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To cite this article: Veena Misra *et al* 2019 *J. Phys.: Conf. Ser.* **1407** 012001

Optimizing the energy balance to achieve autonomous self-powering for vigilant health and IoT applications

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Abstract. With the right combination of disruptive features, such as battery free self-powered operation, multimodal sensing capability, comfort, wearability, and continuous data gathering leading to actionable information, the potential of autonomously powered smart sensing nodes can be realized to provide long-term monitoring for health and IoT applications. This paper reports on recent breakthroughs in technologies essential for achieving self-powered operation and shows how engineering both sides of the power equation, namely generation and consumption, can lead to always on operation. This work is being conducted in the *NSF funded ERC Center on Advanced Self-Powered Systems of Integrated Sensors and Technologies* (ASSIST).

1. Introduction

Self-powered operation of smart sensing nodes can have disruptive impact in healthcare and the Internet of Things (IoT). Autonomous self-powering leads to "always on" operation that can enable vigilant and long term monitoring of multiple health and environmental parameters. When packaged in wearable, comfortable, and hassle-free platforms, these systems increase adoption by users and can be worn to gather information over long periods of time and reveal possible correlation or even causality between different sensor streams. This information can be powerful in chronic disease management such as heart disease, asthma, and diabetes. This can also prevent negative outcomes by vigilantly monitoring critical conditions such as arrhythmia, heart rate variability (HRV), epilepsy, etc. and help build personalized health databases for individuals that span years and even decades. Similarly, in IoT applications, always-on, battery free operation of smart sensing nodes can lead to low maintenance structural monitoring of buildings, cities, and infrastructure along with large scale smart agricultural or industrial monitoring applications.

The NSF Center on Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST) is building disruptive self-powered smart sensing nodes with state-of-the-art energy harvesting technologies, high-power/high-energy density supercapacitors, ultra low-power electronics, and low power health and environmental sensors all integrated into comfortable wearable platforms that work together to achieve “always on” capability (Fig. 1). The ASSIST Center is uniquely optimizing both sides of the power challenge: generation and consumption. Hence the key technical goal of this engineered system is to maximize the power harvested from the body while minimizing the power consumed by the electronics and radios such that sufficient energy is available to continuously power multimodal sensors. Wearability and data, which are key elements of user adoption, are also being addressed.

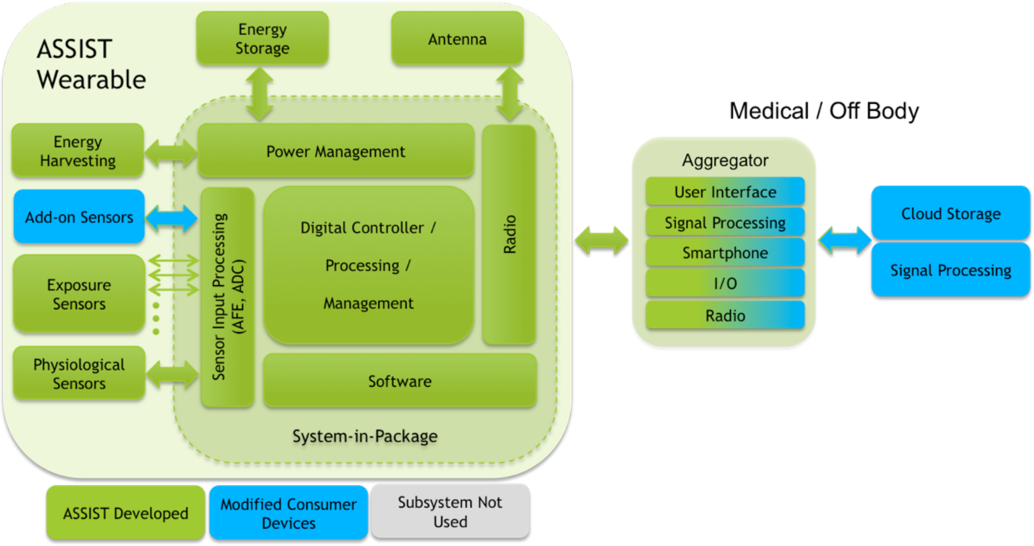
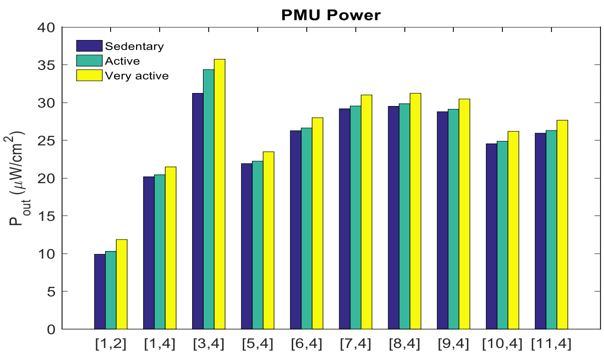


Figure 1: Block diagram for ASSIST’s engineered system for self-powered wearable sensors. (AFE: Analog Front End, ADC: Analog to Digital Converter)



