Impact of Lateral SnO₂ Nanofilm Channel Geometry on a 1024 Crossbar Chemical Sensor Array

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ABSTRACT: We propose a rational strategy to fabricate thermally robust, highly integrated molecular and gas sensors utilizing a lateral SnO₂ nanofilm channel geometry on a 1024 crossbar sensor array. The proposed lateral channel geometry substantially suppresses the detrimental effects of parasitic interconnect wire resistances compared with those of a conventional vertical sandwich-type crossbar array because of its excellent resistance controllability. A conductive oxide top-contact electrode on the lateral SnO₂ nanofilm channel enhances the thermal stability at temperatures of up to 500 °C in ambient air. Integrating this lateral SnO₂ nanofilm geometry with analog circuits enables the operation of a 1024 crossbar sensor array without selector devices to avoid sneak currents. The developed 1024 crossbar sensor array system detects the local spatial distribution of the molecular gas concentration. The spatial data of molecular concentrations include molecule-specific data to distinguish various volatile molecules based on their vapor pressures. Thus, this integrated crossbar sensor array system using lateral nanofilm geometry offers a platform for robust, reliable, highly integrated molecular and gas sensors.

KEYWORDS: chemical sensor array, crossbar array, thermal stability, metal oxide, SnO₂ nanofilm, spatial chemical mapping

Chemical sensor arrays, with multiple chemical sensors integrated on a chip, are attracting increasing interest in applications in the fields of healthcare,1,2 environmental and food monitoring,3−5 and industrial production.6,7 The biomimetic concept of chemical sensor arrays is inspired by the biological olfactory system. Numerous olfactory receptors, which enable efficient combinatorial coding, are essential for distinguishing complex odors consisting of hundreds or thousands of different chemicals.8,9 In a sensor array, chemical sensors mimic olfactory receptors, indicating the significance of large-scale integration of various sensors on a chip. In addition, the high degree of redundancy of integrated sensors enables reliable sensor operation and signal amplification via data processing.10,11 To achieve this large-scale integration of sensors, adapting the crossbar array structure is required, as this structure enables the highest device density with a simple interconnected configuration.12−14

Although crossbar arrays have been intensively studied for decades in memory devices,15−17 a few chemical sensor arrays with crossbar geometries are reported.18−20 In previous studies, the sensor channel material was deposited on crossbar comb-shaped electrodes, which extended the conventional configuration of non-crossbar gas sensor arrays to crossbar structures. In sensors with bottom-contact electrode structures, the electrode-sensor channel interfacial electrical properties are generally not well defined.21−23 The inherent variation of interfacial electrical properties may cause instability and variability issues in nanoscale channel devices suited for large-scale integration.24−26 The parasitic effects of interconnect wire resistances on the measured resistances are another essential issue in highly integrated crossbar array devices.27−30 However, the effect of wire resistance in crossbar chemical sensor arrays has not been considered in detail. Therefore, a reliable, crossbar-compatible configuration of sensor channels and electrodes is required to establish a highly integrated chemical sensor array.

Here, we propose a lateral SnO₂ nanofilm channel geometry for use in a highly integrated crossbar chemical sensor array. SnO₂ nanofilm channels are bridged between two top-contact electrodes in the lateral channel crossbar array geometry (Figure 1), enabling precise control of the electrode-sensor channel interfacial electrical properties. The lateral channel geometry allows us to control the channel resistance up to the MΩ to GΩ range by controlling the sensor channel length, width, and thickness, suppressing the effects of the parasitic interconnect wire resistances. In addition, the exposed surface...
area/volume ratio, which is a critical parameter of chemical sensors that maximizes the adsorption probability of analyte molecules on sensor surfaces,\textsuperscript{31−33} is enhanced using the lateral channel geometry compared to that of the conventional vertical channel geometry.\textsuperscript{15−17} The large exposed surface area/volume ratio of the lateral channel also enables efficient surface functionalization using noble-metal nanoparticles, self-assembled monolayers (SAMs), etc.\textsuperscript{34−38} In this study, the effects of the lateral channel geometry were evaluated regarding the reliabilities of resistance measurements and thermal stabilities of sensors by fabricating a 1024 (32 × 32) crossbar chemical sensor array.

![Figure 1](image1.png)

**Figure 1.** Schematic diagrams of lateral and vertical channel geometries of crossbar sensor arrays. Unit structures in a crossbar array (single crosspoint) are shown.

