# Supplementary Materials

# Nonporous inorganic nanoparticle-based humidity sensor: evaluation of humidity hysteresis and response time

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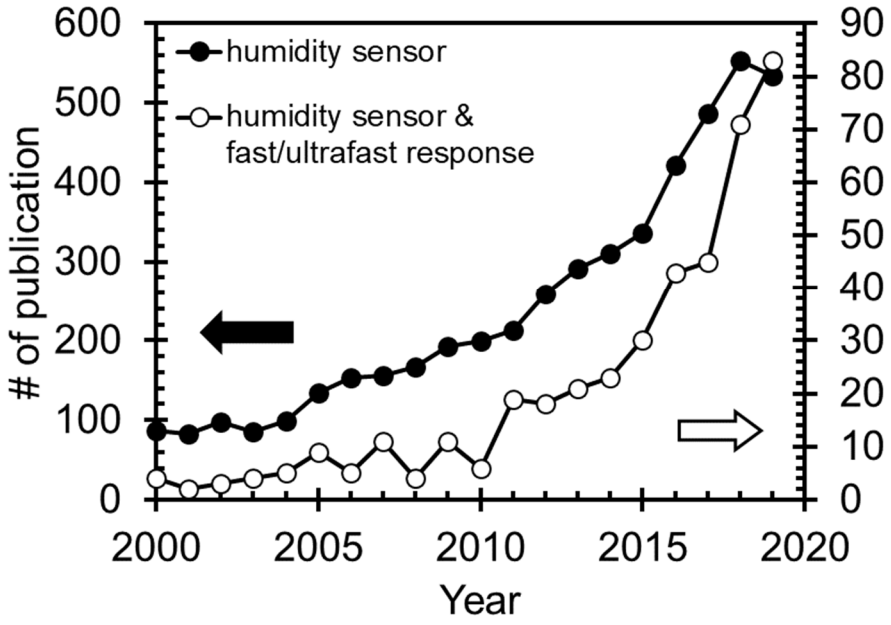


FIG. S1 Numbers of publications reporting fast-response humidity sensors in each year.
(survey date: 26th May 2020, Web of Knowledge)
Keywords of "humidity sensor/sensors, fast response, and ultrafast" are used for the survey.

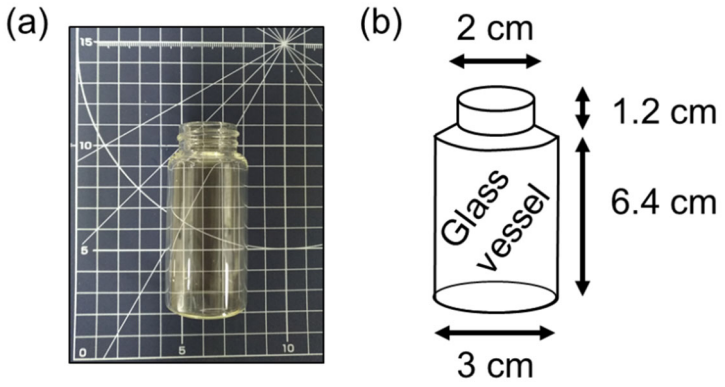


FIG. S2 Dimensions of the glass vessel (volume: 50 ml) used for the experiments. (a) Photo and (b) detailed dimensions are shown.