	Sigma	Seebeck	k	zT	Ref
Commercial n type material	875	-200	1.5	0.7	[2]
Commercial p type material	1250	200	1.5	1.0	[2]
ASSIST n type nanocomposite	295	-303	0.89	0.91	[3]
ASSIST p type nanocomposite	733	205	0.77	1.2	[4]
S. Wang et al.	1415	-197	1.6	1.03	[5]
X. Yan et al.	954	-191	1.16	0.9	[6]
W. Liu et al.	1003	-185	1.00	1.03	[7]
S. Song t al.	527	-220	0.90	0.85	[8]
M. Hong et al.	1100	-168	0.73	0.68	[9]
L. Hu et al.	1248	-166	1.2	0.86	[10]
W. Liu et al	1083	-189	1.21	0.96	[11]

Figure 2: Comparison of calculated power outputs from TEG harvesters using ASSIST n-type and p-type materials relative to other thermoelectrics.

Energy Harvesting and Energy Storage

ASSIST’s work on energy harvesting and energy storage focuses on harvesting human body power from heat and motion. However, the materials and device designs being developed here can also find applications in many IoT realms such as harvesting heat or vibration in industrial or agriculture applications.

Thermoelectric Harvesting: The temperature difference between human skin and the ambient environment can be converted to useable power by thermoelectric materials and devices. ASSIST has developed a family of p- and n-type Bi_2Te_3 thermoelectric nanocomposites with high figure of merit and low thermal conductivity. Over the last three years, materials development has focused on new compositions and new processing methodologies to prepare mechanically robust nanocomposites that can be mechanically diced into legs without fracture. Z_T and thermal resistivity are improved by 40% and 75% for p-type, respectively, and 15% and 140% for n-type material. Microwave (MW) and spark plasma sintered (SPS) methods were introduced to synthesize p-type and n-type materials wih superior properties respectively. These new materials have been incorporated into wristband harvesters that can generate 300 μW at the output. As shown in Figure 2 and the accompanying Table, the ASSIST n-type and p-type thermoelectrics [1-2] offer ~10% higher calculated power at the output of the power management unit (PMU) compared to other thermoelectrics [3-11].

Flexible TEGs are capable of conforming to any type of body surface and will see applications at the upper arm, wrist or shoulder. Previously reported flexible TEGs cannot meet the power needs of typical wearable systems because these devices either rely on new thermoelectric materials (e.g. organic or electrodeposited inorganic materials) whose properties cannot match those of state-of-the-art bulk inorganic materials [4,12-13], or they suffer from parasitic losses resulting from high resistivity interconnects or compromised thermal design of the modules due to a variety of polymeric materials used in their construction. We have demonstrated high performance flexible thermoelectric generators employing a eutectic alloy of gallium and indium (EGaIn) as the interconnect material, At room temperature, EGaIn exists in liquid form providing the ultimate flexibility (and stretchability). Furthermore, EGaIn provides self-healing and very low resistivity [14-15]. Two key strengths of the new technology include incorporation of bulk materials used in rigid TEGs with superior properties and an easy, low-cost entry to the flexible thermoelectric market for existing manufacturers. This new technology offers excellent electrical and mechanical properties resulting in highly efficient and robust flexible harvesters poised to challenge the performance of rigid harvesters (Figure 3). Figure 4 shows an example of the output of a flexible harvester on human wrist as a function of air velocity for two different leg lengths [16]. With a low thermal-conductivity filler elastomer, these devices outperform all other reported flexible thermoelectric harvesters.

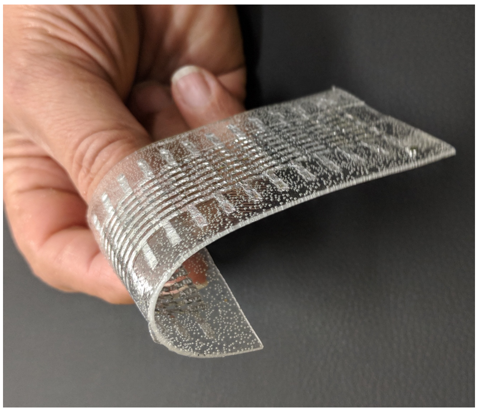


Figure 3. Flexible TEG array made from liquid metal interconnects and flexible polymers

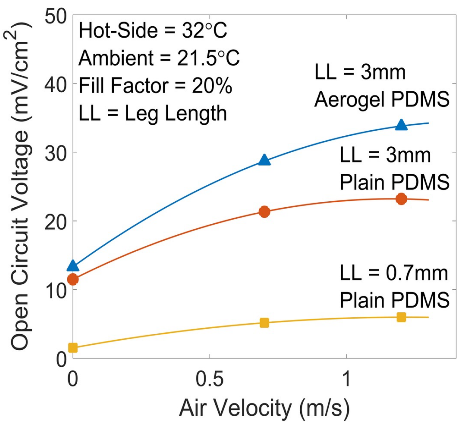


Figure 4: Measured responses for a flexible ASSIST harvester on a human wrist as a function of airflow.

