BODY MOTION POWERED WIRELESS TRANSMISSION PLATFORM

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Abstract: Biomedical implanted sensors will benefit greatly from energy harvesting power sources. Although promising devices have been proposed, system complexity and low power levels have been preventing integration into biomedical wireless sensors. We have proposed a simplified architecture which addresses these critical drawbacks. Here we report a wireless node with increased range (1 meter range) and reduced priming requirements (1 volt range), by the use of improved fabrication techniques. Voltage inputs from passive sensors are amplified using energy from device motion, and the motion also provides switching for signal sampling and pulse transmission.

Keywords: Wireless sensor networks, body sensor networks, energy harvesting, electrostatic

INTRODUCTION

Developments in low power integrated electronics and wireless technology are enabling diverse applications of sensor networks, e.g. in biomedical sensing and environmental monitoring. However, replacing or recharging batteries is increasingly unacceptable as the number of nodes increases, and batteries may also be incompatible with the sensor environment. Energy harvesting is an attractive alternative; a diverse range of devices have been reported, and some have reached commercialization [1]. Sensor nodes powered only by energy harvesting with the use of power handling circuits have also been implemented [2].

For body sensor networks (BSN), body motion is a possible source of ambient energy [3]. This motion has a broad, low frequency spectrum up to ≈ 10 Hz, with stochastic impulses of acceleration. The power available depends on harvester size; for devices around 100 mm^3 the theoretical maximum is tens of μW [1]. Reaching theoretical limits requires maximising proof mass and internal travel range, and for this reason we have previously proposed and demonstrated an electrostatic harvester with an external rolling proof mass [4]. This increases the mass, and avoids spring suspensions, which are resonant and thus have low bandwidth. A priming voltage provides the initial charge in each cycle, and relative motion of the electrodes increases the energy of the stored charge. Our implementation, with proof-mass volume 50 mm^3, demonstrated output power of 0.5 μW from emulated body motion [5]. The steel cylindrical proof mass rolls over a set of dielectric covered plates, causing the capacitance to rise and fall. Charging and discharging is achieved through side electrodes.

Other implementations of electrostatic harvesting systems use electrets and/or require considerable power handling circuitry. Efficient such circuits and systems have been proposed [6-8]. However, constant charge devices such as the one presented here can act as power amplifiers for weak sensor signals, by using the latter as the priming voltage. Furthermore, the stored energy on each cycle can be directly discharged into a resonant transmitter circuit. We presented a proof of principle for this architecture recently, as the first micro-electromechanical wireless system exclusively powered by energy harvesting [9] (Figure 1). However, a large priming voltage (2 – 15 V) was required, which is beyond the output range of typical passive sensors. In addition, the transmission range was only 20 cm. These limitations originated partly from poor contact between the cylinder and the charge/discharge contacts.

Here, an updated rolling rod electrostatic harvester is presented addressing the above limitations. The device is used as an amplifier of passive sensor level signals, in the proposed wireless platform architecture. This is also presented here, with special regard to the power levels relevant to this particular electrostatic implementation. Results of transmission and detection are discussed, showing significant improvement of compatibility with application requirements. The remaining challenges and a plan for further work are presented in the conclusions.

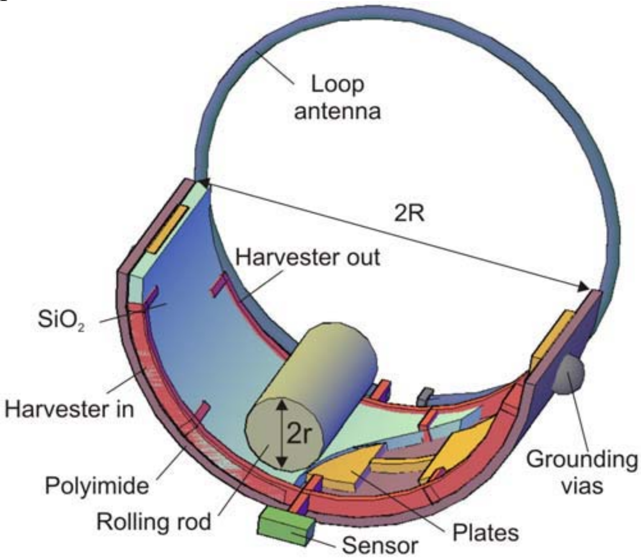

Fig. 1: 3D Schematic of a wireless sensor powered only by motion harvesting [9].

