OPTICALLY-POWERED WIRELESS TRANSMITTER FOR HIGH-TEMPERATURE MEMS SENSING AND COMMUNICATIONS

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ABSTRACT

A high-temperature, low-power silicon-tunnel-diode-based oscillator transmitter with an on-board optical power converter is proposed for harsh environment 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 coil loop serving as the inductor of the LC tank resonator and also as a transmitting antenna. A GaAs photodiode converts an incoming laser beam to electrical energy to power the prototype. The system achieves a telemetry performance up to 250 ^{o}C over a distance of 1.5 meters with a transmitter power consumption of 60 μW.

INTRODUCTION

High-temperature, low-power wireless sensor communication network with on-board power supply is critical for industrial, automotive, and aerospace sensing and data telemetry applications. Typical temperature for these applications ranges from 200 ^{o}C to 600 ^{o}C. Conventional microelectronics BJT and CMOS technologies suffer from severe performance degradation and failure due to excessive leakage currents for temperatures above 150 ^{o}C [1]. Silicon on insulator (SOI) [2] and silicon carbide (SIC) [3] device technologies are promising for increased operating temperatures of 250 ^{o}C and 600 ^{o}C respectively. However, SOI-based electronic telemetry system requiring a few volts of supply voltage is undesirable, discussed in the next section. SiC device technology is still in the research and development stage. Conventional solid state battery technologies currently operate up to 150 ^{o}C [4], and high-temperature battery power source is yet under development [5]. Currently most of the conventional high temperature sensing systems rely on using external wires for power supply and data acquisition [6-8]. The feed-through wires severely degrade the system performance and flexibility, thus imposing a significant limitation on system resolution. It is highly desirable to develop a stand alone high-temperature sensing and data telemetry system which, therefore, can be powered by an on-board energy supply, thus eliminating the need for feed-through wires.

A number of wireless sensing and communication architectures have been developed for room-temperature applications such as biomedical implants [9-15]. 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 [10, 11] or to a voltage which is further digitized [8, 12-15] for wireless transmission. The proposed sensor interface architectures are attractive and can be potentially applied for high-temperature applications with appropriate sensor and electronics technologies. However, passive RF powering and telemetry schemes [10, 14, 15] are commonly implemented with inductive coupling coils, which result in a limited coupling distance. Active RF transmitters [8, 9, 13] can achieve telemetry distances adequate for high temperature applications, but consume significant power dissipation compared to the overall system power dissipation, a critical bottleneck for high temperature operations where power source is highly limited. In this paper, we present a stand alone low-power wireless sensor communication module with an on-board optical-based power generator, achieving a telemetry distance of 1.5 meters under operating temperatures up to 250 ^{o}C.

HIGH TEMPERATURE SENSING AND TELEMETRY SYSTEM

Figure 1 presents the high temperature prototype architecture. The system 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, and a GaAs photodiode which converts an incoming laser to a DC power at high temperatures.

