Camera on a Chip

Eric R. Fossum and Sabrina Kemeny

Electronic imaging chips will extend the visual sense of humankind well beyond the spatial, temporal, and wavelength range of our biological vision.

● From work, you give your house a call on your videophone. The house answers, and you punch in your access code. You open up the kitchen camera and, sure enough, there is your briefcase on the table, just where you forgot it.

● You're backing your car into a tight spot. Where is that curb? You flip on the right rear bumper camera and see that you are a few feet short of the curb and slowly back into position.

● You pull up to the same congested intersection you always pass on your way to work. Today, though, a new smart traffic signal has been installed. For the first time, the traffic light "sees" the cars and changes in response to traffic conditions.

It is nearly certain that electronic cameras will play a greatly increased role in your personal life within the next five years. Some cameras will capture live video for you to watch, others will be the silent eyes of smarter machines that assist you. Some cameras will record documents, some will capture still images of your fondest vacation memories, and some will capture images of distant planets.

Like the ubiquitous microprocessor chips executing the will of their masters at speeds beyond comprehension, electronic imaging chips will also become ubiquitous, extending the visual sense of humankind well beyond the spatial, temporal, and wavelength range of our biological vision and probably beyond our imagination.

Capturing images of the world has occurred continuously since the first cave dweller made the first cave drawing. There has been an accelerated conversion to more practical media since that time, from the earliest paper to woven tapestries, oil paintings on canvas, chemically etched glass plates, photographic film, and, finally, electronic image capture systems.

Photographic film and electronic imaging have coexisted for more than 30 years, each with a fairly well-defined territory of application. Film has dominated the consumer photography market, while electronic imaging has been dominant in many scientific applications and in such applications as broadcast television and digital still photography.

Until recently, the territory of electronic imaging has been necessarily confined by the high cost of the equipment. Now a new development at the Jet Propulsion Laboratory (JPL) in Pasadena, California, the active pixel sensor, promises a second generation of electronic imaging equipment. Due to its lower cost and ease of use, APS technology seems likely to extend electronic imaging further into the traditional territory of photographic film while also opening radically new arenas to remote observation.

Electronic image capture

Thirty years ago, electronic cameras were found in a very limited number of applications outside broadcast television studios and closed-circuit TV systems. Cameras were made using vacuum

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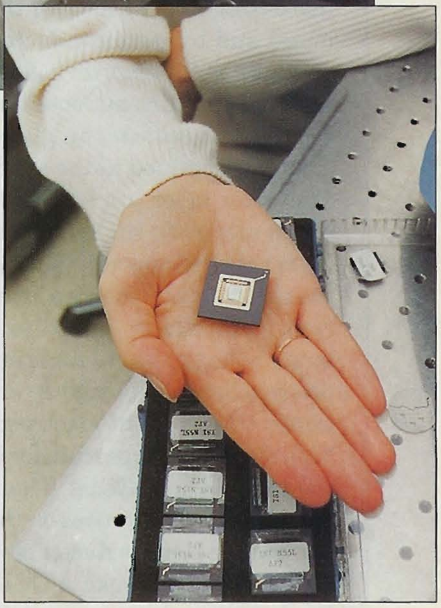

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■ **Eric Fossum, principal inventor, and coinventor Sabrina Kemeny select a multiresolution imaging module for testing. The broad, blue ribbon cable in the center of the photo carries test data to and from the chip, which will be mounted in the white frame at the end of the large lens behind the ribbon. *Inset:* The sensor, the small silver-colored square inside the gray ceramic package, may find its first use as part of the vision package in new NASA robots.**

imaging tubes, which had high performance but short operating lifetimes and consumed hundreds of watts of power while operating at high voltages. Many researchers believed that vacuum imaging tubes would someday be replaced by solid-state image sensors, just as the vacuum tubes that were once pervasive in radios, computers, and audio equipment were replaced by solid-state semiconductor transistors. A solid-state image sensor would be expected to have many practical advantages over its vacuum imaging tube predecessors, including smaller camera size, lower power, lighter weight, and greater reliability.

