Technology and Innovation, Vol. 15, pp. 197–209, 2013
Printed in the USA.
1949-8241/13 $90.00 + .00
DOI: http://dx.doi.org/10.3727/194982413X13790020921744
E-ISSN 1949-825X
www.cognizantcommunication.com

CAMERA-ON-A-CHIP: TECHNOLOGY TRANSFER FROM SATURN TO YOUR CELL PHONE

Eric R. Fossum, *NAI Charter Fellow*

Thayer School of Engineering at Dartmouth, Hanover, NH, USA

The invention of the CMOS active pixel image sensor "camera-on-a-chip" at the NASA Jet Propulsion Laboratory at Caltech and its subsequent development and commercialization via the spinoff company Photobit Corporation are discussed. The article traces the arc of the technology from innovation, technology transfer, and entrepreneurial startup to its use today in nearly all mobile phone cameras, tablet and web cameras, medical and automotive cameras, and many other applications.

Key words: Innovation; Technology transfer; Camera phone; Camera-on-a-chip; CMOS image sensor; Pill camera; Automotive camera; Web camera

INTRODUCTION

As of 2013, over a billion cameras are manufactured every year using the complementary metal oxide semiconductor (CMOS) active pixel sensor (APS) "camera-on-a-chip" technology that was invented at the NASA Jet Propulsion Laboratory (JPL) at the California Institute of Technology (Caltech) in Pasadena, California (8). The technology, originally developed for the US Space Program, is now found in nearly every "camera phone," most web cameras, many DSLRs, automobiles, and even swallowable pill cameras. The widespread proliferation of cameras has transformed the way we communicate and share our personal lives with others through social media. It has also raised difficult issues of privacy versus security and accelerated political change and has enabled us to remotely experience sights across the planet without leaving our armchair. This article discusses the invention and early development of this disruptive and transformational technology and its transfer from JPL to widespread use in consumer electronics.

INCUMBENT CCD TECHNOLOGY AND THE SPACE PROGRAM

The charge-coupled device (CCD) technology was the first commercially successful solid state image sensor technology to supplant vacuum tube-based electronic cameras. Invented in 1969 at AT&T Bell Laboratories by Boyle and Smith (2) as a semiconductor analog to bubble memory, its image capture capability was quickly recognized and demonstrated (24). The invention was followed by rapid development in the 1970s with potential applications in signal processing, memory, and imaging. In 1977, Steve Sasson at Kodak invented the self-contained digital camera using a CCD image sensor (15). In 1982, continuous improvement of CCDs by Japanese companies such as Sony, NEC, Panasonic (Matsushita), and Toshiba (N. Teranishi; J. Nakamura, personal communication, 2013) led to the introduction of the first mass-marketed consumer electronic devices. By the end of the 1980s, annual sales of a million CCDs or more was considered a strong commercial success.

Accepted June 5, 2013.
Address correspondence to Eric Fossum, Thayer School of Engineering at Dartmouth, 14 Engineering Drive, Hanover, NH 03755, USA. E-mail: eric.r.fossum@dartmouth.edu

In the US in the 1980s, a second focus of CCD R&D was on aerospace and defense imaging applications, including scientific space applications, and infrared military applications. JPL was particularly interested in replacing vacuum tube-based camera systems on interplanetary spacecraft such as Voyager with CCD solid state imaging devices for improved scientific performance. Scientific CCD development contracted by NASA/JPL at Texas Instruments, for example, led to the first interplanetary CCD camera, flown on the Galileo mission to Jupiter. JPL developed leading expertise in the characterization and specification of these CCDs (12,13). Among other examples, a CCD and Wide Field Planetary Camera was developed for the Hubble Space Telescope, and with Ford Aerospace, a CCD was developed for the Imaging Science Subsystem (ISS) cameras for the Cassini mission to Saturn (Fig. 1).

The cameras flown on these spacecraft were large. The ISS for the Cassini mission, which includes both wide-angle and narrow-angle cameras, had a combined mass of 57 kg and dissipated power of 19 and 26 W, respectively (20). The engineers and technicians who built the camera are listed in Ref. (4). As with all images returned by interplanetary spacecraft, the images returned by Cassini have an inspiring beauty and contain valuable scientific information.

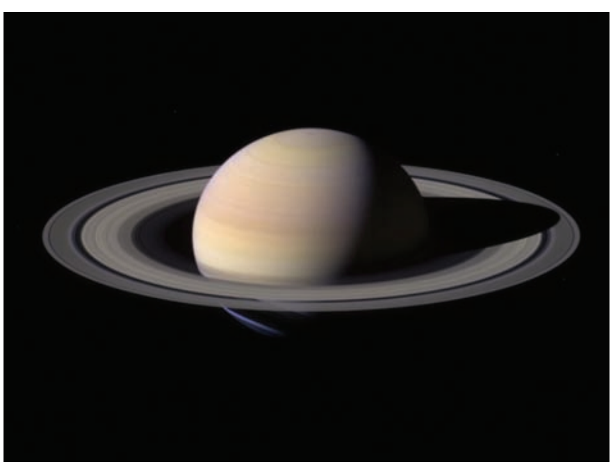

Figure 1. Saturn as seen from 17.6 million miles by the Cassini CCD camera. Photo credit: NASA/JPL/Space Science Institute PIA06077.

MOTIVATION FOR THE INVENTION

CCD devices were generally very successful for both consumer and scientific applications. However, pushing the state of the art of the scientific CCD technology and using them in nonterrestrial environments resulted in the discovery of many CCD reliability and performance issues. These issues motivated the invention of the CMOS APS. To fully understand the invention, a brief discussion of the operating principles of CCD image sensors may be helpful.

