Voltage feedback method by DC-DC converter with high power efficiency for 2-D resistive sensor array

Shoo Saga
Electronics Engineering
Keio University
Yokohama, Japan
nakagawa@iskr.elec.keio.ac.jp

Yohsuke Shiiki
Electronics Engineering
Keio University
Yokohama, Japan
Shiiki@iskr.elec.keio.ac.jp

Hiroki Ishikuro
Electronics Engineering
Keio University
Yokohama, Japan
ishikuro@elec.keio.ac.jp

***Abstract*— This paper proposes a new readout method for 2-D cross-point resistor sensor arrays using operational amplifiers and PI controller for the step-down DC-DC converter. Compared with the conventional method using an operational amplifier, it can solve an operational amplifier's driving force and reduce power consumption. Wiring resistance, which has a significant effect on reading, has not been evaluated. the simulation was run with 16x16 parameters, a 10kΩ sensor resistor, and a 10Ω metal resistor, Then, there is an over 25% readout error. Therefore, I mentioned the effect of it and the switches on resistance. Besides, various parameters were changed, and the simulation results were shown with MATLAB. Design guidelines were provided from the results.**

Keywords—2-D resistive sensor array, olfactory sensing, interface circuit, metal resistance effect

I. INTRODUCTION

For the widespread of Internet of Things (IoT) society, It is expected that a small, low power, low-cost gas sensor system will be required. Several small gas sensor systems have been studied. A sensor system has been developed to detect up to nine gas types by changing the sensitive membrane. In this way, many gas sensors were extensions of a single gas sensor interface and are not suitable for large numbers of sensors.

Applying the 2-D cross-point resistance sensor array structure could be reduced the sensor area. There was an advantage that it was easy to manufacture at low cost because it didn't use a switch under the sensor. Furthermore, the number of control signals for an $M \times N$ array could be reduced to $M + N$ in rows and columns. However, the sneak current flowing around the read resistor made it difficult to measure each resistance value accurately. To avoid the sneak current, the Voltage Feedback Method (VFM) and Zero Potential Method(ZPM) were proposed [2]. In these methods, the output voltage feedbacked to limit the current path and suppress the sneak current. However, measurement errors occurred due to non-idealities such as input offset and output impedance of the operational amplifier. Therefore, the method without using an operational amplifier was proposed [3]. In this method, the sensor's parallel resistance value is read, *and* $M + N$ equations are solved. Then, all resistance values could be found with high accuracy by solving the determinant.

Conventional gas sensor requires power consuming heater to improve the sensitivity. However, when these methods are applied, it is necessary to use an external heater, and an appropriate temperature bias cannot be applied to each sensor. Therefore, it is an essential reading circuit to self-heating by applying a high voltage to each sensor. The method [3] is not suitable for self-heating because the sensor resistance changes due to heating, and the resistance value is calculated when the applied voltage is different. When the VFM and ZPM are used, as shown in Fig. 1, when the scale of the array size and the power supply voltage increase, the current is flowing into the operational amplifier increases, and the power consumption increases dramatically. If a switching regulator is used to solve this problem, it will be highly efficient, but voltage control will be required. Besides, these methods cannot correctly evaluate the effect of metal resistance, which causes a large reading error. Metal resistors have a more extensive read error than switch resistors when the array size is large.

To solve the problems of operational amplifier driving force and power consumption, and operational amplifier non-idealism, we propose a highly efficient method for cross-point 2-D resistor sensor arrays. The proposed circuit controls the output voltage(V_{OUT}) and feedback voltage(V_{FB}) of the array to be equal in the PI-Controller. The DC-DC converter outputs a V_{FB}. The read resistance value's value is determined from the voltage value output by the voltage division of the sensor resistance and the reference resistance(R_S). The problem of power consumption is solved by adopting a switching regulator type DC-DC converter. Using a simplified circuit diagram, evaluate the effects of switch resistance and wiring resistance, which have a large effect on reading error.