Mechanical Harvesting

Mechanical motion of the wrist can be converted to useable power using high performance piezoelectric materials and novel transducer designs. The ASSIST motion harvesting group is increasing the output power of an arm-based harvester by maximizing the materials' figure of merit, the volume of the piezoelectric, At, [17] and S_i^2, the square of the strain in the piezoelectric, for realistic body motions [18-20]. Materials development work has resulted in improving the reliability of 6 μm thick sputtered domain-engineered piezoelectrics (beyond this thickness, cracking was ubiquitous), as well as completely eliminating the thickness constraints for piezoelectric on metal foils by developing a cold-sintering process for crack-free thick films [21] (see Figure 5). The sputtered films were incorporated into wrist harvesters. Circuitry has been co-designed with the harvester to rectify the output and charge the supercapacitor. An intermediate-inductor-based circuit was implemented to simultaneously harvest energy from six beams with decaying signals. A design was created for a reconfigurable circuit voltage-mode as an efficient full-wave active rectifier with power efficiency of > 90% for large input voltages, and in current-mode as an intermediate-inductor circuit with the minimum power efficiency of 60% for voltages as low as 50 mV [22-23]. Projected power output is 100 μW during walking. Benchmarking against other arm-based mechanical energy harvesters clearly indicates that the ASSIST system has very high power and power density relative to other technologies, including electrostatic and electromagnetic devices, as well as previous piezoelectric harvesters. The only system that reports comparable numbers does so for physically implausible motions (e.g., 17G at 3.3 Hz).

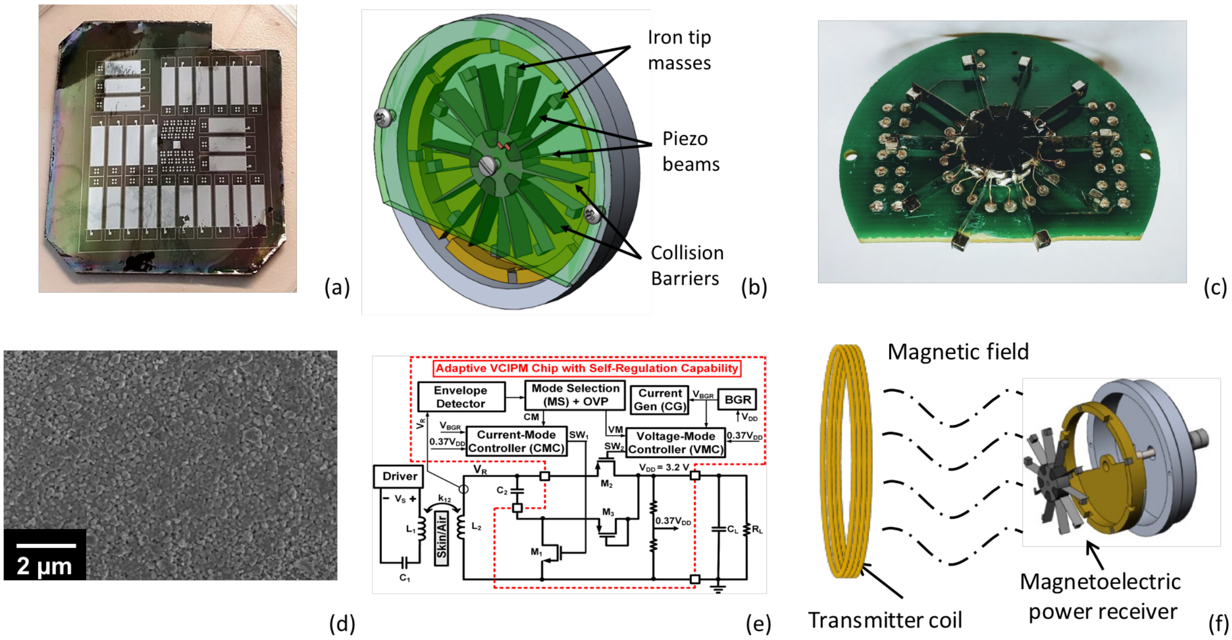


Figure 5: Kinetic and magnetic-based harvesters (a) bimorph PZT foil with thick, hot-sputtered PZT (b, c) schematic and prototype kinetic harvester (d) microstructure of a cold-sintered PZT film on Ni foil, (e) harvester circuit, (f) planned magnetic transmitter for multimode harvester. Reproduced with permission from Smart Materials and Structures.

Energy Storage

Since batteries have limited charging lifetime, ASSIST researchers have developed several families of supercapacitors with world-leading energy storage and leakage performance. Two different types of electrochemical capacitors that include a 3.5V ionic liquid based electric double-layer capacitor (EDLC) and a 4.5V lithium ion capacitor have been developed. An energy density of ~74 Wh/kg for EDLC and ~160 Wh/kg for a lithium ion capacitor were demonstrated. The lithium ion capacitor can deliver ~76 Wh/kg at a power density exceeding 10 KW/kg, which is among the highest reported in literature, [24-37] as shown in Figure 6. High voltage stability was further demonstrated using accelerated voltage hold tests that showed good capacitance retention over 300 hours. The voltage stability of the ASSIST supercapacitors based on Nanographite (NG) showed 80% retention over 21000 cycles. The cycling performance of all carbon-based supercapacitors is significantly better compared

