Potential of Thin Film Detectors

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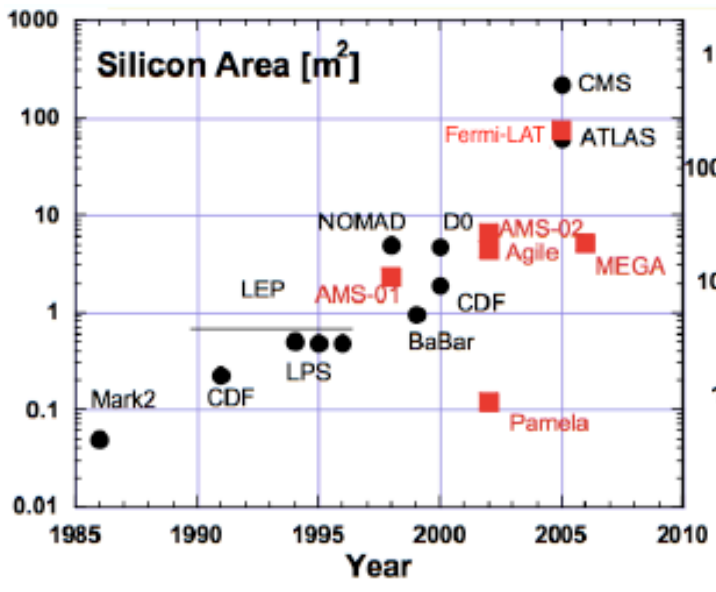
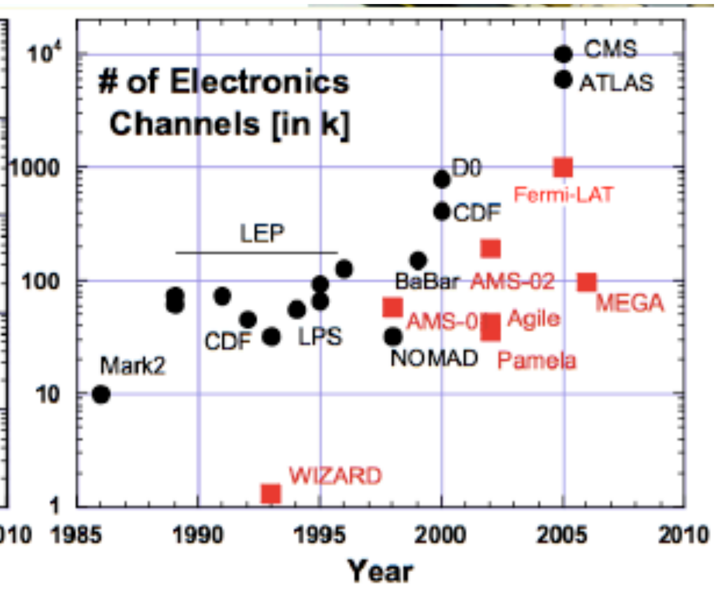
Motivation

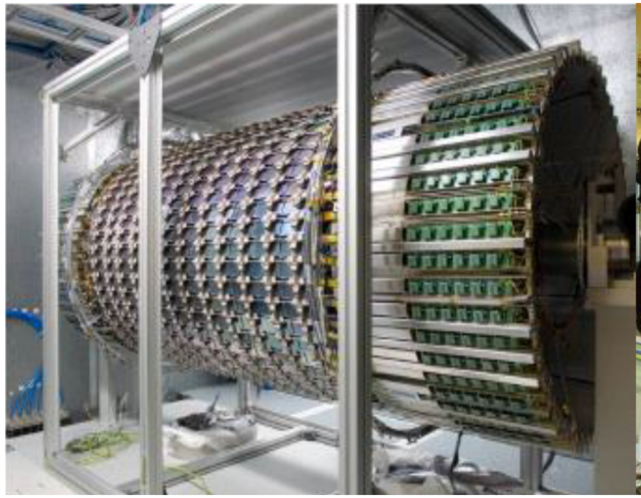
Silicon detectors are a cornerstone of High Energy Physics

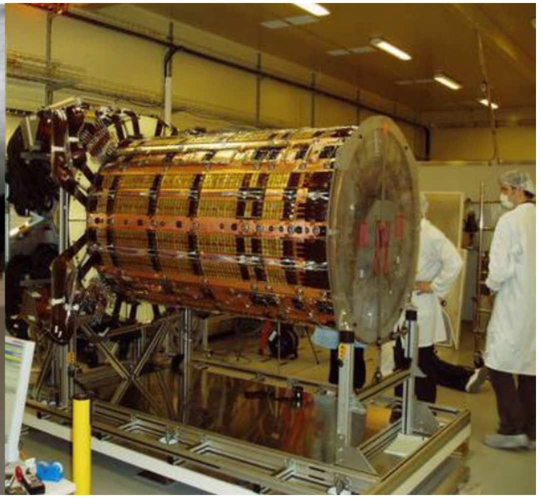
Larger fractions of detectors are made with silicon
- More layers for precise tracking
- Limiting factor is often the cost
- Shift toward high precision silicon calorimeters

Can we come up with an alternative that might have an advantage?





