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A 4-Transistor Monolithic Solution to Highly Linear On-chip Temperature Sensing in GaN Power Integrated Circuits

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*Abstract*—We report the monolithic realization of on-chip temperature sensing design using four transistors (4T) in gallium nitride (GaN) technology. The temperature sensor consists of a voltage reference and a logic inverter, both of which are built from an enhancement-mode (E-mode) and depletion-mode (D-mode) MIS-HEMTs. The temperature-insensitive voltage reference outputs a very stable voltage as the input of the logic inverter, which exhibits good temperature dependence in its voltage transfer characteristics. As the temperature varies from 25 to 250 °C, the output voltage of the logic inverter changes linearly. By configuring the active-load D-mode transistor as a 2DEG resistor in the logic inverter, the temperature sensing solution is improved further, showing stable sensing output, higher sensitivity (31.28 mV/°C), better linearity (R2 = 0.995) and smaller error (±2.74 °C). This demonstrates a compact monolithic sensor for monitoring the on-chip temperature of GaN power integrated circuits (ICs) for protection and control.

*Index Terms*—GaN, MIS-HEMT, monolithic integration, temperature sensor.

# Introduction

Gallium nitride (GaN) power semiconductor devices feature high voltage, high-temperature operation and fast switching, contributing to the application in high-density power conversion systems [1], [2]. The monolithic integration of drive, control, sensing and protection in a high-integration module allows the potential of GaN power high electron mobility transistors (HEMTs) to be further exploited [3]–[6]. While the high-temperature operation of GaN devices and circuits mitigates the demand for complex cooling sections [7], temperature sensing of the IC chips is still required for safe operation and reliable thermal control of the systems.

In previous work on GaN temperature sensing, the Schottky barrier diode (SBD) was shown to have good temperature characteristics with a sensitivity of 2.58 mV/℃. However, the SBD solution to on-chip temperature sensing required additional processing steps in the IC fabrication [8]. 2DEG resistors in GaN were used as simple temperature sensors that give high linearity but only with limited sensitivity [9]. Good linearity in temperature sensing could be achieved in GaN ICs by using sophisticated feedback topology which then requires a complex design [10]. So, it is desirable to have a solution to GaN temperature sensing that has simplicity in monolithic integration and topology. For GaN ICs, the direct-coupled field effect transistor logic (DCFL) and resistor-transistor logic (RTL) inverters have been reported to present their temperature dependence [11], [12]. Whereas this characteristic of GaN inverters is rarely implemented to realize temperature sensing.

In this work, the temperature dependence of GaN logic inverters is exploited to achieve on-chip temperature sensing by integrating with a simple voltage reference. In particular, the DCFL and RTL inverters are circuit building blocks commonly used in GaN ICs; they require no overhead in changing the normal fabrication. A few simple GaN MIS-HEMTs are enough for constructing the temperature sensor. The experimental investigation is reported in the following sections about such an attractive solution to on-chip temperature sensing for real-time safety detection, especially in high-temperature operating conditions such as electric vehicles [13].

# Device Structure and Characteristics

The schematic cross-section of the Al0.25Ga0.75N/GaN MIS-HEMT structure used for the temperature sensor is illustrated in Fig. 1(a). The normally-off operation is achieved by digital etching of the AlGaN recess. The normally-on device also has the threshold voltage adjusted through the etching process. The transfer characteristics of transistors with the size of LGS/LG/LGD = 3/2/3 µm, WG = 100 µm were measured using an Agilent B1500A semiconductor device analyzer as shown in Fig. 1(b). At 25 ℃, the threshold voltage, Vth, is −2.83 V for the D-mode MIS-HEMT and 2.63 V for the E-mode MIS-HEMT obtained by the extended line. The maximum output current, Ids,max, is 532.7 mA/mm for the D-HEMT and 328 mA/mm for the E-HEMT. At 250 ℃, the D-mode (E-mode) device exhibits a Vth of −2.61 V (+2.87 V) and Ids,max of 291.4 mA/mm (193 mA/mm). Fig. 1(c) shows the curves of the 2DEG resistance with temperature dependence for a width of 2 μm and a length of 10/20/50/100/200 μm. The 2DEG resistance is 42 kΩ at 25 ℃ and 63 kΩ at 250 ℃ (for a length of 200 μm). The results show that the 2DEG resistance increases linearly with the chip temperature, similar to that of a complicated structure in [9].