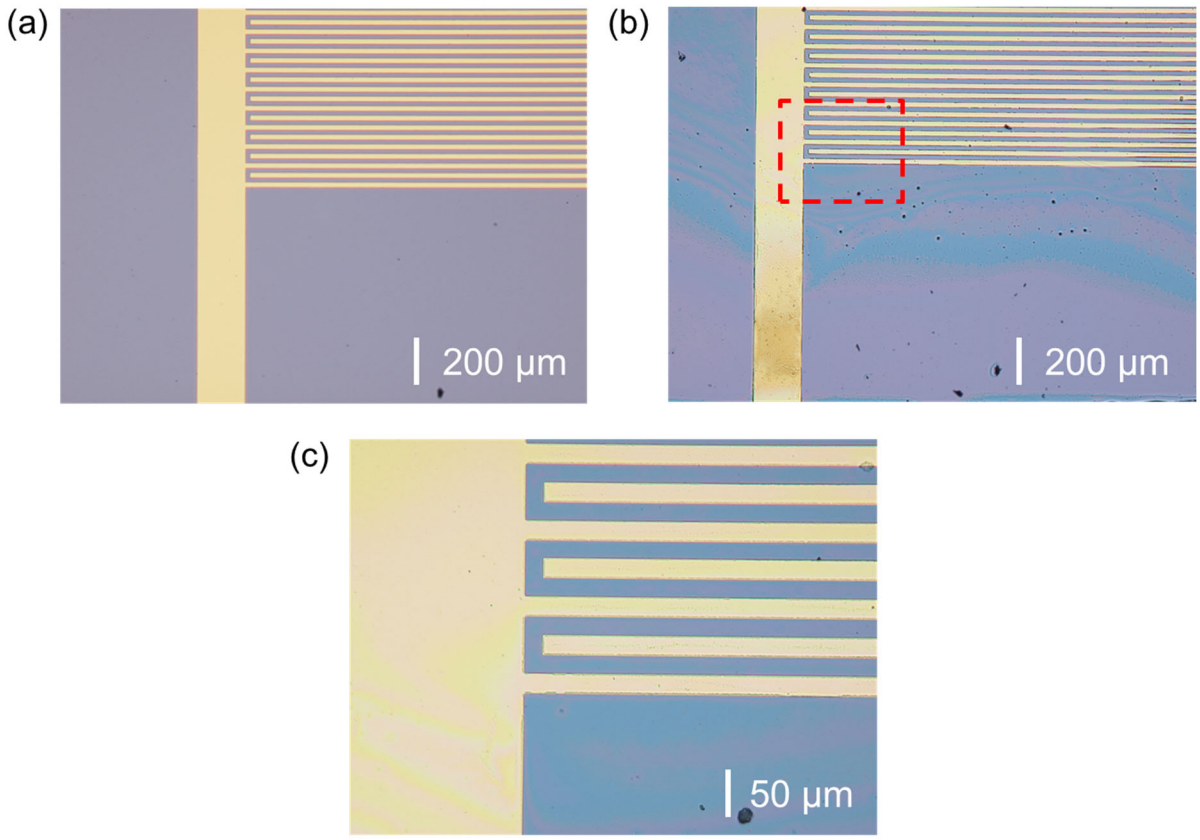


FIG. S3 Optical microscope images of nanoparticle-coated electrodes.
(a) Before and (b) after the coating process. (c) Enlarged area in (b) indicated by the dashed square.

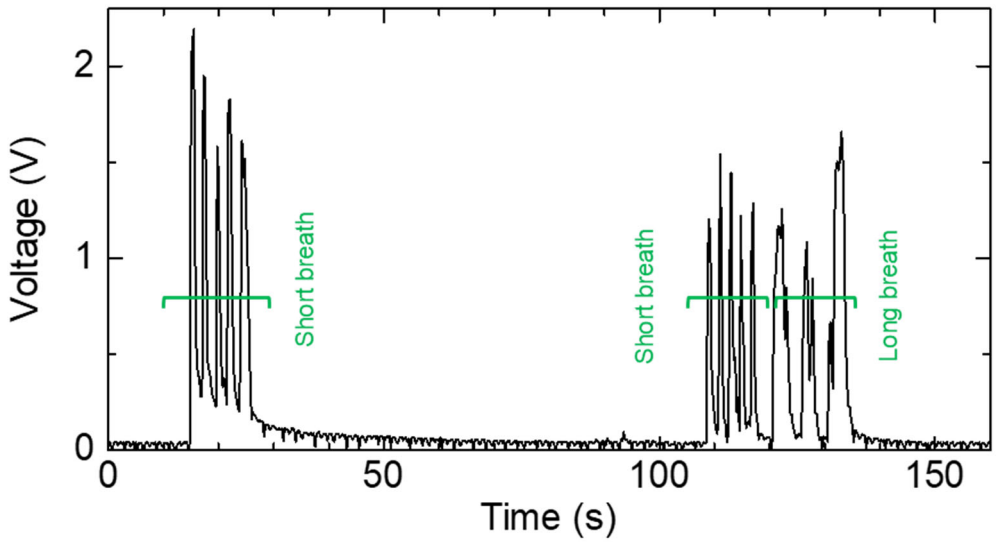


FIG. S4 Another example of breath detection.