An image sensor is divided into pixels (picture elements) that contain the photodetector and readout electronics for the pixel. The CCD uses the CCD pixel structure both as a photodetector for collecting light-generated signal charge and as the readout device. During an exposure or integration period, photons are absorbed by the semiconductor resulting in photogenerated carriers, referred to as photoelectrons. The photoelectrons are captured by the electrostatic forces of the pixel and accumulated. After the integration period is complete, the photoelectron signal must be read out. The readout operation of a CCD is based on the shifting of charge packets in a semiconductor by sequencing voltages on electrodes above the semiconductor surface, thereby dragging the charge in the semiconductor along by electrostatic attraction. Typically, a pixel's charge needs to be transferred thousands of times to the corner of the imaging array before being converted to a voltage. Any losses along the way result in image deterioration.

An analogy for the way a CCD works is as follows. Suppose we want to measure rainfall over a football field. We can populate the field with rows of people holding buckets. The rain is collected in the buckets over a period of time so that a measurable amount accumulates in them. At the end of this "integration period," each person in the row transfers the contents of their bucket to the person next to them in bucket brigade fashion. People at the end of each row (at the edge of the field) perform a bucket brigade down the edge of the field to the corner where each bucketful can be measured and recorded. The process is repeated over and over until all rainwater collected across the field gets transferred to the corner. It is thus possible to make a map of rainfall across the field. It is easy to imagine in this analogy that, if any water is lost or spilled during the bucket brigade transfer, the quality of the measurement map will deteriorate.

For an image sensor, the rain is instead photons of light, and the bucket is the CCD photodetector containing photoelectrons. The charge transfer inefficiency (CTI) of the CCD bucket brigade needs to be less than 0.00001% on each transfer in order to prevent unacceptable image quality deterioration after thousands of transfers. That means that only one photoelectron can be lost from a pixel signal of 100 photoelectrons after 1,000 transfers! It is in fact amazing that these devices work so well and is a testament to many years of device engineering.

Very special fabrication steps and high voltages are required to make CCD image sensors operate well, and these steps are not generally compatible with standard CMOS microelectronics fabrication recipes. This leads to several problems, such as the inability to viably integrate the CCD image sensor with on-chip timing and control circuitry, analog signal processing circuitry, and analog-to-digital converter (ADC) circuits built using standard CMOS. Furthermore, the large capacitance of the MOS charge transfer gates and the relatively high operating voltages make electronic driver circuits power hungry. Thus, CCD cameras require significant power to operate. Old CCD camcorders, for example, had batteries the size of small bricks.

The fundamental CTI-related problems of CCDs get worse when the number of pixels is increased, since the number of transfers goes up. Increasing the size of the chip increases its capacitance and consequently the CCD camera power dissipation. An additional complication occurs if one tries to keep the frame readout time of the sensor constant (e.g., 30 frames/s). More pixels in the same amount of time means the time for any one transfer decreases, further increasing charge transfer inefficiency or requiring improvement in the fabrication process. Faster data rate through the output amplifier also means more noise in the signal due to the larger bandwidth.

In space environments, normal cosmic radiation and radiation belts around the outer planets can cause physical damage to the CCD structure at the atomic crystal level. Such damage can dramatically increase losses during charge transfer in the CCD and result in image deterioration. Other radiation-induced deterioration can occur as well, such as loss in sensitivity to light and an image "fog" that appears even in the dark. In space, it is not practical to be able to fully shield against cosmic ray damage, and the CCD does eventually "wear out."

Aside from performance issues with the CCD operating in space, there were additional motivating factors that led to the invention of the camera-on-a-chip. When NASA Administrator Dan Goldin took office in 1992, one of the themes he soon adopted was "faster, better, cheaper"—which for JPL translated into a focused effort to reduce the size, mass, and cost of interplanetary spacecraft and to speed up adoption of new technology. For cameras, this meant reducing the size, mass, and power of the imaging subsystem. Within JPL, we pictured this goal as reducing the cameras from "bigger than a breadbasket" to "smaller than a coffee cup." The only question was how to get from where we were with CCD cameras to that goal.

THE INVENTION

In 1990, I left Columbia University, where I had worked on CCDs for smart image sensors and high-speed applications, and joined JPL. I was recruited specifically for my expertise in CCD technology. I was joined by two of my Columbia graduate students completing their dissertation research, Bedabrata Pain and Sunetra Mendis. A separate division of JPL also recruited my then-wife Sabrina Kemeny, who had just completed her doctoral research on CCDs at Columbia.

There were two main problems with CCDs: charge transfer inefficiency and camera electronic system size. Eliminating the need for repeated charge transfers would solve nearly all the problems related to charge transfer inefficiency such as radiation sensitivity, power, and use of a specialized microelectronic fabrication process. For reducing size, it was well known that integration of microelectronics almost always resulted in more compact electronics and a concomitant improvement in reliability and, while not as important for the space program, a reduction in cost.

The solution to the charge transfer inefficiency problem was the invention of the CMOS APS with intrapixel charge transfer. The solution to the second problem followed immediately from the first—using a baseline CMOS process to fabricate the imaging array of photodetectors, thus making the integration of other components such as interface electronics, timing and control, analog signal processor, ADC, and digital signal processor become practical. In the camera-on-a-chip, almost all camera electronics are integrated onto a single chip. Just a clock signal and a power supply are required to produce image data.

The idea of an active pixel device where the image signal is amplified by transistor circuits within the pixel dates back to the late 1960s before the CCD was invented, even though the term "active pixel" was not coined until 1991 (16). One of the first active pixel devices was proposed by Peter Noble at Plessey (17). In the rainfall analogy, imagine each person could measure their own bucket and phone in the results, eliminating the whole bucket brigade operation.

In those days, MOS transistor electronics were relatively immature and subject to operating instabilities. This was one reason the CCD was so attractive for imaging applications since it was relatively insensitive to those instabilities. A resurgence of APS concepts occurred in the late 1980s. For a variety of reasons, none of these devices proved to be a commercially viable alternative to the CCD.

At my laboratory at JPL, it became clear that an active pixel sensor approach would eliminate the charge transfer problems of CCDs (6). An internal proposal to investigate intriguing yet unproven APS devices in the JPL Microdevices Laboratory was declined by JPL management due to cost. At the same time in my laboratory, we were investigating ADCs that could be integrated with image sensors. The only viable option for us to fabricate image sensors and ADCs at low cost was to use the University of Southern California's MOSIS multiproject wafer approach (25) and use industry standard CMOS processes.

