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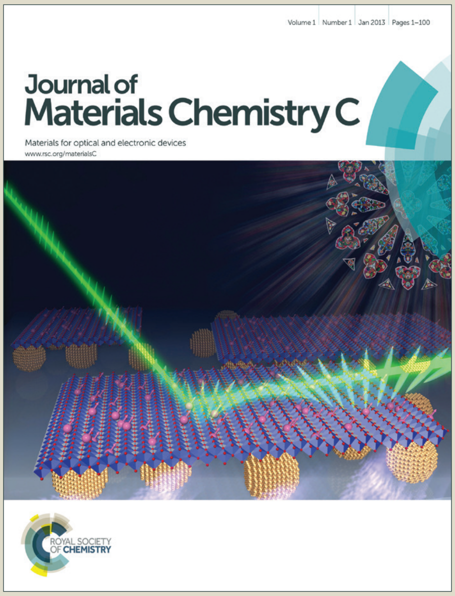

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Electrolyte-gated nanostructured ZnO transistors for environmental and biological sensing

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Electrolyte-gated transistors (EGTs) based on ZnO thin films, obtained by solution processing of nanoparticles suspensions, show low turn-on voltage (<0.5 V), high on/off ratio and transconductance exceeding 0.2 mS. Importantly, the ZnO surface can be functionalized with a large variety of molecular recognition elements, making these devices ideal transducers in physiological and environmental monitoring. We show simple glucose sensing and ion-selective EGTs, demonstrating the versatility of such devices in biosensing.

The development of simple yet reliable sensors for the identification of biomolecules, pathogens, ions and pollutants has become a primary research challenge, due to the expected widespread application and integration of sensors in our society and environment.[1-3] One illustrative example is the glucose sensor which, in spite of being commercially available since 25 years, is still attracting considerable research efforts because of the demand for low-cost and reliable methods for self-monitoring of blood glucose.[4-6] While the commonly applied transduction mechanisms are mostly electrochemical or optical,[7, 8] the application of field-effect transistors (FETs) to biosensing has gained increasing attention due to the intrinsic signal amplification of such devices.[9, 10] With the perspective of low-cost and simple manufacturing, organic thin-film transistors represent the most promising candidates, thanks also to the unique possibility of tuning the properties of organic semiconductor through rational chemical design.[11-13] Apart from a few examples,[14, 15] however, the stability of conjugated molecular materials in aqueous environment is limited. Metal oxides represents a possible alternative as the semiconductor in biosensing applications. They show high carrier mobilities[16], easiness of surface functionalization,[17, 18] and can be processed by simple solution methods, leading to inexpensive devices, even on flexible substrates.[19, 20] Unlike most organic semiconductors, metal oxides are usually stable in air and in water, an essential prerequisite for sensor devices working in aqueous or physiological environment. A type of transistor which is especially suited for biosensing is the electrolyte-gated transistor (EGT). The working principle of EGTs is analogue to that of traditional FETs, in which the gate insulator (usually a solid high-κ dielectric) is replaced by a convenient electrolyte (solid, liquid or gel).[21, 22] The variation of the conductivity of the channel with the gate voltage (V_g) is determined by the capacitance of the nanometrically thin electrical double layer (EDL) that forms at the interface between the electrolyte and the semiconductor channel as a consequence of the ionic displacement. The capacitance of an EDL can be orders of magnitude larger compared to that of traditional insulators, and for this reason EGTs usually show high transconductance (g_m) at very low voltages.[21] Few recently reported examples of EGTs employing semiconducting metal oxides thin films suggest that such devices can have performances superior to the associate FET, and show how they could even be used in the development of bio-sorbable, implantable devices.[23, 24] A unique feature of metal oxides is the possibility of obtaining stable nanoparticles (NPs) dispersions, which can be casted forming nanostructured thin films with enhanced surface area and tunable properties. Taking advantage of the unique properties of metal oxides and EGTs, in this paper we present aqueous EGTs employing solution processed ZnO NPs as the semiconducting material. The high surface area of the nanostructured channel further enhances the EDL capacitance and allows the saturation of the drain current (I_d) at V_g as low as 1.1 V. What makes EGTs ideal candidates to be implemented in sensing is that the drain current is influenced by any physical or chemical modification of the EDL. As a proof of principle, we demonstrate the potential of these devices by showing ion-selective EGTs, realized through integration of an ion-selective membrane (ISM) into the device architecture, as well as simple enzymatic glucose sensors, obtained by covalent binding of the enzyme on the ZnO surface.

