Scientific
Charge-Coupled Devices

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To the Universe.

Contents

Preface xiii

1 History, Operation, Performance, Design, Fabrication and Theory . 3

1.1 Scientific CCD History 3
1.2 Operation and Performance 22
1.2.1 Operation 22
1.2.2 Performance Functions 25
1.2.3 Performance Specifications 36
1.3 Architecture, Design, Photolitography and Fabrication 37
1.3.1 Architecture 37
1.3.2 Design and Photolithography 42
1.3.3 Processing and Fabrication 51
1.4 CCD Theory 61
1.4.1 MOS Capacitor 61
1.4.2 Surface-Channel Potential Well 65
1.4.3 Buried-Channel Potential Well 70
References 92
Further Reading 93

2 CCD Transfer Curves and Optimization 95

2.1 CCD Transfer Curves 95
2.1.1 CCD Performance 95
2.1.2 CCD Camera Performance 96
2.1.3 CCD Camera Calibration 97
2.2 Photon Transfer 97
2.2.1 Photon Transfer Derivation 98
2.2.2 Photon Transfer Curve 101
2.2.3 Camera Gain Constants 105
2.2.4 Camera Gain Histogram 108
2.2.5 Camera Gain Uncertainty 110
2.2.6 Dynamic Range 113
2.2.7 Linearity 117
2.2.8 Flat-Field Signal-to-Noise 120
2.2.9 Contrast Signal-to-Noise 121

2.2.10 High-Speed Photon Transfer Generation 125
2.2.11 Photon Transfer Simulation 130
2.3 X-Ray Transfer 131
2.3.1 X-ray Characteristics and Use 131
2.3.2 Fe^{55} 132
2.3.3 X-ray Images 139
2.3.4 X-ray Transfer 141
2.3.5 X-ray Histograms 143
2.3.6 Fano-Noise-Limited Performance 147
2.3.7 Cadmium X Rays 151
2.4 QE Transfer 151
2.5 CCD Clock and Bias Optimization 156
2.5.1 Clock and Bias 156
2.5.2 Set-point Transfer Curves 160
References 165

3 Charge Generation 167

3.1 Charge Generation 167
3.2 QE Formulas 170
3.2.1 Backside Illumination 170
3.2.2 Frontside Illumination 173
3.2.3 Miscellaneous QE Losses 174
3.2.4 Monte Carlo Simulation 177
3.3 Frontside Illumination 178
3.3.1 Phosphor Coatings 178
3.3.2 Virtual Phase 183
3.3.3 Open Pinned Phase 188
3.3.4 Thin Gate 190
3.3.5 Transparent Gate 194
3.3.6 Poly Hole Gate 194
3.4 Backside Illumination 195
3.4.1 Thinning 195
3.4.2 Quantum Efficiency Hysteresis 196
3.4.3 Accumulation and QE Pinning 199
3.4.4 Self-Accumulation 201
3.4.5 Accumulation Theory 214
3.4.6 Passive Accumulation 227
3.4.7 Active accumulation 256
3.4.8 Antireflection coatings 266
References 268

4 Charge Collection **273**

4.1 Charge Collection 273
4.2 Well Capacity 274
4.2.1 Bloomed Full Well 275
4.2.2 Surface Full Well 277
4.2.3 Optimum Full Well 277
4.2.4 Clocking Modes 280
4.2.5 Full Well Transfer 280
4.2.6 Full Well Data 283
4.2.7 Self-induced Emission and Thermionic Emission 289
4.2.8 Clocked Antiblooming 293
4.2.9 Antiblooming Structures 300
4.2.10 High-Speed Erasure 305
4.2.11 Window Clocking 310
4.2.12 Multipinned Phase (MPP) 310
4.3 Fixed-pattern Noise 318
4.3.1 Pixel Nonuniformity 318
4.3.2 Flat Fielding 321
4.3.3 Fixed-pattern Sources 325
4.4 Charge Diffusion 332
4.4.1 Charge Diffusion 332
4.4.2 Measurement and Modeling Techniques 338
4.4.3 Aliasing and Beating 373
References 383