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700 °C to control the resistivity, resulting in a polycrystalline SnO\textsubscript{2} structure (Figure S1). Two top-contact electrodes are then formed on the channels. Insulating SiO\textsubscript{2} layers are deposited between the electrodes at the crosspoints. Highly conductive thin Sb-doped SnO\textsubscript{2} (ATO: antimony-doped tin oxide) layers are introduced as the contact electrodes between the SnO\textsubscript{2} channels and Pt electrodes, yielding reliable interfacial electrical properties.\textsuperscript{40} The electrical current flows horizontally in the SnO\textsubscript{2} nanofilm channels between the two top-contact ATO electrodes (Figure 2b). Figure 2c shows the dependence of the two-probe resistance \( R \) on the channel length \( L \) of the lateral SnO\textsubscript{2} nanofilm device. The \( R−L \) characteristics are evaluated to determine the contact resistance using the transfer length method (TLM).\textsuperscript{41} The fitted line is extrapolated to \( R \sim 0 \) at \( L = 0 \), indicating negligible contact resistance. Good ohmic characteristics are observed using the ATO contacts, as shown in the inset of Figure 2c. A 1024 (32 × 32) crossbar sensor array is fabricated based on the lateral channel geometry and evaluated using the developed measurement systems (Figure 2d).\textsuperscript{42,43} A crossbar sensor array with the conventional vertical channel geometry is also fabricated for comparison (Figure S2).

**RESULTS AND DISCUSSION**

Figure 2a shows the fabrication process of the lateral channel crossbar sensor array. First, the sputtered SnO\textsubscript{2} nanofilm, which is widely employed as a chemical sensor material,\textsuperscript{39} is patterned. The SnO\textsubscript{2} nanofilm channels are then annealed at 700 °C to control the resistivity, resulting in a polycrystalline SnO\textsubscript{2} structure (Figure S1). Two top-contact electrodes are then formed on the channels. Insulating SiO\textsubscript{2} layers are deposited between the electrodes at the crosspoints. Highly conductive thin Sb-doped SnO\textsubscript{2} (ATO: antimony-doped tin oxide) layers are introduced as the contact electrodes between the SnO\textsubscript{2} channels and Pt electrodes, yielding reliable interfacial electrical properties.\textsuperscript{40} The electrical current flows horizontally in the SnO\textsubscript{2} nanofilm channels between the two top-contact ATO electrodes (Figure 2b). Figure 2c shows the dependence of the two-probe resistance \( R \) on the channel length \( L \) of the lateral SnO\textsubscript{2} nanofilm device. The \( R−L \) characteristics are evaluated to determine the contact resistance using the transfer length method (TLM).\textsuperscript{41} The fitted line is extrapolated to \( R \sim 0 \) at \( L = 0 \), indicating negligible contact resistance. Good ohmic characteristics are observed using the ATO contacts, as shown in the inset of Figure 2c. A 1024 (32 × 32) crossbar sensor array is fabricated based on the lateral channel geometry and evaluated using the developed measurement systems (Figure 2d).\textsuperscript{42,43} A crossbar sensor array with the conventional vertical channel geometry is also fabricated for comparison (Figure S2).

First, the resistances of the single sensors were measured in the lateral and vertical channel geometries. Figure 3a,b shows current \( I \) as a function of voltage \( V \) of the 60 single devices. Nonlinear \( I−V \) characteristics are observed for some vertical channel devices, indicating Schottky barrier junctions between the Pt bottom electrodes and the SnO\textsubscript{2} nanofilm channel. The Schottky barriers cause unreliable \( I−V \) characteristics and resistance variabilities in vertical channel devices. Conversely, ohmic \( I−V \) characteristics are observed for all lateral channel devices because of the double top-contact geometries and thin