THE HARVESTING DEVICE

For the implementation and evaluation of the new platform, a new rolling rod electrostatic harvester was fabricated on a flexible substrate. The Cu plates, Cu contacts and SiO_2 dielectric of the harvester (Fig. 1) were sputtered on a polyimide wafer and patterning by two lithography steps was applied to form the desired structures. The contacts were made to protrude from the dielectric in order to ensure contact with the rolling rod, by Cu electrodeposition. A more detailed description of the MEMS fabrication process can be found in [5].

Three advancements of the harvesting devices used to implement the proposed platform are reported here. Firstly, the edges of the plates were improved to achieve smoothness and isolation from possible short wiring with the rolling rod at defect sites. This was accomplished by a new selective Cu and Cr etching technique which allowed etching under the SiO_2 for a few µm (undercut). The resulting edge shape is illustrated in the Scanning Electron Microscopy (SEM) image of Fig. 2. In addition, a new constant current Cu electrodeposition technique at a voltage of 0.6 V was developed to reduce the roughness of the contacts surface. The optical interferometry profile shown in Fig. 3 demonstrated an average roughness below 60 nm over a 0.16 mm^2 area.

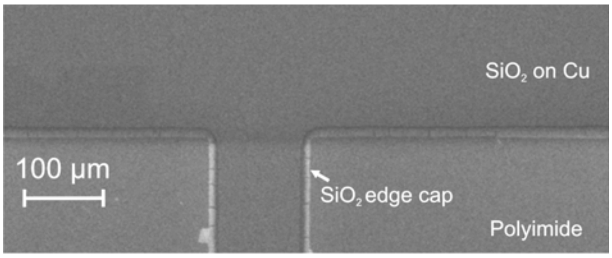

Fig. 2: SEM image of plate edges. Cu etch extends under the SiO_2 at the edges providing complete passivation of the plates.

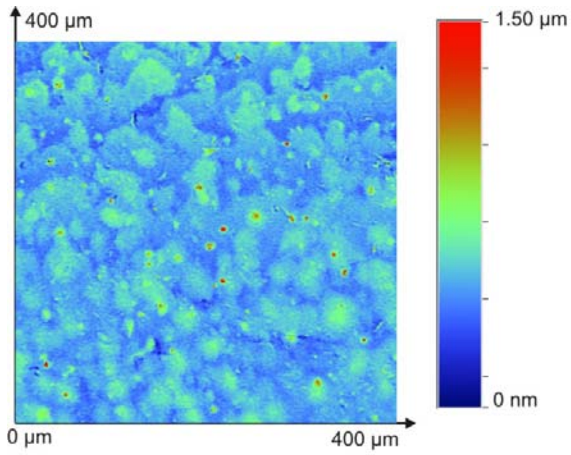

Fig. 3: Optical interferometry measurements on the electroplated Cu surface demonstrates an average roughness below 60 nm over a 0.16 mm^2 area.

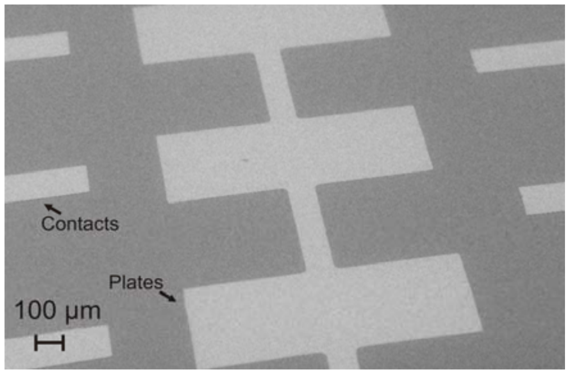

Fig. 4: SEM image of a prototype device fabricated on polyimide showing the SiO2 covered plates and the contacts.

Furthermore, a denser array of plates and contacts was achieved with 7 output contacts over a 10 mm device length, allowing a better electrostatic force distribution and increased number of discharges per cycle, at lower and more convenient voltage levels. A part of such an array is shown in the SEM image of Fig. 4.