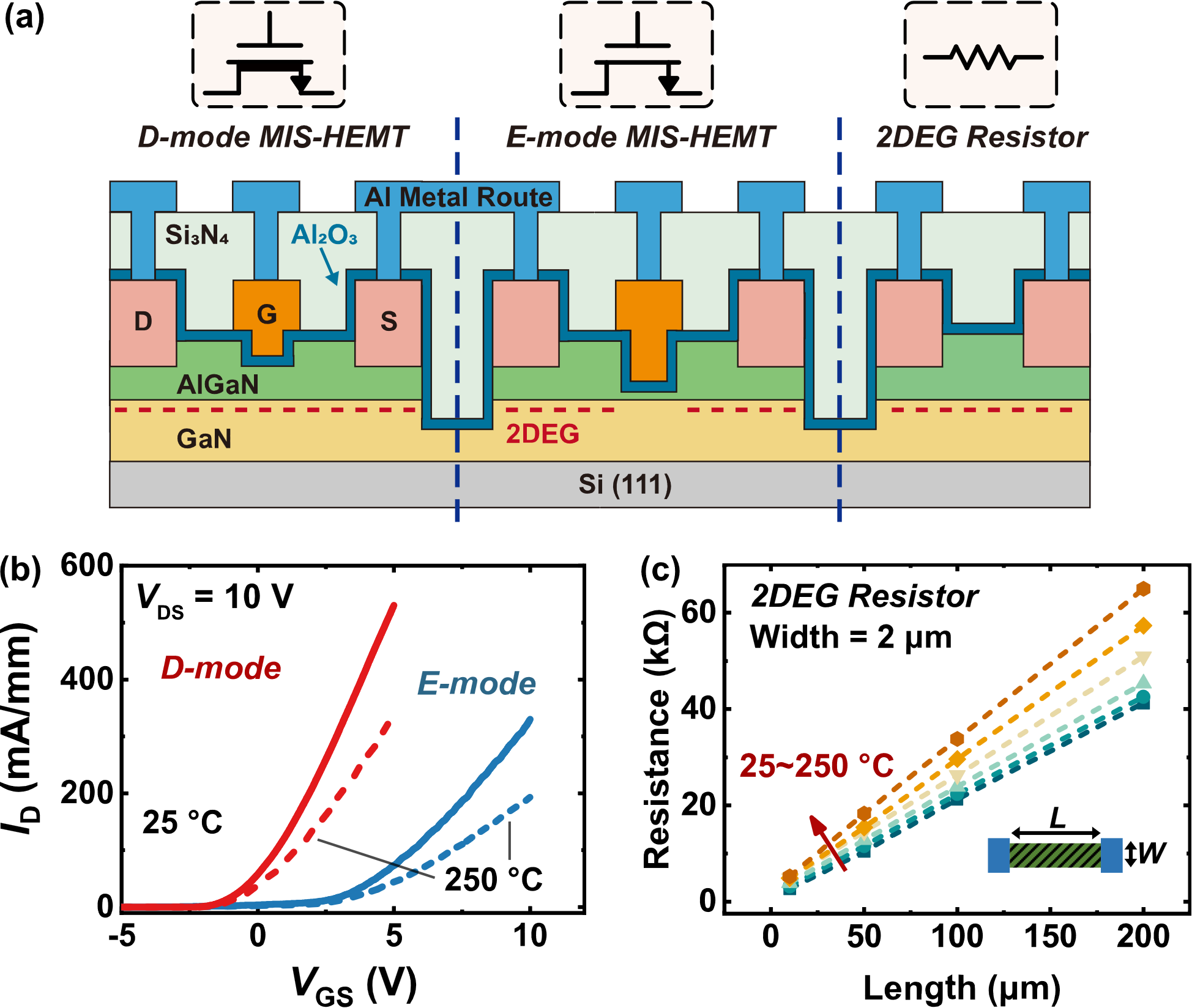


Fig. 1. Schematic cross-section of monolithically integrated D/E-mode GaN MIS-HEMTs and 2DEG resistor (a) Transfer characteristics of GaN MIS-HEMTs at different temperatures, and (b) 2DEG resistance versus the length resistor at the temperature varying from 25 to 250 °C.