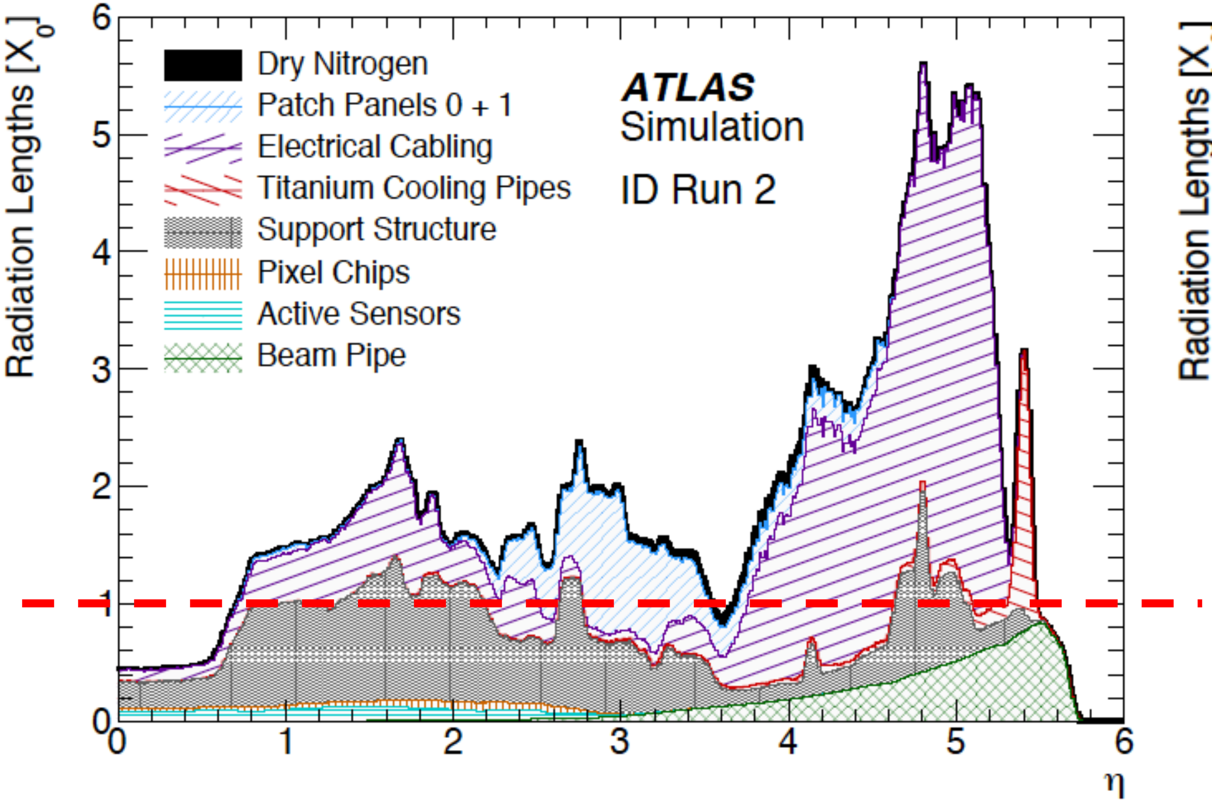




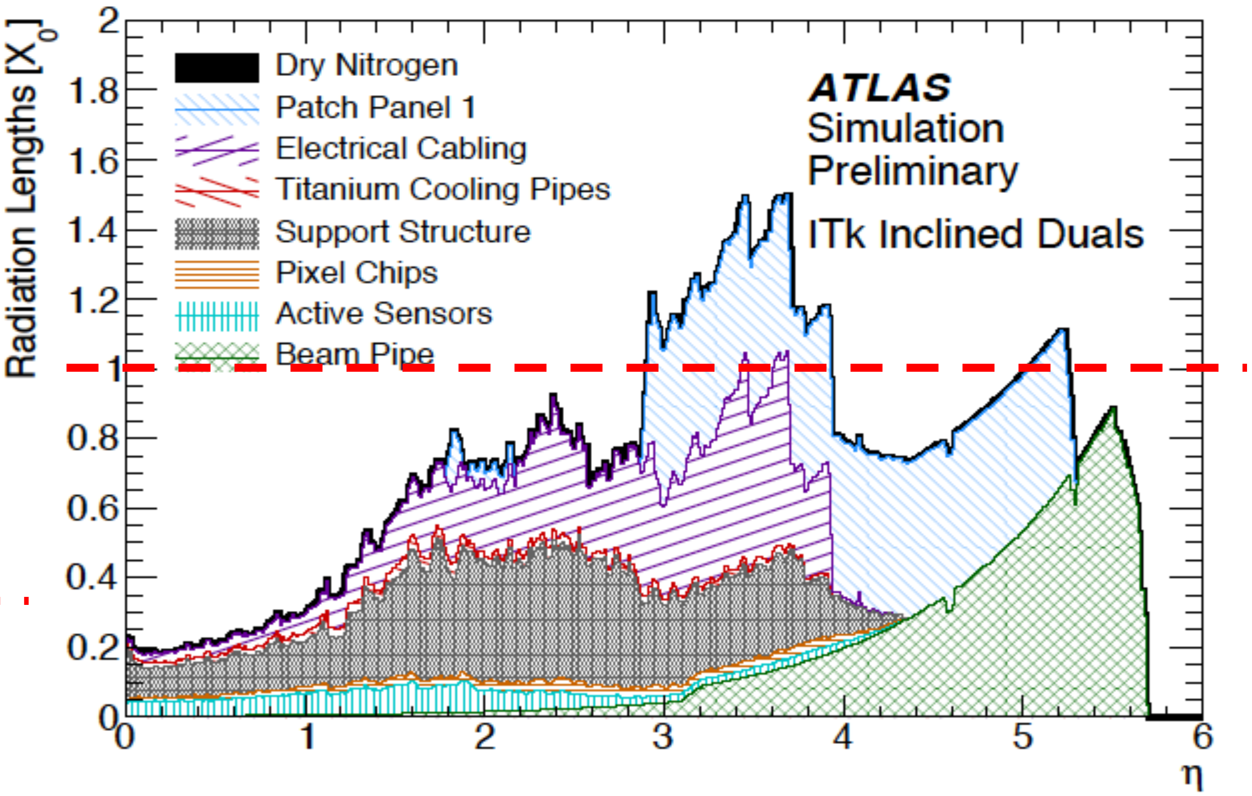
Low Mass Detectors

ATLAS-TDR-030

Run2

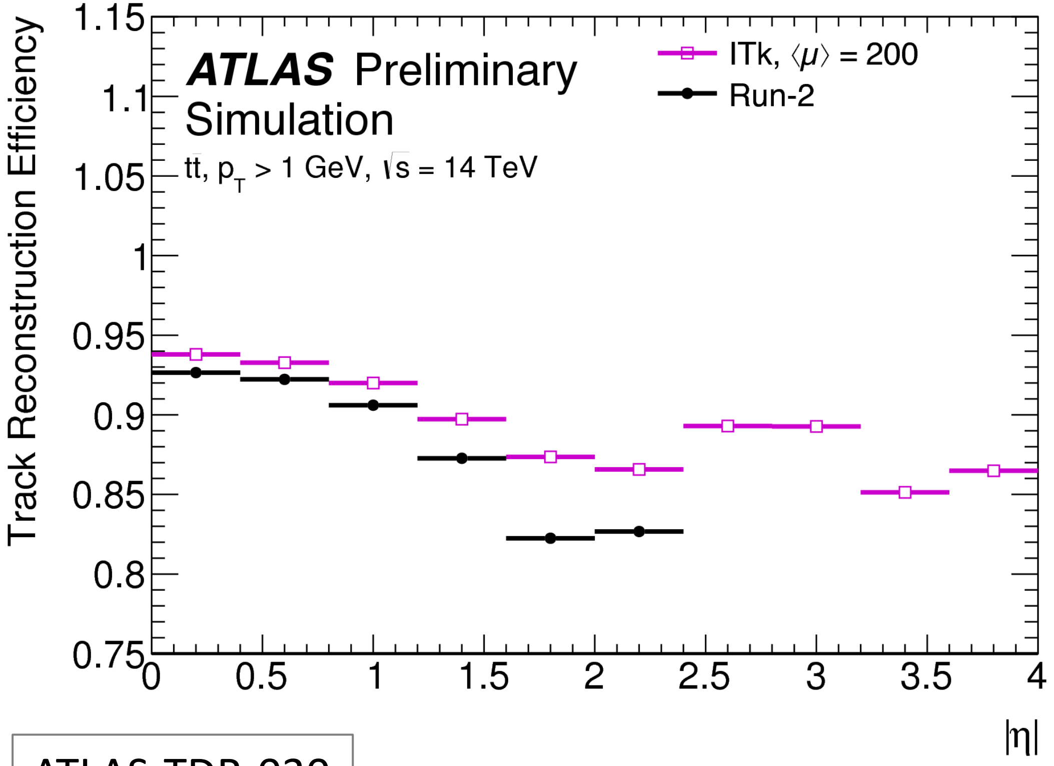


Phase-II Upgrade

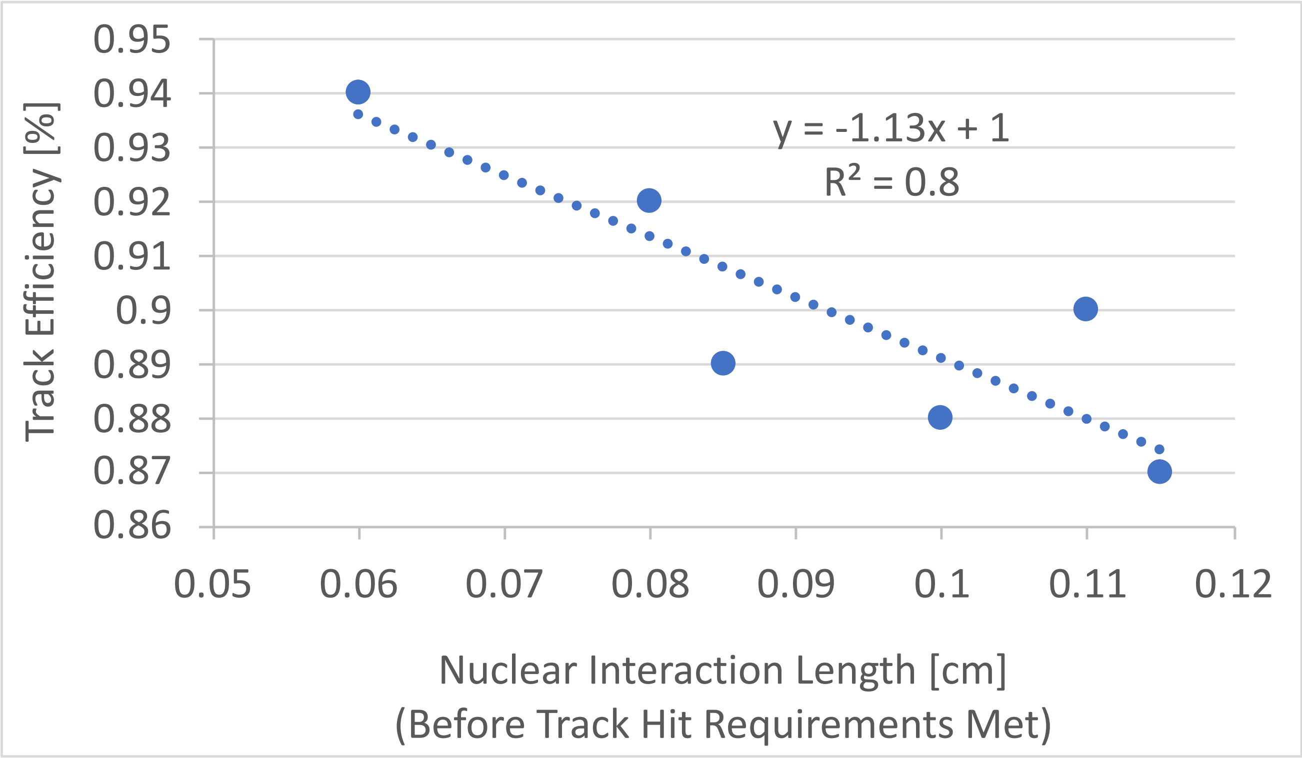


- Tremendous progress since the original ATLAS
- Target support structures & services
- Continue this trend

Low Mass Detectors



ATLAS-TDR-030



- A single silicon sensor has very high intrinsic tracking efficiency > 99%
- A detector system, however, is limited by the dead material
