Guest Editorial
Special Issue on Solid-State Image Sensors

THIS is the fifth special issue of the IEEE TRANSACTIONS ON ELECTRON DEVICES on solid-state image sensors. We continue on our six-year cycle as the previous special issues were in August 1985, May 1991, October 1997, and January 2003. This year we celebrate the 40th anniversary of the invention of the charge-coupled device (CCD) and extend our congratulations to Willard S. Boyle and George E. Smith on winning the 2009 Nobel Prize in Physics "for the invention of an imaging semiconductor circuit—the CCD sensor."

CMOS active-pixel image sensors have become increasingly mature and now dominate image sensor market shipments in volume and revenue, owing mostly to their nearly ubiquitous use in the mobile handset (a.k.a. camera-phone) and webcam markets. CMOS image sensors are also used extensively in high-speed high-resolution cameras. There is increasing use of CMOS image sensors in the high-end digital single-lens reflex market, the high-definition television camcorder, and professional camera market, as well as in defense and aerospace. CCDs continue to be used extensively in point-and-shoot compact cameras and most camcorders. The use of image sensors in security cameras, medical applications, and automobiles seems to be split between CCDs and CMOS image sensors.

With the increase in CMOS image-sensor revenue and competition between suppliers, there seems to be concomitant reluctance to publish papers on leading edge issues in pixel design. The same phenomena occurred with CCDs in the early 1990s. One of the key issues facing image-sensor designers results from the shrink in pixel size. The signal-to-noise ratio (SNR) at 100-lx scene illumination has become limited by the SNR of the incoming photon flux and its shot noise rather than the readout characteristics of the image sensors. Input-referred read noise in commercial devices is routinely below five electrons rms and often below three electrons rms. In pixel pitches smaller than approximately 1.4 μm, the number of photons incident on the pixel is so limited that great emphasis is placed on optically collecting all possible photons and obtaining the highest possible quantum and collection efficiency within the pixel. There has been a growing interest in the mass production of backside-illuminated devices to decrease the competition between pixel wiring and optical aperture. The use of other stacked structures to separate photon detection from pixel readout and signal processing is also of growing interest.

At the same time, the ability to commercially produce multimegapixel image sensors with high-frame-rate readout is rapidly outgrowing our capability to manage and utilize the data from these sensors. For example, image capture at the sensor level for ultrahigh-definition television, now also known as Super-Hi Vision, with 33-megapixel 60-frame/s image sensors, has been readily demonstrated. However, the technology for storing, processing, transmitting, and displaying these images for widespread consumer application is probably over a decade away, at best. With significant obstacles to meaningful continued pixel shrink and bottlenecks with the storage, transmittal, and display of images, the so-called megapixel race for consumers may be waning. Increased emphasis on increasing image quality over shear pixel count can be expected.

On the other hand, the time is ripe for a third generation of solid-state image sensors. While no particular technology has emerged, it is easy to speculate that this could be in the area of photon-counting sensors (e.g., single-photon avalanche detectors), 3-D imaging (color plus time-of-flight range), a combination of both, or, perhaps, something not even on the radar screen nowadays.

In this Special Issue of the IEEE TRANSACTIONS ON ELECTRON DEVICES, an assortment of papers is presented that represents both the broad spectrum of activity in the area of image sensors for consumer, scientific and aerospace applications, as well as illustrating the international nature of the effort.

For over 40 years, the Electron Devices Society has been a home for solid-state image-sensor technologists. However, with the increased integration of on-chip solid-state circuits for analog signal processing, analog-to-digital conversion, digital signal processing, and computer-science image processing functions in the camera-on-a-chip, the multidisciplinary and interdisciplinary nature of solid-state imaging is apparent. In addition, there is increased emphasis on photonic and materials modeling. Interested readers are also referenced to publications and conferences of the IEEE Solid-State Circuits Society as well as the IEEE technical cosponsored International Image Sensors Workshop online library at www.imagesensors.org for additional recent publications in this field.

