Geometry-Driven Temporal Signal Encoding in TiO_2 Gas Sensors for Neural Network Integration

Pavol Nemec[1,2*], Jaromír Klarák[1], Martin Predanocy[1], Matej Horský[2], Jaroslava Škriniarová[1], Boris Hudec[2]
[1] Institute of Informatics, Slovak Academy of Sciences, Bratislava, Slovakia
[2] Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava, Slovakia
[*] pavol.nemec@savba.sk

MOTIVATION / RESEARCH QUESTION

Can sensor geometry encode temporal information?
A gas-sensor transient contains more information than a single steady - state value. We investigate whether controlled sensor geometry can reshape this temporal information.

COMMON TiO_2 SENSOR PLATFORM

To isolate the effect of geometry, all structures were fabricated on the same TiO_2 sensing platform (6″ Si / 300 nm thermal SiO_2 / 21 nm ALD TiO_2).

The sensing material stack was kept unchanged, while the Pt contact and exposed TiO_2 geometry were systematically varied.

Material platform = constant
Geometry = controlled variable

CONTROLLED GEOMETRY ON THE TiO_2 SENSOR PLATFORM

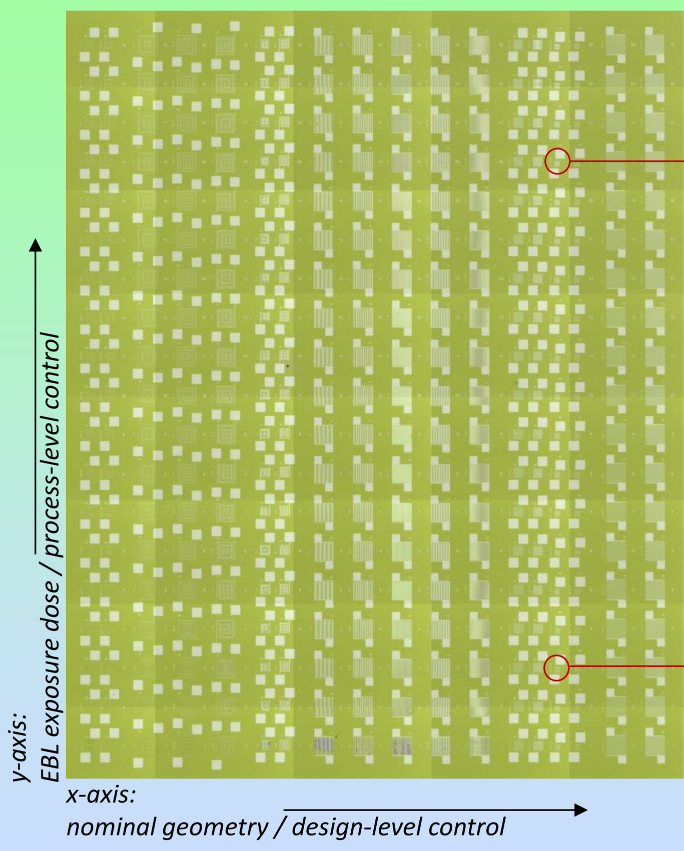
Design-level geometry control: different Pt electrode layouts and line/space dimensions were fabricated on the same TiO_2 sensing platform.

Process-level geometry control: for the same nominal geometry, EBL exposure dose provides fine tuning of the realized line/space dimensions through the proximity effect.

The fabricated sensor geometry can therefore be controlled at both the design level and the process level.

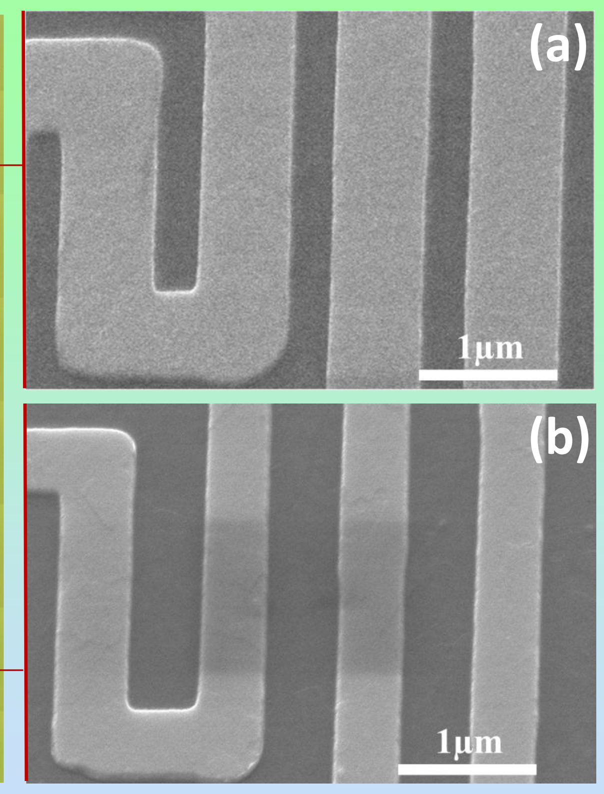
Experimental consequence
The resulting devices form a controlled set of geometrically distinct sensing elements fabricated on the same TiO_2 platform.