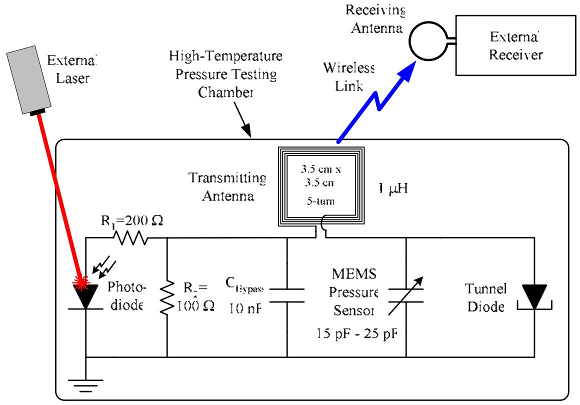

Figure 1. Wireless Transmitter Architecture

The negative resistance characteristic exhibited by the diode under a proper bias condition can compensate the tank loss, thus developing an oscillation. The DC bias voltage typically required to properly bias the device ranges from about 100 mV to 200 mV. This low DC bias voltage can be readily obtained from a GaAs photodiode, thus substantially simplifying the system implementation. The low DC bias voltage also significantly minimizes the power dissipation, which is a key advantage over other conventional electronic oscillator implementations requiring a supply voltage of a few volts. The simplicity of the tunnel diode structure results in a reduced leakage current compared to conventional electronic active devices at elevated temperatures, thus enabling a reliable system operation at high temperatures. The oscillator output frequency is determined by the LC tank resonance. The MEMS capacitive pressure sensor converts the environment pressure information to a capacitance change resulting in the oscillator output frequency variation. This pressure to frequency modulation scheme is attractive for achieving a reliable data transmission compared to other amplitude modulation techniques. The GaAs photodiode converts the power of an incoming laser beam into a DC power supply to power the system, thus eliminating any feed-through wire. This is a critical advantage for realizing stand alone high-temperature wireless sensing module. The GaAs photodiode is chosen for implementing the prototype system for its reliable performance at high temperature. The optical powering method is capable of achieving a much larger coupling distance than conventional RF to DC power conversion schemes and is also attractive as an on-off control means to activate the system.

Figure 2 shows the I-V characteristics measured at various temperatures for a silicon tunnel diode, used for the prototype implementation.

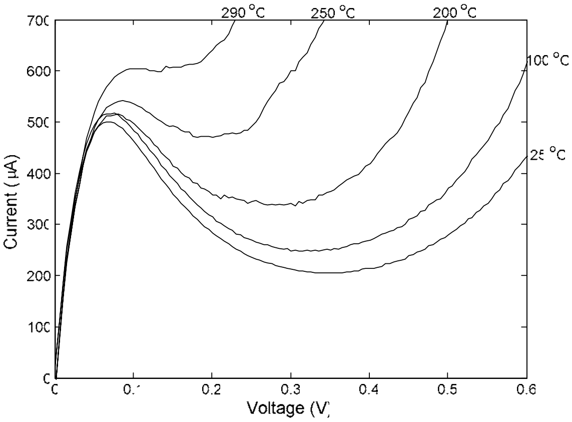

Figure 2. Tunnel Diode I-V Characteristics

The tunnel diode exhibits negative resistance characteristics up to 250 °C. Voltage and current bias levels of approximately 120 mV and 500 μA correspond to a power consumption of 60 μW. Figure 3 shows the I-V characteristics of a 3 mm x 4 mm GaAs photodiode measured over a temperature range from 25 °C to 290 °C with an 8 mW laser beam illuminating the surface, chosen to provide adequate output power for the prototype system. The photodiode area of 3 mm x 4 mm is chosen corresponding to the laser beam spot size. The resistors R_1 and R_2 in Figure 1 form the bias network, critical for ensuring a reliable tunnel-diode oscillator operation. The resistor values are chosen to provide the proper bias voltage and DC resistance for the tunnel diode and to ensure minimum output voltage temperature variation over the temperature range.

A MEMS touch-mode silicon capacitive pressure sensor is employed as a demonstration vehicle for the prototype design. Figure 4 presents a simplified cross-sectioned view of the device with detailed fabrication steps found in [16]. The sensor consists of an edge-clamped silicon diaphragm suspended over a vacuum cavity. The diaphragm deflects under an increasing external pressure and touches the substrate, thus causing a linear increase in sensor capacitance value beyond the touch point pressure.

