A Silicon-on-Sapphire Low-Voltage Temperature Sensor for Energy Scavengers

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Abstract— **We report on the design and test of a low-voltage temperature sensor designed for MEMS power-harvesting systems. The core of the sensor is a bandgap voltage reference circuit operating with a supply voltage in the range of 1-1.5V. The prototype was fabricated on a conventional 0.5μm Silicon-on-Sapphire (SOS) process. The sensor design consumes 15μA of current at 1V. The internal reference voltage is 550mV. The temperature sensor has a digital square wave output whose frequency is proportional to temperature. A linear model of the dependency of output frequency with temperature has a conversion factor of 1.6kHz/^{o}C. The output is also independent of supply voltage in the range of 1-1.5V. We report measured results and targeted applications for the proposed circuit.**

I. Introduction

Untethered sensors are improving the quality of life, enhancing the way information is gathered and analyzed, and streamlining the decision-making process in a diverse set of circumstances - from environmental monitoring to battlefield awareness [1]. In order for these sensors to be cheap, reliable and sustainable for long-term operation, practical power supplies still need to be developed. The requirements include long operating life (years to decades), high power density and small size [2]. Batteries, fuel-cells and other fixed-energy power supplies are not practical for wireless sensor network applications requiring long-term deployment and operation spans longer than a few months, since recharging is not cost-effective. For ubiquitous sensor networks, using ambient energy sources to extract power would enable continuous sensing, communication, computation, and actuation. An energy harvesting approach would be especially useful for long-term, remote applications that would otherwise require multiple battery replacements.

Solar cells are among the most ubiquitous examples of ambient energy harvesting. In applications where direct

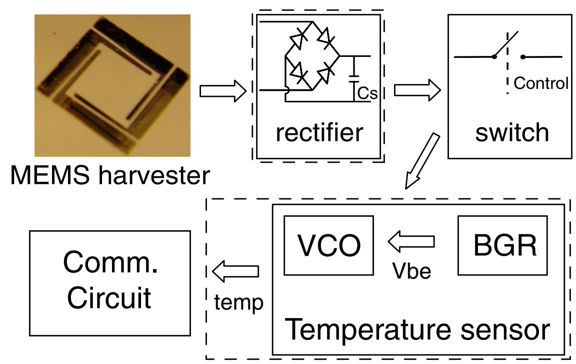

Fig. 1. A MEMS power harvesting device with temperature sensor. The alternating electrical field is rectified and relied to the temperature sensor through an hysteretic switch. A bandgap reference (BGR) senses temperature and a voltage-controlled oscillator (VCO) converts the reading into a digital frequency-modulated signal.

sunlight or large collection surfaces are not available, ambient vibrations constitute a viable alternative as a harvestable energy source. Ventilation systems and other mechanical support structures within indoor environments, engines in vehicles and aircrafts, movement of heavy traffic, and the physical motion of personnel all create plenty of vibration energy [2]. Recently, Micro-Electro-Mechanical Systems (MEMS) fabricated out of silicon substrates have attracted interest as platforms on which the vibration energy harvester can be combined with Integrated Circuit (IC) technology, producing sub-centimeter scale, self-powered wireless sensor network nodes [3]. Typical power levels harvested are measured in micro-Watts, and the IC components need to be designed for an ultra low-power and low-voltage regime of operation.

This paper presents the design and experimental characterization of a voltage reference and a temperature sensor intended to operate with the unstable supplies of

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vibration-based energy harvesting systems. The device innovates in the following ways: (1) Usage of different threshold MOS devices that made the design easier and lower operating power levels. (2) Integration of CMOS circuits with the MEMS design using the silicon-on-sapphire (SOS) fabrication process [4] which is suitable for bulk micromachining. Elimination of substrate capacitance and fully depleted operation of the process improve linearity, speed, and low voltage performance.

II. System Description

We designed and fabricated an electrical interface for recovering and utilizing the energy from a piezoelectric energy-harvesting system. The application of our circuit is illustrated in Figure 1. The core of the harvesting system is a MEMS device with a 100μm wide, 5μm thick and 3mm long tethers sharing a 2.5mm wide, 2.5mm long, and 500μm thick proof-mass, which oscillates when operating in an external vibration field. The silicon beams are covered with a thin film of piezoelectric material.