Geometry control → fabricated sensor geometry → dynamic H_2 response



Keyence optical image of the fabricated Ti/Pt sensor array after metallization and lift-off.

SEM verification of the selected devices and process-level tuning:



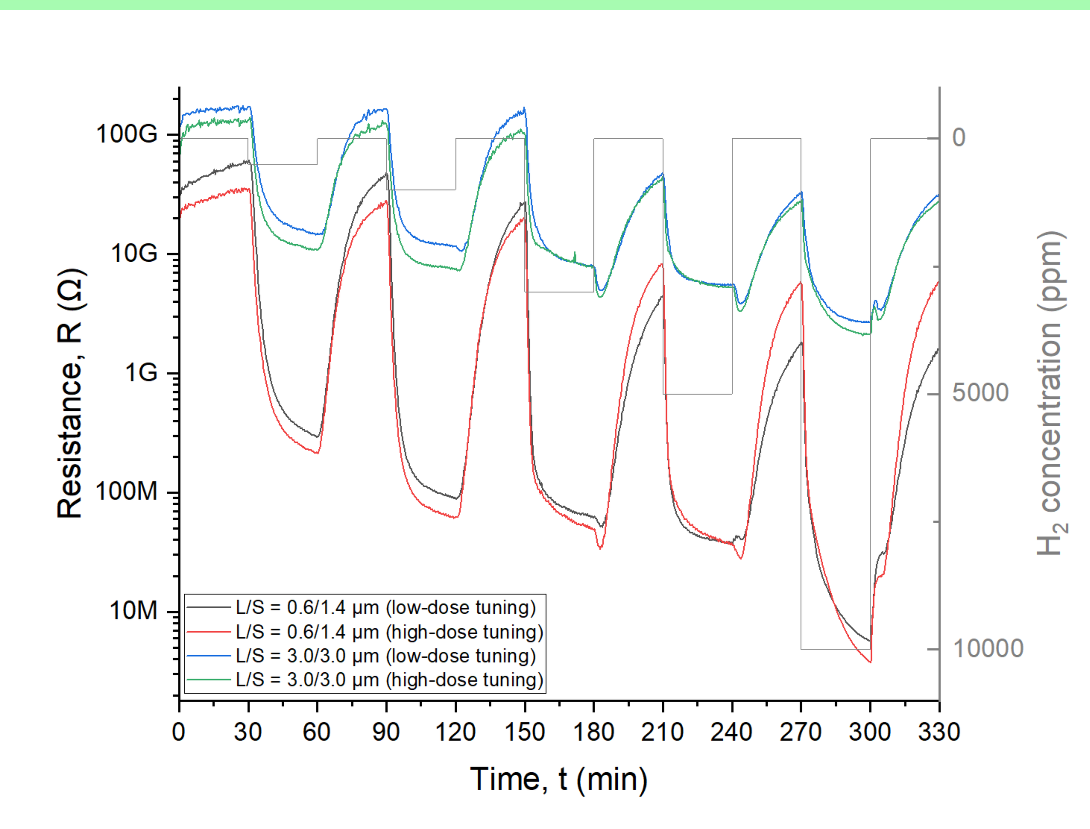
Same nominal $L/S = 0.3/0.7\ \mu m$ structure: a) high-dose and b) low-dose variants. Higher exposure widens the Pt lines L and narrows the exposed TiO_2 gaps S, while the period $L + S$ remains approximately constant.

HOW DOES FABRICATED GEOMETRY RESHAPE THE H_2 RESPONSE?

The sensors were exposed to the same H_2 concentration sequence at 160 °C. Since the TiO_2 sensing platform was kept unchanged, the observed differences can be related primarily to the fabricated IDE geometry.

