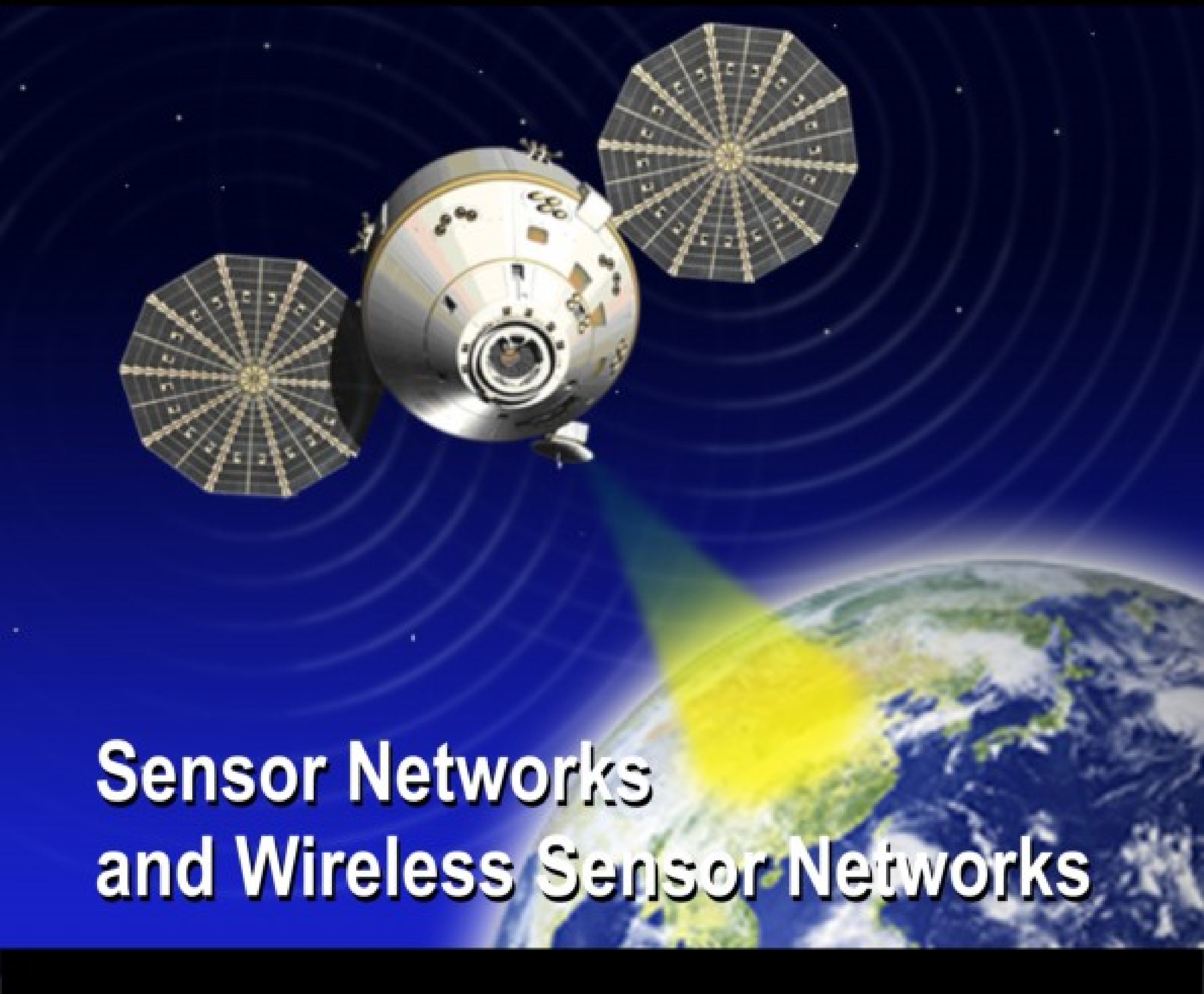
ISSN 1726-5479

SENSORS & TRANSDUCERS

7 vol. 94
/08



Sensor Networks and Wireless Sensor Networks

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 94
Issue 7
July 2008

www.sensorsportal.com

ISSN 1726-5479

Editor-in-Chief: professor Sergey Y. Yurish, phone: +34 696067716, fax: +34 93 4011989,
e-mail: editor@sensorsportal.com

Editors for Western Europe
Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Universitá di Brescia, Italy

Editors for North America
Datskos, Panos G., Oak Ridge National Laboratory, USA
Fabien, J. Josse, Marquette University, USA
Katz, Evgeny, Clarkson University, USA

Editor South America
Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe
Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editor for Asia
Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
Cerda Belmonte, Judith, Imperial College London, UK
Chakrabarty, Chandan Kumar, Universiti Tenaga Nasional, Malaysia
Chakravorty, Dipankar, Association for the Cultivation of Science, India
Changhai, Ru, Harbin Engineering University, China
Chaudhari, Gajanan, Shri Shivaji Science College, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad Nacional de Colombia, Colombia
Courtois, Christian, Universite de Valenciennes, France
Cusano, Andrea, University of Sannio, Italy
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Deshmukh, Kiran, Shri Shivaji Mahavidyalaya, Barshi, India
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding Jian, Ning, Jiangsu University, China
Djordjevich, Alexandar, City University of Hong Kong, Hong Kong
Ko, Sang Choon, Electronics and Telecommunications Research Institute,
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, University of Ulm and KTB Mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Francis, Laurent, University Catholique de Louvain, Belgium
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Hashsham, Syed, Michigan State University, USA
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiang, Wei, University of Virginia, USA
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Kausel, Wilfried, University of Music, Vienna, Austria
Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Kim, Min Young, Koh Young Technology, Inc., Korea South

Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, University of Oklahoma, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
Melnyk, Ivan, Photon Control Inc., Canada
Mendes, Paulo, University of Minho, Portugal
Mennell, Julie, Northumbria University, UK
Mi, Bin, Boston Scientific Corporation, USA
Minas, Graca, University of Minho, Portugal
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Mohammadi, Mohammad-Reza, University of Cambridge, UK
Molina Flores, Esteban, Benemérita Universidad Autónoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, DIMET, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mukhopadhyay, Subhas, Massey University, New Zealand
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucin, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Penza, Michele, ENEA C.R., Italy
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S. National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Raoof, Kosai, Joseph Fourier University of Grenoble, France
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Robert, Michel, University Henri Poincare, France
Rezazadeh, Ghader, Urmia University, Iran
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National University of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University, USA
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Institute for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore,
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Teker, Kasif, Frostburg State University, USA
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tian, Gui Yun, University of Newcastle, UK
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, University, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazques, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung University of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Lisheng, The Chinese University of Hong Kong, Hong Kong
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Ymeti, Aurel, University of Twente, Netherland
Yong Zhao, Northeastern University, China
Yu, Haihu, Wuhan University of Technology, China
Yuan, Yong, Massey University, New Zealand
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zeni, Luigi, Second University of Naples, Italy
Zhong, Haoxiang, Henan Normal University, China
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhou, Zhi-Gang, Tsinghua University, China
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA). Available in electronic and CD-ROM. Copyright © 2007 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 94
Issue 7
July 2008