5 Charge Transfer **387**

5.1 Charge Transfer 387
5.2 Transfer Mechanisms 390
5.2.1 Diffusion Drift 393
5.2.2 Self-induced Drift 395
5.2.3 Fringing Field Drift 396
5.2.4 High-Speed Data 400
5.2.5 Clock Propagation 405
5.2.6 Substrate Bounce 408
5.3 CTE Measurement Techniques 418
5.3.1 X-ray Transfer 418
5.3.2 Extended Pixel Edge Response (EPER) 423
5.3.3 First Pixel Edge Response 429
5.3.4 Pocket Pumping 430
5.3.5 Charge Injection 433
5.4 Traps 433
5.4.1 Design Traps 434
5.4.2 Process traps 439

5.4.3 Bulk Traps . . . 453
5.4.4 Radiation-induced Traps . . . 466
5.4.5 Proportional and Fixed Loss . . . 466
5.4.6 Fat-zero . . . 469
5.4.7 Notch Channel CCD . . . 472
5.5 Transfer Power . . . 476
5.5.1 Charge Motion Power . . . 478
5.5.2 Potential Power . . . 482
5.5.3 Reactive Power . . . 482
References . . . 486

6 Charge Measurement . . . 489

6.1 Charge Measurement . . . 489
6.2 Output Amplifier Characteristics . . . 490
6.2.1 Operation . . . 490
6.2.2 Voltage Gain . . . 498
6.2.3 Loading . . . 499
6.2.4 Output Impedance . . . 503
6.2.5 Time Response . . . 504
6.2.6 Frequency Response . . . 504
6.2.7 Bias . . . 507
6.2.8 Sensitivity . . . 509
6.2.9 Linearity . . . 516
6.2.10 Temperature Characteristics . . . 519
6.2.11 Lightly Doped Drain . . . 520
6.2.12 Amplifier Luminescence . . . 523
6.2.13 Multistage Amplifiers . . . 527
6.2.14 Power Consumption . . . 531
6.3 Output Amplifier Noise . . . 532
6.3.1 Johnson Noise . . . 532
6.3.2 Reset Noise . . . 537
6.3.3 White Noise . . . 541
6.3.4 Flicker Noise . . . 543
6.3.5 Shot Noise . . . 553
6.3.6 Contact and Popcorn Noise . . . 555
6.3.7 Output Amplifier Noise Equation . . . 555
6.4 Correlated Double Sampling . . . 556
6.4.1 Correlated Double Sampling Circuit Elements . . . 557
6.4.2 Correlated Double Sampling Circuits . . . 558
6.4.3 Camera Gain Constant . . . 561
6.4.4 Correlated Double Sampling Transfer Function . . . 563
6.5 Dual Slope Processor . . . 578
6.5.1 Dual Slope Circuit Elements . . . 578
6.5.2 Dual Slope Transfer Function . . . 579

6.6 Remnant Signal and Noise 582
6.6.1 Remnant Signal 582
6.6.2 Remnant Noise 583
6.7 Skipper Amplifier 585
6.7.1 Introduction 585
6.7.2 Operation 586
6.7.3 Performance 588
6.7.4 Design 592
6.7.5 Signal-to-Noise (Extended Images) 595
6.7.6 Signal-to-Noise (Point Images) 599
References 602

7 Noise Sources 605

7.1 On-chip Noise Sources 605
7.1.1 Dark Current 605
7.1.2 Spurious Charge 649
7.1.3 Fat-zero 654
7.1.4 Transfer Noise 656
7.1.5 Residual Image 657
7.1.6 Luminescence 665
7.1.7 Cosmic Rays and Radiation Interference 670
7.1.8 Excess Charge 674
7.1.9 Cosmetic Defects 678
7.1.10 Blem Spillover 679
7.1.11 Seam Noise 680
7.2 Off-chip Noise Sources 684
7.2.1 Light Leak 684
7.2.2 Preamplifier Noise 684
7.2.3 ADC Quantizing Noise 686
7.2.4 Clock-Jitter Noise 697
7.2.5 Electromagnetic Interference 699
7.2.6 Grounding 706
7.2.7 Image Cross Talk 711
7.2.8 Noise-Reduction Techniques 714
7.2.9 Noise-Reduction Summary 716
References 719

8 Damage 721

8.1 Radiation Damage 721
8.1.1 Introduction 721
8.1.2 Near-Earth Radiation Environment 723
8.1.3 Radiation Units 726
8.1.4 Transient Events 736