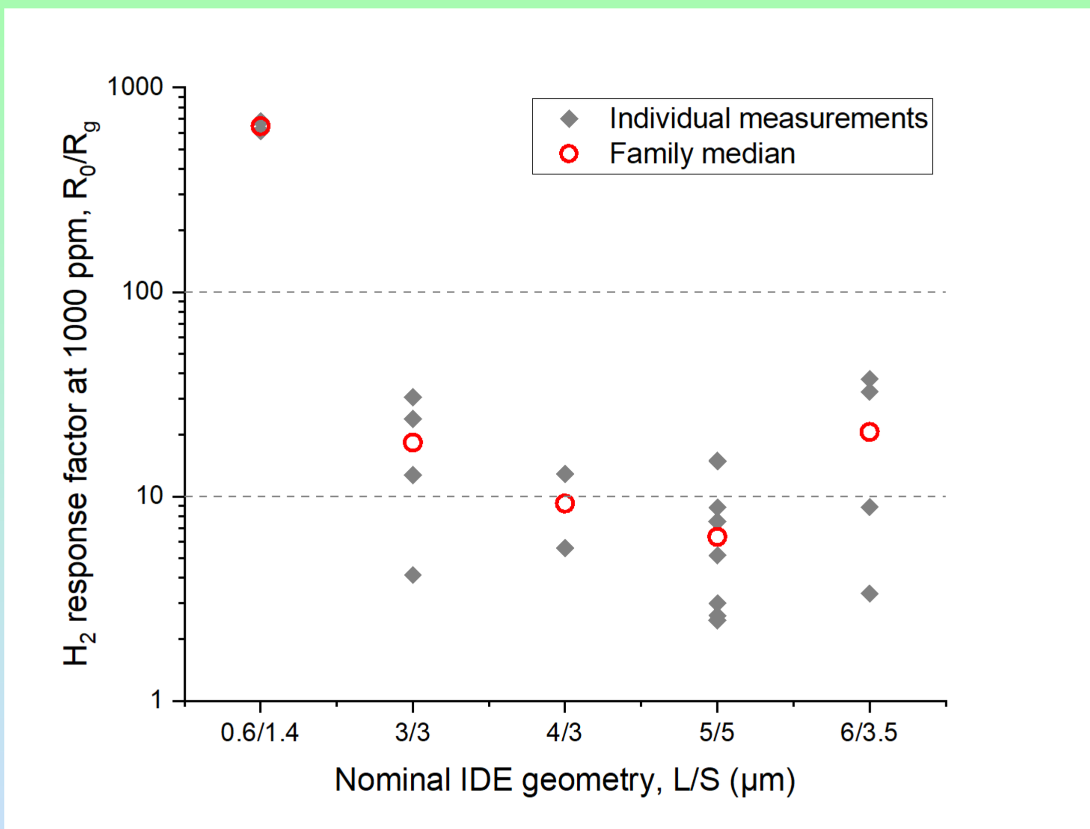
Geometry changes not only the response magnitude, but also the transient shape and the temporal evolution of the signal.

Dynamic response under identical H_2 exposure



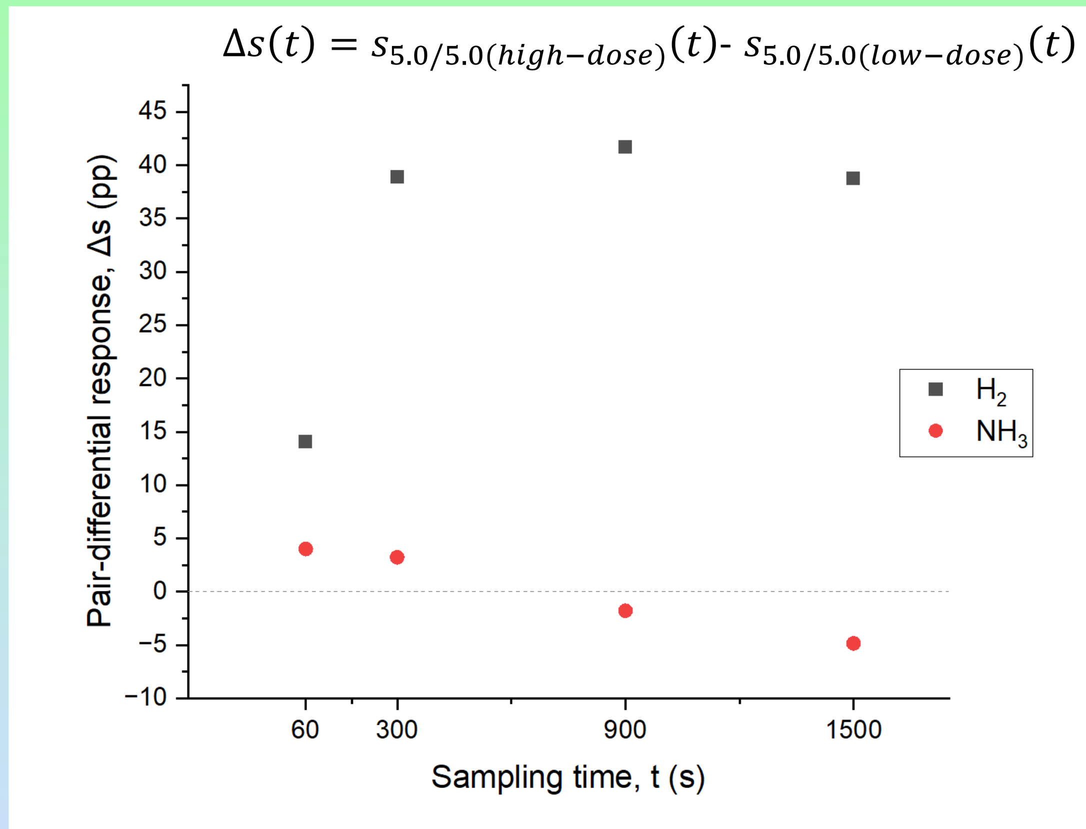
Two nominal IDE geometries (L/S = 0.6/1.4 and 3.0/3.0 μm), each represented by low- and high-dose variants, generate distinct resistance–time trajectories under the same H_2 exposure sequence.

