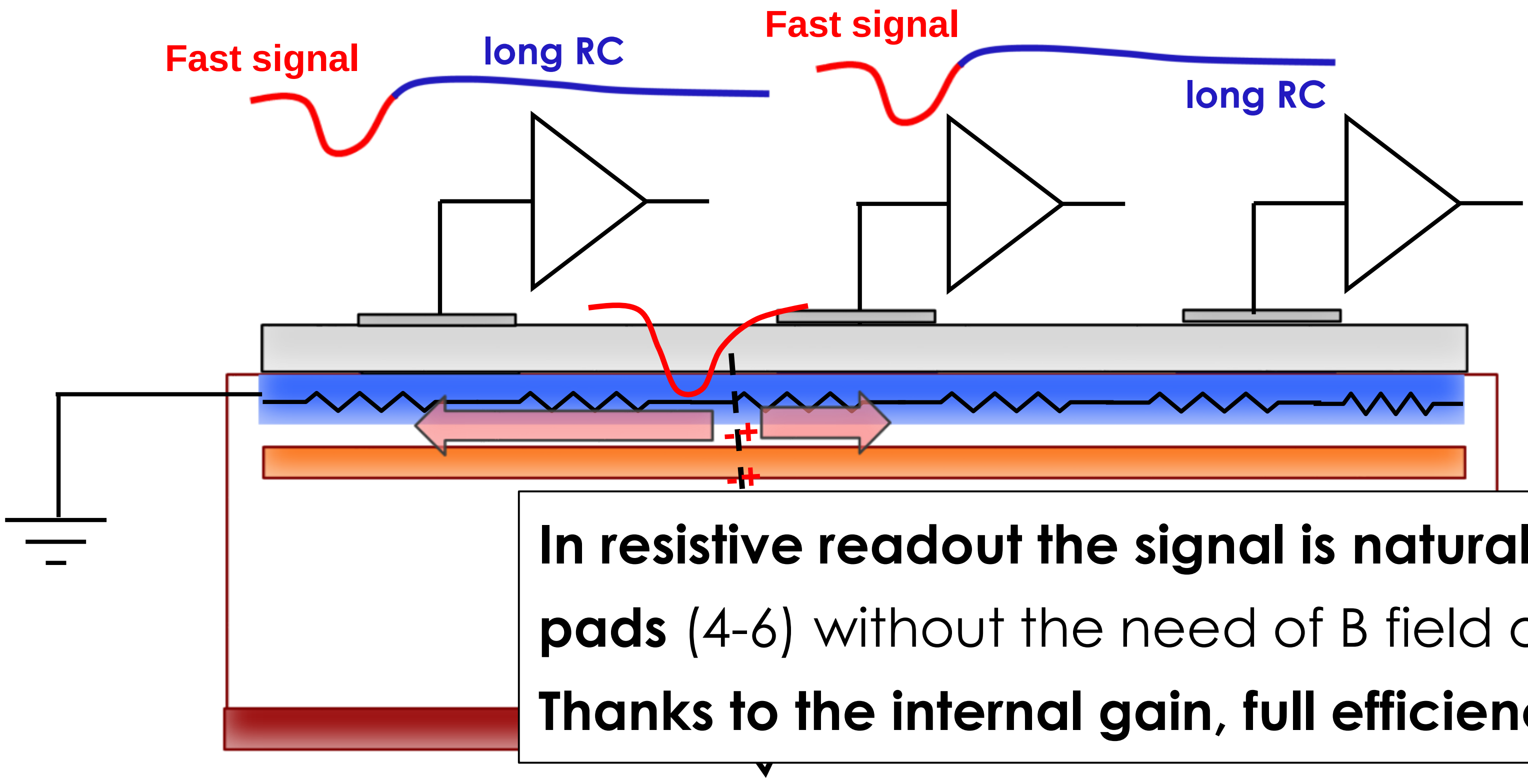
Increase bias to compensate for gain implant doping deactivation.



