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Title: Integrated SMD pressure / flow / temperature multisensor for compressed air in LTCC technology: Thermal flow sensor

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Abstract: In this work, we present and analyse the flow-sensing part of a recently-developed multisensor in LTCC (low- temperature co-fired ceramic) technology; this device integrates flow / pressure / temperature sensing and is designed for diagnostics monitoring of standard industrial compressed air circuits and devices such as valves and actuators. In this prototype, flow is sensed using the constant-temperature anemometric principle, with temperature-sensing active and reference thermistors placed in the fluidic channel integrated within the LTCC structure. The LTCC bridge structuration technology and electronics are analysed, and possible improvements in fabrication yield and efficiency outlined.

Integrated SMD pressure / flow / temperature multisensor for compressed air in LTCC technology: Thermal flow sensor

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COVER LETTER **10.12.2010**

Dear Editor,

Please find attached the files for the paper entitled "Integrated SMD pressure / flow / temperature multisensor for compressed air in LTCC technology: Thermal flow sensor", which is an extension of a contribution presented at ELTE-IMAPS Poland 2010.

This contribution reports analyses different aspects of the flow-sensing part of a recently developed LTCC multisensor, namely the structuration of the temperature-sensing thermistor bridges that are integrated into the sensing channel, and the electronics, and discusses possible improvement both in structuration technology, towards the reliable achievement of finer structures, and in the electronics, towards using switching regulation. These steps would allow the achievement of flow sensors with much reduced power requirements.

Please let me know in case you find anything missing during the review of the paper.

Best regards

Thomas Maeder

Integrated SMD pressure / flow / temperature multisensor for compressed air in LTCC technology: Thermal flow & temperature sensing

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(Revised + extended version of paper presented at ELTE-IMAPS Poland 2010, conference in Wroclaw)

Abstract

In this work, we present and analyse the flow-sensing part of a recently-developed multisensor in LTCC (low- temperature co-fired ceramic) technology; this device integrates flow / pressure / temperature sensing and is designed for diagnostics monitoring of standard industrial compressed air circuits and devices such as valves and actuators. In this prototype, flow is sensed using the constant-temperature anemometric principle, with temperature-sensing active and reference thermistors placed in the fluidic channel integrated within the LTCC structure. The LTCC bridge structuration technology and electronics are analysed, and possible improvements in fabrication yield and efficiency outlined.

Keywords: multisensors; flow; fluidics; temperature; LTCC; structuration

1. Introduction

Recently, LTCC technology has attracted considerable interest due to its ease of 3D structuration [1-3], combined with good thermal stability [4]. These advantageous features, coupled with the high achievable degree of compatibility with different thick-film materials, naturally predisposes LTCC for application to a wide variety of devices [5-12] that can be integrated into a single efficient LTCC package.

In fluidics, while LTCC cannot achieve the degree of miniaturisation of traditional silicon MEMS (microelectromechanical systems), it is better suited to less controlled industrial environments, where the presence of contaminants, for instance, would clog minute micromachined channels. Therefore, we endeavoured to apply this technology to an integrated flow / pressure / temperature multisensor (Fig. 1) for diagnostics of industrial compressed air systems [13-15].

The device [15] is intended for oversight of valves / actuators, in order to improve system reliability by early detection of anomalies such as excessive friction (high temperature), leaks and defective actuation (flow and pressure).

FIGURE 1

2. Multisensor concept

Both the pressure and flow measurement sections were first developed as separate devices [13,14] before their integration into the present one [15] (Figs. 1 & 2), whose salient features are:

- Anemometric flow sensing using a heated LTCC bridge in an inner channel [11], with PTC (positive temperature coefficient) thermistor heating+sensing elements
- Temperature sensing in the same channel using passive structures identical to that of the flow sensor
- Piezoresistive pressure sensing
- Combined electrical + fluidic surface-mount device (SMD) – style assembly onto a printed circuit board (PCB) or similar substrate.

The device comprises 5 LTCC layers:

T1 Top lid & pressure-sensing membrane

T2 Flow channel above sensing bridges

T3 Temperature-sensing bridges (Fig. 3)

T4 Flow channel below sensing bridges

T5 Bottom lid – soldering

The (yet unoptimised) footprint is 50 x 12.7 mm. For convenience, the electrical connections are also provided at the edge. When mounted onto a PCB (Fig. 1), the solder joints are also used for heat dissipation, especially the central ground pad. The nominal supply voltage is +15 V, but the sensor can work with any voltage sufficient for flow measurement and for regulation of the +5 V supply voltage for the pressure and temperature sensors.

