Contents

Abstract **iv**

Preface **v**

Acknowledgments **vii**

1 Introduction **1**

1.1 A Very Brief History of Visible Detectors in Astronomy 1

1.2 The CCD: Astronomy's Champion Workhorse 4

1.2.1 CCD Operation 4

1.2.2 Drawbacks of the CCD in Astronomy 7

1.2.3 Where the CCD Wins in Astronomy 11

1.3 CMOS: Motivation for a New Detector 13

1.3.1 Overview of CMOS Imager Operation 14

1.3.2 Monolithic CMOS Imagers 15

1.3.3 Hybrid CMOS Imagers 16

1.3.4 Advantages of CMOS Arrays for Astronomy 19

1.3.5 Disadvantages of CMOS Arrays in Astronomy 22

2 Overview of Silicon PIN Detectors **24**

2.1 PIN Diodes 24

2.1.1 General Discussion of PIN Diodes 24

2.1.2 PIN Diode Circuit Equivalent Model 26

2.1.3 Punch Trough Voltage 27

2.2 HyViSI Detector 29

2.2.1 HyViSI PIN Diode 29

2.2.2 The HyViSI Pixel 34

3 Hybrid Imager Features **40**
3.1 Full Frame Mode . . . 40
3.1.1 Up the Ramp Terminology . . . 42
3.2 Window Mode . . . 42
3.2.1 Variation of Multiple Window Readout Sequences . . . 44
3.3 Guide Mode . . . 44
3.4 Reference Pixels . . . 45
3.5 Readout Electronics: SIDECAR ASIC . . . 49
3.5.1 Pre-Amplification Stage . . . 51
3.5.2 Conversion Gain . . . 54
3.5.3 Averaging Multiple Channels . . . 55
3.5.4 Noise Performance vs. Pixel Time . . . 58
3.5.5 Reference Voltages for SIDECAR when Connected to an HxRG . . . 59

4 Laboratory Testing of SiPIN Detectors **62**
4.1 Description of Laboratory Setups and Devices Tested . . . 62
4.2 Pixel Classification and Operability . . . 65
4.2.1 Dead or Railed Pixels . . . 65
4.2.2 Hot Pixels . . . 65
4.2.3 Open Pixels . . . 66
4.2.4 Volcanoes . . . 66
4.2.5 Summary of Pixels . . . 67
4.3 Conversion Gain and Nodal Capacitance . . . 68
4.3.1 Contributions to the Gain . . . 68
4.3.2 Electronics Gain – G_{AMP} & $G_{A/D}$ . . . 68
4.3.3 Unit Cell Source Follower Gain – G_{UC} . . . 69
4.3.4 Output Source Follower Gain – G_{OUT} . . . 69
4.3.5 Net Conversion Gain – G_{NET} . . . 71
4.3.6 Nodal Capacitance – G_{PIXEL} . . . 72
4.3.7 Results for HyViSI Detectors . . . 73
4.4 Read Noise . . . 75
4.4.1 Sources of Read Noise in Hybrid CMOS Detectors . . . 75
4.4.2 Noise Reduction Techniques . . . 78
4.4.3 HyViSI Measurements . . . 81
4.5 Dark Current . . . 84
4.5.1 Sources of Dark Current . . . 84
4.5.2 Estimating Dark Current . . . 84
4.5.3 HyViSI Dark Currents . . . 86

4.5.4 Reset Anomaly in HyViSI . . . 87
4.6 Quantum Efficiency . . . 90
4.6.1 PIN Diode Quantum Efficiency . . . 90
4.6.2 HyViSI Detective Quantum Efficiency (DQE) . . . 90
4.7 Linearity/Well Depth . . . 92
4.7.1 Sources of Nonlinearity in HyViSI Detectors . . . 92
4.7.2 Measurements of Nonlinearity in HyViSI Detectors . . . 93
4.7.3 HyViSI Well Depths . . . 97

