SELF-POWERED HUMIDITY SENSOR POWERED BY NICKEL-63 RADIOISOTOPE

Rajesh Duggirala, Amit Lal and Clifford Pollock

SonicMEMS Laboratory, School of Electrical and Computer Engineering, Cornell University, Ithaca, NY USA

Michael Kranz

Morgan Research Corporation, Huntsville, Alabama USA

ABSTRACT

We demonstrate a self-powered humidity sensor that can significantly extend the operating lifetime of battery powered wireless sensor suites. The self-powered sensor employs a radioisotope powered humidity sensitive polymer capacitor, which modulates the conductance of a MOSFET. The current modulation of the MOSFET is enough to wake-up a circuit in power-sleep mode. We demonstrate two capacitor biasing architectures. One is based on changes in the leakage resistance of the polymer capacitor, and the other on changes in the capacitance of the polymer capacitor. We present results on the testing and characterization of prototype assemblies of the microfabricated polymer capacitor chiplet, the MOSFET chiplet, and the radioisotope thin-film source. The polymer capacitor was measured to have a humidity sensitivity of 0.33pF/%RH and a capacitance decay time constant of ~50 seconds. The humidity sensitivity of the output current of the self-powered sensor was measured to be ~10uA/%RH @ 5V bias.

INTRODUCTION

Wireless sensor suites deployed in remote and inaccessible areas need long operating lifetimes as battery monitoring and replacement is often cost-prohibitive. Such applications include long-term health monitoring of tactical missiles, industrial equipment, buildings [1], etc. In addition to efforts on increasing the lifetime of the conventional electrochemical batteries currently in use, work is being done on alternative power solutions. These approaches include powering the sensor suite using energy scavenged from ambient vibrations [2], solar [3], tidal energy [4], etc. Additionally, alternative fuel-based power sources such as fuel cells [5] and radioisotope power generators [6] have also been proposed. All these solutions look promising, but are yet to be adopted widely.

An alternate approach to increasing the lifetime of battery powered sensor suites employs zero-power sensors, which can be passive or self-powered. Such self-powered sensors can wake-up the rest of the sensor node ("mote") when required, conserving the battery power for emergency computations and communications. Self-powered sensors based on passive fiber-optics [7] have been demonstrated previously. However, fiber-optic based approaches can require complicated signal processing for conversion of optical signals to electrical. In this paper, we address the need for a self-powered sensor with an electronic readout that can be processed easily by the mote electronics.

We demonstrate a radioisotope powered humidity sensor based on a water sensitive polymer capacitor which modulates the conductance of a MOSFET. The novel radioisotope-biased-MOSFET circuit gives out a self-powered amplified electronic readout, making signal conditioning easy for the electronics. Moreover, the demonstrated sensor topology can be readily adapted to sensing other physical phenomena including temperature, shock, chemical concentrations. Our sensor consumes zero-battery-power and can potentially extend the lifetime of condition monitoring sensor suites to multiple decades. These

zero-battery-power sensors allow event-based power management of unattended sensor systems and orders of magnitude reduction in average power consumption.

We use Nickel-63, a safe radioisotope, whose power output is nearly independent of the ambient conditions, and can have several decades of useful life as the half-life is 100.2 years. The 2-millicurie Nickel-63 thin-film emits low energy (average energy = 17keV) β -particles with penetration depths < 10 μ m in solids. As a result, it can be deployed safely without substantial shielding or concerns about security.

THEORY

Radioisotope Biasing

An electrically isolated β -particle emitting radioisotope thin-film always develops a voltage bias because of the continuous emission of electrons. The voltage bias level depends on the balance between the voltage dependant charge leakages from the film into ambient air and the electron current output from the source. Hence, weak sources with low current output (e.g. 1-millicurie outputs ~5.9pA) need to be placed in vacuum (~1-1000mtorr) to achieve voltage biases in the 1-20V range. Such biases have been used previously to drive electrostatic resonators [8]. We use it here for the first time to bias sensors and electronics.