I would like to thank J. A. Marsh of the IEEE for her excellent administrative assistance and her patience in the publication of this Special Issue. I would also particularly like to thank my Associate Guest Editors, J. Hynecek, J. Tower, N. Teranishi, J. Nakamura, P. Magnan, and A. Theuwissen, for their significant effort and cooperation in the creation and implementation of this Special Issue. Without their important contributions and those of the authors, this Special Issue would not have been possible.

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From 1984 to 1990, he was a Member of the Faculty of Electrical Engineering, Columbia University, New York, NY, and an Adjunct Professor with the University of Southern California, Los Angeles, from 2001 to 2007. In 1990, he joined the NASA Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, CA, and managed JPL's image sensor and focal-plane technology research and advanced development. While at JPL, he invented the CMOS active pixel sensor camera-on-a-chip technology and led its development and subsequent transfer of the technology to the U.S. industry. In 1995, he cofounded Photobit Corporation to commercialize the technology and served in several top management roles, including Chief Executive Officer (CEO). In late 2001, Photobit was acquired by Micron Technology, Inc. From 2005 to 2007, he was CEO of Siimpel Corporation, developing camera modules with MEMS-based autofocus and shutter functions for cell phones. He is currently a Consultant with the Semiconductor R&D Center, Samsung Electronics Company, Ltd., Yongin, Korea, where he leads a team of researchers in advanced image sensors. He has published over 240 technical papers and is the holder of more than 120 U.S. patents. He has been Primary Thesis Adviser to 13 graduating Ph.D. students.

Dr. Fossum founded the biannual IEEE Workshops on CCDs and Advanced Image Sensors (currently the International Image Sensor Workshop) and was Guest Editor-in-Chief for IEEE TRANSACTIONS ON ELECTRON DEVICES special issues on Solid-State Image Sensors in 1997, 2003, and this issue. He has received Yale's Becton Prize, the IBM Faculty Development Award, the National Science Foundation Presidential Young Investigator Award, the JPL Lew Allen Award for Excellence, and the NASA Exceptional Achievement Medal. He was inducted into the U.S. Space Foundation Technology Hall of Fame. He has also received the Photographic Society of America's Progress Medal and the Royal Photographic Society's Progress Medal for the invention of the CMOS active pixel image sensor technology. In 2009, he will receive the IEEE Andrew S. Grove Award for his significant contributions to invention and commercialization of CMOS image sensors.

Jaroslav (Jerry) Hynecek (M'73–SM'00) was born in Czechoslovakia, on November 26, 1940. He received the Dipl.Ing. degree in electrical engineering from Czech Technical University (CTU), Prague, Czech Republic, in 1962 and the Ph.D. degree in electrical engineering from Case Western Reserve University (CWRU), Cleveland, OH, in 1974.

From 1962 to 1969, he was with the A. S. Popov Research Institute, Prague, and as an Assistant Professor of physics with CTU. From 1974 to 1976, he was with CWRU. In 1976, he joined Texas Instruments Incorporated, Dallas, and achieved position of TI Fellow in 1990. In 1978, he invented Virtual Phase CCD Technology that became the basis for the Pinned Photodiode concept and reduction of dark current by accumulation of holes at the Silicon–Silicon dioxide interface. In 1993, he invented "Impactron" a charge multiplying CCD image sensor that is the solid state equivalent of vacuum tube Image Intensifiers. In 1998, he founded a consulting corporation, ISETEX, Inc., Allen, TX, where he is Chief Technology Officer. He has published 56 papers and is author or coauthor of 84 U.S. patents.

Dr. Hynecek served as an Associate Editor for IEEE TRANSACTIONS ON ELECTRON DEVICES from 1997 to 2006. He received the Paul Rappaport Award for the best paper published in any IEEE Electron Devices Society journal during 1983, 2003 Walter Kosonocky Award, and three NASA Group Achievement Awards. He has also participated in numerous image-sensor-related conferences and workshops as a member of the paper selection committees or as a session chairman or cochairman.

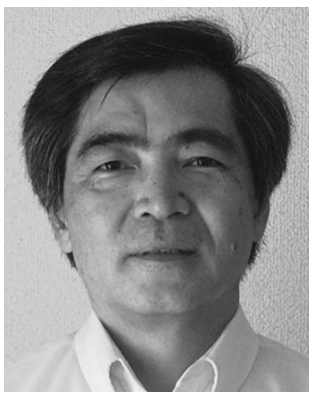
John Tower (SM'03) received the B.S.E.E. and M.S.E.E. degrees and the Ph.D. degree in electrical and systems engineering from the University of Pennsylvania, Philadelphia in 1976, 1980, and 1993 respectively.

