Low-voltage temperature sensor for micro-power harvesters in silicon-on-sapphire CMOS

T. Kaya, H. Koser and E. Culurciello

A low-voltage temperature sensor designed for MEMS power harvesting systems is fabricated. The core of the sensor is a bandgap voltage reference circuit operating with a supply voltage in the range 1–1.5 V. The prototype was fabricated on a conventional 0.5 µm silicon-on-sapphire (SOS) process. The sensor design consumes 15 µA of current at 1 V. The internal reference voltage is 550 mV. The temperature sensor has a digital square wave output the frequency of which is proportional to temperature. A linear model of the dependency of output frequency with temperature has a conversion factor of 1.6 kHz/°C. The output is also independent of supply voltage in the range 1–1.5 V. Measured results and targeted applications for the proposed circuit are reported.

Introduction: Untethered sensors are improving quality of life, enhancing the way information is gathered and analysed, and streamlining the decision-making process in a diverse set of circumstances—from environmental monitoring to battlefield awareness [1]. For these sensors to be cheap, reliable and sustainable for long-term operation, practical power supplies still need to be developed. An energy harvesting approach would be especially useful for long-term, remote applications that would otherwise require multiple battery replacements. 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-centimetre scale, self-powered wireless sensor network nodes [2]. Typical power levels harvested are measured in microwatts, and the IC components need to be designed for an ultra-low-power and low-voltage regime of operation. In this Letter we present the design and experimental characterisation of a voltage reference and a temperature sensor intended to operate with the unstable supplies of vibration-based energy harvesting systems. The device innovates in the following ways: (i) Use of the silicon-on-sapphire (SOS) fabrication process [3], and in particular different threshold MOS devices, to operate at low power levels; and (ii) Design of a ultra-low-voltage CMOS bandgap reference suitable for integration with MEMS bulk micromachining. Elimination of substrate capacitance and fully depleted SOS devices also improve the bandgap linearity.

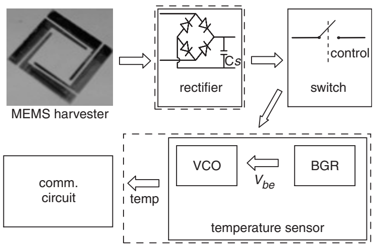

Fig. 1 *MEMS power harvesting device with temperature sensor*

Alternating electrical field is rectified and relayed to temperature sensor through a hysteretic switch. A bandgap reference (BGR) senses temperature and a voltage-controlled oscillator (VCO) converts reading into a digital frequency-modulated signal

System description: We designed and fabricated an electrical interface for recovering and utilising the energy from a piezoelectric energy-harvesting system. The application of our circuit is illustrated in Fig. 1. The core of the harvesting system is a MEMS device with a 100 µm-wide, 5 µm-thick and 3 mm-long tether sharing a 2.5 mm-wide, 2.5 mm-long and 500 µm-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 vibration amplitude, a voltage-controlled switch is utilised to disconnect the load. The peak-to-peak AC voltage generated by the harvesting system was modelled and simulated to be approximately 0.6–1.5 V. This voltage range was limited to 1–1.5 V to make it suitable for use of the sensor circuitry. Here we report on the double-rimmed circuit interfaces of Fig. 1. A bandgap reference circuit is here used as a 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 Fig. 1. Preliminary measurements for the mechanical part showed that power levels of 30 µW are possible for a mm^3 device.

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. Fig. 2 shows a schematic caption of the bandgap reference (BGR). The BGR was designed to operate at the low supply voltages (1–1.5 V) 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 [4]. 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 for the negative temperature coefficient of V_f. A five-transistor transconductance stage ensures that the voltages at nodes 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 175 fF compensation capacitor is used to stabilise 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 [3]. 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 Fig. 2. Notice also that the input NMOS transistors of the five-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 is SOS native high-resistivity silicon strips of the SN-type and the capacitor is a MIM type. The output of the BGR is signal V_{be}, of approximately 700 mV, and V_{ref}, of approximately 550 mV (see Fig. 2). The use of silicon-on-sapphire technology and its six 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 Fig. 1 is also obtained using low-threshold devices.

