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Hybrid-Type Temperature Sensor Using Thin-Film Transistors

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ABSTRACT We have developed a hybrid-type temperature sensor using thin-film transistors. First, we evaluate temperature dependences of transistor characteristics and find that the temperature dependence of the off-leakage current is much larger than that of the on current. Next, we combine a transistor, capacitor, and ring oscillator to develop the hybrid-type temperature sensor and detect the temperature by measuring the oscillation frequency. The large temperature dependences of the off-leakage currents can be utilized, and simultaneously only a digital circuit is required to count the digital pulse.

INDEX TERMS Hybrid-type, temperature sensor, thin-film transistor (TFT).

I. INTRODUCTION

Thin-film transistors (TFTs) have been widely applied to flat-panel displays (FPDs), such as liquid-crystal displays (LCDs), organic light-emitting diode displays (OLEDs), and electronic papers (EPs) [1]. Because display characteristics of the liquid crystals [2] or operational stability of the organic light-emitting diodes [3] have temperature dependences, it is required to compensate them by controlling driving conditions. Actually, discrete temperature sensors are prepared near the LCDs for light valves, and the temperature dependences of the liquid crystals are compensated. However, because the temperatures have spatial distributions on the FPDs, it is required to measure the temperatures at several points and compensate the temperature dependences locally point by point. Therefore, temperature sensors integrated on the FPDs are meaningful. In addition to those integrated on the FPDs, the temperature sensors using TFTs are themselves promising for real-time area sensors.

First, we developed a T&C-type temperature sensor using TFTs [4]. The advantage of the T&C-type temperature sensor is that large temperature dependences of the off-leakage and sub-threshold currents can be utilized, whereas the problem is that a voltage meter is required to measure the analog voltage, which is difficult to integrate using TFTs. Next, we developed a ring oscillator-type temperature sensor using TFTs [5]. The advantage of the ring oscillator-type

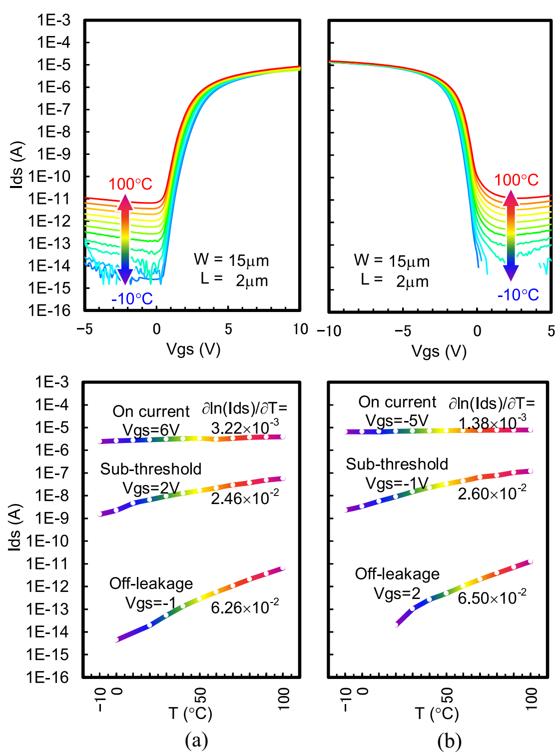

FIGURE 1. Temperature dependences of transistor characteristics. (a) n-type TFT. (b) p-type TFT.