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**Figure 2.** (a) Fabrication process of the lateral SnO\textsubscript{2} nanofilm channel crossbar sensor array. (b) Top- and side-view schematic diagrams of lateral SnO\textsubscript{2} nanofilm channel sensor devices. (c) Channel length dependence of the two-probe resistances of the SnO\textsubscript{2} nanofilm devices; the inset shows the current \( I \) as a function of voltage \( V \) of a typical device. (d) Images of the measurement system and fabricated crossbar sensor array chip.
energy barriers between Pt and highly doped ATO. Therefore, the unreliable electrical characteristics of the bottom-contact vertical channel devices are overcome in the top-contact lateral channel devices. The sensor resistance distribution in a crossbar array was then evaluated using the 1024 crossbar sensor array devices, consisting of 32-row and -column electrodes. Figure 3c,d shows the resistance deviations of the crossbar devices from the average resistance of the 60 single devices. Unusually high resistance devices in the lateral channel crossbar devices originate from unexpected failures during device fabrication, such as particles located at the SnO2 nanofilm channel on substrates, partial removal of electrodes at steps of crosspoints or channels, and incomplete photoresist development. Histograms of the relative frequencies of the 1024 resistances in the crossbar array devices with (e) vertical or (f) lateral channel geometries. Cumulative distribution functions of the 1024 resistances in the crossbar array devices with (g) vertical or (h) lateral channel geometries.

Figure 3. I–V characteristics of the 60 single devices with (a) vertical or (b) lateral channel sensor arrays. Heatmap of the resistance deviations of crossbar devices from the average resistance of the 60 single devices in the (c) vertical and (d) lateral channel crossbar array devices. Unusually high resistance devices in the lateral channel crossbar devices originate from unexpected failures during device fabrication, such as particles located at the SnO2 nanofilm channel on substrates, partial removal of electrodes at steps of crosspoints or channels, and incomplete photoresist development. Histograms of the relative frequencies of the 1024 resistances in the crossbar array devices with (e) vertical or (f) lateral channel geometries. Cumulative distribution functions of the 1024 resistances in the crossbar array devices with (g) vertical or (h) lateral channel geometries.

Figure 4. (a) Circuit model of a crossbar sensor array. The measured $R_s$, $r_v$, and $r_l$ values used in the simulations. (b) Deviations of the calculated crossbar array resistances from the actual sensor resistance $R_s$ as a function of the number of sensors in the crossbar array. The line and error bars indicate the averages and ranges of the calculated resistance deviations, respectively. (c) Deviations of the calculated 1024 crossbar array resistances from $R_s$ as a function of $R_s$. The line and error bars indicate the averages and ranges of the calculated resistance deviations, respectively.
array consisting of the sensor resistance ($R_s$), unit resistance of row interconnect wires ($r_{i,r}$), and unit resistance of column interconnect wires ($r_{i,c}$). The resistances of the lateral and vertical channel crossbar arrays were calculated by numerically simulating the measurement circuit with identical $R_s$ values for all crosspoints. The calculated resistances in a crossbar array are higher than the given sensor resistance $R_s$ because of the additional interconnect wire resistances. Figure 4b shows the deviations of the calculated crossbar array resistances from the sensor resistances $R_s$. The calculated deviation corresponds to the measured resistance deviation (Figure 3c,d). A 1024 mapping of the calculated resistance deviations is shown in Figure S3. As shown in Figure 4b, the resistance deviation of the vertical channel geometry is significantly higher than that of the lateral channel geometry, reproducing the over-estimations of resistances in the vertical channel crossbar array (Figure 3e). In addition to the average deviation, the resistance variability is significantly higher for the vertical channel geometry. The large variability in measured resistances renders estimation of the sensor resistances in sensor array applications challenging. Conversely, the lateral channel crossbar array exhibits a low deviation (<10%) and variability, even in the 4096 ($64 \times 64$) crossbar array (Figure 4b). The resistance deviation increases as the number of arrays increases. The crossbar array resistance is generally higher than the single device resistance because the wire resistance is added to the sensor resistance in a crossbar array structure (Figure 4a). Therefore, the increase in the total wire resistance, which is the summation of $r_{i,r}$ and $r_{i,c}$ in the array, may cause the larger resistance deviation in the larger array. To investigate the effects of the interconnect wire resistances, the resistance deviation of the 1024 sensor array is calculated using varying $R_s$ with constant interconnect wire resistances (Figure 4c). The resistance deviation rapidly increases for smaller $R_s$ values, with the contributions of $r_{i,c}$ and $r_{i,r}$ to the total resistance enhanced. Therefore, $R_s$ should be larger than $r_{i,c}$ and $r_{i,r}$ for reliable resistance measurements. $R_s$ is defined as $\rho L/(W t)$ and $\rho t/(L W)$ in the lateral and vertical geometries, respectively, where $\rho$, $L$, $W$, and $t$ are the resistivity, length, width, and thickness of the channel, respectively. The available $R_s$ range of the lateral channel geometry is much broader than that of the vertical channel geometry because $L$ and $W$ are larger than $t$ in a typical fabrication process. Note that resistance normalization in sensing operation effectively cancels an intrinsic resistance variability that corresponds to the resistance distribution of the single devices (“60 single devices” in Figure 3c,d). However, when extrinsic resistance, such as wire resistance, is added to the sensor resistance, the obtained sensor responses decrease from intrinsic values even after the normalization because of the reduced contribution of sensor resistance to the measured total resistance. Thus, the lateral channel geometry enables reliable sensor measurements by suppressing the parasitic effects of interconnect wire resistance in a large-scale crossbar array.

