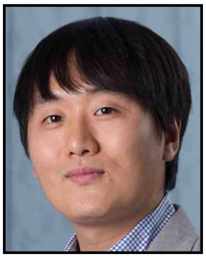
F7: *Advanced Circuits and Technologies for Wearable and Implantable Devices*

Organizer:



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Qinwen Fan, *Delft University of Technology, Delft, The Netherlands*
Yan Lu, *University of Macau, Taipa, Macao, China*
Mehdi Kiani, *The Pennsylvania State University, University Park, PA*

Champions: **Makoto Ikeda,** *University of Tokyo, Tokyo, Japan*
Arun Natarajan, *Oregon State University, Corvallis, OR*

Over the past decades, we have witnessed remarkable advances in wearable and implantable devices for diagnosing and treating a wide range of diseases and for vigilant healthcare monitoring. This forum will be a great venue to learn and discuss recent advances in system-level architectures, circuit techniques, and emerging technologies for various wearable and implantable applications. Presentations will include discussions of sensors, interface circuits, on-chip signal processing, powering, and communication for wearable and implantable devices.

Biopotential Sensing in Consumer Wearables

Yun-Shiang Shu, *MediaTek, Hsinchu, Taiwan*

With the advances of design and process technologies, the circuits and systems for wearable and implementable devices have been becoming more power efficient, highly integrated, together with better performance and versatile features. These achievements open up new opportunities to receive biosignals in unprecedented ways, yet in the meantime, bring about new design challenges in practical applications. For example, biopotential sensors can now be integrated into watches, patches, or clothes, but coming with a more vulnerable sensing interface compared with conventional medical devices. This talk introduces the major challenges of potential sensing in consumer wearables, including the use of dry electrode, power-line interference, motion artifact, and lead-on detection for on-demand user scenarios. It is followed by the discussion of circuit and system techniques to maintain the signal quality which is good enough for target applications.

Yun-Shiang Shu (S'05–M'10–SM'19) received the B.S. and M.S. degrees in Electrical Engineering from National Taiwan University, Taiwan, in 1997 and 1999, respectively, and the Ph.D. degree in electrical and computer engineering from University of California at San Diego, CA in 2008. He is currently a Deputy Technical Director at MediaTek Inc., Hsinchu, Taiwan, where he leads the development of biosensors for wearable devices and involved in the design of data converters for wireless communications. His main interests range over various kinds of ADCs and sensor front-ends, with a focus on signal processing techniques to compensate for analog circuit imperfections. Dr. Shu was a TPC member of the Symposium on VLSI Circuits from 2013 to 2017 and an ITPC member of the IEEE ISSCC from 2017 to 2022.

Skin-Interfaced Wearable Electrochemical Biosensors

Wei Gao, *California Institute of Technology, Pasadena, CA*

The rising research interest in personalized medicine promises to revolutionize traditional medical practices. This presents a tremendous opportunity for developing wearable devices toward predictive analytics and treatment. Here, we report the design and performance of fully integrated wearable electrochemical biosensors for the continuous analysis, in sweat during physical exercise and at rest, of trace levels of a variety of biomarkers including metabolites, electrolytes, nutrients, hormones, drugs, and other small molecules. The clinical value of our wearable sensing platforms is evaluated through multiple human studies involving both healthy and patient populations toward physiological monitoring, nutritional monitoring, disease diagnosis, mental health assessment, and drug personalization. These wearable and flexible devices could open the door to a wide range of personalized monitoring, diagnostic, and therapeutic applications.

Wei Gao is an Assistant Professor of Medical Engineering and Ronald and JoAnne Willens Scholar at the California Institute of Technology. He received his Ph.D. at University of California, San Diego and was a postdoctoral fellow at the University of California, Berkeley. He is an Associate Editor of Science Advances. He is a recipient of IAMBE Early Career Award, NSF Career Award, ONR Young Investigator Award, Sloan Research Fellowship, IEEE EMBS Early Career Achievement Award, IEEE Sensor Council Technical Achievement Award, MIT Technology Review 35 Innovators Under 35, World Economic Forum Young Scientist, and Highly Cited Researcher. His research interests include wearable sensors, flexible electronics, and micro/nanorobotics.

Flexible and Integrated Power Sources for Wearable Devices

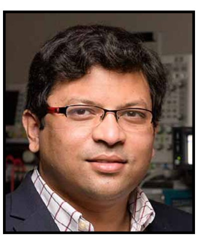
Ana Arias, *University of California, Berkeley, CA*

