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MEMS energy harvesting powered wireless biometric sensor

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Abstract—**One of the main challenges in developing wireless biometric sensors is the requirement for integration of various systems into a very compact device. Such systems include sensing units, conditioning electronics, transmitters and power supplies. In this work, a novel system integration architecture is presented. A unique feature of this new architecture is that the sub-systems are selected and designed for direct output-to-input connection. An array of active pH sensors is used to transform a pH level to an electrical potential in the range of 0 - 2 Volts. This signal is amplified by an electrostatic energy harvester suitable for human motion operation. The amplified signal drives a custom LC transmitter specially designed to suit the harvester output. A system of notable simplicity is achieved and may serve as a demonstrator for other wireless sensors.**

I. INTRODUCTION

Implantable biometric sensor networks have become a major field of research both from the engineering and the medical points of view because of their great promise in health monitoring. One of the major challenges for the implementation of such applications is powering the implantable devices. In the last decade, advances in microelectronics and bioengineering have reduced the power requirements of such devices to levels in principle as low as 1 μW [1]. Nevertheless, the requirement of a (low) power source remains.

The use of miniature batteries or fuel cells is a popular approach offering abundance of power, but at the expense of limited lifetime and eventual need for replacement, which is impractical for implanted devices. Electromagnetic energy induction from an external power source, e.g. using Radio Frequency Identification (RFID) technology, is a promising alternative but is more suitable for discrete measurements rather than continuous monitoring and data logging.

Energy harvesting from ambient power sources such as light, temperature and motion is a practical technology for long term energy autonomy. From these sources, motion is most promising for implantable devices, because of light unavailability and limited temperature gradients in the human body.

Extensive work has been published the last decade on motion energy harvesting [2],[3]. Depending on the physical mechanism used, motion energy harvesting can be piezoelectric [4], electromagnetic [5] or electrostatic [2], with the latter having advantages in small scale devices and for the low-frequencies and high amplitudes of human body motion.

In previous work, an electrostatic energy harvester has been developed, based on appropriate charging and discharging of a capacitor with one moving plate [6]. A schematic of this device is shown in Figure 1a.

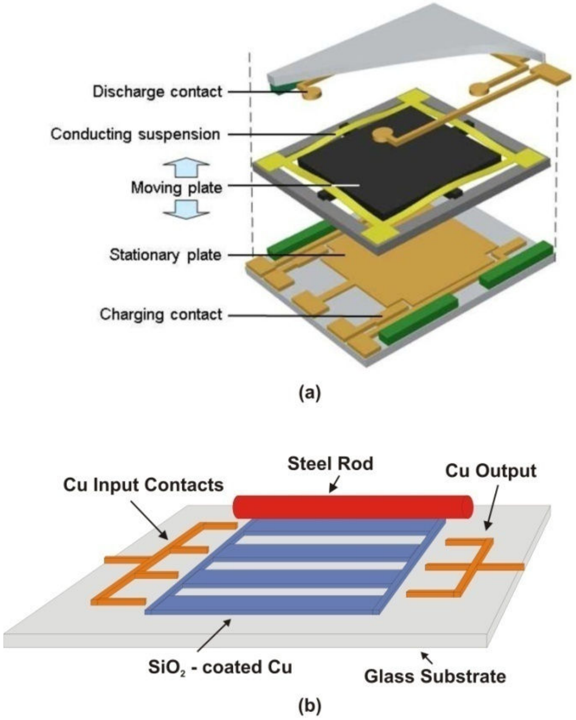

Figure 1. Moving plate (a) and rolling rod (b) electrostatic energy harvesters [6], [7].

When the device is accelerated, inertia causes the plate to move with respect to the frame. At the lowest plate position (maximum capacitance C) the capacitor is charged with a priming voltage through an input contact. As the plate continues to move it breaks contact with the charging electrode and the plate-plate

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gap is increased. During this movement, the stored charge remains constant while the capacitance decreases, causing the voltage to rise. In energy terms, external work is done to pull away the moveable plate against the attractive electrostatic force; this additional energy is stored in the capacitor. At the top of its trajectory, the moving plate makes contact with an output electrode which drains the harvested energy. Energy as high as 150 nJ per cycle was achieved by this device.

