# Strategies for enhancing the analytical performance of nanomaterial-based sensors

Celine I.L. Justino, Teresa A.P. Rocha-Santos, Susana Cardoso, Armando C. Duarte

**We provide a state-of-the-art review of the main strategies for the enhancement of analytical performance of sensors using nanomaterials, particularly nanowires and carbon-based materials. We emphasize the way to overcome the problem of device-to-device variation. We discuss the study of the influence of nanomaterial characteristics, sensor dimensions and operational conditions on sensing performance, and the application of appropriate calibration models.**


*Keywords:* Analytical performance; Calibration; Carbon nanotube (CNT); Device fabrication; Device-to-device variation; Graphene; Nanomaterial; Nanowire (NW); Operational condition; Sensor

**Celine I.L. Justino*, Teresa A.P. Rocha-Santos, Armando C. Duarte**
Department of Chemistry & CESAM, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal

**Teresa A.P. Rocha-Santos**
ISEIT/Viseu, Instituto Piaget, Estrada do Alto do Gaio, Galifonge, 3515-776 Lordosa, Viseu, Portugal

**Susana Cardoso**
INESC-MN, Rua Alves Redol 9, 1000-029 Lisbon, Portugal

## 1. Introduction

The incorporation of nanomaterials in chemical and biological sensors has been responsible for the development of a wide variety of nanoelectronic systems on environmental, food and clinical applications, since such nanostructures display particular electrical, chemical and transport properties. For example, sensors based on field-effect transistor (FET) configurations with carbon nanotubes (CNTs) [1–3], graphene [4–7], and nanowires (NWs) [8–10] have been widely used for sensing the electric charge of biomolecules (e.g., glucose, proteins and DNA) after their adsorption on the FET surface. The most reported biological interactions with nanomaterial-based FET sensors are enzymatic glucose detection, antibody-antigen binding (immunoreaction) and DNA hybridization [1,11,12].

Besides the advantages of applying nanomaterials, it is also known that some nanomaterial characteristics may cause considerable variability in device properties, so affecting the analytical performance of sensing systems, as shown in Fig. 1. For example, the role played by CNT density in FET-biosensor performance has been reported [11,13–15], demonstrating that it is critical in achieving high uniformity and analytical performance. Following that perspective, the influence of NW dimensions and doping levels for the sensitivity of NW-FET devices has also been demonstrated by theoretical and experimental studies [10,16–20]. Sensitivity and limit of detection (LOD) are figures of merit that are closely associated with the transduction mechanism and morphological characteristics of sensors [21], being important tools for assessing analytical reliability, capacity, and variability in techniques and devices [22].

From such considerations, the main objective of the present review paper is to identify the main factors of sensor fabrication and integration that can influence the final analytical performance. This review therefore discusses recent works on the main strategies for the enhancing the analytical performance of nanomaterial-based sensors, and highlights the way to overcome the problem of device-to-device variation. We also identify the advantages and the limitations of integrating nanomaterials on sensing platforms.

*Corresponding author.
Tel. +351 232 910 100;
Fax: +351 232 910 183.;
E-mail: celinejustino@ua.pt,

0165-9936/$ - see front matter © 2013 Elsevier Ltd. All rights reserved. doi:http://dx.doi.org/10.1016/j.trac.2013.02.004 