When the system vibrates, the stress on the piezoelectric material generates an alternating voltage that is rectified by a diode bridge and stored on a capacitor C_S. Because the voltage on that capacitor changes with the circuit loading and vibration amplitude, a voltage-controlled switch is utilized. This switch connects the capacitor to the circuitry only if the required operational voltage level is reached. When the voltage level is below this point, the switch is off and the storage capacitor is charged. The device's package is also used to limit the displacement of the cantilever beam, to prevent damage to the MEMS harvester. The peak-to-peak AC voltage generated by the harvesting system was modeled and simulated to be approximately 0.6-1.5V. This voltage range was limited to 1-1.5V in order to make it suitable for use of the sensor circuitry. Here we report on the double-rimmed circuit interfaces of Figure 1. A bandgap reference circuit is here used as temperature sensor. A voltage controlled oscillator converts the temperature reading into a digital square wave $temp$. A ring oscillator required for driving a transmission circuit was also designed and fabricated. The MEMS part of the system has been designed and preliminary beams were fabricated as shown in Figure 1. Preliminary measurements for the mechanical part showed that power levels of $30\mu W$ is possible for a mm^3 device.

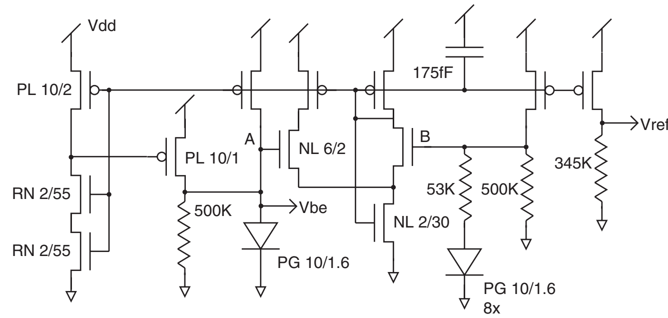

Fig. 2. Schematic caption of the bandgap reference circuit. MOS widths and lengths are given in micron.

A. Bandgap Reference

The core circuitry of the power harvesting electrical interface is a CMOS bandgap reference with a sub-1V output and a temperature sensor with digital output. Figure 2 represents a schematic caption of the bandgap reference (BGR). The BGR was designed to operate at the low supply voltages (1-1.5V) suitable for the harvesting system. The voltage reference is generated by two circuit branches containing two diodes, one of which is an array of eight parallel diodes. The two diodes are biased by current mirrors controlled by a feedback loop [5]. The reference output voltage depends on the diode built-in voltage V_f and the thermal voltage V_T, which is proportional to kT/q. This difference in diode sizes affects the V_{ref} output and helps to compensate the negative temperature coefficient of V_f. A 5-transistor transconductance stage ensures that the voltages at node A and B are equal in a feedback loop. The circuit contains a start-up stage to prevent instabilities when the circuit is powered-on. A 175fF compensation capacitor is used to stabilize the gate terminal of PMOS transistors of the current mirror. For low-voltage operation, we take advantage of the multi-threshold MOS devices available in the SOS process [4]. Low-threshold PMOS (PL) transistors are used as current sources for the entire bandgap circuit. The PL MOSFETs are all identical with a W/L = 10/2, unless specified in Figure 2. Notice also that the input NMOS transistors of the 5-transistor transconductance amplifier are also low-threshold NL-type. The NL input transistors allow the transconductor to operate at low voltages and provide high-gain. The diodes are native devices of the PG-type. The resistor are SOS native high-resistivity silicon strips of the SN-type and the capacitor is a MIM type [6]. The output of the BGR is signal V_{be}, of approximately 700mV, and V_{ref}, of approximately 550mV (see Figure 2). The use of the silicon-on-sapphire technology and its 6-types of MOS devices extends the operation of the BGR to very low power supplies and thus is a fundamental component of the electrical interface of this energy-harvesting system. Notice that the rectifying diode bridge of Figure 1 is also obtained using low-threshold devices.