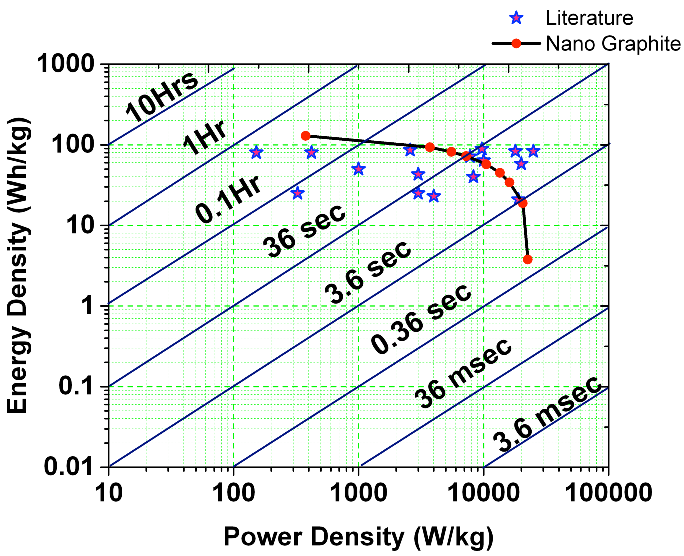


Figure. 6: Performance metrics for ASSIST Energy Storage Devices

to other high energy density lithium ion capacitors made using tin or silicon anodes reported in the literature.

Low Power Systems on Chip (SoC) and Radios

To maintain always on operation for health or IoT applications, it is important to reduce the power consumption of the SoC and the radios. The energy harvesting materials and technologies interface to the power management circuits on the SoC to provide the node with harvested power which can then drive low power sensing functionality.

The ASSIST center is using a multi-chip solution for the SoC-based platform with integrated ultra-low power chip-to-chip IO, that includes a new microcontroller (MCU)/bus, non volatile memory (NVM), lower power SRAM, new ADC, ECG AFE, and RF transmitter. This allows the SoC to interface with supercap, wearable antenna, energy harvesting sources, and even an off chip NVM for booting and for storing critical data during power blackouts. It also allows interfacing to external radios, providing flexibility for configuring the communication needs in different applications. Figure 7 shows a System in Package (SiP) integration using its ultra low power SoC with an NVM and a low power RF transmitter (TX) in separate chips. The SoC itself was tested and verified as functional. During standard operation, it beat the Center's aggressive 1 µW power target and achieved an active power consumption of 507 nW [38].

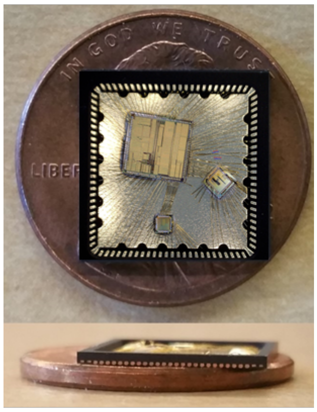


Figure 7: System in Package showcasing 507nW SoC.

ASSIST is also building Bluetooth-compatible radios that can communicate with standard BL radios but with signficant reduction in power consumption. Three major techniques are used to reduce the total power consumption of only 0.5 mW, which is an 8X reduction over a state of the art Dialog BLE radio: 1) the TX only transmits in one advertising channel packet with open loop direct modulation after every frequency calibration cycle; 2) a successive approximation register (SAR)-assisted frequency locked loop (FLL) is implemented by utilizing a RF/4 frequency ring oscillator (RO) with 4X phases; and 3) a switch-capacitor digital PA (SCDPA) optimized for high efficiency below -5dBm. As shown in Figure 8, this TX communicates with a smartphone. The second radio was a 150 µW (>26X less than the Dialog BLE radio) custom BLE back-channel receiver able to decode a message that is encoded into the sequence of advertising packets sent by a compliant BLE transmitter. The chip was fabricated in a 65nm CMOS process.

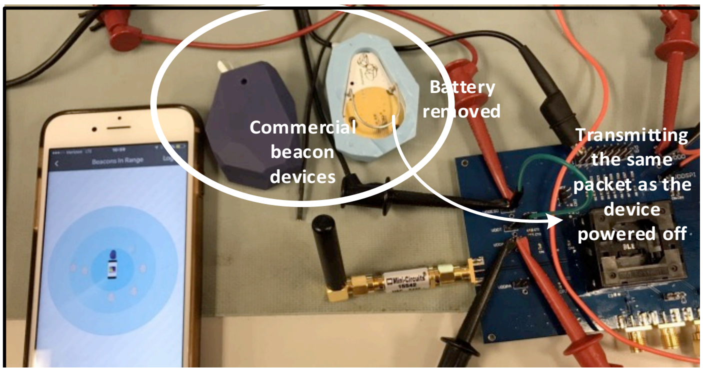


Figure 8: Low power RF transmitter successfully tested communicating directly to a phone

Figure 9: Flexible antenna demonstrated in textiles

ASSIST has also developed high-performance antennas that are integrated with textile material system (Fig. 9) [39]. This low-profile antenna with a size of 53 mm by 53 mm by 4 mm thick demonstrated a peak gain of 5.9 dBi at 2.44 GHz. This performance indicates a radiation efficiency of approximately 83%, which is higher than any previously reported textile antennas. The proposed antenna has much more stable performance under bending and human body loading than conventional antennae. These results demonstrate that the proposed textile antenna represents an ideal candidate for integration into a wearable garment.