II. PROPOSED READOUT METHOD

A. Circuit Design

This technique can be applied to 2-D resistor arrays with $M \times N$ sensors. If the feedback voltage and the output voltage

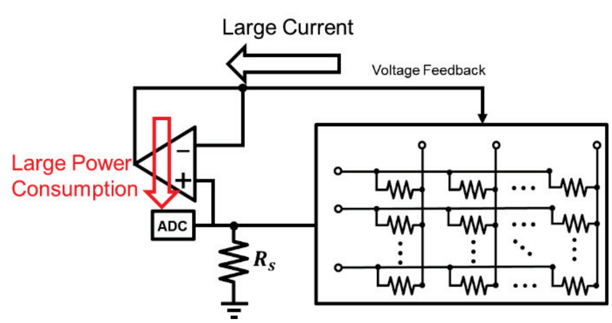

Fig.1 Problems with the conventional interface circuit due to an op-amp

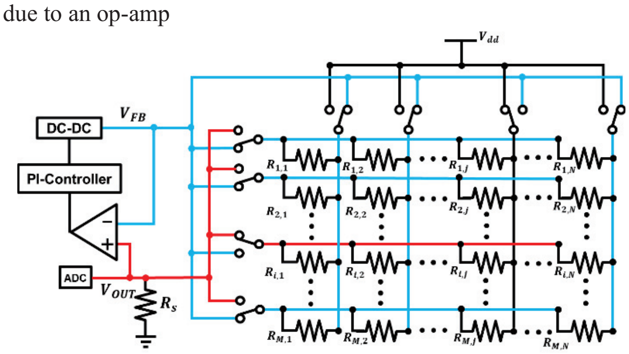

Fig.2 Proposed circuit using the DC-DC converter

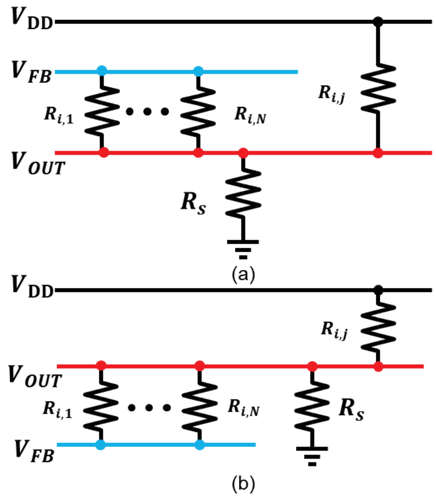

Fig.3 (a) Simplified circuit when V_{FB}> V_{OUT}

(b) Simplified circuit when V_{FB} <V_{OUT}

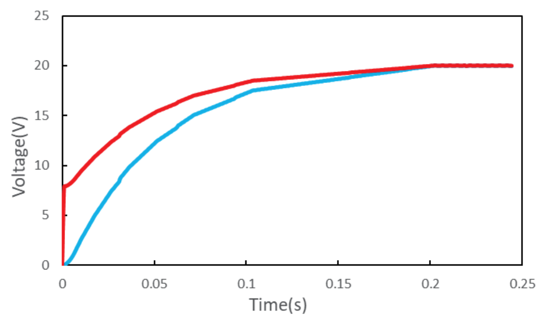

Fig.4 V_{FB} and V_{OUT} response by PI-control

are equal, the sensor resistance to be measured ($R_{i,j}$) and the reference resistance(R_s) are in series. $R_{i,j}$ can be obtained from V_{OUT} and R_s. Connect a single pole double throw switch to the upper electrode and left electrode ($M + N$) of the array and switch $M \times N$ times. And measure the resistance of all sensors. PI-Controller is required for control as the V_{OUT} and V_{FB} are equal. Figure 3 shows a circuit diagram showing the relationship between V_{FB} and V_{OUT}.

As shown in Fig. 3, the relationship between V_{FB} and V_{OUT} is determined by the selected column resistor and a reference resistor.If the circuit equalizes the feedback voltage and the output voltage, In an ideal state V_{OUT} is as follows :

$$V_{out} = V_{FB} + \frac{\frac{(V_{DD} - V_{FB})}{R_{i,j}} - \frac{V_{FB}}{R_s}}{\sum_1^i \frac{1}{R_{i,N}} + \frac{1}{R_s}} \tag{1}$$

Therefore, the difference between the change in V_{FB} and the change in V_{OUT} is as follows :

$$\Delta V_{FB} - \Delta V_{out} = \Delta V_{FB} \frac{\frac{1}{R_{i,j}} + \frac{1}{R_s}}{\sum_1^i \frac{1}{R_{i,N}} + \frac{1}{R_s}} \tag{2}$$