5 Silicon PIN Detectors in Astronomy 98
5.1 Observations with the Kitt Peak 2.1m Telescope . . . 98
5.2 Data Reduction and Calibration . . . 100
5.2.1 Data Reduction Theory . . . 100
5.2.2 Reference Pixel Correction . . . 102
5.2.3 Dark Subtraction . . . 103
5.2.4 Slope Fitting . . . 103
5.2.5 Flat Fielding . . . 105
5.2.6 Combining Dithers . . . 106
5.2.7 Telescope Calibration with Multiple Windows . . . 106
5.2.8 Expected Point Spread Function . . . 108
5.3 Photometry . . . 112
5.3.1 Aperture Photometry . . . 113
5.3.2 Crowded Field Photometry . . . 116
5.3.3 High Speed Photometry with Guide Windows . . . 118
5.3.4 Variability Measurements of BE Lyn . . . 118
5.4 Astrometry . . . 122
5.4.1 Sources of Astrometric Error . . . 123
5.4.2 Astrometric Reduction . . . 124
5.4.3 Astrometric Results with H2RG-32-147 and H1RG-022 . . . 125
5.4.4 Astrometric Results with H4RG-10-007 . . . 126
5.5 Telescope Guiding in Guide Mode . . . 127
5.5.1 Purpose of Experiment . . . 127
5.5.2 Results without Guide Mode . . . 128
5.5.3 Results with Guide Mode . . . 129
5.5.4 Comparison between Exposures with and without Guide Mode . . . 130
5.5.5 Saturated Pixels . . . 133
5.5.6 Summary of Results . . . 133
5.5.7 Discussion . . . 134

5.6 Near Infrared Response . . . 135

6 Pixel and Electronic Crosstalk 137

6.1 Pixel Crosstalk . . . 137
6.1.1 Mechanisms of Pixel Crosstalk . . . 138
6.1.2 Measurement via Cosmic Rays . . . 140
6.1.3 Measurement via Fe^{55} . . . 150
6.1.4 Measurement via Single Pixel Reset . . . 160
6.2 Electronic Crosstalk . . . 168
6.2.1 Column Bleeding . . . 168
6.2.2 Output Coupling . . . 171

7 Persistence in HyViSI Detectors 174

7.1 Trap Theory . . . 174
7.1.1 Hole Capture and Release from Shallow Traps . . . 176
7.1.2 Hole and Electron Capture from Deep Level Traps . . . 178
7.2 Latent Images and Persistence . . . 180
7.2.1 Persistent Charge Emission . . . 181
7.2.2 Dependence on Flux and Fluence . . . 186
7.2.3 Dependence on Detector Activity . . . 191
7.2.4 Dependence on Temperature . . . 192
7.2.5 Dependence on V_{SUB} . . . 194
7.3 Semi-Permanent Offsets: Laser Burn-In . . . 198
7.4 Effect of Forward Biasing . . . 201
7.4.1 Theory of Bias-Direction Switch . . . 201
7.4.2 Forward Bias to Full Reverse Bias of $V_{SUB} = 15$V . . . 202
7.4.3 Incrementing Reverse Bias with $\Delta V_{SUB} = 2$V . . . 205
7.5 Model, Simulations, and Summary . . . 207
7.5.1 Phenomenological Description . . . 207
7.5.2 Persistence Simulations . . . 209
7.5.3 Summary . . . 214
7.6 Dealing with Persistence . . . 217
7.6.1 Persistence Reduction by Design . . . 217
7.6.2 Reduction After Design . . . 218

A Data Reduction 222

A.1 IRAF Parameters . . . 222

B Signal to Noise Ratio 223

C Numerical Simulations **224**
C.1 PN Junctions 224
C.2 Basic Semiconductor Physics 224
C.3 Numerical Methods: Finite Volume Scheme 225
C.4 Results for Abrupt PN Junction 229
C.5 Cylindrically Symmetric Persistence Simulations 233

D Conversion Gain Reference **236**

Bibliography **238**

List of Tables

3.1 C_{FAC} Values for Individual Detectors 48
3.2 SIDECAR Conversion Gain Table 55
3.3 SIDECAR Clocking Table for Averaging Multiple Channels 56
3.4 SIDECAR Operating Parameters at Different Sampling Rates 59

4.1 HyViSI Detectors Tested in the Laboratory 64
4.2 Pixel Type Fractions for HyViSI Detectors Tested 67
4.3 Fe^{55} Lines from Radioactive Decay 71
4.4 Conversion Gains, Nodal Capacitances, and Well Depth of HyViSI Devices 73
4.5 HyViSI Well Depths 97

5.1 Details for Observing Runs at Kitt Peak 2.1m Telescope 98
5.2 Filter Characteristics 99
5.3 Measured Magnitude for Landolt Standards 114
5.4 Magnitude Transformation Equations for Landolt Standards 115
5.5 Parameters from M13 Exposures 116
5.6 Variability Parameters for the Delta Scuti Star BE Lyn 119
5.7 Comparison of Astrometric Error with and without Guiding 126
5.8 Comparison of Guide Mode vs. No Guiding 133