I decided that we should try a new, yet relatively simple, APS approach, which relied on intrapixel charge transfer to achieve low noise and yet could be fabricated in the CMOS process. The intrapixel charge transfer would allow the use of true correlated double sampling and suppression of kTC noise—a technique used to reduce noise in CCD output amplifiers (23).

With my coinventors Sunetra Mendis and Sabrina Kemeny, we solved the practical problems associated with implementing the CMOS "active pixel sensor with intra-pixel charge transfer" (10) and made several test chips via MOSIS. Some funding for the implementation work, which was mostly "under the table" at that point, came from a DARPA low-power electronics project already underway at JPL under PI Bob Schober with the sponsor's blessing. The chips worked quite well with little test setup effort, especially compared to that needed to test a CCD, and by April 1993, we knew we had created something important (Fig. 2).

Creation of a camera-on-a-chip based on the CMOS APS followed rapidly. Very large-scale integration (VLSI) implementation of the camera-on-a-chip, now supported by NASA funding, was primarily performed by Bob Nixon and demonstrated within a year or so of the first demonstration of the CMOS APS (11). More complex and other specialized sensors followed.

In addition to the image sensor technology development, the investigation of on-chip ADC was a major activity. Conventional wisdom in Japan and the US was that it was a bad idea to put the analog-to-digital converter on the same chip as the image sensor (7). It would be difficult to do with a CCD, but with the CMOS APS technology, it was practical. Digital output from the chip simplified use of the chip in a camera system and also allowed on-chip digital signal processing (Fig. 3). Several architectures were investigated, including a single ADC on the chip and also a column-parallel approach in which every column in the image sensor array had its own ADC, resulting in hundreds or thousands of ADCs per chip. Different ADC circuits were implemented such as single-slope, successive approximation and $\Sigma\Delta$ (18). Today, on-chip ADC is taken for granted with CMOS image sensors, and the same general approaches for implementation are used.

One of the early promises of CMOS image sensors was that, by using mainstream CMOS, the price of image sensors could be reduced (9). Factors included the use of larger wafers and amortization of production equipment over more wafer starts. It was predicted that the cost of a CMOS image sensor could be as low as US$10 per megapixel—five times less than a CCD in 1994. In fact, the selling price of CMOS image sensors in 2013 is about an order of magnitude lower than that (i.e., 50× less). CMOS image sensor competition caused a large drop in CCD pricing (and margins) as well.

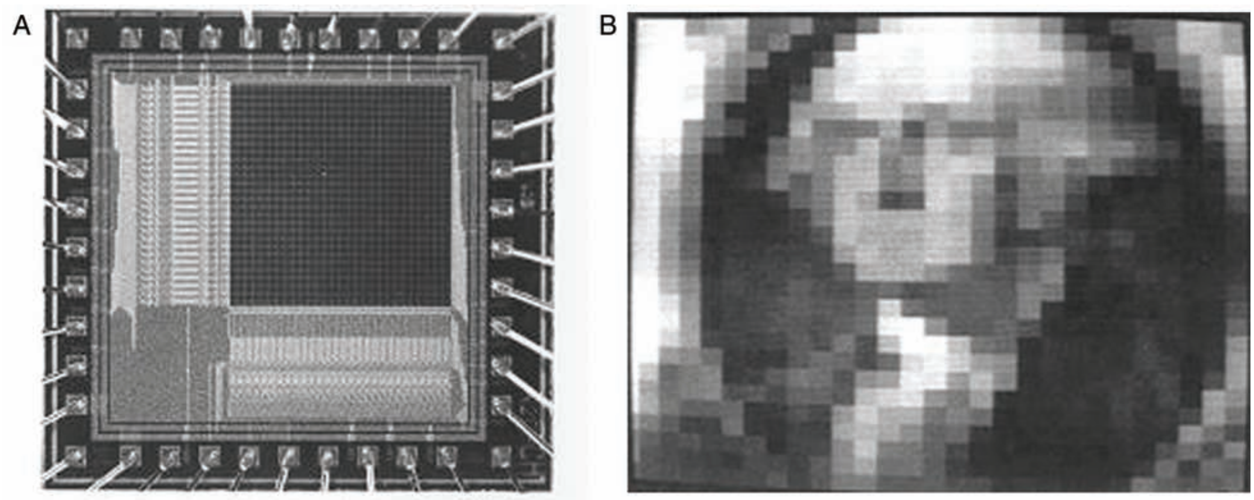

Figure 2. First CMOS APS chip (A) and image captured by chip displayed on a monitor, George Washington from a US $1 bill (B).

It is probably worth noting that the early response to the new technology was hardly enthusiastic. Within JPL, the CCD development team was threatened by the new technology and, like antibodies reacting to an intrusion, gathered forces in an attempt to quash the new endeavor. The reaction, common when new disruptive technologies are introduced inside organizations, divides the organization's focus and results in "camp conflict." This reaction has been observed by other inventors (21). For years following the technology's invention, the CCD group at JPL regularly steered its science colleagues away from the risk of using a new technology. Only recently, some 15 to 20 years after its invention, after widespread use by consumers and industry and long after adoption by European Space Agency projects, has NASA begun to utilize the new technology in science missions—certainly an irony considering the motivating factors for its invention.