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal’s webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol. 94, Issue 7, July 2008, pp. 103-115

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Wearable Battery-free Wireless 2-Channel EEG Systems Powered by Energy Scavengers

[1]Mieke VAN BAVEL, [2]Vladimir LEONOV, [2]Refet Firat YAZICIOGLU, [2]Tom TORFS, [2]Chris VAN HOOF, [3]Niels E. POSTHUMA and [4]Ruud J. M. VULLERS

[1]IMEC, Business Development Department, Kapeldreef 75, 3001 Leuven, Belgium
Tel.: +32-16-28 80 10
[2]IMEC, Integrated Systems Department,
Kapeldreef 75, 3001 Leuven, Belgium
[3]IMEC, Solar and Organic Technologies Department,
Kapeldreef 75, 3001 Leuven, Belgium
[4]Stichting IMEC Nederland/Holst Centre, Wireless Autonomous Transducers Solutions Department,
High Tech Campus 31, 5656 AE Eindhoven, The Netherlands
[1]E-mail: vanbavel@imec.be, www.imec.be

Received: 23 June 2008 /Accepted: 21 July 2008 /Published: 31 July 2008

Abstract: Thermoelectric generators worn on a person's body have demonstrated their capability to power a variety of wireless sensor nodes that are to improve his/her health or comfort. In this article, the design, fabrication and performance of two prototypes of a battery-free wireless 2-channel electroencephalography (EEG) system are presented. The first system is powered solely by a thermoelectric generator that produces 2-2.5mW of power and is worn as a headband. The second system resembles a diadem or headphones and uses a hybrid power supply that combines a thermoelectric generator and photovoltaic cells in one device. This portable EEG headset considerably improves the comfort of patients in clinical as well as in non-clinical environments and opens perspectives for a new range of non-clinical applications. *Copyright © 2008 IFSA.*

Keywords: Thermoelectric generator, Wireless sensor node, Wireless electroencephalography, Photovoltaic cell

---

1. Introduction: Scavenging Thermal Energy on Human Beings

Body area networks consisting of multiple sensors, transducers and transceivers deployed on the human body, call for new types of power supply that last longer than traditional batteries. Solar cells seem an obvious first solution in view of their efficiency and the maturity of photovoltaic technology. However, at indoor conditions, sufficient access to solar energy is seldom guaranteed. Miniaturized thermoelectric generators (TEGs) that harvest human body heat offer a promising alternative: they are environmentally friendly, have an unlimited lifetime and offer the possibility of monolithic integration with other components. TEGs exploit the Seebeck effect to transform a temperature difference into electricity. A TEG is made of thermopiles sandwiched in between a hot plate and a cold plate. Thermopiles are in turn made of a large number of thermocouples connected thermally in parallel and electrically in series.

The design of an efficient TEG for application on a human body is however difficult for two main reasons. Firstly, the temperature difference between the human skin and ambient air is usually small, between 10 and 15°C. Secondly, only a small fraction of this temperature difference drops across the thermopile due to the necessity of a large temperature drop between the cold plate and air to dissipate the heat.

To make efficient TEGs that are able to produce tens or hundreds microwatts, which in addition are comfortable for their wearer and which are interesting for moving into mass production, a few rules must be obeyed. Firstly, the TEG cannot be designed independently from its environment, and the conditions of its thermal matching with the latter, i.e., the heat source (human being) and the heat sink (ambient air), must be satisfied [1], see Fig. 1. The thermal resistance of the thermopile may not be much less than the one of the heat source and ambient air, otherwise, the temperature difference on the thermopile becomes too small. Modeling an optimal thermopile that allows thermal matching and simultaneously produces a voltage large enough (e.g., 1V or more) to power electronics holds requirements for the small cross section, the high aspect ratio (the ratio of the length of thermocouple legs to their lateral dimension) and the large number of thermocouple legs (over one thousand). Small-size thermopiles available on the market do not fit the requirements coming out of modeling, unless multi-stage thermopiles are used. To provide better thermal matching of the TEG to the environment for maximizing power generation, some other helpful practical hints exist. E.g., proper positioning of the TEG on the human being offers much lower local thermal resistance of the body than its average value. Another useful tool is a small radiator on the outer side of the TEG for efficient heat dissipation into ambient air. It effectively reduces the thermal resistance of both ambient air and the human body itself [2].

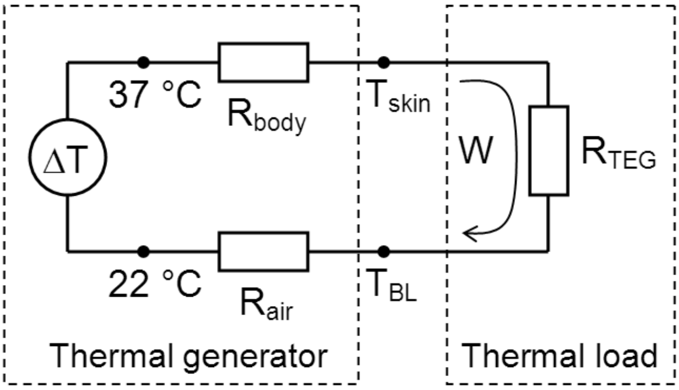


Fig. 1. Generalized thermal circuit of a wearable thermoelectric generator. Typical parameters are R_{body}=200-500 cm^{2}K/W, R_{air}=500-1000 cm^{2}K/W, optimal R_{TEG}=300-800 cm^{2}K/W.