- Overall tracking efficiency can be optimized by reducing dead material

Goals

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- Low Mass
- Low power
- High position resolution
- Fast timing resolution
- Monolithic
- Radiation Tolerance

- Energy resolution
- Energy range: signal/noise
  - Low electron energies

- Low cost

- Reduce services
- Reduce cooling needs

- All-in-one?
  - Fewer 'sub-systems'
    - Reduce cost
    - Optimize resources

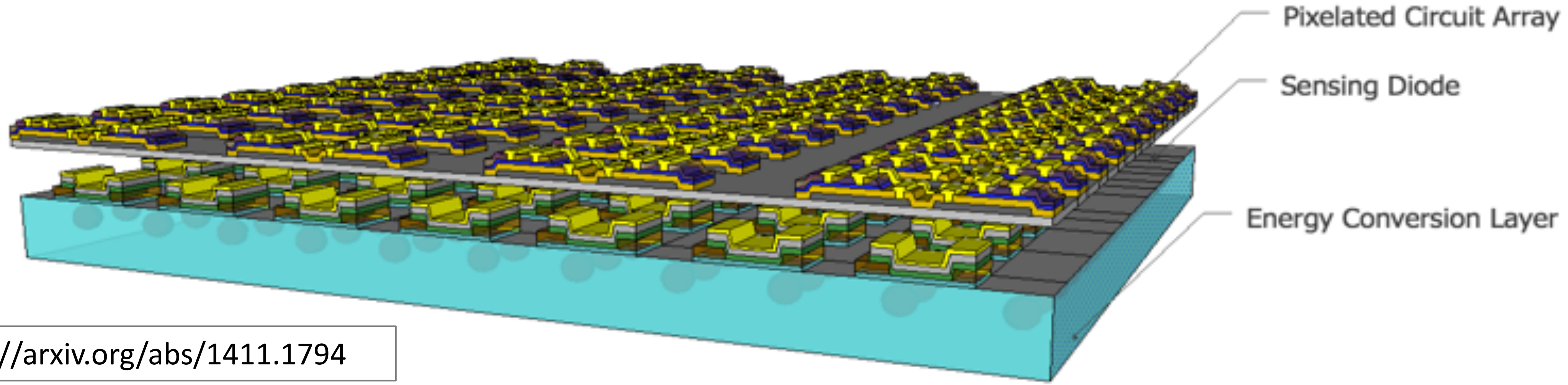
- Faster development cycle

How many features can we combine into one detector technology?