B. Voltage Controlled Oscillator

The V_{be} voltage of the BGR is fed to the sensor's digital data converter and communication circuit that is presented in Figure 3. The circuit is a self-reset asynchronous oscillator that generates a square wave signal whose frequency depends on the input voltage. Here the V_{be} signal is converted from the voltage reference into the $temp$ square-wave output. The core of the oscillator is a capacitor-feedback integrator based on linear discharge. The input transistor converts an input voltage into a non-linear current that drains the capacitor of its reset-state charge. When the capacitor is discharged, a feedback loop composed of four inverters provides a delayed reset signal to restart the integration. Notice that we take advantage of the multiple threshold devices in the SOS process to implement two of the inverters in the feedback loop. These inverters use intrinsic transistors to provide self-bias. These first stages also provide a delay before communicating the reset signal to the integrator.

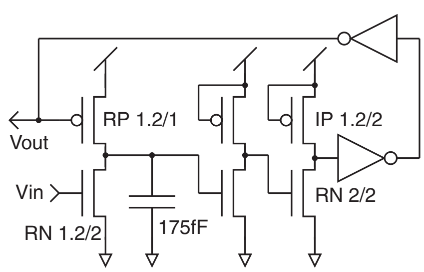

Fig. 3. Voltage controlled oscillator used to convert analog signal into a digital clock with varying frequency.

III. RESULTS

We measured the performance of the bandgap circuit by evaluating the temperature measurement capabilities and the stability of the output V_{ref} with a power supply of 1.2V. In order to measure the supply voltage dependence of V_{ref} and V_{be}, the supply voltage was swept both from 0V to 1.5V and from 1.5V to 0V. The output voltages were read using digital multimeters. The supply currents were monitored with a HP4155A Semiconductor Parameter Analyzer. The frequency of the $temp$ signal was obtained using an Agilent 54641A digital scope with HZ35 1x probes. In order to eliminate the ripples and the high frequency noise, a simple low-pass RC filter was connected to the output of the $temp$ signal. The filter's cut-off frequency was 500kHz, in order to avoid affecting the output frequency. The temperature measurements were performed in a convection oven. A K-type thermocouple was placed onto the package to monitor the actual temperature of the circuit while oven temperature was increasing. Readings were recorded during both raising and falling temperature. Both measurements were consistent.

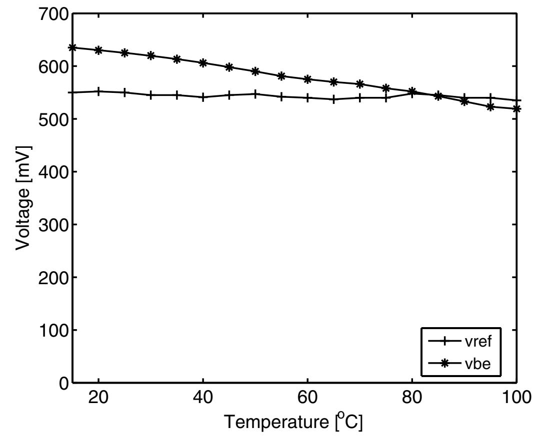

Fig. 4. Voltage reference output V_{ref} and V_{be} as a function of the temperature.

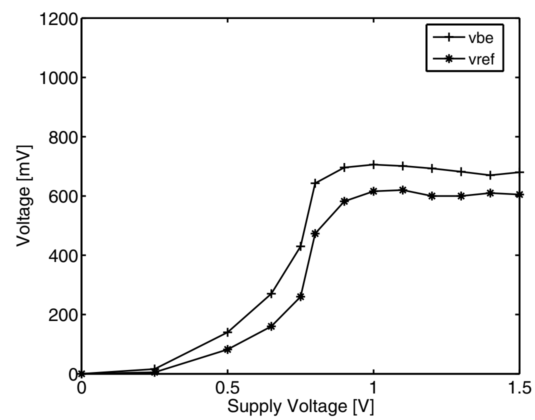

Fig. 5. Reference voltage with respect to supply voltage.