As the object of the present work is not the pressure sensor (Fig. 2, left) this part will only be described shortly. The pressure-sensing element is a 3.6 mm diameter membrane carrying a thick-film piezoresistive Wheatstone bridge, with a dedicated IC (integrated circuit) for signal conditioning, the ZMD 31010 (ZMDI, Dresden, Germany), that also provides, through a field-effect transistor (Fig. 1 #3), a local +5V voltage supply used for pressure and temperature measurement. The pressure measurement lies at the nominal fluidic inlet, but the flow direction may be reversed if required; its mechanical design ensures efficient decoupling from thermal gradients generated by the flow measurement, and from stresses arising from the solder bond to the PCB. The pressure sensor is trimmed digitally, using the internal interface of the ZMD chip.

FIGURE 2

FIGURE 3

2.1. Temperature sensor

In contrast to the pressure sensor, which uses additional specific technological steps, the temperature sensor simply uses two extra outlying thick-film PTC thermistors in the flow-sensing structure (Fig. 3, "R_T"), and its fabrication is thus integrated in that of the flow sensor (see hereafter). Both temperature-sensing resistors are connected in series, making the measurement relatively insensitive to flow direction. Passive resistors are added to build a bridge, whose signal is amplified by one half of the LM358 dual amplifier (Fig. 4).

Although it was implemented with fixed resistors in this prototype [15], the temperature sensor may be easily laser trimmed, by replacing these resistors with thick-film ones:

1) At the reference temperature (typically $T_{ref} = 25°C$), trim R_{Th} so the temperature output signal U_{temp} is equal to the "neutral point" of the amplifier circuit set by the fixed divider resistors R_{dl} and R_{dh}, e.g. so that: $U_{temp} = U_T = +5V \cdot R_{dl} / (R_{dl} + R_{dh})$, which is the reference room-temperature output signal. As there is only one offset adjustment resistor, R_{Th} must be initially too low.

2) At another temperature, for instance T_{hot} = 100°C, trim R_g (gain up) or R_d (gain down) to match the expected signal at this temperature. Note that if the reproducibility of the temperature coefficient of the PTC thermistor (±5% is normally achievable) is deemed good enough, this second step may be omitted (i.e. R_g and R_d become fixed resistors), which greatly speeds up trimming.

FIGURE 4

3. Flow sensor design

The flow measurement, is based on the hot-wire anemometric principle, with an LTCC bridge acting as the filament in a flow channel defined by the LTCC structure in the flow, and carrying a thick-film PTC thermistor used for both heating and measurement (Figs. 3, 5 and 6).

FIGURE 5

To complete the resistive divider used for sensing, 10 (5 upstream + 5 downstream, Fig. 3) thermistors nominally identical to the sensing one and connected in parallel act as the reference resistor. Due to the nominally 10x better overall thermal coupling to the flowing gas and the LTCC structure and 10x lower dissipation, the temperature increase of the reference resistor vs. the package is very small compared to that of the measuring one.

As for the temperature sensor, and in contrast to the pressure sensor, simple analogue signal conditioning is used for flow (Fig. 6), where the voltage applied to the flow measurement resistive bridge comprised of the four resistors $R^{\pm}_{\mathrm{hi/lo}}$ is controlled by the other amplifier of the LM358 across an NPN transistor, so that the output of the measuring resistive divider ("+" branch) matches that of the setpoint divider ("-"). The flow output signal is simply this applied bridge voltage U_{flow}, which increases with flow due to the heat carried away by convection. A pull-up resistor R_{pu} ensures "start-up" of the circuit by always supplying it with a minimal amount of current, and the target temperature rise is set by the initial imbalance (in the "cold" state) between the passive and active voltage divider.

As for the temperature sensor, discrete passive resistors were used for R_{lo}^{-} and R_{hi}^{-} in this prototype, but laser trimming may likewise be carried out, by replacing these fixed resistor with printed ones, that can be deposited in the same step as those used for trimming the temperature sensor (see previous section). In this case, only the zero-flow output voltage is adjusted, by powering the sensor and trimming for R_{lo}^{-} and R_{hi}^{-} to obtain the required base value of U_{flow}. Note that this will also set the nominal temperature rise ΔT_{nom} of the "hot" sensing thermistor R_{hi}^{+}. The actual value of ΔT_{nom} after trimming will of course vary somewhat, due to the value of R_{hi}^{+} and of the thermal resistance between thermistor and sensor body being dependent on process variability.