Improvement of such electrostatic devices requires increase of the proof mass (the moving plate in the above case) which is difficult when made monolithically. The problem becomes severe when integration with electronic circuits is desirable. In addition, the plate suspension system inevitably introduces resonance effects which limit the optimum operation of the device to a particular bandwidth, which is typically much higher than that of human motion.

To address these limitations, an electrostatic harvester with an external proof mass has been developed [7]. The architecture of this device is shown in Figure 1b. A steel rod can roll freely over an array of dielectric-coated Cu plates. The capacitance formed between the plates and the rod changes periodically with rod displacement following the plate geometry. Appropriate charging and discharging is achieved by side contacts which are made to slightly protrude from the dielectric surface. Advantages of this architecture include the lack of a suspension system, and the capability for a large proof mass. In addition, the output power can be delivered in a series of pulses per cycle rather than having one very high output pulse. An output power of 12 nJ per cycle has been reported for this device.

One limitation of electrostatic harvesters is the requirement for a priming voltage. In addition, power storage, conditioning and distribution is needed to fulfil the power requirements of sensing units, conditioning circuits and transmitter modules. In this paper, a novel architecture is proposed, in which the energy harvester amplifies directly the information signal rather than delivering a power supply line for additional electronics.

II. SYSTEM ARCHITECTURE

The architecture of the wireless biometric sensor is illustrated in Figure 2. A specially developed array of active pH sensors with a voltage output proportional to the measured pH is deployed. The output of the sensor array is connected to the input of an electrostatic energy harvester, serving as priming voltage. The relationship between the input and output of the harvester satisfies equation $V_{out} = (C_{\max} / C_{\min}) \cdot V_{in}$. Therefore for fixed maximum to minimum capacitance ratio V_{out} is linearly related to V_{in}, hence linearly related to the pH value. In this way, power amplification of the sensor signal is achieved.

This output further drives a passive LC oscillator that serves as a transmitter, emitting short electromagnetic pulses at a certain frequency. These pulses are captured from a vicinal detector and the pH monitoring information is extracted from the amplitude of the electromagnetic pulses.

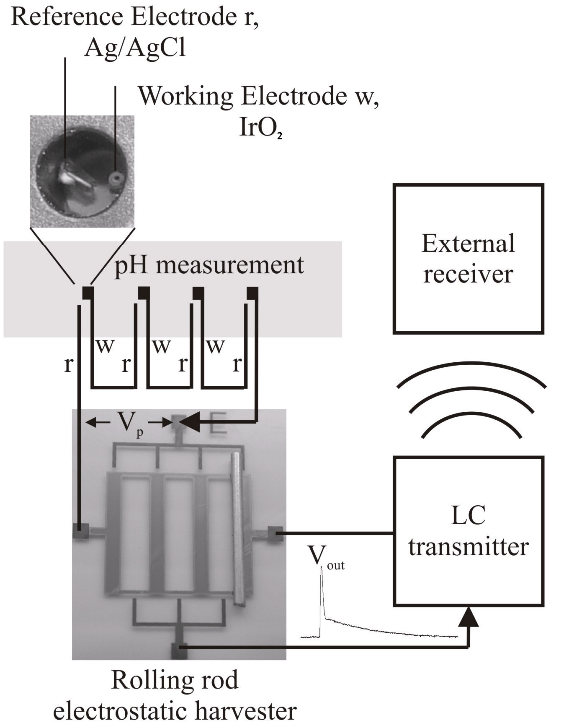

Figure 2. System level illustration of the wireless biometric pH sensor.