Response in the image sensor technical community was also mostly negative. This community was (also) dominated by CCD specialists. A technology specialist is someone who earns a living and supports their family on specialized technology know-how and skills. Obviously, the introduction of a new technology would be viewed more as a potential threat to their individual livelihood rather than as an opportunity for change and growth. At the 1993 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors held in Waterloo, Canada, in June 1993, there was a lively impromptu debate on the merits of the CMOS APS versus CCDs. Savvas Chamberlain, founder and CEO of DALSA—a Canadian supplier of CCDs and CCD-based cameras and Workshop Chair—and I (the Workshop Technical Program Chair) took the stage and engaged in a discussion of the new technology. Only a few people in the audience raised their hands when asked if they thought the new technology was worthwhile to explore. Many

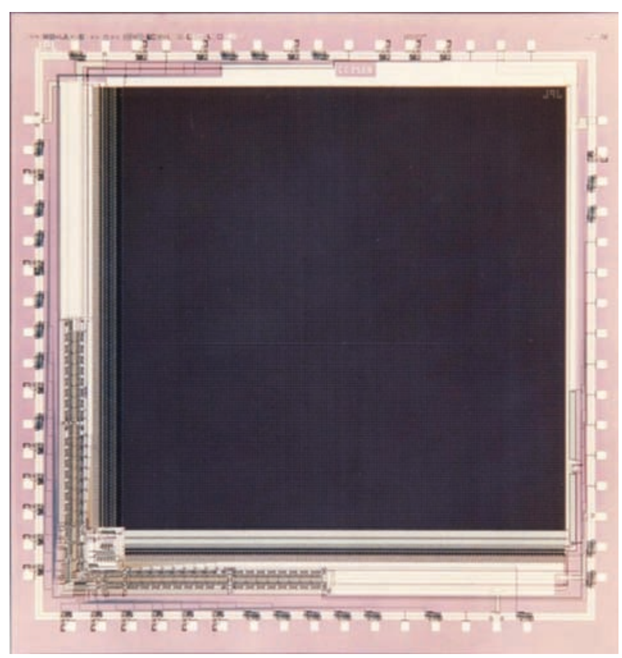

Figure 3. JPL CMOS APS camera-on-a-chip with a 256×256 array circa 1994.

Figure 4. Advanced Imager Technology Group, JPL circa 1995. Back row: Roger Panicacci, Barmak Mansoorian, Craig Staller, Russell Gee, Peter Jones, John Koehler. Front row: Robert Nixon, Quiesup Kim, Eric Fossum, Bedabrata Pain, Zhimin Zhou, Orly Yadid-Pecht.

were strong naysayers. Chamberlain took the position that MOS image sensors had been investigated prior to the invention of the CCD (including by himself) and that CCDs were already proven to be superior. Personally, I found it to be a challenging time, but our group persevered (see Fig. 4).

What Chamberlain and others failed to recognize was the importance of timing in the introduction of the CMOS active pixel sensor technology. By 1993, MOS (now CMOS) technology had dramatically improved since the late 1960s in operating stability, operating parameters, feature size, and cost since it was the mainstream microelectronics technology. The importance of integration in improving the reliability of imaging systems for portable applications while reducing their size and weight was going to be important in consumer applications. Perhaps most importantly, the power reductions afforded by the CMOS APS camera-on-a-chip would have a profound impact on their use in the upcoming, but nearly unrecognized (in 1993), market for portable consumer electronics, especially mobile "camera phones."

TECHNOLOGY TRANSFER FROM JPL TO THE US INDUSTRY

Another thrust of NASA Administrator Dan Goldin was to maximize the transfer of technology developed in NASA-sponsored programs to the US industry to strengthen the US economy. The new camera-on-a-chip technology was a ripe candidate for transfer. In the early 1990s, nearly all consumer imaging products (camcorders) came from Japan, and aside from Kodak, nearly all nonaerospace consumer CCDs were manufactured in Japan. Since the CMOS APS no longer required the highly specialized CCD processes captive in Japan and baseline CMOS processes were well established in the US by companies such as IBM, Intel, Motorola, National Semiconductor, and others, an opportunity existed for the US to "reclaim" a portion of the image sensor and perhaps camera business from Japan. Through publications and personal visits to the US industry, I "evangelized" this message and opportunity.

JPL signed several "Technology Cooperation Agreements" (TCA) with interested industry partners for technology transfer and development related to the CMOS APS camera-on-a-chip technology. Under a TCA, there was no exchange of funds. NASA funded JPL costs, and industry funded their own costs. From the JPL side, the advantage is additional funding for R&D on the technology and the opportunity to participate in technology transfer and fulfill the ancillary NASA mission. JPL also gained access to advanced CMOS processes not otherwise affordable, resulting in acceleration of technology development. In some cases, NASA also gained a potential source of CMOS APS chips for future instruments and missions. Industry gained access to the new technology and received the direct engagement of JPL personnel who had a working knowledge of the technology. The company also gained preferred licensing stature for the technology. JPL TCA partners included AT&T Bell Labs, Kodak, National Semiconductor, and Schick Technologies.

AT&T Bell Labs

AT&T Bell Labs was interested in the technology for a revival of the "picture phone" concept and PC-based videoconferencing. With JPL's involvement and Bell Labs' established expertise in VLSI design and test, we made rapid progress on various image sensors with on-chip ADC (21). Despite the rapid technical progress and success of the technology transfer from NASA, the technology was not commercialized. The reasons relate to the coincident restructuring of AT&T Bell Labs to Lucent Technologies and the consequent loss of momentum to transfer the technology from inside Bell Labs onward to AT&T operating companies such as AT&T Microelectronics and AT&T Consumer Products.

Kodak

In addition to its gargantuan photographic film and chemical business, Kodak also had a growing digital imaging business including the manufacture and sale of CCDs. Tom Lee, a senior engineer at Kodak, immediately recognized the potential of this technology and was enthusiastic about exploring it in cooperation with JPL. Together, he and I decided to explore a "pinned photodiode" version of the CMOS APS. The pinned photodiode (PPD), which is a kind of junction photogate, was invented by Nobu Teranishi et al. at NEC in 1980 for use in interline transfer CCDs (22). The advantages of the PPD were its good blue response and low dark current along with the complete transfer of signal carriers. It is a challenging technology to fabricate, and Kodak had mastered it for its own CCDs. However, relatively high voltages were required to effect complete charge transfer in a CCD, and the voltages used in CMOS were significantly lower. So, the challenge was to devise an improved PPD process that allowed it to work with Kodak's internal baseline CMOS fabrication recipe.