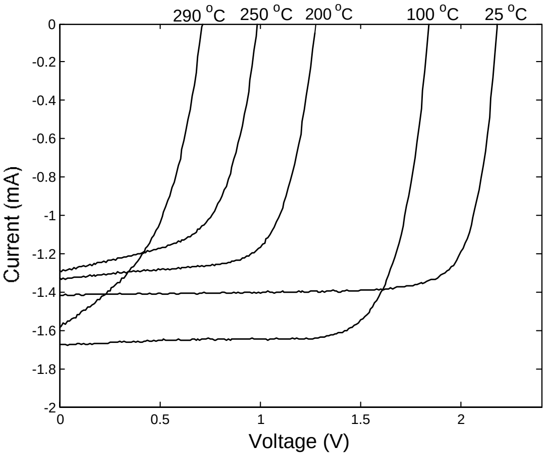

Figure 3. Photodiode I-V Characteristics

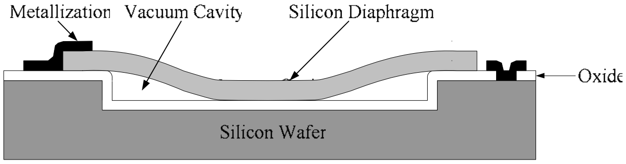

Figure 4. Sensor Cross-Section View

Figure 5 shows a typical device characteristic response between the capacitance value and applied pressure, exhibiting a linear characteristic beyond the touch point pressure.

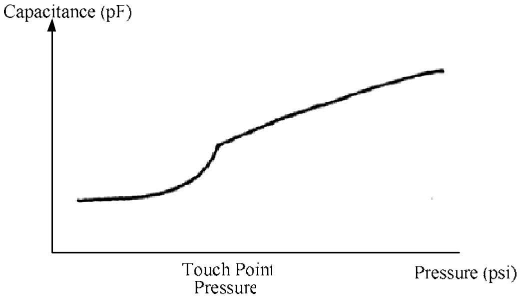

Figure 5. MEMS Pressure Sensor Characteristic

Figure 6 shows a photo of a fabricated pressure sensor. The device exhibits a touch point pressure of 10 psi and capacitance values ranging from 15 pF at 2 psi to 25 pF at 32 psi (absolute pressures). The device has an estimated series resistance of 25 Ω, which limits the oscillator operating frequency.

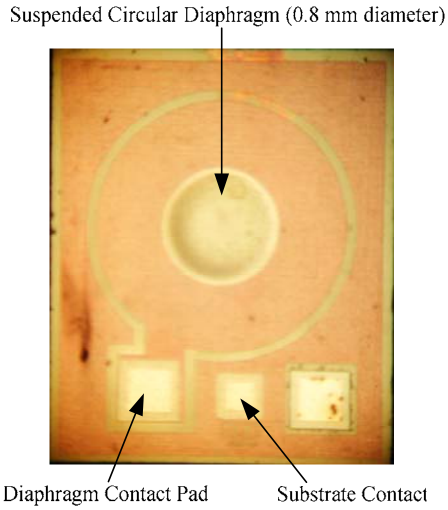

Figure 6. MEMS Pressure Sensor Photo

A 23 MHz oscillation frequency is chosen to ensure the LC tank resistance can be compensated by the tunnel diode over the temperature range. A 5-turn, 1 μH spiral inductor with a peripheral dimension of 3.5 cm x 3.5 cm is employed in the prototype system to achieve the desired frequency. Increased operating frequencies can be obtained with redesigned low resistive loss capacitive sensors thus reducing the spiral inductor dimension, attractive for further system miniaturization. Low loss capacitive sensors and spiral inductors are also critical for minimizing bias current required for tunnel diodes, crucial for low power applications. Figure 7 shows a photo of the prototype wireless MEMS sensing and data telemetry system. High temperature grade components and ceramic substrate with gold traces are used to ensure reliable high temperature operations.

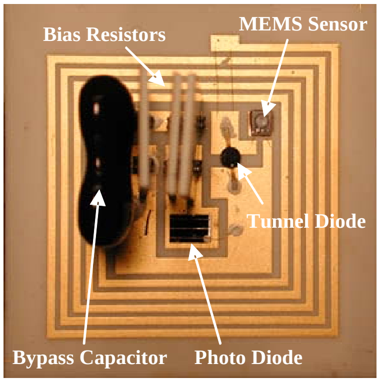

Figure 7. Prototype Board Photo

EXPERIMENT RESULTS

Figure 8 shows the experiment setup for the prototype high-temperature wireless sensor communication module.

