Introduction

Silicon radiation detectors have been used extensively for many years in a large variety of industrial, medical, and scientific applications and are part of the core instrumentation in many areas of fundamental and applied research.

In the early 1980s, Joseph Kemmer achieved a major technological breakthrough in silicon sensors processing with the pioneering use of the planar fabrication process derived from microelectronics. The key innovations consisted of (1) exploiting the passivation properties of silicon dioxide, which allowed keeping the thermal budget to a minimum, and (2) using detectors with ion-implanted junctions making possible the design of fine pitch electrodes segmentation with very low leakage currents. This revolution, along with the development of low-noise, low-power microelectronic readout circuits, opened the field of position-sensitive radiation detection and imaging using planar silicon sensors. Silicon strip and silicon drift detectors became available first, followed by silicon pixel detectors a few years later.

Ever since this historical moment, silicon detector technologies have been continuously advancing. Now more complex and reliable detectors can be obtained, with outstanding performance in terms of energy, timing and position resolution, long-term stability, and radiation tolerance.

A new paradigm shift in silicon sensor technology became possible in the mid-1990s when Sherwood Parker and collaborators introduced bulk micromachining in combination with microelectronics' very-large-scale integration (VLSI) in the processing. By exploiting the third dimension within the silicon substrate, several interesting features could be obtained, related either to radiation-sensing properties or to some ancillary functions. Unlike planar detectors, where electrodes are confined to the wafer surfaces, in 3D, electrodes penetrate partially or entirely throughout the substrate, perpendicularly to the surface. This architecture offers a number of substantial advantages with respect to the planar one such as fast signals, reduced bias voltage and power dissipation, and extreme radiation tolerance, making 3D detectors ideal candidates for some critical applications, especially in high-energy or nuclear physics. These advantages, however, come at the expense of a more complicated and expensive fabrication process, which is only possible in facilities with microelectronic and micro-electro-mechanical-systems (MEMS) technologies in the same cleanroom.

For about a decade since their invention, 3D sensors have undergone a relatively slow research and development (R&D) phase, with only a small number of scientists working on few prototypes built at the Stanford nanofabrication facility by the original inventors. But starting in the mid-2000s, more devices inspired by the original design were processed at European facilities using modified technologies, and experimental results confirmed the great potential of these devices. The establishment of the ATLAS 3D Sensors Collaboration for the Large Hadron Collider (LHC) luminosity upgrade in 2007 led to an impressive boost in the development of 3D sensors, with experimental confirmation of their remarkable radiation tolerance with relatively low power dissipation, and the demonstration of medium-volume production, which culminated in their use for the ATLAS Insertable B-Layer (IBL) project in 2014. These accomplishments paved the way for the use of 3D sensors in other pixel detector systems in Phase 1 upgrades at the LHC such as ATLAS Forward Physics (AFP) and CMS-TOTEM Precision Proton Spectrometer (CT-PPS), and made them an appealing option for the innermost tracking layers at further high luminosity LHC (HL-LHC) phases.

This book presents a comprehensive and up-to-date review of 3D detectors, covering relevant aspects of device physics and simulation, fabrication technologies and design issues, selected experimental results, and application fields.

The book is organized as follows:

Chapter 2 provides a brief overview of some basic theoretical concepts necessary to understand 3D sensors. These concepts include interaction of radiation with silicon, the operation principle of silicon sensors, main sensor types, and signal formation and processing.

Chapter 3 reviews the effects of radiation damage on silicon (both surface and bulk), their macroscopic consequences for sensors performance, and some measures to counteract the effects in practice.

Chapter 4 provides a comprehensive description of 3D silicon sensors, from the operation principle to simulations and experimental results relevant to both the original Stanford device and all the alternative design variants reported thus far.

Chapter 5 describes the key fabrication technology steps used in 3D silicon sensors, ranging from general aspects of the processing to detailed descriptions of the different flavors made at facilities, which developed alternative 3D designs.

Chapter 6 addresses the radiation hardness of 3D sensors, with details on its dependence on electrodes' geometry and a comprehensive overview of experimental results supporting the theoretical model used to explain the signal formation of 3D sensors.

Chapter 7 describes the industrialization process for the ATLAS IBL project, explaining the strategy adopted to reach this crucial milestone, the quality assurance system used during the production, and the main achievements of the 3D ATLAS Collaboration, which led to the first application of 3D sensors in a high-energy physics (HEP) experiment.

Chapter 8 reports active edges and slim edges applied to planar sensors, which are one of the key side products of 3D technology. The different design solutions so far reported are reviewed, and selected experimental results are recalled.

Chapter 9 outlines the applications of 3D silicon sensors and related concepts, ranging from those that are well established such as HEP to emerging applications, including medical imaging, dosimetry, and neutron detection. The chapter ends with an outlook on 3D sensors made from different semiconductor substrates.

Finally, the Appendix presents excerpts from Sherwood Parker's recollections of his work on silicon detectors, including 3Ds.