Secondly, TEGs on a living being should be comfortable for their wearer. This means that the heat flow through the TEG and therefore through the skin must be limited in order not to decrease the skin temperature below comfortable values of 30-35°C and not to overcool the inner organs in cold weather. Hence, a proper and safe location of the device on living beings is required and the knowledge of its body properties is very important for designing wearable TEGs. E.g., small wrist devices seem the most convenient for users because they resemble a watch, however, the nighttime power generation can be interrupted, e.g. by putting the hand under a blanket/pillow while sleeping. It is obvious that on a sleeping person the head is the only body part which could provide continuous performance. Moreover, the brain temperature is well-maintained, and therefore, a large heat flow can be reached. However, a TEG in this location may cause overcooling of the brain in cold weather. IMEC has therefore extensively studied thermal features of the human body such as local thermal resistance and heat flow from the skin [2, 3].

Thirdly, the size of energy scavengers is an important factor for their acceptance by industry and for moving them into mass production. Their size should be small enough in order to successfully compete with battery-powered devices. Such small-sized devices are also imposed by the applications they target, i.e., wearable wireless sensor nodes.

An intensive study of the performance of TEGs developed at IMEC and the Holst Centre allowed predicting the average limits for power production on man. At normal indoor conditions, the upper level is equal to about 30 μW per square centimeter occupying on the skin, on 24-hour average. It should be stressed that this is the acceptance-related limit [2, 3]. Taking into account the requirement of 50-100 μW necessary for the data processing and radio transmission, the self-powered wireless sensor nodes typically occupy an area of several square centimeters like a watch.

In 2004, IMEC and Holst Centre have fabricated their first wearable thermoelectric generators serving as power supplies for wireless sensor nodes worn on a wrist [2]. At 22°C, the TEGs produced 100μW of power, enough for powering the electronics and a few-meter range radio for transmitting several measured parameters to a nearby PC every 15 s. However, even the best commercially available thermopiles arranged in a 4-stage assembly did not offer a good thermal matching and resulted in a comparatively bulky device. In 2005, improved versions were fabricated, which were better adapted to the human body and ambient air because of reduced dimensions of the thermopiles. As a result of decreasing the leg cross section by a factor of two, the TEG dimensions were successfully halved to the size of a man's watch, thereby significantly improving its acceptance by the users. At typical indoor temperatures, it generated a daytime power of 0.2-0.3 mW. Two versions have been developed, one for indoor use and one for outdoor use, each with a specially designed radiator (see Fig. 2). In 2006, a wireless pulse oximeter has been designed, powered by a TEG similar to the one of 2005. In this device, the power consumption of the electronics has been dramatically reduced to match it with the power produced by the TEG. More details of this first battery-free medical device can be found in [4], see also Fig. 3. These systems have demonstrated that the power unobtrusively obtainable on the human body is large enough to power practical applications.

In this article, a more complex device, a wireless 2-channel electroencephalogram (EEG) system is described. The device is powered by a TEG that is the most powerful among the TEGs fabricated and is located on a person's forehead. In an improved design, solar cells are added as a second power supply.

Fig. 2. Wrist TEGs fabricated in 2005 for outdoor use (left, waterproof) and for indoor use (right). The thermopile unit of the indoor version is shown in the middle assembled with a hot plate.

Fig. 3. Body-powered pulse oximeter [4] and the application running on a laptop with a measurement time of 4 s and an update rate of 15 s.

2. Human Electroencephalograms

Electroencephalography (EEG) refers to the measurement of electrical activity produced by the brain as recorded from electrodes placed on the scalp. EEG is principally used as a non-invasive clinical tool to evaluate the brain function, especially for patients suffering from epilepsy, sleeping disorder etc. EEG signals are generated by post-synaptic potentials and are composed of multiple oscillations, each having different characteristic frequencies, amplitudes and spatial distributions. From the frequency distribution of the brain waves, the function of an organ can be identified or diseases can be recognized. The EEG signal is typically described in terms of rhythmic activity, which is divided into frequency bands. E.g., rhythmic activity between 8-12 Hz is described as ‘alpha’ rhythm and is evoked by closing the eyes and by relaxation.

EEG signals are recorded by connecting electrodes on the scalp. These electrodes act as a transducer and convert the ionic current inside the brain into electronic current so that the readout circuit can amplify this biopotential signal. The main features of these signals are their very low amplitude (typically 1-100 μV) and very low frequency behavior (usually within 0.5-40 Hz) that causes various aggressors to be dominant. Therefore, the quality of the extracted EEG signal is dependent on how good the acquisition system can reject these aggressors. Mathematical tools are needed for spectral analysis of EEG signals [5, 6].

So far, monitoring of EEG signals has been limited to clinical applications. However, there is a growing demand for using EEG in non-clinical applications such as human-computer interfaces and gaming. While the main concern for clinical applications is signal quality, the non-clinical applications also require that the biopotential monitoring device should be comfortable, miniaturized and unobtrusive. These improvements to traditional monitoring systems should eventually also favor the autonomy and comfort of the patient in clinical applications.

3. Wireless EEG Headband Powered by Body Heat

IMEC's wireless autonomous EEG system contains different building blocks as shown in Fig. 4: (1) the thermoelectric generator and power conditioning electronics provide power to the electronics; (2) EEG electrodes and ultra-low EEG amplifiers record the EEG signals from the scalp and (3) the low-power processor (a TI MSP430 microcontroller) and radio (a nRF2401 transceiver) with integrated dipole antenna acquire and transfer the EEG waveform wirelessly to a PC at 2.4 GHz. Below, the most critical blocks are presented in more detail.

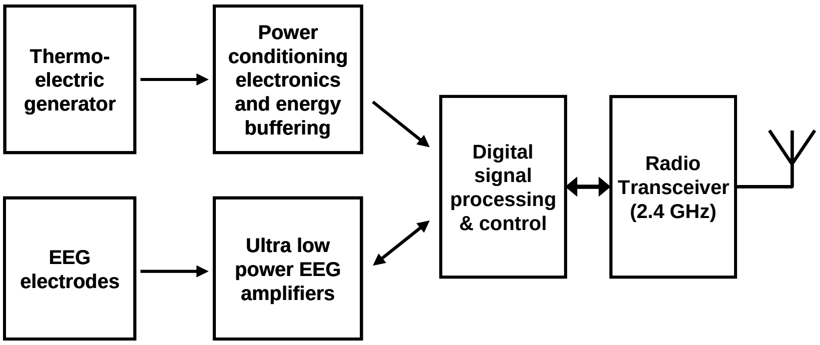


Fig. 4. Block diagram of the wireless EEG system.