Present LGAD designs provide large signals and low noise up to 2.5E15 n/cm2

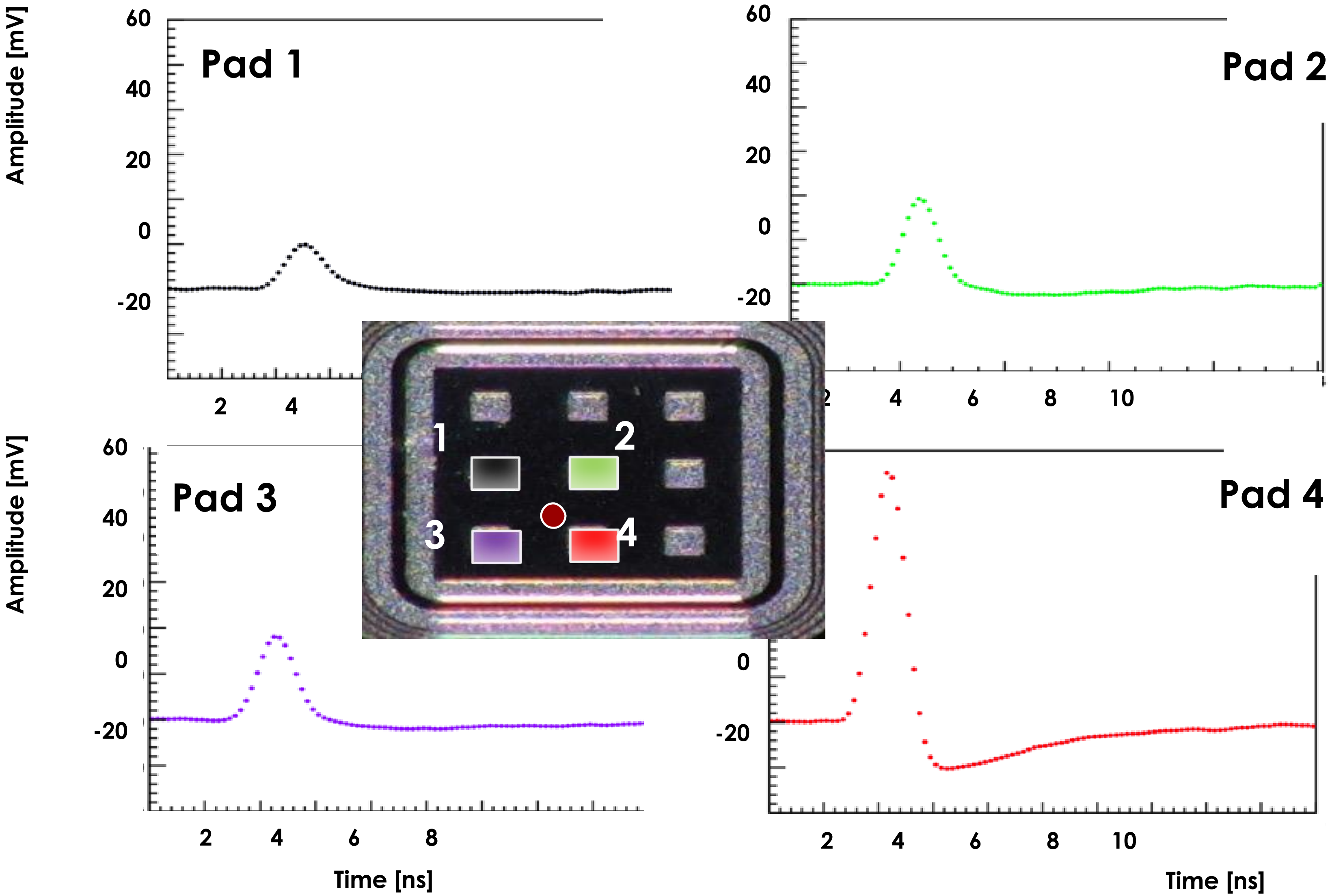
Second design innovation: resistive read-out

- The signal is formed on the n+ electrode ==> no signal on the AC pads
- The AC pads offer the smallest impedance to ground for the fast signal
- The signal discharges to ground



In resistive readout the signal is naturally shared among pads (4-6) without the need of B field or floating pads
Thanks to the internal gain, full efficiency even with sharing