# On-Chip Temperature Sensor

The temperature sensing structure consists of a voltage reference and the sensor section. A 2-transistor (2-T) configuration is adopted for the simple but robust voltage reference as reported in our previous work [14]. The design can withstand variations in ambient temperature and in the supply voltage to output a stable reference voltage. In its monolithic integration for building the GaN temperature sensor, a D-mode MIS-HEMT (W/L = 50/2 μm) and an E-mode MIS-HEMT (W/L = 50/2 μm) are used. At a supply voltage VDD = 10 V (or above), the 2-T voltage reference output is 3.02 V at 25 °C and 3.044 V at 250 ℃, with a temperature drift of 0.11 mV/℃, with more details explained in [14].

## GaN PTAT Voltage Source

With the almost temperature-independent reference voltage, a compact temperature sensor can be formed by adding a proportional-to-absolute-temperature (PTAT) block driven by this stable bias voltage. Considering the simplicity of temperature sensing, the logic inverter can be adopted as a PTAT building block. As shown in Fig. 2(a), the temperature sensor, consists of a voltage reference (built by M1 and M2) cascaded by a DCFL inverter (built by M3 and M4). When using the RTL inverter, the load usages as a 2DEG resistor (R2DEG) with the device structure and geometry shown in Fig. 2(b). The device sizes in the monolithic realization are W/L=100/2 μm for M3, 10/2 μm for M4, length = 200 μm for R2DEG.

In the DCFL temperature sensor, the voltage reference produces a stable VREF as the input to the logic inverter. VREF is set slightly larger than Vth,E, the threshold voltage of the E-mode MIS-HEMT. This is to make the gate overdrive voltage (VGS,E – Vth,E) of the E-mode M3 small. As a result, M3 operates in the saturation region but passes only a small ID. The small ID cannot support the D-mode active load (M4) working in its saturation, forcing M4 to operate in the linear region. This relationship is shown as

where μeff is the effective mobility, Ceff is the effective capacitance, and Vth,E/Vth,D which are temperature dependent [11], resulting in the temperature-dependent output Vout. However, once the temperature dependence makes ID become larger, the subsequent operation mode of this active load (M4 in Fig. 2(a)) could be in saturation mode [15]. The relationship can be expressed as

which output exhibits a different variation with temperature when compared to Equation (1). The operation mode ambiguity of the former and latter half of the transition stage can lead to the challenge of choosing a suitable bias voltage, especially with process-voltage-temperature (PVT) variations [16].

