Influence of Terrestrial Cosmic Rays on the Reliability of CCD Image Sensors—Part 2: Experiments at Elevated Temperature

Albert J. P. Theuwissen, *Fellow, IEEE*

***Abstract*—An aging effect in solid-state image sensors is studied: the generation of hard errors resulting in hot spots, warm pixels, or white pixels. This effect even occurs in image sensors that are simply stored on the shelf. The first paper described experiments that were set up to prove that the main origin can be found with neutrons that create displacement damage in the silicon bulk. These neutrons are part of terrestrial cosmic rays. This second paper is based on measurements done on devices that were stored on the shelf, but at elevated temperatures. In addition, annealing experiments were performed on packaged devices. The creation of these hot spots is independent of technology, architecture, sensor type, or sensor vendor, and it is observed in CCDs as well as in CMOS image sensors. However, the generation, and particularly the stability, of the hot spots seems to depend strongly on the storage temperature or on the annealing temperature.**

***Index Terms*—Annealing effects, CCD image sensors, CMOS image sensors, displacement damage, high-temperature storage, hot spots, radiation damage, terrestrial cosmic rays.**

I. INTRODUCTION

IT IS QUITE well known in the imaging community that image sensors are subject to degradation effects due to radiation. These effects show up as an increase in dark current, a loss in transfer efficiency [in the case of CCDs], and the generation of extra "hot spots" [2]–[4]. Simply storing imaging devices on the shelf does result in a few extra "hot spots" over time. The problem is shown in Fig. 1: a dark image generated by a particular imager at two time points separated by 1.5 years. Notice the creation of a few extra hot spots (the horizontal line shape of the hot spots is due to the stretching of the image).

It is important to point out that these hot spots are permanent. It is not a soft error, in the sense that a high-energy particle was absorbed in the silicon, generated a cloud of charge carriers, and after the next image, all effects are gone. The effects investigated in this paper are hard errors: Once they are created, they are very stable, and they remain present in the bulk of the solid-state image sensors.

The first paper of this research described the origin of the hot spots in relation to their storage at various altitudes and latitudes. It could be shown that the neutrons present in terrestrial cosmic rays are causing the creation of hot spots [1]. Devices were stored at various altitudes and were transported by various means all over the world. A strong correlation could be shown between the number of hot spots created and the number of neutrons present at the storage or transporting location of the solid-state image sensors.

This paper is the second publication that will further focus on the behavior of these hard errors when the devices are stored at elevated temperatures and after higher temperature annealing steps.

II. EVALUATION METHOD

The evaluation method used for devices stored at higher temperatures or heat treated at elevated temperatures is the same as the one used to study the hot-spot generation in the image sensors described in the first part of this research. By comparing dark images obtained during various measurement cycles, research can be done to study the growth of hot spots. All measurements reported are done at 60 °C on CCD frame-transfer imagers with the following characteristics:

1) active area of 8.8 (H) $\times$ 6.6 (V) mm^2;
2) pixel size of 9 (H) $\times$ 22 (V) μm^2;
3) collection depth of 2.5 μm;
4) exposure time of 20 ms;
5) pixel clock of 18 MHz.

The dark images were captured by a camera (internal gain setting: 256×; internal black level: 0), a 12-b ADC (1 DN dark signal = 2 electrons dark signal), a frame grabber, and a PC. The images were analyzed using conventional software tools. All data shown in this paper are the result of measurements done on the devices stored and/or annealed at sea level (N 51° 08′ 29″, E 05° 35′ 19″, 40 m above sea level).

III. "ON-THE-SHELF" STORAGE

Devices were stored for a very long period of time at room temperature and were measured at regular time intervals. Fig. 2 shows a typical result obtained from such a series of sequential measurements: On the horizontal axis, the amplitude of newly grown hot spots is shown, whereas the vertical axis shows the probability (per sensor and per day) that such a hot spot will be created. The data are represented in a reverse cumulative histogram. Every thin line represents the result of two measurement cycles obtained from 60 sensors. These devices were stored on the shelf for periods of six weeks up to six months

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The author is with Harvest Imaging, Kleine Schoolstraat 9, 3960 Bree, Belgium (e-mail: a.theuwissen@harvestimaging.com).