By 1995, together we had achieved the first CMOS image sensor using the PPD (14) (Fig. 5). The technology transfer to Kodak was a large success and ignited a whole new product line of CMOS image sensors from Kodak. Kodak and Photobit, described below, along with Motorola, also worked together to create the new products (26). Subsequently, Kodak failed to capitalize on its early first-to-market position with CMOS image sensors as it did with Sasson's digital camera, and years later, its digital imaging business collapsed. This has now become a classic example of the difficulty of creating new enterprises within existing companies whose momentum is centered around an older profitable technology—in this case photographic film and chemicals.

National Semiconductor

Technology cooperation with National Semiconductor was initiated during a second round of TCAs signed at JPL. By this time, JPL needed a foundry source to develop new scientific image sensors based on the inventions. The two principals at National Semiconductor, Kevin Brehmer and Dick Merrill, were interested in entering the image sensor business. A 1-megapixel CMOS APS with on-chip ADC was successfully demonstrated during the cooperation agreement (Fig. 6). However, with the creation of Photobit, the two TCA principals at JPL, Barmak Mansoorian and I, left JPL in 1996 to join Photobit full time. Furthermore, the principals at National Semiconductor also left to found start-up companies. Kevin Brehmer founded PixelCam and sold it 2 years later to Zoran. Dick Merrill left National to cofound Foveon with Carver Mead and others. Foveon garnered great interest and investment by commercializing a slightly different sort of CMOS active pixel sensor they called X3, involving three layers of vertically stacked and integrated photodetectors to eliminate the need for RGB filters and the associated aliasing. Unfortunately, the larger pixel size, higher noise, and more difficult color separation of the Foveon sensor were not widely accepted. Eventually, Foveon was acquired by Sigma at a substantial loss to investors.

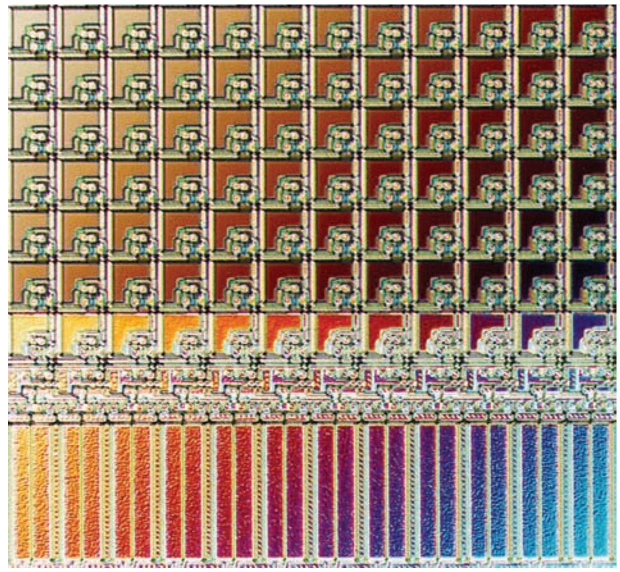

Figure 5. First CMOS APS with pinned photodiode (Kodak and JPL).

Schick Technologies

Of all the signed TCAs, perhaps the most significant in the long term also started as the smallest. Shortly after the earliest trade publications of

Figure 6. One-megapixel CMOS APS with 1,024 single-slope ADCs developed as collaboration between JPL and National Semiconductor.

the CMOS APS technology in early 1994, I was contacted by David Schick, who had just recently founded Schick Technologies, then a three-person company. His interest was in applying the CMOS APS technology to the emerging area of "computed dental radiography," which was, in essence, the replacement of dental X-ray film with a solid state image sensor. The sensor, fully encapsulated, would be placed in the patient's mouth. After exposure to X-rays, the X-ray image would be read out and made instantly available to the dentist for viewing, manipulation, and record keeping. This was the first biomedical application proposed for the CMOS APS technology, and JPL was immediately positive about signing a TCA.

The collaboration with Schick Technologies was also quite successful. By 1996, Schick Technologies had grown to over 60 people and would eventually grow to several hundred before being merged with Sirona in 2006. Sirona continues to develop and improve the technology under license to Caltech. The technology is now used in over 60% of dental offices in the US (J. Slovin, personal communication, 2012). One significant advantage for patients is lower total X-ray exposure (Fig. 7).

Other Transfer Mechanisms

In addition to transfer by technical publications and presentations, travel and meetings, and signed Technology Cooperation Agreements, transfer of CMOS APS camera-on-a-chip technology from NASA/JPL took place in other important ways. The JPL Technology Affiliates program brought in collaboration with EG&G Reticon and ITT. Informal cooperation took place with Polaroid, Hewlett Packard, and IBM. Of these, the Hewlett Packard seed grew and resulted in a deep effort at HP, helped in large part by my now-former student, Sunetra Mendis, taking a job there. However, the majority of the transfer of technology from JPL took place with the creation of Photobit in 1995.

THE SPIN-OFF OF PHOTOBIT CORPORATION

At the start of 1995, the CMOS active pixel sensor R&D effort at JPL was continuing to grow. Outside interest in the technology was also growing. There were inquiries about specific commercial applications coming in weekly, it seemed. The limited funds set aside for TCA work were fully utilized, and generally, private companies were not inclined to fund work at a Federally Funded R&D Center (FFRDC) such as JPL, so most inquiries ended with an apology for not being able to help. The companies that we were transferring the technology to were moving along, but it felt like slow progress, and I grew increasingly frustrated with their pace.

In February 1995, Sabrina Kemeny was home on maternity leave with our second daughter and not quite ready to return to full-time work at JPL. I suggested that we start a small company to design custom image sensors in response to the inquiries I was receiving at JPL that I was unable to respond to. A powerful PC and PC-based layout software was all that was needed to get started. Thus, in February 1995, we founded a small business entity, which eventually became Photobit Corporation.