3.1. Two-channel Biopotential Readout Frond-end

Practical implementation of an EEG system thermoelectrically powered from the head faces significant difficulties that affect the design of the readout front-end. First, the brain waves are low-frequency signals in the order of microvolts, which appear in the $1/f$ noise region of typical CMOS transistors. This considerably increases the noise of the readout circuit affecting the signal-to-noise ratio. Next, the polarization voltage of the biopotential electrodes results in a net DC voltage input to the readout circuit that is orders of magnitude larger than the EEG signals. Moreover, the EEG signals are disturbed by large amounts of interference coupled from mains to human body. All these issues can degrade the signal-to-noise ratio of the extracted EEG signal or saturate the readout circuit output. Therefore, the readout circuit should have high common-mode rejection ratio (CMRR) for rejecting the interference from mains, should be AC coupled to the electrodes for filtering the electrode polarization voltage, and should minimize the $1/f$ noise for improving the signal-to-noise ratio of the extracted EEG signals. Finally, the power consumption of the front-end directly impacts the size of the TEG. Therefore, the readout front-end must consume minimal possible power to make the wearable TEG comfortable and unobtrusive.

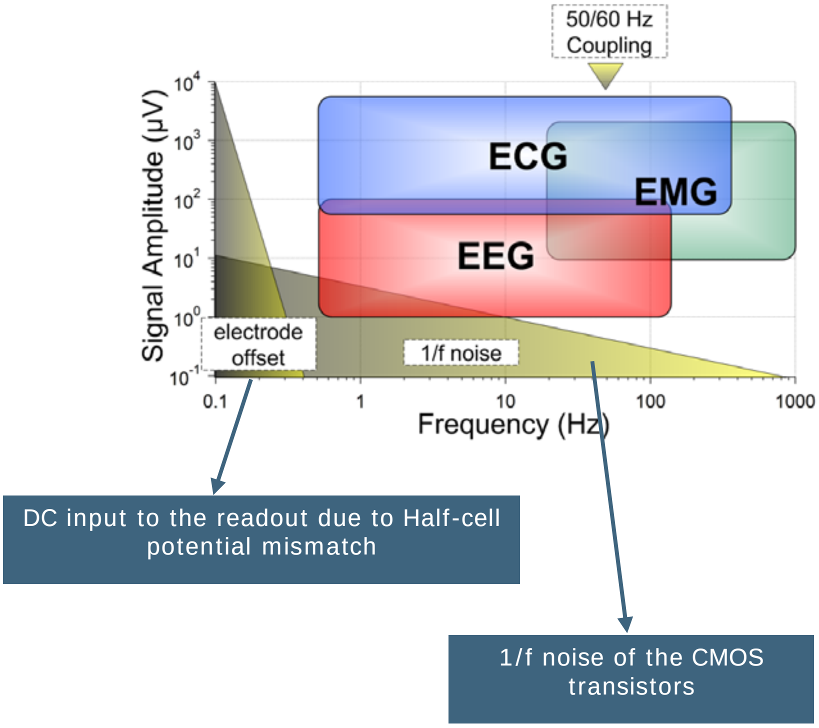


Fig. 5. Characteristics of biopotential signals (electroencephalogram, electrocardiogram and electromyogram).

Recently IMEC and Holst Centre have developed a low-power analog readout front-end ASIC that extracts high-quality EEG signals with micro-power consumption (see Fig. 6) [7]. The preamplifier of the readout front-end uses an AC-coupled chopped stabilized instrumentation amplifier (ACCIA). This ACCIA introduces AC coupling to chopper stabilized amplifiers. Thus, it can achieve high CMRR while eliminating both the 1/*f* noise of CMOS transistors and the differential DC voltage appearing between two biopotential electrodes due to the mismatch of the electrode polarization voltage. The implemented ACCIA consumes only 20 µA from 3 V, while achieving 57 nV/√Hz input referred voltage noise density. The CMRR of the amplifier is above 120 dB.

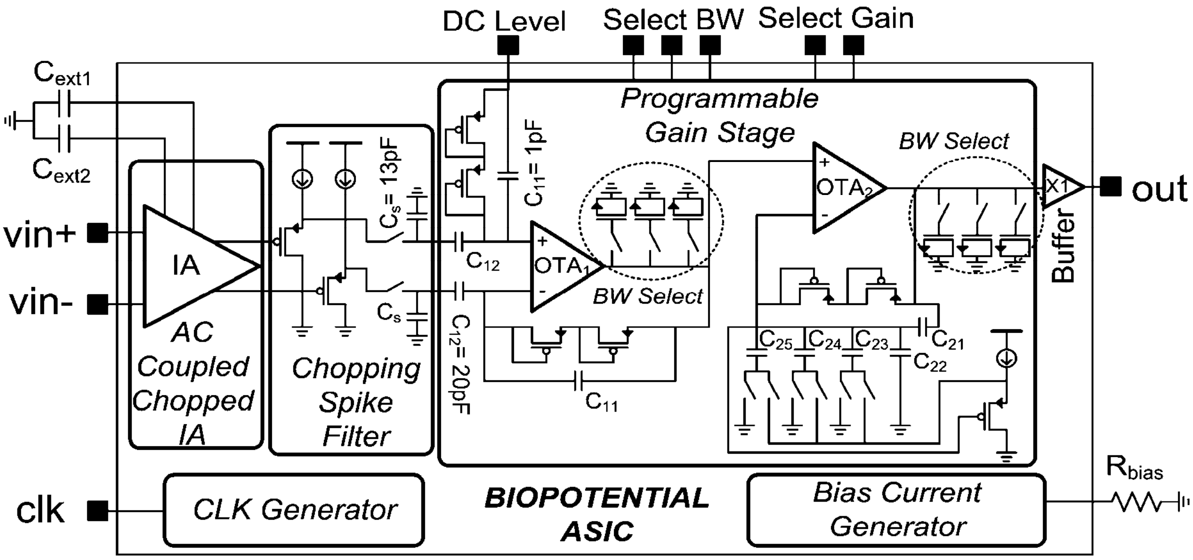


Fig. 6. Architecture of the biopotential readout front-end for the acquisition of EEG signals.

In addition to the ACCIA, the readout front-end includes a digitally programmable gain stage that enables the user to select the most convenient dynamic range and bandwidth depending on the focus of the application. Hence, the system is capable of extracting not only EEG signals, but also electrocardiogram and electromyogram signals.

The ASIC has been implemented in 0.5 µm CMOS technology (Fig. 7). The entire EEG system, which includes two of the readout front-end ASICs, a low-power microcontroller and a low-power radio, is mounted in a stretchable headband. The whole system consumes only 0.8 mW of power.