FIGURE 6

4. Device Fabrication

The device was fabricated using DuPont (DP) 951 LTCC tape and associated materials (Table 1), with DP 2041 (10 kΩ sheet resistance piezoresistive composition) and DP 5092D (100 Ω PTC thermistor) compositions being classical alumina thick-film compositions, i.e. not designed for LTCC. After printing and drying, the tapes were aligned and stacked, then laminated at 160 bar at room temperature. Finally, firing was carried out in a lamp furnace, using a standard LTCC profile, with a maximum temperature of ca. 875°C [13].

Besides the encountered LTCC structuration issues [15], one aspect that would turn to be problematic (see section 5) is the considerable value decrease of the thermistors (ca. 120 Ω, vs. ca. 500 Ω expected), brought about by thermistor-LTCC chemical interactions during co-firing. Decreasing the printed resistor thickness was not practical, as this led to very irreproducible values.

TABLE 1

5. Results and discussion - flow sensor

Fig. 7 gives the flow response (0…20 normal litres / min) of a sensor. The regulated hot-wire temperature increase is ca. $\Delta T \approx +60$ K, and the no-flow thermal resistance of the bridge is estimated to be ca. 750 K/W, dropping to 180 K/W at the maximal investigated flow.

FIGURE 7

While the measurement is robust and repeatable, the sensor power requirements are much too high, and would further increase had the nominal +15 V voltage been used. This is due to the inefficient linear regulation electronics, and the high ΔT value for the measuring thermistor. Given the high thermistor response (around +3'000 ppm/K), ΔT (and hence the resistor heating power) could be decreased by a factor of at least 5…10. However, taking full advantage of this using the existing linear electronics would require correspondingly higher bridge resistances, which is not practical with the current DP 5902D (100 Ω) thermistor composition, as the thermistors are already quite elongated (Fig. 5).

The simplest possible solution would be changing the PTC thermistor composition to DP 5093D (1 kΩ). The drastically reduced current (<20 mA) would in turn allow replacing both the LM358 and the transistor by a moderately high-current rail-to-rail amplifier, bringing further improvements in size and efficiency (less voltage drop).

If this replacement is not possible due to materials compatibility issues, laser shaping [16] of the resistor before firing could be used to increase its value.

Finally, for even more efficiency, a switching circuit may be used, possibly even combining switching with A/D conversion into thermal delta-sigma modulation [17] using a specialised circuit. However, several aspects must be borne in mind:

- A switching circuit tends to create noise on the power lines due to the intermittent power draw. This may be alleviated by using a large power supply decoupling capacitor.
- The square-wave output is also a source of noise, and must be RMS-filtered (root mean square) to be supply-independent. This is of course not a problem if the supply voltage is well defined.

6. Conclusion

In this work, a multisensor for industrial compressed air, combining the measurement of flow, pressure and temperature, was presented and its flow-sensing part demonstrated. Further improvements will concentrate on reducing the power drawn by the flow sensor, which was identified as the main issue in this device.

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8. Figure captions

Fig. 1. Multisensor soldered onto fluidic test PCB.

Fig. 2. Sensor top & bottom side. Elements / components: pressure sensor (1), flow & temperature sensor (2), power supply (3), edge electrical (4), SMD electrical (5) and SMD fluidic (6) connections.

Fig. 3. Layout in flow channel – bridges & thermistors. Top: actual photograph of open test device fabricated without T1; bottom: schematic diagram.

Fig. 4. Temperature-sensing electronics. Resistors with diagonal bands are for laser trimming.

Fig. 5. Flow-sensing bridge geometry: (a) cross section with indicated tape levels, (b) layout. Standard dimensions [mm]: $h_2 = h_3 = h_4 = 0.21$; $b_r = 0.3$; $b_p = 1.0$; $L_r = 1.6$; $L_p = 3.0$.

Fig. 6. Simplified electronics schematic of the flow sensor. See Fig. 2 for component location. Resistors with diagonal bands are for laser trimming.

Fig. 7. Flow sensor output voltage and power consumption (measuring resistor alone and total) vs. flow, at 5 bar outlet gauge pressure and with +10 V supply.

9. Table captions

Table 1. Sensor fabrication – materials.

Table

Table 1. Sensor fabrication – materials.

