High Temperature MEMS Based Transmitter for Wireless Sensor and Communication Network

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ABSTRACT
The paper presents a thought experiment as to the feasibility of using large scale wireless sensor networks as a vehicle for high level scientific investigation. A sensor payload is proposed, which includes means of seismic, chemical, temperature and visual exploration. The power and communications systems are also discussed, based on the needs of a mission profile which provides no special 'base station' nodes on the planet's surface, requiring each sensor package to be capable of information extraction, in-network collaboration and communication with an orbiting satellite. And different sensor technologies are also discussed. 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 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 oC over a distance of 1.5 meters with a transmitter power consumption of 60 μW.

Keywords
Distributed computation,information extraction, intelligent sensing, MEMS sensors, wireless sensor networks.

1. INTRODUCTION
The research agenda in Wireless Intelligent Sensor Networks (WSN) has often been promoted in the specialist literature through scenarios and case studies. 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 200oC to 600oC. Conventional microelectronics BJT and CMOS technologies suffer from severe performance degradation and failure due to excessive leakage currents for temperatures above 150oC. Silicon on insulator (SOI) and silicon carbide (SIC) device technologies are promising for increased operating temperatures of 250oC and 600oC respectively. 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.

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 or to a voltage which is further digitized for wireless transmission. Active RF transmitters 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.

2. SENSOR TECHNOLOGY
The initial design decisions of sensor technology to use a single type of node, it is required that every node carry a complete sensor package. For a probe with the envisaged dimensions, the overall sensor package will need to be designed in an integrated way, allowing for reuse of as many subsystems as possible. As each sensor type is discussed below:

2.1 Acceleration Sensor:
Accelerometers are an important part of the instrument package on the Daisy, reflecting their ubiquity in the overall field of sensing. High performance capacitive pick-off accelerometers can be integrated 'side-by-side' with adequate ancillary electronics using a CMOS process.

2.2 Atmospheric Sensor
The chemical sensing technology for atmosphere and soil composition detection require a further design choice. Electronic 'noses' are an established MEMS technology, but generally need to be tailored for the detection of a specific chemical or class of chemicals.

2.3 Pressure Sensing
Pressure sensors have been one of the earliest MEMS applications, and well established designs are available using either capacitive or piezo-electronic pick off techniques.

2.4 Soil Chemical Sensor
The difficulty in chemical sensing soil in an environment without water is conveying the constituent chemicals to the analyzer. A simple solution would be to use the transmission laser to vaporize the sample. The 7mW of power available should be sufficient.

2.5 Magnetometer
Magnetometers typically require a magnetically active element which moves according to the prevalent magnetic field, the movement being sensed using any of the established MEMS pick-off techniques. The magnetically active element can be provided using either a permanent magnet using electromagnetism, which consumes current.

2.6 Thermal Sensing

Temperature sensors can use thermocouples or semiconductor junctions, the latter having the advantage of being readily available as components within standard semiconductor technologies. Thermal sensing has also been used for wind speed and direction sensing.

2.7 Image Sensor

This subsystem is straight forward, being a silicon CCD or CMOS image sensor, as used in modern digital cameras. The resources that need to be integrated are an estimated 500 pixel array for the pick-off and image sensors for imaging the surroundings. This requires an 8500 pixel array, on a 5mm square chip, easily within current technological capabilities.

3. HIGH TEMPERATUR SENSING AND TELEMETRYSYSTEM

Fig1 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. 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. 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. The optical powering method is capable of achieving a much larger coupling distance than conventional RF to DC power conversion schemes. Fig2 shows the I-V characteristics measured at various temperatures for a silicon tunnel diode, used for the prototype implementation.

