THEORETICAL AND EXPERIMENTAL VALIDATION ON THE TUNING CAPABILITY OF A PERCOLATION-BASED GAS SENSOR.

Farhan Sadik Sium[1], Shakir ul Khan[1], Seungbeom Noh[1], and Hanseup Kim[1]
[1]Electrical and Computer Engineering, University of Utah, USA

ABSTRACT

This paper reports the theoretical and experimental validation of the tuning capability of a novel sensor based on percolation as the operation principle. To enable the tuning capability, an array of both the commercial and the microfabricated MEMS gas sensors was constructed. The array size and the degrees of freedom (DOF) for current flows within the array were manipulated. Theoretical and experimental results validated (1) that the percolation-based sensor tuning was feasible; (2) that the tuning became more deterministic with increasing array sizes and (3) the tuning threshold became lower with increasing DOF for current movement.

KEYWORDS

Percolation theory, switching tuning, switching uncertainty, gas sensor.

INTRODUCTION

Increasing demands are recently found in an effort to monitor environments through various distributed sensor nodes, and distributed gas sensor nodes have become of some interests in research communities. However, distribution of gas sensors has been mostly impractical with current technology, as conventional gas sensors as well as associated electronics, such as a wireless tethering module, tend to consume significant amounts of power and thus shorten the lifetime down to an impractical level when supported by a battery.

Such a limited lifetime issue of distributed gas sensors was addressed by constructing a normally dormant gas sensor or so-called a near-zero-power gas sensor by some research groups [1-3]. One example was a molecular-bridge mediated gas sensor developed by the authors [5]. The molecular-bridge gas sensor utilized the capture of a target gas as a switch element to allow and disallow current flow to activate the whole sensor node.

However, the previously developed molecular-bridge gas sensor inevitably experienced statistical uncertainty due to non-uniformity of a nanogap size across a wafer as well as random or uncontrolled behaviors of gas molecules entering to the nanogap.

As a method to minimize the device uncertainty, a statistical concept of percolation was previously suggested and validated with limited experimental results with array size variations [4]. However, it lacked a holistic modeling and any expansion to other parameters, failing to provide fundamental understanding on its applicability to device operation.

This paper reports an improved simulation and theoretical modeling of the switching behavior of a percolation-based gas sensor as well as experimental results as a proof.

SIMULATION AND THEORY

A theoretical model for percolation-based sensing was developed through Monte Carlo simulation that computed numerous case probabilities from various design choices. Specifically, the model performed 500 numbers of trials for specific occupancy within a matrix (Fig.1-(A)), and the percolation probability was determined by dividing the total number of percolated cases by the total trial numbers. Whether a matrix was percolated or not was decided by the existence of a spanning cluster of occupied nodes. The developed theoretical model allowed a wide range of input parameters for grid sizes and shapes (or degrees of freedom) to facilitate the prediction and comparison of distinctive designs.

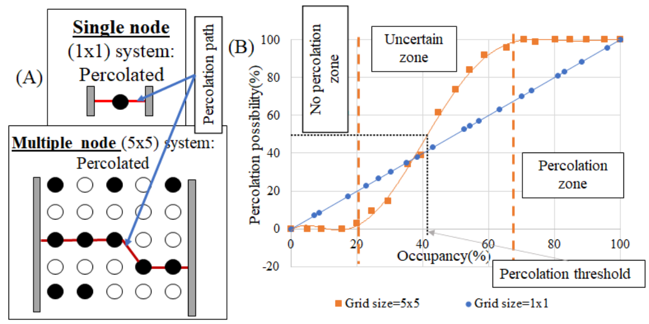

Figure 1: (A) Multiple conductive node system can mimic a single node switching system. Harmonical accord among several nodes result in percolation, depending on forming a conductive path. (B) Simulation results of percolation probability vs. occupancy. The probability could be categorized into three sections: no percolation, uncertainty and percolation zones. The middle zone is the uncertainty-zone that needs to be minimized.

