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The 25th Anniversary of IISW: Reflections on Directions

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We are like dwarfs on the shoulders of giants, so that we can see more than they, and things at a greater distance, not by virtue of any sharpness of sight on our part, or any physical distinction, but because we are carried high and raised up by their giant size..

- Bernard of Chartres, c. 1115 AD

I. Introduction

It is truly astonishing how quickly 25 years can pass. On the other hand, I must confess that while certain memories remain vivid, others are faded with the passage of time. In those 25 years, I went from the new guy on the block to the old guard. My daughter went from diapers to marriage. Imagers went from CCDs to CMOS.

In 1986, an advanced image sensor was a 1.4 Mpixel, 6.8 um pixel CCD and a wafer scale sensor was announced with 2k x 2k pixels on a 100 mm wafer. Low dark current was 5 nA/cm^2. Readout speed for consumer grade devices was 10 Mpixels per second with read noise of 200 e- rms. CMOS image sensors were in the distant past and already written-off. In 25 years it seems the scale of advancement is about 50x. In 2011 an advanced image sensor has 900 nm pixels, and more than 50 would fit inside a 6.8 um pixel. In 2011 an advanced image sensor has 33 Mpixels with 120 fps readout speed. Noise is often below 3 e- rms. Room temperature dark current is so low it is hardly mentioned. It is the same with white spots. CCD image sensor dominance is in the past and already written-off by some. I am anxious to write the paper *"Quanta Image Sensors - Are CMOS image sensors dinosaurs?"*

II. The 1986 Meeting

At this meeting we celebrate the 25th anniversary of the IISW which really means the 25th anniversary of the first workshop that I held in 1986, which was the 1986 IEEE Workshop on Charge-Coupled Devices. I had just turned 29 years old and was an Asst. Professor at Columbia working on CCDs for on-chip image processing and wanted to learn more about CCDs. But as far as I knew, the last meeting on CCDs was ancient history. In fact, there were regular CCD meetings in 1973, 1974, 1975, two in 1976, one in 1978 and then the CCD conference circuit turned cold. To educate myself, I thought it would be good to bring experts to Columbia's Arden House and have a Workshop on CCDs. Keeping the participants "captured" with a remote location and prepaid meals would foster interaction. I recall discussing a workshop with Dan McGrath over a beer at the IEDM in 1985. He was very encouraging and I think it was Dan who suggested I contact Marvin White for advice. Marvin was also full of encouragement and gave me very valuable ideas on whom to invite for what subject.

I was very nervous about how the whole thing would turn out and if anyone would show up who was not an invited speaker. In fact, about 70 people attended. We even had one attendee from outside the US, so I suppose it was already "International". Since this was way before the modern internet and mostly before widespread emailing, we did alright. Michael Tompsett gave a talk on "CCD Memories" the night before the workshop started while we all stood around the foyer and had a beer. Much of the program was on signal processing with CCDs and some on imaging. A subsequent evening discussion was on "The Future of CCDs: More than a Pretty Picture?" Well, I guess we know how that turned out – "Not really."

III. More Meetings

The 1986 workshop was well appreciated and I was urged to organize a do-over by many in the community. Since organizing that first meeting exhausted me, I was not ready to do it again until 1990, just before I left Columbia for JPL. That time Walter Kosonocky helped me put together the all-invited program and we again held it at Columbia's Arden House. The very next year, in 1991, Savvas Chamberlain hosted an all-invited meeting in Canada with a greater emphasis on tutorials. After that meeting we learned two important lessons. First, every other year was a better frequency, and second, we did not want to stay in university dormitories with gang showers anymore. Nevertheless, in 1993, after our first-choice location fell through, we repeated the meeting in Canada. At this meeting Savvas suggested we formalize the meetings with an organizing committee. Nobu Teranishi and Albert Theuwissen, representing Asia and Europe respectively, joined with Savvas and myself. We also decided to accept contributed papers and form a Program Committee for paper selection. The 1995 Workshop at Dana Point CA was the first contributed papers meeting. At Dana Point we decided that the Workshop would circle the globe on a 6-year cycle. Also at Dana Point we decided that holding the Workshop in scenic locations was good idea. The 1997 meeting in Bruges was very well attended and received as was the 1999 meeting in Karuizawa. By now there was strong pressure on the organizers to pick great locations and organize an even better meeting than the meeting before. In 2001 we were at Lake Tahoe, and in 2003 at the amazing Schloss Elmau in the Bavarian Alps. In 2005 we returned to volcanic Karuizawa. In 2007 we met on the rocky Atlantic coast in Ogunquit Maine, and in 2009 we met on the fjords in Bergen Norway. Now in 2011, we meet resolutely in Hokkaido Japan, despite the earthquakes, tsunami and nuclear disaster that have plagued Japan the last few months.

IV. ImageSensors, Inc.

Starting in 2007, we made a major change that we hoped would not adversely affect the meeting. Prior to 2007 we had to apply to the IEEE EDS for sponsorship of our workshop, on a workshop-by-workshop basis. We had to apply, from scratch, each time for a starter loan to pay hotel deposits, etc. At the close of each workshop, we would add up the net income from the meeting and give it all to the IEEE. We were not allowed to carry over any "profit" from previous years to improve the subsequent meetings. The IEEE just ate everything. In 2007 we formed a non-profit public-benefit corporation, ImageSensors, Inc. and renamed the meeting the International Image Sensor Workshop (IISW). Now we could carry over left-over funds from year to year to better serve the next Workshop, as well as provide funds for the Walter Kosonocky Award. We also opened our website, www.imagesensors.org that contains a free on-line public library of past workshop material. It has

been my philosophy that scientific information should be freely available to all, and that charging fees for on-line papers is just wrong, especially when none of those collected fees is shared with the authors. These changes were successfully implemented. We continue to "sell-out" our limited attendance workshops within just a few days of opening registration. It is hard to resist raising the attendance limit but we think a smaller meeting is better. I would like to see a Workshop where almost everyone in attendance presents their recent work.