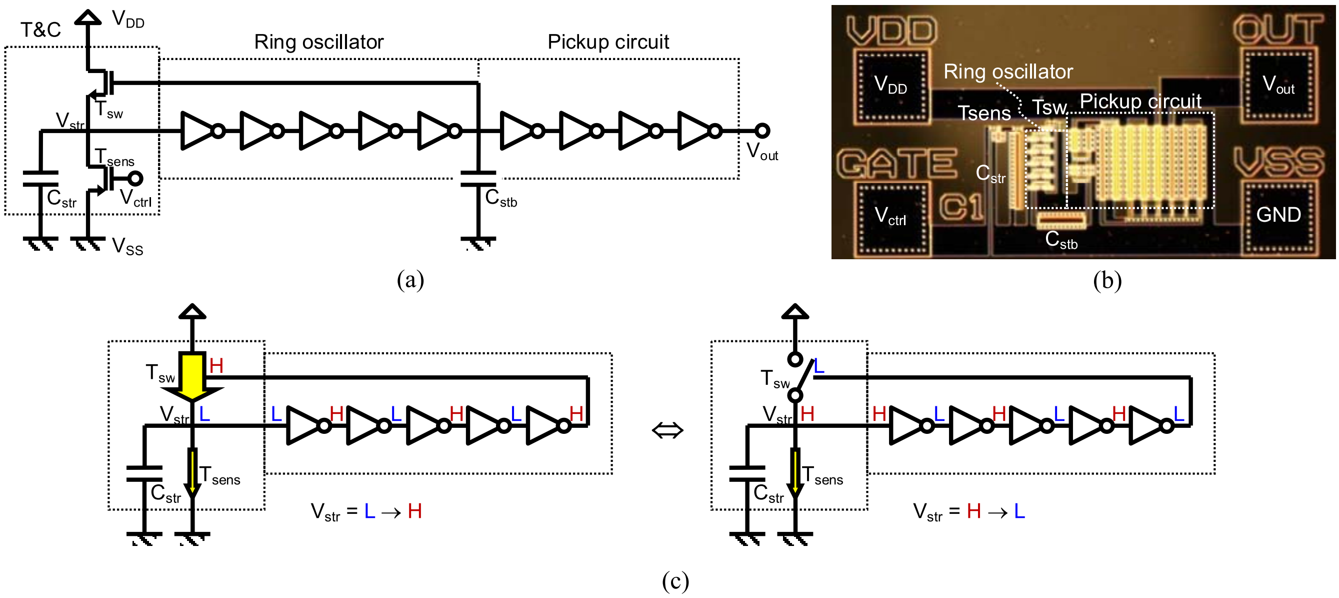

FIGURE 2. **Hybrid-type temperature sensor using TFTs. (a) Circuit configuration. (b) Microscope photograph. (c) Working mechanism.**

temperature sensor is that only a digital circuit is required to count the digital pulse, whereas the problem is that the oscillator frequency is sometimes too fast to surely count.

In this study, we have developed a hybrid-type temperature sensor using TFTs. First, we evaluate temperature dependences of transistor characteristics. Next, we combine a transistor, capacitor, and ring oscillator to develop the hybrid-type temperature sensor. In contrast to the T&C-type and ring oscillator-type temperature sensors, the advantage of the hybrid-type temperature sensor is that the large temperature dependences of the off-leakage currents can be utilized, and simultaneously only a digital circuit is required to count the digital pulse. In the previous rapid report [6], we merely demonstrated a hybrid-type temperature sensor using a n-type TFT. On the other hand, particularly in this paper, we minutely evaluate the temperature dependences of transistor characteristics, demonstrate a hybrid-type temperature sensor using a p-type TFT, and analyze the size and bias dependences.

II. TRANSISTOR CHARACTERISTICS

Top-gate, coplanar, and solid-phase crystallized (SPC) TFTs are fabricated [7], [8]. An amorphous Si film is deposited on a quartz substrate using low-pressure chemical vapor deposition (LPCVD) of SiH_4 and crystallized using furnace annealing in N_2 ambient to form a poly-Si film. A SiO_2 film is grown using thermal oxidation in O_2 ambient and another SiO_2 film is stacked using chemical vapor deposition (CVD) to form a gate insulator film. The poly-Si film is upgraded using post annealing at 1000 °C for 1 hr. A metal film is deposited and patterned to form gate electrodes, and a photoresist is patterned using photolithography as implantation masks. Phosphorus and boron ions are implanted and activated using furnace annealing to form source-drain