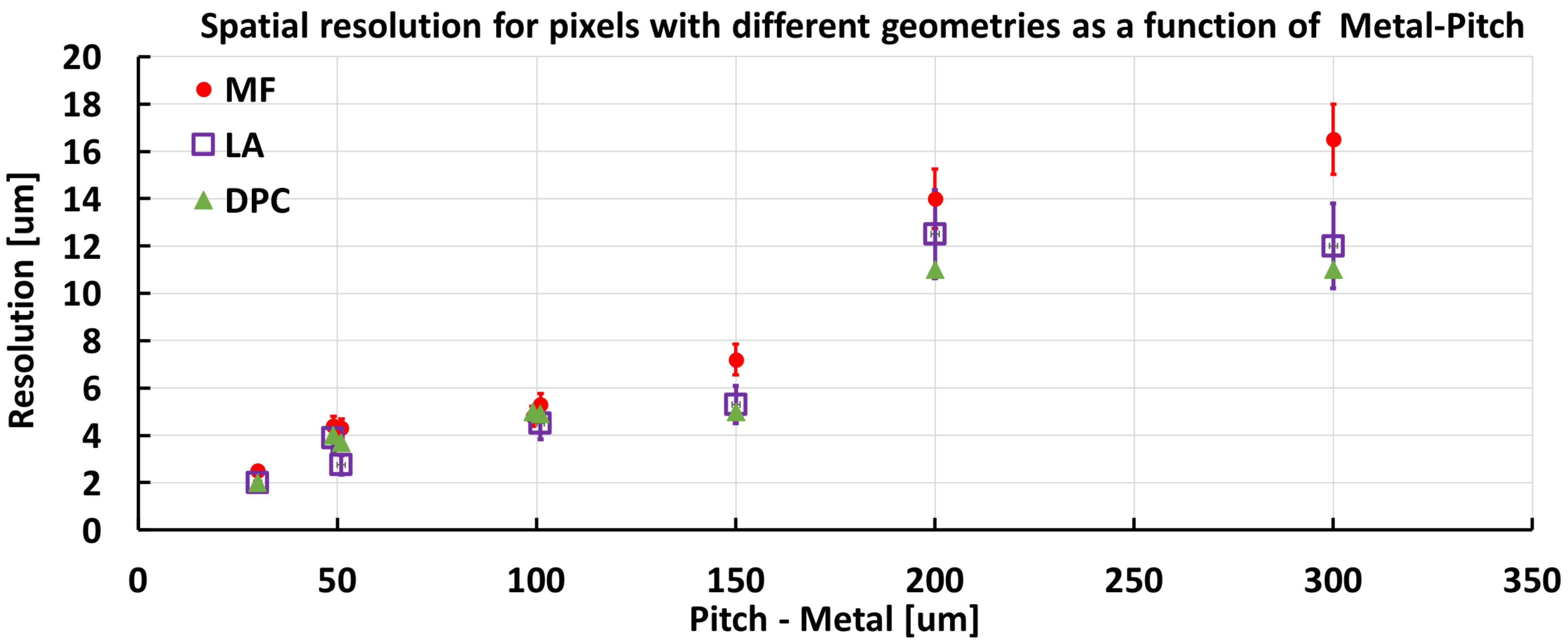
Example of a signal in an RSD



50-mm thick RSD,
Gain ~ 20

The laser is shot at the position of the magenta dot: the signal is seen in 4 pads

Summary of RSD position resolution



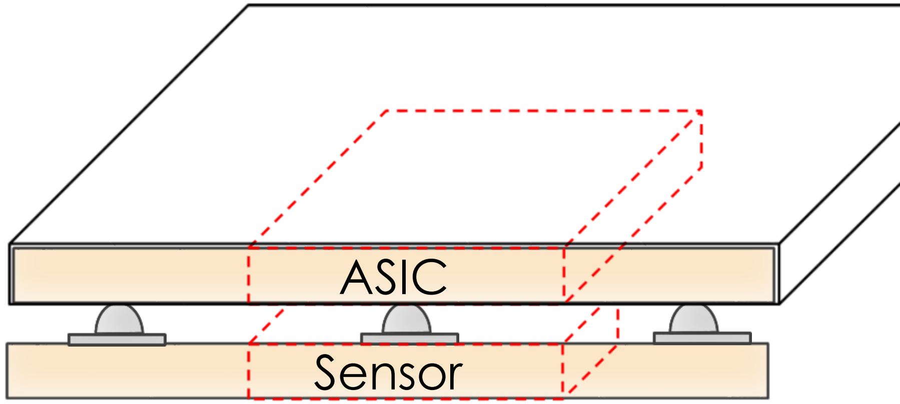
RSDs reach a spatial resolution that is about 5% of the inter-pad distance

➔ ~ 5 μm resolution with 150 μm pitch

RSDs have the "usual" LGAD temporal resolution of 30-40 ps

ASIC for RSD

Very important point: in hybrid technology (sensor bump-bonded to the ASIC), **the area available for each read-out channel is identical to the pixel area**