Thin Film Detectors

Thin Films: thin layers of materials ranging from nm to µm
- Current popular applications
  - solar cells
  - LCD screens
- Thin Films for Particle Detectors:
  - Thin Film Diodes + Thin Film Transistors

Potential:
- Large area ‘printing’
- Low mass
- Low cost
- Pixelated
- Integrated/monolithic design



https://arxiv.org/abs/1411.1794

Thin Film Detectors: Materials

- Many potential materials with promising properties
- Catalogue potential material candidates
  - Fabrication techniques
  - Key performance parameters
  - Challenges related to individual materials

Material	μ_e $\left(\frac{cm^2}{V \cdot s}\right)$	μ_h $\left(\frac{cm^2}{V \cdot s}\right)$
Diamond	1800	1200
Si	1350	480
CdTe	1050	100
CdS	340	50
PbS	600	700
ZnO	130	
IGZO	15	0.1
GaAs	8000	400
InP	4600	150
HgI	100	4
InSb	78000	750
InAs	33000	460
HgTe	22000	100
CdZnTe	1350	120

Material	Z	ρ (g/cm^3)	$\frac{-dE}{dx}$ [MeV/(g/cm^2)]	MIP in 10μm (keV)	E_i (eV)	$< N_{e-h\ pairs} >$ in 10 μm
Diamond	6	3.51	1.78	6.25	13	0.5k
Si	14	2.329	1.664	3.9	3.62	1.1k
CdS	32	4.8	4.0*	19.08	6.49*	2.9k
PbS	49	7.6	6.2*	46.8	1.98*	23.6k
ZnO	19	5.6	4.4*	24.8	8.25*	3.0k
GaAs	32	5.32	1.4	7.45	4.2	1.8k
InP	32	4.97	4.0*	20.5	4.2	4.8k
HgI	66.5	6.4	5.6*	35.8	4.3	8.3k
InSb	50	5.78	4.9*	28.1	1.57*	17.9k
InAs	41	5.67	4.7*	26.8	1.94*	13.8k
HgTe	66	8.1	6.7*	54.7		
CdZnTe	43.3	6	5.0*	29.8	4.7	6.3k
IGZO	29.5	6			7.58*	

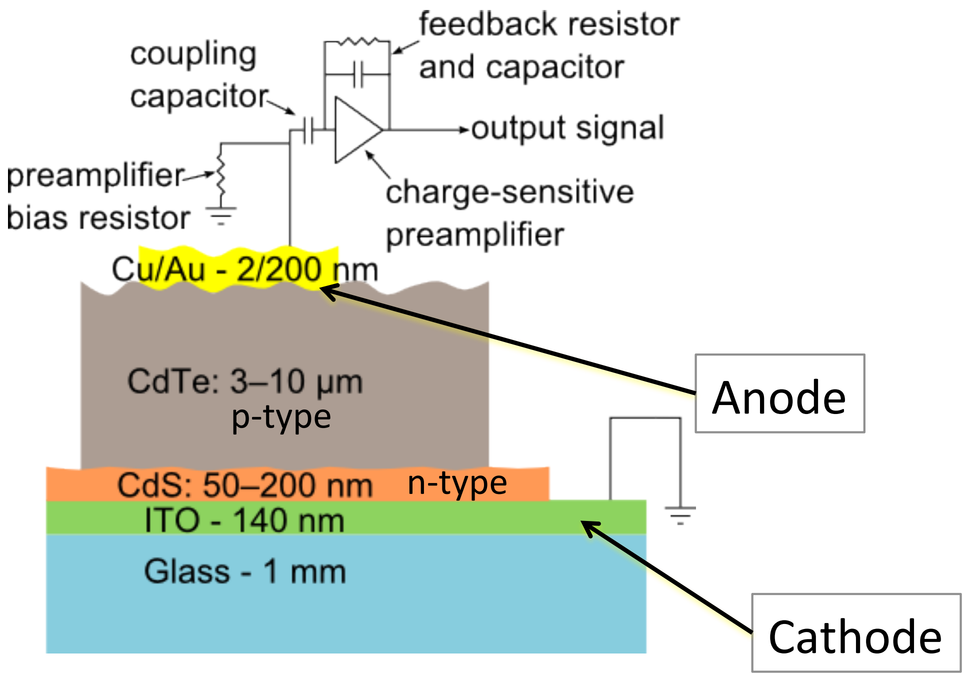
*calculated

https://arxiv.org/abs/1411.1794

Thin Film Detectors: Fabrication

Thin Film (TF) Fabrication

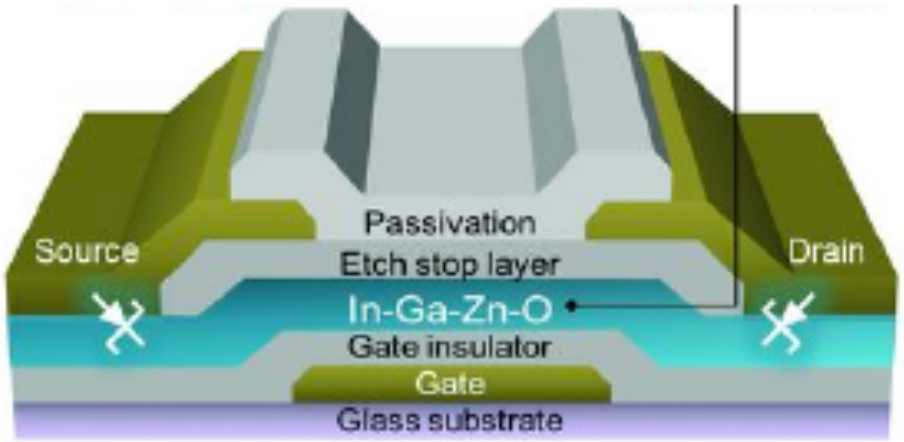
- Films are grown in thin layers on a substrate with high precision
- Compare to traditional silicon that relies on growing a large crystal and then drilling, etching, etc.
- Thin Films can be fabricated using
  - chemical bath deposition
  - close-space sublimation
  - Atomic layer deposition
- TF's can be grown at least 200 µm thick (not standard)
- Certain types of Thin Film fabrication are much less expensive
  - < $10 per m^2 for a 2.5 µm thick CdTe film
- TF can be deposited on flexible substrates such as organic polymers and plastics