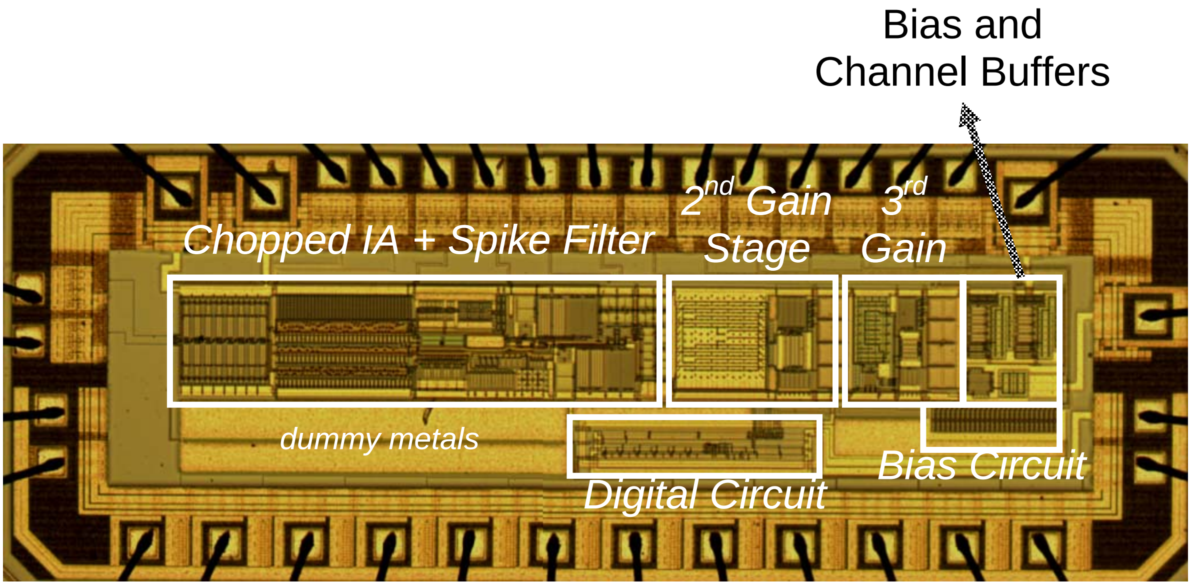


Fig. 7. Analog readout front-end ASIC implemented in 0.5 µm CMOS technology.

The implemented battery-powered version of the wireless EEG acquisition system (excluding the thermoelectric generators) has been compared with a commercial cabled polysomnography (PSG) recording system. In order to perform this comparison, the signals that are extracted from a person simultaneously wearing the commercial PSG system and the system using the ASIC are compared quantitatively in terms of sleep staging during his entire sleep at the hospital. It has been verified that both systems show very close results demonstrating the comparable performance of our system with a commercial mains powered PSG system. In addition, the implemented system clearly has superior autonomy and comfort compared to the commercial PSG system [8, 9].

Table 1. [table n°2] Performance summary of the biopotential readout front-ends of the EEG.

Voltage Supply	3 V
Current Consumption	20 µA
Input Common Mode Range	1.05 V – 1.7 V
Electronic Gain Selection (IA Gain = 10)	390, 800, 1550, 2500
Continuous Gain Adjustment	via R_2
Input Referred Voltage Noise Density	57 nV/√Hz
THD (@ 5 mVpp input and minimum gain)	0.52 %
CMRR (0 mV DEO)	> 120 dB
CMRR (50 mV DEO)	> 110 dB
PSRR + (@ 50Hz)	> 80 dB
PSRR – (@ 50Hz)	> 78 dB
Low Cut-Off Frequency (C_{ext2}=1 µF, C_{ext2}=22 nF)	0.30 Hz, 14.0 Hz
High Cut-Off Frequency	Electronically Selectable
DC Input Current (@50 mV DEO)	< 0.5 nA

3.2. Body-powered EEG Acquisition System

The forehead is a logical location for a TEG on the head because the forehead provides a large heat flow on a large area which is free of thermally isolating hair. (Even with a short haircut, the power produced on hair approximately halves.) To obtain the necessary heat flow, a TEG with a total area of hot plates of 64 cm^2 has been designed. To fit such a TEG to any user of the device, it was designed as 10 sections of 1.6×4 cm^2 each, which are rotatable to each other in order to follow the shape of the patient's forehead. The radiators on the outer side of the 2-stage thermopiles (having an aspect ratio of 8.2) ensure effective heat dissipation into ambient air and a satisfactory thermal matching with the environment (see Fig. 8). The TEG is designed for indoor use at ambient temperatures of 21-26 °C, i.e., around typical temperatures maintained in hospital wards. At 23 °C, the TEG produces approximately 2-2.5 mW or 30±2 μW/cm^2 [10], which is the theoretical limit of power production on man on average at a thermoelectric quality ZT of 1 [1,3]. At a temperature of 19 °C, the heat flow increases by about 20% and already exceeds the limit of thermal comfort. Therefore the device becomes cold, one more time confirming a theory.

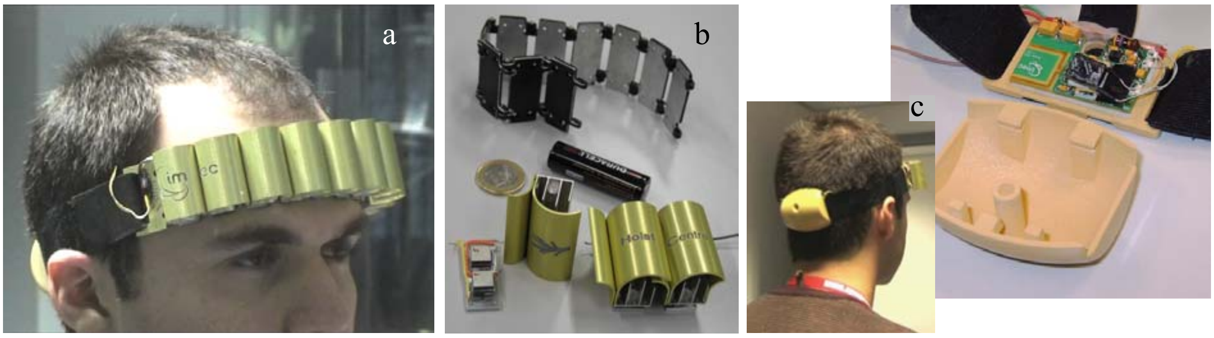


Fig. 8. TEG of the EEG system in a stretchable headband (a), its components compared with an AA battery (b), and the electronic module with low-power EEG readout, signal processing, power conditioning and a transceiver (c).

