

## **CONTENTS**

Symbol list	xiii
List of figures	xix
Preface	xxv
Chapter 0 : Introduction	1
Chapter 1 : Fundamentals of charge-coupled devices	7
1.1. An ideal MOS capacitor	7
1.1.1. MOS capacitance in accumulation	8
1.1.2. MOS capacitance in deep depletion	10
1.1.3. MOS capacitance in inversion	13
1.1.4. MOS capacitance in weak inversion	16
1.2. A real MOS-capacitor in a charge-coupled device	18
1.3. Charge transfer	25
1.3.1. Thermal diffusion	28
1.3.2. Self-induced drift	29
1.3.3. Fringing fields	31
1.4. Charge transfer (in)efficiency	36
1.5. Buried channel CCD	39
1.5.1. From SCCD to BCCD	40
1.5.2. Fringing field and transfer time	42
1.5.3. Charge-handling capability	45
1.6. One-dimensional potential analysis	48
1.7. Conclusions	51
Chapter 2 : Into, through and out of a charge-coupled device	53
2.1. Transport systems	54
2.1.1. Four-phase system	54
2.1.2. Three-phase system	57
2.1.3. Two-phase system	58
2.1.4. One-and-a-half phase system	62
2.1.5. Virtual-phase system	63
2.1.6. Ripple clock	63
2.2. Channel definition	66
2.3. Input structures	69
2.3.1. Diode cut-off	70

	SOLID-STATE IMAGING WITH CHARGE-COUPLED DEVICES	ix
2.3.2. Fill-and-spill	73	157
2.4. Output structures	75	159
2.4.1. Floating diffusion with reset	76	161
2.4.2. Floating gate without reset	79	161
2.5. Conclusions	83	161
 Chapter 3 : A real CCD delay line	 85	 162
3.1. Effect of transport inefficiency	87	165
3.2. Effect of dark current	92	166
3.3. Effect of dark-current nonuniformities	94	168
3.4. Effect of noise	97	170
3.4.1. Shot noise	97	171
3.4.2. Trapping noise	98	171
3.4.3. KTC noise	99	173
3.4.4. Amplifier noise	99	173
3.5. Sampling of an electrical signal	100	176
3.6. Conclusions	106	176
 Chapter 4 : Solid-state imaging at a glance	 109	 183
4.1. Photon sensing	109	184
4.2. Imager configurations	112	184
4.2.1. Linear imagers	112	188
4.2.2. Array imagers	114	188
Frame-transfer CCD	114	
Interline-transfer CCD	117	
Frame-interline-transfer CCD	119	
MOS-XY imager	120	
Charge-injection device	123	
Overview array imagers	125	
4.3. Conclusions	128	
 Chapter 5 : Fundamentals of solid-state imaging	 131	 193
5.1. Absorption of photons	131	193
5.2. Collection of generated carriers	134	195
5.3. Spectral response	136	196
5.4. Quantum efficiency	139	201
5.5. Resolution	142	202
5.5.1. Diffusion MTF	143	205
5.5.2. Transport MTF	145	205
5.5.3. Geometric MTF	148	207
5.6. Aliasing and Moiré effects	152	208
5.7. Conclusions	154	211
 Chapter 6 : Solid-state imaging for television applications	 157	 211
6.1. Scanning modes	159	212
6.1.1. Interlaced scanning	161	213
Frame-transfer CCD	161	213
(Frame-)interline-transfer CCD	161	214
6.1.2. Progressive scanning	162	215
6.2. Color imaging	165	215
6.2.1. Stripe filters	166	217
6.2.2. Mosaic filters	168	
6.2.3. Primary or complementary, stripe or mosaic	170	
6.2.4. Color separation by a prism	171	
6.2.5. Color imaging with linear arrays	173	
6.3. Blooming and antiblooming	176	
6.3.1. Lateral or horizontal antiblooming	177	
6.3.2. Charge-pumped or clocked antiblooming	178	
6.3.3. Vertical antiblooming	179	
6.4. Charge reset or electronic shutter	183	
6.4.1. Charge reset in frame-transfer CCDs	184	
6.4.2. Charge reset in (frame-)interline-transfer CCDs	184	
6.4.3. Charge reset in MOS-XY and CID imagers	188	
6.5. Conclusions	190	
 Chapter 7 : Advanced imaging : light sensitivity	 193	 217
7.1. Increasing the light sensitivity	193	217
7.2. Aperture ratio of the pixels	195	
7.2.1. Microlenses	196	
7.2.2. Photoconversion top layer	201	
7.2.3. Optimizing the vertical CCDs	202	
7.3. Light transmission of multilayered structure	205	
7.3.1. Adapting the optical thicknesses	205	
7.3.2. Minimizing the number of gates	207	
7.3.3. Transparent conductive gates	208	
7.4. Back-side illumination	211	
7.5. Pixels with an amplification function	211	
7.5.1. Static-induction transistor	212	
7.5.2. Charge-modulation device	213	
7.5.3. Bulk charge-modulated device	213	
7.5.4. Amplified MOS intelligent imager	214	
7.5.5. Base-stored image sensor	215	
7.6. Conclusions	217	