V. Reflections

In 1986, almost all consumer-grade CCDs came from Japan. I did not have any connections with Japan at that time, and if anything, there was a sentiment within the United States that we were rapidly losing high-tech leadership ground to Japan, and in a sense, Japan was the national R&D competition. It was a hard time to be in the semiconductor field, but things got better in the US and a bubble burst in Japan. Not long afterwards, American venture-capital group-think pushed for overseas manufacturing to increase short-term profits, which inevitably leads to tech-transfer. Along with tech transfer and manufacturing growth, there are many smart engineers in Japan, Korea, Taiwan, China and elsewhere that are making ground-breaking and important innovations. Europe too, has seen a resurgence in advanced image sensor R&D, especially recently in the areas of 3D imaging and single-photon imaging. It is an irony that now as I re-enter academia, almost all consumer grade CCDs and CMOS image sensors still come from somewhere else in the world. In 2011, we are a global technical community and the International Image Sensor Workshop reflects the strength of the many world-wide efforts in advanced image sensor devices. I am very pleased to be part of this group.

It became apparent in the 1980's and early 1990's that CCDs were the technology-of-choice for image capture, but their role in memory devices and signal processing was in decline to the point of having no role whatsoever. This made me sad since charge-domain analog signal processing was just so interesting to me. It seemed an elegant, compact, low-power solution to many signal processing problems. From this reflection springs my own personal first law of semiconductor device R&D: *Hundreds of engineers working on improving digital signal processing circuits will, within a few years, trump a few engineers working on clever analog signal processing circuits.*

My second law of semiconductor R&D is similarly based on my experiences with making high speed III-V CCDs: *Never do in III-Vs that which can be done in silicon a few years hence.* Surely in 1986 we did not think that Gpixel/s readout speeds would be possible with anything but III-V devices. Yet today, using on-chip ADCs and fast I/O, Gpixel/s readout speeds are easily achieved.

My third reflection on the last 25 years of image sensors, especially considering the adoption of CMOS image sensors over CCDs, is that *simpler and cheaper is better than clever and sophisticated*. That is a hard lesson when your profession is to be clever. When I first wanted to work on active-pixel image sensors at JPL, my funding request was denied because the devices I wanted to explore were complicated devices like the CMD or BCMD that NASA could not afford to develop. Instead I had to use what I could get at low cost, which was CMOS through MOSIS. Well, I was pretty sure we could not make a competitive image sensor in CMOS but at least we could explore on-chip ADC. So, I just tried to make the best image sensor I could given the technology readily available by using some of the best known techniques from CCDs. These included intra-pixel charge transfer, source-follower amplifiers and correlated double sampling. And, as soon as we could implement a pinned-photodiode we did. (Thanks Smith, Kosonocky, White, Hynecek and Teranishi!) *In the end, I think CMOS image sensors made large in-roads not only because of low power and high integration, but also because they were simple for non-CCD camera engineers to use.* With digital inputs and outputs, they are much easier to use than CCDs.

Of course, CMOS active pixel image sensors were not easily nor well received in the CCD community. At the 1993 Workshop, Savvas Chamberlain and I had a public debate on stage on CCDs v. CMOS. I remember at the time just a few brave souls in the audience raised their hands when we asked who thought CMOS was an interesting avenue to take. I also remember as various CCD community leaders, one by one, conceded the advantages of using CMOS image sensors. I, on the other hand, imagined CCDs would be long gone by now but such extinction does not seem imminent, despite the volume dominance of CMOS active pixel image sensors.

VI. Possible Directions

So, here we are in 2011. In 1990 Gene Weckler gave a talk on "Future Trends in Solid-State Image Sensors". He said it was not easy to predict the future and it depends on many factors besides the technology. I don't think I could add much to what he said in 1990.

My current quest is for the Quanta Image Sensor (QIS), where we count individual photon strikes. To make this work well requires another 50x reduction in pixel size, an increase in readout rates from Gpixel/s to Tbits/s, and another 10x reduction in read noise. On the other hand, we move the digital domain another step, from *a chip* in a CCD chip set to *on-chip* for CMOS APS to right to the very pixel or *jot* in the QIS. We move the concept of integration and pixel boundaries from hard-defined devices to firmware. Using firmware, we can implement conventional bucket integration, TDI, and even a digital film sensor. To me, this seems to be consistent with my reflections above and my new one: *Go digital as soon as you can and keep it digital.*

Between here and the QIS I see an opportunity for an in-between solution that I am terming the Digital Integration Sensor (DIS), where full-well issues and dynamic range are solved through higher frame rate readout and digital integration using memory. Is this a step forwards or a step backwards? Hard to tell. As Gene said, it depends on many factors. I hope I am here in another 25 years to see how it all turned out. If not in body, then at least in spirit!

VII. Acknowledgments

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