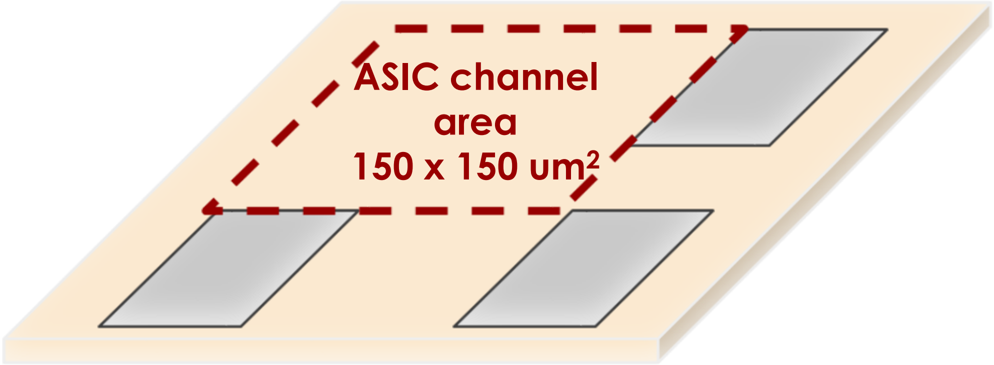


Assuming a goal of ~ 5 μm spatial resolution,
the RSD pitch can be 150-200 μm

➔ At least a factor of 10-20 more space than using binary readout

➔ Can concentrate the power available for that area into a single channel

➔ The needed circuits for timing might actually fit

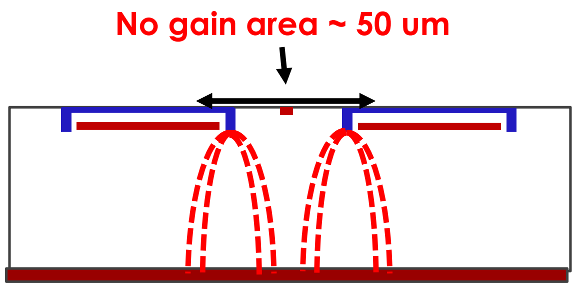


Manufacturers: a pretty large pool

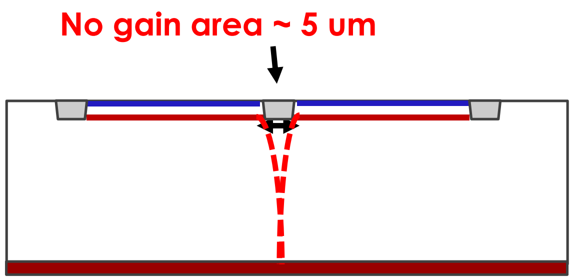
Red: Research Institutions
Blue: large commercial manufacturers

Producer	LGAD	RSD	Funding Source	Collab. Institute	Projects
CNM Barcelona (Spain) RD50 member	Doping Radiation Arrays Carbon, Gallium	Time Resolution	Spanish Ministr. RD50 (DoE R&D) AIDA, AIDAInnova	IFAE RD50 IFCA	ATLAS HGTD CMS-ETL
FBK Trento (Italy) RD50	Radiation Carbon Isolation	Geometry Spatial & Time Resolution.	INFN, ERC, AIDA, AIDAInnova RD50 (DoE R&D)	INFN Torino RD50	ATLAS HGTD CMS-ETL
Micron (UK)	Small Pixels		UK Science Council	Glasgow U.	X-ray Diamond
HPK (Japan)	Doping , Thickness Radiation, Arrays	Time Resolution	(DoE R&D) BNL ATLAS CMS	UCSC KEK	ATLAS HGTD & CMS-ETL Collaboration
BNL, (US) RD50 member		Time Resolution	DoE LDRD	BNL, FNAL UCSC	EIC
NDL (China)	8"		Chinese Gov	IHEP	ATLAS HGTD
IME (China)	8"		CAS	USTC	ATLAS HGTD
T-e2v	Time Resolution		STFC	Birmingham, Oxford, RAL	

Present results & short term evolutions - I



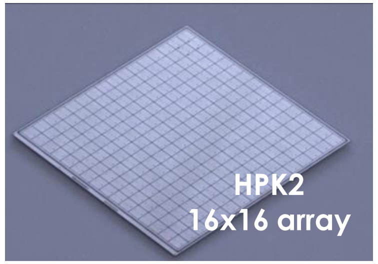
JTE + p-stop design



Trench-isolated design

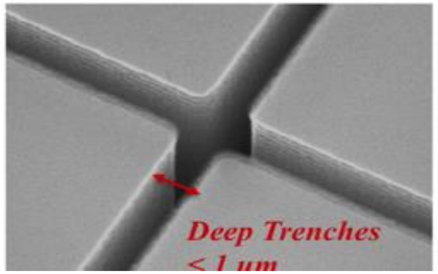
JTE/p-stop LGAD

- CMS && ATLAS choice
- Signal in a single pixel
- Not 100% fill factor
- Very well tested
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness ~ 1-2E15 n/cm2