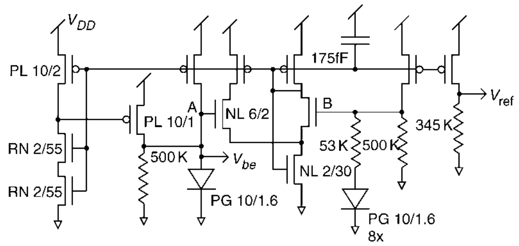

Fig. 2 *Schematic caption of bandgap reference circuit*

Voltage controlled oscillator: The V_{be} voltage of the BGR is fed to the sensor's digital data converter and communication circuit, presented in Fig. 3. The circuit is a self-reset asynchronous oscillator that generates a square wave signal the frequency of which 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 nonlinear 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. We use intrinsic transistors to implement two of the inverters in the feedback loop, to provide a delay before communicating the reset signal to the integrator.

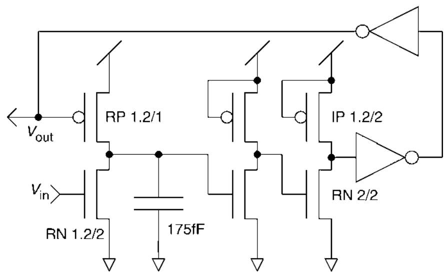

Fig. 3 *Voltage controlled oscillator used to convert analogue signal into digital clock with varying frequency*

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 1.2 V. To measure the supply voltage dependence of V_{ref} and V_{be}, the supply voltage was swept both from 0 to 1.5 V and from 1.5 to 0 V.

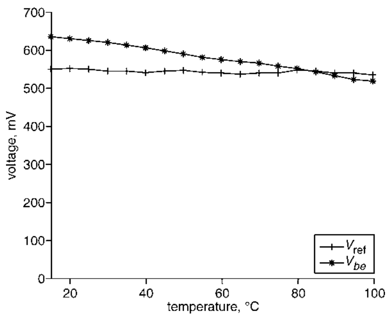

Fig. 4 *Voltage reference output V_{ref} and V_{be} against temperature*

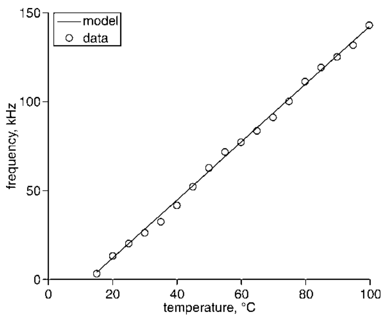

Fig. 5 *'Temp' signal frequency with respect to temperature*

Fig. 4 shows the dependence of signals V_{be} and V_{ref} on temperature where the supply voltage is kept at 1.2 V. 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 550 mV. Notice that in Fig. 4 the V_{ref} signal is constant with temperature in the [15°C, 100°C] range. The V_{ref} voltage ripple is approximately 6%, a satisfactory result given the low reference voltage. Fig. 5 represents the frequency of the square wave of the signal *temp* against temperature for a V_{DD} of 1.2 V. Notice the linearity of the output frequency as it increases with room temperature. A linear model of the frequency of the *temp* signal against temperature resulted in a conversion factor of 1.6 kHz/°C. The measured average current was 15 µA in the range 1–1.5 V. The frequency of the temperature sensor is almost constant in the range of 1–1.5 V. This allows use of the temperature sensor reading even if the supply voltage changes within the above range. A bare die was bonded onto a DIP16 chip carrier and 10pF capacitors were connected to V_{ref} and V_{be} nodes to eliminate high-frequency parasitic effects and node ringing. The packaged circuit and other components were assembled on a printed circuit board (PCB).

Conclusions: We have designed, fabricated and assembled a temperature sensor based on a bandgap voltage reference circuit that works between 1–1.5 V of supply voltage. The prototype was fabricated on a conventional 0.5 µm silicon-on-sapphire process. We measured the generated reference voltage to be 550 mV. A bandgap reference implements the temperature sensors and also provides 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 1.6 kHz/°C. The output is also independent of supply voltage in the range 1–1.5 V. Our circuit implementation consumes only 15 µA of current, making it an ideal electrical interface for ultra-low-power energy harvesters such as MEMS vibration recovery systems.

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