PREFACE

When semiconductor detectors were introduced in the 1960s, their primary use was in energy spectroscopy. By virtue of their dramatically improved energy resolution they revolutionized gamma ray and charged particle spectroscopy. Detector systems typically consisted of a single sensor, often cooled to liquid nitrogen temperature, and a bin filled with electronics, highly optimized for energy resolution and count-rate capability. In the early 1980s a new development began, which would bring about a second revolution. Instead of emphasizing energy resolution, these system exploited the micron-scale patterning capabilities of semiconductor technology to form detectors with many electrodes as position-sensing devices. Efficient readout of these detectors required high-density front-end electronics. Detector systems now consisted of a highly segmented sensor, typically with strip electrodes on a $50 - 100$ μm pitch, combined as a unit with an array of custom integrated circuits, often with 128 channels of readout electronics per chip. These systems required a radically different design approach from previous semiconductor detector systems. Rather than emphasizing primarily one or two performance parameters, energy resolution and count-rate performance, these systems needed to fulfill many conflicting requirements, *i.e.* low noise, low power and minimum material. Later – in systems for high-luminosity colliders – additional demands on fast timing and radiation resistance had to be met.

So different were these requirements from the established paradigm, that conventional wisdom among the experts held these systems to be impractical, if not impossible. Today, highly integrated semiconductor detector systems with tens of thousands of channels are routine and new detectors are under construction covering hundreds of square meters with millions of channels. Although advances in technology – especially in integrated circuit density – have played a major role in bringing this about, this development required more than the magic of modern technology. These systems are bounded by rather fundamental constraints, which were already well-understood in the 1970s. The challenge was to take a fresh look at these constraints and develop new architectures that balanced experimental demands with practical technology.

The goal of this book is to show how this balance comes about, so it emphasizes both sensors and electronics as a system. It is written primarily for physicists who devise new detectors and bring them into operation, so I include basic discussions of amplifiers, circuits, and electronic noise that are familiar to engineers, but not covered in a typical physics curriculum. The choice of topics and the organization of the book resulted from courses I have taught in the Physics Department of the University of California at Berkeley and from numerous short courses on detectors and signal processing on six continents, ranging from the undergraduate to the faculty level. Much of the material was developed in my attempts to educate my collaborators and the reviewers of funding proposals. The exposition of topics results from many interactions with students, who on occasion have made abundantly clear to me what doesn't work. This has led to a "cyclical" approach, where I return to topics for more detailed discussions and reiterate explanations in different contexts. This does lead to some redundancy, but also allows chapters to be read individually, although they do build on one another.

Since new detectors will be always be stretching the envelope, it is important to understand the basic principles underlying the technology to see how far one can push, so I emphasize physical principles and how they are applied. Although the big picture is important, details are crucial, so in important areas I go into some detail, especially in the sections on noise, signal processing and devices. What I don't do, is delve deeply into the intricacies of detector technology and circuit design. Engineers have developed very powerful analysis techniques and technological tools that are essential for a working design. Fortunately, knowledge of sensor and IC fabrication details, complex frequency space, and Laplace transforms is not needed to understand the key principles of the systems and then go to the experts with the right questions. This is not a cookbook. Technology progresses continually, so specific examples are included to illustrate concepts, rather than prescriptions for designs. I emphasize the key mechanisms and their interplay, with the goal of helping readers focus the analysis of their own designs, as the usual curricula tend to teach how to calculate, rather than what to calculate.

The foundations provided by a good undergraduate physics education should be sufficient to follow the discussions in this book. The book is designed to be self-contained. Key elements are derived, to make clear their origins and limits. Some of the derivations can be found readily in the more specialized literature, but I've included them since it allows me to emphasize those aspects that are important for this specific application, for example in the diode equation and the treatment of the bipolar transistor. Whenever the derivations would disrupt the main thread of the discussion, I've moved them to the appendices. For those who are not familiar with equivalent circuits or with complex notation to describe phase shifts, brief tutorial descriptions are also included as appendices.

Chapter 1 gives an overview and summarizes key aspects of semiconductor detector arrays to provide context for the subsequent more detailed discussions. It can also serve as an executive summary for those who wish to appear knowledgeable without going to the trouble of understanding too much. Chapters 2 and 3 cover signal formation and electronic noise and lead to Chapter 4, which discusses signal processing and optimization of signal-to-noise ratio. Chapter 5 discusses digitization techniques, including their flaws, which provides some key insights needed for a brief introduction to digital signal processing. Up to this point the discussions are largely technology-independent, *i.e.* these principles can be applied to either old or new technology and remain valid as technology progresses. Technology limits enter into Chapter 6, Transistors and Amplifiers, which discusses how technology affects the device parameters that are critical in detector systems. This gives insight into practical noise limits and also provides the basis for Chapter 7, which discusses radiation effects and mitigation techniques. This area shows clearly how degradation of individual device properties can be mitigated by system architecture and appropriate choice of system parameters. Chapter 8 selects some specific detector designs to illustrate conflicts and trade-offs, and shows how different solutions address the same goals. This chapter also includes some comments on design and assembly techniques, reliability issues, and testing. In closing, Chapter 9 turns to what is probably the most important problem, why things don't work. Although not exhaustive, it discusses many of the interference sources and design flaws that cause systems to perform more poorly than expected, or even be unusable. This is a complex topic, rife with simple recipes, which tend to be wrong.

In the past two decades semiconductor detector arrays have come a long way. We have encountered many difficulties that were not foreseen, but silicon technology is mature and highly developed, so the power of the technology has always provided the flexibility to find solutions. Although the next generation of detector arrays is still under construction, future accelerator upgrades now under discussion will tax detector capabilities even more. Furthermore, we see developments coming full circle. After being driven by tracking applications in high-energy physics, we now see increasing interest in applying array technology to x-ray spectroscopy for astrophysics, materials science, and medical imaging. Even though the requirements are daunting and solutions not always obvious, we can be assured that semiconductor detector arrays will be key components in frontier experiments for years to come.