An incredibly opportune and lucky break came within a week or two of our forming the company. A reporter from *Business Week* was at JPL to report on new technology, and on a spur of the moment, I was added to his interview list. He was intrigued with the technology and wound up writing a feature

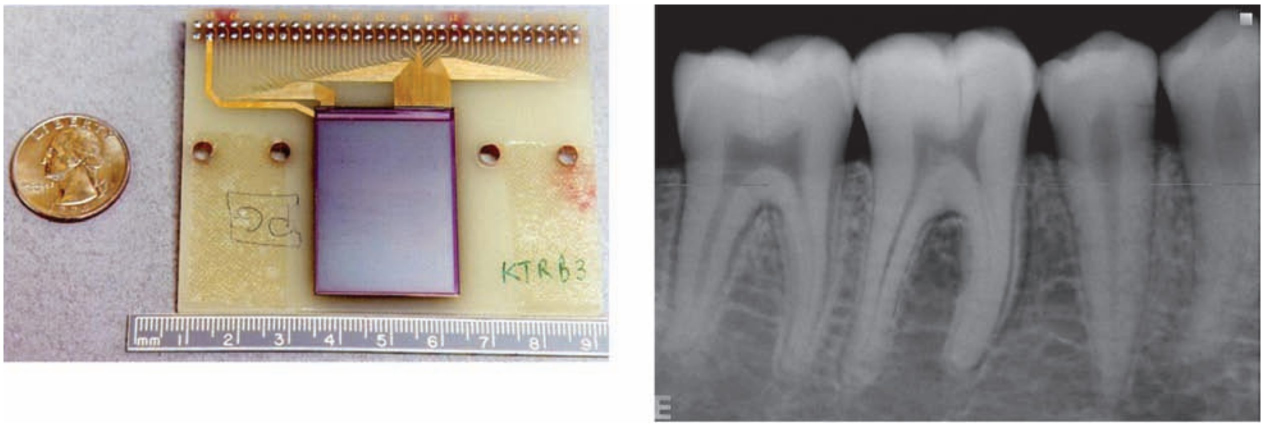

Figure 7. Early CMOS APS sensor for dental X-ray applications and associated X-ray image.

article on it. The article appeared in the March 5, 1995 issue, and he was kind enough to mention our fledgling company (1). It was only the day before the issue was to hit the newsstands that I realized we needed to get a separate business phone number for Photobit. For the article, I had mentioned that "portable video phones" would be a possible application of the new technology. Little did I know that this would, in fact, be the "killer app."

Once we had formed the formal company, Sabrina became CEO, and I eventually served as Chairman of the Board. I continued with my position at JPL, being sure to keep JPL management informed of the Photobit development and avoiding conflicts of interest in deed and appearance.

One of the first things Sabrina initiated was the negotiation and securing of an exclusive license to the CMOS APS technology from Caltech, with carve-outs for the TCA participants. Photobit was the first company coming out of JPL to receive such a license from Caltech. Generally, due to concerns about even the appearance of a conflict of interest, Caltech was reluctant to license technology to JPL inventors. However, Larry Gilbert in the patent licensing office at Caltech believed that licensing the inventors, themselves, would be more likely to lead to a better financial return for Caltech for the licensed IP than licensing third parties. After some time, he was successful in making his case to Caltech management. In 1995, the Caltech Office of Technology Transfer was created, and since then, it has established a significant track record of spinoff companies with the principal innovators at the helm (3).

Photobit was literally operated out of our home for a few months. We created an LLC with two other colleagues from JPL, Bob Nixon, a senior electronics designer and manager from JPL, and Nick Doudoumopoulos, another former student of mine from Columbia who had spent time at Hughes Aircraft before coming to JPL. Of the four founders, Nick was the second to leave JPL and joined Sabrina. Soon afterwards, they were joined by Roger Panicacci from JPL, who was our first employee, but eventually considered a fifth founder. Between them, they managed to secure a large design contract that enabled them to hire additional designers and finally move into 2,000 square feet of office space. Additional contracts followed, including federal SBIR funding from several agencies along with private sector contracts, and Photobit grew at an average pace of about two new hires per month during its first 2 years. Since Photobit was running in the black and financed by a growing number of design contracts, venture capital funding was not needed.

By October of 1996, the company was entering a critical phase of growth, and it was clear that it needed "all hands on deck" in order to take maximum advantage of the opportunities that were presenting themselves. I resigned from JPL, with an odd mix of sadness and excitement, and joined Photobit as a full-time member.

We now refer to the "spin-off" of Photobit from JPL. That improperly implies that it was an event nurtured and planned by the management of JPL/Caltech. Certainly, a few people in JPL/Caltech management provided critical nurturing. But the actual formation of Photobit happened in just one small step without any crystal ball and was motivated by timing of children, by frustration with the seemingly slow uptake of the technology by established industry, and perhaps by latent entrepreneurial instincts of Sabrina Kemeny and myself.

TECHNOLOGY DEVELOPMENT AND COMMERCIALIZATION AT PHOTOBIT

The commercialization of the technology at Photobit started as custom sensor design contracts. Some of these contracts were for real products, such as the Schick dental radiography sensor, and others were, in actuality, continuation of the technology transfer process from JPL. These latter contracts were a necessary evil to finance the company, and we were fortunate that, due to factors internal to the customers, we did not create any strong competitors. Examples include an early contract with Intel and one with Kodak. Intel declined to enter the market, possibly foreseeing it as a near-commodity market like DRAM memory, and Kodak later fumbled the commercialization as was described previously.

Of the other “real” custom sensor design contracts, some matured to supply contracts for niche market applications. Identifying real customer opportunities from “looky-loos” became an important screening step. Nearly all sensors we delivered met the customer’s full specifications, but due to factors beyond the sensor, itself, some “hot” opportunities fizzled. A good example was a holographic optical memory readout chip Photobit designed for a startup backed by Microsoft. The chip, which had many challenging design aspects, was a complete success and was delivered on time. But after Microsoft apparently declined to invest in a second round, their financing collapsed, and they closed their doors. The chip later became part of our high-speed sensor catalog product lineup.