Developing flexible and stretchable batteries with mechanical endurance that is on par with commercial standards and offer compliance while retaining safety remains a significant challenge. Battery chemistries that rely on aqueous electrolytes are inherently safer and thus, are more suitable for powering wearable technologies. Zinc-air and zinc-carbon aqueous batteries with linear capacities of 0.9 and 0.18 mAh cm-1 respectively have been demonstrated. However, the non-rechargeable nature of these batteries acts as a limitation for non-disposable applications. Silver-zinc battery, also based on aqueous electrolyte, is gaining interest for applications in wearable energy storage devices, where safety and energy density are of the primary importance. In addition to being intrinsically safe and rechargeable, silver-zinc battery chemistry provides energy density superior to that of commercially available Li-ion batteries. We have developed new cathode architecture with silver nanoparticle ink embedded into conductive thread and demonstrated rechargeable silver-zinc wire batteries. The battery has specific discharge capacity of 1.4 mAh cm-1 at 0.5C discharge rate with capacity retention of above 98% after 170 cycles. We have also developed flexible lithium-ion batteries based on graphite (anode) and lithium cobalt oxide (cathode) for systems that require higher power density. These flexible batteries show areal capacity of 2 mAh/cm2, discharge up to 3C rate with negligible capacity loss and is stable after repeated cycling and flexing. The battery operates at 4.2 - 3.6 V and has capacity of ~ 23 mAh (Active Area = 10.9 cm2) with capacity retention of 99.2 % after 100 electrochemical cycles. The battery was able to power a commercial oximeter with 20mA, at a 3.6V requirement. An alternative approach is to integrate batteries directly with silicon ICs in the form of microbatteries so that every chip has its own power source. We have transferred the printing process of lithium-ion (Li-ion) battery to microchips. The battery consists of printed anode and cathode layers based on graphite and lithium cobalt oxide (LCO) respectively. These miniature batteries show discharge capacity (6.4 mAh/cm2) and energy density (23.6 mWh/cm2) which is capable of powering MEMS-based wireless sensor system with peak current requirements as high as 4 mA.

Ana Claudia Arias is a Professor at the Electrical Engineering and Computer Sciences Department at the University of California in Berkeley and a faculty director at the Berkeley Wireless Research Center (BWRC). Prior to joining the University of California she was the Manager of the Printed Electronic Devices Area and a Member of Research Staff at PARC, a Xerox Company, Palo Alto, CA. She went to PARC from Plastic Logic in Cambridge, UK where she led the semiconductor group. She received her PhD in Physics from the University of Cambridge, UK. Prior to that, she received her master and bachelor degrees in Physics from the Federal University of Paraná in Curitiba, Brazil. Her research focuses on devices based on solution processed materials and application development for flexible sensors and electronic systems. Dr. Arias is a co-founder of InkSpace Imaging, a startup company that aims to commercialize flexible MRI coils for pediatric patients.

Secure and Efficient Internet of Bodies (IoB) using Body as a ‘Wire’

Shreyas Sen, *Purdue University, West Lafayette, IN*



We will explore the fundamentals of radio communication around the human body to lead to the evolution of EQS-HBC and show recent advancements in the field which has a strong promise to become the future of Body Area Network (BAN). I will show the theoretical development of the first Bio-Physical Model of EQS-HBC with >100x improvement in energy-efficiency over Bluetooth and applications in the fields of HCI, Medical Device Communication, and Neuroscience including a few video demonstrations.

Shreyas Sen is an Elmore Associate Professor of ECE & BME, Purdue University and received his Ph.D. degree from ECE, Georgia Tech. His current research interests span mixed-signal circuits/systems and electromagnetics for the Internet of Things (IoT), Biomedical, and Security. He has authored/co-authored 3 book chapters, over 175 journal and conference papers and has 15 patents granted/pending. Dr. Sen serves as the founding Director of the Center for Internet of Bodies (C-IoB) at Purdue. Dr. Sen is the inventor of the Electro-Quasistatic Human Body Communication (EQS-HBC), or Body as a Wire technology, for which, he is the recipient of the MIT Technology Review top-10 Indian Inventor Worldwide under 35 (MIT TR35 India) Award in 2018 and the Georgia Tech 40 Under 40 Award in 2022. To commercialize this invention Dr. Sen co-founded Neuranova (a VC-backed stealth startup) and serves as the Chairman and CTO. His work has been covered by 250+ news releases worldwide, IEEE Spectrum feature, invited appearance on TEDx Indianapolis, Indian National Television CNBC TV18 Young Turks Program, NPR subsidiary Lakeshore Public Radio and the CyberWire podcast.

Hybrid Implantable Neural Systems: From Soft, Biomimetic Devices to Translational Interfaces

Stéphanie Lacour, *EPFL, Lausanne, Switzerland*

The introduction of soft materials and microtechnology provides an opportunity to tailor the design of neural implants and explore interfaces with increased selectivity and improved biointegration. Microfabrication allows for customized electrode layouts with micrometric to millimetric electrode diameter, low to high (0.1 to >10 /mm2) electrode density and small to large (mm2 to 10s cm2) surface area. Soft carrier materials and elasticity engineering support neural implants with mechanical signature closer to that of the neural host tissue and potential for long-term biointegration. Deployment of such soft neural interfaces also requires close integration of electronic hardware to record, process neural information, and eventually feedback information. Hybrid integration of miniaturized and customized integrated circuits with soft microelectrode designs is being explored and quantified, both on the electrical and mechanical standpoint. Multimodal characterization methods are being developed to assess the stability and reliability in vitro of the soft neural systems under electrochemical and mechanical ageing and envision in vivo validation. This talk will report on our methodical approach to design, manufacture and test soft neural systems deployed in the central or peripheral nervous systems, and illustrate these concepts with designs from lab-tailored to neuroprosthetic applications.