Element	Code	Notes
LTCC tape	DP 951 PX	All 5 layers ; 254 µm thick unfired, ≈210 µm fired
Via fill	DP 6141	Ag, for all vias
Inner conductor (1)	DP 6145	Ag, only for some tracks + shield ground plane
Inner conductor (2) Outer conductor	DP 6146	Ag:Pd → tracks, solder pads & all resistor terminations
Piezoresistor	DP 2041	On T1; co-fired; for pressure measurements + misc.
Thermistor (PTC)	DP 5092D	On T3; co-fired; for flow + temperature measurement
Overglaze	DP QQ550	Post-fired 510°C ; also serves as solder stop mask
Solder (1)	SnAgCu or SnAg	On T1; Sn-Ag[-Cu] eutectic for components on sensor
Solder (2)	SnPbAg or SnBi	Lower-temperature eutectic solders for soldering to PCB

Figure 1

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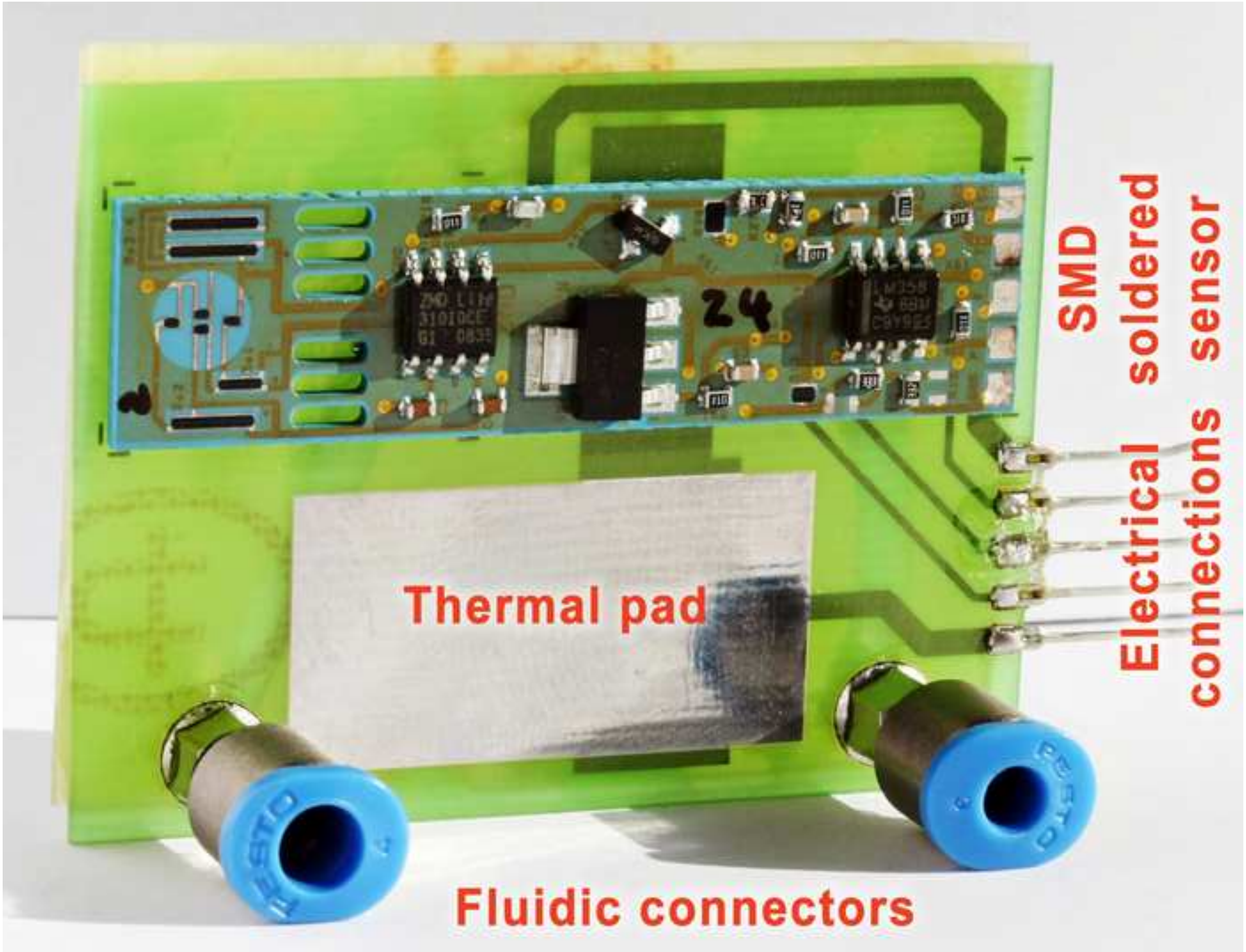