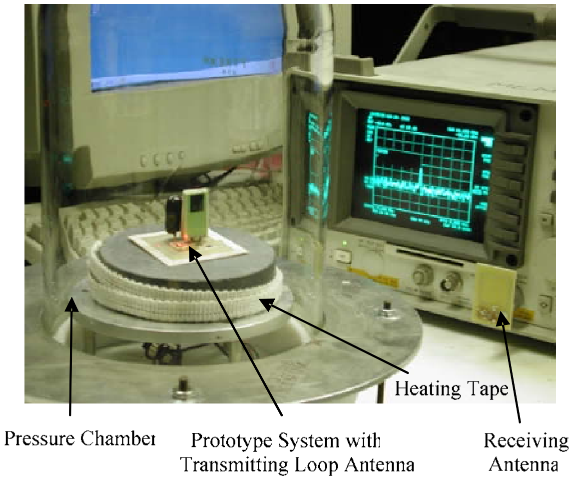

Figure 8. Experiment Setup

The sensor telemetry system is positioned inside a pressure testing chamber with temperature elevated and controlled through resistive heating tape. An external laser source, not shown in the figure, is used to power the system. 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 around 23 MHz under 1 atm at 250 °C and can be varied over 1.5 MHz through pressure increase from 2 psi to 32 psi (absolute pressures) limited by the tunnel diode parasitic capacitance, as shown in Figure 9.

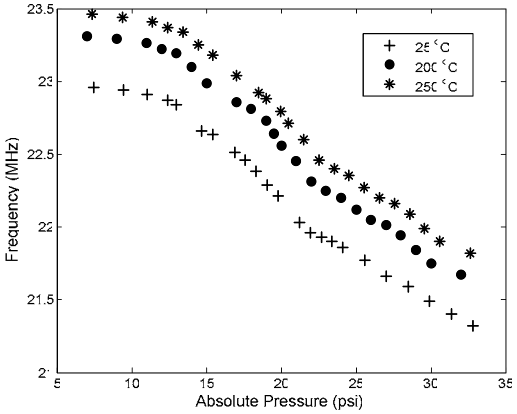

Figure 9. Oscillator Frequency vs. Pressure

The oscillator exhibits an output frequency shift of approximately 500 kHz over the temperature range due to components temperature dependent characteristics variation and tunnel diode bias point shift. Figure 10 presents the received power versus telemetry distance under 1 atm measured at 25 °C, 200 °C, and 250 °C, respectively, indicating that the spectrum analyzer can receive an incoming signal with an SNR of at least 10 dB over telemetry distances of 1.5 m. Figure 11 shows the corresponding received power spectrum at 1.5-meter telemetry distance from the prototype oscillator operating at 250 °C. An extended communication range is expected through using a more sensitive receiver.

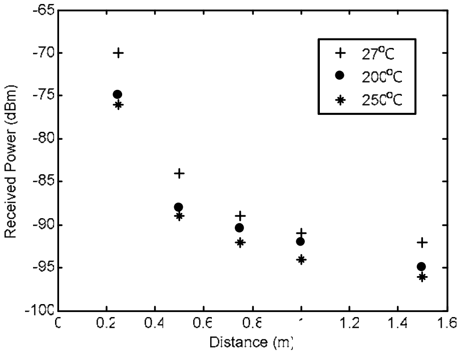

Figure 10. Received Power vs. Distance

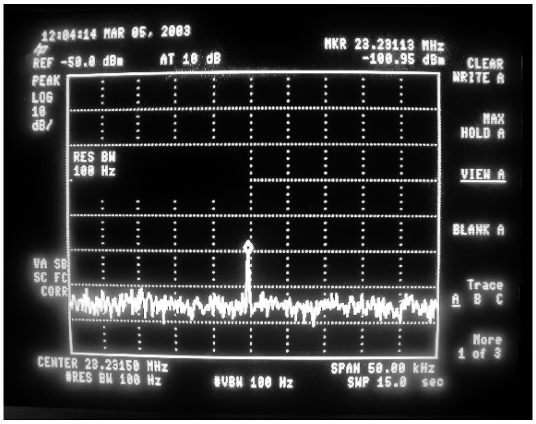

Figure 11. Received Power Spectrum

A high-temperature frequency variation over time has been observed in the current prototype. The prototype exhibits an initial frequency decline of approximately 150 kHz over 30 minutes, then a random frequency variation of 20 kHz, thus limiting the system resolution.