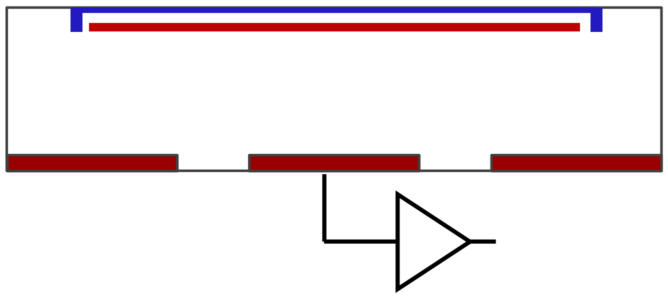


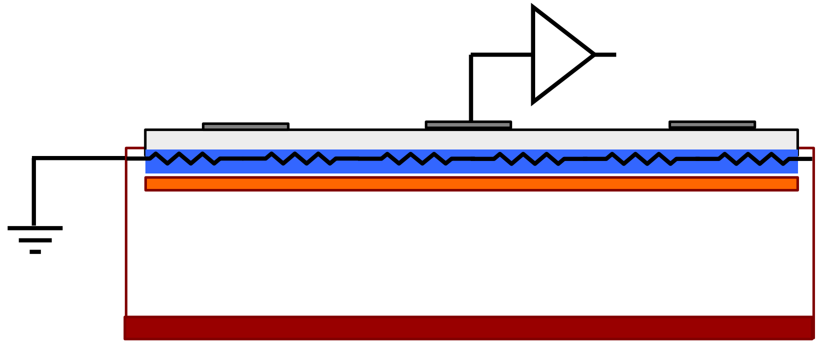
LGAD evolution: use trenches

- Signal in a single pixel
- Almost 100% fill factor
- Temporal resolution (50 μm) : 35-40 ps
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness: to be studied



Present results & short term evolutions - II



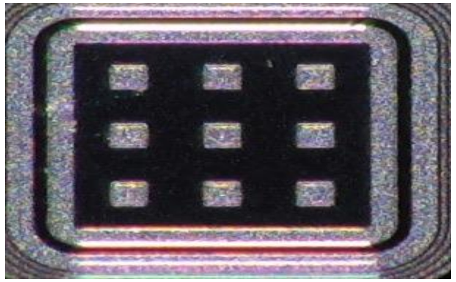


i-LGAD

- p-side segmentation
- Signal in a single pixel
- 100% fill factor
- Thin i-LGAD with single side processing under development (using trenches, spring 2021 @ CNM)
- High Occupancy OK
- Rate ~ 50-100 MHz
- Rad hardness: to be studied

RSD: resistive readout

- Signal in many pixels
- 100% fill factor
- Excellent position resolution:
  ~ 5 μm with large pixels
- Temporal resolution (50 μm) : 35-40 ps
- Rate ~ 10-50 MHz
- Rad hardness: to be studied



Contacts and future projects

In the recent past, many experiments have expressed interests in pursuing R&D projects on fast timing

Existing experiments:

- ALICE3
- CMS LS3
- NA62++
- LHC-b
- HADES

Future projects

- FCC-ee,
- CLIC,
- FCC-hh,
- μ-μ collider

Despite this large group of experiments, there is not a coordinated effort yet on 4D tracking. Each experiment does its own R&D

For the sensors: RD50 is the focal point

4D tracking in the far future - I

Dead area:

- **Now: 50-80 μm between pads**
- most likely it will become very small, <5 μm

Production yield:

- **Now: maximum sensor dimensions are ~ 3x3 cm^2**
- it will increase with experience, maybe even to the full 10x10 cm^2
- Foundries might switch to 8" and dramatically increase productivity

Radiation hardeness :

- **Now: ~ 2E15 n_{eq}/cm^2**
- Difficult to say, a possible hard limit on the safe bias voltage (10V/μm) might reduce possible improvements. Near goal: ~ 5E15 n_{eq}/cm^2