III. THE PH SENSOR ARRAY

Metal – metal oxide pH electrodes (e.g. Au/IrO_2) work on the principle where measured electrode potential versus a reference electrode (normally Ag/AgCl) is due to the equilibrium between a sparingly soluble salt and its saturated solution [8]. The output potential depends on the thermodynamic solubility product. These solid state electrodes can be easily miniaturized and their response time is faster compared to glass electrodes. A typical Au/IrO_2 pH electrode works as a small galvanic cell and gives an open circuit potential against a Ag/AgCl reference electrode. This potential lies in the range from 0.55 V (at pH 1.5) to 0.15 V (at pH 7.0). By connecting more than one pH electrode in a series a sum potential is achievable.

For the system presented here, Au/IrO$_2$ pH electrodes were fabricated using the following technique. A gold wire (diameter 250 µm and length 1 cm, Goodfellow, purity > 99.99%) was connected to a copper wire (length 5 cm) using conductive epoxy glue or wood metal. The gold wire then was casted in an epoxy resin mixture (1 part hardener and 2.5 parts resin by volume). Care was taken to ensure the gold wire remains in the centre of the pipette tip. The resin was allowed to dry overnight at room temperature. The electrode tips were prepared by bevel - sawing using a low speed saw (Buehler) followed by polishing on emery paper (1200 and 2500 grit) and aqueous alumina slurry (1, 0.3 and 0.05 µm) on polishing cloths with ultrasonic cleaning in water between grades. Prior to iridium oxide deposition the electrodes were cleaned using a series of cleaning steps. The IrO$_2$ film was deposited from an electrochemical IrO$_2$ solution [9], applying 0.6 V against a standard calomel reference electrode for 10 minutes. A platinum mesh was used as the counter electrode. The growth of the IrO$_2$ film on the exposed gold surface was monitored by obtaining cyclic voltammograms in 0.5 M sulphuric acid at 100 mV s^{-1} before and after deposition.

The voltage output of such pH electrodes can be used to prime an electrostatic energy harvester, thereby achieving signal power amplification to transmittable levels. However, the low voltage output of a single pH electrode results in low power gains [7]. Hence, a larger priming voltage is desirable and for this purpose, the connection of several pH electrodes in series is proposed.

The Open Circuit Potential (OPC) of two pH electrodes measured against a Ag/AgCl reference electrode is shown in Figure 3. The OCP of the first and the second pH electrode was 0.146 V and 0.176 V respectively. When these two electrodes were connected in a series the measured sum potential was 0.310 V, which was slightly less than the theoretical sum (0.322 V). On connecting the electrolytes of both pH electrodes, by overflowing the individual reservoirs to mimic the one electrolyte condition of the human body, the sum potential was reduced to 0.232 V. The sum potential was still bigger than the individual electrode potentials. The electrodes were connected in a series for 80 seconds. After disconnection the individual potentials of first and second pH electrodes dropped to 0.126 V and 0.131 V. This reduction of potential for both electrodes can be attributed to electrochemical changes at the iridium oxide surfaces. The above experiment demonstrates the ability to increase the achievable voltage output of such pH sensors by using an array of electrodes.

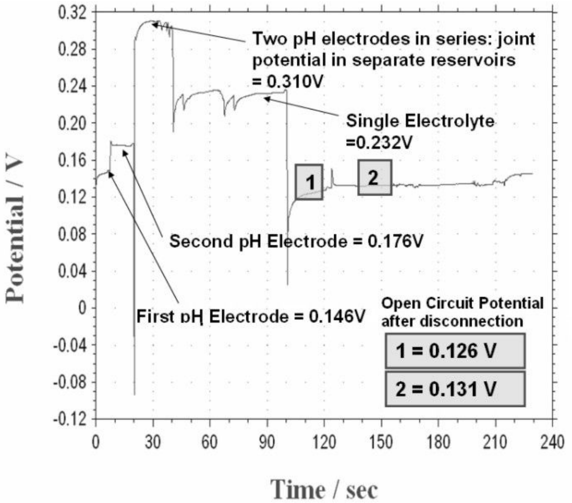

Figure 3. Open circuit potentials (Vs Ag/AgCl reference electrode) of two Au/IrO pH electrodes.