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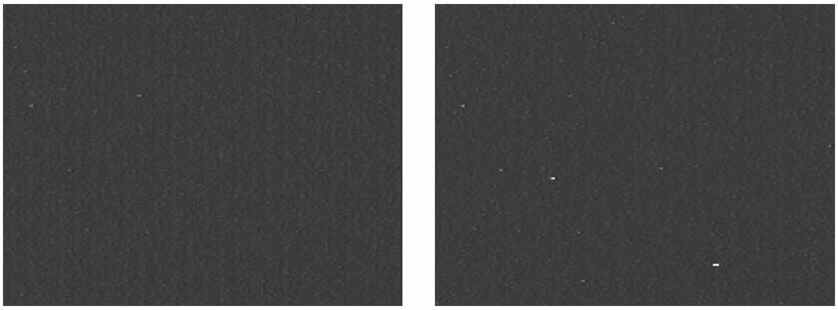

Fig. 1. Problem definition: Two dark images (200 × 150 pixels out of a large image) taken by the same image sensor; time elapsed between the two pictures is 1.5 years.

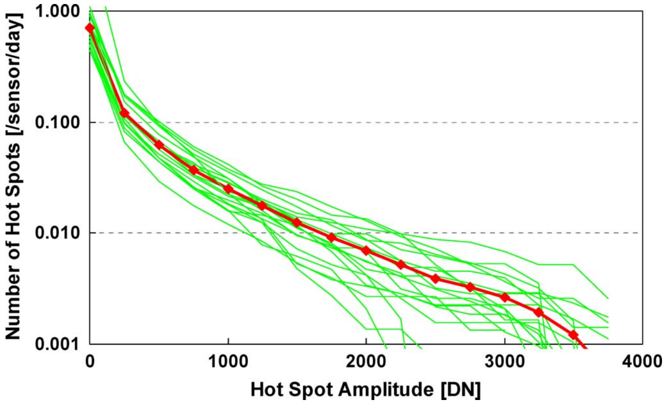

Fig. 2. Reverse cumulative probability of hot-spot creation: The number of hot spots created per sensor and per day as a function of the amplitude of the hot spots $(1\ \mathrm{DN} = 2$ electrons$)$. Every thin line represents the results of two measurement cycles; the thick line (with diamond symbols) represents the average of all measurements.

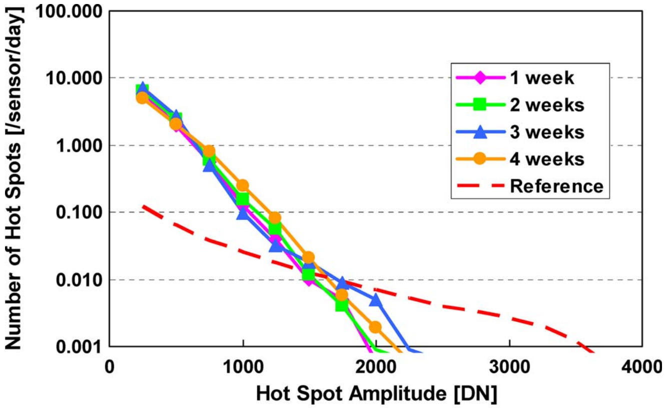

Fig. 3. Results obtained after storing the imagers at 180 °C during one, two, three, and four weeks, respectively. Solid lines with symbols represent the measurements; dashed curve without a symbol illustrates the reference material.

between two measurements. The thick solid line with diamond symbols shows the average behavior over a time period of almost six years. This latter curve will be used as the reference for the results obtained in other experiments reported in this paper.

From these results, it is clear that the generation of new hot spots can be relatively high, but it strongly depends on the amplitude of the hot spot. Notice the repeatability of the effects during this long testing period. An important remark needs to be made: All data shown in Fig. 2 are 100% related to the devices under test and to the reported measurement conditions. Changing any setting in the measurement setup or switching to another type of imager will give other absolute numbers. Although hot-spot generation by means of cosmic rays is not depending on technology, architecture, design, or vendor, extrapolation of the numbers shown in Fig. 2 to other devices is very difficult.

Next to storage at room temperature, the devices were also stored at elevated temperatures during a period of three months $(\#\mathrm{DUT} = 30)$. Dark frames were obtained at the beginning and at the end of the storage period. After comparison of the dark frames, similar histograms, as shown in Fig. 2, could be obtained.