Figure 2

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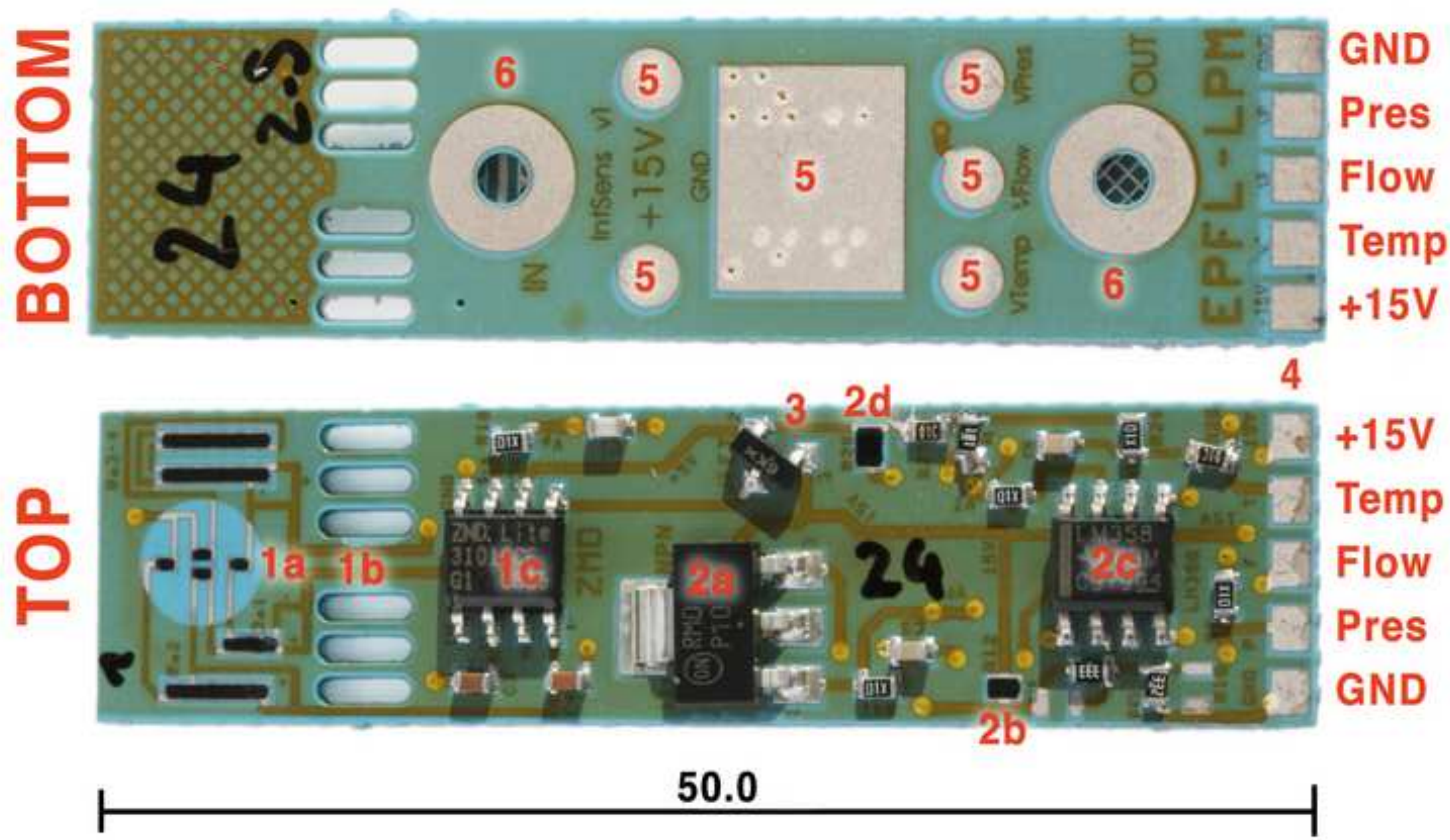