IV. THE ELECTROSTATIC ENERGY HARVESTER

A Microelectromechanical Systems (MEMS) – fabricated first prototype of the rolling rod electrostatic energy harvester has been presented in [7]. For the wireless biometric sensor, an improved device generation is used. In particular, the dielectric thickness has been reduced in order to enhance the rod – plate capacitance. In agreement with the theoretical predictions from the device analysis [7], these modifications allowed the observation of energy gains higher than those of the prototype.

The device working principle has been described in section 1. An optical image of the improved device without the rod is shown in Figure 4. The sputtered Cu plates are covered by a 50 nm thick SiO$_2$ dielectric and appear dark in the image. The light top and bottom contacts correspond to the (charging) input and (discharging) output of the device. The light squares on the left and right of the device provide electrical access to the plates. The substrate material is glass, allowing the device shade on the underlying bench to be visible in the image.

In order to visualize the glass-Cu-SiO$_2$ interfaces, Scanning Electron Microscopy (SEM) was used as shown in Figure 5. The glass, Cu and SiO$_2$ regions can be easily identified. The adhesion enhancement layer of Cr that has been sputtered before Cu sputtering is also visible as a dark region between the Cu and glass.

Capacitance (C) versus rod displacement (d) measurements were made possible by probing the rod with an in-plane oriented probe pin. Typical C-d curves for the prototype and the improved device are shown in Figure 6. The capacitance behaviors are identical in shape, with the 2nd generation giving a capacitance of around 6 pF when the rod is above a plate and around 1 pF in between plates. This capacitance difference from the charging to the discharging position corresponds to a voltage gain of 6. In comparison with the prototype a 30% increase of the charging position capacitance is observed (from 4.5 pF to 6 pF). These measurements should not be directly compared with the peak capacitance measurements reported in [7]. Here, capacitance monitoring was performed automatically, allowing measurements at 10 samples per second, thereby increasing reliability at the cost of noise.

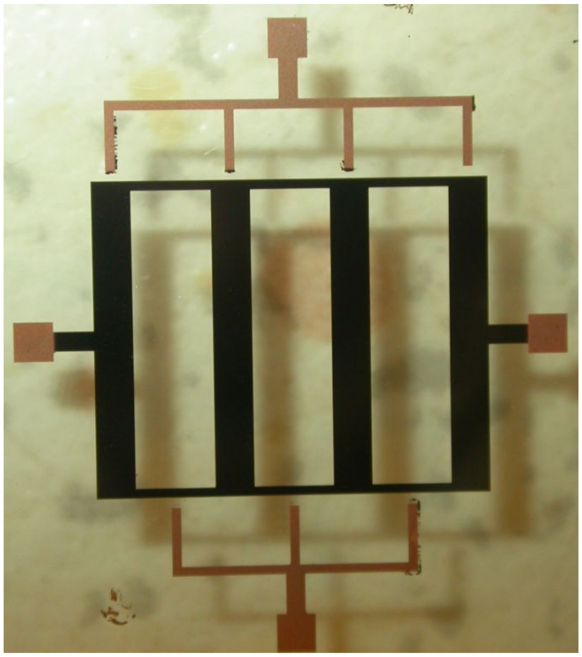

Figure 4. Rolling rod electrostatic energy harvester deposited on a glass substrate. The rod is not shown in the picture.

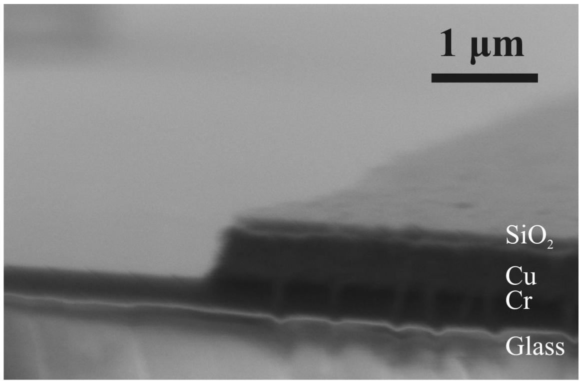

Figure 5. Scanning Electron Microscopy (SEM) image of the Cu plate - SiO2 interface at a plate edge.