In 1970, AT&T Bell Laboratories reported on the invention of a new solid-state imaging sensor, called the charge-coupled device, or CCD. Over the ensuing 25 years CCDs have been steadily improved, leading to their present very high level of imaging performance. CCDs have established a host of basic concepts about electronic imaging and provide a benchmark by which to evaluate new approaches to electronic imaging.

A CCD chip is divided into a matrix of small adjoining regions called pixels. (A typical CCD chip may, for example, be a matrix of

The Electronic Imaging Mainstream

In a charge-coupled device (CCD), light hitting the surface of a semiconductor chip subdivided into a matrix of hundreds or thousands of small photosensitive pixels triggers the release of electrons into the chip material. For each pixel, electrons are gathered by electrostatically corralling them using a set of three electrodes on the surface of the thin-film sandwich of three different materials. The electrodes are the top layer of the metal-oxide-semiconductor sandwich, in which the oxide forms an insulating layer between the metal and the semiconductor.

Like iron filings on a glass tabletop that are attracted by a magnet beneath the glass, electrons confined in the semiconductor layer are attracted by an electrode (in the metal layer) on the opposite side of the oxide layer. When an adjacent electrode is pulsed to a larger voltage, the electrons are dragged laterally until they are under the adjacent electrode. This electron charge transfer is the main idea of CCDs. Thousands of small electrodes on the surface of a semiconductor chip are required to make a CCD. Each electrode is pulsed in sequence to gradually drag the electrons to a particular spot on the chip, where they are converted into a voltage using an output amplifier.

The further the pixel is from the output amplifier, the more transfers it takes for the electrons to reach the output amplifier. By knowing the time at which a given voltage comes from the output amplifier, the exact location of the origin of the electrons can be ascertained and the image reconstructed. The process of transferring the electrons to the output amplifier is called *readout*.

The voltage from the amplifier is converted to a digital value through the use of an analog-to-digital converter circuit.

The Achilles' heel for a CCD is fundamental to the way a CCD operates. In most CCDs, the charge is being transferred from electrode to electrode at a rate of over 10 million times per second. Yet because each packet might contain only a few hundred electrons, the transfer efficiency from one electrode to the next must be nearly perfect. If even one electron were left behind, the packet would run out of electrons long before the packet reached the output amplifier. In fact, to achieve reasonable performance in a commercial CCD, the transfer efficiency must be at least 99.999 percent—anything less would yield unsatisfactory imaging performance.

This transfer efficiency means that for a packet of 1,000 electrons, only one electron can be left behind for every 100 transfers. Almost any semiconductor defect will result in a reduction in charge transfer efficiency. To try to achieve perfect transfer efficiency, CCDs are fabricated using a special and hence costly process. They are also operated with large voltages (for example, 20 volts—large by microelectronics standards!), whose levels must be very carefully adjusted. These large, precise voltages require a relatively large, heavy, and, hence, costly power supply. Given the high costs of their fabrication, power supply, and supporting electronics, CCDs would seem to be an intrinsically costly and relatively cumbersome technology.

—E.R.F and S.K.

600 x 600 pixels, or 360,000 pixels.) The photons of light impinging on each separate pixel liberate electrons from being bound to a particular atom in the crystal. In a process called detection, liberated electrons from each pixel are collected into a discrete packet. Then, in a process called readout, the stream of packets is transferred to a specific location on the chip, where each packet is

converted to a voltage by an output amplifier and then sent off the chip. An image can be reconstructed based on the CCD's output stream because the chip is designed to keep track of the originating pixel for each packet of electrons.

CCDs were initially developed for the picture phone, which was to transmit pictures as well as sound. Unfortunately for the picture phone, ordinary telephone wires could not handle the information data rate required to transmit the digitized moving pictures, and the technology had to wait for the development of today's sophisticated compression technologies. NASA began developing CCDs for space applications in the mid-1970s, and by now CCDs have been used on many earth-orbiting satellites to record images of the earth, as well as in the Hubble Space Telescope cameras. Today, nearly all ground-based telescopes use CCDs to capture images from space. Such "scientific CCDs" typically contain from 1–16 million pixels, and costs range from $1 to $5 per thousand pixels.

