MICRO-POWER WIRELESS TRANSMITTER FOR HIGH-TEMPERATURE MEMS SENSING AND COMMUNICATION APPLICATIONS

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ABSTRACT

A low-power silicon-tunnel-diode-based LC-tuned oscillator transmitter is proposed for high-temperature MEMS sensing and wireless data transmission applications. The prototype sensing and transmitting module employs a MEMS silicon capacitive pressure sensor performing pressure to frequency conversion and a miniature on-board coil loop serving as the inductor for the LC tank and also a transmitting antenna. The system achieves telemetry performance up to 290 ^{o}C over a distance of 2.5 meters with a total power consumption of 110 ?W.

INTRODUCTION

Low-power high-temperature wireless sensor communication network is critical for industrial, automotive, and aerospace sensing and data communications. Typical temperature for these applications ranges from 200 ^{o}C to 600 ^{o}C. Higher temperatures up to and beyond 1000 ^{o}C are required for extreme harsh environments such as turbine engines, nuclear power generators, etc. Conventional microelectronics based upon BJT and CMOS technologies suffer from severe performance degradation and failure due to excessive junction leakage currents for temperatures above 150 ^{o}C [1]. SOI [2] and SiC [3] devices technologies are promising for increased operating temperatures of 300 ^{o}C and 600 ^{o}C, respectively.

A number of wireless sensing and communication modules have been developed for room-temperature applications such as biomedical implants [4, 5, 6, 7, 8, 9, 10, 11]. In these applications, MEMS sensors such as pressure sensors, strain gauge transducers, etc. are interfaced with active electronics that convert the sensing information to frequency [6, 11] or to voltage which is further digitized [7, 8, 9, 10] before wireless transmissions. These sensor interface architectures are attractive and can be applied for high-temperature applications with appropriate sensors and electronics technologies. However, wireless transmitters employing active RF oscillators capable of achieving an adequate telemetry distance required for high-temperature applications consume a significant amount of power compared to overall system power dissipation [10]. This presents a critical bottleneck for high-temperature operations where power source is highly limited. In this paper, we present a 110 ?W wireless sensor communication module achieving a telemetry distance of 2.5 meters with operating temperatures up to 290 ^{o}C, suitable for various harsh environment applications.

MEMS SENSOR AND HIGH TEMPERATURE TRANSMITTER

Figure 1 presents the prototype architecture, which consists of a silicon-tunnel-diode-based LC-tuned oscillator transmitter employing a MEMS capacitive pressure sensor with an on-board loop inductor also functioning as a transmission antenna. The negative resistance characteristic exhibited by the diode under a proper bias condition compensates the tank loss, thus developing an oscillation. A DC supply voltage around 110 mV is typically needed to properly bias the device thus significantly minimizing power dissipation, a key advantage over other conventional electronic oscillator implementations. The simplicity of the tunnel diode structure substantially reduces the leakage currents exhibited in conventional electronics at elevated temperatures, thus capable of high-temperature operations. The oscillator output frequency is determined by the LC tank resonance. The MEMS capacitive pressure sensor converts the pressure information to a capacitance change resulting in the oscillator output frequency variation, which can be detected by an external receiver. This pressure to frequency modulation scheme is attractive for achieving a reliable data transmission compared to other amplitude modulation techniques.

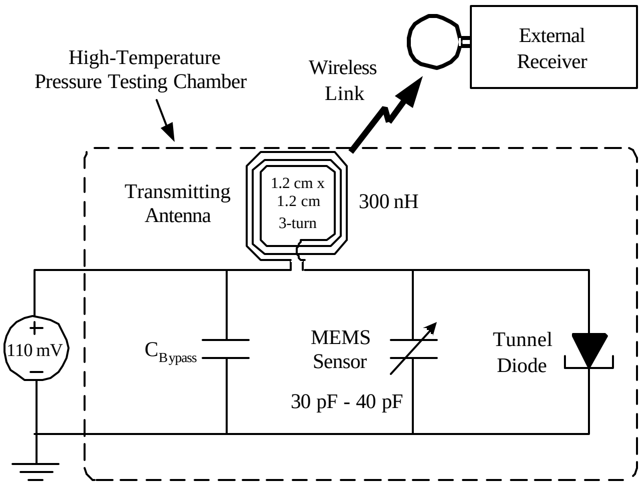

Figure 1. Wireless Transmitter Architecture

Figure 2 shows the I-V characteristics measured at various temperatures from a commercial silicon tunnel diode employed in the current prototype design. The device provides negative resistance characteristics up to 290 °C, significantly higher than operating temperatures of conventional electronics.

