HYBRID CMOS SIPIN DETECTORS AS ASTRONOMICAL IMAGERS

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Abstract

Charge Coupled Devices (CCDs) have dominated optical and x-ray astronomy since their inception in 1969. Only recently, through improvements in design and fabrication methods, have imagers that use Complimentary Metal Oxide Semiconductor (CMOS) technology gained ground on CCDs in scientific imaging. We are now in the midst of an era where astronomers might begin to design optical telescope cameras that employ CMOS imagers.

The first three chapters of this dissertation are primarily composed of introductory material. In them, we discuss the potential advantages that CMOS imagers offer over CCDs in astronomical applications. We compare the two technologies in terms of the standard metrics used to evaluate and compare scientific imagers: dark current, read noise, linearity, etc. We also discuss novel features of CMOS devices and the benefits they offer to astronomy. In particular, we focus on a specific kind of hybrid CMOS sensor that uses Silicon PIN photodiodes to detect optical light in order to overcome deficiencies of commercial CMOS sensors.

The remaining four chapters focus on a specific type of hybrid CMOS Silicon PIN sensor: the Teledyne Hybrid Visible Silicon PIN Imager (HyViSI). In chapters four and five, results from testing HyViSI detectors in the laboratory and at the Kitt Peak 2.1m telescope are presented. We present our laboratory measurements of the standard detector metrics for a number of HyViSI devices, ranging from 1k×1k to 4k×4k format. We also include a description of the SIDECAR readout circuit that was used to control the detectors. We then show how they performed at the telescope in terms of photometry, astrometry, variability measurement, and telescope focusing and guiding.

Lastly, in the final two chapters we present results on detector artifacts such as pixel crosstalk, electronic crosstalk, and image persistence. One form of pixel crosstalk that has not been discussed elsewhere in the literature, which we refer to as Interpixel Charge Transfer (IPCT), is introduced. This effect has an extremely significant impact on x-ray astronomy. For persistence, a new theory and accompanying simulations are presented to explain latent images in the HyViSI.

In consideration of these artifacts and the overall measured performance, we argue that HyViSI sensors are ready for application in certain regimes of astronomy, such as telescope guiding, measurements of fast planetary transits, and x-ray imaging, but not for others, such as deep field imaging and large focal plane astronomical surveys.

Preface

More than four centuries have passed since Galileo first pointed a telescope at the sky and observed things that no human being had ever laid eyes upon. In that moment, he opened up an entirely new realm for exploration. We could see farther into the depths of space than ever before and find objects that lay hidden to our naked eyes.

When we look back in history, we see many cases like this. They are cases in which a new technology allowed us to venture into uncharted territory. The invention of the frigate allowed humans to cross seas and explore lands new to them, the submarine opened our eyes to the depths of the seas, the microscope made us aware of new micro-worlds.

Since Galileo's time, our exploration space in astronomy has continued to increase in its vastness. With the invention of photography, we became aware of very dim objects and structures in the cosmos, and a new search was possible. New detectors sensistive to wavelengths of light that we cannot even see revealed a host of new features on the sky. Through the use of this technology, there has been a veritable explosion in the areas in which we can explore.

However, the space we are able to explore in astronomy is still very limited in a fundamental way. We are forced to make theories and postulate about the nature of the universe based solely on the signals we receive here on earth. We make guesses about how massive or hot or distant things are, what composes seemingly empty space, or what causes unfathomably intense bursts of energy in other galaxies purely based upon the light we receive. In essence, we are stuck in exploration space purely because we are stuck here on earth. It is impossible for us to truly *grasp* the cosmos from this limiting vantage point. It is like trying to explore a forest while tied to a tree.

There is no denying that we have made–and will continue to make–progress in understanding the cosmos while we remain tethered to our home planet. Bigger, better, and newer instruments and technology will most certainly open new doors. But the surprises that await us down the road, when we leave our solar system and journey into interstellar space, seem far more likely to provide the kind of shock and revelation that Galileo brought when he first pointed that telescope at the sky.

Some researchers believe that money spent on space exploration is a waste and others argue that funding for fundamental astronomy is. In the end it boils down to differing opinions; not a logical argument. Like anything else in this world, a good balance between the two seems the best path to take. After all, we cannot simply venture aimlessly into outer space in search of answers without a destination in mind or without properly preparing ourselves for the exotic and harsh environment it presents. That would be like going to a casino with a few quarters and hoping to win a sports car.