Finally, while the above SoC uses CMOS devices operating in the subthreshold region, significant opportunities are available with emerging ultra-low power devices that can create further reduction of power consumption. With rapid progress in low voltage steep slope transistors and embedded non-volatile memory technologies such as Ferroelectric RAM and Ferroelectric FET, a new generation of nonvolatile ultra-low power microprocessors is feasible in the near future. Non-volatile processors that can store system state on demand within embedded non-volatile memory have zero standby power, fast wake up/recovery cycles, extreme resilience to power interrupt, and fine-grained dynamic power management capability. In the emerging nanodevices area, ASSIST has demonstrated steep slope ferroelectric field-effect-transistors leveraging negative differential capacitance (NC-FET). NC-FETs fabricated using an ultra-thin (10nm) CMOS compatible ferroelectric ($Zr{:}HfO_2$) technology exhibited sub-kT/q switching characteristics. The time resolved response of NC and the resulting impact on logic performance have been evaluated for logic applications and their advantages over sub-threshold CMOS. An additional research focus was on the design and fabrication of FeFETs for use as on-chip backup element in non-volatile processors (NVP). The fabricated FeFETs were used to develop an experimentally calibrated compact model that enables efficient design of instant backup and wakeup circuits and architectures.

Low Power Health and IoT Sensors

As described above, ASSIST is developing breakthrough technologies that maximize energy harvesting levels and minimize the power consumption by the SoC and radios so that saved power can be directed towards sensing and necessary functionality. In the ASSIST sensor effort, the focus is on minimizing the power consumption while maintaining sensitivity, selectivity and reliability. Discussed below are examples of two such sensors important for health and IoT applications: environmental sensing and optical heart rate sensing.

Detection of gases in cities or in buildings can be important for assessment of human risks in respiratory or other health problems. Key gases of interest include ozone and variety of volatile organic compounds (VOCs). For gas sensors, two distinct approaches (Figure 10) have been pursued to address different analytes: (i) atomic layer deposition (ALD)-based metal-oxide nanolayers operating at room temperature for sensing O_3, NO, and NO_2; and (ii) polymer functionalized mechanical resonators for detection of VOCs. The ALD metal oxide layer can be operated at room temperature and can be reset using UV exposure or a short intermittent heating cycle both of which significantly reduce the operating power to below 150μW [40]. For mechanical resonance-based sensing, we use capacitive micromachined ultrasonic transducers (CMUTs) as they offer advantages of massive parallelism, large sensing area, vacuum cavity, and high quality factor compared to cantilevers [41]. Our primary goal is to decrease the average power consumption by scaling the frequency of operation and power cycling. Through a novel fabrication process flow we have demonstrated high quality factor resonators for use in gas sensing applications. We functionalized these CMUT resonators

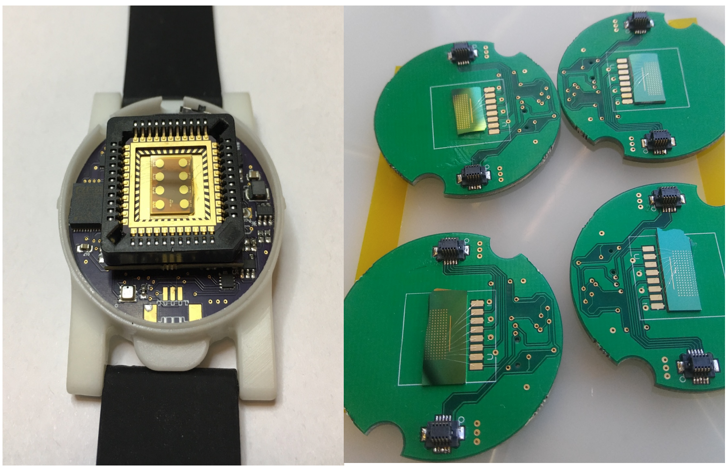


Figure 10: Gas sensing of VOCs and ozone enabled by CMUT (a) and nanolayered Metal oxides (b). These sensors demonstrated ultra low power, selectivity and reliability

with polyisobutylene (PIB) and polyvinylalcohol (PVA) and demonstrated multichannel operation for selective sensing [42]. For a one second measurement every minute, the sensor consumes 10 µW with this interface IC [43].

Reduction of optical sensing power consumption was undertaken for photoplethysmography (PPG). Power reduction was mainly achieved by system level optimization [44]. In collaboration with imec, we demonstrated that by designing a custom integrated circuit and employing compressive sensing techniques, a record-low PPG power consumption (172 µW) is possible [45]. We have integrated this frontend in a wearable form factor.