When the binary search is used, V_{OUT} follows V_{FB}, and the difference does not shrink. Therefore, it is necessary to use PI-Controller. Fig. 4 shows V_{FB} and V_{OUT} controlled by the PI-Controller. Until measuring resistance, control so that the V_{OUT} and V_{FB} are equal. PI-Controller is required for control when V_{OUT} and V_{FB} are equal. Fig. 3 shows a circuit diagram showing the relationship between V_{FB} and V_{OUT}. As a result, if the current path is ideal, V_{OUT} is expressed as follows :

$$V_{OUT} = \frac{R_s}{R_s + R_{ij}} V_{dd} \tag{3}$$

Furthermore, the voltage of the difference between the power supply voltage and V_{OUT} is applied to the selected column resistor, and sensor's power consumption is expressed as follows :

$$P = (V_{DD} - V_{OUT})^2 / R_{ij} \tag{4}$$

The sensor temperature can be changed for each row by changing the power supply voltage for each row according to

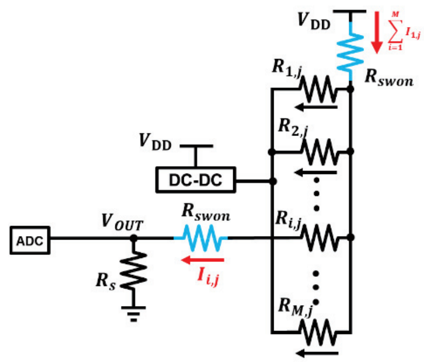

Fig.5 Simplified circuit considering switch resistance

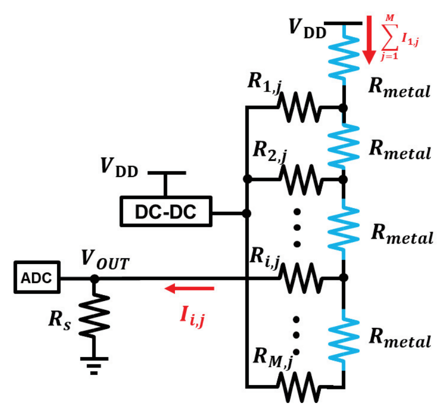

Fig.6 Simplified circuit considering the metal resistors

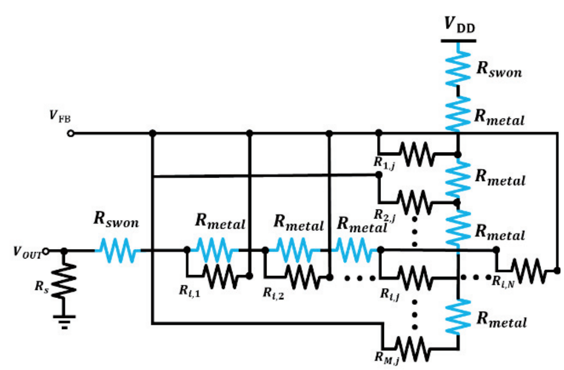

Fig.7 Simplified circuit considering the switch resistance and metal resistance

the sensor's power-temperature characteristics. A large current flows into the switching regulator, but the inductor can store it, so it is expected that power consumption will be reduced. However, To use a switching regulator causes switching noise. It makes accurate sensor measurement difficult. However, this problem can be avoided by sampling in synchronization with the switching noise cycle.

B. Switch Resistance Effect

When self-heating is applied, the power supply voltage is large, so the switch resistance becomes large and cannot be ignored. Fig.5 shows a simplified circuit diagram considering the switch ON resistance. (R_{swon}). If the feedback voltage and the output voltage are equal, Figure 5 shows the sensor through which the current flows and R_{swon}. Looking at Fig. 5, it seems that M currents flow through the switch resistors on the row side because current flows through all the selected row resistors. When the switch resistance in each row is, V_{OUT} is expressed as follows :

$$V_{OUT} = \frac{R_s}{R_s + R_{ij} + R_{swon}(M+1)} V_{DD} \qquad (5)$$

The switch resistance is more extensive than usual and affects the reading accuracy.

C. Metal Resistance Effect

Conventionally, the influence of this metal resistance has been ignored. However, when the array size is large, the effect of metal resistance causes more severe problems than switch resistance. This is a problem that cannot be avoided by increasing the driving force [4]. Fig.6 shows the metal resistance Simplified circuit of the column resistor. Since current flows through all the column sensor resistors and the switch resistor, the i-th sensor has (2M-i+1) metal resistors.