6.1 Pixel Crosstalk Parameters for H2RG-001 155

7.1 Parameters for Core-Halo Simulation 212

List of Figures

1.1 Multi-Color Image of M13 Globular Cluster Taken with HyViSI H4RG-10-007 3
1.2 Simple Diagram of a 4×4 CCD 4
1.3 Illustration of the Process of Clocking in a CCD 7
1.4 Cartoon of CCD Destructive Readout 8
1.5 Simplified Diagram of Passive and Active CMOS Pixel Architecture 13
1.6 Simplified Diagram of CMOS Multiplexer and 3T Pixel 15
1.7 Diagram of Per-Pixel Depleted and Fully Depleted Hybrid CMOS Arrays 17

2.1 Diagram of PIN Diode 25
2.2 Circuit Equivalent of a PIN Diode 27
2.3 Resistivity of Silicon as a Function of Doping Density 28
2.4 Image and Cross Section Diagram of HyViSI detector 29
2.5 Diagram of PIN Diodes in a HyViSI Detector 30
2.6 PIN Diode Quantities for Backside Voltage $V_{SUB} = 0 - 10$V 32
2.7 PIN Diode Quantities for Backside Voltage $V_{SUB} = 15 - 35$V 33
2.8 A Mock Schematic of the Full HyViSI Pixel 34
2.9 PIN Diode as Capacitor During and After Reset 35
2.10 HyViSI Pixel Circuit Equivalent 37
2.11 Lateral Diffusion and Blooming in an Undepleted Detector 39

3.1 Ramp Sequence Diagram and Clocking Patterns for HxRG Multiplexers 41
3.2 Window Mode Diagram 43
3.3 Signal of Science and Reference Pixels for H1RG-022 with no C_{FAC} 45
3.4 Difference of Science and Reference Pixels for H1RG-022 46
3.5 Slope Error with C_{FAC} 47
3.6 Difference of Science and Reference Pixels for H1RG-022 after Applying C_{FAC} 48
3.7 SIDECAR ASIC Block Diagram and Photograph 50
3.8 SIDECAR ASIC Development Kit in RIT Laboratory 51
3.9 SIDECAR Amplification Stage 52

3.10 SIDECAR Noise Images: Reset Schemes 53
3.11 SIDECAR Conversion Gain 54
3.12 Multiple Channels Averaged in SIDECAR 57
3.13 Read Noise of H1RG-022 with Multiple Channels Averaged 58
3.14 SIDECAR Images and Histograms with Non-ideal Operating Parameters 61

4.1 Dewar Used at Rochester Imaging Detector Laboratory 63
4.2 Flat Field Image Showing Open Pixels 67
4.3 Diagram of Unit Cell, Bus Lines, and Output of H2RG 69
4.4 Electronic Gain for H1RG-022 70
4.5 Fe55 Histogram for H2RG-001 72
4.6 Temperature Dependence of Conversion Gain with Constant $V_{BIASGATE}$ 74
4.7 Simplified Diagram of Noise Associated with Resetting Pixels 75
4.8 Up the Ramp Exposure Diagram with Fowler Sampling 80
4.9 CDS Read Noise Map for H2RG-001 at 100 K 81
4.10 Temperature Dependence of CDS Read Noise for H2RG-001 82
4.11 Read Noise vs. Fowler Pair and Temperature Dependence for H2RG-001 83
4.12 Dark Current Histogram for H1RG-022 85
4.13 Dark Current vs. Temperature for HyViSI Detectors 86
4.14 Pixel Ramp Showing Reset Anomaly in H1RG-022 88
4.15 Reset Anomaly at Different Reset Voltages 89
4.16 Detective Quantum Efficiency of H4RG-10-007 91
4.17 Fringing in Monochromatic Flat Field near 1 μm 91
4.18 Photon Transfer Curves for H2RG-32-147 with Output Source Follower Enabled . . 93
4.19 Linearity of H2RG-32-147 and H2RG-001 as a Function of Electrons Integrated on Nodal Capacitance. 96

5.1 Photograph of RIDL Dewar Mounted to Kitt Peak 2.1m Telescope 99
5.2 Drift of Telescope from Sidereal Tracking Rate 108
5.3 Expected Ellipticity and FWHM in Guiding and Unguided Operation 111
5.4 Magnitude Plot for Landolt Photometric Standards 115
5.5 M13 Color Magnitude Diagram in g and i 117
5.6 M13 Color Magnitude Diagram in g and y 117
5.7 Magnitude vs. Time for BE Lyn and Reference Star GSC 03425-00544 120
5.8 Magnitude vs. Time for BE Lyn after Normalization by Reference Star and Filtering 121
5.9 Astrometric Error vs. Exposure Time for H2RG-32-147 Observations of Open Cluster NGC 956 125
5.10 Long Time Exposure Taken with H1RG-022 with No Guiding 129