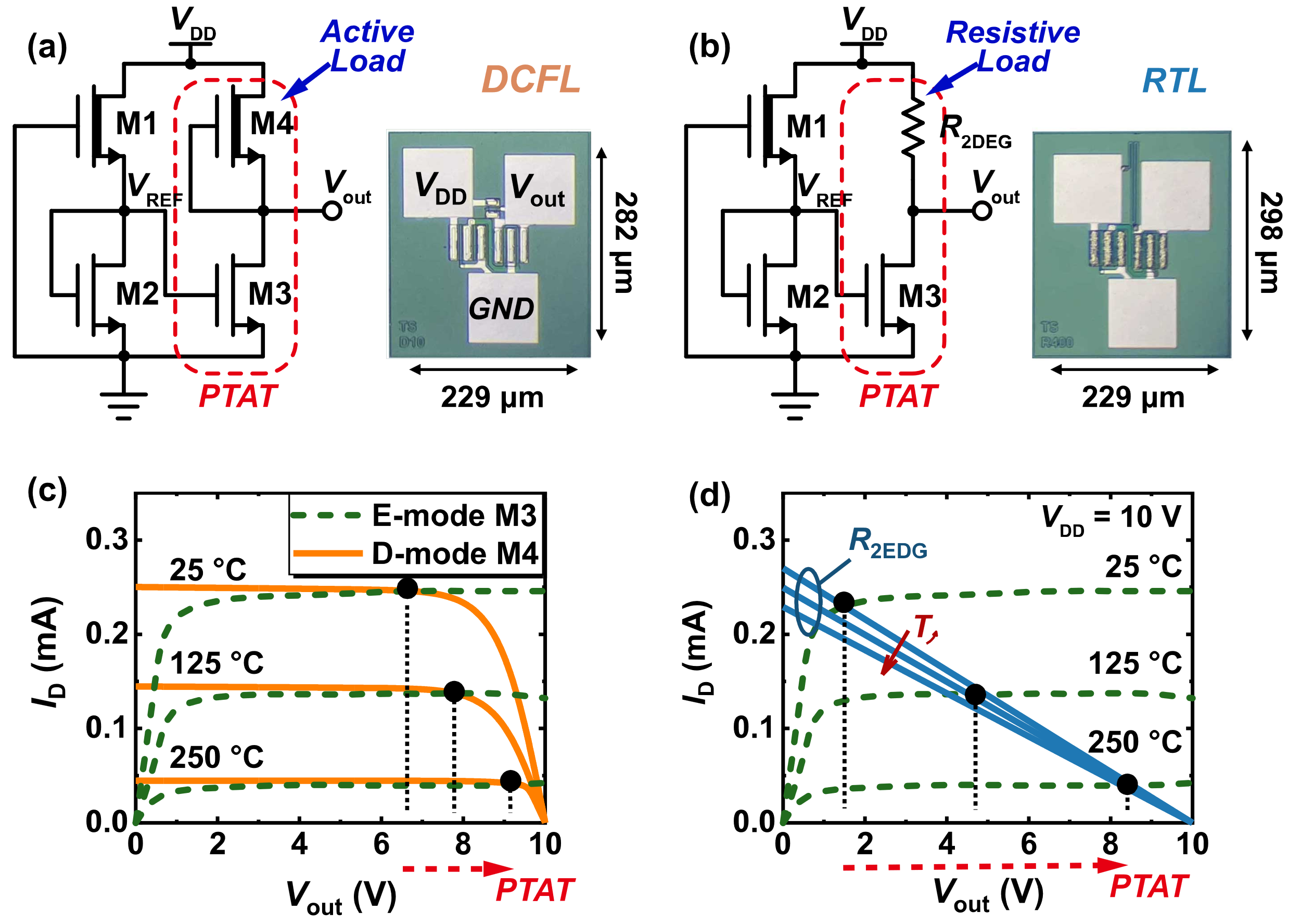


Fig. 2. Schematics and photograph of proposed temperature sensor:(a) DCFL and (b) RTL structure. Measured load-line characteristics of the (c) DCFL and (d) RTL inverter from 25 to 250 °C, Vgs,3=VREF, Vgs,4 = 0 V.

As for the sensor with the RTL inverter, it has a resistive load of the 2DEG resistor. Then the transition of the inverter output voltage has a constant slope since [17]

where β = qnsμR/kE and Vth,E and they also show temperature dependence. The temperature sensing of the RTL inverter can work well as long as its input (the gate terminal of M3) is biased within the transition region of the voltage transfer characteristics (VTC). Compared to the DCFL implementation, it is more convenient to bias the RTL-based sensor at a proper operation point and then it is more robust to provide the margin for PVT variations. Thus, the RTL implementation can be used to improve the sensor performance and stability over the DCFL counterpart. As illustrated in the load-line diagram in Figs. 2(c) and 2(d), there is a clear temperature-dependent trend in the intersections of the output characteristics of the devices in the DCFL- and RTL- based inverters.