By 1997, competition in the CMOS image sensor market was heating up. In a sense, the technology transfer from JPL via technical papers, presentations, and evangelizing was too successful. Toshiba in Japan became the first major sensor company to enter the CMOS image sensor space, but there were already a number of other competitors (19). Toshiba’s entry, however, gave additional credibility to the technology, benefiting all CMOS image sensor companies.

Several customers also became strategic investors in the company, such as Schick, Gentex, and Basler. At some point, we decided that Photobit needed to offer “catalog” products that would cover a large number of customer needs. Financing from strategic corporate investors was used to complete the catalog product R&D initiated, in part, under federal SBIR funding.

From the beginning, we adopted a fabless semiconductor business model. Foundry capabilities for color filter arrays, microlenses, and low dark current in pixels needed to be developed almost from scratch. Low-yield fab run costs were a significant factor in the rate of early product R&D. As leaders in the technology, we quickly discovered the market place was ill-defined, so that specifications common today for pixel and sensor formats were not established beyond CIF and VGA, causing some early missteps in catalog product definition. Eventually, these development issues were resolved, and Photobit found traction in supplying sensors to the emerging webcam market, sharing the Logitech webcam socket with Hewlett Packard, now Agilent. The short-lived but very successful Intel webcam used the Photobit sensor as sole source for its socket.

While the baseline technology was licensed from Caltech, numerous other innovations were required for creating real products. Photobit filed over 100 patent applications for its inventions to further develop the technology and enable applications in consumer products, high-speed imaging, biomedical imaging, and automotive high dynamic range imaging, among others.

By the year 2000, the camera phone application was being taken very seriously (28). First explored as an aftermarket add-on for cameras, putting a camera module into the handset represented enormous volume potential for Photobit and its competitors, and Photobit put a large effort into meeting the application requirements.

The business model for the catalog consumer electronic sensor product business evolved to be quite different from the custom design contract and niche market business. At the end of 2000, Photobit decided to spin out the latter business as a wholly owned subsidiary, Photobit Technology Corporation (PBT). I became CEO and Chairman of the Board of PBT, in addition to being Chairman of the Board of the parent Photobit Corporation. Design centers in

Tokyo and Oslo opened by Photobit were absorbed into PBT.

PBT was a nicely profitable operation. Key customers included Schick Technologies for their dental radiography sensors, Given Imaging for low-power sensors that enabled their pioneering “swallowable pill” cameras, automotive supplier Gentex for smart-beam headlight control and safety sensors, and Basler, an inspection equipment and industrial camera manufacturer, for high-speed custom sensors.

While Photobit Corporation had substantially more revenue than PBT, totaling approximately US$25 million annually, it was not yet profitable, partly due to rapid price erosion of image sensors, in turn due to strong competition. Probably all image sensor suppliers were operating at a net loss in 2001. In addition, we had not yet reached the point where we viewed widespread defense of our licensed IP against large companies such as Toshiba or Agilent as being viable from a business perspective. However, we did have a successful settlement with our nemesis, Omnivision.

In 2001, having closed a second round of strategic investment earlier in the year, Photobit had significant cash reserves. But with strong competition on the horizon from semiconductor giants with deep pockets and due to down-market conditions in the electronics and semiconductor market, a majority of our shareholders, including some founders, pushed for a sale of the company to generate needed cash. At the end of 2001, all of Photobit’s assets were acquired by Micron Technology, a US manufacturer of DRAM memory products headquartered in Boise, Idaho.

Micron brought advanced fabrication capability to the image sensor product development and the resources to finance continued advanced product development. When the camera phone market exploded a few years later, Micron became the world’s largest supplier of image sensors for several years. Eventually, Micron management determined that the image sensor business was best served by a stand-alone company and spun out Aptina Imaging. Currently, Aptina remains in the top five image sensor suppliers worldwide, with Sony (Fig. 8), Samsung, and Toshiba as market leaders, all using IP now licensed from Caltech. The worldwide CMOS image sensor business is projected to reach US$10 billion by 2016 (27).

Figure 8. Camera phone pictures are fun to share. A photo taken of the author and his daughter at Pikes Peak, Colorado, using his camera phone (iPhone 4S with Sony 8-megapixel CMOS APS camera-on-a-chip).

CONCLUSIONS

This article has discussed transfer of the CMOS image sensor technology from its US space program origins at JPL to its incorporation today in billions of camera phones and a myriad of other applications. As anyone who has gone through a successful technology transfer process knows, one cannot just license technology to a company and expect that the transfer is complete. Even when JPL transferred the CMOS image sensor technology to highly capable companies such as AT&T Bell Labs and Kodak, a significant amount of effort was required to truly transfer the know-how and experiences of what works and what does not work to the company. Technology transfer to large companies, even when the technology is in their core area of business, does not always “stick,” despite the best of original intentions. Successful transfer depends on priorities at the upper reaches of a large company, as well as on the particular individuals at the transfer interface level. Changes in either can cause disintegration of the transfer process or “infant mortality” following successful transfer. Technology transfer is as much about people as it is about technology.

The successful transfer of the CMOS image sensor technology from JPL depended on the efforts of a large number of people. Many avenues that looked promising turned out, for one reason or the other, to be dead ends. Other avenues that looked insignificant turned out to be major. Of those that were successful, it was truly a combination of the right technology, the right timing, a degree of luck, and determined persistence that made them work.

ACKNOWLEDGMENTS: It is impossible to individually thank all the persons involved in the R&D and technology transfer process even though I wish I could, but I do wish to thank the entire team at JPL and Photobit and especially Sabrina Kemeny, who had the foresight to insist on the patenting of the CMOS APS technology and to drive Photobit forward, as well as for reviewing this manuscript for accuracy. A second very important person in this story is Bob Nixon, an engineer's engineer and good friend who was actually the first to suggest, one night over a bottle of wine, that we really ought to start a company to exploit the CMOS APS technology. I appreciate comments and suggestions by David Schick and editing by Susan Fossum and Terrie Scott. The encouragement of the NAI to document this technology transfer story is also greatly appreciated. The author is the inventor of the CMOS active pixel sensor camera-on-a-chip technology.