Systems Integration for Self-Powered Operation

The above technologies are being integrated into engineered systems in the ASSIST Center. A few examples of the built systems are shown below. These systems are useful for vigilant health detection such as atrial fibrillation for cardiac arrhythmia, asthma monitoring, environmental monitoring, non-invasive detection of glucose levels, wound monitoring, and many other use cases outside health. One of the key requirements for an always on system is level of comfort when worn by the user for long periods of time. In the case of atrial-fibrillation, a type of cardiac arrhythmia, it is essential that the electrodes on the chest provide no burden. To this end, ASSIST has developed dry electrodes integrated in a compression garment to not only provide comfort but also achieve good electrical contact (Fig 11a) [46,47]. The body harvested systems have been integrated into ECG shirts (Fig 11b) that can provide battery free detection of R-R intervals (Fig 11c) [48].

These systems provide medically validated information to users and inform their lifestyle decisions, enable correlation of personal health and personal environment (Fig 11d and e), and lead to rapid and effective management of health conditions.

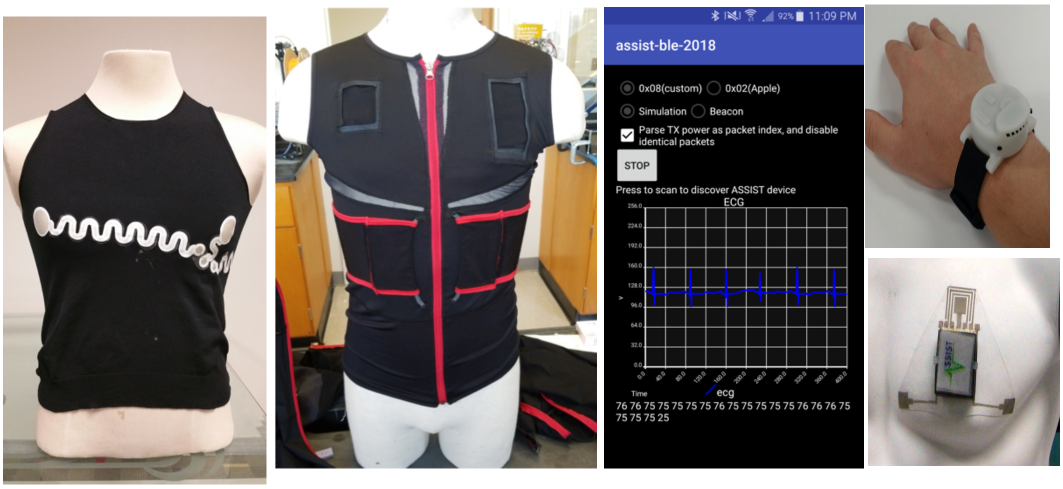


Figure 11: (a) ink jet printed Ag/AgCl metal electrodes on textiles, (b) fully functional A-Fib shirt indicating location for harvesters and antenna, (c) typical R-R measurements, (d) environmental detection watch and (e) ECG/hydration patch

Acknowledgements

This work was supported by the Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), a Nano-Systems Engineering Research Center funded by National Science Foundation (EEC1160483).

References

[1] Misra V, Bozkurt A, Calhoun B, Jackson T, Jur J, Lach J, Bongmook L, Muth J, Oralkan O, Ozturk, M, Trolier-McKinstry S. Vashaee D, Wentzloff D, Zhu Y. (2015). Flexible Technologies for Self-

Powered Wearable Health and Environmental Sensing. Proceedings of the IEEE, 103(4), 665-681.

[2] Commercial n type material and p type materials

[3] Hyland, M., Hunter, H., Liu, J., Veety, E., & Vashaee, D. (2016). Wearable thermoelectric generators for human body heat harvesting. Applied Energy, 182, 518-524.

[4] Norouzzadeh, P. & Vashaee, D. (2016). Classification of Valleytronics in Thermoelectricity. Scientific reports, 6.

[5] Shanyu Wang, Gangjian Tan, Wenjie Xie, Gang Zheng, Han Li, Jihui Yang and Xinfeng Tang, Enhanced thermoelectric properties of $Bi_2(Te_{1\_x}Se_x)_3$-based compounds as n-type legs for low-temperature power generation, J. Mater. Chem., 22, 20943–20951, 2012.

[6] X. Yan, B. Poudel, Y. Ma, W. S. Liu, G. Joshi, H. Wang, Y. C. Lan, D. Z. Wang, G. Chen, Z. F. Ren, Experimental studies on anisotropic thermoelectric properties and structures of n-type $Bi_2Te_{2.7}Se_{0.3}$, Nano Lett. 2010, 10, 3373.

[7] Wei-Shu Liu, Qinyong Zhang, Yucheng Lan, Shuo Chen, Xiao Yan, Qian Zhang, Hui Wang, Dezhi Wang, Gang Chen, and Zhifeng Ren, Thermoelectric Property Studies on Cu-Doped n-type $Cu_xBi_2Te_{2.7}Se_{0.3}$ Nanocomposites, Adv. Energy Mater., XX, 1–11, 2011.

[8] Shaowei Song, Jueling Wang, Bo Xu, Xiaobo Lei, Hongchuan Jiang, Yingrong Jin, Qinyong Zhang and Zhifeng Ren, Thermoelectric properties of n-type $Bi_2Te_{2.7}Se_{0.3}$ with addition of nano-ZnO:Al particles, Materials Research Express, 1, 035901, 2014.

