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# CMOS Compatible Electrostatically Formed Silicon Nanowire for Selective Ppb Level Sensing Platform

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**Summary:**

Electrostatically Formed Nanowire (EFN) sensor is a CMOS based multi-gate silicon nanowire (NW) field effect transistor (FET) where the nanowire is formed electrostatically post fabrication. By employing a specially designed large area sensing antenna we improve the EFN sensor response by several orders of magnitudes. We demonstrate a world record response of ~ 90 % to 30 ppb $H_2$ which can be further improved by several orders of magnitude with increasing antenna size.

**Keywords:** Gas Sensors, Electrostatically Formed Nanowire, Hydrogen Sensing, CMOS Compatible Sensors, Ppb detection, Antenna effect.

## Background, Motivation and Objective

Hydrogen sensors for sub-ppm levels are vital for early indication of leaks in various facilities of green energy, storage, chemical industry, nuclear reactors. Silicon nanowire (Si-NW)-based field-effect transistors (FETs) have been demonstrated in the last two decades as highly sensitive and selective chemical sensors operating at room temperature. Inspired by the Si-NW performance, we introduced in 2013 the Electrostatically Formed Nanowire (EFN), a multi-gate very large-scale integration (VLSI) compatible transistor for bio-sensing [1]. We show here that the EFN response is improved by several orders of magnitude when a large sensing area is coupled to the EFN channel. This antenna EFN combines the advantage of a nanometer-sized transistor channel with excellent electrical characteristics and a very large sensing area. This paves the way to a VLSI-based gas sensing platform with Ppt-level gas sensing capabilities.

## Description of the New Method or System

Fig.1 shows a cross-sectional schematic of a small (Fig.1(a)) and large area (Fig.1(c)) EFN fabricated in this work. The EFN was decorated with a 20 nm thick Pd layer for $H_2$ sensing; The Pd was deposited on the EFN by first defining a mask using e-beam lithography, followed by a coating of a 20 nm Pd layer using an e-beam evaporator with a deposition rate of 0.5 Å/s.

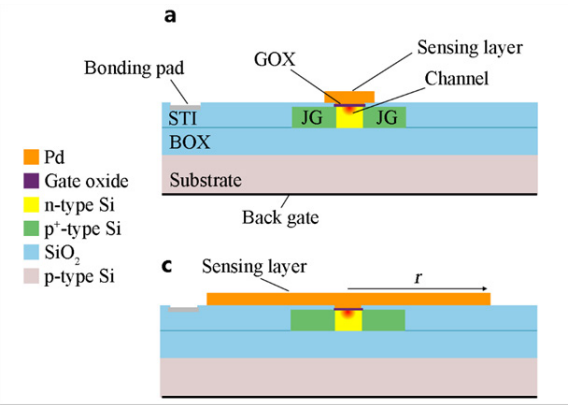


*Fig. 1. (a) Schematic cross-section illustration of the EFN sensor, showing all the device layers. The channel (red) size can be adjusted post-fabrication by applying biases to the control gates (JG or BG). The top Pd molecular gate above the GOX 6 nm layer is the sensing layer to $H_2$; the drain-source direction is into the page.* (c) *Schematic of the large area EFN.*

## Results

Fig. 2 shows the sensor response of the large area (red) and the small area (blue) EFN to $H_2$ concentration in the range of 30 ppb to 100 ppm. The error bars are a result of variations in device surface chemistry, contamination, dimensions, and noise. For the concentration of 30 ppb, the large area antenna EFN shows a normalized average response of ~87%, whereas, for the small area, the response is lower than the device current drift; at 7 ppm $H_2$ concentration, there is a

two-orders-of-magnitude difference in the response between the large and small areas EFNs.

