Monolithic Pixel Sensors

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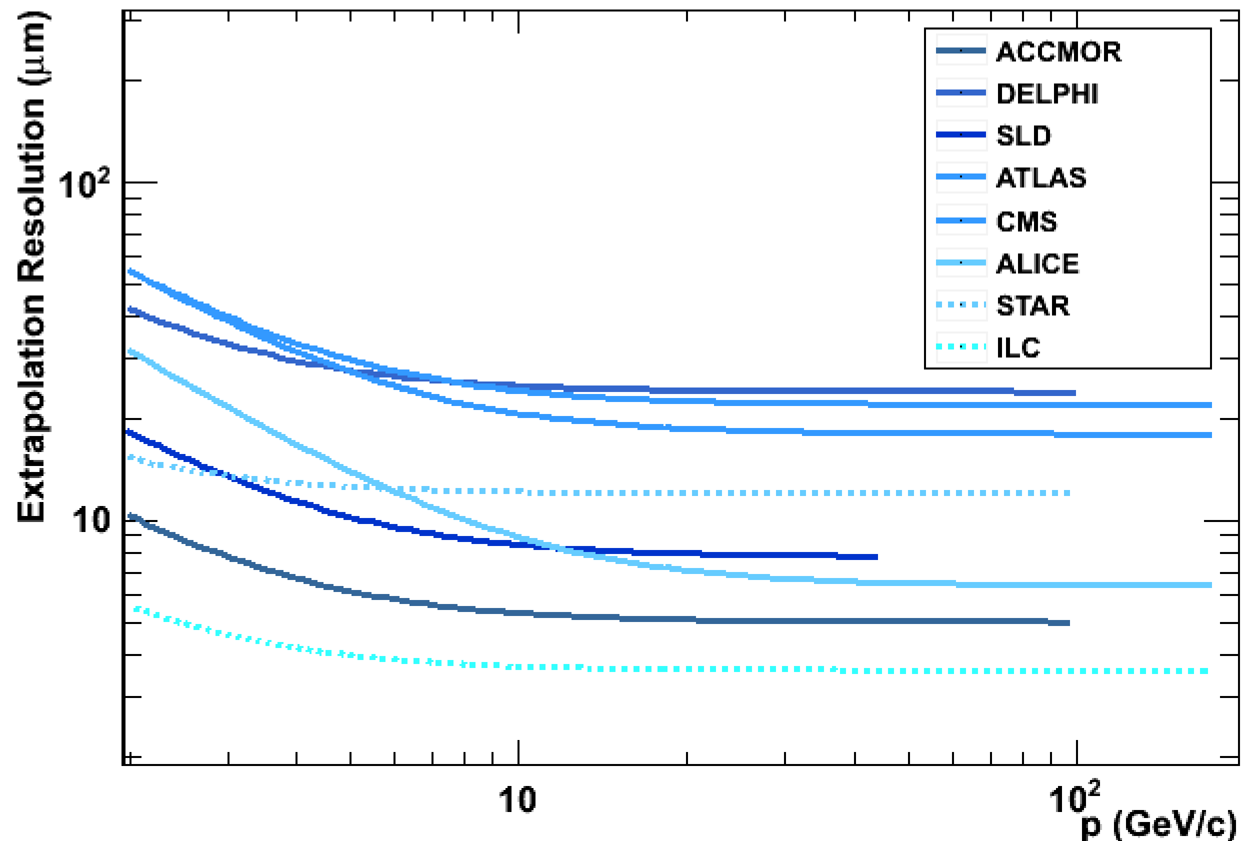
Main drivers for sensor pixel pitch, P, are single point resolution + two-track separation (both proportional to P) and occupancy, scaling as pixel area (i.e. P^2) x integration time;

Fast time-stamping, required by occupancy, has become part of the overall optimisation and the space-time granularity to be considered as the appropriate parameter space for characterising vertex detectors.

Thin sensors essential to maintain extrapolation resolution over full kinematic range:



Even more than spatial resolution, two-track separation emphasised by physics program at LHC and future colliders at energy and intensity frontiers;

Two track separation depends not only on pixel size:
charge carrier distribution at readout nodes is crucial
→ charge diffusion, electric field in sensitive volume, thickness of sensitive volume, ...