[9] Min Hong, Thomas C. Chasapis, Zhi-Gang Chen, Lei Yang, Mercouri G. Kanatzidis, G. Jeffrey Snyder, and Jin Zou, n-Type $Bi_2Te_{3-x}Se_x$ Nanoplates with Enhanced Thermoelectric Efficiency Driven by Wide Frequency Phonon Scatterings and Synergistic Carrier Scatterings, ACS Nano, 10, 4719−4727, 2016.

[10] Hu, L.; Zhu, T.; Liu, X.; Zhao, X. Point Defect Engineering of High-Performance Bismuth-Telluride-Based Thermoelectric Materials. Adv. Funct. Mater. 2014, 24, 5211−5218.

[11] Weishu Liu, Kevin C. Lukas, Kenneth McEnaney, Sangyeop Lee, Qian Zhang, Cyril P. Opeil, Gang Chen and Zhifeng Ren, Studies on the Bi_2Te_3–Bi_2Se_3–Bi_2S_3 system for mid-temperature thermoelectric energy conversion, Energy Environ. Sci., 2013, 6, 552–560.

[12] Hyeongwook Im, Hyung Geun Moon, Jeong Seok Lee, In Young Chung, Tae June Kang , Yong Hyup Kim, Flexible thermocells for utilization of body heat, Nano Research, Volume 7, Issue 4, pp 443-452 (2014)

[13] Min-Ki Kim, Myoung-Soo Kim, Seok Lee, Chulki Kim and Yong-Jun Kim, Wearable thermoelectric generator for harvesting human body heat energy, Smart Mater. Struct. 23, 105002, (2014)

[14] Francisco Suarez, Dishit P. Parekh, Collin Ladd, Daryoosh Vashaee, Michael D. Dickey and Mehmet C. Öztürk, "Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics", Applied Energy, 2017, vol. 202, issue C, 736-745

[15] Dickey, M. D. Stretchable and Soft Electronics using Liquid Metals. Adv. Mater. (2017). doi:10.1002/adma.201606425

[16] Francisco Suarez, Dishit P. Parekh, Collin Ladd, Daryoosh Vashaee, Michael D. Dickey, Mehmet C. Öztürk," Flexible thermoelectric generator using bulk legs and liquid metal interconnects for wearable electronics, Applied Energy 202, 15 September 2017, Pages 736-745

[17] Hong Goo Yeo, and Susan Trolier-McKinstry, "Effect of Piezoelectric Layer Thickness and Poling Conditions on the Performance of Cantilever Piezoelectric Energy Harvesters on Ni Foils," Sens. Act. A 273 90-97 (2018).

[18] Shad Roundy and Susan Trolier-McKinstry, "Materials and Approaches for On-body Energy Harvesting," accepted MRS Bulletin 43 (2018)

[19] Tiancheng Xue; Hong Goo Yeo; Susan Trolier-McKinstry; Shad Roundy, "A Wrist-worn Rotational Energy Harvester utilizing Magnetically Plucked {001} Oriented Bimorph PZT Thin-film Beams," Proc. 2017 19th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS) 375-378 (2017)

[20] Tiancheng Xue and Shad Roundy, "On Magnetic Plucking Configurations for Frequency Up-Converting Mechanical Energy Harvesters," Sens. Act. A 253 101-111 (2017).

[21] Dixiong Wang, Hangzheng Guo, Carl Morandi, Clive Randall, and Susan Trolier-McKinstry, "Cold Sintering and Electrical Characterization of Lead Zirconate Titanate Piezoelectric Ceramics," APL Materials 6 016101 (2018); https://doi.org/10.1063/1.5004420

[22] H. Sadeghi and M. Kiani, "Self-regulated reconfigurable voltage/current-mode inductive power management," IEEE J. Solid State Cir., 2017.

[23] H. Sadeghi and M. Kiani, "An adaptive reconfigurable voltage/current-mode power management with self-regulation for extended-range inductive power transmission," IEEE Int. Solid State Cir. Conf. (ISSCC), Feb. 2017.

[24] Ren J, et al. Pre-lithiated graphene nanosheets as negative electrode materials for Li-ion capacitors with high power and energy density. Journal of Power Sources 264 (2014) 108-113.

[25] Zhang J , Shi Z and Wang C. Effect of pre-lithiation degrees of mesocarbon microbeads anodeon the electrochemical performance of lithium-ion capacitors. Electrochimica Acta 125 (2014) 22–28

[26] Zhang T, Zhang F, Zhang L, Lu Y, Zhang Y, Yang X, Ma Y and Huang Y. High energy density Li-ion capacitor assembled with all graphene-based electrodes. Carbon 92 (2015) 106 –118

[27] Kim Haegyeom et al. A Novel High-Energy Hybrid Supercapacitor with an Anatase TiO_2 –Reduced Graphene Oxide Anode and an Activated Carbon Cathode. Adv. Energy Mater. **2013**, *3*, 1500–1506.