Acknowledgments

The commitments and sacrifices involved in undertaking my graduate degree and completing this dissertation were by no means trivial. After finishing my coursework at Stanford, the amount of "free time" I found during the regular work weeks dwindled to an almost nonexistent level. Luckily, the work in itself was extremely enjoyable, and the people I came to know and friendships I formed along the way made it an experience I would gladly repeat. I am extremely grateful to these acquaintances for all of the knowledge they imparted to me and help they offered. Many of them deserve special recognition, which I will attempt to give here in a somewhat chronological fashion.

The first person who stands out in my recollections of graduate school is my advisor, Steve Kahn. Right after accepting me as his student, Steve gave me a veritable "zoo" of opportunities to pursue for my research. Although there were certain ones which he thought would be more beneficial or worthwhile, he never pushed me in any direction that I did not wish to follow. And his incredible breadth of knowledge, along with his many experiences in the world of physics, meant I was always learning something from him no matter the topic of discussion. Despite his extremely busy and chaotic schedule, Steve always found the time to meet with me when necessary. And in circumstances where I needed more attention, he never failed to find an appropriate expert that could advise me.

Among these experts, I owe a very special thanks to Kirk Gilmore. After taking me in during my first year at Stanford, Kirk quickly appreciated my desire to work with detectors and astronomical instrumentation. Being the expert he is, he immediately opened many doors for me in this arena. Throughout the years that followed, he constantly taught me new things, including great laboratory expressions like "Don't King Kong it" — a reference to how much force should be applied to screws when tightening them. There were plenty of other things he did to make me laugh and appreciate the fun side of working on instruments. Plus, he always made sure there "was not too much on my plate".

I also owe special thanks to David Burke and Garrett Jernigan. I did my first real scientific research with David on the atmospheric turbulence at Cerro Pachon (the future site of the Large Synoptic Survey Telescope), and it is an experience I will never forget. He basically taught me how research is meant to be done; every step from organizing and analyzing data to searching through scientific literature to efficiently presenting results. In a slightly different vein, Garrett first introduced me to the how the scientific community operates and what I needed to consider at each step of my graduate career and beyond. He has continually offered me a very valuable and unique perspective on these sorts of issues and brought my attention to ones that I would not have considered otherwise. And despite his desire to hold on to hardware that clearly belongs in a museum, I can also say he has taught me a great deal about the new and relevant technology in astronomy.

The infancy of my thesis work would not have been possible without two special individuals at Rochester Institute of Technology: Don Figer and Brandon Hanold. Don gave me a first look at laboratory detector work at the Space Telescope Science Institute and showed me a perfect example of how one can be successful in managing and operating a lab while also doing top-notch science. At RIT, he fostered my love for detectors and electronics further. Working in the lab there everyday with Brandon under Don's guidance and hastily preparing a camera system for the Kitt Peak 2.1m telescope was an incredibly rewarding experience. And when the time actually came to do real astronomy, their company made the long nights of observing quite enjoyable.

I also managed to see the other side of the astronomical instrumentation world thanks to Jim Beletic. Jim graciously offered me the opportunity to do an internship at Teledyne Scientific and Imaging, where the real magic of making the detectors happens. At TSI, my appreciation for detectors was greatly enriched by working directly with Yibin Bai, Markus Loose, and Raphael Ricardo. They exposed me to many interesting things and improved my understanding of the devices I had been working with for so long. I am also indebted to Mark Farriss, Rebecca Blockman, Greg Jacques, Richard Blank, Luis Gordillo, and Kevin Peralta for their help there.

Although they do not fit as nicely into the chronological ordering, there are several other people to whom I owe thanks. Andrew Rasmussen and John Peterson spent a great deal of time with me at the blackboard explaining things. Stuart Marshall revealed to me the secrets of Unix. Kirby Hnat and Richard Schickling taught me about cryogenic systems and showed me how to have fun in Tucson. And Dick Joyce, Skip Andree, and a number of other people at Kitt Peak National Observatory deserve thanks for helping us make our telescope observations a reality.

Of course, none of this would have been possible with some very special and dear people in my life that predate this chronology. In addition to being great parents in a general sense, my mother and father have given me every opportunity I could have asked for in life. My older brother has served as a great role model and given me great advice throughout grad school. And I also owe thanks to my sisters and sister-in-law for their constant encouragement throughout this period. I could not have done any of this without them.