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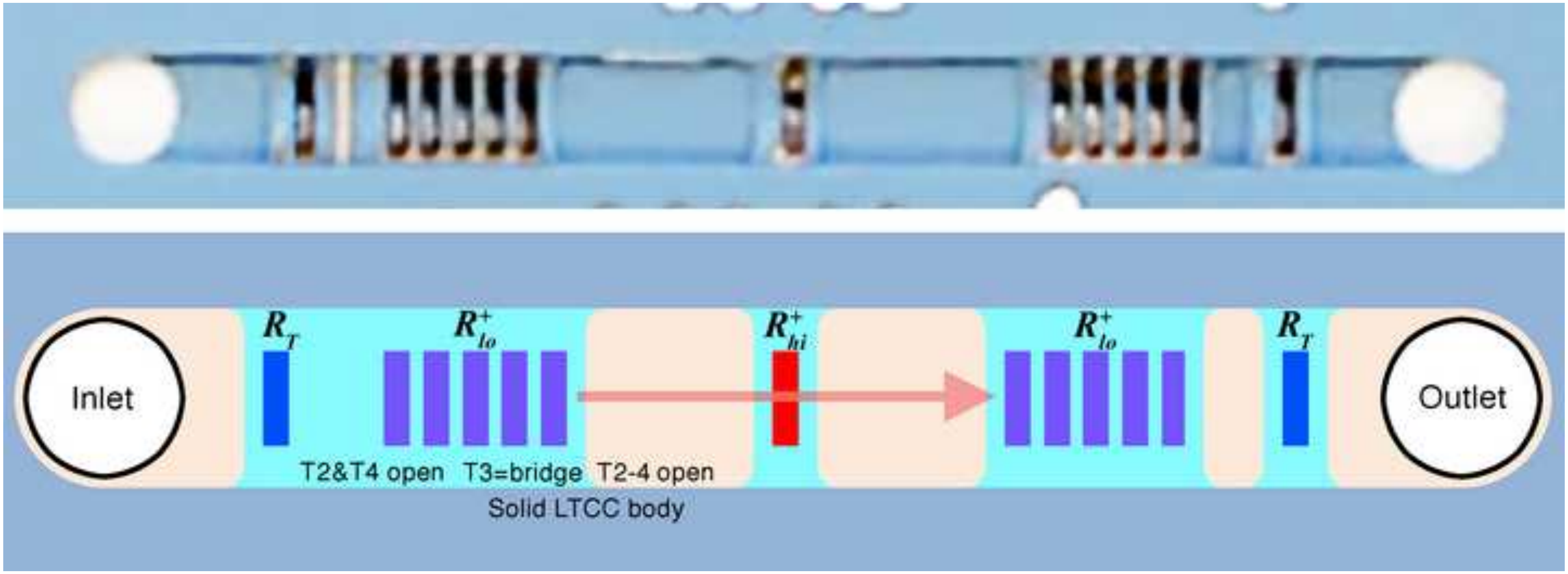

Figure 4
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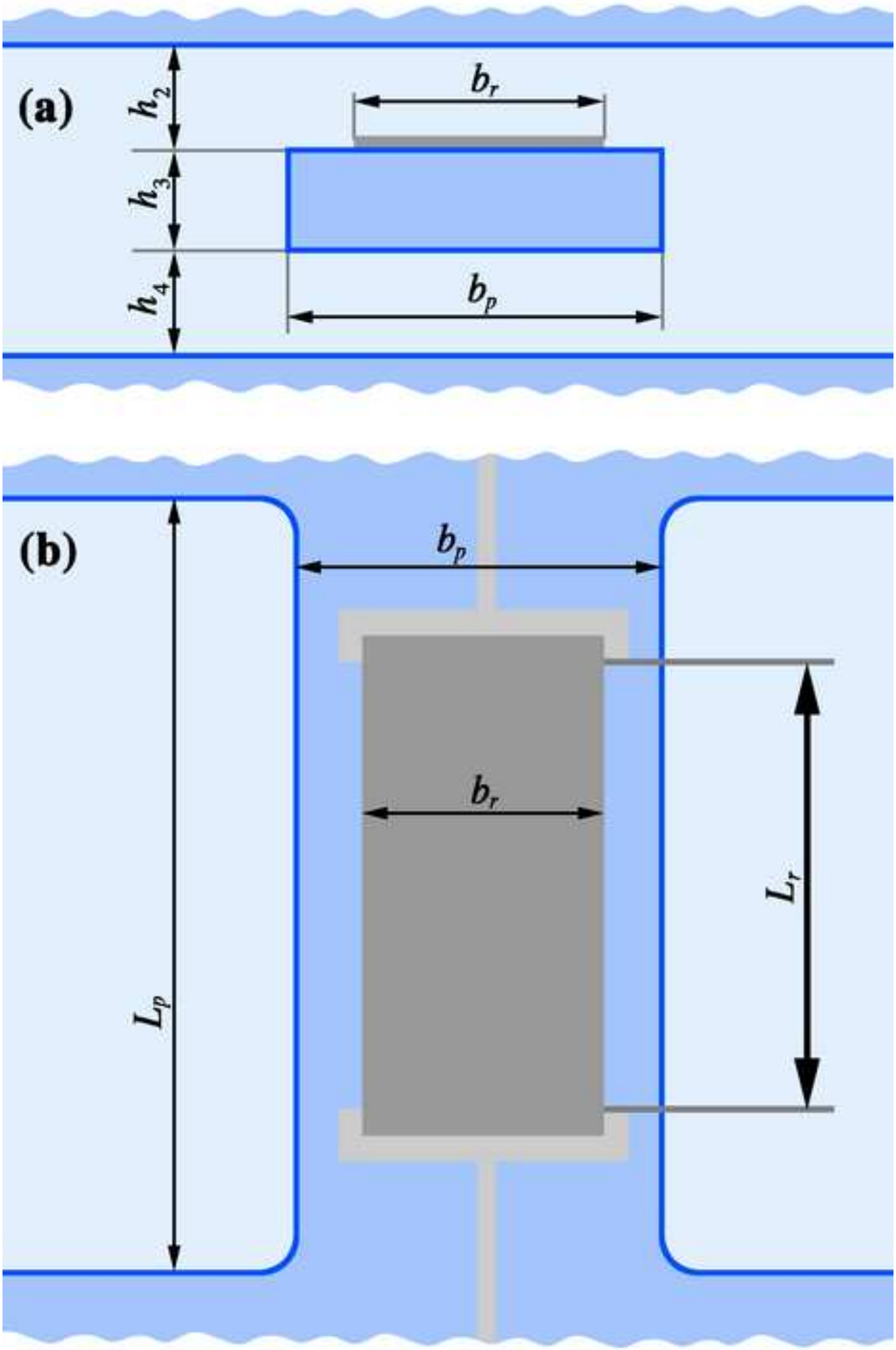