[28] Yong Cai, et al. Non-aqueous hybrid supercapacitors fabricated with mesoporous TiO_2 microspheres and activated carbon electrodes with superior performance. Journal of Power Sources 253 (2014) 80-89
[29] Sun et al. Hybrid lithium-ion capacitors with asymmetric graphene electrodes. J. Mater. Chem. A, 2017, 5, 13601–13609.
[30] Kim et al. High-Performance Hybrid Supercapacitor Based on Graphene-Wrapped $Li_4Ti_5O_{12}$ and Activated Carbon. ChemElectroChem 2014, 1, 125 – 130
[31] Ajuria J ,et al. Graphene-based lithium ion capacitor with high gravimetric energy and power densities. Journal of Power Sources 363 (2017) 422-427
[32] Byeon et al. Lithium ion capacitors with 2D Nb_2CTx (Mxene)- carbon nanotube electrodes, J. Power Sources 326, 686-694 (2016).
[33] Kim et al., A Novel high energy hybrid supercapacitor with an anatase- TiO_2 reduced Graphene oxide anode and an activated carbon cathode, Adv. Energy Materials 3, 1500 – 1506 (2013).
[34] Luo et al., Pillared structure design of Mxene with ultralarge interlayer spacing for high performance lithium ion capacitors, ACS Nano 11, 2459 – 2469 (2017).
[35] Jon et al., Graphene based lithium ion capacitor with high gravimetric energy and power densities, J. Power Sources 363, 422-427 (2017).
[36] Sun et al., A high performance lithium ion capacitor achieved by the integration of a Sn-C anode and a biomass derived microporous activated carbon cathode, Scientific Reports 7, 40990 (2017).
[37] Lim et al., Advanced Hybrid Supercapacitor based on a mesoporous Niobium pentoxide/Carbon as high performance anode, ACS Nano 8, 8968 – 8978 (2014).
[38] A. Klinefelter, N. Roberts, Y. Shakhsheer, P. Gonzalez, A. Shrivastava, A. Roy, K. Craig, M. Faisal, J. Boley, S. Oh, Y. Zhang, D. Akella, D. D. Wentzloff, B. H. Calhoun, "A 6.45 µW Self-Powered IoT SoC with Integrated Energy-Harvesting Power Management and ULP Asymmetric Radios," IEEE International Solid-State Circuits Conference, 2015.
[39] Z. H. Jiang, D. E. Brocker, P. E. Sieber, and D. H. Werner, "A compact, low-profile metasurface-enabled antenna for wearable medical body-area network devices," Submitted to the IEEE Trans. Antennas Propagt.
[40] Mills S., M. Lim, B. Lee, and V. Misra, April 2015, "Atomic Layer Deposition of SnO2 for Selective Room Temperature Low ppb Level O3 sensing," ECS Journal of Solid State Science and Technology, Vol. 4, No. 10, Pages S3059-S3061
[41] M. Li, E. B. Myrs, H. X. Tang, S. J. Aldridge, H. C. McCaig, J. H. Whiting, R. J. Simonson, N. S. Lewis and M. L. Roukes, "Nanoelectromechanical resonator arrays for ultrafast, gas-phase chromatographic chemical analysis," *Nano Lett.,* 2010.
[42] M. M. Mahmud, M. Kumar, X. Zhang, F. Y. Yamaner, H. T. Nagle, and Ö. Oralkan, "A capacitive micromachined ultrasonic transducer (CMUT) array as a low-power multi-channel volatile organic compound (VOC) sensor," in *Proc. IEEE Sensors Conf.,* 2015.
[43] M. Kumar, C. Seok, M. M. Mahmud, X. Zhang, and Ö. Oralkan**,** "A low-power integrated circuit for interfacing capacitive micromachined ultrasonic transducer (CMUT) based gas sensor," in *Proc. IEEE Sensors Conf.,* 2015.
[44] Dieffenderfer, J.P.; Beppler, E.; Novak, T.; Whitmire, E.; Jayakumar, R.; Randall, C.; Weiguo Qu; Rajagopalan, R.; Bozkurt, A., "Solar powered wrist worn acquisition system for continuous photoplethysmogram monitoring," *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE* , vol., no., pp.3142,3145, 26-30 Aug. 2014.
[45] P. V. Rajesh, J. M. Valero-Sarmiento, L. Yan, A. Bozkurt, C. Van Hoof, N. Van Helleputte, R. F. Yazicioglu, M. Verhelst," A 172-µW compressive sampling photoplethysmographic readout with embedded direct heart-rate and variability extraction from compressively sampled data," *2016 IEEE International Solid-State Circuits Conference (ISSCC)*, San Francisco, CA, 2016, pp. 386-387.
[46] Yokus, M. A. and Jur, J. S. "Fabric-Based Wearable Dry Electrodes for Body Surface Biopotential Recording" IEEE Transactions on Biomedical Engineering 63 (2) 423-430 (2016).
[47] Yokus, M. A., Foote, R., & Jur, J. S. (2016). Printed Stretchable Interconnects for Smart Garments: Design, Fabrication, and Characterization. IEEE Sensors Journal, 16(22), 7967-7976.Jes
[48] Dawai Fan, Luis Lopez Ruiz and John Lach, Senior Member, IEEE, " Application-Driven Dynamic Power Management for Self-Powered Vigilant Monitoring, 2018th IEEE 15t International Conference on Wearable and Implantable Body Sensor Networks (BSN).