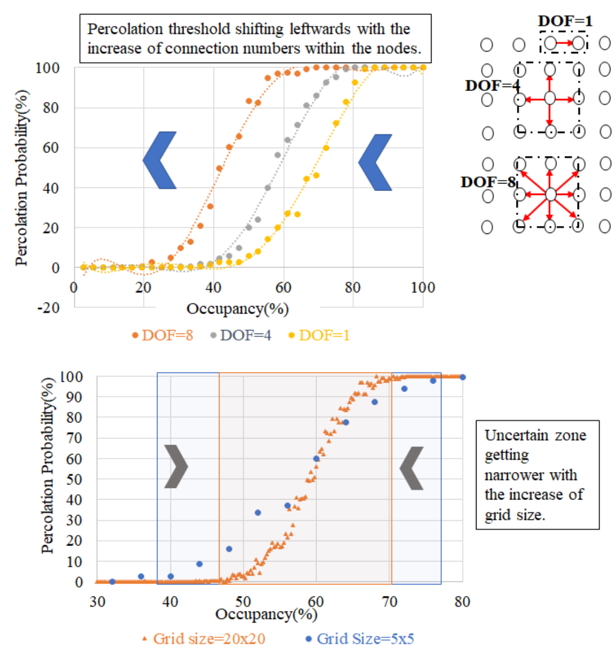

Figure 2: Simulation results of percolation probability vs occupancy depending on (top) degrees of freedom or lattice shapes and (bottom) the array sizes. (Top) As the degrees of freedom (DOF) for current flow through a network of individual stations increase, percolation threshold shifted leftwards or lower. With the increase in grid sizes the system will become more deterministic by shrinking uncertainty zone.

The modeling result showed that (1) a percolation characterizing graph was clearly split into three zones: no-percolation, uncertainty, and percolation zones (Fig.1-(B)); that (2) the uncertainty zone was modulated by changing the degrees of freedom (Fig.2-(top)) and the grid sizes (Fig.2-(bottom)). Thus, these modeling results clearly predicted that the percolation behaviors such as reducing uncertainty and modulating the threshold point could be achieved by design choices.

PROOF OF PERCOLATION IN MACRO LEVEL

To verify the modeling results, a macro-level hardware system was established by connecting multiple units of the MQ-3 commercial ethanol sensor (Vendor: Sparkfun) in various DOFs (Fig. 3-(A)). The circuit diagram is shown in Fig. 3-(B). The digital output pin of the sensor module was attached to the gate of the transistor. Thus, each transistor worked as conductive node for percolation. It was plausible to change percolation controlling parameters by simply altering connection among the nodes. (Fig. 3-(B)). The whole sensors were kept inside a shielded gas testing chamber having dimension of 60 x 30 x 40 cm^3**.** An LED was connected to the end of the circuit output and utilized to verify percolation switching when it was lit up.

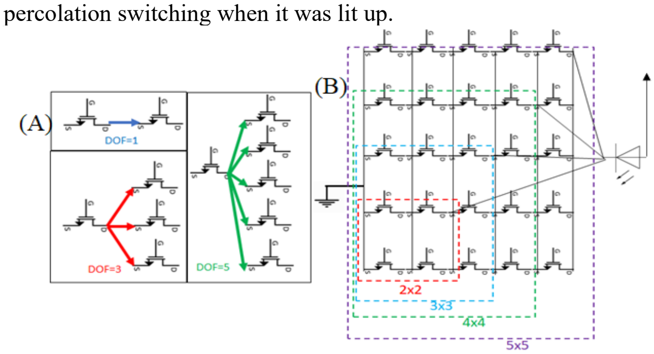

Figure 3. Hardware testing setup diagrams. (A) illustration of variable DOFs realized in multiple units of sensor. (B) circuit diagram for different grid sizes during testing.

(A)

	Grid Size (DOF=5)				
μg/L	1x1	2x2	3x3	4x4	5x5
10	0	0	0	0	0
45	0	0	0	0	0
55	1	0	0	0	0
72	1	1	0	0	0
81	2	3	0	0	0
96	4	3	3	0	0
115	6	7	5	5	0
142	7	10	5	7	0
160	10	10	8	7	7
170	8	11	7	10	10
190	9	11	8	8	11
200	11	12	11	12	11
230	12	12	12	12	12
400	12	12	12	12	12

Concentration of Ethanol in the chamber; No. of events where percolation occurred (out of 12)

Uncertain zone Certain zone

(B)

DOF=5(Grid size 5x5)		DOF=3(Grid size 5x5)		DOF=1(Grid size 5x5)	
μg/L	No. of events where percolation occurred(out of 12)	μg/L	No. of events where percolation occurred(out of 12)	μg/L	No. of events where percolation occurred(out of 12)
45	0	50	0	60	0
55	0	75	0	78	0
72	0	88	0	95	0
81	2	100	0	110	0
96	4	118	0	124	0
115	6	135	1	145	0
142	7	170	5	178	1
160	10	190	6	198	2
170	11	210	8	219	2
190	12	230	9	237	6
200	12	245	11	254	7
230	12	260	11	267	8
255	12	300	12	320	10
300	12	350	12	365	11
400	12	400	12	410	12

Uncertain zone Certain zone Percolation Threshold

Figure 4. (A) As the grid size increased the uncertainty zone was reduced by 30% (B) With the increase of DOFs for current movement within the gird, the percolation tendency increased from 237μ/L to 115μ/L.