However, it is the camcorder market that has led to the greatest development and proliferation of CCDs. Camcorder CCDs typically contain 350,000 pixels, at an original manufacturer's cost of about one nickel per thousand pixels, or about $17.50 per CCD. These CCDs contain an integrated color filter array made from a thin polymer film dyed different colors. The color filter array covers some pixels with red, some with green, and some with blue filters. Thus, some pixels are sensitive only to red photons, some to green photons, and some to blue photons. After readout, subsequent processing is used to reconstruct the original color image at each pixel by using information from neighboring, different-colored pixels.

Because of the lower cost enabled by the large camcorder market and the progress made in very large scientific CCD arrays, CCDs are being applied to photographic applications previously served by film. Digital still photography is the term used for electronic cameras that capture scenes electronically instead of on chemical film. Once the scene is recorded electronically, it can be instantly reviewed and, if need be, erased and recaptured. CCDs have gained increasing use from

■ The mainstream technology for capturing digital images today is the CCD (charge-coupled device), which has become less expensive thanks to the economies of scale gained in producing the ubiquitous camcorder.

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Imaging by Film or by Chip?

Chemical photography, in use for more than 130 years, involves basic operations that nearly everyone understands. Film is loaded into a camera. A shutter on the camera is activated, allowing light focused by a lens to fall on one frame of a roll of film for a very short period. A typical roll of film permits 24 exposures, after which the roll is developed in a two-step chemical process that produces first a negative image and then paper prints that can be handled, archived in a picture album, or hung on your refrigerator door. With automated film processors, the time from exposure to the finished print can easily be under one hour. For a slightly higher cost per picture and with somewhat lower photographic quality, "instant" photographic film can be used to reduce the time from exposure to finished print to only a minute or two.

The benefits of film-based image capture are its high resolution, portability, maturity, relatively low cost, and tangibility—you can physically see and touch the captured image.

However, the disadvantages of chemical film when compared to electronic image capture systems are growing. Chief among these is the necessarily long time between exposing the film and viewing the captured image. It would be convenient to be able to view a captured image instantaneously to ascertain if the exposure and scene were properly captured. For example, in studio photography, did someone blink? What amateur photographer hasn't felt that great disappointment when the photo opportunity of a lifetime dissolves as the prints come back from the photo lab.

Another disadvantage of chemical film is the relative inability to manipulate the image's appearance. Contrast enhancement, color balancing, and graphical manipulation of images are only a few of the many tools readily available for use with electronically captured images, but they are very difficult to affordably accomplish by nonelectronic means.

A third and growing disadvantage of chemical film is the potential environmental damage caused during the creation, use, and disposal of chemical products necessary for film processing. Electronic image capture, in contrast, permits instant feedback on captured image quality, enables the use of digital computer-based manipulation of image data, and is more environment friendly.

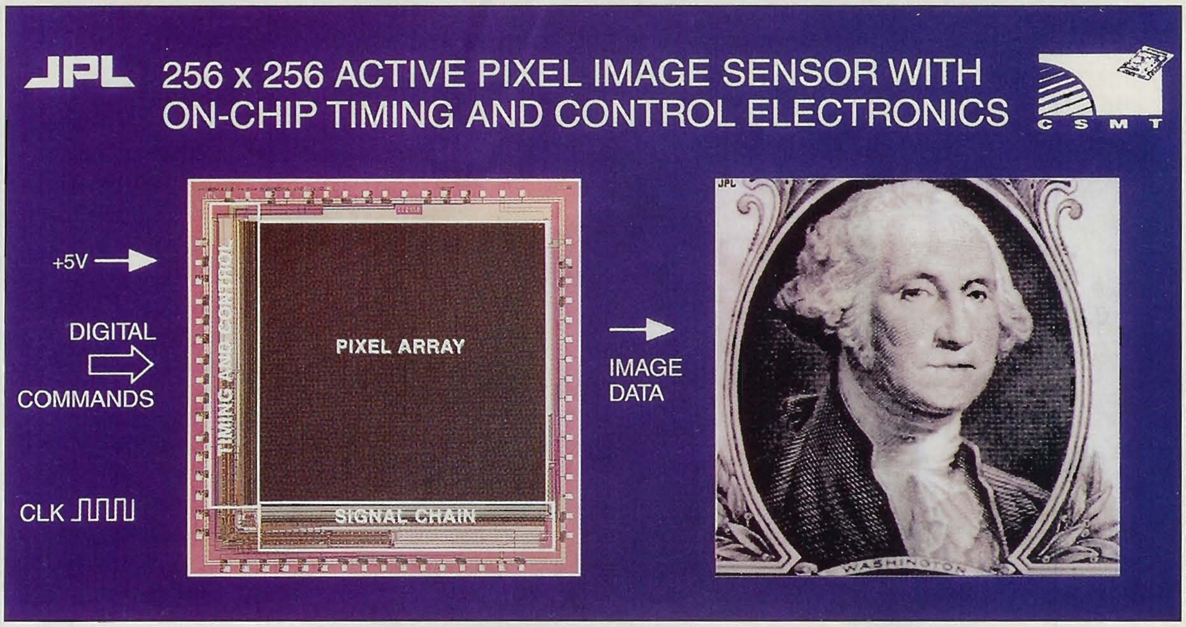
—E.R.F and S.K.