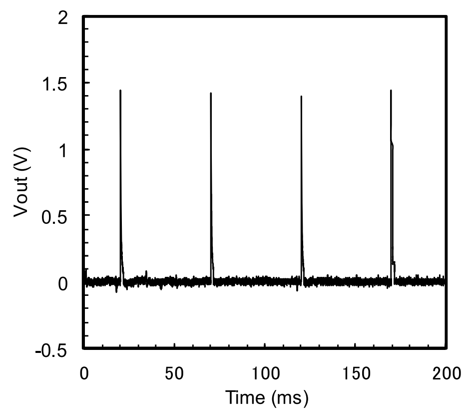

FIGURE 3. **Voltage waveform for oscillation behavior.**

regions. The poly-Si film thickness (t_s) and gate insulator film thickness (t_i) are 54.0 nm and 33.7 nm, respectively.

Temperature dependences of transistor characteristics are shown in Fig. 1. The slopes of the logarithmic graphs ($\partial \ln(I_{ds})/\partial T$) are also shown. It is found that the temperature dependences of the off-leakage and sub-threshold currents are much larger than that of the on current. This is because the off-leakage and sub-threshold currents are subject to the carrier generation mechanism such as Schockley-Read-Hall generation (SRH), phonon-assisted tunneling with Poole-Frenkel effect (PAT), and band-to-band tunneling (BBT), which have strong temperature dependences [9]. Moreover, the temperature dependence of the p-type TFT is slightly larger than that of the n-type TFT. It is well known that p-type TFTs are more stable against characteristic degradation [10]. Therefore, it is suggested that the off-leakage current of the p-type TFT should be used for the temperature sensors.

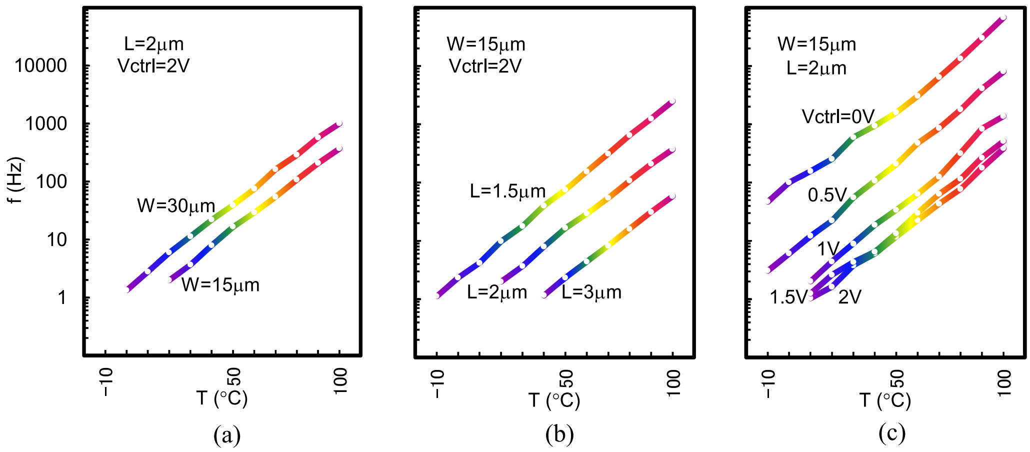

FIGURE 4. Temperature dependences of oscillation frequency. (a) W dependence. (b) L dependence. (c) Bias dependence.

III. HYBRID-TYPE TEMPERATURE SENSOR

A hybrid-type temperature sensor using TFTs is shown in Fig. 2. Cstr = Cstb = 0.768 pF, Vdd = 5 V (H), and Vss = GND (L). As shown in Fig. 2(a) and (b), we combine a transistor, capacitor, and ring oscillator to develop the hybrid-type temperature sensor. As shown in Fig. 2(c), when Vstr = L, H is applied to the gate terminal of Tsw, Tsw is switched on, and Vstr is charged from L to H. When Vstr = H, Tsw is switched off, and Vstr is discharged from H to L through Tsens, which is the abovementioned p-type TFT. As a result, this circuit oscillates between these two states, and the oscillate frequency depends on the temperature because of the temperature dependence of the off-leakage current of Tsens as the discharging current. In other words, this temperature sensor is an expansion of a resistor based temperature sensor. A TFT is utilized instead of a resistor because it is difficult to integrate a resistor with proper resistance using TFT fabrication processes and it is easy to control the effective resistance of the TFT by changing the size and gate bias. An example of voltage waveform for oscillation behavior is shown in Fig. 3. The oscillator frequency is not too fast owing to the small off-leakage current. The pulse width is narrow because Vstr is immediately charged from L to H when Tsw is switched on.