The test result showed a matching result to the model prediction. Figure 4-(A) showed that as the grid size (x-axis) increased from 1x1 to 5x5, the uncertainty zone (orange-colored) gradually reduced from a concentration span of 135 µg/L to that of 40 µg/L by 70.4%. Specifically, the 1x1 or a single sensor switched at any concentrations between 55 and 190 µg/L, while the larger grid sensors of 2x2, 3x3, 4x4 and 5x5 responded to gradually narrower concentrations of between 72 and 190 µg/L, 96 and 200 µg/L, 115 and 190 µg/L, and 160 and 200 µg/L. Figure 4-(B) showed that 5x5 sensor arrays lowered the average threshold points from 237 and 210 to 115 µg/L, as they increased the degrees of freedom from 1 and 3 to 5 dimensions. In other words, they demonstrated switching at a lower concentration when their lattice shapes were more prone to become connected. Based on the results it was evident that uncertainty of switching and switching threshold could be tuned by modulating grid sizes and node connections.

PROOF OF PERCOLATION IN MICRO LEVEL

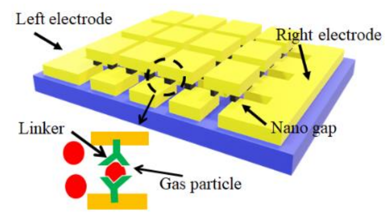

Figure 5: Rhetorical image of the percolation-based gas sensor.

To further verify the modeling prediction on grid sizes vs uncertainties, a micro-level nanogap gas sensor with an array configuration was fabricated based on sacrificial layer removal technique as previously described [3] (Fig.5). This sensor was exposed to a cadaverine gas. The measurement results also confirmed that as the nano-gap array size increased from 1x1 to 36x36, the variance of the amount of gas that is needed for switching gradually decreased from a standard deviation of 15.7 ppm to 2.1 ppm.

CONCLUSION

Both the theoretical and experimental validation on the tuning capability of a percolation-based gas sensor was reported. The theoretical modeling was established based on Monte Carlo Simulation and provided an insightful relationship between switching performance and design parameters. Experimental results confirmed such prediction by theoretical modeling: (1) the tuning of a percolation-based sensor was feasible, (2) the increasing array sizes improved the deterministic character of a switching, and (3) the increasing degrees of freedom lowered the threshold point.

REFERENCES

[1] “Zero-power infrared digitizers based on plasmonically enhanced micromechanical photoswitches”, Qian, Z., Kang, S., Rajaram, V., Cassella, C., McGruer, N.E. and Rinaldi, M., Nature nanotechnology, 12(10), pp.969-973, (2017)

[2] “Ultra-low-power chemical sensor node.”, Khan, S.H., Jung, Y.J., Hsieh, H.C., Wu, T., Mastrangelo, C.H., Kim, H., Broadbent, S.J. and Looper, R. Proceedings of the GOMAC Tech, (2018).

[3] “Development of a Gas Sensor for Green Leaf Volatile Detection”, Khan, S.U.H., Tope, S., Dolpati, R., Kim, K.H., Noh, S., Bulbul, A., Mural, R.V., Banerjee, A., Schnable, J.C., Ji, M. and Mastrangelo, C. IEEE Transducers, pp. 250-253, (2021).

[4] "Statistics-Based Gas Sensor.," Khan, S.U.H., Banerjee, A., Broadbent, S., Bulbul, A., Simmons, M.C., Kim, K.H., Mastrangelo, C.H., Looper, R. and Kim, H., IEEE 32nd International Conference on Micro Electromechanical Systems (MEMS), 137-140, (2019).

[5] “Molecular bridge-mediated ultralow-power gas sensing”, Banerjee, A., Khan, S.U.H., Broadbent, S., Bulbul, A., Kim, K.H., Noh, S., Looper, R., Mastrangelo, C.H. and Kim, H., Microsystems & nanoengineering, 7(1), pp.1-11, (2021).

CONTACT

Hanseup Kim; Email: hanseup.kim@utah.edu