The output voltage of the thermoelectric generator varies over time, mainly due to fluctuating ambient temperatures. In addition, the radio transmissions occur in bursts, and the generator by itself is not able to provide the resulting peak currents. Therefore, a power-conditioning electronic circuit is included which has the following tasks: (1) short-time energy buffering for peak power demands and for bridging short periods without (sufficient) input power; (2) DC/DC conversion of the generator voltage to a stable and sufficiently high voltage to power the electronics. The power conditioning circuit uses a small supercapacitor as the energy storage element. A charging circuit charges this capacitor from the thermoelectric generator. A DC/DC conversion circuit boosts the varying capacitor voltage to a stable supply voltage of 2.05 V for the electronics. A special start-up circuit is implemented to allow proper start-up from the generator even from a fully discharged state without external energy. This makes the EEG system operational in about 40 s after putting the device on. (For commercial systems a rechargeable battery could be added to store all the excess energy that is gained but not used, and keep it for example if the ambient temperature is occasionally too high. Such redistribution of the energy evenly over days or weeks would allow a significant decrease of the TEG size.)

The analog EEG circuitry requires a higher supply voltage (2.7-3.3 V). For that purpose a second DC/DC step-up converter provides 2.75 V from the 2.05 V. Since the EEG circuitry consumes only 2 × 20 μA, this is a significantly more efficient solution than it would be to run the entire system on 2.75 V, because the most power-consuming elements in the system, i.e., the radio (approx. 20 mA peak) and the processor, can now run on a low supply voltage where they are much more power efficient. The signals crossing the voltage domains require an analog voltage translation circuit to avoid linear operation of digital input transistors which would consume significant leakage current.

To recapitulate, the TEG charges a supercapacitor through the charging circuit; the power conditioning electronics controlled by the startup circuit provides stabilized voltage; the EEG electrodes and ultra-low-power analog EEG readout monitor the brain waves; the low-power processor and the low-power radio with integrated antenna acquire and transfer the EEG waveform wirelessly to a PC at 2.4 GHz. The measured signal bandwidth is 0.3-70 Hz, the sampling rate is 256 Hz per channel and the sampling resolution is 12 bit.

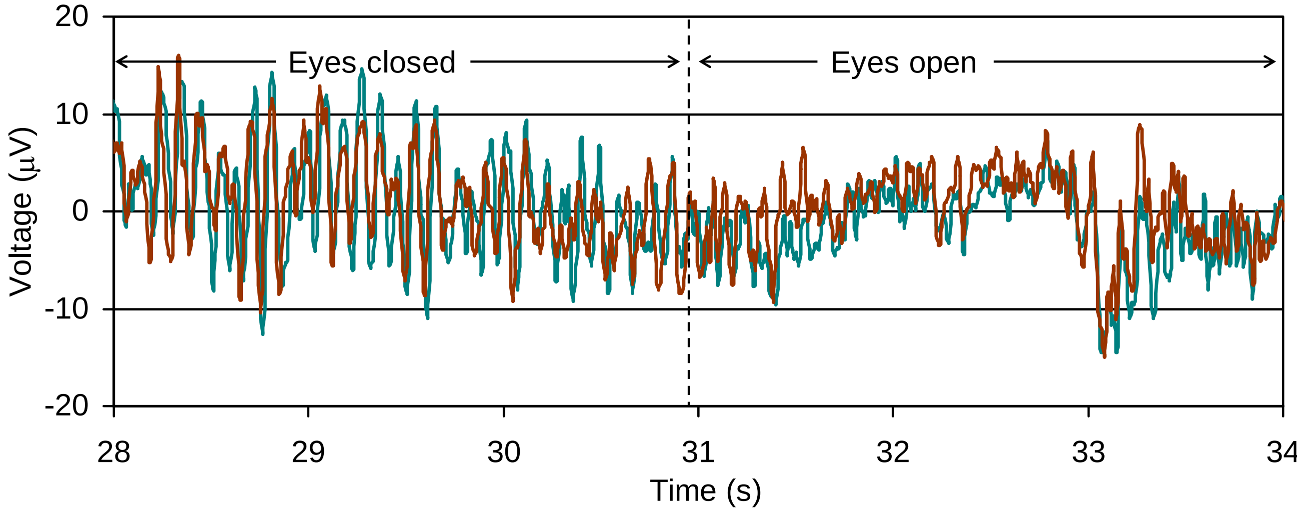


Fig. 9. Transmitted EEG signals in two channels, evoked by opening and closing the eyes.

4. Wireless EEG System Powered by a Hybrid Power Supply

The above concept of the EEG mounted in a headband has been demonstrated to be very effective, both in terms of performance and comfort for its user. It has however some drawbacks. Firstly, it has been designed especially for indoor use in hospitals, where the average temperature is about 22-23 °C. When the ambient temperature is in range of the body temperature, e.g. on a hot summer day or in tropical countries, thermoelectric generators show a dramatic drop in generated power that scales quadratically to the temperature drop on a thermopile. Secondly, the location of the TEG (it has to cover the skin of the forehead to harvest heat), its weight and size still leave room for improvement. After all, the EEG system consumes only 0.8 mW, which is well below the 2-2.5 mW power produced by the TEG. This would allow considerable size reduction. And thirdly, the high fabrication cost of the device, which is determined by the cost of the commercial thermopiles, diminishes its acceptance by a broader industry.

Recently, IMEC and Holst Centre have proposed another solution that copes with these problems (see Fig. 10), i.e., a hybrid power supply. This power supply combines a TEG that uses the heat dissipated from a person's temples and Si photovoltaic cells. The entire battery-free 2-channel EEG system is wearable and integrated into a device resembling headphones. The thermoelectric modules are however not located on the ears, but above them, on hair.