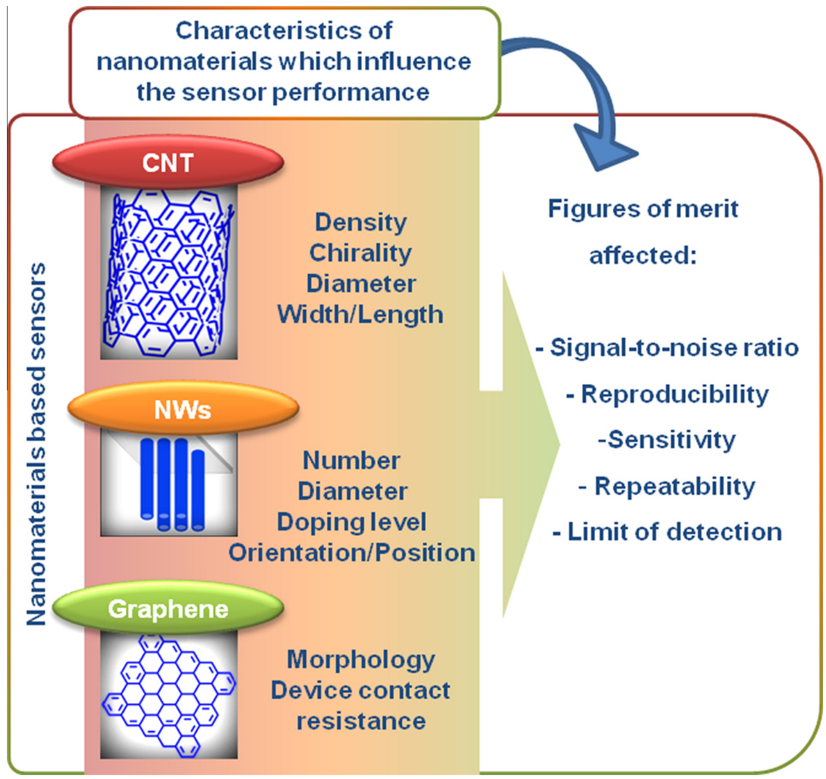


**Figure 1.** Characteristics of nanomaterials that can influence the analytical performance of chemical and biological sensors.

## 2. Advantages of the integration of nanomaterials in sensors

Of existing nanomaterials, we focus the present review on CNT, graphene and graphene-based materials [e.g., graphene oxide (GO) and reduced GO (rGO)] and Si-NWs and metal-oxide based NWs, since they are the most reported in existing literature. The various physical, chemical and optical properties of such nanomaterials are identified in Table 1 together with their main applications.

The development of sensing systems is the main application of nanomaterials, since they can enhance the analytical performance of such devices. CNT and graphene have carbon atoms on all their surfaces, enabling facile interaction with biological molecules. While CNTs have increased chemical reactivity due to large curvatures [24], graphene was also recently used as the transduction surface for chemical sensing [31] and biosensing systems [12,30,32,33] due to its physical and chemical properties [29,34].

In some works, the incorporation of multiple single-walled CNTs (SWCNTs), also called SWCNT networks, onto FET devices is preferred over individual SWCNTs, due to higher uniformity and higher reproducibility [35–37]. Such SWCNT networks have been used as the conducting channel of FET-sensing devices for environmental and clinical applications [26,36,38–41], since they average the global properties of large random individual SWCNTs, and provide larger surface area for sensing [14,35].

Graphene and graphene-based materials (e.g., GO, rGO, and exfoliated graphite) have also been used in various sensing systems, as recently reviewed by Liu et al. [12], Kochmann et al. [30] and He et al. [33]. For example, graphene-based FETs provide significant conductance changes with acceptable signal-to-noise ratio [5], high sensitivity [6] and specificity [7].

Regarding Si-NW-FET devices, their potential for biosensing has been demonstrated – due to their ultrasensitivity, specific, label-free and real-time detection abilities, mainly for biomedical diagnosis and cellular recording investigation, and proteins, DNA sequences, small molecules, cancer biomarkers, and viruses [28]. In addition, the possibility of controlling electrical properties, chemical composition and size of NWs by doping [42,43] provides an advantage over the carbon-based materials (e.g., graphene and CNTs), since the charge-carrier density in devices can be controlled leading to set the sensor-response magnitude.

Understanding of the sensing-transduction mechanisms of FET sensors will lead to better interpretation of the analytical response, and allow the design of strategies for their improvement before fabrication and