## Characterization of the Temperature Sensor

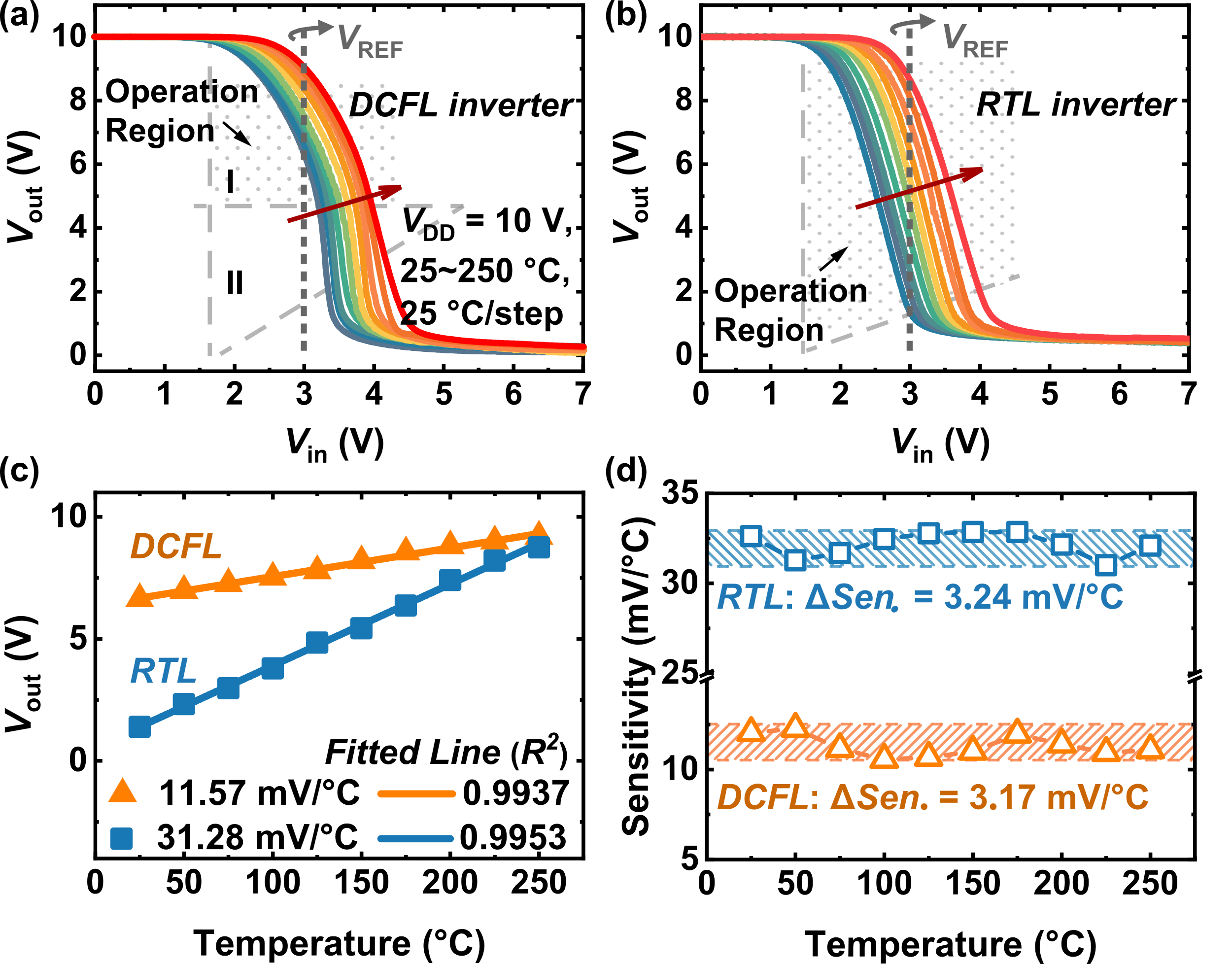


Fig. 3 The VTC of the inverter inside the temperature sensor with (a) (Region I, M3: saturation, M4: linear; Region II, M3/M4: saturation) and (b) RTL inverter. (c) The sensor output performances versus temperature, (d) the extracted sensitivity of each temperature.