He started his career at RCA Advanced Technology Laboratories, Moorestown, NJ, developing charge-coupled-device (CCD) technology for signal-processing and imaging applications from 1976 to 1987. This organization became part of General Electric Aerospace in 1987. From 1987 to 1989, he was involved in the development of imaging solutions for space applications. In 1989, he joined Sarnoff Corporation, Princeton NJ (formerly RCA David Sarnoff Research Center). He has been directing the development of CCD and CMOS APS imagers and cameras for custom high-performance applications. He has published 44 papers in publications, including the IEEE TRANSACTIONS ON ELECTRON DEVICES, the IEEE JOURNAL OF SOLID STATE CIRCUITS, the IEEE TRANSACTIONS ON NEURAL NETWORKS, the PROCEEDINGS OF THE IEEE WORKSHOP ON CCDS AND ADVANCED IMAGE SENSORS RCA REVIEW, the *Proceedings of the International Conference on Scientific Optical Imaging*, and *SPIE Conference Proceedings*. He is the holder of 11 U.S. patents. He is currently the Technical Director of Sarnoff Imaging Systems, focusing on very high speed CCD imagers/cameras, CCDs for aerospace applications, and high-performance backside-illuminated CMOS imagers for X-ray, UV, visible, and NIR applications. He is the Editor for *Image Sensors* of the IEEE TRANSACTIONS ON ELECTRON DEVICES.

Nobukazu Teranishi (M'96–SM'08) was born in 1953. He received the B.S. and M.S. degrees in physics from the University of Tokyo, Tokyo, Japan, in 1976 and 1978, respectively.

From 1978 to 2000, he was with the NEC Corporation, where he was involved in the research and development of solid-state image sensors for visible and infrared. From 1986 to 1987, he was with Arizona State University, Tempe, as a Visiting Researcher, studying quantum transport. Since 2000, he has been with the Panasonic Corporation, Nagaokakyo, Japan, where he is currently the General Manager in charge of marketing and application technology of image sensors with the Image Sensor Business Unit, Semiconductor Company. He and his group invented the pinned photodiode technology, vertical overflow structure, and smear reduction structure. He is the author or a coauthor of 78 papers. He is the holder of 95 patents.

Mr. Teranishi was selected as a Fellow of the Institute of Image Information and Television Engineers in 2003, where he served as the Chairman of the paper editorial committee and the information sensing committee. He received the Prize of the President of KEIDANREN of National Invention Awards in 1994, the Commendation by the Minister of State for Science and Technology in 1997, and the Niwa-Takayanagi Award from the Institute of Image Information and Television Engineers in 2000. His group received the Technology Progress Award in 1986 from the Institute of Television Engineers of Japan, the Technology Award in 1986 from the Motion Picture and Television Society of Japan, and the Emmy Award in 1991 from the Academy of Television Arts and Sciences. His group also received the Fujio Award in 1993 from the Institute of Television Engineers of Japan. He was a Guest Editor of the IEEE TRANSACTIONS ON ELECTRON DEVICES for the Special Issue on Solid-State Image Sensors in 1997 and 2003. He served as the General Chairman for the 1999 and 2005 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors. He cofounded the International Image Sensor Workshop (IISW) in 2006 and will be a Cochair of the 2011 IISW. He is a program committee member of IS&T/SPIE Electronic Imaging.



Junichi Nakamura (M'91–SM'01) received the B.S. and M.S. degrees in electronics engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1979 and 1981, respectively, and the Ph.D. degree in electronics engineering from the University of Tokyo, Tokyo, in 2000.