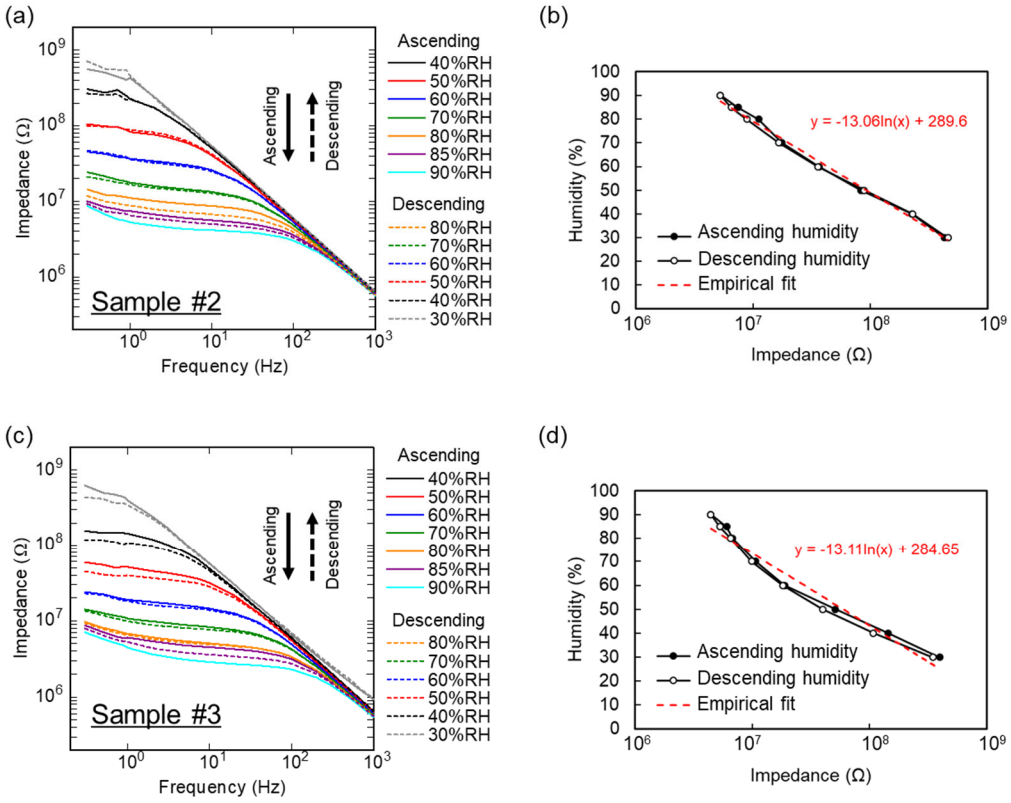


FIG. S5 Humidity dependence of impedance on other sensors (#2 and #3).
(a) and (c): Frequency dependence. (b) and (d): humidity versus impedance plot at 1 Hz. A dashed line in (b) and (d) is an empirical fit using a logarithmic function.

Table S1 List of literature for comparison of specifications (response time and recovery time).