Geometry-dependent H_2 response at 1000 ppm



At 1000 ppm H_2, the response factor R_0/R_g varies by more than two orders of magnitude across the investigated nominal IDE geometries. Individual measurements and family medians reveal pronounced geometry-dependent response variability.

Pair-differential temporal features at 1000 ppm

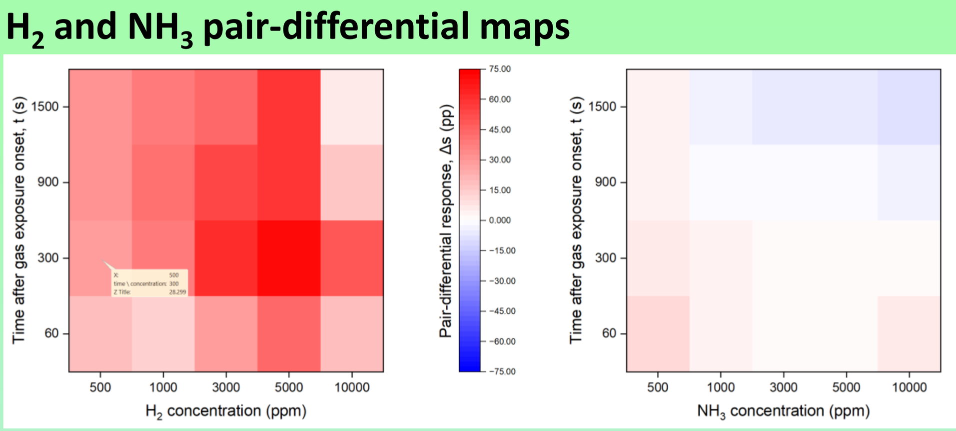


For L/S = 5.0/5.0 μm, low- and high-dose variants produce gas-dependent temporal features. At 1000 ppm, H_2 remains strongly positive, while NH_3 becomes negative at later times.

FROM TEMPORAL RESPONSE TO GAS-DEPENDENT FEATURES

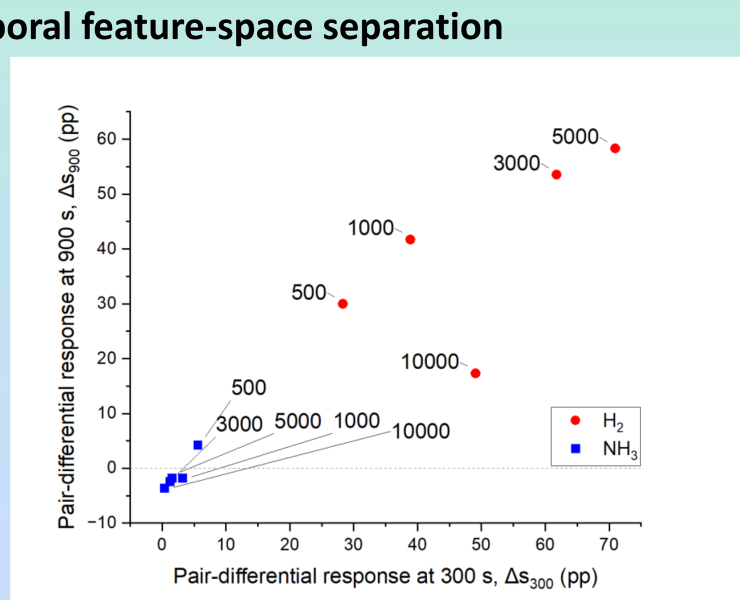
Pair-differential temporal responses reveal concentration- and gas-dependent signatures that are not captured by a single steady-state value.