THE WIRELESS NODE ARCHITECTURE

The device described above is used in the proposed wireless node architecture. It operates in a sample, store, amplify and transmit scheme. An illustration of the architecture is shown in Fig 5. A passive sensor with voltage output is connected to the priming input of the harvester. As the rod rolls onto an input contact, the voltage of the sensor is sampled and stored into the capacitor formed by the rod and the plates. During sampling, this capacitance is at its maximum and for this particular implementation, in the range of tens of pF. At 1V, the corresponding energy is tens of pJ.

As the rod rolls off the input contact and towards the output contact, due to relative acceleration, the capacitance is reduced at constant charge. The work done against the corresponding electrostatic force is stored as additional energy in the rod-plate capacitor which leads to a linear increase of voltage by a gain equal to the ratio of the maximum and minimum capacitances C_{max} / C_{min}. The corresponding energy increase is hundreds of pJ.

The output contacts are connected to a loop antenna with inductance L. As the rod rolls on an output contact, an LC_{min} circuit is formed. Discharge through the loop initiates oscillation at the resonant frequency. The initial energy of the oscillation is hundreds of pJ and with a high quality factor of the LC circuit, most of it can be transmitted, corresponding to a transmission range of a few meters in a typical noise environment.

In this architecture, the harvested motion energy is stored directly into the information signal, eliminating the requirement for additional power handling and storing circuitry. The motion is also used to provide the necessary sampling switching, and, in addition, the transmission switching. As a result, an integrated MEMS wireless sensor node is achieved, powered only from motion energy harvesting. The mechanical energy requirement is extremely low, in the range of 0.1 nJ per pulse. Depending on the pulse amplitude resolution, a word of information with a certain number of bits can be transmitted with every pulse. As an example, if one assumes an amplitude resolution of 16, a 4-bit word is transmitted with every pulse. With a motion of average frequency of 10 Hz and 14 output pulsed per motion cycle, an average sampling and detection rate of 560 bits per second. The corresponding required power transduction will be 14 nW. This, in turn corresponds to a proof mass volume requirement below 0.1 mm^3. This consideration shows that the proposed architecture is promising for mm and sub-mm scale, battery-less integrated wireless senor nodes. This is achieved at the expense of a relatively low resolution and sampling rate, which are nevertheless adequate for a variety of biomedical applications such as blood pressure, pH, glucose and temperature sensor implants.

RESULTS AND DISCUSSION

An implementation of the proposed wireless platform with the harvester presented above is shown in Fig. 6. A flexible substrate device with seven outputs is used. The external passive sensor can be directly connected to the input of the harvester. The output is directly connected to a Cu wire loop antenna with loop radius 15 mm and wire radius 0.75 mm. This corresponds to an inductance of about 60 nH.

The voltage gain of the harvester was measured by replacing the antenna with a high input impedance and low input capacitance operational amplifier circuit [4]. A value of 4 ± 20% is obtained, showing a 33% increase in value and higher regularity over our previously reported devices [5]. An improvement of the consistency of the pulses was also achieved, allowing regular observation of complete sequences of pulses from a single rod swing. Finally, operation at priming voltages as low as 1 V is reported. This is a critical result, as it makes the input of the device compatible with the output of passive sensors for quantities such as pH [10] and vibration [11]. These improvements are attributed to the better surface and edge profiles of the plates and the contacts, shown in Fig. 2 and Fig. 4, achieved by the new fabrication technique.

Characterization of the oscillations of the LC transmitter operation was performed by local monitoring of the voltage across the inductor during normal harvesting operation. A custom made high impedance operational amplifier circuit was used particularly for this purpose. A characteristic oscillation corresponding to a priming input of 1 V for the harvester is shown in Fig. 7. An oscillation duration of 50 ns, at a frequency of 330 MHz, is observed. From the decay profile, a quality factor of 12 is extracted. Taking into account the calculated value of the loop inductor from its geometry, a value of 4 pF for the minimum capacitance is extracted. This in turn corresponds to an input capacitance of 16 pF. Experiments for confirmation of these capacitance values by complementary methods are underway.