5.11 Long Time Exposure Taken with H2RG-32-147 in Guide Mode 130
5.12 Comparison of Long Time Exposures With and Without Telescope Guiding 131
5.13 Exposure Time Required to Reach Limiting Magnitude 132
5.14 Interpixel Capacitance of Guide Window with Surrounding Pixels 134
5.15 Tri-color Image of Orion Nebula Showing Near IR Response 136

6.1 Cosmic Ray Ramps and Decay of Signal After Incidence 141
6.2 Charge Lost by Pixel in 800 Seconds as a Function of Charge Deposited by Cosmic Ray 144
6.3 Histograms of Time Constant c_n in Cosmic Ray Decays for Different Temperatures 145
6.4 Muon Track Showing Different Charge Loss at Opposing Ends 146
6.5 Dependence of Charge Loss on Depth of Interaction for Extended Muon Tracks . . . 147
6.6 Cosmic Ray Pixels Sharing Charge 148
6.7 No Coupling of Reference Pixels to Science Pixels During Cosmic Ray Event 149
6.8 Examples of Single and Multiple Pixel Events from Fe^{55} Exposure 151
6.9 Examples of Fe^{55} Distributions from Guess and Check Iteration Process 153
6.10 Pixel Crosstalk vs. Temperature for H2RG-001 155
6.11 Fe^{55} Ramps Showing Charge Loss 156
6.12 Pictorial Plot Showing Loss of Charge After Fe^{55} Hit 157
6.13 Shift and FWHM of Fe^{55} Peak in temperature range 140-170 Kelvin 159
6.14 The Effect of Charge Loss on Fe^{55} Spectrum at 170 K 159
6.15 Pixel Crosstalk with Single Pixel Reset 162
6.16 The Effect of Single Pixel Reset on Column Voltage 163
6.17 Charge Diffusion and Persistence in Single Pixel Reset Experiments at Temperatures from 100-180 K. 164
6.18 Signal Measured for Pixel Subject to Single Pixel Reset as a Function of V_{RESET} . . 166
6.19 Zoom-in of Signal Measured for Pixel Subject to Single Pixel Reset as a Function of V_{RESET} 167
6.20 Column Bleeding in Horsehead Nebula Mosaic Taken with H2RG-32-147 168
6.21 Star Showing Column Bleeding and Threshold 169
6.22 Output Coupling in Mosaic of SAO 117637 Taken with H2RG-32-147 171
6.23 Output Coupling Circuit Diagram 172
6.24 Output Coupling with No Source Follower 173

7.1 Saturn: Saturated and Persistent Images 180
7.2 Temporal and Spatial Evolution of Persistence Structure 183
7.3 Diagram of Core-Halo Persistence Structure 184
7.4 Ramps for Pixels in Region Surrounding Persistence Center 185

7.5 Maximum Persistence Signal in 14 Second Exposure 187
7.6 Minimum Persistence Signal in 14 Second Exposure 188
7.7 Decay of Dark Current in Core-Halo Persistence 190
7.8 Histograms of Time Constants for Latent Image Decays 190
7.9 Latent Image Lasting More than One Hour 191
7.10 Pixel Ramp Showing Reset Anomaly in H1RG-022 193
7.11 Latent Images at Different Values of V_{SUB} 195
7.12 Stored and Excess Hole Populations Under Saturation in Undepleted Detector . . . 197
7.13 Semi-Permanent Offset in H2RG-32-147 Burned in by Mars 198
7.14 6 Month Decay of Laser Burn-In on H2RG-32-029 200
7.15 Dark Current after Forward Bias and Return to Reverse Bias in H1RG-022 204
7.16 Dark Current after Increasing V_{SUB} in H1RG-018 205
7.17 Toy Model of Charge Density, Electric Field, and Electric Potential in PIN Diode . . 208
7.18 Drift and Diffusion Currents Responsible for Negative Persistence 210
7.19 Comparison of Ramps and Radial Profiles for Simulated Persistence and Real Data . 212
7.20 Comparison of Simulated Hole and Electron Distributions with and without Drift . . 214
7.21 Dither Sequence Showing Persistence in all Dither Locations 219

C.1 PN Junction Diagram 226
C.2 Results for PN Junction with No Applied Bias 231
C.3 Results for PN Junction Under Reverse Bias 232