By applying priming voltages in the range between 5 V and 30 V, different output pulses were detected with gains as high as 6. A typical output pulse corresponding to 5 V priming from a voltage source is shown in Figure 7. The peak output voltage is 28 V, corresponding to a gain of 5.6, close to the expected value (6) from the capacitance measurements.

The low pH sensor output requires successful priming by voltages below 5 Volts. This can be challenging for two reasons. Firstly, low voltage means smaller charge and hence, any charge loss due to leakage or other effects during the rod movement may have a larger effect on device performance. In addition, imperfections at the rod-to-Cu substrate contacts interface due to rod surface roughness can make successful charging or discharging more difficult for low voltages. By improving the device fabrication techniques to give structures with minimum defects and proper plate passivation at edges (see Figure 5), pulse generation from priming voltages as low as 1 V were made possible. An output pulse corresponding to voltage source priming of 2 V is shown in Figure 7 as a dashed curve. The peak output voltage is 10 V corresponding to a gain of 5.

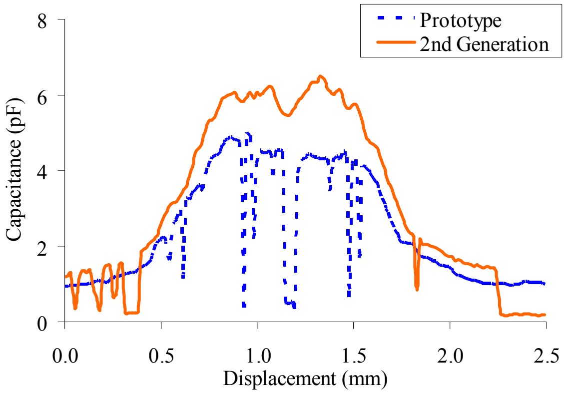

Figure 6. Capacitance - rod displacement measurements of the electrostatic energy harvester.

On the other hand, connection of more than one pH electrodes in series, as discussed in section 3, allowed the increase of the sensor output voltage, to levels exceeding the minimum priming requirements of the electrostatic generator. An array of four pH electrodes provided output voltage as high as 1.6 V. This voltage was used to prime the generator, resulting in output pulses with voltage gain around 6. A typical output pulse primed by the pH electrode array is shown in Figure 8. The detected pulse has the same shape as those of Figure 7. It is noted that the two discharging regions observed for the device output pulses are correlated to the pulse detection circuit and have been discussed in [7]. The pH information is represented by the amplitude of the first (sharper) pulse.

V. THE LC TRANSMITTER

The energy generated for a priming voltage of 1.6 V is about 100 pJ, based on a measured final capacitance of 2 pF and a final voltage of 10 V. State-of-the-art off-the-shelf short range low power transceivers require more than 5nJ/b for successful wireless transmission [10].

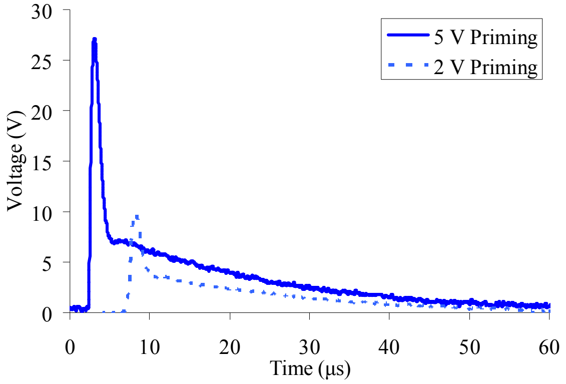

Figure 7. Typical output pulses obtained for voltage source priming.