The first result is shown in Fig. 3 for storage of the imagers at 180 °C during a period of one, two, three, and four weeks, respectively. From this figure, a few conclusions can be made.

1) Storing the devices at a temperature of 180 °C reshapes the cumulative histogram into a steeper curve.
2) Hot spots of a larger amplitude no longer show up; hot spots with a lower amplitude are increased in number.
3) Storage time at 180 °C is not important; there is no major difference between storage times of one, two, three, or four weeks.

The second result of storing the devices at elevated temperatures is shown in Fig. 4: Image sensors were stored for several weeks at 60 °C, 85 °C, 110 °C, 150 °C, and 180 °C, respectively. The reference curve obtained from Fig. 2 is included as well. From Fig. 4, a few interesting observations can be made.

1) Storing the devices at a higher temperature than room temperature reshapes the cumulative histogram into a steeper curve, resulting in an overall improvement (= reduction of the number of hot spots with a large amplitude).
2) There is only a minor difference between storage at 60 °C, 85 °C, and 110 °C, but overall, storing the devices at these temperatures reduces the generation of hot spots considerably. In particular, hot spots with a large amplitude $(> 1500\ \mathrm{DN})$ no longer show up. Apparently, the higher storage temperatures have a kind of instant annealing effect and keep the imagers free of the "warmest" hot spots.
3) For storage temperatures of 150 °C and 180 °C, a kind of mixed result is obtained, no observation of large-amplitude hot spots can be made, but unfortunately, the small-amplitude hot spots considerably grow. Apparently,

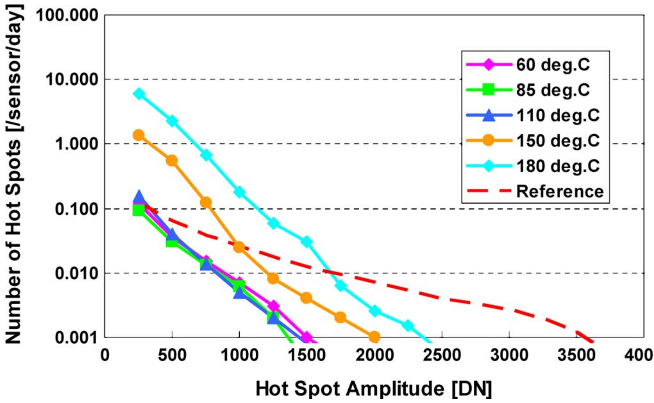

Fig. 4. Results obtained after storing the imagers at various temperatures of 60 °C, 85 °C, 110 °C, 150 °C, and 180 °C, respectively. Solid lines with symbols represent the measurements; dashed curve without a symbol illustrates the reference material.

two different effects are popping up: on one hand, the instant annealing effects of hot spots generated by cosmic rays, and on the other hand, the generation of new hot spots through another mechanism.

4) All measurements are done at 60 °C, but the time that the sensors stay at this temperature during the evaluation is very short (4 min) compared with the storage times used to generate Fig. 4. Apparently, to notice a serious effect on the number of hot spots, the sensors need to be stored during a much longer time at 60 °C than just a few minutes.

Another way of representing the same data is shown in Fig. 5. On the horizontal axis, the reciprocal temperature is plotted (1000/T), whereas on the vertical axis, the average number of generated hot spots is shown (per sensor per day). The seven curves shown belong to hot spots with amplitudes of 250, 750, 1250, 1750, 2250, 2750, and 3250 DN, respectively. Because the data of Figs. 4 and 5 are exactly the same, the same conclusion can be drawn. However, from Fig. 5, it should be clear that the best temperature to store the image sensors is between 60 °C and 110 °C, with 85 °C being a very good compromise.

In this experiment, the storage temperature was limited to 180 °C because the devices were covered with a special antireflection coating of which the deposition and processing is done around 200 °C. One set of samples ($\#\mathrm{DUT} = 30$) was stored during more than nine months at 180 °C, they were still fully functional after this storage experiment, and the hot-spot generation was similar to the results shown in Fig. 3.

As a conclusion from these experiments, storage of the devices at elevated temperatures (e.g., 85 °C) can be a good remedy against the creation of hot spots due to cosmic rays.