Therefore, V_{OUT} is expressed as follows:

$$V_{OUT} = \frac{R_s}{R_s + R_{ij} + \sum_1^i (M-i) R_{metal}} V_{DD} \qquad (6)$$

The effect of metal resistance is more dependent on array size than switch resistance. Fig. 7 shows a simplified circuit diagram that considers the effects of switch resistance and metal resistance.

Therefore, considering both the metal resistance and the switch resistance, V_{OUT} is expressed as follows :

$$V_{OUT} = \frac{R_s V_{DD}}{R_s + R_{ij} + R_{swon}(M+1) + (N+1)R_{metal} + \sum_1^i (M-i) R_{metal}} \qquad (7)$$

III. SIMULATION RESULT

To verify the proposed method, the simulation was carried out using MATLAB/Simulink.For example, the simulation was performed using parameters of 8 × 8, sensor resistance of 100 kΩ, and metal resistance of 10 Ω. Fig. 8 shows a measurement resistance map. The measurement error became larger toward the right or lower sensor for the measured sensor resistance value. The maximum measurement error was used as the measurement error. The measurement error rate used was expressed as follows:

$$Error = \frac{R_s - R_{ij}}{R_{ij}} \times 100 - 100 \qquad (8)$$

The actual sensor resistance varies. As the current flowing in the selected column changes, it is expected that metal resistance will also change. Consider the case where the sensor resistance is typically distributed to determine that range. The metal resistance was set to 10Ω, and the average sensor resistance value was set to 100kΩ. Each of the resistance value is set randomly by using the MATLAB function randn(). Standard deviations of the resistance distribution were set around 10, 50, 100, 500, 1k, 5k, and 10kΩ.The simulation was run five times for each standard deviation, and the average value was used. Figure 9 shows the simulation results. The reading accuracy deteriorated significantly from 1% in the ratio of the standard deviation to sensor resistance. Large variations cannot be tolerated in this circuit.

To analyze the effect of switch and metal resistance on reading accuracy, $R_{swon,}$ and R_{metal}. The parameters in Fig. 10 were set to an array size of 16 x 16 and all sensor resistors were set to 100 kΩ, and the switch resistors were changed. It is shown that the switch resistance in Fig. 10 is linear concerning the reading accuracy. The parameters in Fig. 11 are set with a metal resistance of 10Ω, an array size of 16 × 16, the sensor resistance was changed. Fig. 11 shows that