| Materials | Type | Response time (s) | Recovery time (s) | Humidity change (%) | Reference |
|---|---|---|---|---|---|
| Nanostructured $TiO_2$ | capacitive | 0.064 | 0.064 | 2-95 | J. Steele, Sens. Act. B 2009[1] |
| HMDS-modified silicon nanowire | capacitive | 15 | 23 | 11.3-57 | X. Chen, Sens.Act B 2011[2] |
| Graphene oxide | capacitive | 10.5 | 41 | 23-86 | H. Bi, Sci. Rep. 2013[3] |
| Polyimide with carbon nanotube electrode | capacitive | 0.15 | 0.31 | 0-100 | E. Itoh, JJAP 2017[4] |
| $SnS_2$ nanoflower/$Zn_2SoO_4$ hollow sphere | capacitive | 18 | 1 | 0-97 | D. Zhang ACS AMI 2018[5] |
| $ZnO/MoS_2$ | capacitive | 138 | 166 | 25-85 | D. Burman, IEEE Sens. 2019[6] |
| Polyester fiber | capacitive | 3.5 | 4 | 6-33 | L. Ma, Adv. Func. Mat. 2019[7] |
| $In_2O_3$ nanocube/graphene oxide nanosheet | capacitive | 15 | 2.5 | 0-43 | B. Li, Sens. Act. B 2019[8] |
| PDMS-$CaCl_2$ | capacitive | 120 | 120 | 30-60 | Y. Komazaki, Sens. Act. B 2019[9] |
| $CsPbBr_3/TiO_2$ | capacitive | 5 | 5 | 40-88 | M.-Y. Cho, Adv. Func. Mat. 2020[10] |
| Porous silica nanoparticle aerogel | impedance | 41 | 55 | 20-80 | C. Wang, Sens. Act. B 2005[11] |
| $TiO_2$ nanoparticles/polypyrrole composite | impedance | 40 | 20 | 30-80 | P. Su, Sens. Act. B 2007[12] |
| Gallium-doped ZnO | impedance | 70 | 90 | 30-90 | P. Su, Sens. Act. B 2009[13] |
| $Al_2O_3$ nanotube film | impedance | 10 | 20 | 11-95 | B. Cheng, J. Mater. Chem. 2011[14] |
| Graphene oxide | impedance | 0.03 | 0.03 | — | S. Borini, ACS Sens. 2013[15] |
| Graphene/methyl-red | impedance | 0.251 | 0.35 | 35-100 | S. Ali, Carbon 2016[16] |

| | | | | | |
|---|---|---|---|---|---|
| Poly(ionic liquid)s | impedance | 6 | 30 | 11-95 | L. Wang, Chem. Comm. 2016[17] |
| $TiO_2/SrTiO_3$ composite | impedance | 3.1 | 76 | 11-75 | M. Zhang, Sensors 2017[18] |
| $La_{0.7}Sr_{0.3}MnO_3$ nanocrystal film | impedance | 0.8 | 4.9 | 11-95 | Z. Duan, Sens. Act. B 2018[19] |
| <10 nm silica nanoparticle | impedance | 31.4 | 6.5 | 30-84 | S. Kano, ACS Sustain. Chem. Eng. 2018[20] |
| Microporous silica nanoparticle | impedance | 5 | 40 | 11-95 | H. Zhao, Sens. Act. B 2018[21] |
| Graphite | impedance | 1 | 12 | 11-95 | Y. Zhang, Sens. Act. B 2018[22] |
| $TiO_2/NaNbO_3$ | impedance | 11 | 15 | 12-94 | R. Si, Sens. Act. B 2020[23] |
| Attapulgite | impedance | 3 | 70 | 0-91.5 | Z. Duan, Sens. Act. B 2020[24] |
| 50-nm silica nanoparticle | impedance | 2 | 2 | 30-70 | This work |
| SnO single nanowire | resistive | 120 | 20 | 5-85 | Q. Kuang, J. Am. Chem. Soc. 2007[25] |
| $CeO_2$ nanowires | resistive | 3 | 3 | 15.2-85 | X. Fu, Nanotechnology 2007[26] |
| $NiMn_2O_3$ nanoparticle | resistive | 50 | 60 | 11-92 | Y. Gawli, Sens. Act. B 2014[27] |
| Supramolecular nanofibers | resistive | 2.2 | 1.05 | 5-65 | U. Mogera, Sci. Rep. 2014[28] |
| Silicon nanocrystal film | resistive | 12 | 2 | 20-95 | S. Kano, ACS Sens. 2017[29] |
| $MoO_3$ nanosheet | resistive | 0.3 | 0.5 | 0-40 | J. Yang, Small 2019[30] |
| Agarose coated fiber | optical | 0.05 | 0.7 | 60-90 | J. Mathew, Sens. Act. A 2012[31] |
| Graphene oxide | optical | 0.096 | 0.5 | — | X. Gan, Appl. Phys. Lett. 2017[32] |
| Titania microsphere | optical | 0.02 | 0.038 | 20-90 | S. Mohd-Noor J. Mater. Chem. A 2019[33] |