Low Power Electronics

- Services is a large part of the dead material
- Low power electronics can help
- Thin Film Transistors is a large area of nanoscience development
- Explore options for HEP
    - Example:
        - High gains > 400
        - Low power < 1 nW
        - Potential integration in thin film detector

Thin Film Transistors (TFTs): Ultralow Power

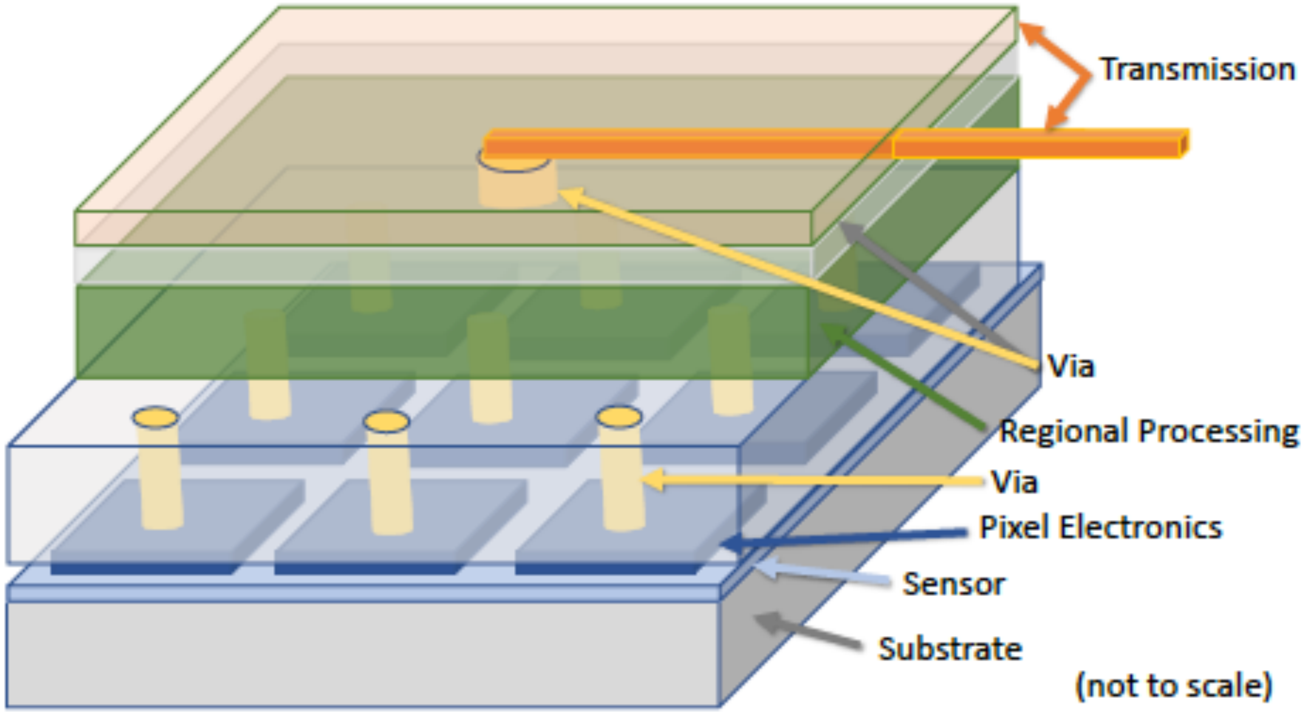


Sungsik Lee and Arokia Nathan. Subthreshold Schottky-barrier thin-film transistors with ultralow power and high intrinsic gain. *Science*, 354(6310):302–304, 2016.

Thin Film Detectors

- Combine thin film layers into a complete detector
- Consider thin film deposition techniques
  - Potential to be large area low cost like LCD screens
- Options for many different semi-conductor materials
- Potential for monolithic integration of sensor + electronics
- Minimize services radiation length
- < 1% X/X_0

Thin Film Detector Layers:

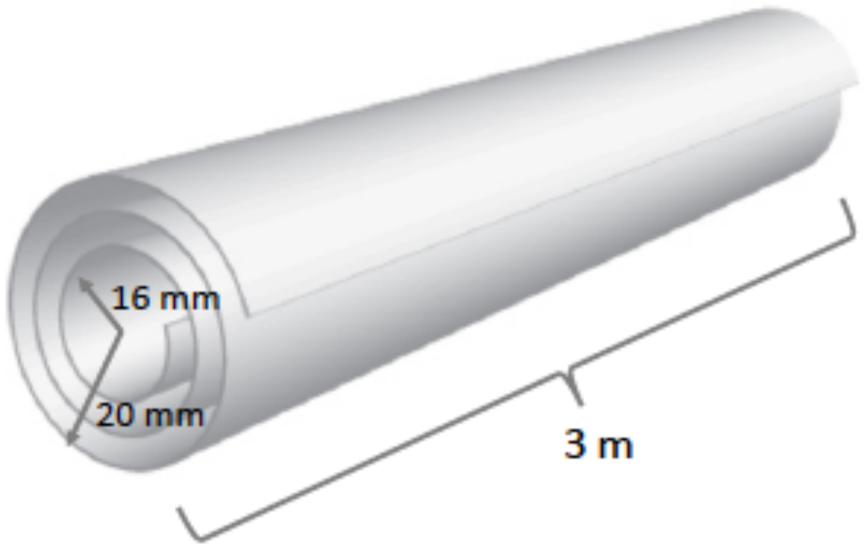


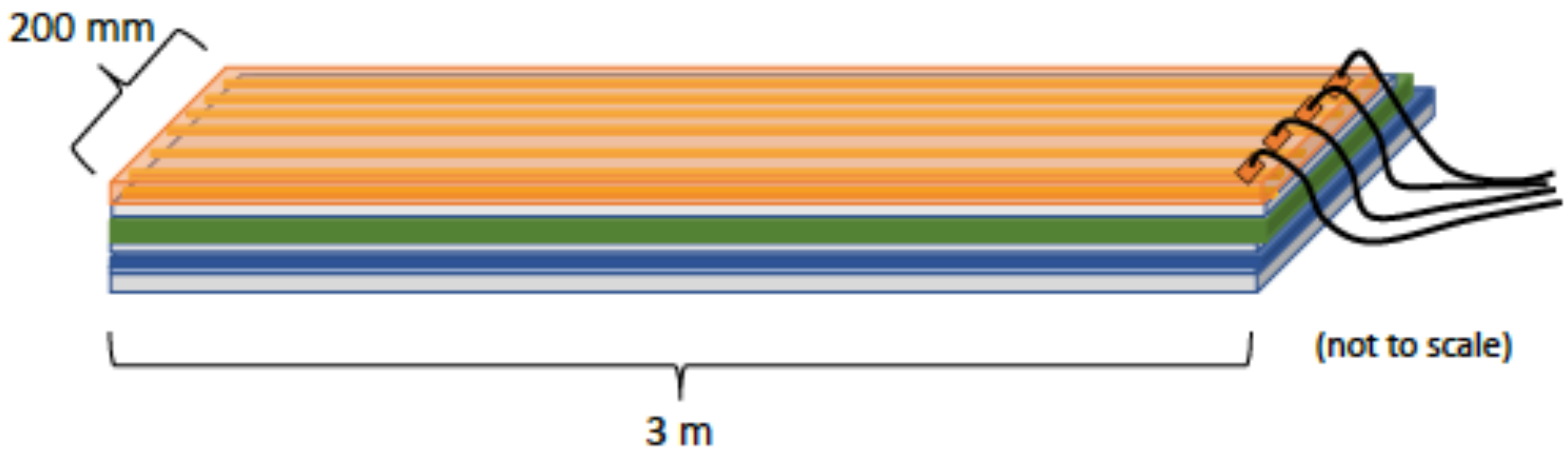
Layer	Material	thickness [μm]	X_0 [cm]	X/X_0	λ_0 [cm]	λ/λ_0
Substrate	PET	250	29	0.088%	60.6	0.041%
Sensor	InSb	10	15	0.0065%	46.8	0.0021%
Electronics	InGaZnO	200	10	0.20%	45.0	0.044%
1st Via	Cu/dielectric	100	29	0.035%	60.2	0.017%
Electronics	InGaZnO	200	10	0.20%	45.0	0.044%
2nd Via	Cu/dielectric	100	25	0.04%	51.2	0.020%
Transmission	Cu/dielectric	250	20	0.13%	45.4	0.055%
Total				0.70%		0.22%

Thin Film Detectors

Large area design possibilities:

- Fabricate on a single flexible substrate
- Creative detector geometries like spiral cylinder roll
- Simplify detector construction process
- Move toward a single active detector system





Thin Film Detectors

Key Challenges:

- Sensor performance
  - Want to match silicon sensor performance
- Transistor designs
  - Compatible fabrication processes on top of sensor
  - Transistor footprint
- Vertical integration
  - How to reliably stack layers
  - Over large areas
- Transmission signal integrity over long distances
- Radiation damage
- Process industrialization

Thin Film Detectors

Potential of a Thin Film Detector design:

- Material level understanding to design and optimize a given detector design for a specific application
  - Tracking efficiency
  - Timing resolution
  - Energy resolution
  - Occupancy
  - Radiation damage
  - Etc.
- Simplify fabrication techniques to follow industrial standards
  - Large area
  - ‘Printable’ designs
  - monolithic
  - Low cost
  - Fast turn-over cycle
- A lot of unknowns to realize the full potential → Long-term blue-sky R&D
- Interesting path to see where it leads