4D tracking in the far future - II

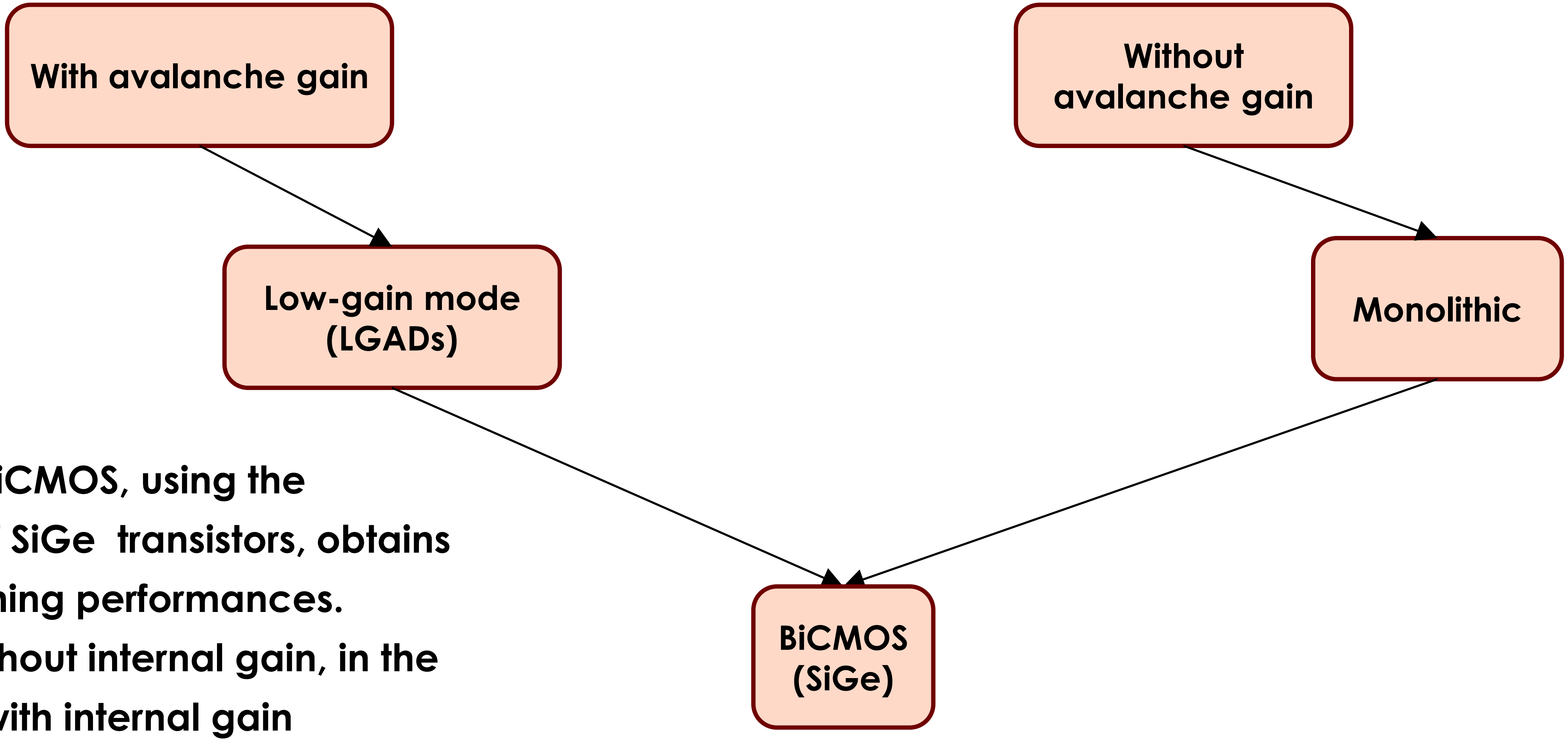
Timing resolution:

- **Now: 30 ps for 50 μm thick sensor**
- Thinner LGAD do better, but the signal charge is less.
- The improvements will depend on the ASIC more than on the sensor.

Spatial resolution:

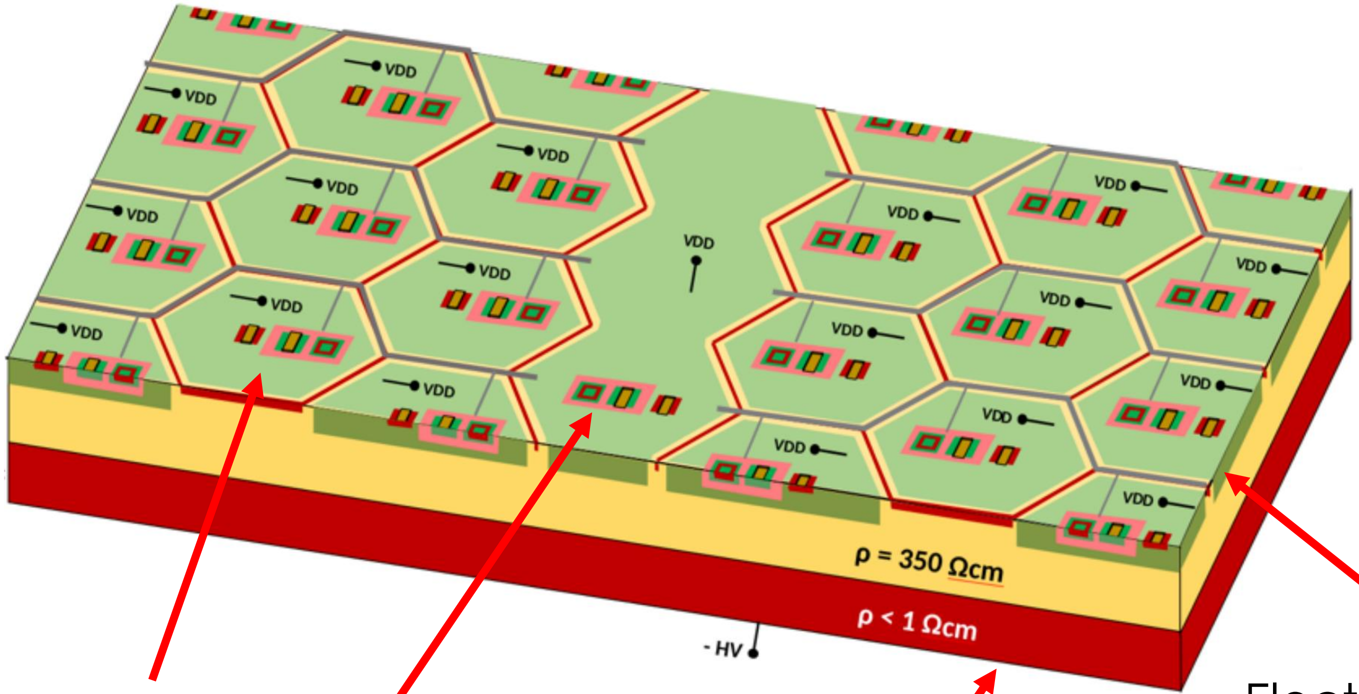
- **Now: < 5 μm in RSD, ~ 100' μm in LGADs**
- LGAD have a resolution of pixel/sqrt(12).
- Very difficult to measure accurately time in very small pixels.
- Resistive read-out has an extraordinary position resolution with large pixels ==> only for low occupancy experiments