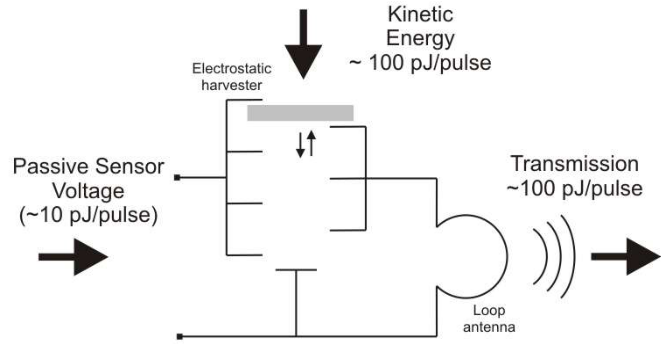

Fig. 5: Circuit model of the wireless platform

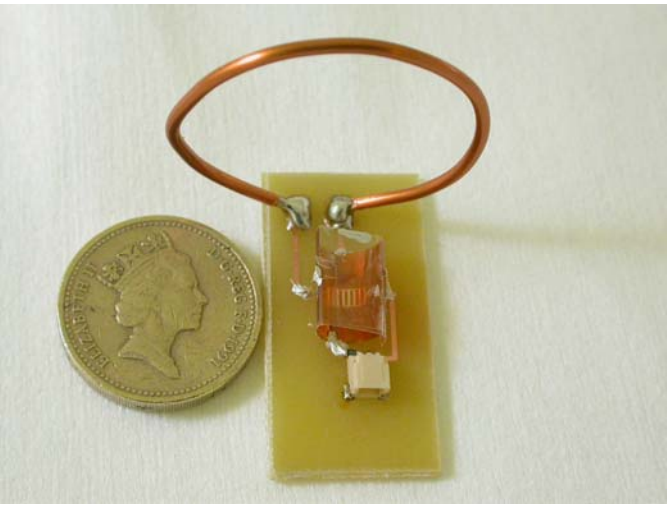

Fig. 6: Optical image of the device including the loop antenna.

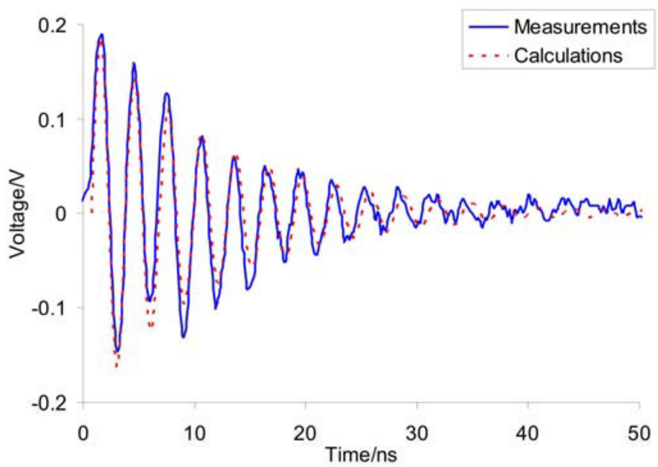

Fig. 7: Capacitively tapped measurement of the discharge of the harvested power through the loop antenna showing oscillation at 330 MHz.

Detection of the electromagnetic pulses transmitted by the sensor node was performed using a commercial Ultra High Frequency antenna directly connected to a high bandwidth oscilloscope. Detection for node to antenna distances greater than 1 m was observed, for a priming voltage of 1 V at the input of the harvester. One such pulse is shown in Fig. 8. Compared to our previously reported device [5] the distance is five times longer, with half the priming voltage, and the received signal-to-noise ratio is higher. This particular result demonstrates that at priming voltages within the voltage range of available passive sensors, transmission to distances adequate for biomedical applications is possible, although for implanted sensors the signal attenuation through body tissue will be significant.

CONCLUSION

In this paper a battery-less platform for wireless sensor nodes, powered only by energy harvesting, is demonstrated. The required input and output energy levels are discussed and it is shown that integrated wireless sensor nodes at sizes below 1 mm^3, including the harvesting system, are possible. This is because the introduced platform allows amplification and transmission of low voltage amplitude signals, over a range of a few metres, with energy below 0.1 nJ per bit of information in the speed range of hundreds of bits per second.