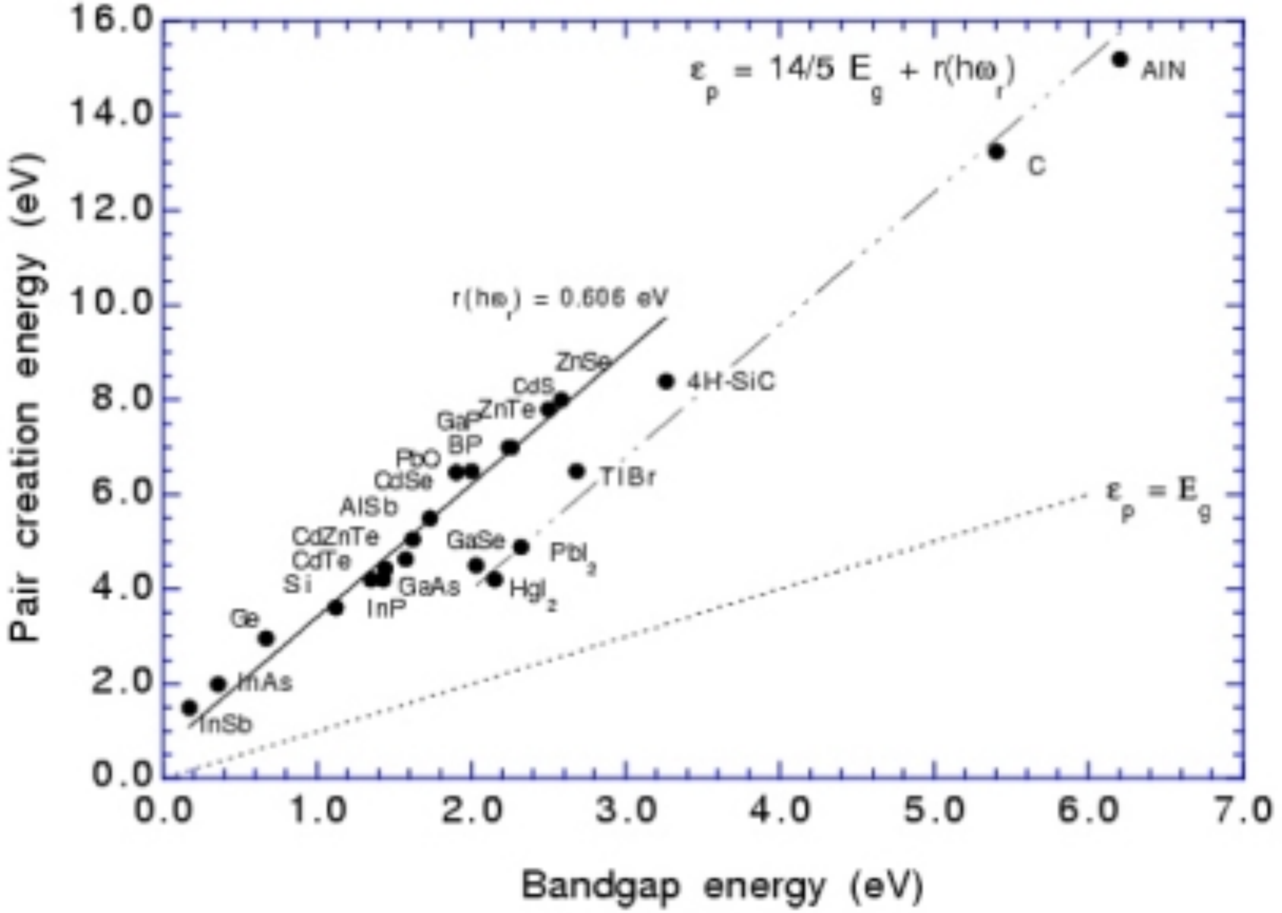
Backup

Thin Film Detectors

Use the bandgap energy, E_g, to estimate E_i:

$$E_i \propto E_g$$

$$E_i \approx 2.0877 \cdot E_g + 1.2122$$



Material	E_g (eV)	E_i (eV)
Ge	0.67	2.96
Si	1.11	3.62
CdTe	1.4	4.43
GaAs	1.43	4.2
diamond	5.5	13

Thin Film Detectors

Design Goals

Meet current tracking performance of a typical tracking detector such as ATLAS

- Charge yield 1,000 – 10,000 electrons
- Energy resolution 5-10%
- Position resolution ~45 µm
- Timing resolution 25 ns
- Signal/Noise ~20

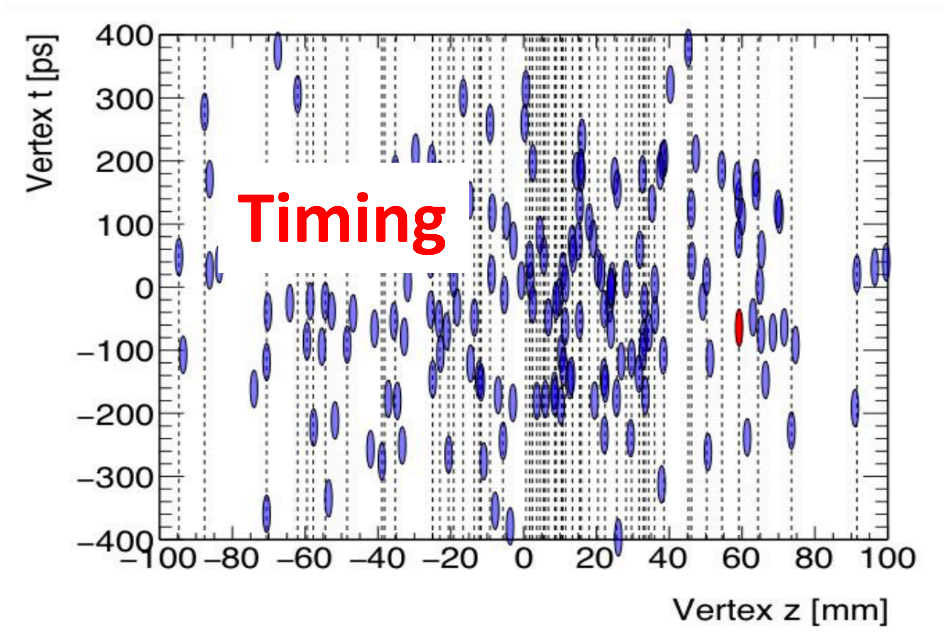
Other applications: ILC

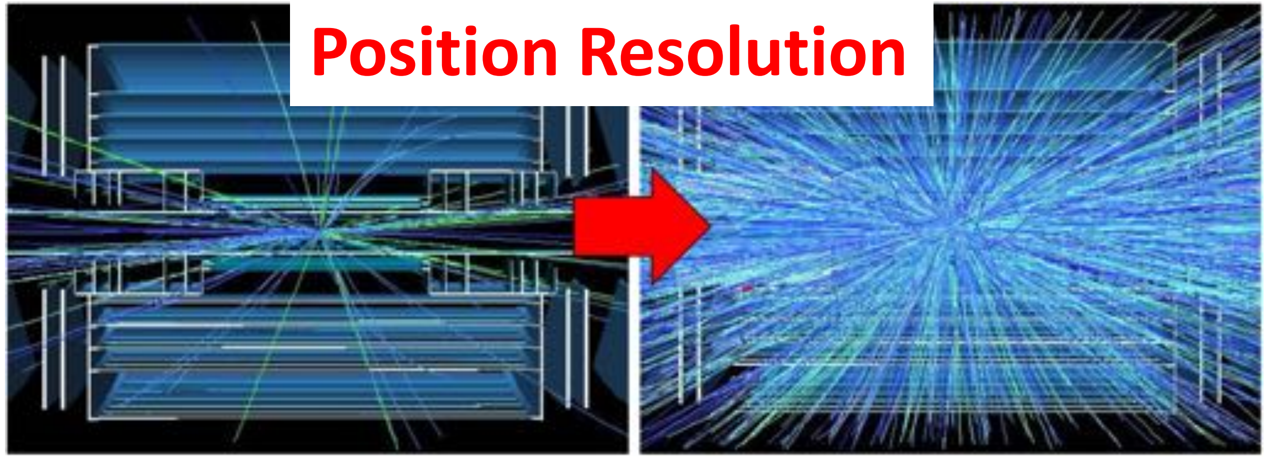
- Timing resolution 5 ms
- Tracking precision 3 µm
- 0.1% X_0
- ~10^{14} 1 MeV $N_{eq/}cm^2$