IV. LOW-TEMPERATURE ANNEALING

In the next set of experiments, the devices are stored (unbiased) at room temperature. At random time intervals, an annealing was performed. Different annealing temperatures were tried, but ultimately, the best compromise to perform an annealing seems to be 110 °C. This is fully in line with the experiments reported in the previous section.

Fig. 6 shows the results obtained after this experiment. On the horizontal axis, the time is shown (in days), whereas on the vertical axis, the number of hot spots of a certain amplitude (250, 750, 1250, 1750, 2250, 2750, and 3250 DN) is shown. It is important to note that an annealing step of 24 h at 110 °C took place at $t = 0$ days, 69 days, 195 days, 307 days, and 573 days. These time points were randomly chosen. Fig. 7 shows the same data again, as shown in Fig. 6, but this time, the numbers on the vertical axis are normalized to 100% at time $t = 0$ days.

With respect to Figs. 6 and 7, the following remarks can be made.

1) Annealing at 110 °C for 24 h seems to be very efficient in reducing the number of hot spots, and this statement is true for hot spots of all amplitudes. The number of extra hot spots created between two annealing cycles can be reduced almost completely; this is clearly noticeable in Fig. 7.
2) The results are fully in line with the ones shown in Fig. 4, annealing is close to 100%, and the higher temperature has no effect on the creation of extra hot spots with a low amplitude.
3) Although the number of measurement points between two anneal cycles is low to perform any meaningful statistics, the growth rate of hot spots of a certain amplitude seems to be fairly constant over time, which is consistent with the data reported in part 1 of this study [1].

As a conclusion from these experiments, an anneal of 24 h at relatively low temperatures can be a good alternative to the storage at elevated temperatures. The overall effect seems to be the same. After 24 h at 110 °C, most (not to state "all") of the hot spots are annealed.

V. MODEL FOR THE GENERATION AND ANNEALING OF HOT SPOTS

As was shown in part 1 of this work, the creation of hot spots can be very well linked to the number of neutrons present in terrestrial cosmic rays [1]. As a result, our model is based on the fact that these high-energetic neutrons can create damage in the bulk of the silicon substrate. The energy of the cosmic rays is high enough to displace a silicon atom from its original location in the monocrystalline lattice. Typically, a 150-keV electron can displace a silicon atom in the bulk lattice [5]. In this way, a vacancy and an interstitial are created. This model is shown in Fig. 8, in which an ultrahigh-energy primary cosmic ray penetrates into the Earth's atmosphere. This primary cosmic ray will collide with atoms and molecules in the atmosphere and will create secondary cosmic rays that still have energies in the megaelectron volt range. The latter are composed of pions, muons, electrons, protons, neutrons, etc. As was shown in part 1 of this work, the neutrons are responsible for the creation of the hot spots [1]. When such a high-energy neutron hits a silicon atom right in its center, it can displace the atom from its rigid crystal structure. This results in a vacancy and an interstitial.

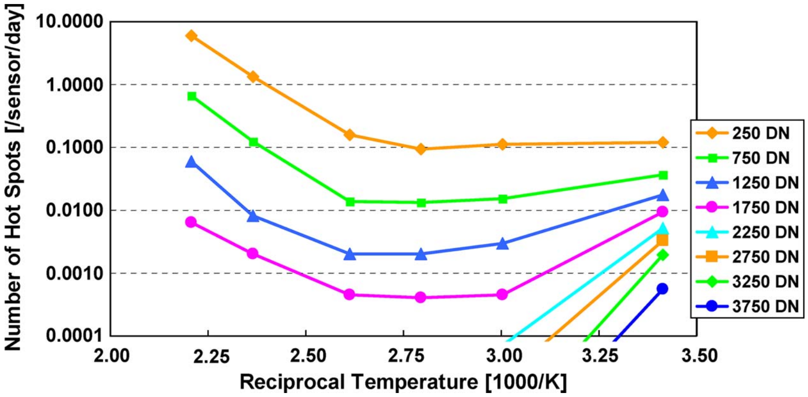

Fig. 5. Generation of hot spots as a function of the reciprocal temperature at which the sensor is being stored. The amplitude of the hot spots is being used as parameter.