The electrode–SnO$_2$ nanofilm interfacial electrical properties of the lateral channel devices were then investigated because these properties critically affect the performances of nanoscale electron devices. Low-work-function metals, such as Ti, Al, and Cr, are generally used as contact electrodes on nanoscale oxide semiconductors because of their low Schottky barriers and good adhesion to oxides. However, these metals are easily oxidized and become insulators or semiconductors under high-temperature chemical sensing conditions, causing degradation in sensor performance.

The thermal stability of chemical sensors is one of the most important issues because sensor and electrical device operation under high-temperature condition is essential in the chemical industry, aerospace application, frame detection, etc. To overcome this thermal degradation, ATO, which is a thermally stable heavily doped n-type oxide semiconductor, was utilized as the top-contact electrode on the SnO$_2$ nanofilm channels. Figure 5a,b shows the $I$–$V$ characteristics of the lateral SnO$_2$ nanofilm devices with ATO or conventional Ti-contact electrodes, respectively. The ATO- and Ti-contact devices exhibit good ohmic characteristics just after fabrication. The ATO-contact device maintains good ohmic characteristics after thermal loading at 500 °C for 10 h, whereas the resistance of the Ti-contact device increases significantly during the thermal stability test (Figure S4 shows the thermal stability tests at temperatures of <500 °C). To clarify the origin of the resistance increase, the contact resistance, which is the electrode–SnO$_2$ nanofilm interfacial electrical resistance, was determined by combining two- and four-probe measurements of four-terminal devices. Figure 5c shows the contact resistances of the ATO- and Ti-contact devices under thermal loads of 500 °C in ambient air. The contact resistance of the Ti-contact device increases rapidly after 5 h thermal load, possibly due to the formation of semiconducting TiO$_x$ resulting in significant degradation in the $I$–$V$ characteristics (Figure S5b). In contrast, the contact resistance of the ATO-
contact device is sufficiently low during the thermal stability tests up to 500 °C. The outstanding thermal stability of the ATO-contact lateral channel SnO₂ nanofoil sensor is challenging to achieve using typical bottom-contact sensors, such as conducting polymers. Therefore, the proposed ATO-contact lateral channel crossbar sensor array exhibits promise in long-term chemical data collection under harsh environments required in big data analysis.54,55 Finally, we demonstrated the detection of the local spatial distribution of molecular concentration as a possible application of a reliable lateral SnO₂ nanofoil crossbar sensor array. A spatial chemical mapping system is useful for safety purposes by detecting and localizing harmful chemicals in public facilities.56,57 NO₂ sensing was initially performed to verify the fundamental chemical sensing properties of the SnO₂ channels, including temperature and concentration dependences. The SnO₂ nanofoil sensors successfully respond to NO₂ gas flow depending on the concentration and sensor temperature (Figure S5), exhibiting the typical chemical sensing characteristics of metal oxide semiconductor channels.58–60 Sensor resistance controllability of the lateral SnO₂ channel structure is demonstrated by adjusting channel length, indicating that resistance can be controlled without significant change in sensor response (Figure S6). To evaluate the local spatial distribution of molecular concentration on the sensor array chip, vaporized molecules are detected using the 1024 lateral crossbar sensor array by placing an ethanol droplet on the side of the sensor chip (Figure 6a). Figure 6b shows the row-averaged sensor responses of the 1st, 16th, and 32nd rows to ethanol vapor from a droplet. Ethanol was mounted at 60 s adjacent to the 32nd row. Data of rows 21, 22, 27, and 28 are not shown because of a failure in the I/O connector of the measurement board. The difference between 1st-row side and 32nd-row side was presumably caused by disturbance of ambient airflow around the sensor array chip. (d) Calculated spatial distribution of ethanol concentration during vaporization (initiated at 0 s) and diffusion processes. (e) Calculated molecular concentrations as functions of row number or distance from the droplets. The molecular concentrations in the region of each row at 10.2 s are averaged. (f) Time dependence of the slopes of the row-averaged sensor responses to methanol, ethanol, 1-propanol, and 1-butanol droplet sensing. The slope values were averaged for three measurements. (g) Relationship between the maximum slope ($a_{max}$) observed in (f) and alcohol vapor pressure. The plotted points and upper and lower error bars represent the average, maximum, and minimum values of $a_{max}$ among four measurements.