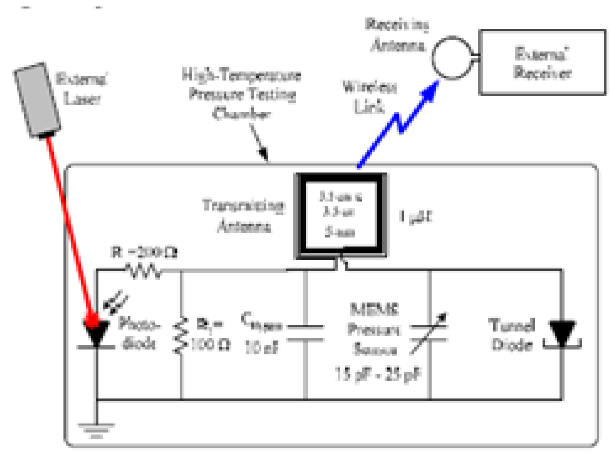

Fig1. Wireless Transmitter Architecture

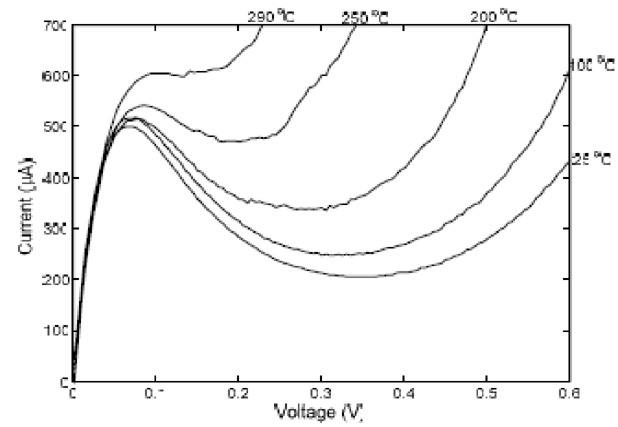

Fig: 2 Tunnel Diode I-V Characteristics

The tunnel diode exhibits negative resistance characteristics up to 250°C. Voltage and current bias levels of approx. 120 mV and 500 µA correspond to a power consumption of 60 µW.

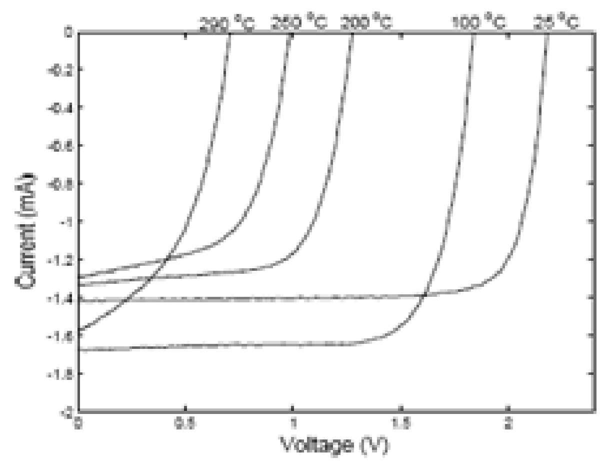

Fig: 3 Photodiode I-V Characteristics

Fig4 shows the I-V characteristics of a 3 mm x 4 mm GaAs photodiode measured over a temperature range from 25°C to

290^{o}C with an 8 mW laser beam illuminating the surface. It also shows a typical device characteristic response between the capacitance value and applied pressure, exhibiting a linear characteristic beyond the touch point pressure.

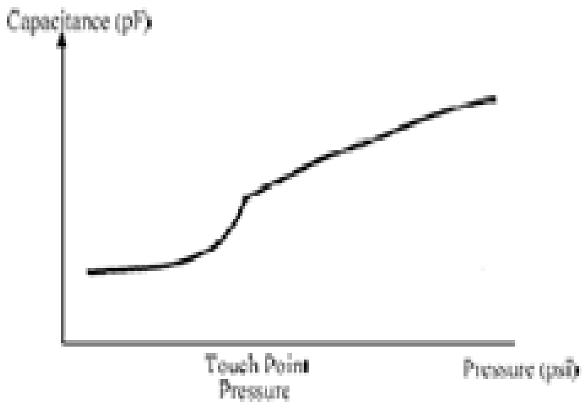

Fig: 4 MEMS Pressure Sensor Characteristic

Fig5 shows a photo of a fabricated pressu re 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.

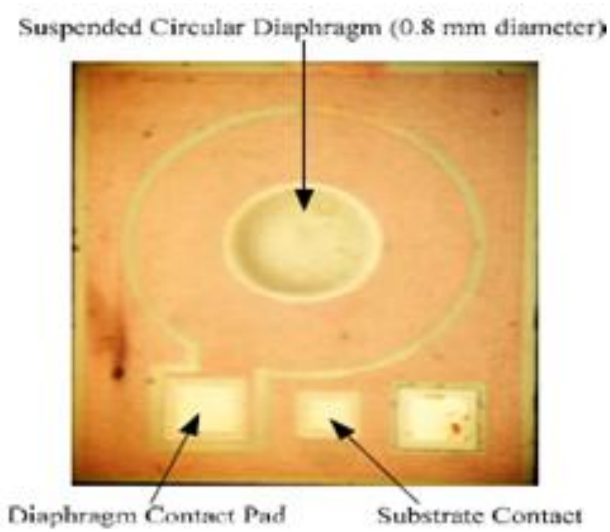

Fig: 5 MEMS Pressure Sensor Photo

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. Low loss capacitive sensors and spiral inductors are also critical for minimizing bias current required for tunnel diodes, crucial for low power applications. Fig7 shows a photo of the prototype wireless MEMS sensing and data telemetry system.