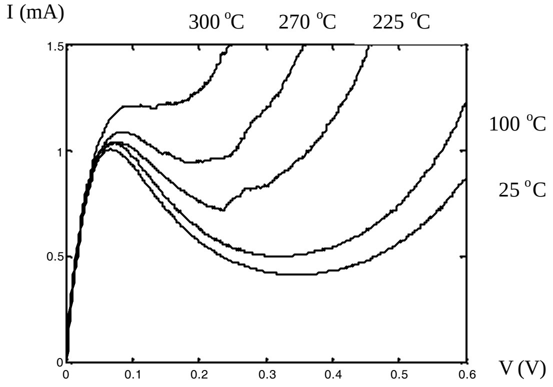

Figure 2. I-V Curves vs. Temperatures

A DC bias condition of 110 mV and 1 mA is chosen for ensuring a reliable oscillation over the wide temperature range. A reduced power consumption is expected through using small-current devices. Diodes made of semiconductor materials with higher energy band gap such as GaAs will be explored to achieve further increased operating temperatures, planned as the next step.

Figure 3 shows a photo of the prototype wireless MEMS sensor and transmitter prototype system.

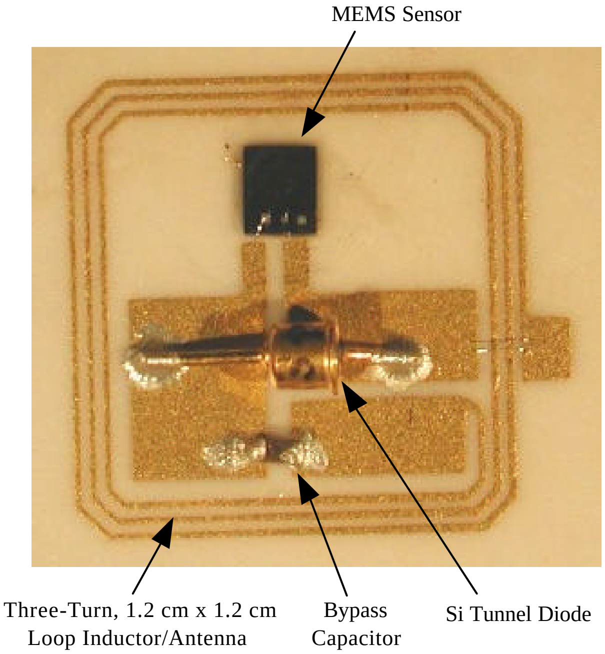

Figure 3. Photo of Prototype System

It consists of a MEMS pressure sensor interfaced with a discrete silicon tunnel diode and an on-board square loop inductor with gold wire bonding. A ceramic substrate with gold interconnect traces is chosen for high–temperature operations. A MEMS touch-mode silicon capacitive pressure sensor [12] is employed as a demonstration vehicle for the current prototype. Figure 4 presents a simplified cross-section view of the device with detailed fabrication process outlined in [12].

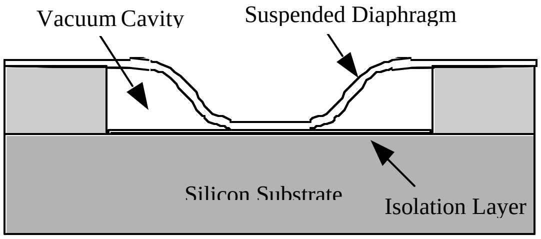

Figure 4. Sensor Cross-Section View

The sensor consists of an edge-clamped silicon diaphragm over a vacuum cavity. The diaphragm deflects under an increasing external pressure and touches the substrate causing a linear increase in sensor capacitance value beyond the touch point pressure. Figure 5 shows a typical device characteristic response between the capacitance value and applied pressure.