He joined Olympus Optical Company, Ltd., Tokyo, in 1981. After working on optical image processing, he was involved in developments of active pixel image sensors, including static induction transistor image sensors and MOS-type image sensors. From September 1993 to October 1996, he was resident with the NASA Jet Propulsion Laboratory, California Institute of Technology, as a Distinguished Visiting Scientist. In 2000, he joined Photobit Corporation, Pasadena, CA, and established Photobit's Japan Branch, where he led several custom sensor developments. In November 2001, he was appointed Manager of Japan Imaging Design Center, Micron Japan, Ltd. Since March 2008, he has been Director of Japan Design Center of Aptina Japan, LLC., Tokyo, Japan. He was Editor and a Contributor for a textbook "Image Sensors and Signal Processing for Digital Still Cameras" (CRC Press, 2005).

Dr. Nakamura is also a member of the Institute of Image Information and Television Engineers of Japan. He served as Technical Program Chairman for the 1995, 1999, and 2005 IEEE Workshop on Charge-Coupled Devices and Advanced Image Sensors and as a committee member on Detectors, Sensors and Displays for the IEDM 2002 and 2003. He received the Takayanagi Memorial Award in 2009 for his contribution to the CMOS Active Pixel Sensor developments.

Pierre Magnan (M'99) was born in Nevers, France, in 1958. He received the M.S. and D.E.A. degrees in integrated circuit design from the University of Paris 11, Orsay, France, in 1982 and the Agregation degree in electrical engineering from the Ecole Normale Superieure de Cachan, Cachan, France.

From 1984 to 1993, he has been involved in CMOS analog and semicustom design with LAAS CNRS Research Laboratory, Toulouse, France. In 1995, he joined the CMOS Imagers Research Group, SUPAERO, Toulouse, where he was involved in Active Pixels Sensors research and development activities. In 2002, he got his Accreditation for Ph.D. Supervision and became Full Professor with SUPAERO, currently called ISAE, where he is currently Head of the CMOS Imagers Research Group working on both Ph.D. subjects in cooperation with European companies (including STMicroelectronics, EADS-Astrium, and French Space Agency) and development of custom image sensor dedicated to space instruments, particularly for European Space Agency programs. He has been supervising eight Ph.D. candidates in the field of image sensors and has authored or coauthored 35 papers and a patent.

Prof. Magnan has been a member of the program committee of the IEEE cosponsored International Image Sensor Workshops 2007 and 2009.

Albert J. P. Theuwissen (SM'95–F'02) was born in Maaseik, Belgium. He received the M.S. degree in electrical engineering and the Ph.D. degree from the Catholic University of Leuven, Leuven, Belgium, in 1977 and 1983, respectively.

In 1983, he joined Philips Research Laboratories, Eindhoven, The Netherlands, as a member of the scientific staff. In 1991, he became Department Head of the division Imaging Devices of Philips. In March 2001, he was appointed as part-time Professor with the Delft University of Technology, Delft, The Netherlands, and in April 2002, he joined DALSA Corporation. After he left DALSA in September 2007, he started his own company, Harvest Imaging, Bree, Belguim, focusing on consulting, training, teaching, and coaching in the field of solid-state imaging technology. In 2006, he cofounded (together with his peers E. Fossum and N. Teranishi) ImageSensors, Inc. (a California nonprofit public-benefit company) to address the needs of the image-sensor community. He is author or coauthor of over 120 technical papers in the solid-state imaging field and issued several patents.

Dr. Theuwissen is member of editorial board of the magazine "Photonics Spectra" and member of SPIE. He is Coeditor of the IEEE TRANSACTIONS ON ELECTRON DEVICES special issues on Solid-State Image Sensors in May 1991, October 1997, January 2003, and November 2009, and of IEEE Micro special issue on Digital Imaging in November/December 1998. In 1995, he authored a textbook *Solid-State Imaging with Charge-Coupled Devices*. He acted as General Chairman of the IEEE International Workshop on CCDs and Advanced Image Sensors in 1997, 2003, and 2009. He is founder of the Walter Kosonocky Award, which highlights the best paper in the field of solid-state image sensors. Since 1999, he has been a member of the Technical Committee of the International Solid-State Circuits Conference. He has been elected to be International Technical Program Vice-Chair and Chair for the ISSCC 2009 and ISSCC 2010, respectively. Recently, in 2008, he received the SMPTE's Fuji Gold Medal for his contributions to the research, development, and education of others in the field of solid-state image capturing.