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# Recent developments on silicon detectors

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ABSTRACT

Silicon detectors have risen to a predominant role in high energy physics experiments since their introduction just over thirty years ago. Their outstanding capabilities of high resolution, low mass and fast response to ionising radiation have given silicon detectors the role of device of choice for the inner regions of collider experiments. Their evolution over the years has been notable, and it is possibly accelerating in the present times with the impulse coming from stringent requirements of future experiments and from developments in the microelectronics industry. Recent advancements of silicon detectors are reviewed and reported from the perspective of future challenges.



## 1. Introduction

Since their introduction in high energy physics (HEP), in the 1980's of the last century, silicon detectors have been in a 'virtuous' feedback mechanism with the physics goals of the experiments: they were conceived to satisfy experiment needs and their excellent performance suggested and enabled new techniques to accrue the results of the same experiments (e.g. with the ability to accurately detect secondary and higher order vertices from particle decays).

In fact, silicon sensors have been introduced as tracker devices in high energy physics (HEP) in fixed target experiment at CERN (Geneva, CH) in 1980 [1]. Their use expanded following a version of Moore's law both in term of surface covered and number of readout channels, as shown in Fig. 1. The rise of silicon sensors was due to the accrued demand for faster rates, higher resolution and finer granularity (to face ever increasing energies and luminosity in the experiments). Their use has become predominant in this function starting with the detectors installed at LEP at CERN and Tevatron at Fermilab, where they provided vertexing and tracking up to relatively large radii (to include precise momentum measurement in magnetic field). In the current ATLAS [2] and CMS detectors [3] at the CERN/LHC the area covered by silicon sensors has attained large proportions. The largest silicon system is the CMS micro-strip tracker with a total area of $\sim 200\ m^2$ with over 10 million readout channels. If the pixel detector systems are included, both ATLAS and CMS have a total number of readout channels from silicon sensors counting up to about 80 million. In the future upgrade of the LHC at CERN (the High Luminosity LHC, HL-LHC [4]) the area covered will be about the same as that of the current CMS tracker for both ATLAS and CMS experiments but with the channel count increased by a factor of 10–30. This is dictated mainly by occupancy: the increased luminosity (with the number of interactions per bunch crossing going from 20–200) will entail large multiplicity and consequently the need of adequate granularity (smaller individual channel size) for efficiently resolving the closed spaced tracks. The trend keeps going in the direction of smaller channel size (small pixels, macro-pixel, strixels and short strips in increasing radius order) instrumenting greater tracker volumes to face the augmented multiplicity and resolution needs for future physics. The demand is still pushing the boundaries of the technology, and it is interesting to examine the status of silicon sensors in the perspective set by future requirements.

## 2. Current silicon sensors (LHC at CERN)

In the LHC, the vertex and tracker detectors of the four experiments are equipped with hybrid pixels, micro-strip and silicon drift sensors. The first type is used in the innermost volumes, where the need for fine granularity to face high track multiplicity is more stringent. They provide the hit position in two dimensions. These devices [5] are made with high resistivity silicon and can be biased to high voltage (between 500 and 1000 V) for fast collection and good radiation tolerance. The typical size of individual pixels is $50 \times 400\ \mu m^2$ (ATLAS and ALICE) and $100 \times 150\ \mu m^2$ (CMS), DC coupled to the readout electronics. The readout ASIC sits on top of the sensor and the electronics for each channel is realised over the same area of the readout sensor cell. The connection between sensor and overlapping ASIC is performed by means of bump-bonding. Micro-strips [6] are large area sensors with typical strip lengths going from a few to 12 cm, with distance between channels from 40 to 500 μm. Every strip is AC coupled to readout electronics

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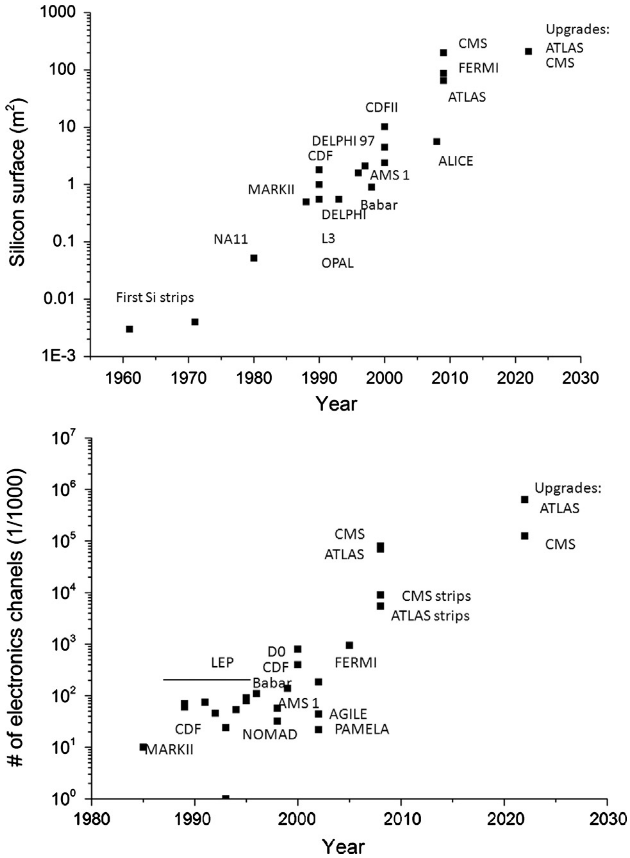