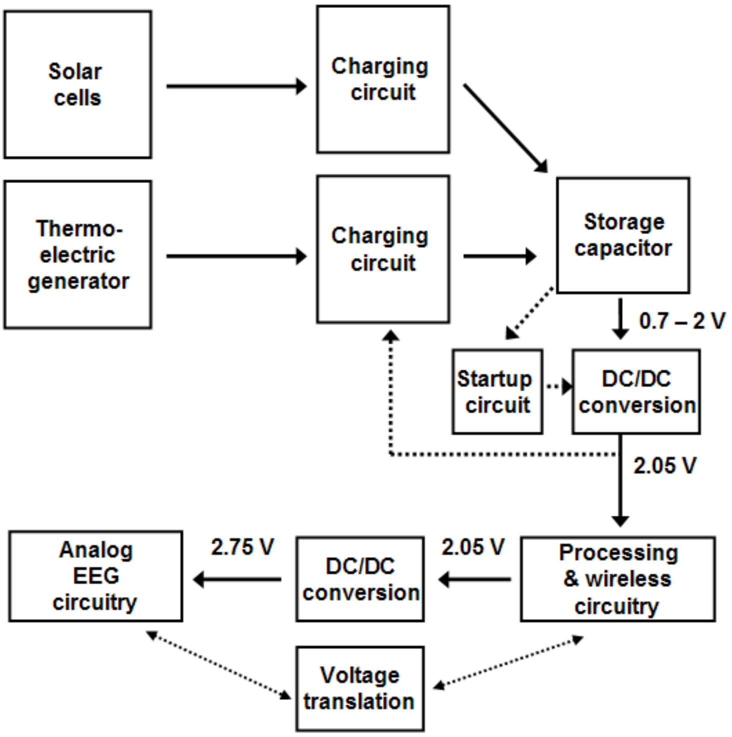


Fig. 10. Joint power management circuit for thermoelectric generator and solar cells.

The EEG system uses IMEC's proprietary ultra-low-power biopotential readout ASIC, the same as is used in the headband EEG (see section 3). Again, the whole system consumes only 0.8 mW.

The TEG is composed of six thermoelectric units made up from miniature commercial thermopiles. Each of the two radiators, on left and right sides of the head, has an external area of 4x8 cm^2 that is made of high-efficiency Si photovoltaic cells. So, the photovoltaic cells, besides converting ambient light into electricity, additionally serve as a part of the radiator and as such ensure an effective heat transfer from the head into the environment through convection and radiation. Since the TEG is to be positioned on a person's hair, thermally conductive comb-type structures (so-called thermal shunts) have been used to eliminate the thermal barrier between the skin and the thermopiles caused by the person's hair.

The photovoltaic cells have been fabricated at IMEC on p-type float zone (FZ) monocrystalline Si substrates. A standard industrial fabrication process was slightly adapted to obtain increased solar cell efficiencies in comparison with state-of-the-art industrial type monocrystalline Si solar cells (typical 15-16 % efficiency). The sequence of process steps consists of protecting the substrate back side and texturing the front end using random pyramid formation; industrial type of emitter formation using $POCl_3$, adapted to obtain a thinner and lower doped emitter; Si nitride front-surface passivation; Al screenprinting at the back and firing (to realize a back surface field that enables passivation of the back surface); lithography to define the front-side finger pattern; front-side metallization and contact sintering. Subsequently, the substrate has been sawed into 2x3 cm^2 and 2x2 cm^2 solar cells. In comparison with a standard industrial type process, the application of random pyramids and lithography defined front-side finger pattern on a FZ substrate have enabled an enhanced efficiency of about 17%. Using lithography to define the front-side finger pattern enables much smaller metal lines and hence less metal coverage of the solar cell, resulting in a higher current than obtained with traditionally used screenprinted patterns. The cells are interconnected in the device in a checkmate way in two parallel circuits. This allowed obtaining an almost perfect dependence of power versus direction of light: while the wearer makes a complete turn around him/herself in direct sunlight, the power output varies only within 5 %.

The hybrid power supply provides more than 1 mW on average in most circumstances, which is more than enough for the targeted application. The absolute and relative input power gained from the thermoelectric and photovoltaic power supplies constantly changes, reflecting variations in illumination and in heat transfer from the head. E.g., the power generated by the solar cells was 45 mW as measured in direct sunlight near noon, whereas a power of 0.2 mW was measured in the office, far from the window on a cloudy day. The thermopiles provide more uniform power than the solar cells. At 21.8 °C, indoor, they generate 1.5 mW, while outdoor, at 9.5 °C with no wind, the power increases to 5.5 mW. As tested down to an ambient temperature of 7 °C, the device is very comfortable for the user. As a rule of thumb, outdoor solar cells generated 8 times more power at 9.5 °C than thermopiles while indoor, the latter produced 8 times more power than solar cells in the office.

By using a two-way power supply that exploits both the heat dissipated from a person's temples and ambient light as energy sources, the dimensions (size and weight) of the TEG could be reduced with respect to the previous demonstrator, and the highest power/volume ratio is obtained. Moreover, the location on the hair is much more convenient for the user, according to responses. This further increases the patient's quality of life. Compared to the previous demonstrator, the EEG system works more reliably at high ambient temperatures such as 28 °C. Finally, using less thermopiles reduces the cost of the device, even if high-efficiency (more expensive) solar cells are used.

The portable headset (Fig. 11) allows providing a look at the brain in environments it has not been studied in before. E.g., it can be used to study sleep in people's own bedrooms instead of in hospital wards where sleep patterns can be disturbed. Or, cars able to track the brainwaves of drivers can reduce people's mental workload at times of stress by responding to brain states. A portable headset could make that possible. It could also be used to monitor patients at risk of seizure or, in future, as an interface for computer games. At least, thinking "yes" or "no" can be already differentiated [6].

Fig. 11. Wearable wireless EEG system with hybrid power supply.

The new EEG acquisition ASIC of IMEC is expected to further improve the systems functionality and reduce the power dissipation [11]. On the level of a TEG, new approaches for the thermopile fabrication using microelectronic technologies are targeted, mainly for reasons of cost reduction [12 -

15]. Several routes are being explored. Firstly, micromachined thermopiles are considered as a cost-effective breakthrough solution. Theoretically, a 1 cm^2 die with a micromachined thermopile replacing the thermopiles in above devices may provide almost the same power and much larger voltage than the above TEGs. IMEC and Holst Centre are currently investigating the use of BiTe and poly-SiGe micromachined thermopiles. Alternatively, the development of membrane-type thermopiles is ongoing [16].

5. Conclusions

We have demonstrated that TEGs on living beings, if designed accounting for the thermal properties of the latter reach high performance characteristics and the ability to power a variety of wireless autonomous smart sensors. Several prototypes for various applications have been fabricated. Focus of this article was on a self-powered wireless wearable EEG sensor. The TEG located on the forehead produces about 30 $\mu W/cm^2$, which is the theoretical limit of power production on man on average. This is more than enough to power the 2-channel ultra-low-power EEG system (consuming only 0.8 mW of power). An alternative EEG system has been developed, worn in a way similar to headphones and powered by both body heat and ambient light. This design is useful for both indoor and outdoor conditions and, through its reduced size and weight, increases the patient’s quality of life. Further research targets at a significant reduction in the production cost of film-based thermopiles by using modern microelectronic and MEMS technologies.