A new electrostatic energy harvester device with improved structural features, capacitance, power and operation regularity is presented. A consistent voltage gain of 4 and operation with a priming voltage of 1V is reported. This performance allowed the implementation of the proposed wireless sensor platform, at priming voltages compatible with currently available passive sensors. In addition, a transmission range of 1 m is achieved. These features, along with the capability of operation at low frequency or impulse motion excitation [5], make the presented system particularly suitable for body sensor networks.

A compact, fully MEMS and integrated implementation of the proposed system would allow optimisation of capacitance, gain stability and packaging requirements. Higher transmission frequency will allow considerable reduction of the loop antenna size for such a system. Piezoelectric pressure sensors and electrode potential biochemical sensors are potentially suitable for such an integrated network node. Further challenges include data calibration at the receiver using transmission of a reference voltage level, and node identification in a multi-sensor network. Possible device structures and electronic circuits for the above are currently under investigation.

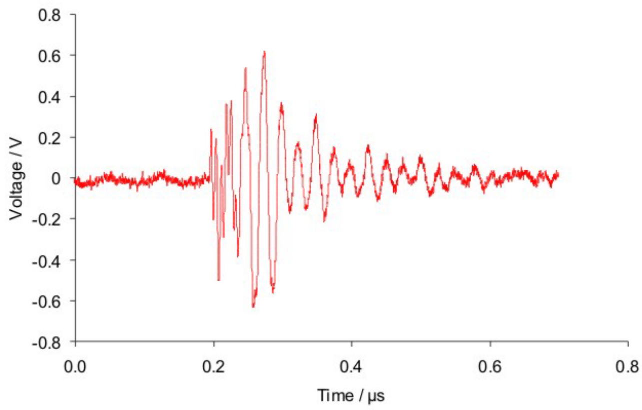

Fig. 8: Detection of oscillation primed by 1 V, at a distance of 1 m. The distortion is due to limitations of the detection system used.

REFERENCES

[1] Mitcheson P D, Yeatman E M, Rao G K, Holmes A S , Green T C, 2008 Energy Harvesting From Human and Machine Motion for Wireless Electronic Devices *Proc. IEEE,* **96**, 1457-1486

[2] Chee Y -H, Koplow M, Mark M, Pletcher N, Seeman M, Burghardt F, Steingart D, Rabaey J, Wright P, Sanders S 2008 PicoCube: a 1 cm3 sensor node powered by harvested energy *Proceedings of the 45th annual Design Automation Conference, (Anaheim, California: ACM, 2008).*

[3] Starner T, Paradiso J A 2004 Human generated power for mobile electronics *Low-Power Electronics Design* (C. Piquet, Ed., Boca Raton, FL: CRC Press) 1–35.

[4] Kiziroglou M E, He C, Yeatman E M 2009 *IEEE Trans. on Industrial Electronics*, **56**, 1101-1108

[5] Kiziroglou M E, He C, Yeatman E M 2010 *Electronics Letters*, **46** 166–167

[6] Torres E O, Rincon-Mora A 2010, *IEEE Journal of Solid-State Circuits,* **45,** 483-496

[7] Sterken T, Fiorini P, Altena G, Van Hoof C and Puers R, 2007 A micromachined electret generator, *Solid-State Sensors, Actuators and Microsystems Conference, Transducers 2007 International (Lyon, France,10-14 June 2007)*

[8] Basset P, Galayko D, Paracha A M, Marty F , Dudka A, Bourouina T, 2009 A batch-fabricated and electret-free silicon electrostatic vibration energy harvester, *J. Micromech. Microeng.* **19** 115025.

[9] He C, Kiziroglou M E, Yates D C, Yeatman E M 2010, *IEEE MEMS Conference 2010 (Hong-Kong, 24-28 January 2010)* 172-176

[10] He C, Arora A, Kiziroglou M E, Yates D C, O' Hare D, Yeatman E M, MEMS energy harvesting powered wireless biometric sensor 2009, *6th International Workshop on Wearable and Implantable Body Sensor Network 2009 (Berkeley, California, 3-5 June 2009)*

[11] http://www.meas-spec.com, Mini-Sense 100 vibration sensor, 2009