TA 7.4 Programmable Mixed-Voltage Sensor Readout Circuit and Bus Interface with Built-In Self-Test

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As integrated sensors and microactuators are combined with embedded microcontrollers to form microsystems, there is an increasing need for highly-accurate interface circuits to provide the transducers with bus compatibility, programmable control, and self-test. Several readout circuits for capacitive sensors have been reported recently, including a generic interface that has been used extensively in a multi-element microsystem [1]. This paper reports a bus-compatible interface chip (Figure 7.4.1, Table 7.4.1) that introduces several additional features, including a programmable mixed-signal mixed-voltage switched-capacitor (SC) readout circuit with self-test and on-line calibration capabilities. This 4.5x4.5mm^2 chip is in a 1μm n-well BiCMOS 2P/2M process with high-voltage CMOS, large-value resistor, and non-volatile memory options (Figure 7.4.2).

A bus interface circuit block connects this chip to a nine-line sensor bus, which links several front-end transducer nodes to the microcontroller [1]. Serial input data (4b chip address, 8b instruction byte, and 16b data word) received by the interface chip selects a sensor element to be read or writes to on-chip static RAM. During a read instruction, output is enabled from an on-chip temperature sensor, one of five capacitive transducers multiplexed into the SC readout circuit, or an external sensor having its own readout circuitry. During a write instruction from the bus, data is stored in on-chip RAM for precise programmable control of actuators or other circuit blocks on the chip, including the DAC, high-voltage generator, SC circuit, and temperature sensor. In addition, an on-chip self-contained EPROM [2] can be used to store predetermined transducer calibration coefficients to set the gain and offset of the SC circuit. Five 8b offset and three 10b gain settings can be stored on-chip. The bus interface also includes a pass-through interface to external sensors, consisting of a data line, a 3b address, and read/ write enable signals. This allows the microsystem to access, through the sensor bus, a wide variety of sensors which otherwise would not be bus compatible.

For reading out a variety of capacitive transducers, the chip contains a three-stage SC circuit (Figure 7.4.3) that can multiplex up to five sensor elements at its input. This circuit features programmable capacitor arrays capable of calibrating gain and offset over a wide range of base capacitances and sensitivities. Its analog front-end consists of a fully-differential charge integrator with a self-biased folded-cascode amplifier which uses continuous-time current-summing common-mode feedback for DC stabilization. The output of the first stage feeds a differential gain stage with single-ended output conversion. The clocking scheme uses correlated double sampling to suppress 1/f noise and amplifier offset effects.

Many transducers display undesirable temperature sensitivities which can be removed using in-module digital processing algorithms [1]. A temperature sensor has been integrated on-chip to facilitate this as well as to provide data for general use. The temperature sensor (Figure 7.4.4) uses vertical bipolar transistors and high-value resistors to generate temperature-dependent currents which charge the input node of a Schmitt ring oscillator. The oscillator output pulses are counted on-chip to generate a 12b digital temperature code with an acquisition time of 1ms.

The chip has several features for on-line self-test and drift correction. Drift in the circuit itself can be measured independent of the input transducer using an array of on-chip reference capacitors. For self-test of movable-electrode transducers, a charge pump generates a high voltage (≤30V) DC bias for electrostatic actuation. The programmable output of the charge pump can be used to set several test points, allowing the transducer drift to be measured. The input sampling voltage of the SC integrator can also be selected (Figure 7.4.3) from several on-chip elements including a 2V reference, a 6b DAC output, or the high-voltage charge-pump output. The DAC allows the sampling voltage to be controlled with 55mV resolution and provides readout offset control independent of the reference capacitors. If a field self-test detects minor drift in the circuit or the transducer, this feature allows the output to be brought back to its original calibrated value.

The low-voltage components in the SC circuit are isolated from the high-voltage sampling input of the charge pump by a switching path composed of high-voltage CMOS transistors (Figure 7.4.3). The clock voltages on the gates of transistors 5-8 are limited to 5V to minimize charge injection effects when high-voltage inputs are applied. When the gate voltage, Vg, of pMOS transistors 5,6 is 5V and the input voltage, Vs, is a high voltage such that $Vs > Vg + |Vt|$, devices 5,6 continue to source current. In this case, nodes A and B will be partially discharged because devices 5,7 and 6,8 form carefully ratioed voltage dividers. For example, if the input is 20V during the sampling phase then nodes A,B will drop to 19V during the integration phase for an average DC bias of 19.5V. The resulting DC level can be used for sensor self-test via electrostatic actuation.