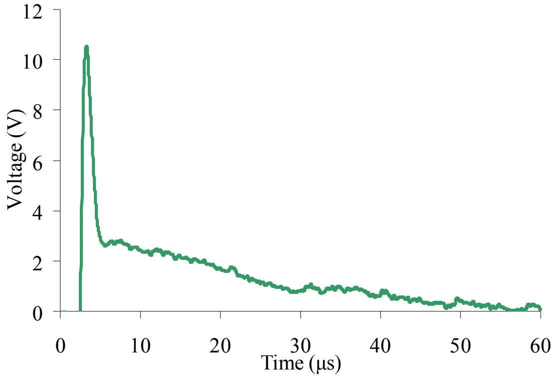

Figure 8. Energy pulse at the output of the harvester primed by 1.6 V from an array of pH sensors.

Nonetheless, theoretical analysis using the Friis formula demonstrates that there is, in principle, enough energy available to achieve short range (50 cm or so) wireless transmission of the pH measurement. Figure 9 shows the equivalent number of bits of accuracy versus range for three different transmission frequencies, assuming 1/10th of the generated energy is radiated, a receiver noise figure of 20 dB, a fade margin of 20 dB and two isotropic antennas. Considering 6 bits as desirable it can be seen that a transmission distance of almost 50 cm can be achieved at 434 MHz even with these worse case assumptions. With the simple resonator proposed below it is in fact likely that at least 1/3rd of the energy can be radiated and furthermore, it is shown in [11] that the fade margin is no more than 10 dB for short range on-body communications. Therefore, with careful design, an improvement of at least 2.4 bits can be expected.

Given the limited energy available, a passive wireless link is proposed to directly transmit the generated energy, which is proportional to the measured pH voltage. The preferred approach, shown in Figure 10, is to use each generator discharge to kick a resonant circuit in which the tank inductor doubles as a loop antenna.

By correctly choosing the size of the loop antenna reasonable radiation efficiency can be achieved whilst realizing a high Q-factor [12], the latter being necessary to limit the required receiver bandwidth.

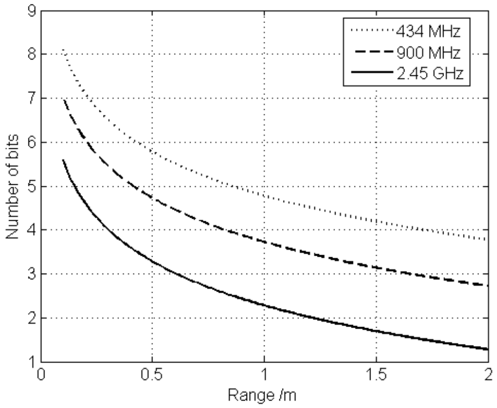

Figure 9. Equivalent number of bits versus range.

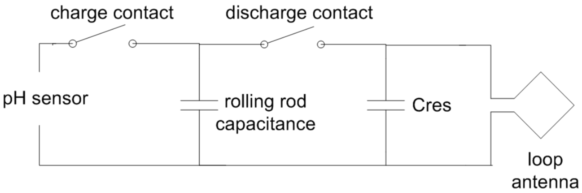

Figure 10. Proposed wireless transmitter.

For instance a single turn loop antenna, with an inductance of 320 nH operating at 200 MHz, and sized around 10 cm in diameter, can achieve a Q in the hundreds whilst radiating over 40% of the generated energy, assuming the series resistance of the generator to be equal to the loss resistance of the antenna. The major challenge lies in reducing the antenna size, whilst not significantly reducing the transmission efficiency. Possible solutions include moving to higher frequencies, by isolating the resonant antenna circuit from the generator capacitance (which currently limits the maximum frequency to just less than 200 MHz), or careful design of a high-Q multi-turn loop antenna, capable of operating efficiently at lower frequencies.

VI. CONCLUSION

In this paper, a novel wireless sensor architecture has been proposed. An array of active IrO_2 pH sensors is used to provide a low power voltage, proportional to the pH level, in the range of 0-2 V. This signal is amplified by an electrostatic energy harvester achieving times 6 as high voltage and power, in the form of short output pulses. Such pulses are suitable for direct transmission by a high quality LC oscillator at UHF frequencies. Signal reception at short distances with accuracy of several bits is possible by appropriate design of the antenna, taking into account the output capacitance of the harvester.