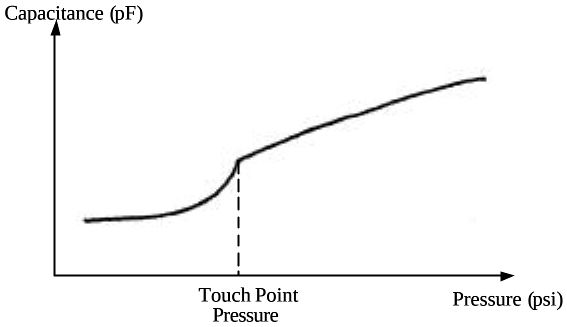

Figure 5. MEMS Pressure Sensor Characteristic

A MEMS pressure sensor consisting of a circular diaphragm with a diameter of 0.8 mm, shown in Figure 6, exhibits a touch point pressure of 8 psi and capacitance values ranging from 30 pF at 2 psi to 40 pF at 32 psi (absolute pressures). This device is interfaced with a 3-turn 1.2 cm x 1.2 cm on-board square loop providing inductance value around 300 nH to form the LC tank circuit as illustrated in Figures 1 and 3. The loop is also used as a transmitting antenna for data telemetry. The inductance value is constrained by the operating frequency around 26 MHz in this prototype design, limited by the resistive loss associated with the pressure sensor. Increased operating frequencies in ISM bands can be achieved with redesigned high-Q capacitive sensors thus reducing the loop dimension, attractive for system miniaturization. High-Q capacitive sensors and loop inductors are also critical for minimizing bias current required for tunnel diodes, crucial for low power applications.

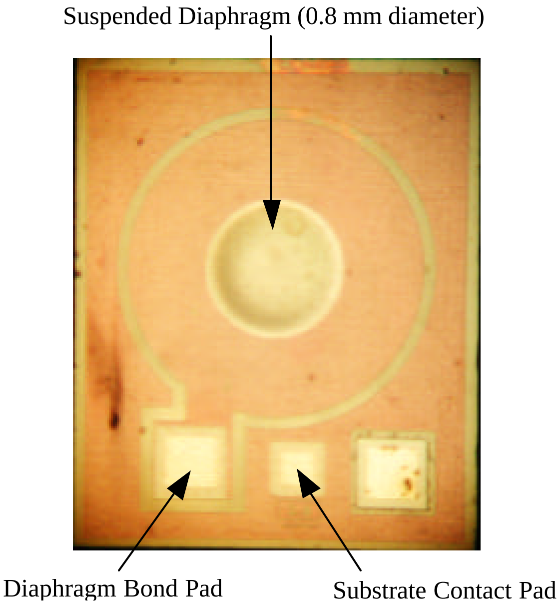

Figure 6. MEMS Pressure Sensor

EXPERIMENT RESULTS

Figure 7 shows the experiment setup for the prototype high-temperature wireless sensor communication module.

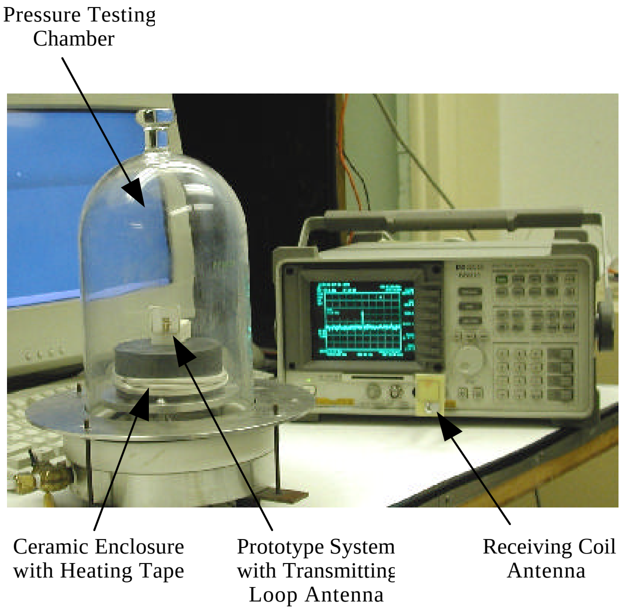

Figure 7. Experiment Setup

The sensor telemetry system is positioned inside a pressure testing chamber with temperature elevated and controlled through resistive heating tape around a ceramic high-temperature enclosure. The prototype is shown above the ceramic enclosure for illustration purpose. A spectrum analyzer is used as an external receiver with a tuned receiving loop antenna connected to the input port through a buffer. The oscillator operates at 26.6 MHz under 1 atm at 270 °C and can be varied over 400 kHz through pressure increase from 2 psi to 32 psi (absolute pressures) limited by the tunnel diode parasitic capacitance, as shown in Figure 8. The oscillator exhibits an output frequency shift of approximately 200 KHz over the temperature range from 25 °C to 270 °C due to components temperature dependent characteristics variation.