Figure 5
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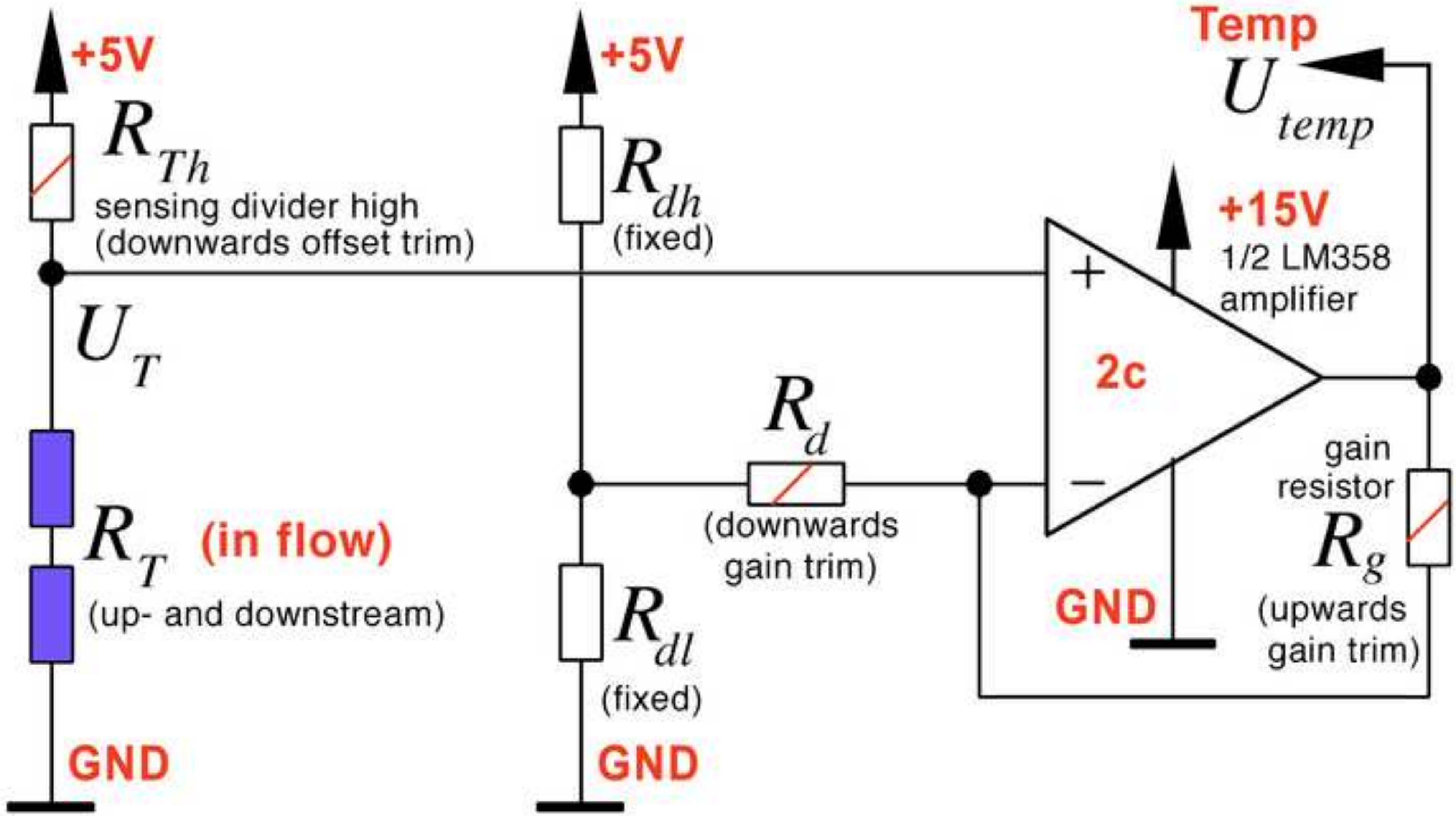