The BiCMOS charge pump is based on the Dickson pump configuration and uses vertical bipolar transistors for high-voltage generation with adequate current drive/recovery capacity [3]. The circuit uses a programmable 2 to 33MHz Schmitt-based relaxation oscillator. This provides eight different output voltages up to 30V which can be selected on-line (Figure 7.4.5). The charge pump generates up to 10mW of output power as a current driver. This chip is used with a multi-element barometric pressure sensor and humidity sensor in a multi-transducer microsystem [1]. Figure 7.4.6 shows the circuit output at various gain and offset control settings when connected to a capacitive transducer.

References:

[1] A. Mason, N. Yazdi, A. V. Chavan, K. Najafi, and K. D. Wise, "A Generic Multielement Microsystem for Portable Wireless Applications," Proc. IEEE, 86 (8), pp. 1733-1746, August 1998.
[2] R. Reed, et. al, U. S. Patent 5796655, "Memory having Programmed Margin Verification Feature," August 18, 1998.
[3] J. F. Dickson, "On-Chip High Voltage Generation in NMOS Integrated Circuits Using an Improved Voltage Multiplier Technique," IEEE J. of Solid State Circuits , 11, pp. 374-378, June 1976.

Technology	1μm BiCMOS
Chip Size	4.5mm x 4.5mm
Power Consumption	< 10mW at 5V
Bus Interface	4b Chip ID 8b Instruction Register 65b EPROM Array 56b Static RAM
Temperature Sensor Range	-30 to 70 °C
Resolution	0.2 °C
SC Sensitivity	1mv/fF
Noise Floor	200μV-rms (100kHz BW)
Base Cap. Range	16fF - 40pF
Gain Range	20.8μV/fF - 1mV/fF
Output Voltage Accuracy	2mV
SC Sampling Voltage Resolution	55mV (6b DAC)
Charge Pump Output	8 V to 30 V

Table 7.4.1: Sensor interface circuit characteristics.

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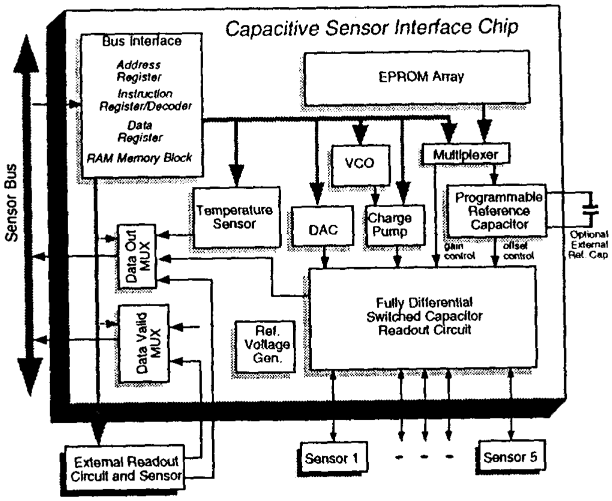