**Fig. 1.** 'Moore's law for silicon detectors in HEP and space experiments: top, the evolution of the surface; bottom, the number of channels. The figure includes the anticipated ATLAS and CMS future detectors at the HL-LHC.

by means of micro-wire bonding. They provide high resolution one 1-d hit information with a reduced number of channels. Silicon drift sensors [7] are 2-d measuring devices where the ionised charge is driven at constant velocity from the impact point towards the segmented anodes. The hit anodes provide the position information in one dimension, while the drift time provides the other. The performance of the current silicon devices is up and often beyond the design requirements (e.g. in the capability of handling larger hit occupancy than the design limit).

## 3. Next challenge: high luminosity LHC (HL-LHC)

The exciting physics results obtained by the current LHC already with an integrated luminosity ($L$) of $\sim$22 $fb^{--1}$ (as of the end of 2012) and reduced (with respect to nominal) interaction energy of 8 TeV indicate that its physics programme should be extended to 3000 $fb^{-1}$ (at the nominal interaction energy of 14 TeV). This goal can be achieved only through 10 years of operation of a collider with an average luminosity about an order of magnitude larger than that of the LHC. This is the aim of the planned next machine at CERN (HL-LHC). The consequences of this upgrade on the detectors are so important that major replacements and improvements will be required. In particular, with over 200 collisions per bunch crossing (every 25 ns) in CMS and ATLAS, the individual readout cell size at different radii will have to shrink sufficiently to keep the hit occupancy in the order of 1%. This leads to a large increase of the number of channels in the experiments (Fig. 1) with severe consequences on sensors and services (data links, power supplies and cooling systems). Moreover, the anticipated physics programme requires that the vertex sensors will operate after fluences up to 2–3 $\times 10^{16}$ $n_{eq}$ $cm^{--2}$. The system aspects (the services mentioned above) are very important but they will not be treated here. The radiation hardness though is an inherent detector property: the state-of-the-art is briefly discussed below.

## 4. Radiation hardness

Hadron radiation to silicon detectors causes lattice damage that degrades the electrical characteristics of the devices. The crystal damage can be point-like (single atoms are removed from the lattice) or cluster-like (a high concentration of damaged crystal in a volume with radius comprised between 10 nm and 200 nm. The relative importance of these two types of crystal degradation depends on the particle energy and type: in general, high energy charged particles produce more point-like and less cluster defects those bythan fast neutrons. To study the radiation effects on silicon, the damage from different particles and energies is scaled using the non-ionising energy loss (NIEL) function [8]. This quantity allows expressing the fluence of any particular radiation field in term of a reference monochromatic particle, namely the 1 MeV neutron ($n_{eq}$). The defects can interact with themselves and other mobile impurities in silicon (hydrogen, carbon or oxygen, interstitial silicon, etc.) and form permanent complexes with a possibly different electrical nature than the original ones. This annealing process is a function of time and temperature and again changes the electrical properties of the detectors. The defects introduce electrically active centres in the silicon band-gap that increase reverse current, charge density ($N_{eff}$) in the space charge region (changing the full depletion voltage, $V_{FD}$) and charge trapping (removal of charge carriers from the pulse induced by the ionising particle). These effects will eventually cause failure of the sensors. Radiation resilient detectors capable of providing efficient track information during the whole experimental time of the experiments need to be developed. The HL-LHC expected doses represent a formidable challenge for radiation tolerance of silicon devices. The anticipated fluence for the ATLAS and CMS upgraded experiments at the HL-LHC are about 1–2 $\times 10^{15}$ $n_{eq}$ $cm^{-}$ $^{-2}$ for the micro-strip sensors instrumenting the tracker and over $2\times 10^{16}$ $n_{eq}$ $cm^{-2}$ for the innermost pixel in the vertex sensors. The issue of the survival of sensors to elevated radiation doses is being investigated within the experiments and by a dedicated research collaboration (CERN/RD50) [9]. The results from this collaboration are reported elsewhere [10] and represent the current understanding of radiation effects and tolerance on silicon sensors. Here we just remark that given certain operating conditions (operating temperature of about −−20 °C and high bias of up to 1000 V), planar silicon sensors can deliver sufficient signal for efficient tracking (when read out with modern low noise electronics) for efficient tracking after $2\times 10^{16}$ $n_{eq}$ $cm^{--2}$). In particular, extremely encouraging results have been obtained with sensors thinner than the standard size for high energy physics (300 μm). Fig. 2 shows the charge collected as a function of $n_{eq}$ fluence by silicon detectors of different thicknesses (from 50 to 300 μm). It can be seen that after large doses the thin devices yield larger signals than those of the thicker ones.

## 5. Column electrode (3D) detectors

A different concept for realising the $n^+$ and $p^+$ electrodes in both silicon bulk polarities, as columns etched through the silicon wafers, was proposed in 1997 [11]. The charge drifts are now parallel to the sensor surface, as opposed to the vertical drift in planar sensors, and the distance depends on the column separation. This method