Another possible future: the BiCMOS way



Monolithic BiCMOS, using the properties of SiGe transistors, obtains excellent timing performances. Presently without internal gain, in the near future with internal gain

Monolithic design for 4D tracking (FASER)



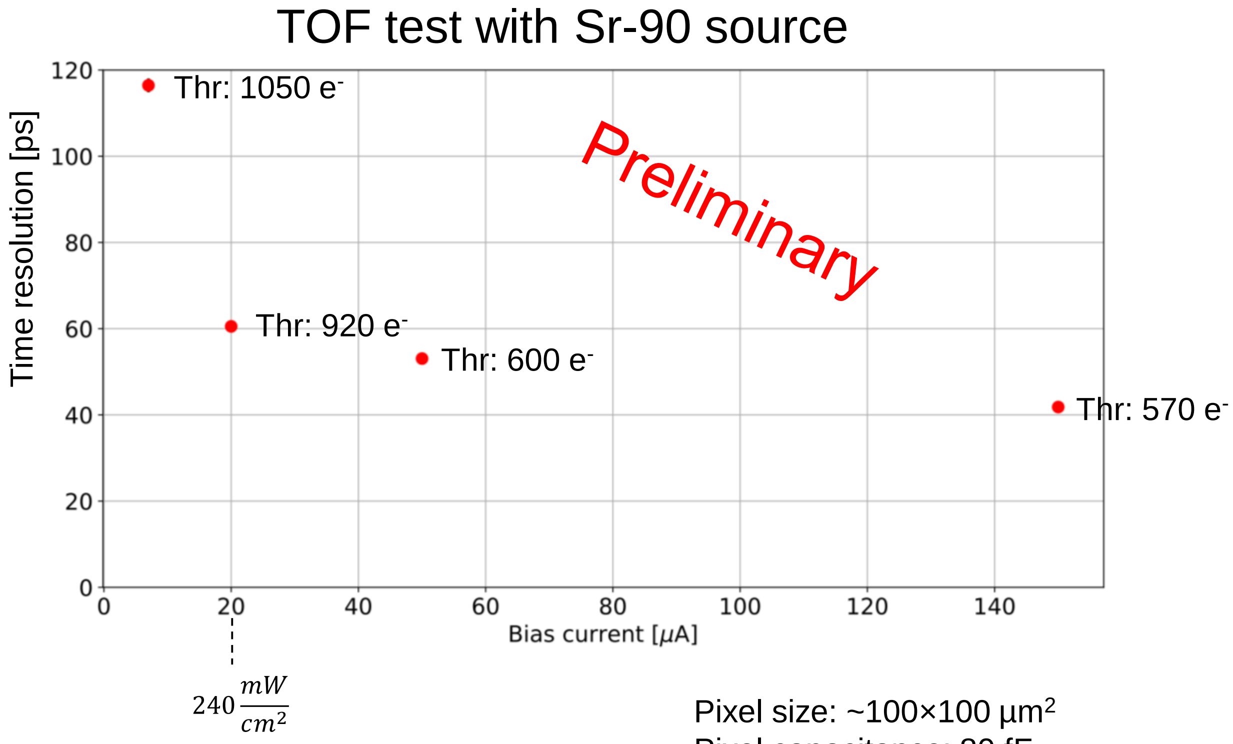
Isolated HBT for signal amplification.

Analogue electronics in pixel, digital electronics in a separate deep-nwell to improve noise robustness.
>95% fill factor.