We use the voltage bias on the radioisotope thin-film to bias the gate of a MOSFET, via a humidity sensitive polymer capacitor, which modulates the bias. We demonstrate two architectures, to be used depending on the leakage resistance R_{PC} of the capacitors. Since the current output from the source is just 10.2pA, anything connected across the radioisotope-collector should have impedance greater than or equal to 100G Ω . Capacitors with $R_{PC} \gg 1000G\Omega$ can be placed in a series stack as shown in Figure 1(b), with the capacitor ratio in the stack controlling the gate voltage V_{gs} of the MOSFET as follows:

$$V_{gs} = V_{Ni} \frac{C_{PC}}{(C_{PC} + C_{bias})}, \text{ for } R_{PC} \gg 1000G\Omega.$$

For capacitors with $R_{PC} \sim 1000G\Omega$, the capacitor divider architecture cannot be used as the leakage resistance of the polymer capacitor starts to dominate. The ratio of the leakage resistances of C_{PC} and C_{bias} starts controlling V_{gs} , and since the leakage resistance of the on-chip capacitor $R_{bias} \gg 1000G\Omega$, any variation in resistance due to humidity doesn't alter V_{gs} significantly. In such cases, the polymer capacitors can be connected directly across the gate and source of the MOSFET as shown in Figure 1(d). Since V_{gs} is then given by

$$V_{gs} = I_s R_{PC}, \text{ for } R_{Ni} \gg R_{PC}.$$

Any change in the humidity that alters the leakage resistance in the capacitor will change V_{gs} , and hence the conductance of the MOSFET. The MOSFET amplifies the change in the capacitor current, making the signal processing easy.

Humidity Sensitive Polymer Capacitor

In a humidity sensitive capacitor, a polymer or other porous dielectric layer absorbs water from the atmosphere. The large

polarizability of the absorbed water molecules alters the capacitance between the electrodes on either side of the material. That final capacitance can be calculated by modeling the moist polymer as a composite material, as follows

$$C = \frac{\epsilon_o A}{d} * (\epsilon_p + f_w * (\epsilon_w - \epsilon_p)).$$

Here, C is the capacitance of the structure, A is the electrode area, ϵ_p is the relative dielectric constant of the polymer dielectric, ϵ_w is the relative dielectric constant of water, and f_w is the volume fraction of water within the polymer. The capacitance of the structure depends primarily on the geometry, but the sensitivity and transient response of the structure depend on f_w , which can be controlled by varying the electrode mesh size on the top electrode.

In addition to the capacitance, the leakage resistance of the layer stack is also a critical parameter. Nominally, this leakage resistance is extremely high, meaning that the conductivity of the polymer dielectric is low, as would be expected. However, as water is absorbed, ionic groups within the material are disassociated, thereby increasing the conductivity between the electrodes. The resistance of the structure can also be modeled by treating the moist polymer as a composite material, as follows

$$R^{-1} = \left(\frac{L}{A} \rho_p\right)^{-1} + \left(\frac{L}{A} f_w \rho_w\right)^{-1}.$$

Here, R is the resistance of the capacitor, L is the thickness of the dielectric, A is the capacitor's electrode area, ρ_p is the conductivity of the polymer, ρ_w is the conductivity of the water and disassociated ionic species, and f_w is the volume fraction of water absorbed within the dielectric. The resistance depends primarily on the material processing and the existence of impurities within the material. Leakage resistances ranging from $10G\Omega$ to $>10T\Omega$ have been demonstrated. Furthermore, at these large levels of resistance, other charge leakage mechanisms, including the removal of charge directly from the electrode surface through interactions with the external gas, become significant percentages of total current through the circuit. These mechanisms must be mitigated through careful attention to packaging, interconnect lengths, and electrical isolation.

FABRICATION

The goal of this work was to demonstrate radioisotope biasing of the humidity sensitive polymer capacitor and the MOSFET. Discrete components were used for the radioisotope source, the humidity sensitive capacitor chip and the MOSFET chip, with the goal of a hybrid chip solution to integration in mind. A 1mCi Nickel-63 thin-film electro-less deposited on a 10mm x 10mm X 0.1mm Ni foil was used in all the experiments. The MOSFETs were fabricated in the AMI-AMS 1.5um technology available through MOSIS, and the humidity sensor was designed and microfabricated at Morgan Research Corporation. The components were finally assembled in a 6"x6"x6" vacuum chamber with electrical and gas feed-throughs.

The humidity sensor was microfabricated using a simple surface micromachined process. An initial layer of aluminum was first electron beam evaporated onto an SOI wafer, and then patterned to form a bottom electrode and wire bond pad. An SOI substrate was used because it allows the fabrication of other MEMS devices on the same chip. Subsequently, a layer of HD Microsystems PI2723 polyamide was spin cast on the Aluminum electrodes, and then patterned to realize a capacitor dielectric layer. Then, a second aluminum layer was evaporated onto the structure, and patterned into a mesh. Finally, the structure was encapsulated with nitride to protect it during subsequent process steps. A final nitride strip exposed the humidity sensor materials to the external environment.

TESTING

The discrete components were first characterized individually, and then assembled in a vacuum chamber to test the system for functionality.