journalists, insurance adjusters, medical trauma teams, realtors, and many others who can benefit from being able to use a simple phone line to transmit the image to a distant location for viewing, printout, archiving, or processing. Images can be stored on diskettes or in flash memory cards.

Camera on a chip

In 1993, the JPL reported a new solid-state imaging technology called the CMOS active pixel sensor, or APS, which maintains the high performance of a CCD and also permits a second-generation revolution in miniaturization. (CMOS, complementary metal oxide semiconductor, is the name of one of several types of processes for making integrated semiconductor circuits.)

Despite the great advances of electronic image capture using CCDs, more improvement in system functionality is desired. For example, lower power is desired to prolong battery life in portable applications. A typical CCD imaging system requires 5–10 watts to operate. Camcorder batteries last only an hour due to the high power drain. It is also desirable to shrink the size of camera electronics so very small cameras can be built, with consequent reductions in the power and size of the camera. Lighter-weight cameras are desired for many applications, particularly in space missions,



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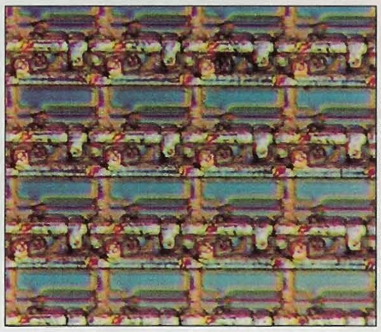
where the weight of a remote sensing instrument may significantly affect the cost of a launch vehicle. Hence, in the 1990s, JPL began the development of a second-generation solid-state image sensor that could greatly reduce the cost, weight, and size of imaging instruments.

To miniaturize instrument imaging systems, it is necessary to reduce the number of discrete electronic components. This can be achieved by using very large scale integration (VLSI) to integrate all electronic components onto a single chip. However, the highly specialized CCD fabrication process is not well suited for also manufacturing conventional electronic components, which are typically made by the CMOS process and operate at lower voltages than CCDs. Several groups in the United Kingdom, Sweden, and Japan have explored the use of CMOS for implementation of image sensors, but the performance of the sensors has fallen far short of the excellent performance of the CCD.