The DCFL and RTL inverters’ VTC curves were obtained for temperature ranging from 25 to 250 ℃ (25 ℃/step), as shown in Figs. 3(a) and (b). The grey dashed lines of the set input Vin = VREF = 3.02 V are shown as the reference to indicate the sensing ranges of the DCFL- and RTL-based implementation as 6.2~9.1 V and 1.2~9.3 V, respectively. The results show that the range of the RTL inverter output is larger than that of the DCFL inverter. This is because the DCFL implementation is designed to work in a single mode for good linearity, while its output range and sensitivity must be sacrificed.

Table 1. Comparison of Temperature Sensors

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Reference** | **Technology** | **Temp.**  **Range (℃)** | **Sensitivity**  **(mV/℃)** | **Linearity**  **(R2)** |
| [10] (2014) | GaN HEMT | 25~250 | 0.35 | 0.993 |
| [18] (2015) | SiC SBD | 30~300 | 5.11 | 0.985~0.999 |
| [9] (2016) | GaN 2DEG | 25~175 | 10 Ω/℃ |  |
| [8] (2020) | GaN SBD | 25~200 | 2.58 |  |
| [19] (2020) | GaN SBD | 25~200 | 1.60 | 0.995~0.998 |
| This work | GaN HEMT | 25~250 | 31.28 | 0.995 |

Fig.  3(c) shows the sensor output voltage measurement results versus temperature. The sensitivity (ΔVout/ΔT) is 31.28 mV/℃ using the RTL inverter while 11.57 mV/℃ for the DCFL inverter. The variance between the linear fit and actual data can be examined by the linearity (R2), which is over 0.99 in both configurations. Therefore, it verifies that the output has high relevance to the straight line. As a temperature sensor, the RTL structure shows better sensitivity than the DCFL. The DCFL temperature sensor is constrained in the first operation mode (region I, as Equation (1)) to maintain linearity, which will sacrifice its sensitivity. It also indicates a smaller Vout range by biased VREF (Fig. 3(a)). In comparison, the RTL structure is benefited from its single-mode operation and avoids this issue. Therefore, it can be biased to obtain a higher sensitivity, which is a competitive level compared to previous GaN temperature sensors [8], [10].

Meanwhile, the sensitivity variations for different temperatures, are 3.24 mV/℃ (DCFL) and 3.17 mV/℃ (RTL), as shown in Fig.  3(d). These results show that both structures can produce a stable output voltage with high sensitivity and linearity at 25~250 ℃. Table I compares several implementations of temperature sensing in GaN and SiC processes. The proposed design for RTL implementation shows better performance in sensitivity. It also performs competitively in terms of temperature range and linearity.

Fig. 4(a) shows the measured temperature error of 10 samples from one processing batch. The sensors were placed along with a thermocouple calibrated to 50 mK. The 3σ errors in the temperature range of 25 to 250 °C for the DCFL- and RTL-based sensor implementations are ±2.82°C and ±2.74 °C, respectively. To characterize the power supply variation immunity of the temperature sensor, the power supply rejection ratio (PSRR) was measured and the results are shown in Fig.  4(b). At various frequencies and temperatures in measurements, the corresponding PSRR achieved is always above 40 dB. All these results of the temperature sensing solution demonstrate good accuracy and robustness.