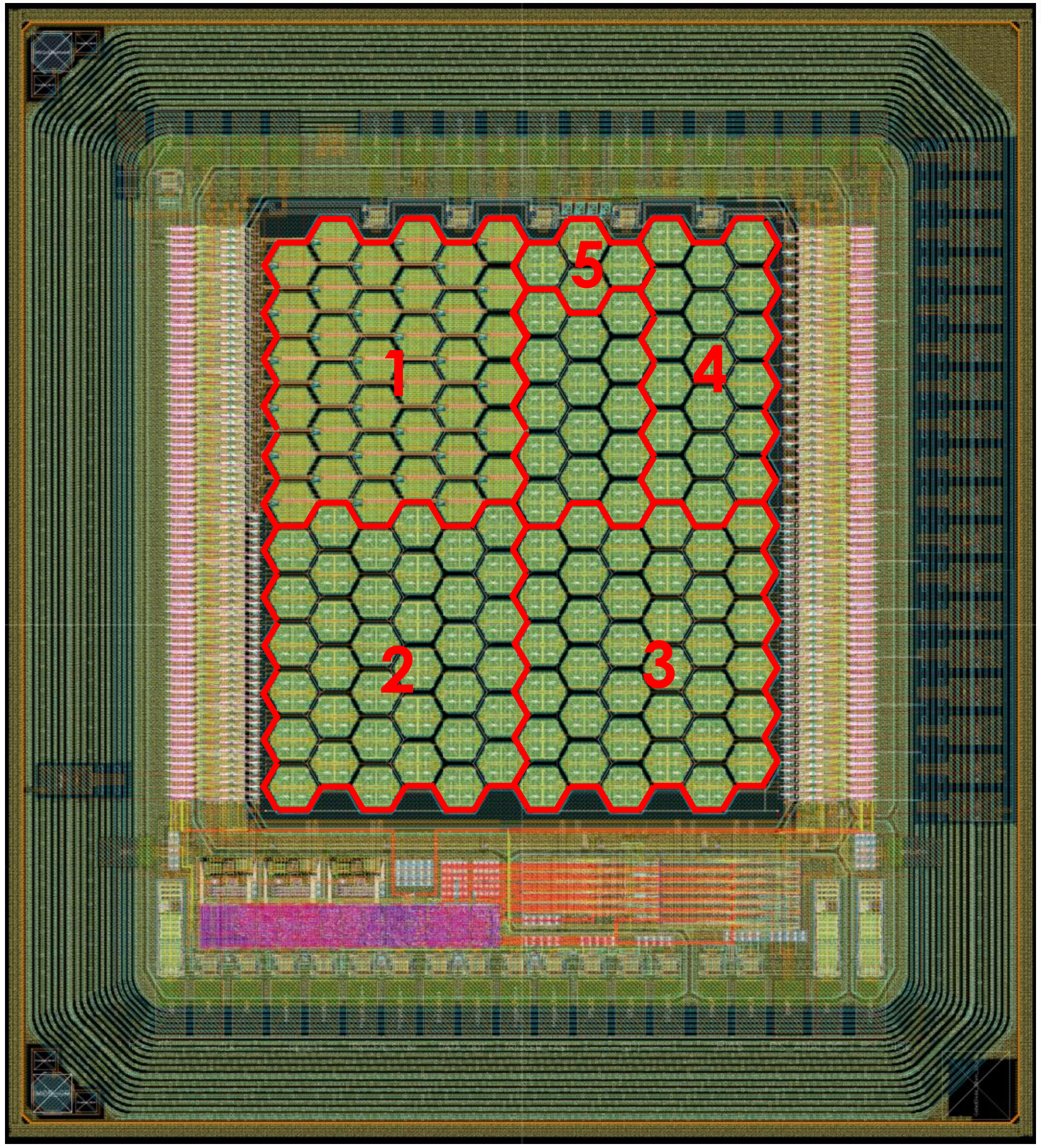
Negative High Voltage applied to the heavily p-doped substrate.

Electronics inside the guard-ring, isolated from substrate using deep n-well.

Prototype chip in SiGe BiCMOS



Pixel size: ~100×100 μm^2
Pixel capacitance: 80 fF
MPV input charge: 0.25 fC
No cut on data



R&D in progress at the University of Geneva

MONOLITH Project:

- ERC advanced for the development of monolithic silicon pixel sensors in SiGe BiCMOS with picosecond time resolution. Sensor design based on PicoAD concept of the University of Geneva.

FASER :

- SNSF project to build of a new pre-shower module for FASER experiment at LHC based on monolithic pixels in SiGe BiCMOS with very large dynamic range, 100 µm pixel size and 100ps time resolution.

100 µPET:

- SNSF project to build a small animal PET scanner with 100 µm resolution based on monolithic silicon pixel sensors in SiGe BiCMOS.

Conclusions

- 4D tracking based on internal gain is a very young development
- Presently, the first 2 large timing layers are being built
- Intense R&D in many aspects, many new experiments are planning to have a flavor of 4D tracking
- Possible to achieve excellent position and time resolutions
- Each experiment is different in term of requirements (material budget, fluence, resolutions, etc): there is not a fit-all design

Very difficult to improve from 30 ps to 10 ps per hit