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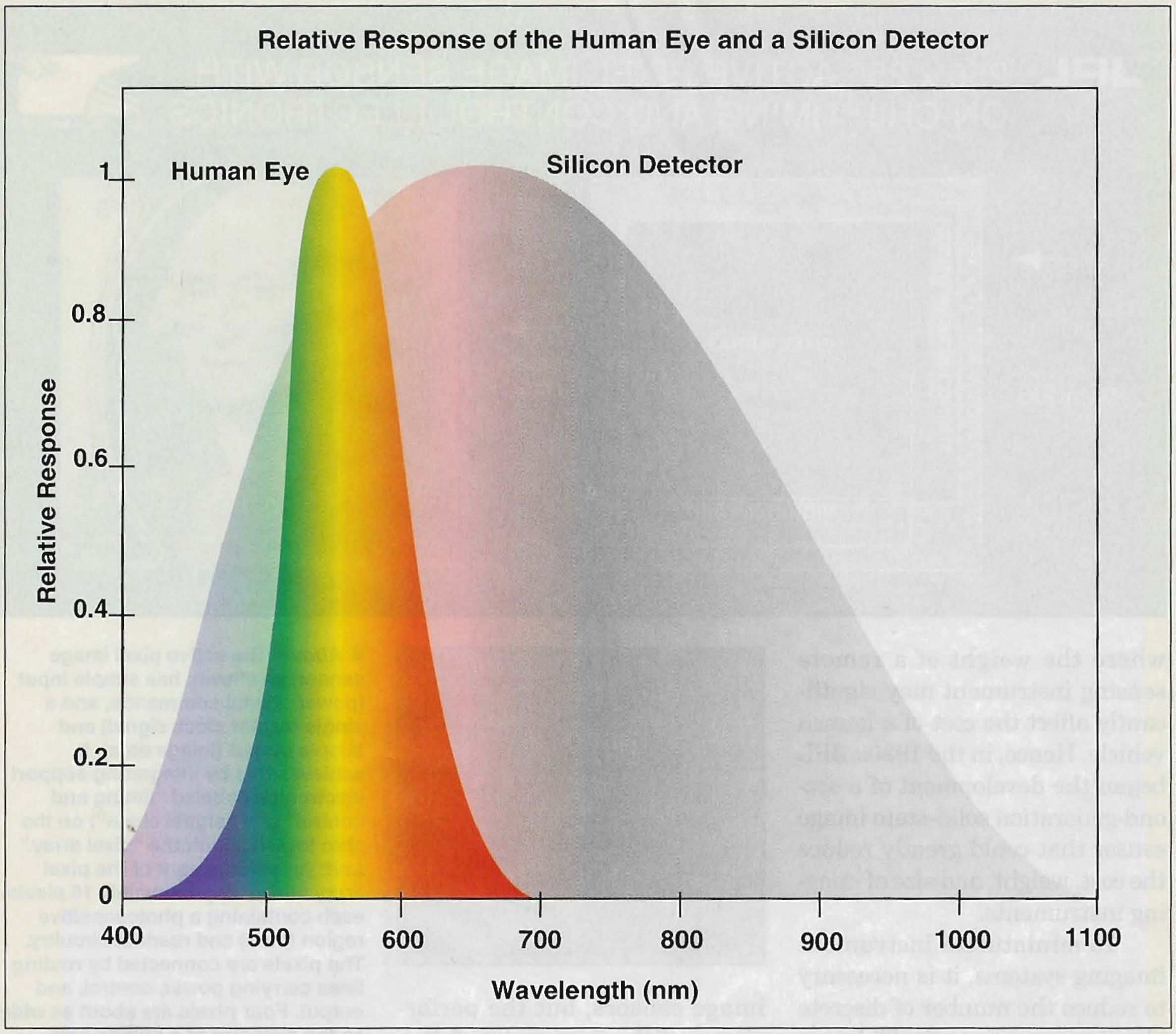
■ ***Above:*** **The active pixel image sensor, as shown, has simple input (power, digital commands, and a single master clock signal) and simple output (image data). It achieves this by integrating support electronics (labeled "timing and control" and "signal chain") on the chip together with the "pixel array."** ***Left:*** **An enlargement of the pixel array shows approximately 16 pixels, each containing a photosensitive region (blue) and readout circuitry. The pixels are connected by routing lines carrying power, control, and output. Four pixels are about as wide as the diameter of a human hair.**

The CCD amplifier is one of the reasons the CCD performs so well. However, a major drawback of the CCD design is that it requires all the packets of electrons from all of the pixels to be transported to that single amplifier with a near-perfect efficiency that cannot be realized by the widely used and well-developed CMOS process.

If the amplifier could be brought to the pixel instead of the electrons being brought to the amplifier, reasoned the team at JPL, the need for perfect transfer efficiency would be eliminated. The very small feature sizes available from state-of-the-art CMOS chip manufacturers allow the insertion of amplifier circuitry into the pixel without much impact on pixel size. Such a sensor with an amplifier in



■ **Silicon detectors, such as CCDs and APS integrated circuits, are sensitive to "light" that is far beyond the range of human vision, especially in the infrared regions.**

each pixel is called an active pixel sensor. In the Jet Propulsion Lab's CMOS APS, the best features of the CCD and CMOS image sensors are combined. Photogenerated charge is collected just as it is in a CCD. However, for readout, the charge is transferred only once to the output amplifier in the pixel. To save power, the output amplifier in each pixel is turned on only during readout.