Temperature dependences of oscillate frequency are shown in Fig. 4. The dependence on the gate width (W), gate length (L), and gate bias (Vctrl) of Tsens are shown. It is found that the oscillate frequency (f) depends on the temperature, which means that the temperature can be detected by measuring f. Moreover, as W increases, as L decreases, and as Vctrl decreases, f increases. This is because the off-leakage current increases. Although it is believed that the off-leakage current is subject to the condition near the drain junction and independent on L, the reason why f increases as L decrease would be related to the dynamic behavior, where the transient off-leakage current when the applied voltages rapidly change is much different from the dc off-leakage current when the applied voltages do not change, and the transient off-leakage current is also dependent on L [11]. In any case, it is possible to optimize the range of by varying W, L, and Vctrl.

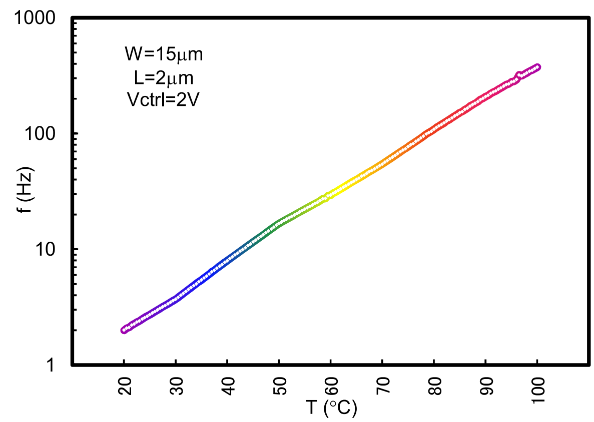

FIGURE 5. Oscillation frequency for a fine temperature step.

Oscillation frequency for a fine temperature step is shown in Fig. 5. Here, we increase the temperature from 20 °C to 100 °C. Since the relationship between the temperature and oscillation frequency is monotonic increase even if the temperature is changed every 0.5 °C, it is concluded that the detectable temperature resolution is less than 0.5 °C.

Characteristic variations including off-leakage currents are known to be small for SPC TFTs in comparison with excimer-laser crystallized (ELC) TFTs, but they are not completely zero. Therefore, it is expected that any additional procedures are not necessary for some applications that do not require high correctness such as consumer electronics, while it is necessary to measure temperature dependences of oscillation frequency for each hybrid-type temperature sensor, make look-up tables, and compensate every time for other applications that require extremely high correctness. On the other hand, characteristic degradations are known to be negligible for poly-Si TFTs, and p-type TFTs are more stable. Actually, we have never observed any hysteresis and shifts for the temperature dependences of oscillation frequency even after many times of the measurements and a long duration of the working.

IV. CONCLUSION

We have developed a hybrid-type temperature sensor using thin-film transistors. First, we evaluated temperature dependences of transistor characteristics and found that the temperature dependence of the off-leakage current is much larger than that of the on current. Next, we combined a transistor, capacitor, and ring oscillator to develop the hybrid-type temperature sensor and detected the temperature by measuring the oscillation frequency. The large temperature dependences of the off-leakage currents can be utilized, and simultaneously only a digital circuit is required to count the digital pulse. As written in Introduction, by integrating the temperature sensors using TFTs on the FPDs, it becomes possible to measure the temperatures at several points and compensate the temperature dependences of the display characteristics locally point by point. In addition to those integrated on the FPDs, the temperature sensors using TFTs are themselves promising for real-time area sensors.

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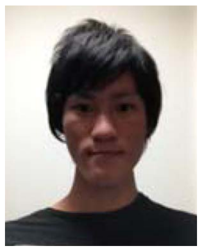

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