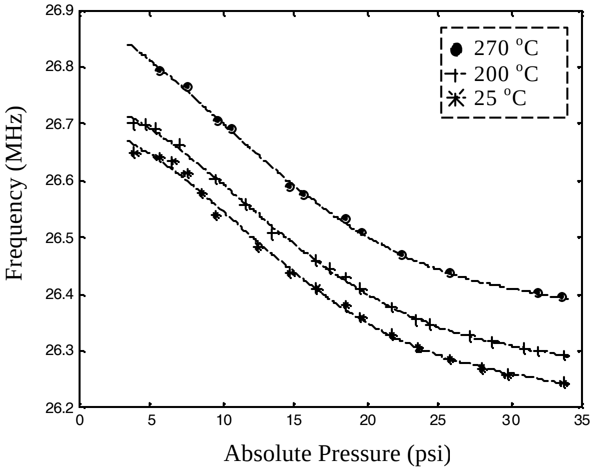

Figure 8. Oscillator Frequency Versus Pressure

Figure 9 presents the received power versus telemetry distance under 1 atm measured at 25 °C, 200 °C, and 270 °C, respectively, indicating that the spectrum analyzer can receive an incoming signal with an SNR of at least 10 dB over telemetry distances of 2.5 meters, 3 meters, 3.3 meters at the corresponding temperatures. The reduced oscillator output signal swing at high temperature results in a shortened telemetry distance.

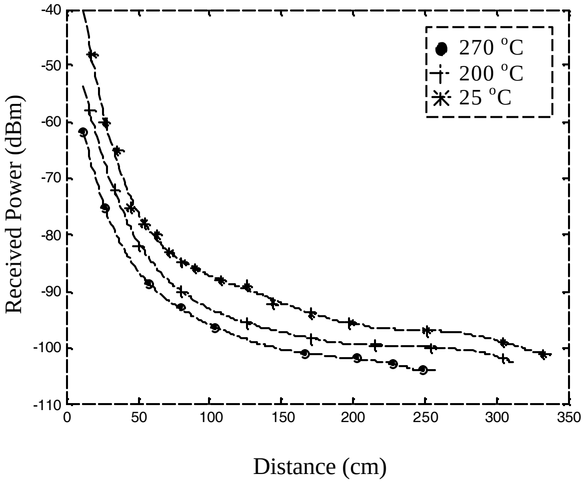

Figure 9. Received Power Versus Distance

Figure 10 shows a corresponding received power spectrum at 2.5-meter telemetry distance from the prototype oscillator operating at 270 °C. An extended communication range is expected through using a more sensitive receiver.

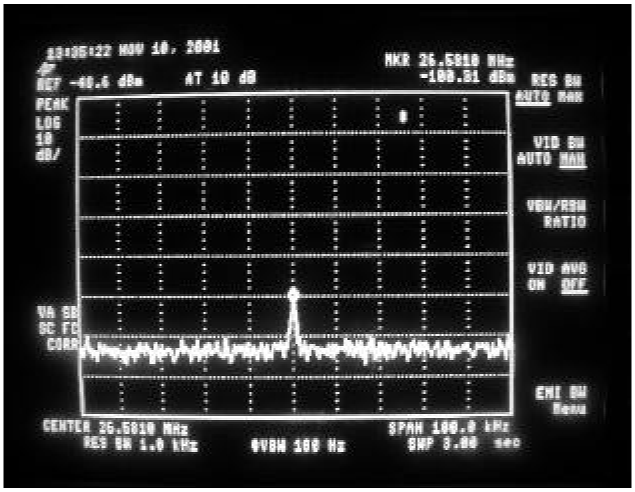

Figure 10. Received Power Spectrum

The oscillator output frequency under 1 atm drops from 26.6 MHz to 14 MHz after a short period of testing at 270 °C due to failure of the on-board bypass capacitor. High-temperature-grade capacitors such as glass or ceramic dielectric capacitors will be used in the future to obtain an improved stability. A high-temperature frequency drift of approximately 100 KHz over a few hours has been observed in the current prototype, thus limiting the system resolution. An improved system design employing sensor interface and analog to digital conversion circuits combined with a tunnel-diode-based frequency-shift-keying (FSK) oscillator transmitter will be considered to achieve a low-power high-resolution performance at high temperature. The FSK oscillator implementation will also become less susceptible to frequency shift due to large temperature variations. The overall power dissipation can be further minimized through using a low duty cycle clock to activate the transmission system for small bandwidth signals.

CONCLUSION

Silicon-tunnel-diode-based oscillator transmitter is attractive for low power high-temperature MEMS sensing and telemetry applications. The prototype wireless sensing and communication module achieves high-temperature operations up to 290 °C over a telemetry distance of 2.5 meters with a total power consumption of 110 ?W. The low supply voltage and power dissipation make it feasible to potentially operate the system through using thermoelectric generator, converting temperature gradients available from a high-temperature environment to DC power, or RF inductively powering techniques, thus enabling the realization of a stand-alone high-temperature wireless sensor communication module. The proposed architecture can also serve as a low-power telemetry platform for general sensing and wireless communication applications.

ACKNOWLEDGEMENTS

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