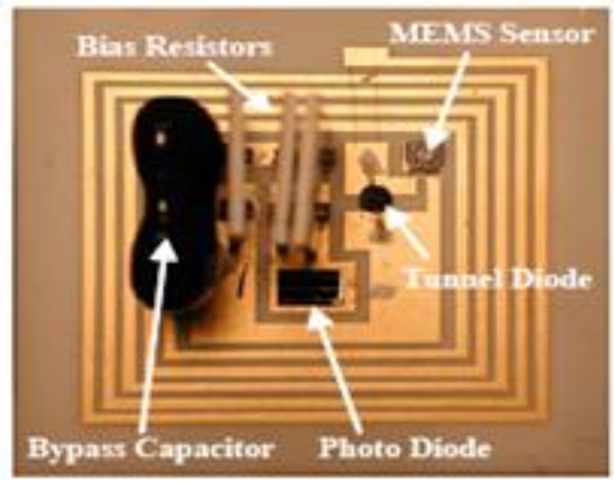

Fig: 6 Prototype Board Photo

4. EXPERIMENT RESULTS

The sensor telemetry system is positioned inside a pressure testing chamber with temperature elevated and controlled through resistive heating tape. 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 oC and can be varied over 1.5 MHz through pressure increase from 2 psi to 32 psi limited by the tunnel diode parasitic capacitance, as shown in Fig 7.

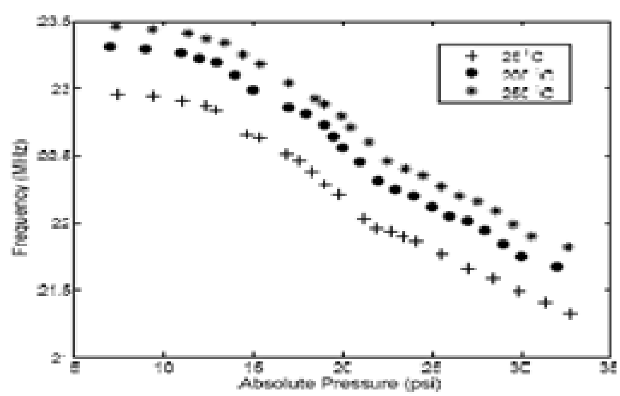

Fig: 7 Oscillator Frequency vs. Pressure

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. Fig8 presents the received power versus telemetry distance under 1atm measured at 25^{o}C,200^{o}C, &250^{o}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. Fig9 shows the corresponding received power spectrum at 1.5-meter telemetry distance from the prototype oscillator operating at 250^{o}C. An extended communication range is expected through using a more sensitive receiver. 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.

5. 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 60μW. Together with MEMS actuation technologies, the sensing technologies allow for new adaptive systems, providing more efficient aerodynamics and hydrodynamics. MEMS sensors have already proven to be a potent technology in terms of size and cost reduction of everyday sensors. When integrated with processing capability they can handle a range of further applications, in particular being more readily deployed and adapted to a specific application problem.

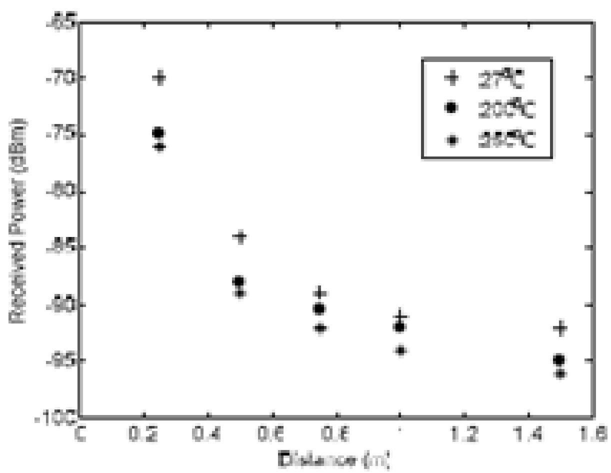

Fig: 8 Received Power vs. Distance

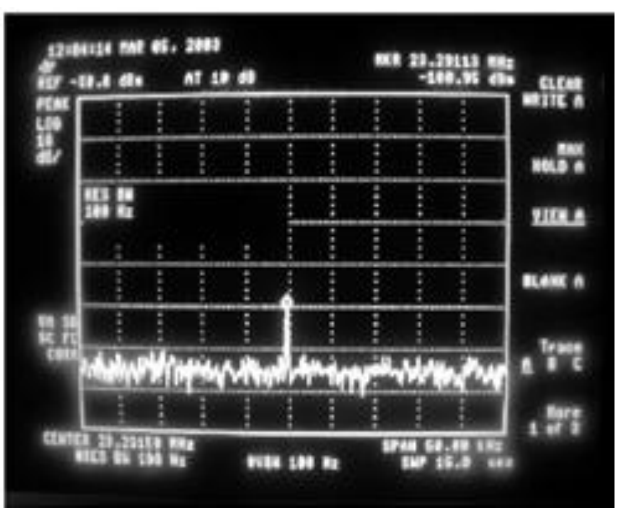

Fig: 9 Received Power Spectrum

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