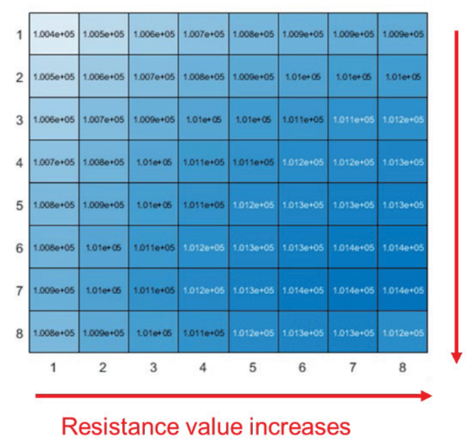

Fig.8 Sensor resistance measurement map

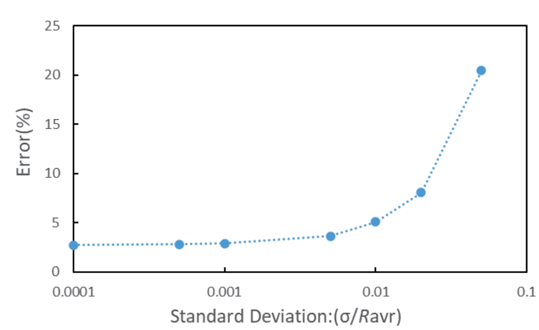

Fig9 Readout error analysis when the resistance values have variation

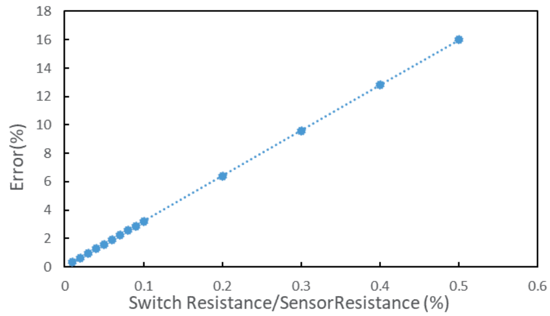

Fig10. Effects of the switch resistance on readout accuracy

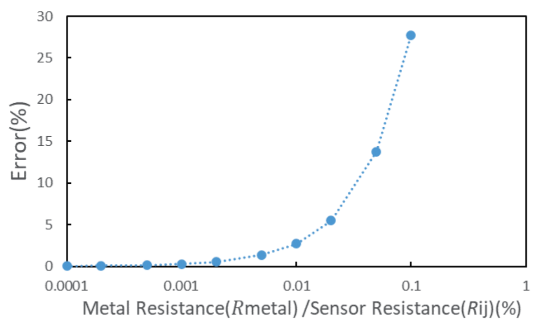

Fig11. Effects of the metal resistance on readout accuracy

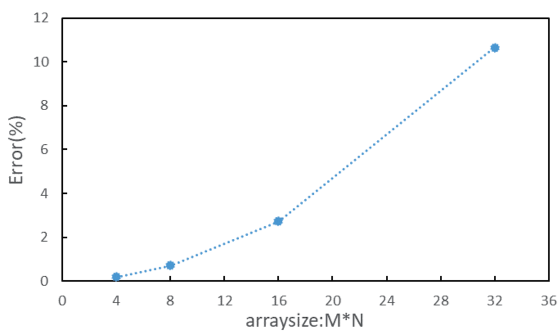

Fig12. Effects of the Array Size on readout accuracy

reading accuracy has a large exponential effect on metal resistance. Since the gas sensor resistance value is 100kΩ or more, the reading accuracy is sufficient even under the influence of parasitic resistance.

The relationship between reading accuracy and array size is also simulated as a factor that increases non-ideality. The simulated arrays are 4x4, 8x8, 16x16, 32x32. The wiring resistance was set to 10 Ω. Figure 12 shows that the reading accuracy deteriorated exponentially as the array size increased.

Finally, the design guidelines for the gas sensor system are shown. In the proposed circuit, each row is heated, and the same voltage is applied to the same row, so it is required that the sensor resistances in the same row have similar resistance values and the required power is the same. Also, since the applied voltage cannot avoid the influence of parasitic resistance such as switch resistance and metal resistance, the sensor with low required power should be placed on the right and bottom. Increasing the sensor resistance value can reduce the effect of parasitic resistance, but it is a trade-off that reduces power. Therefore, the required measurement accuracy is determined better to determine the array size and sensor resistance value.

IV. Conclusion

We proposed a new readout method for self-heating a 2-D cross-point resistor sensor array using a DC-DC converter. The proposed switch and metal resistance calibration evaluated the non-ideal and adverse effects of switch and metal resistance. Finally, It provided design guidelines for achieving self-heating and high-precision readout of the resistance sensor array. It indicated the need to set the sensor resistance value of the array correctly.

Acknowledgements

This work was performed under the Research Program for Next Generation Young Scientists of "Network Joint Research Center for Materials and Devices: Dynamic Alliance for Open Innovation Bridging Human, Environment and Materials.

References

[1] G. Yoshikawa, T. Akiyama, F. Loizeau, K. Shiba, S. Gautsch, T. Nakayama, P. Vettiger, N. F. de Rooij, M. Aono, "Two Dimensional Array of Piezoresistive Nanomechanical Membrane-Type Surface Stress Sensor (MSS) with Improved Sensitivity", Sensors, vol. 12, pp. 15873, 2012

[2] Hong Liu, Yuan-Fei Zhang, Yi-Wei Liu, Ming-He Jin, "Measurement errors in the scanning of resistive sensor arrays", *Sensors and ActuatorsA: Physical*, pp. 198-204, 2010

[3] Y. Shiiki and H. Ishikuro, "A High Accuracy Opamp-less Interface Circuit for 2-D Cross-Point Resistive Sensor Array with Switch Resistance Calibration," *2019 IEEE Asia Pacific Conference on Circuits and Systems (APCCAS)*, Bangkok, Thailand, 2019, pp. 105-108

[4] J. Wu et al., "A novel two-wire fast readout approach for suppressing cable crosstalk in a tactile resistive sensor array", Sensors, vol. 16, no. 5, pp. 720, 2016