Figure 4 shows the dependence of signals V_{be} and V_{ref} on temperature when the supply voltage is kept $1.2V$. The V_{be}, which is equal to kT/q, voltage of the bandgap reference is linearly proportional to room temperature as expected. The voltage V_{ref} was designed to be approximately 550mV. Notice that in Figure 4 the

V_{ref} signal is constant with temperature in the [15C, 100C] range. The V_{ref} voltage ripple is approximately 6%, a satisfactory result given the low reference voltage. In Figure 5 V_{ref} and V_{be} are plotted with respect to the supply voltage up to the maximum voltage of 1.5V. Figure 6 represents the frequency of the square wave of signal $temp$ as a function of temperature for a V_{dd} of 1.2V. Notice the linearity of the output frequency as it increases with room temperature. A linear model of the frequency of the $temp$ signal versus temperature resulted in a conversion factor of 1.6kHz/^{o}C. The average current consumption was 15μA in the range of 1-1.5V. The frequency of the temperature sensor is almost constant in the range of V_{dd} of 1-1.5V. This allows to use the temperature sensor reading even if the supply voltage changes within the above range.

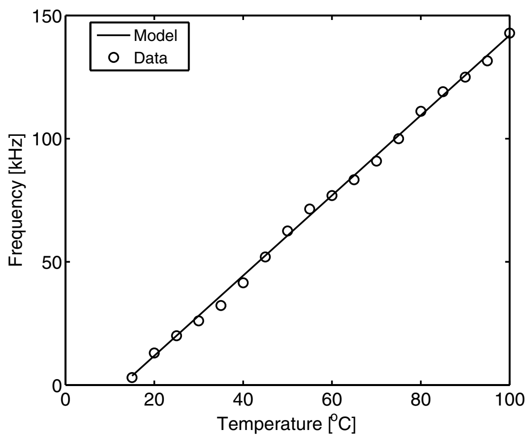

Fig. 6. $temp$ signal frequency with respect to temperature.

A micrograph of the fabricated die is shown in Figure 7. The bottom-right circuit is the temperature sensor. The circuit on the the left side of Figure 7 consists of a full-wave rectifier and a ring oscillator intended for data communication. These devices will be used to integrate the MEMS harvester to the electrical circuit interface. A bare die was bonded onto a DIP16 chip carrier and 10pF capacitors were connected to V_{ref} and V_{be} nodes in order to eliminate high-frequency parasitic effects and node ringing. The packaged circuit and other components were assembled on a printed circuit board (PCB).

IV. Summary

We designed, assembled and tested a temperature sensor based on a bandgap voltage reference circuit that works between 1-1.5V of supply voltage. The prototype was fabricated on a conventional 0.5μm silicon-on-sapphire process. We measured the generated reference voltage to be of 550mV. A bandgap reference implements the temperature sensors and also provide a stable temperature-independent voltage. The relationship between the output frequency and the room temperature of the sensor is linear with a conversion factor of 1.6kHz/^{o}C. The output is also independent of supply voltage in the range of 1V-1.5V. Our circuit implementation consumes only 15μA of current, making it an ideal electrical interface for ultra-low power energy harvesters as MEMS vibration recovery systems.

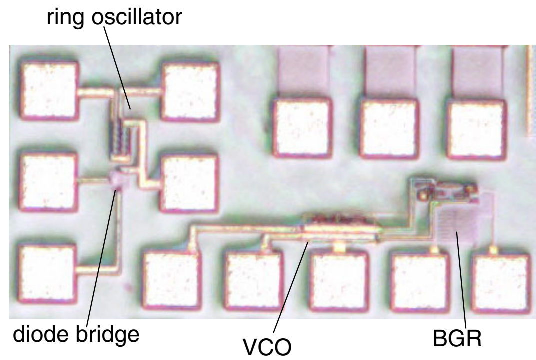

Fig. 7. Die photo of the temperature sensor, ring oscillator and rectifier.

V. Acknowledgements

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