Radioisotope Voltage Source

The radioisotope thin-film source was enclosed in a 2" X 2" X 1" aluminum box, which serves as a collector for the electrons emitted. The voltage bias build-up on the thin-film depends on the collector material, the source-collector geometry and placement, and the pressure in the vacuum chamber. The aluminum box collector was chosen for the proof-of-concept experiments and may be further optimized.

Figure 1. (a) Schematic the hybrid on-chip radioisotope powered humidity sensor concept. (b) Electrical equivalent circuit and (c) schematic illustrating the working principle of the sensor system with the capacitive divider architecture. (d) Electrical equivalent circuit and (e) schematic illustrating the working principle of the sensor system with the leakage resistance architecture.

Figure 2. (a) Schematic of radioisotope bias generation test circuit. On-chip C_{bias} was designed to be 5.9pF. (b) Plot of measured I_{ds} vs. pressure @ $V_{ds}=5V$, with switch SW1 open. The equivalent V_{gs} was calculated from the MOSFET characteristics of the N-MOSFET (AMI-AMS 1.5μm technology, $W/L=2.5$) (c) Measured shift in MOSFET (poly1-N-MOSFET with $W/L=2.5$) I_{ds} - V_{ds} characteristics with exponential build-up of radioisotope bias after opening the switch SW1.

Figure 3. (a) Photograph of the polymer capacitor (b) Photograph of the polymer capacitor package used for testing.

The radioisotope source-collector can be modeled electrically as shown in Figure 1(b). The flux of electrons is modeled by the current source I_s , the leakage resistance by R_{Ni} and the air gap capacitance by C_{Ni} . In order to characterize the radioisotope source-collector system, the aluminum box with the source inside was placed in a vacuum chamber (~1millitorr) and the short circuit current output of the source measured using a Keithley Parametric Analyzer. The measured current value of 10.2pA was found consistent with the 2milliCurie (=11.2pA current output) activity of the source. R_{Ni} was calculated to be ~7TΩ @ 1millitorr from the

slope of the I-V curve of the source-collector terminals. A capacitance meter measured C_{Ni} to be ~2pF.

The radioisotope source-collector were then connected across the gate-source of an N-MOSFET as shown in Figure 2 (a). The chamber was then pumped down and the I_{ds} at $V_{ds}=5V$ monitored (Figure 2(b)) during pump-down. This was used to characterize the bias generation with respect to pressure. The corresponding V_{gs} was calculated from the I_{ds} - V_{gs} curve measured for the MOSFET. As expected, lower pressure results in fewer particles getting ionized, or lower charge leakages, and hence higher voltage bias generated. Measurements show that moderate levels of vacuum (~100millitorr) are sufficient for the operation of the bias generation. At atmospheric pressure, a drain current of 26μA was measured for an applied drain voltage of 5V, indicating a build-up of 1.05V on the radioisotope source. To further confirm that it indeed is the radioisotope source generating the bias, the radioisotope source-collector capacitor was shorted using switch SW1, and then opened. The I_{ds} - V_{ds} for the MOSFET was measured at periodic intervals to illustrate exponential build-up of thin-film voltage due to the constant emission of electrons from Nickel-63.

Humidity Sensitive Polymer Capacitor

The devices were characterized at the die level and suitable devices epoxy attached in a ceramic pin grid array package. A copper lid with a 1/4" pipe fitting was then soldered onto the package. This was for the interface with the gas feed-through in the vacuum chamber which would expose the sensor capacitor to the external atmosphere. The package was placed inside a controlled environmental chamber for testing at various levels of humidity. One electrode of the sensor element was excited with a 1V_{p-p} sinusoidal voltage at 0.2 Hz. The other electrode of the sensor was connected to the input of a trans-impedance amplifier with a 1×10^9 gain. The current through the sensor element due to the slow sinusoid was then measured and the capacitance calculated at various levels of humidity (Figure 4). For 2mmX2mm devices with 20% of the top electrode exposed to the atmosphere, a sensitivity of 0.33pF/%RH was measured with a capacitance delay time constant of approximately 50s (Figure 5).

Self-powered Humidity Sensor

For the self-powered humidity sensor demonstration, the radioisotope source-collector, the humidity sensor package and the MOSFET chip were assembled in the vacuum chamber. The humidity sensor was exposed to atmosphere through a gas feed through. The opening of the gas feed through was exposed to a solution of sodium chloride to achieve 75%RH at thermal equilibrium. Leaving the gas feed-through exposed to ambient resulted in an estimated 30%RH. Two types of sensors were tested. One type was designed to have polymer capacitors with $R_{PC} \gg 1T\Omega$, and the other with $R_{PC} \sim 1T\Omega$.

Figure 4. Capacitance vs. RH for a 22pF@ 45RH polymer capacitor.

