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A review on efficient self-heating in nanowire sensors: Prospects for very-low power devices

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ABSTRACT

Self-heating operation, or the use of the resistance-probing signal to warm up and control the temperature of nanowire devices, has been the subject of research for more than a decade. In this review, we summarize the most relevant achievements reported to date in the specialized literature. The state-of-the-art shows that this approach is serving to lower the power demand in temperature-activated devices, especially in conductometric gas sensors, but the simplicity of eliminating the heating element comes with the complexity of integrating 1-dimensional nanomaterials in electronic devices. Results show however that this is feasible, and in some cases, even cost-effective.

To contribute to the further development and optimization of the self-heating approach, we compile here a set of recommendations on how to increase the efficiency of the future devices. These suggestions aim at clarifying the impact on the power efficiency of factors like the nanowire cross-section, the electrical and thermal conductivities of the material, the thermal insulation characteristics, and the operating conditions.

To facilitate the comparison of the performances obtained in past and future works, we also propose a figure of merit: the efficient self-heating coefficient (ESH), which accounts for the maximum temperature increase (in Kelvin) per microwatt of Joule power dissipated in the material. In this way, ESH values about 1 or above are indicative of highly efficient technologies, capable of raising the temperature over hundreds of degrees with less than a milliwatt of dissipated power.

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1. Introduction

Controlling the operating conditions of a sensor is crucial to obtain accurate, repeatable, and long-term stable readings. Otherwise, factors like vibration, ambient light, or temperature can interfere with the sensor signal, leading to readings not related to the magnitude being monitored. To prevent this cross-talk interference, many sensor technologies integrate some kind of actuator, either mechanical, optical or thermal. This is, in most of the cases, the main power hungry part of the device [1].

Concerning temperature control, it is mostly based on electrical resistors (for heating) and thermoelectric elements (for heating and cooling). The optimization of their power budget has usually relayed on more miniaturization (to reduce the thermal masses to be heated up [2,3]), and on better thermal isolation (to minimize the thermal losses related to heat conduction through solid parts [4–6]). This trend already started in the first generation of sensors with active areas at a millimeter scale [7], which was later reduced to tens-to-hundreds of microns with the use of microfabrication techniques (MEMS) [3,5,8–11]. Today, with the advent of nanotechnology (NEMS), we are approaching to the submicron regime [12,13]. In fact, nanotechnology enables the use of a nanowire-based heating method with potential for ultra-low power consumption, *the self-heating effect*, which is the subject reviewed in the following pages.

1.1. Conductometric gas sensors

Chemical sensing is one of the fields in which the control of temperature is more critical. When there is an interaction between molecules in a fluid phase and a transducing substance (e.g. a liquid or a solid electrolyte [14,15], a semiconductor [16,17], a polymer [18–20], a catalyst [21,22], etc.), the temperature is usually a key parameter. In fact, the ambient temperature at which theses sensors operate has a strong influence on the sensing performance. To minimize this interference, sensors are normally operated at temperatures above the expected operational environment (e.g. above room temperature for environmental sensing, much higher temperatures for combustion monitoring in engines, boilers, etc.). This solution is more effective and simple than attempting to compensate temperature fluctuations by continuously cooling and heating the sensor.

Conductometric gas sensors based on semiconductor materials are a paradigmatic example of the need for temperature control and the challenges related to achieving it in a power efficient manner [23]. In this type of sensors, the presence of gases is detected by monitoring the electrical resistance of a gas-sensitive material (typically a metal oxide [16,24], a polymer [18–20], a carbon-based material [25,26], or other semiconductors [27,28]) (see Fig. 1a). In the presence of gases, the resistance changes due to the chemical-electrical interactions between the gas molecules and the semiconductor surface, being most of these processes thermally activated [29].

The most accepted models describe this phenomenon as a steady balance between chemisorbed species at the surface, followed by their immediate desorption [30–32]. This dynamic picture is crucial to explain the recovery of the sensor baseline when the target gas is removed. From an energy point of view, the gas-solid interactions are ruled by a Lennard-Jones type of potential [33]. First, molecules may need some energy to approach the semiconductor surface to be adsorbed onto or to initiate a dissociative process. Later, some more energy might be needed to desorb the molecules back again into the gas phase. These steps define two

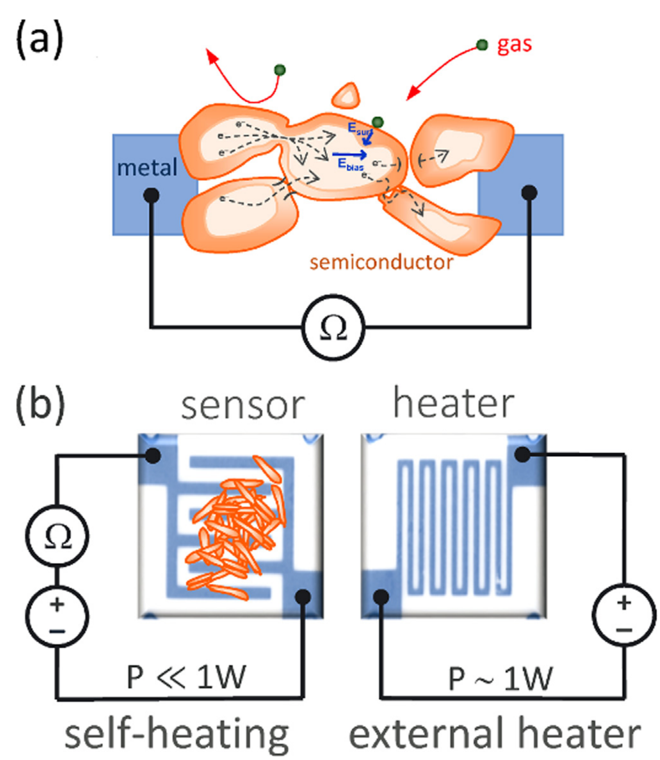

Fig. 1. (a) A conductometric gas sensor based on a semiconductor material. Gas molecules interact with the semiconductor surface (E_{surf}), influencing the electron transport properties within the material. To measure these effects, an external bias signal (E_{bias}) is applied to the semiconductor placed across a pair of conducting electrodes. Ultimately, gas interactions are recorded as changes in the resistance/conductance of the device. (b) Physical construction of a conventional conductometric gas sensor: a two-sided substrate containing the sensor element (a semiconductor material and a pair of interdigitated metal electrodes) and the heating element (a metal meander). Both elements must be biased: the former to probe the resistance of the material, the latter to heat up the device. The amounts of power in each element are very dissimilar. In self-heating operation, the small amount of power used to probe the sensor resistance is enough to reach the optimum temperature for working, saving the need of a power-hungry heater.