Table S2 List of literature for comparison of specifications (response time and humidity hysteresis).

| Materials | Type | Response time (s) | hysteresis (%) | Reference |
|---|---|---|---|---|
| Polymer | Capacitive | 10 | 2 | H. Grange, Sens. Act. 1987[34] |
| HMDS-modified silicon nanowire | Capacitive | 15 | 1.1 | X. Chen, Sens. Act B 2011[2] |
| Graphene oxide | Capacitive | 10.5 | 5 | H. Bi, Sci. Rep. 2013[3] |
| $SnS_2$ nanoflower/$Zn_2SoO_4$ hollow sphere | Capacitive | 18 | 0.1 | D. Zhang ACS AMI 2018[5] |
| $ZnO/MoS_2$ | capacitive | 138 | 0.1 | D. Burman, IEEE Sens. 2019[6] |
| Polyester fiber | capacitive | 3.5 | 9 | L. Ma, Adv. Func. Mat. 2019[7] |
| $CsPbBr_3/TiO_2$ | capacitive | 5 | 1.7 | M.-Y. Cho, Adv. Func. Mat. 2020[10] |
| Porous silicon | capacitance | 90 | 6 | M. Bjorkqvist, Sens. Act. A 2004[35] |
| Porous silica nanoparticle aerogel | impedance | 41 | 3.3 | C. Wang, Sens. Act. B 2005[36] |
| Gallium-doped ZnO | impedance | 70 | 4 | P. Su, Sens. Act. B 2009[13] |
| $Al_2O_3$ nanotube film | impedance | 10 | 4 | B. Cheng, J. Mater. Chem. 2011[14] |
| Graphene/methyl-red | impedance | 0.251 | 3 | S. Ali, Carbon 2016[16] |
| Poly(ionic liquid)s | impedance | 6 | 1 | L. Wang, Chem. Comm. 2016[17] |
| $TiO_2/SrTiO_3$ composite | impedance | 3.1 | 1 | M. Zhang, Sensors 2017[18] |
| $La_{0.7}Sr_{0.3}MnO_3$ nanocrystal film | impedance | 0.8 | 4 | Z. Duan, Sens. Act. B 2018[19] |
| <10 nm silica nanoparticle | impedance | 31.4 | 10 | S. Kano, ACS Sustain. Chem. Eng. 2018[20] |
| Microporous silica nanoparticle | impedance | 5 | 2 | H. Zhao, Sens. Act. B 2018[21] |
| Graphite | impedance | 1 | 3 | Y. Zhang, Sens. Act. B 2018[22] |
| $TiO_2/NaNbO_3$ | impedance | 11 | 2 | R. Si, Sens. Act. B 2020[23] |
| Attapulgite | impedance | 3 | 3.4 | Z. Duan, Sens. Act. B 2020[24] |
| 50-nm silica nanoparticle film | impedance | 2 | 5 | This work |
| $MoO_3$ nanosheet | resistive | 0.3 | 2 | J. Yang, Small 2019[30] |
| Porous silicon nanoparticles | resistive | 36 | 0.02 | T. Jalkanen, Appl. Phys. Lett. 2012[37] |

Table S3 List of commercial humidity sensors.

| Sensor (manufacture) | Type | Response time (s) | Recovery time (s) | A change of humidity (%) | Hysteresis error (%) |
|---|---|---|---|---|---|
| HIH-4000 (Honeywell) | capacitive | 6 | 20 | — | 6 |
| CHS-UGS (TDK) | impedance | 60 | 60 | 30-85% | 5 |
| HR202L (Aosong Guangzhou Electronics) | impedance | 20 | 40 | — | 5 |
| HTU21 (TE connectivity) | capacitive | 5 | 5 | 33-75% | 2 |

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