Figure 5. Plot illustrating the transient response of the polymer capacitor in an environmental chamber when subjected to a step increase in relative humidity from 0%RH to 60%RH

For the sensor using high R_{PC} polymer capacitor, the components were connected in the capacitive divider architecture (Figure 1(b)) and the chamber pumped down with the sensor feed-through exposed to ambient. The I_{ds} at $V_{ds}=5V$ was measured to be 1.65mA when the pressure settled at ~1millitorr. This was compared to the final I_{ds} of 2.95mA reached without the polymer capacitor, and it was estimated that the final V_{gs} dropped from 18.9V to 9.25V as expected due to voltage division in the capacitor stack. Based on the value of C_{bias} and the measured parasitic capacitances (~7pF in parallel with C_{bias}) in the system, C_{PC} was estimated to be ~12pF in ambient conditions. The MOSFET I_{ds} - V_{ds} was measured at two different values of humidity and an expected upward shift (Figure 6) observed at elevated humidity levels. As the humidity increases, the capacitance of the sensor increases, raising the voltage bias on the gate of the MOSFET, and that consequently modulates drain current. From measured I_{ds} , C_{PC} was estimated to be ~28pF. Both the calculated values were close to the measurements made on the polymer capacitor.

For the sensor using $R_{PC} \sim 1T\Omega$ polymer capacitor, the components were connected in the leakage resistance architecture (Figure 1(d)). Comparison of measured I_{ds} at ~1millitorr (sensor exposed to ambient) with that measured without the polymer capacitor revealed estimation for the leakage resistance R_{PC} of 1.05T Ω . The MOSFET I_{ds} - V_{ds} was measured at two different values of humidity and an expected downward shift (Figure 7) observed at elevated humidity levels. As the humidity increases, the leakage in the capacitor increases, pulling the voltage bias down and hence reducing the drain current.

CONCLUSIONS

Two different architectures for long half-life radioisotope biasing of sensor elements were presented. The resulting self-powered sensors output easily readable amplified electronic signals through a unique MOSFET biasing scheme. Such zero-battery-power-consuming sensors can greatly extend the operating lifetime of the battery powered sensors, by using the battery only in the case of an event. Future work will involve realization of a hybrid on-chip platform for the self-powered sensor and characterizing the sensitivity of the polymer capacitors. The sensitivity can be increased to completely switch the MOSFETs ON or OFF, which could be used to digitally wake up a mote.

Figure 6. Measured shift in the capacitive divider architecture sensor's I-V characteristics with relative humidity increase. A poly1-N-MOSFET in the AMI-AMS 1.5 μ m process with W/L=2.5 was used for the experiments.

Figure 7. Measured shift in the leakage resistance architecture sensor's I-V characteristics with relative humidity increase. A poly1-N-MOSFET in the AMI-AMS 1.5 μ m process with W/L=2.5 was used for the experiments.

ACKNOWLEDGEMENTS

This work was supported by DARPA-MTO under the RIMS program, and contracted under the U. S. AMRDEC.

REFERENCES

- [1] N. A. Tanner, "Structural health monitoring using modular wireless sensors", *Journal of Intelligent Material Systems and Structures*, v 14, n 1, Jan. 2003, p 43-56.
- [2] S. Roundy, "A study of low level vibrations as a power source for wireless sensor nodes", *Computer Communications*, v 26, n 11, 1 July 2003, p 1131-44.
- [3] B. A. Warneke, "An autonomous 16 mm³ solar-powered node for distributed wireless sensor networks", *Proceedings of IEEE Sensors 2002*, pt. 2, vol.2, p 1510-15.
- [4] G. W. Taylor, "The Energy Harvesting Eel: a small subsurface ocean/river power generator", *IEEE Journal of Oceanic Engineering*, v 26, n 4, Oct. 2001, p 539-47.
- [5] J. Pavio et al., "LTCC fuel cell system for portable wireless electronics", *Advancing Microelectronics*, v 29, n 5, Sept. 2002, p 8-11.
- [6] A. Lal, R. Duggirala, H. Li, "Pervasive power: a radioisotope-powered piezoelectric generator", *IEEE Pervasive Computing*, v 4, n 1, Jan.-March 2005, p 53-61.
- [7] F. J. Arregui et al., "Optical fiber-based sensor of harmful gas fabricated using the electronic self-assembly monolayer process", *Proceedings of the SPIE - The International Society for Optical Engineering*, v 4253, 2001, p 84-91.
- [8] S. Kan and A. Lal, "Self-powered IC-compatible DC bias for electrostatic resonators", *Technical digest of IEEE MEMS 2004*, Maastricht, 2004, pp 817-820.