An integrated organic circuit array for flexible large-area temperature sensing

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7.5 An Integrated Organic Circuit Array for Flexible Large-Area Temperature Sensing

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Traditionally, several technologies have been used for temperature sensing, including integrated silicon $\Delta V_{BE}$ and $\Delta V_t$ circuits, resistance temperature detectors, and thermocouples [1]. The organic thin-film transistor (OTFT) is a new technology suitable for temperature sensing because of two key advantages. First, OTFTs have the ability to be fabricated on flexible and large-area substrates [2]. This ability allows an OTFT temperature sensor to be used for applications such as electronic skin, biomedical thermal imaging, and structural temperature monitoring [2]. Second, the OTFT’s semiconductor trap states make OTFTs highly responsive to temperature. This paper presents the first integrated OTFT temperature sensing circuit array. The array is compatible with flexible and large-area substrates, and its outputs are 22 times more responsive than the MOSFET implementation while dissipating 90nW of power per cell.

The pentacene-based OTFTs are fabricated using an integrated photolithographic process that is kept below 95°C to ensure compatibility with large-area and flexible substrates [3]. Figure 7.5.1 shows the measured OTFT transfer characteristics as die temperature is increased from -20°C to 60°C. In comparison to the OTFT, Fig. 7.5.2 shows simulated BSIM3 silicon pMOSFET transfer characteristics versus temperature. Two important differences are observed between the OTFT and the MOSFET. First, the OTFT’s current increases with temperature in both subthreshold and above-threshold regimes, whereas the MOSFET’s above-threshold current decreases with temperature. Second, when biased at a constant $I_D$, the OTFT’s $V_{DS}$ is approximately 20 times more responsive to temperature than the MOSFET’s $V_{DS}$. Both differences are due to the fact that pentacene is a disordered semiconductor with substantial trap states [4].

A temperature sensing circuit that takes advantage of OTFT’s responsiveness to temperature is shown in Fig. 7.5.3. OTFTs $M_1$, $M_2$, and $M_3$ form two current mirrors that bias the two branches at different $I_D$. Diode-connected and identically sized $M_1$ and $M_2$ act as temperature sensing transistors whose $V_{GS1}$ and $V_{GS2}$ are functions of temperature. The differential output $V_{O}=V_{GS1}-V_{GS2}$ performs curvature cancellation and removes any common-mode $V_t$ drifts of $M_1$ and $M_2$.

If $M_1$ and $M_2$ are subthreshold MOSFETs, then this circuit is analogous to a $\Delta V_{BE}$ circuit. From Fig. 7.5.3’s MOSFET implementation, one can graphically see that $V_{GS2}$ decreases faster than $V_{GS1}$ over the same temperature range. Because of this, the transfer curves converge at a higher $I_D$. As a result, the circuit’s output $V_{O}=V_{GS1}-V_{GS2}$ decreases with temperature.

The OTFT temperature sensing circuit is fabricated with the device dimensions shown in Fig. 7.5.4 and occupies an area of 1mm×1mm. Wide transistors are used in order to lower the $V_{DP}$ voltage and to increase the temperature sensing area. The circuit uses a 5V voltage supply and a 3nA current sink from an Agilent 4156C. At each temperature, 240 samples of $V_O$ are taken at two samples/second and the standard deviation of the samples is 1.9mV. The averaged $V_O$ at each temperature is plotted in Figure 7.5.4. The temperature responsivity ($|dV_O/dT|$) is 6.3mV/°C and the temperature sensitivity is $2.5+10^{-9}$ppm/°C. The maximum power dissipation of the circuit is 170nW at 50°C. In the unit of temperature, the implementation shows that $V_{GS2}$ decreases slower than $V_{GS1}$ over the same temperature range of ISINK and VDD bias settings. In Fig. 7.5.6 (left), $V_O$ is plotted versus temperature as ISINK is swept from 0.5nA to 10nA. The $R^2$ value remains above 98% for ISINK=0.5nA to 4.3nA. Linearity worsens at high ISINK currents because the high $V_{DP}$ of $M_1$ and $M_2$ cause the current mirrors to enter the triode regime. In Fig. 7.5.6 (right), $V_O$ is plotted versus temperature as VDD is swept from 2V to 10V. Transistors $M_1$ and $M_2$ are in the saturation regime as long as VDD stays above 3V, where the $R^2$ value remains above 98% and is nominally independent of VDD because the circuit’s operating point is set by ISINK.

In conclusion, this work has demonstrated the first integrated OTFT temperature sensing circuit array compatible with large-area and flexible substrates (die Photo Fig. 7.5.7). The circuit outputs an average responsivity of 6.8mV/°C, which is 22 times more responsive than the MOSFET implementation while dissipating 90nW of power per cell from a 5V supply. Output linearity is guaranteed across the array as long as the current mirrors stay in the saturation regime. The linearity enables two-point calibrations, which remove the effects of cell-to-cell variations and make large-area implementations feasible.

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References:

Figure 7.5.1: The OTFT's device cross-section and measured transfer characteristics versus temperature (W/L=1,000µm/5µm).

Figure 7.5.2: The BSIM3 pMOSFET's simulated transfer characteristics versus temperature (W/L=10µm/0.18µm).

Figure 7.5.3: The temperature sensing circuit with its operating principles stylized for MOSFET and OTFT.

Figure 7.5.4: The OTFT temperature sensing circuit schematic and averaged $V_O$ versus temperature with best-fit line.

Figure 7.5.5: The OTFT temperature sensing circuit array's schematic, measured outputs, and output variations.

Figure 7.5.6: The dependence of output linearity on $I_{\text{sink}}$ (left) and $V_{DD}$ (right) with $R^2$ values (bottom).
Figure 7.5.7: Die photo of the 3×3 OTFT temperature sensing circuit array.