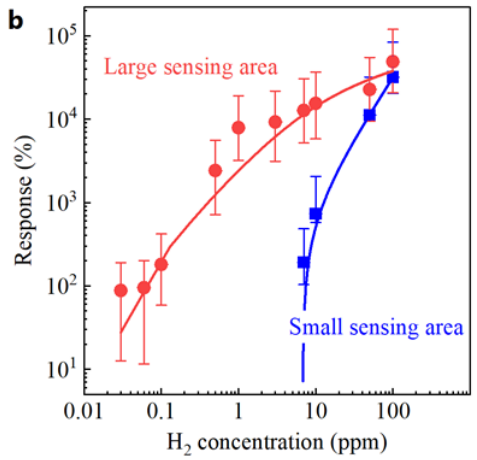


*Fig. 2: The large area EFN sensor response (red) to $H_2$ relative to the conventional EFN response (blue).*

The origin of $H_2$ sensitivity in Pd-based sensors has been discussed extensively, and various models have been reported in the literature (e.g., the recent perspective [2]). The increase of current in Pd-Si-FET-based sensors following $H_2$ adsorption is commonly attributed to the changes in band bending at the $SiO_2$/Si interface of the transistor channel. One of the widely accepted models is based on the fact that Pd nanoparticles catalyze the dissociation of $H_2$ molecules into atoms on the Pd surface. The H atoms then diffuse to the Pd/$SiO_2$ interface, polarize, and, as a result, induce an interfacial dipole layer with the $H_2$ very close to the metal side [3]. This induced dipole layer changes the channel band bending and, as a result, the sensor source-drain current.

To explain the observed results in Fig.2, we argue that the induced H dipoles are not electrically symmetric, but the positive charge is larger than the negative one due to partial screening by the Pd layer. Due to the antenna effect explained below, H atoms (asymmetric dipoles) are transported along the Pd/$SiO_2$ interface towards the channel region. This increases the dipole density above the channel with increasing sensing area, and as a result, the sensor response increases exponentially. The mechanism is to a certain extent, similar to the antenna effect in CMOS transistors. According to this effect, charges in plasma processes are collected by metal areas (antennas) connected to the transistor gate.

Using COMSOL Multiphysics, we have determined the net charge distribution at the Pd/$SiO_2$ interface for several surface densities of hydrogen atoms. Our calculations showed that the charge concentration above the channel increases with increasing sensing area; this is because the charged H atoms migrate from the surrounding areas with very low capacitance (field oxide thickness ≈ 520 nm) to the region right above the channel with the high capacitance (GOX thickness = 6 nm). Using first-order approximation, neglecting the exact complex structure of the device, we can estimate the difference in surface charge densities between the channel ($\sigma_c$) and the surrounding regions ($\sigma_s$). Since the Pd potential ($V_{Pd}$) is constant,

$$V_{Pd} = \frac{Q_c}{C_c} = \frac{Q_s}{C_s} = \sigma_c d_c = \sigma_s d_s \rightarrow \sigma_c \approx 86\sigma_s \quad (1)$$

where $Q$ is the total charge, $C$ is the capacitance, $d$ is the dielectric thickness, and the subscripts $c$ and $s$ denote the channel and surrounding region, respectively; $d_c$ is 6 nm whereas $d_s$ is 520 nm, yielding a ratio of 86 between the channel and the surrounding dipole density; a similar (but more accurate) result was obtained using numerical analysis.

## Summary

We have presented a novel sensing device based on the antenna EFN concept, which couples an electrostatically tunable nano-sized transistor channel with a large (up to 3,500 μm²) sensing area. It is shown that the large sensing area improves the EFN response by several orders of magnitudes, especially at low analyte concentrations. Based on the EFN sensor response as a function of the sensing area, we argue that the sensing mechanism can be attributed to the formation of asymmetric charged H atomic dipoles at the Pd/$SiO_2$ interface (thick silicon dioxide) and their migration to the channel area with the small GOX thickness, resembling the antenna effect. The outstanding response of ~ 90 % to 30 ppb $H_2$ can be improved by several orders of magnitude with increasing antenna size and paves the way to a VLSI-based gas sensing platform with Ppt-level gas sensing capabilities.

## References

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