CONCLUSION

Silicon-tunnel-diode-based oscillator transmitter with an on-board optical power converter is attractive for stand alone, low power high-temperature MEMS sensing and data telemetry applications. The prototype wireless sensing and communication module achieves high-temperature operations up to 250 °C over a telemetry distance of 1.5 meters with a transmitter power consumption of 60 μW. The proposed architecture can also serve as a low power telemetry platform for general wireless sensing and communication applications.

REFERENCES

[1] Jay Goetz, “Sensors That Can Take the Heat,” *Sensors*, June, 200, pp. 20-38.

[2] A. J. Auberton-Herve, “SOI: Materials to Systems,” *Int. Electron Devices Meeting*, 1996, pp.3-10.

[3] D. M. Brown, *et al.*, “High temperature silicon carbide planar IC technology and first monolithic SiC operation amplifier IC,” in *Trans. 2nd Int. High-Temp. Elec. Conf.*, 1994, pp. XI-17 to XI-22.

[4] J. B. Bates, *et al.*, “Rechargeable Solid State Lithium Microbatteries,” in Proc. *IEEE MEMS Workshop*, pp, 82-86, 1993.

[5] David Linden, Handbook of Batteries, 2nd Edition, McGraw-Hill, Inc, 1994.

[6] M. Suster, *et al*., “Micro-Power Wireless Transmitter for High-Temperature MEMS Sensing and Communication Applications,” *The 15th IEEE Int.l Conference on MEMS*, pp. 641-644, January, 2002.

[7] Zorman

[8] R. S. Okojie, *et. al.*, “α(6H)-SIC Pressure Sensors for High Temperature Applications,” *Proceedings of MEMS ’96*, pp. 146-149, Feb., 1996.

[9] S. Chatzandroulis, *et.al.*, “A miniature Pressure System with a Capacitive Sensor and a Passive Telemetry Link for Use in Implantable Applications,” IEEE *J. MEMS*, V. 9, No. 1, pp. 18-23, Mar., 2000.

[10] C. Hierold, *et al*, “Implantable Low Power Integrated Pressure Sensor System For Minimal Invasive Telemetric Patient Monitoring,” *Proceeding of MEMS 98*, pp. 568-573, January, 1998.

[11] K. Stangel, *et. al*, “A Programmable Intraocular CMOS Pressure Sensor System Implant,” *IEEE Journal of Solid-State Circuits*, Vol. 36, No. 7, pp. 1094-1100, July, 2001.

[12] W-H Ko and M-R Neuman, “Implant Biotelemetry and Microelecctronics,” *Science*, Vol.15, No. 3773, pp. 351-360, April, 1967.

[13] D. Dudenbostel, *et. al.*, “A New Passive CMOS Telemetry Chip To Receive Power and Transmit Data For A Wide Range of Sensor Applications,” *1997 International Conference on Solid-State Sensor and Actuators*, pp. 995-998, June, 1997.

[14] Q Huang, M. Oberle, “A 0.5-mW Passive Telemetry IC for Biomedical Applications,” *IEEE J. Solid-State Circuits.*, Vol.33, No. 7, p.937-946, Jul. 1998.

[15] M. A. Fonseca, *et. al.*, “Wireless Micromachined Ceramic Pressure Sensor for High-Temperature Applications,” IEEE Journal of Micromechanical Systems, Vol. 11, No. 4, August 2002.

[16] W. H. Ko and Q. Wang, “Touch Mode Capacitive Pressure Sensors,” *Sensors and Actuators* 75 (1999), pp. 242-251.