References

[1]. V. Leonov, P. Fiorini, Thermal matching of a thermoelectric energy scavenger with the ambience, In *Proceedings of the 5th European Conference on ‘Thermoelectrics (ECT)’,* Odessa, Ukraine, 10-12 September 2007, pp. 129-133.

[2]. V. Leonov, R. J. M. Vullers, Thermoelectric generators on living beings, In *Proceedings of the 5th European Conference on ‘Thermoelectrics (ECT)’,* Odessa, Ukraine, 10-12 September 2007, pp. 47-52.

[3]. V. Leonov, R. J. M. Vullers, Wearable thermoelectric generators for self-powered devices, *Journal of Electronic Materials,* 2008, unpublished.

[4]. T. Torfs, V. Leonov, R. J. M. Vullers, Pulse oximeter fully powered by human body heat, *Sensors & Transducers Journal,* 80, 6, 2007, pp. 1230-1238.

[5]. S. Murali, V. Kulish, Modeling of evoked potentials of electroencephalograms: an overview, *Digital Signal Processing*, 17, 2007, pp. 665-674.

[6]. V. Kulish, A. Sourin, O. Sourina, Human electroencephalograms seen as fractal time series: mathematical analysis and visualization, *Computers in Biology and Medicine,* 36, 2006, pp. 291-302.

[7]. R. F. Yazicioglu, P. Merken, B. Puers, C. Van Hoof, A 60 μW 60 nV/√Hz Readout Front-End for Portable Biopotential Acquisition Systems, *IEEE JSSC*, 42, 2007, pp. 1100-1110.

[8]. N. de Vicq, F. Robert, J. Penders, B. Gyselinckx, T. Torfs, Wireless body area network for sleep staging, In *Proceedings of the International Conference on ‘Biomedical Circuits and Systems’*, Montreal, Canada, 27-30 November 2007.

[9]. J. Penders, B. Gyselinckx, R. Vullers, M. De Nil, J. van de Molengraft, F. Yazicioglu, T. Torfs, V. Leonov, P. Mercken, C. Van Hoof, Human++: from technology to emerging health monitoring concepts, In *Proceedings of the 5th International Workshop on ‘Wearable and Implantable Body Sensor Networks (BSN 2008)’,* Hong Kong, China, 1-3 June 2008, pp. 94-98.

[10].V. Leonov, B. Gyselinckx, C. Van Hoof, T. Torfs, R. Yazicioglu, R. Vullers, P. Fiorini, Wearable self-powered wireless devices with thermoelectric energy scavengers, In *Proceedings of the 2nd European Conference on ‘Smart Systems Integration (SSI)’*, Barcelona, 9-10 April 2008, T. Gessner, Ed. (Berlin: VDE VERLAG GMBH, 2008), pp. 217-224.

[11].R. F. Yazicioglu, P. Merken, R. Puers, C. Van Hoof, A 200μW Eight-Channel Acquisition ASIC for Ambulatory EEG Systems, *IEEE ISSCC Dig. of Tech. Papers*, Febr. 2008*,* pp. 164-165.

[12]. V. Leonov, R. Vullers, Wireless microsystems powered by homeotherms, In *Proceedings of the 1st European Conference on 'Smart Systems Integration (SSI)'*, Paris, 27-28 March 2007, T. Gessner, Ed. (Berlin: VDE VERLAG GMBH), pp. 349-358.

[13]. V. Leonov, P. Fiorini, S. Sedky, T. Torfs, C. Van Hoof, Thermoelectric MEMS generators as a power supply for a body area network, In *Proceedings of the 13th International Conference on 'Solid-State Sensors, Actuators and Microsystems (Transducers '05)'*, IEEE 2005, pp. 291-294.

[14]. Z. Wang, V. Leonov, P. Fiorini, C. Van Hoof, Micromachined thermopiles for energy scavenging on human body, In *Proceedings of the 14th International Conference on 'Solid-State Sensors, Actuators and Microsystems (Transducers'07)',* Lyon, France, 10-14 June 2007, pp. 911-914.

[15]. V. Leonov, Z. Wang, R. Pellens, C. -Q. Gui, R. J. M. Vullers, J. Su, Simulations of a non-planar lithography and of performance characteristics of arcade microthermopiles for energy scavenging, In *Proceedings of the 5th International 'Energy Conversion Engineering' Conference (IECEC)*, St. Louis, 25-27 June 2007, AIAA-2007-4782-754, pp. 1-15.

[16]. V. Leonov, R. Vullers, M. Goedbloed, Self-supported and membrane-supported bulk-micromachined thermopiles for energy scavengers, In *Proceedings of the 6th European Conference on 'Thermoelectrics (ECT 2008)',* Paris, 2-4 July 2008 (in press).

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2008.pdf

Smart Sensors Systems Design

A five-day advanced engineering course

10-14 November 2008, Barcelona, Spain

SMARTSES
Marie Curie Chair (EXC) project

General Information

This course is suitable for engineers who design different digital and intelligent sensors, data acquisition, and measurement systems. It is also useful for researchers, graduate and post graduate students. Course will be taught in English.

Course Description

An advanced engineering course describes modern developments and trends in the field of smart sensor systems and digital sensors design.

After a general overview of data acquisition methods, modern smart, digital and quasi-digital sensors, smart systems details are discussed. A systematic approach towards the design of low-cost high-performance smart sensors systems with self-adaptation and self-identification possibilities is presented.

Contact Person

Susana Escriche
Fundació UPC. Edifici Vèrtex
Plaça Eusebi Güell, 6, 08034 Barcelona
Tel.: +34 93 401 08 94
E-mail: susana.escriche@fundacio.upc.edu

Course Instructor

Prof. Sergey Y. Yurish,
Centre de Disseny d'Equips Industrials (CDEI),
Universitat Politecnica de Catalunya (UPC-Barcelona)
Tel.: + 34 93 401 74 37, fax: + 34 93 401 19 89
E-mail: syurish@sensorsportal.com

Online Registration:
http://www.sensorsportal.com/HTML/SSSD_Course_2008.htm

Deadline for Registration:
31 October, 2008

Fundació UPC   MARIE CURIE ACTIONS   IFSA

www.sensorsportal.com