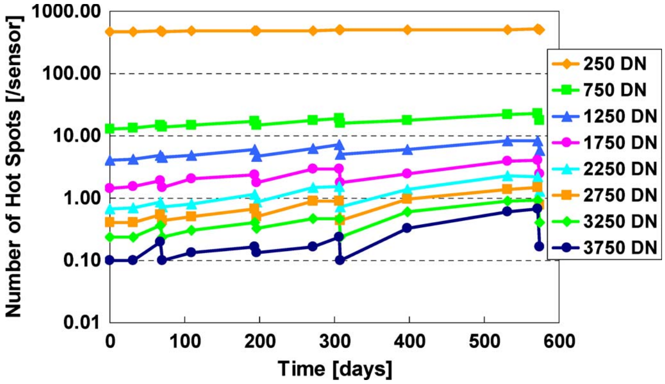

Fig. 6. Absolute number of hot spots measured after storing and annealing (at 110 °C for 24 h) the imagers over a period of almost 600 days, including five annealing cycles. The amplitude of the hot spots is being used as parameter.

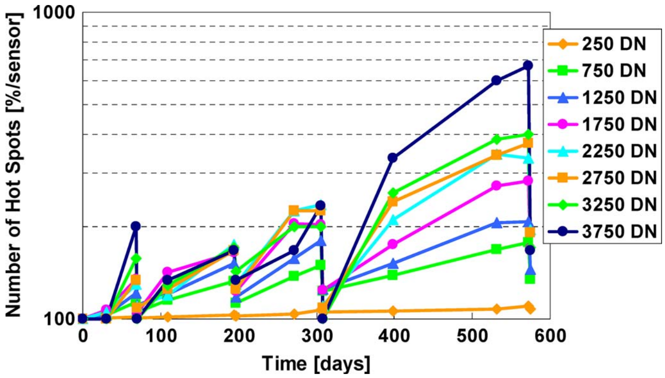

Fig. 7. Normalized number of hot spots (100% at $t = 0$ days) measured after storing and annealing (at 110 °C for 24 h) the imagers over a period of almost 600 days, including five annealing cycles. The amplitude of the hot spots is being used as parameter.

Vacancies created by incident radiation are unstable and migrate to energetically favorable positions in the lattice. Then, the vacancies become trapped near impurity atoms due to the stress imposed on the lattice by the impurities and remain in a stable position. Typically, only 2% of the initially generated vacancies "survive" and create a hot spot in the image captured by the image sensors [6].

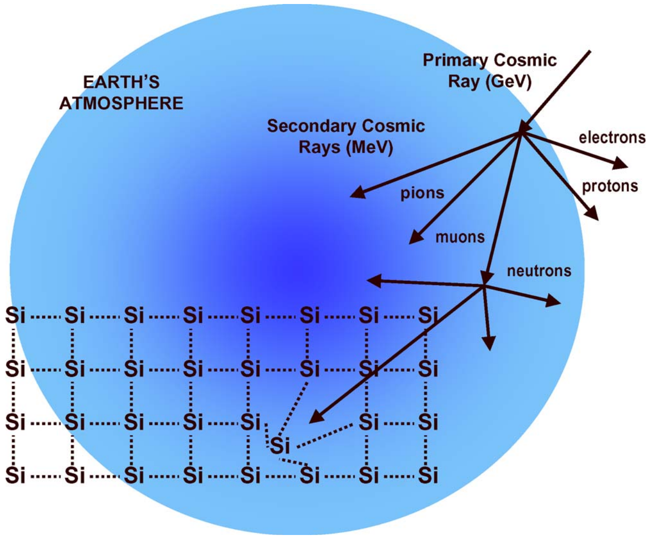

Fig. 8. Model to explain the displacement damage introduced by the high-energy neutrons that are being generated when primary cosmic rays penetrate into the Earth's atmosphere.

In the case of storing the sensors at higher temperatures, the mobility of the vacancies and interstitial silicon atoms becomes higher as well, and the chance that the vacancy and silicon interstitial "recombine" is becoming higher. Apparently, if the storage temperature is chosen high enough, none of the vacancies finds an impurity to get trapped, or the energy of the vacancy is high enough to get instantly released again from the trap. This simple model explains the effects seen at higher storage temperatures as well as the effects observed when the devices are stored at room temperatures in combination with anneals at 110 °C.

At this point, the aforementioned model is the most plausible one that can explain the observed annealing effects. Although it is necessary to mention that other mechanisms can take place as well, not enough information is available to get more insight about other possible underlying processes that may explain the observed behavior. More research work in this field is going on.