H_2 and NH_3 pair-differential maps



Pair-differential maps reveal markedly different concentration–time signatures for H_2 and NH_3 on the same −75 to +75 pp scale. H_2 exhibits a strong positive differential response, whereas NH_3 remains close to zero and becomes negative at later sampling times.

Temporal feature-space separation



Each point represents one measured concentration state. H_2 and NH_3 occupy clearly distinct regions of the $(\Delta s_{300}, \Delta s_{900})$ feature space.

FEATURE ENCODING FOR NN INTEGRATION

Geometry-dependent temporal responses are transformed into a compact and interpretable feature representation suitable for NN processing.

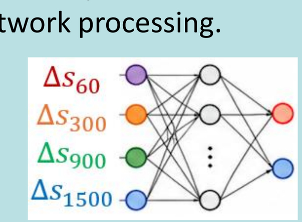
1. MEASURED RESPONSES
Low-dose and high-dose variants of the same nominal geometry produce distinct transient responses.

2. PAIR-DIFFERENTIAL ENCODING
The differential signal emphasizes geometry-sensitive temporal information.

3. TEMPORAL FEATURE EXTRACTION
Four sampling times (60, 300, 900 and 1500 s) convert each pair-differential response into a compact feature vector.

$$x = \begin{bmatrix} \Delta s_{60} \\ \Delta s_{300} \\ \Delta s_{900} \\ \Delta s_{1500} \end{bmatrix}^T$$

4. NN INPUT — 4 FEATURES
The four temporal features form an interpretable input vector for subsequent neural-network processing.



5. OUTPUT
Gas identity

H_2 (hydrogen) | NH_3 (ammonia)

A. EXAMPLE FEATURE VECTORS AT 1000 PPM

H_2 (1000 ppm): $x = [14.1,\ 38.9,\ 41.7,\ 38.7]$ pp (Δs_{60}, Δs_{300}, Δs_{900}, Δs_{1500})

NH_3 (1000 ppm): $x = [4.0,\ 3.2,\ -1.8,\ -4.9]$ pp (Δs_{60}, Δs_{300}, Δs_{900}, Δs_{1500})

The same four temporal coordinates produce markedly different feature patterns for H_2 and NH_3.

B. FEATURE SPACE — 2D PROJECTION
The measured H_2 and NH_3 states occupy distinct regions of the temporal feature space, demonstrating that the pair-differential transient contains gas-dependent information.

C. WHY THESE FEATURES?
Δs_{60} - Early response initial interaction with the gas
Δs_{300} - Developing response
Δs_{900} - Evolved response
Δs_{1500} - Late response
A single steady - state value suppresses information contained in the transient. Temporal sampling preserves the evolution of the geometry-dependent signal while reducing the full response trajectory to a compact descriptor.

KEY MESSAGE
Controlled sensor geometry reshapes the transient response before digital processing, enabling compact temporal encoding for subsequent neural-network integration.

$$geometry \xrightarrow{\Delta} R(t) \xrightarrow{\Delta} \Delta s(t) \rightarrow x \rightarrow NN$$

PHYSICAL INTERPRETATION

The pair-differential signal suppresses response components common to the low- and high-dose variants and emphasizes geometry-dependent transient behavior. Process-controlled differences in fabricated sensor geometry are thereby converted into compact temporal features.

SCOPE OF NN INTEGRATION

The present work demonstrates an NN-ready temporal representation and gas-dependent feature-space separation. Independent classifier validation requires a larger dataset.

KEY FINDINGS / DESIGN IMPLICATIONS

- ✓ Controlled IDE geometry modifies both the magnitude and the temporal evolution of the H_2 response.
- ✓ **At 1000 ppm H_2, the measured response factor spans more than two orders of magnitude across the investigated geometries.**
- ✓ Pair-differential temporal signatures remain gas-dependent across the investigated concentration range.
- ✓ H_2 and NH_3 occupy distinct regions of the measured temporal feature space.

Sensor geometry can therefore act as a physical encoding mechanism before digital signal processing.

Funded by the European Union NextGenerationEU
RECOVERY AND RESILIENCE PLAN

Acknowledgments: This work was supported by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I05-03-V02-00058 (NeuralSens). The authors also acknowledge support from the VEGA project No. 2/0140/26 and the APVV project No. APVV-23-0173.