Hybrid pixel sensors face limitations from
Increased Capacitance from bumps bonding limits thickness reduction to keep S/N
Feasibility of high bump density limits reduction of pixel size

Monolithic pixel technologies offer us sensors with thin active layers, pixel cells of O(10x10) μm^2 in size, typical capacitance of O(1) fF, low noise (10-40 e^- ENC) and posibly significant data processing capabilities implemented in-pixel or on-chip.
Thin active volume of 15-30 μm thickness sufficient for achieving >99% efficiency even at operating temperatures in excess to 40°

Practical pixel size in monolithic pixel for HEP determined by charge carrier distribution, number of channels and readout speed, technologically pixels of O(1 μm) are feasible

Monolithic pixel sensors have emerged at the end of the '90s in the framework of R&D towards a future linear collider as the way forward towards thin Si sensors with very high granularity, well beyond the technological capabilities for the hybrid pixels. Development was made possible by the progress in deep sub-micron CMOS processes and availability of commercial processes with thick epitaxial layers aimed at sensors for optical imaging and consumer digital cameras.

CMOS sensors for HEP tracking initially designed following classical NMOS-only 3-T cell of image sensors to collect charge generated in almost field-free epitaxial layer.

Implementation of complex circuitry in pixel cell requires to insulate transistors from charge collection volume, to avoid parasitic charge collection and back-gating. Various viable approaches have been investigated:
deep N-well electrodes, thin BOX insulating layer in SOI, multi-tier 3D, ...

Use of moderate- to high-resistivity substrate latest step in development exploited by monolithic pixels. The use of a depleted sensitive layer enhances amount of collected charge, collection time and reduce charge carrier spread compared to almost field-free epi-layer of the standard CMOS APS, without compromising the sensor competitive thickness.

EUDET beam telescope adopts sensors based on high-resistivity CMOS pixels thinned to 50 μm providing ~3μm single point resolution, frame rate of $\sim 10^4$ f/s over active surface of ~ 2 cm^2 paved with 670,000 pixels, can cope with particle flux $> 10^6/cm^2$ s

180nm CMOS process featuring a nearly 20μm thick epitaxial layer with resistivity exceeding 1kΩ cm, 6 to7 metallisation layers and additional p-wells offers the possibility to use both types of transistors inside the pixels thus allowing for a substantial increase of the in-pixel micro-circuit complexity

Thin SOI pixels tested on 200~GeV π beam at CERN successfully operated fully depleted, with (1.8+/-0.06)μm point resolution and particle detection efficiency above 97%

Multi-tier 3D sensors provide high resistivity active volume.

Back-thinning technologies, grinding and chemical etching, available as commercial services, successfully applied to obtain 40-50μm-thick CMOS sensors for the STAR HFT at RHIC and in the R&D for linear colliders and B-factories.
DEPFET sensors can be thinned to less than 100μm in the sensitive region, using wafer bonding technology, retaining a frame which ensures sufficient stiffness of mechanical module

Sensors of thickness achievable with monolithic technologies and back-thinning, ~50μm, are compatible with achieving a material budget of ~0.1% X_0/layer, needed to meet the value of b ~10μm/GeV for the multiple scattering term in the impact parameter resolution, identified as a requirement at a linear collider and also the b-factory requirements.

Ladder support is of major importance for counteracting chip warping and insuring module stability and planarity. In designs of thin ladders for applications at B-factories, STAR and LC with thin sensors, as well as those for an LHC upgrade, Si ceases to be dominant contribution to layer material budget with cable routing signals, power and clocks, cooling, etc becoming dominant.

PLUME collaboration addressing challenges related to ladder based on thin monolithic pixels

Monolithic CMOS pixels combine particle detection and (at least part of their) front-end electronics (FEE) in the same device is a prominent advantage, but may turn into a limitation as industrial manufacturing relies on processes optimised for commercial products which may depart substantially from those needed for charged particle detection.

CMOS industry has evolved in directions which allow CMOS pixels to progressively approach their real potential. Developments towards future vertex detector systems rely on further advances in the CMOS technology.

CMOS technologies bring along desirable features that pixel R&D projects are exploring. Metal interconnections are isolated by low-k dielectrics to reduce parasitic capacitance and time constants of transmission lines. Exploited by minimising electronic functions in pixel cell and by connecting each pixel to signal processing blocks in chip periphery. Very high integration density of CMOS processes, gives peripheral readout strategy small area outside the pixel matrix.

Monolithic pixels developed for HEP tracking are spreading out to a large variety of applications in scientific imaging from transmission electron microscopy, to X-ray imaging and spectroscopy at light sources and astronomy to beam monitoring in hadrontherapy where science is performed with single sensors or small arrays to provide opportunities for cross-field fertilisation and early scientific outputs of sensor R&D.