Performance of the CMOS APS has been steadily improving over the two years since its invention. An early concern was the uniformity of such a large number of amplifiers, but uniformity competitive with CCDs (about 1 percent) has been achieved in recent arrays. Extremely low power dissipation (lower than 10 milliwatts) has been achieved at 30 hertz operation, compared to 5,000 milliwatts for a CCD system. This means that tiny watch batteries can power a CMOS APS camera.

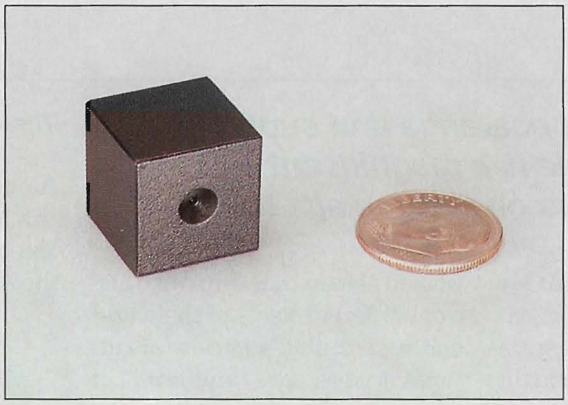
To realize a camera on a chip, functions beyond detection and readout are required. All timing and control signals to operate the sensor, as well as the analog-to-digital converter (ADC), must be realized by circuits integrated on

Our children will inherit a world where the limitations of four walls dissolve into a worldwide network of remote eyes.

the same chip. Although it would be possible to integrate onto the imaging array a single conventional ADC circuit that would sequentially digitize the signals from all the pixels, to reduce the chip's power consumption, the JPL architecture uses one tiny ADC circuit for each column of pixels. By increasing the number of ADC circuits handling the pixel outputs, this design decreases the operating rate of a single ADC, with the net effect of substantially reducing the chip's power dissipation.

Single-chip APS electronic cameras have already been developed and are expected to enter the commercial market by 1997. A single-chip, high-performance, low-power electronic image capture system enables many new applications that were previously impractical. The camera on a chip technology will result in low-end cameras that cost between $10 and $30. These cameras will be virtually disposable and will be suitable for applications such as rear bumpers on cars, children's toys, and home security. Higher-end cameras suitable for digital still photography will also incorporate APS technology.

In addition to making cameras smaller, cheaper, and lighter weight, new types of "smart" functions can be incorporated into cameras for machine vision applications. For example, a multiresolution camera on a chip has been developed by JPL that will allow computers to "see" the world in a continuously variable resolution. This will dramatically reduce the amount of computation required to allow a robotically driven car to maneuver. Sensors that track stars for satellite navigation will be able to see both dim and bright stars simultaneously without overloading the sensor using a random-access camera on a chip. Security systems that can sense motion and automatically take a snapshot or short video clip of the intruder can also be easily envisioned.



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Mockup of the camera that the JPL Digital Imaging Camera Experiment aims to achieve in 1997 using the active pixel sensor chip. Similar low-power, low-cost cameras are likely to find widespread consumer applications ranging from PC video conferencing to traffic surveillance to applications not yet imagined.

A network of remote eyes

Where will this all lead? Our children will inherit a world where the limitations of four walls dissolve into a worldwide network of remote eyes, accessible from their favorite armchair. Gone too will be the traditional privacies of walls and distance.

New ethical questions regarding the viewing public's right to see all and be everywhere through the new telepresence need to be debated and decided. Concerns over "big brother's" ability to visually penetrate our personal lives need to be balanced with humans' seemingly insatiable appetite for visual stimulation and new information. ■

Eric R. Fossum is a senior research scientist at the Jet Propulsion Laboratory in Pasadena, California, and leads the team developing the CMOS active pixel sensor technology. Sabrina Kemeny, a former member of the team, is the CEO of Photobit, a new company commercializing the CMOS APS technology.