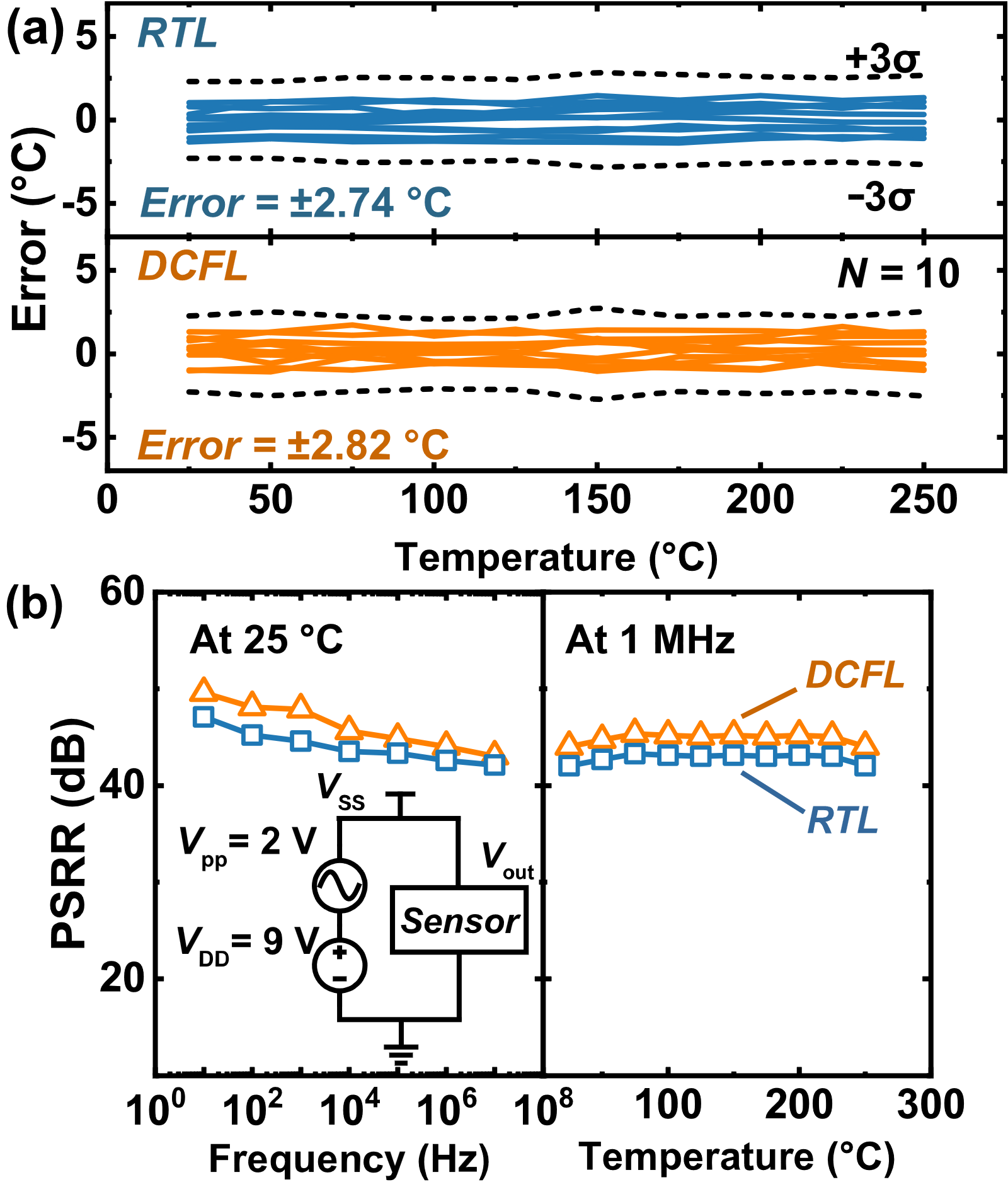


Fig. 4 Measured (a) temperature errors of 10 samples with ±3σ without calibration (25°C/step), (b) PSRR from 10 Hz to 10MHz and 25 to 250 °C, with the inset schematic circuit showing the test setup conceptually.

# Conclusion

Detailed experimental results have been presented about the GaN temperature sensor with the monolithic realization using four MIS-HEMTs. Both DCFL- and RTL-based designs work well with excellent temperature sensitivity and linearity. In particular, the RTL approach using a 2DEG resistor have more superior sensor performance over a wider temperature sensing range. With its simplicity in IC design and fabrication, the on-chip temperature sensing devices provide valuable solutions for integrating high-performance sensing and protection modules in all-GaN smart power systems.

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