of Figure 6b). The sensor resistance decreases when ethanol is
mounted (60 s) and then recovers to the initial values, indicating that the 1024 lateral channel crossbar sensor array
detects ethanol vapor from the droplet. The response of the
row near the droplet (32nd row) is higher than that of the row
on the other side (1st row). Conversely, the response of the 1st
row is higher than that of the 32nd row when the ethanol
droplet is placed at the opposite (1st-row) side, as shown in
Figure 6c. The spatial distribution of the sensor response is
attributed to the spatial distribution of the ethanol
congcentration because of the reliable, uniform resistance
measurements of the lateral channel crossbar sensor array
(Figure 3d). To validate the correlation between the spatial
distributions of the sensor responses and molecular concen-
tration, the vaporization and diffusion processes were numeri-
cally analyzed using a 3D finite element method. Figure 6d
shows the spatial concentration distribution of ethanol vapor
diffused from a droplet near the sensor array chip. The
molecular concentration is higher near the droplet and
decreases with distance from the droplet, resulting in a spatial
concentration gradient. The sensor response distribution
shown in Figure 6c is due to the molecular concentration
distribution because the sensor response increases at higher
molecular concentrations. Thus, the lateral channel crossbar
sensor array detects the local distribution of the molecular
concentration. The observed spatial distribution of sensor
response, corresponding to the spatial ethanol concentration
distribution, is determined by the properties of ethanol. The
spatial distributions of the molecular concentrations in the
sensor array region were calculated for various alcohol
molecules to investigate the correlation between the concentra-
tion distribution and molecular properties. Figure 6e shows the spatial concentration distributions of methanol, ethanol, 1-propanol, and 1-butanol vapors, indicating that
smaller molecules display higher concentration and spatial
gradients. The vapor pressure and diffusion constant of the
molecular species affect the spatial concentration distribution
carried by vaporization and diffusion. The influences of these
parameters were numerically investigated, as shown in Figure
S7, indicating that vapor pressure dominates the concentration
gradient of the experimental system and measured alcohols.
The vapor pressure-dependent spatial concentration gradient
was experimentally examined using a 1024 crossbar sensor
array. Figure 6f shows the slopes of the row-averaged sensor
responses to various alcohol droplets (methanol, ethanol, 1-
propanol, and 1-butanol): slope \( a = d(R_p/R_g)/dD \), where \( R_p \)
and \( D \) are the resistance in air, resistance with vaporized
molecules, and distance along the column direction in the
sensor array chip, respectively. Steeper response slopes are
observed for the smaller molecules with higher vapor pressures,
as predicted by the simulations (Figure 6fg). The response
slope of the sensor array may assist in distinguishing vaporized
molecular species based on their vapor pressures. In addition
to the vapor-pressure-based molecular discrimination, mole-
cular-selective chemical sensing can be achieved by combining
the lateral SnO\textsubscript{2} channel structure with surface functionaliza-
tion techniques such as noble-metal nanoparticles, self-
assembled monolayers (SAM), etc.\textsuperscript{34–38} These surface
functionalization efficiently enhance molecular selectivity
because of the large exposed surface area/volume ratio of the
lateral SnO\textsubscript{2} nanofilm channel structure. Therefore, the
proposed lateral SnO\textsubscript{2} nanofilm channel crossbar sensor
array might be a promising platform for complex molecular
discrimination using surface functionalization techniques.