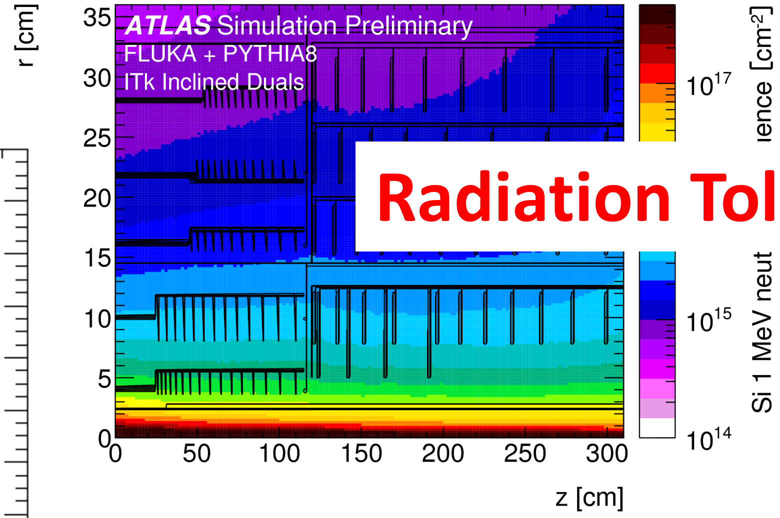
Flexible layers “printed” in large sheets

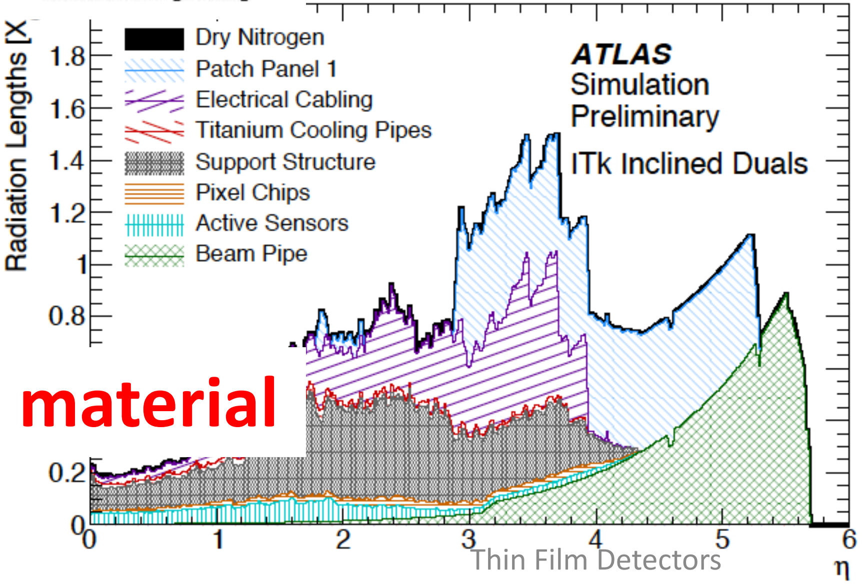
➔Possibility for unique geometries with less dead space

Challenges









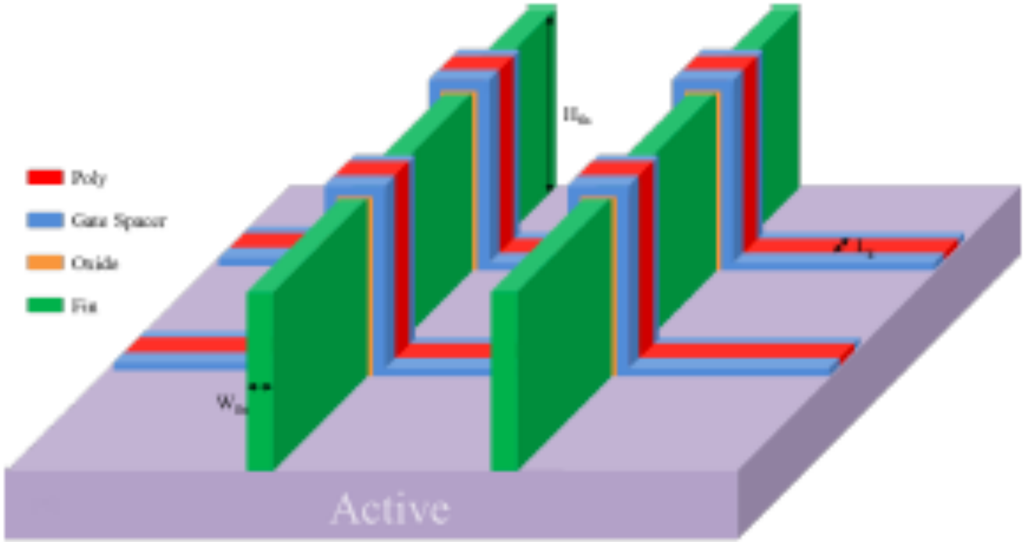
…Typical of large accelerator experiments

Low Power Electronics

- FinFETs
  - ~30% less power than CMOS
  - Faster switching times
  - Energy harvesting interfaces
    - 'self-powering'
    - Can we take advantage?

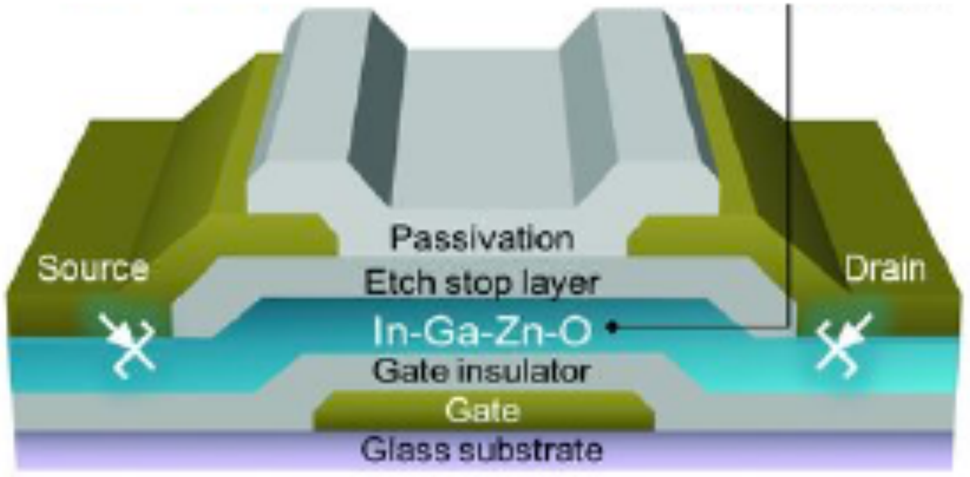
- TFTs
  - High gains > 400
  - Low power < 1 nW
  - Potential integration in thin film detector

FinFETs



Katrine Lundager, Behzad Zeinali, Mohammad Tohidi, Jens K. Madsen, and Farshad Moradi. Low Power Design for Future Wearable and Implantable Devices. *J. Low Power Electron. Appl*, 6(64):20, 2016.

Thin Film Transistors (TFTs)



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