REFERENCES

1. Armstrong, L. NASA's tiny camera has a wide angle future. Business Week. 54–55; 1995. Retrieved May 2013 from http://www.businessweek.com/stories/1995-03-05/nasas-tiny-camera-has-a-wide-angle-future
2. Boyle, W. S.; Smith, G. E., inventors. Bell Telephone Laboratories, Incorporated, assignee. Information storage device, US Patent 3,858,232. December 31, 1974.
3. Caltech Office of Technology Transfer. Past/current startups. Retrieved May 2013 from http://ott.caltech.edu/startups/
4. Cassini Imaging Central Laboratory for Operations. Imaging science subsystem. Retrieved May 2013 from http://www.ciclops.org/iss/iss.php
5. Dickinson, A.; Ackland, B.; Eid, E-S.; Inglis, D.; Fossum, E. R. Standard CMOS active pixel image sensors for multimedia applications. In Proc. 16th IEEE conference on advanced research in VLSI. New York: Institute of Electrical and Electronics Engineers; 1995:214–224.
6. Fossum, E. R. Active pixel sensors—Are CCD's dinosaurs? In Blouke, M. M., ed. Proc. SPIE Charge-coupled devices and optical Sensors III, vol. 1900. San Jose, CA: SPIE; 1993:2–14.
7. Fossum, E. R. Assessment of image sensor technology for future NASA missions. In Proc. Charge-coupled devices and solid state optical sensors IV, vol. 2172. SPIE—The International Society for Optical Engineering; 1994:38–53.
8. Fossum, E. R. Digital camera system on a chip. IEEE Micro. 18(3):8–15; 1998.
9. Fossum, E. R. Ultra low power imaging systems using CMOS image sensor technology. In Proc. advanced micro-devices and space science sensors, vol. 2267. SPIE—The International Society for Optical Engineering; 1994: 107–111.
10. Fossum, E. R.; Mendis, S. K.; Kemeny, S. E., inventors. California Institute of Technology, assignee. CMOS active pixel image sensor, US Patent 5,471,515. November 28, 1995.
11. Fossum, E. R.; Nixon, R. H., inventor. California Institute of Technology, assignee. CMOS active pixel sensor type imaging system on a chip, US Patent 5,841,126. November 24, 1998.
12. Janesick, J. R. Scientific charge-coupled devices. Bellingham, WA: SPIE—The International Society for Optical Engineering; 2001.
13. Janesick, J. R.; Collins, S. A.; Fossum, E. R. Scientific CCD technology at JPL. In Proc. NASA Technology 2000 Conference, vol. 1. Washington, DC: The National Aeronautics and Space Administration; 1990.
14. Lee, P. P. K.; Gee, R. C.; Guidash, R. M.; Lee, T-H.; Fossum, E. R. An active pixel sensor fabricated using CMOS/CCD process technology. In Program IEEE workshop on CCDs and advanced image sensors. Dana Point, CA: 1995. Retrieved from http://www.imagesensors.org/Past%20Workshops/1995%20Workshops/1995%20Papers/20%20Lee%20et%20al.pdf
15. Lloyd, G. A; Sasson, S. J., inventors. Eastman Kodak Company, assignee. Electronic still camera. US Patent 4,131,919, December 26, 1978.
16. Nakamura, T.; Matsumoto, K. Active pixel image sensors: Recent developments of the CMD. In Proc. International symposium on advanced image-acquisition technology (SAIT '91), Tokyo, Japan; 1991.
17. Noble, P. J. W. Self-scanned silicon image detector arrays. IEEE Trans. Electron. Devices 15(4):202–209; 1968.
18. Panicacci, R.; Pain, B.; Zhou, Z.; Nakamura, J.; Fossum, E. R. Progress in voltage and current mode on-chip analog-to-digital converters. In Proc. solid state sensor arrays and CCD cameras, vol. 2654. SPIE—The International Society for Optical Engineering; 1996:63–71.
19. Pollack, A. Imaging device makes chip-sized cameras a real world possibility. New York Times; 1997. Retrieved May 2013 from http://www.nytimes.com/1997/05/27/business/imaging-device-makes-chip-sized-cameras-a-real-world-possibility.html
20. Porco, C. C.; West, R. A.; Squyres, S.; McEwen, A.; Thomas, P.; Murray, C. D.; Delgenio, A.; Ingersoll, A. P.; Johnson, T. V.; Neukum, G.; Veverka, J.; Dones, L.; Brahic, A.; Burns, J. A.; Haemmerle, V.; Knowles, B.; Dawson, D.; Roatsch, T.; Beurle, K.; Owen, W. Cassini imaging science: Instrument characteristics and anticipated scientific investigations at Saturn. Space. Sci. Rev. 115:363–497; 2004.
21. Stern, B. Inventors at work: The minds and motivation behind modern inventions. New York, NY: Springer-Verlag New York, Inc.; 2012.
22. Teranishi, S.; Ishihara, Y.; Shiraki, H., inventors. Solid state image pickup device and driving method therefor, Japanese Patent 1,728,783. September 4, 1990.
23. Theuwissen, A. J. Solid-state imaging with charge-coupled devices. New York, NY: Springer Press; 1995.

24. Tompsett, M. F.; Amelio, G. F.; Bertram, W. J., Jr.; Buckley, R. R.; Mcnamara, W. J.; Mikkelsen, J. C., Jr.; Sealer, D. A. Charge-coupled imaging devices: Experimental results. IEEE Trans. Electron. Devices 18(11):992–996; 1971.
25. University of Southern California. The MOSIS service. Retrieved May 2013 from http://www.mosis.com/
26. Wilson, R. Kodak, Motorola team on imaging chips for cameras. EE Times 959:10; 1997.
27. Yole Développement, Status of the CMOS image sensors industry. Lyon, France: Yole Développement; 2012.
28. Yoshida, J. Vendors race to pack cameras into cell phones. EE Times; 2000. Retrieved from http://www.eetimes.com/electronics-news/4168263/Vendors-race-to-pack-cameras-into-cell-phones-.