## CONCLUSIONS

We showed the effect of the lateral Sn\textsubscript{2} nano-
mfilm channel geometry on a 1024 crossbar chemical sensor array. The proposed lateral channel geometry enabled a larger resistance
range of up to M\textOmega{} to G\textOmega{} compared to that of the
conventional vertical channel geometry, suppressing the
parasitic effects of interconnect wire resistances in a crossbar
array. A reliable measurement of the resistance of 1024 sensors
was achieved using the lateral channel crossbar array without
selector devices based on sensor resistance engineering. ATO
was utilized as the top-contact electrodes of the lateral Sn\textsubscript{2}
nanofilm channel, and these devices showed excellent thermal
stabilities at temperatures of up to 500 °C compared with
those of typical Ti-contact devices. Chemical sensing of the
1024 lateral channel crossbar sensor array was performed by
detecting alcohol molecules vaporized from a droplet near the
sensor chip. The sensor response distribution, which reflected
the spatial distribution of the molecular concentration,
was observed for various alcohol molecules, including methanol,
ethanol, 1-propanol, and 1-butanol. The numerical simulations
confirmed that the spatial slope of the sensor response of the
1024 sensor array correlated with the vapor pressure of each
alcohol, indicating the possibility of molecular discrimination
based on the slope of sensor response.

## METHODS

### Device Fabrication.

The vertical or lateral channel crossbar sensor arrays were fabricated on 100 nm SiO\textsubscript{2}/p-type Si substrates
using radiofrequency (RF) sputtering, photolithography, and lift-off
techniques. The sizes of the sensor array chips were 9 x 9 mm\textsuperscript{2}, and the areas of the crossbar sensor arrays were 6 x 6 mm\textsuperscript{2}. For the
conventional vertical channel crossbar array, the 200 nm Sn\textsubscript{2} sensor
channel layers were sandwiched between the bottom (row) (7.5/30
nm Ti/Pt, 25 \textmu{}m width) and top (column) electrodes (18/60 nm
ATO/Pt, 15 \textmu{}m width). The fabricated devices were annealed at 400
°C for 10 min in air to increase the electrical conductivities of the
ATO layers.\textsuperscript{10} For the lateral channel crossbar array, the Sn\textsubscript{2} sensor
channel layers (50 nm thickness and 5 \textmu{}m width) were initially
formed, followed by annealing at 700 °C for 1 h in air. The two top-
contact electrodes (18/120 nm ATO/Pt, 10 \textmu{}m width) were then
formed as the rows and columns of the crossbar array. These row
and column electrode layers were electrically insulated using 70 nm SiO\textsubscript{2}.
The length of the sensor channel between the electrodes was 40 \textmu{}m.
Finally, the devices were annealed at 400 °C for 10 min in air, similar
to the vertical channel crossbar array. Single-sensor devices were also
fabricated via the same process.

### Electrical Characterizations.

The single-sensor resistance was measured using a semiconductor parameter analyzer (4200-SCS, Keithley Instruments, Cleveland, OH) with a probe station. The contact resistance \( R_c \) was calculated as \( R_c = R_{np} - R_{np} \), where \( R_{np} \)
and \( R_{np} \) are the resistances measured using the two- and four-probe
techniques, respectively. A specifically developed measurement system
for the crossbar sensor array was used to measure its resistance.
The measurement system consisted of main and sub-boards. The readout
circuit elements, field-programmable gate array (FPGA), and
transmission control protocol-internet protocol I/O were imple-
mented on the main board. The sensor array and microheater chips
were placed on the sub-board. The microheater chip below the sensor
array chip was fabricated by depositing a 240 nm Pt layer through
a metal mask on a glass substrate. The sensor array chip was heated to
217 °C during chemical sensing using Joule heating of the
microheater (Figure S8). The long-term stability of the Pt
microheater chip was verified for at least 100 h (Figure S9). The
resistances of the 1024 sensors in the sensor array were obtained every 0.6 s. Two types of methods were utilized for the analog front-end circuit. One was denoted the voltage feedback method (VFM), wherein an opamp was used to achieve an imaginary short between the row electrode connecting the target sensor and the other electrodes.42 The VFM requires a high-drivability opamp because its output current flows into all resistive sensors in parallel with the target sensors for unity gain feedback. Such a high-output-current opamp consumes a large area if the circuit was implemented in the complementary metal oxide semiconductor (CMOS) process. Thus, an opamp-less method was also designed for our sensor readout circuit.43 This opamp-less readout did not suppress sneak currents while reading resistance but controlled them with various switch selections. The output voltage was determined using the ratio of the parallel sensor resistance to the reference resistance. In the opamp-less interface circuit, the measured data of defective devices or electrodes were compensated via linear interpolations using data from adjacent rows or columns because the data of the defective components affect the entire signal in the sensor array. The total defective data was <7% of all measured data. In both measurement systems of VFM and opamp-less, each sensor in a crossbar array was operated by voltage-biased mode during resistance measurements.