8.1.5 Ionization Damage Equivalence 749
8.1.6 Ionization Damage 750
8.1.7 Clock and Bias for Minimum Ionization Damage and Control 759
8.1.8 Ionization Damage Measurements 761
8.1.9 Bulk Damage 773
8.2 Electrical, Thermal and ESD Damage 837
8.2.1 Electrical Damage 837
8.2.2 Thermal Damage 838
8.2.3 Electrostatic Discharge (ESD) Damage 839
References 841

Appendixes **847**

Glossary of CCD Terms **871**

Index **899**

Preface

This book began from a series of lecture notes for courses held on charge-coupled devices and digital camera systems at UCLA Extension and SPIE meetings in the mid-1980s. These sessions were well attended and met with great enthusiasm by the scientific and commercial imaging communities. The courses, and the enthusiasm, continue today after 15 years.

The courses are intended for scientists, engineers, and hardware managers involved with CCD imaging sensors and camera systems. The material details advances made in pixel count (arrays as large as 10,000 by 10,000 pixels), quantum efficiency (spectral coverage of 1 to 11,000 Å), charge transfer efficiency (99.9999% efficient per pixel transfer), read noise (less than 1 e^- rms), large dynamic range (greater than 10^6), and high-speed operation (diffusion-limited). The CCD technologies used to achieve such high levels of performance are discussed. The courses also review the electronic design of slow-scan and fast-scan CCD imaging camera systems. Applications include near-IR, visible, UV, EUV, x-ray, and particle cameras. The success of these courses prompted us to bring these notes together, along with additional detailed discussions, into a single comprehensive reference manual and tutorial. It is a timely collection, as the CCD has recently celebrated its thirtieth birthday.

This book is written for a wide audience—from the novice to the advanced CCD user. The level of the book's presentation is suitable for students in physics and engineering who have received a standard preparation in modern solid state physics and electronic circuits. Numerous examples throughout the text provide valuable exercises for students and perspective for the professional imaging engineer in terms of modern CCD performance. The text captures 30 years of experimentation with the technology, giving the less-experienced engineer the benefit of the lessons learned during the development of the CCD. Although the book focuses on scientific devices, it is also of interest to other imaging engineers who work with commercial CCDs for broadcasting and photography. Other areas of overlap include CMOS, CID, and photodiode imaging arrays. The book can be used as a reference for participants in educational short courses organized by SPIE and other educational institutions as well.

Scientific Charge-Coupled Devices contains more than 500 figures and illustrations which present experimental and modeling data products taken from many scientific CCDs in operation. The majority of these sensors are found in space imaging cameras that are currently generating new and exciting facts about the universe in which we live. The book provides hundreds of modeling equations used to support the data presented. It has been very important that theory and experiment work hand-in-hand to bring about a sensor that is nearly textbook perfect. This intimate connection also shows us the physical limitations of device performance and what potential advances might be made in the future. Also, the CCD has inspired its own language to describe its unique characteristics and operational features. Therefore, we have included a glossary of CCD terms to which the reader can refer.

The book is organized into eight chapters. Chapter 1 reviews historical aspects of the scientific CCD as taken from the author's perspective and experiences. As with most celebrated technologies, the CCD of today was not born overnight; the technical and political climates that gave rise to the CCD imaging revolution was complex and interesting. Chapter 1 also includes a review of the basics of CCD operation and performance which serve as the book's skeleton—charge generation, charge collection, charge transfer and charge measurement—as well as performance characteristics and related specifications. The chapter will also acquaint the reader with different CCD architectures and how the sensors are designed and fabricated. Presented is basic solid state CCD theory, which is necessary to understand and support the experimental findings presented in subsequent chapters. In particular the potential well, which is responsible for collecting and transferring charge, is studied in detail.

Chapter 2 introduces standard tests and absolute units used to characterize, optimize, and calibrate CCD performance, presented in the form of transfer curves. For example, an important transfer curve called photon transfer produces a multitude of critical performance data products: read noise, full well, dynamic range, linearity, signal-to-noise, etc. The chapter will also take the reader through a CCD clock and bias optimization procedure using transfer curves as a guide. The material in this section is considered advanced but it is critically important in order to achieve the high and reliable performance results that CCD camera users demand.

Chapter 3 discusses the first major operation performed by the CCD: charge generation. It is shown that the charge generation process is capable of covering an enormous wavelength range, from the IR to the hard x ray, covering more than four decades of spectral range (i.e., 1 to 11,000 Å). We will review several loss mechanisms that prevent incoming photons from interacting with the CCD. Discussions are then given to high-performance frontside-illumination CCDs whose design features reduce interaction loss. We then discuss the highest-sensitivity device available to the imaging community, the backside-illuminated CCD. Detailed studies are given on the backside accumulation process required by this technology.