VI. CONCLUSION AND FUTURE WORK

The experiments described in this paper illustrate that the creation of hot spots due to terrestrial cosmic rays can be avoided by storing the devices at higher temperatures. Any temperature between 60 °C and 110 °C seems to limit the growth of hot spots; temperatures higher than 110 °C still have a positive effect on the large-amplitude hot spots, but they have a negative effect on the low-amplitude hot spots.

In the case when storing the image sensors at higher temperatures is not an option, a good alternative might be a 24-h treatment at 110 °C to anneal all the previously created hot spots.

In combination with part 1 of this work, a lot of data are available about the creation of hot spots by means of terrestrial cosmic rays. All data nicely fit into the model described in this paper. Although not explicitly mentioned in the two papers, some of the created hot spots show some very interesting RTS effects. RTS behavior of the hot spots will be the subject of study in the near future. By extensive characterization of the RTS pixels with dedicated measurement setups, it is expected that more knowledge about the exact defect mechanism of the RTS pixels generated by means of terrestrial cosmic rays can be gained.

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Albert J. P. Theuwissen (F’02) was born in Maaseik, Belgium, on December 20, 1954. He received the M.S. degree in electrical engineering from the Catholic University of Leuven, Leuven, Belgium, in 1977, where his thesis work was based on the development of supporting hardware around a linear CCD image sensor, and the Ph.D. degree in electrical engineering from the Catholic University of Leuven, Leuven, Belgium, in 1983, where his dissertation was on the implementation of transparent conductive layers as gate material in the CCD technology.

From 1977 to 1983, he was with the ESAT Laboratory, Catholic University of Leuven, where his work was focused on the semiconductor technology for linear CCD image sensors. In 1983, he was a Member of the Scientific Staff at the Micro-Circuits Division, Philips Research Laboratories, Eindhoven, The Netherlands. Since that time, he has been involved in research in the field of solid-state image sensing, which resulted in the project leadership of SDTV and HDTV imagers. In 1991, he became Department Head of the Imaging Devices Division, including CCD as well as CMOS solid-state imaging activities. In March 2001, he was appointed as Part-Time Professor with the Delft University of Technology, Delft, The Netherlands, where he teaches courses in solid-state imaging and coaches Ph.D. students in their research on CMOS image sensors. In April 2002, he was with DALSA Corporation as the company’s Chief Technology Officer. In September 2004, he retired as CTO and became the Chief Scientist with DALSA Semiconductors. After he left DALSA in September 2007, he started his own company “Harvest Imaging,” Bree, Belgium, focusing on consulting, training, teaching, and coaching in the field of solid-state imaging technology (www.harvestimaging.com). He cofounded (together with his peers Eric Fossum and Nobukazu Teranishi) ImageSensors, Inc. (a California nonprofit public benefit company) to address the needs of the image sensor community (www.imagesensors.org). He is author or coauthor of over 120 technical papers in the solid-state imaging field and issued several patents. In 1995, he authored the textbook *Solid-State Imaging With Charge-Coupled Devices*.

Dr. Theuwissen is a member of SPIE and of the editorial board of the magazine *Photonics Spectra*. In 1988, 1989, 1995, and 1996, he was a member of the International Electron Devices Meeting paper selection committee. He was coeditor of the IEEE TRANSACTIONS ON ELECTRON DEVICES Special Issues on Solid-State Image Sensors, May 1991, October 1997, and January 2003, and of the IEEE MICRO Special Issue on Digital Imaging, November/December 1998. In 1998, he became an IEEE Distinguished Lecturer. He acted as General Chairman of the IEEE International Workshop on Charge-Coupled Devices and Advanced Image Sensors in 1997 and 2003, and he will organize the workshop again in 2009. He is member of the Steering Committee of the aforementioned workshop and Founder of the Walter Kosonocky Award, which highlights the best paper in the field of solid-state image sensors. During several years, he was a member of the technical committee of the European Solid-State Device Research Conference and of the European Solid-State Circuits Conference. Since 1999, he has been a member of the technical committee of the International Solid-State Circuits Conference, for which he acted as Secretary, Vice-Chair, and Chair in the European ISSCC Committee. He is also a member of the overall ISSCC Executive Committee. Recently, he has been elected as International Technical Program Vice-Chair and Chair for the ISSCC 2009 and ISSCC 2010, respectively.