**Circuit Simulations.** To analyze the overestimations of readout resistances, a circuit simulation was developed in MATLAB/Simulink (MathWorks, Natick, MA). The VFM was developed for the analog front end in the simulation. Compared to our amp-less readout method, the VFM is a simple method of analyzing the readout error caused by the metal wire resistance. The opamp parameters in the VFM were set as follows: gain, 60 dB; input impedance, 1000 GΩ; output impedance, 1 Ω; bandwidth, 1 GHz. The input impedance was much higher than that in practice, and therefore its influence on the readout error was ignored. For the analog switches to select the target sensor, all on- and off-resistances were set to 10 Ω and 10 GΩ, respectively, which are common values for a CMOS switch. As shown in Figure 4a, the metal wire resistances $r_{cc}$ and $r_{ff}$ were set to 11.9 Ω. The simulated sensor arrays were 4 × 4, 8 × 8, 16 × 16, 32 × 32, and 64 × 64. As shown in Figure 4c, $r_{cc}$ and $r_{ff}$ were set to 20 Ω, and simulations were conducted at sensor resistance values of 100 Ω, 1, 10, and 100 kΩ and 1 and 100 MΩ.

**Chemical Sensor Operations.** For the chemical sensing of vaporized molecules, 0.05 mL of liquid alcohols was mounted 5 mm from the sensor array in atmospheric air. Methanol (99.8%), ethanol (99.5%), 1-propanol (99.5%), and 1-butanol (99.0%) were evaluated. These alcohol molecules evaporated and diffused over the sensor array chip, changing the resistances of the sensors. The sensor response was calculated as $R/D$ where $R$ and $D$ are the sensor resistances in atmospheric air and in the presence of alcohol molecules, respectively.

**Molecular Diffusion Simulations.** COMSOL Multiphysics (version 5.6, COMSOL, Burlington, MA) was used to calculate the spatial distribution of the vaporized molecule concentration. Molecular diffusion was modeled under unstirred air under standard conditions (25 °C, 1 atm). The effects of convection and migration were not considered in this study. Open boundary conditions were applied to the side and top boundaries of the simulated region. The sensor region in the simulation was designed to correspond to the actual dimensions. The distance between the evaporation source and sensor array edge was 5 mm. The convection-diffusion equation was applied to calculate molecular diffusion: $\frac{\partial c}{\partial t} + \nabla j = R$, $j = -D \nabla c$, where $c$, $R$, and $D$ are the molecular concentration, evaporation rate, and diffusion coefficient, respectively. The parameters used in the simulations are listed in Table S1.

**ASSOCIATED CONTENT**

*Supporting Information* The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssensors.1c02173.

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Effects of annealing on the crystallinitities and resistivities of the SnO2 nanofilms, fabrication process of the vertical channel geometry crossbar sensor array, 1024 mapping of the calculated resistance deviation, thermal stability tests of the ATO- and Ti-contact lateral channel devices, NO2 sensing characteristics of the 1024 lateral channel crossbar sensor arrays, sensor response of lateral SnO2 channel devices with varied channel length, effects of vapor pressure and the diffusion constant on vaporization and diffusion of alcohol molecules, sensor chip temperature control via the Pt microheater chip, long-term stability test of Pt microheater chip, and parameters of the molecular diffusion simulations (PDF)
Monitoring.

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Notes

The authors declare no competing financial interest.

Acknowledgments

This work was supported by KAKENHI (Grant Numbers JP20H02208 and JP18H05243). T.T. was supported by the Japan Science and Technology Agency (JST) PRESTO Grant Number JPMJPR19M6, Japan. T.T., G.Z., K. Nagashima, and T.Y. were supported by JST CREST (Grant Number JPMJCR1912, Japan). This work was performed under the Cooperative Research Program of the Network Joint Research Center for Materials and Devices and the Japanese Ministry of Education, Culture, Sports, Science, and Technology (MEXT) Project of the Integrated Research Consortium on Chemical Sciences.

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