Stéphanie P. Lacour is full professor at the School of Engineering at the Ecole Polytechnique Fédérale de Lausanne. She received her PhD in Electrical Engineering from INSA de Lyon, France, and completed postdoctoral research at Princeton University (USA) and the University of Cambridge (UK). She joined EPFL in 2011. She is the first director of EPFL newly formed interdisciplinary institute, the Neuro-X institute, homed at Campus Biotech in Geneva. She is the recipient of the 2006 MIT TR35, the 2011 Zonta award, and she was selected as one of the 2015 WEF Young Global Leaders. She was awarded the ERC Starting Grant (2011), ERC POC Grants (2016 & 2018) and the SNSF Consolidator grant (2016).

Bioelectronics - Where Technology Meets Biology

Refet Firat Yazicioglu, *Galvani Bioelectronics, London, United Kingdom*

Bioelectronic medicines, a new treatment modality that modulates signals in peripheral nerves, hold the promise to sit alongside today's molecular medicines and neuromodulation devices. Bioelectronics uses miniature therapeutic implants to control organs and systems central in disease and could make medicines with improved precision, personalisation, adherence, and ultimately access. This presentation will discuss the promise of Bioelectronics therapies and how it harnesses the emerging technologies for the benefits of patients. An introduction to modulation of peripheral nerves will be presented, existing neuromodulation and their technologies systems will be discussed and emerging/enabling technologies will be highlighted.

Firat Yazicioglu is serving as Vice President of Translational Sciences and Engineering at Galvani Bioelectronics, a joint venture between GSK (GlaxoSmithKline) and Verily (former Google Lifesciences). He joined GSK Bioelectronics in 2015 after spending 13 years at imec, Europe's largest independent research centre in microelectronics and nanoelectronics. He has developed medical devices and technologies for wearable and implantable applications. With a Ph.D. from KU Leuven in Belgium, Firat has authored more than 100 peer-reviewed publications along with more than 30 patents, including a book on low-power biomedical microsystems. He has served on the technical program committees of European Solid State Circuits Conf (ESSCIRC), International Solid State Circuits Conf (ISSCC), and Biomedical Circuits and Systems Conf (BioCAS).

Towards Battery-Free Millimeter-Sized Bioelectronic Implants

Kaiyuan Yang, *Rice University, Houston, TX*

Miniaturized bioelectronic implants promise transformative applications in medicine, health, and scientific research. This talk will discuss challenges and solutions towards next-generation bioelectronic implants with unprecedented power, volume, and wireless demands. I will overview various technologies for powering miniaturized implants, and present our latest progresses in magnetoelectric wireless power and communication, and developing and validating battery-free implantable systems.

Kaiyuan Yang is an Assistant Professor of ECE at Rice University, USA. He received his B.S. degree in Electronic Engineering from Tsinghua University, China, in 2012, and his Ph.D. degree in Electrical Engineering from the University of Michigan - Ann Arbor, in 2017. His research interests include digital and mixed-signal circuit and system design for secure and intelligent microsystems, bioelectronics, and hardware security. Dr. Yang is a recipient of the 2022 NSF CAREER award and multiple best paper awards from premier conferences in various fields, including 2022 ACM MobiCom, 2021 IEEE CICC, 2016 IEEE Symposium on Security & Privacy, 2015 IEEE ISCAS, and best paper nominations at 2022 RFIC and 2019 CICC. He is currently serving as an associate editor of IEEE TVLSI, a TPC member of multiple conferences, and a co-chair of SSCS Houston chapter.

Neuron-Inspired Wireless Telemetry for Implantable Neural Interfaces

Yao-Hong Liu, *imec, Eindhoven, The Netherlands*

With the advancement in micro-electrode arrays, high-fidelity neural sensing can achieve high spatial and temporal resolutions. However, one key challenge yet to overcome, is the lack of a high-bandwidth, miniature and energy-efficient wireless telemetry, which allows neural sensors to be chronically implanted without infection risks. In this talk, we will discuss a neuron-inspired wireless telemetry for future implantable neural interfaces.

Yao-Hong Liu is currently Scientific Director in imec, and Distinguished Research Associate in Technical University Eindhoven. He is a recipient of European Research Council Consolidator grant. His current research focuses on wireless technologies for implantable brain-computer interfaces and IoT. Dr. Liu received his Ph.D. degree from National Taiwan University, Taiwan, in 2009. He was with Terax, Via Telecom (now Intel), and Mobile Devices, Taiwan, from 2002 to 2010, developing wireless transceiver ICs. Since 2010, he joined imec, the Netherlands, and is leading the research of the ultra-low power ASIC design. He served as a technical program committee of IEEE ISSCC and is currently a steering committee member of IEEE RFIC symposium.