## CONTENTS

## SOLID-STATE IMAGING WITH CHARGE-COUPLED DEVICES

Chapter 8 : Advanced imaging : noise and smear	219	10.1.2. Buttable devices	281
8.1. Decreasing noise levels	220	10.1.3. Notch CCD	282
8.2. Technology-related noise	221	10.1.4. Skipper CCD	283
8.2.1. Point defects	221	10.1.5. Pinned-phase CCDs	285
8.2.2. Column defects	222	Open-phase pinned CCDs	287
8.2.3. Transfer noise	222	Multi-phase pinning CCDs	288
8.2.4. Striations	222	Dynamic pinning	290
8.2.5. Pixel nonuniformities	222	10.2. Smart image sensors	293
8.2.6. Dark-current shot noise	223	10.2.1. ASIC Vision	293
8.3. Output-amplifier noise	224	10.2.2. Three-dimensional integrated image sensor	294
8.3.1. Thermal noise	225	10.2.3. Foveated-retina sensor	296
8.3.2. 1/f noise	227	10.3. Nonvisible imaging	297
8.3.3. Reset noise	227	10.3.1. Infrared imaging	298
8.3.4. Elimination of the reset noise	228	10.3.2. UV imaging	302
8.3.5. New output-amplifier architectures	231	10.3.3. X-ray imaging	306
8.4. Output-amplifier sensitivity	234	X-ray imaging for spectroscopic purposes	306
8.5. Smear	236	X-ray imaging for medical purposes	308
8.5.1. Smear in frame-transfer CCDs	236	10.4. High-speed imagers	310
8.5.2. Smear in (frame-)interline-transfer CCDs	237	10.4.1. Imagers with multiple outputs	310
8.5.3. Smear compensation techniques	239	10.4.2. Gallium-arsenide CCD Imagers	311
8.5.4. Smear in MOS-XY and CID imagers	240	10.5. Contact-type linear imagers	311
8.5.5. State of the art in smear suppression	242	10.6. Conclusions	313
8.6. Conclusions	244		
Chapter 9 : Advanced imaging : device architectures	247	APPENDIX 1 : How CCD imagers are made	317
9.1. Increasing horizontal pixel density	248	A1.1. Substrate preparation	320
9.1.1. Design adaptation	253	A1.2. Implantation of the p well	321
9.1.2. Gate tapering	253	A1.3. Drive-in of the p well	322
9.1.3. Extra channel implantations	254	A1.4. Implantation of the CCD channel	323
9.1.4. Compound channels	257	A1.5. Drive-in of the channel implant	324
9.1.5. Combined techniques	258	A1.6. Implantation of the channel stoppers	325
9.2. New clocking schemes for vertical registers	258	A1.7. Gate oxidation	326
9.2.1. Accordion CCD	259	A1.8. Deposition of the first poly-Si layer	327
9.2.2. Charge-sweep device (CSD)	262	A1.9. Definition of the first poly-Si layer	328
9.2.3. High-speed clocks for vertical CCDs	262	A1.10. Interpoly isolation	329
9.2.4. Dynamic pixel management	264	A1.11. Deposition of the second poly-Si layer	330
9.3. Electronic still picture	267	A1.12. Definition of the second poly-Si layer	331
9.4. Time-delay and integrating CCD	274	A1.13. Interpoly isolation	332
9.5. Conclusions	276	A1.14. Deposition of the third poly-Si layer	333
Chapter 10 : Nonconsumer imaging	279	A1.15. Definition of the third poly-Si layer	334
10.1. Scientific imagers	280	A1.16. Source and drain implantation	335
10.1.1. Large-area devices	280	A1.17. Back-end isolation	336
		A1.18. Contact-hole definition	337
		A1.19. Deposition of the metal layer	338

A1.20. Definition of the metallization pattern	339
A1.21. Scratch-protection deposition	340
A1.22. Deposition of the first color filter layer	341
A1.23. Lift-off of the first color filter	342
A1.24. Deposition of the second filter layer	343
A1.25. Lift-off of the second color filter	344
A1.26. Deposition of planarization layers	345
A1.27. Etch-back of the planarization layers	346
A1.28. Deposition of the lens material	347
A1.29. Reflow of the microlenses	348
 APPENDIX 2 : How to interpret CCD artifacts	349
A2.1. Reference picture	349
A2.2. Smear	350
A2.3. Charge reset	350
A2.4. Blooming	351
A2.5. Integration-time shortening	351
A2.6. Column defects	353
A2.7. Cover glass damage	354
A2.8. Damage by electrostatic discharge	355
A2.9. Gate dielectric damage	355
A2.10. White point defects	356
A2.11. Fixed-pattern noise	357
A2.12. Other noise sources	358
 APPENDIX 3 : How to compromise on CCD specifications	359
A3.1. Sensitivity and quantum efficiency	359
A3.2. Resolution	359
A3.3. Horizontal modulation transfer function	360
A3.4. Vertical modulation transfer function	360
A3.4.1. Frame-transfer CCD	360
A3.4.2. Frame-interline-transfer and interline-transfer CCD	362
A3.5. Antiblooming	363
A3.6. Smear	364
A3.7. Cost price	365
 References	367
 Index	381