Figure 6

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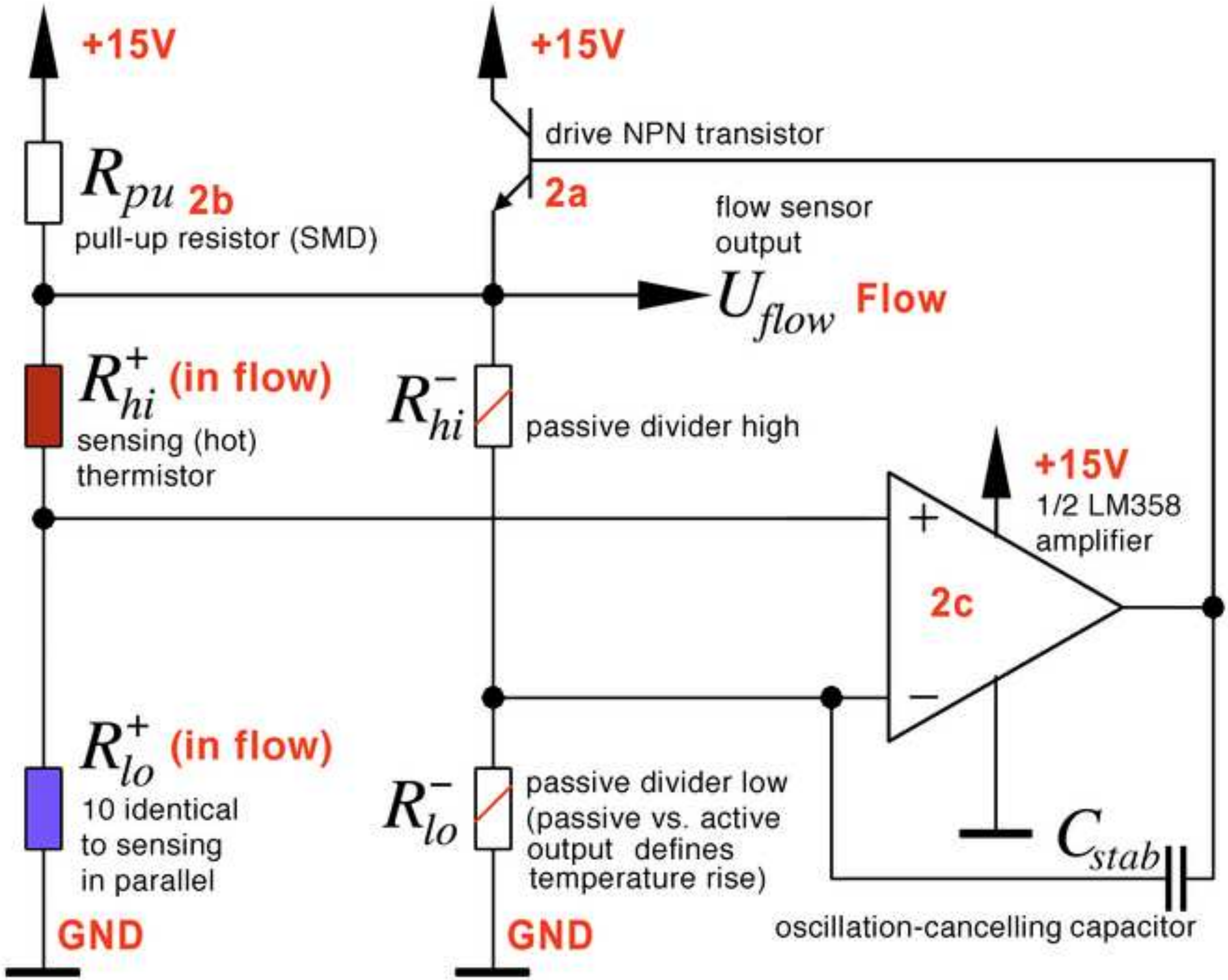

Figure 7

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