Chapter 4 on charge collection explores the ability of the CCD to form an image after charge is generated. Three performance parameters associated with charge collection efficiency are elaborated: well capacity, pixel nonuniformity, and charge diffusion. The modulation transfer function (MTF) is discussed in considerable detail in quantifying charge diffusion effects and limiting performance.

Chapter 5 deals with charge transfer, the third basic CCD operation. Discussions include a review of the charge transfer efficiency (CTE) requirements for high-performance large-area arrays and physical descriptions responsible for high-speed charge movement. The chapter discusses several CTE measurement techniques in characterizing charge traps that limit CTE performance. Numerous operational, process and design solutions are given to solve CTE problems when encountered. We close the chapter with a short discussion on the power dissipated behind the charge transfer process.

Chapter 6 discusses charge measurement, the last major CCD operation. Discussions here are devoted to the sensor's output amplifier and off-chip signal processing electronics. We will describe the progress that has been achieved in the areas of design, processing and operation to achieve ultralow-noise performance. The chapter discusses other amplifier characteristics such as loading, output impedance, frequency response, sensitivity, linearity, and power consumption. The technique of correlated double sampling (CDS) is reviewed in detail, an important video processing circuit that delivers optimum S/N performance. The last section reviews a floating gate amplifier that allows subelectron noise performance.

Chapter 7 focuses on noise sources other than the CCD's output amplifier. The sources are grouped into two major categories: on-chip and off-chip. This chapter familiarizes the reader with the multitude of known noise sources, which can fundamentally be reduced below that of the noise generated by the output amplifier. Important noise sources include dark current, spurious charge, fat-zero, residual image, luminescence, cosmic rays, cosmetic defects, quantizing noise, clock jitter, electromagnetic interference, grounding noise and other sources.

Chapter 8 is on the subject of CCD damage. The majority of the chapter is devoted to the damage induced by high-energy radiation sources. Numerous design, processing, and operational solutions are given to address and alleviate the problem. Discussions on transient events produced by high-energy particles and photons are also provided. A technique that converts a complicated radiation environment into a single energy that produces the same damage is described. The last subject of this chapter is on electrical, thermal and ESD damage mechanisms.

In the course of the writing this book, many people have assisted me and offered their support. I would like to express my appreciation to the management of NASA's Jet Propulsion Laboratory for providing the rich environment for the research and investigation of CCDs from their conception; without their support this book could have not been written. I also thank Pixel Vision for the R&D environment directed toward high-speed backside-illuminated CCDs discussed in Chapter 5. I wish to express my gratitude to Tom Elliott for being my partner for nearly 15 years in generating the majority of the data products presented in this book. His artistic skills and ingenuity in conjunction with his natural curiosity about CCDs reflects upon the figures presented. Special thanks go to Jeff Pinter and Jim McCarthy, who through countless hours of CCD discussions on the black board brought excitement into the book. I have benefitted significantly from technical discussions with Stewart Collins, Taner Dosuoglu, Morley Blouke, Denis Heidtman, Dick Bredthauer, George Soli, Jim Westphal, Fred Landauer, Jim Gunn, Bob Locke, Mark Wadsworth, Michael Lesser, Bob Hlivak, Lloyd Robinson, Barry Burke, Willard Boyle, Jim Early, Albert Theuwissen, George Smith, Gene Weckler, Rudy Dyck, Ken Klaasen, Charles Chandler, Kurt Liewer, Dave Burrows, Gorden Garmire, Paul Vu, Dick Savoye, Rusty Winzenread, Andrew Holland, David Lumb, Fred Harris, Russ Schaefer, Taher Daud, Jerry Hynecke, Dave Norris, Robert Groulx, Raymond Frost, Arsham Dingzian, Gorden Hopkinson, Bev Oke, Terrence Lomheim, Gary Sims, Walter Kosonocky, Nelson Saks, Cheryl Dale, Paul Marshall, Fred Pool, Loren Acton, Bob Lockart, Dave Swenson, John Geary, Jim Beletic, Alice Reinheimer, Larry Hovland, Sandra Faber, Bedabrata Pain, John Flemming, and Harry Marsh.

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