In order to ensure reliable information extraction from the electromagnetic pulse amplitude, a reference is required. This is especially the case when the distance between the sensor and the receiver is not fixed; a distance variation would affect the amplitude of the detected pulses introducing noise to the measurements. Such a reference could be provided by a calibration pulse, corresponding to a reference voltage at the input of the electrostatic harvester. A possible implementation of this approach is to connect every other input contact (top of Figure 4) to a reference voltage. Then, reliable pH information could be extracted at the receiver by comparing the amplitudes of the pH pulses to that of the reference.

The system level design of the proposed device was based on the combination of suitable, state-of-the-art sensing, transmitting and powering systems. The resulting wireless biometric sensor is of high simplicity, and hence is promising for integration into a biomedical pH monitoring system. In addition, it serves as a demonstrator for the development of other wireless biometric sensors using the same electrostatic harvesting amplification and direct transmission architecture.

REFERENCES

[1] B. C. Yen and J. H. Lang, "A variable-capacitance vibration-to-electric energy harvester," *Circuits and Systems I: Regular Papers, IEEE Transactions on,* vol. 53, pp. 288-295, 2006.

[2] S. Roundy, P. K. Wright, and J. M. Rabaey, *Energy Scavenging for Wireless Sensor Networks*. Boston, Massachusetts: Kluwer Academic Publishers, 2003.

[3] P.D. Mitcheson, E.M. Yeatman, G.K. Rao, A.S. Holmes and T.C. Green, “Energy harvesting from human and machine motion for wireless electronic devices”, *Proceedings of the IEEE*, Vol. 96 (9), pp. 1457-1486, 2008.

[4] H. A. Sodano and D. J. Inman, "A Review of Power Harvesting from Vibration Using Piezoelectric Materials," *The Shock and Vibration Digest,* vol. 36, pp. 197-205, 2004.

[5] P. Glynne-Jones, M. J. Tudor, S. P. Beeby, and N. M. White, "An electromagnetic, vibration-powered generator for intelligent sensor systems," *Sensors and Actuators A: Physical,* vol. 110, pp. 344-349, 2004/2/1 2004.

[6] P. Miao, P.D. Mitcheson, A.S. Holmes, E..M. Yeatman, T.C. Green and B.H. Stark, “MEMS inertial power generators for biomedical applications”, *Microsystem Technologies* , Vol. 12, pp. 1079-1083, 2006.

[7] M.E. Kiziroglou, C. He and E.M. Yeatman, “Rolling rod electrostatic microgenerator”, *IEEE Transactions on Industrial Electronics*, in press.

[8] D. O’Hare, K.E. Parker and C.P. Winlove, “Metal-metal oxide pH sensors for physiological application”, *Medical Engineering & Physics* 28, pp. 982 -988, 2006.

[9] K. Yamanaka, “Anodically Electrodeposited Iridium Oxide Films (AEIROF) from Alkaline Solutions for Electrochromic Display Devices”, *Jpn. J. Appl. Phys.* 28, pp. 632-637, 1989.

[10] D.C. Yates and E. Rodriguez-Villegas, “A Key Power Trade-off in Wireless EEG Headset Design,” *Neural Engineering, 2007. CNE '07. 3rd International IEEE/EMBS Conference on*, pp.453-456, 2-5 May 2007.

[11] M. R. Kamarudin, Y. I. Nechayev and P. S. Hall, “Antennas for on-body communication systems,” *IEEE Int. Workshop on Antenna Tech.*, pp. 17-20, 7-9 March 2005.

[12] D.C. Yates, A.S. Holmes, A.J. Burdett, “Optimal transmission frequency for ultralow-power short-range radio links,” *IEEE Trans. on Circuits and Systems*, Vol. 51 (7), pp. 1405-1413, 2004.