Figure 7.4.1: **Block diagram of the sensor interface chip.**

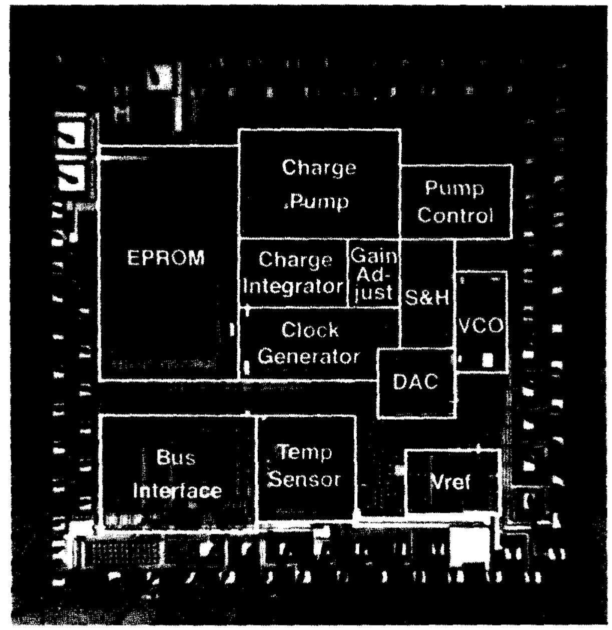

Figure 7.4.2: **Sensor interface chip die micrograph.**

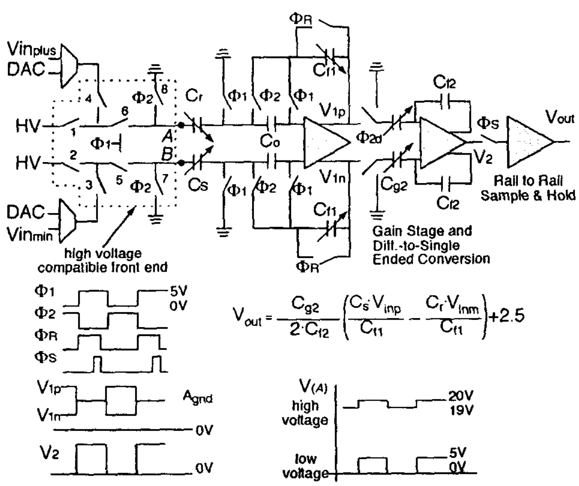

Figure 7.4.3: **Schematic and timing diagram of the switched-capacitor circuit.**

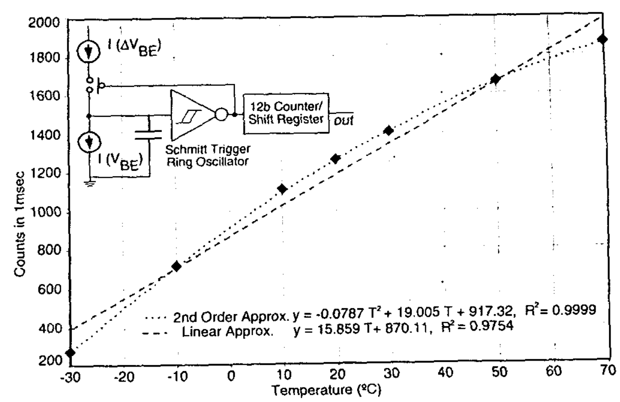

Figure 7.4.4: **Schematic and output plot of the on-chip temperature sensor.**

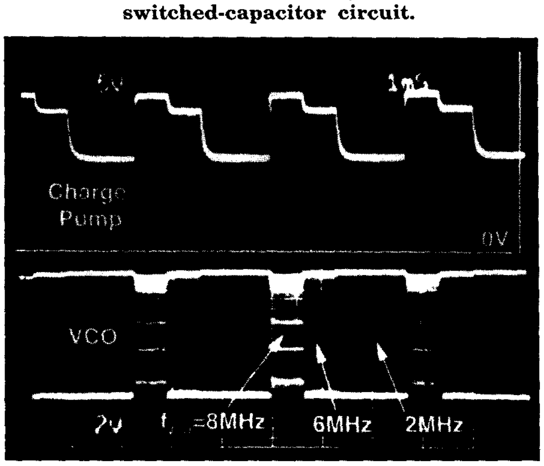

Figure 7.4.5: **Charge pump and VCO output at three of the eight programmable settings.**

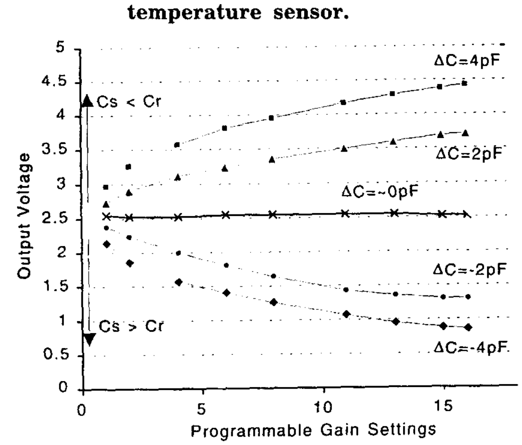

Figure 7.4.6: **Output voltage vs. programmable gain settings of the SC circuit for a range of ΔC (Cref-Csensor).**