EGTs were prepared on glass slides with pre-patterned indium tin oxide (ITO) source-drain electrode, with channel width (*W*) and length (*L*) of 2 mm and 20 µm, respectively (*W*/*L* =100, Figure 1a). The ITO/glass substrates were cleaned by chemical and plasma methods. Commercial 5 wt% ZnO NPs suspension in ethanol were filtered through a 0.22 µm PTFE membrane and spin-coated onto the substrates. The layers were subsequently annealed at 450° C for 30 minutes in order to remove the stabilizing ligands (Figure S1). The final thickness of the layers was about 60 nm. In spite of the high annealing temperature, the ZnO surface shows a high porosity (Figure 1b), with grain size resembling the average particle size of the suspension (< 35 nm). The grazing incident X-ray diffraction (GIXRD) pattern confirms a high degree of crystallinity of the nanostructured film. Moreover, the crystal size estimated from signal broadening on the (101) direction is 35 nm, thus consistent with morphological measurements and producer datasheet. Glass wells, used to confine the electrolyte, were integrated onto the transistor array using a thin layer of polydimethylsiloxane (PDMS). An Ag/AgCl pellet electrode or a platinum wire immersed in the electrolyte were used as the transistor gate electrode.

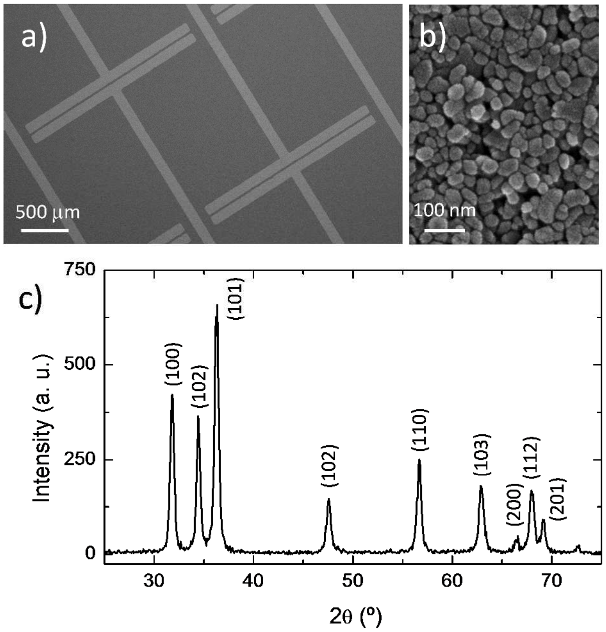

Figure 1. (a) SEM image of the transistor array with visible ITO source-drain electrodes and (b) detail of the ZnO nanostructured surface. (c) GIXRD pattern with Cu Kα_1 radiation (λ = 1.54056 Å) of the thin films.

The performance of the transistors was evaluated in aqueous electrolyte (KCl 0.1 M) using a porous Ag/AgCl pellet as the gate electrode (Figure 2). The output characteristic at five different gate voltages are reported in Figure 2a. The device shows a high modulation of the current both in the linear and saturation regimes, with large saturation currents > 75 µA at very low driving voltages (V_g = 1.1 V, V_d > 0.5 V). A turn on voltage (V_{on}) of only 0.4 V is observed from the transfer curve measured at V_d = 0.4 V (Figure 2b), with a corresponding threshold voltage V_{th} = 0.57 V and a current *on*/*off* ration of about 10^3. The high current modulation at very low voltages is the hallmark of EGTs, and can be quantified by the device transconductance $g_m = \partial I_d/\partial V_g$. The maximum g_m = 215 µS was obtained for V_g = 0.88 V (Figure 2b), giving a normalized transconductance per channel width g_m/W = 107 µS mm^{-1}, which compares favorably to the values reported for atomically flat, single crystal ZnO EGTs (~800 µS mm^{-1}).[25] It is important to point out that the device performances are limited by the absence of insulation between the ZnO NPs films and the electrolyte in the area surrounding the channel. Moreover, nanostructured films, when compared to poly-/mono-crystalline layers, will suffer from reduced charge mobility due to the intrinsically high defect concentrations. In spite of these limitations, the ZnO NPs EGT performs favorably and exhibits a saturation electron mobility of 0.81 cm^2 V^{-1} s^{-1} (calculated using the EDL capacitance C_{dl} = 8.04 µF cm^{-2}, Supporting Information), in agreement with values obtained using compact ZnO thin films gated through ion-gel dielectrics.[26] The capacitance of the EDL for the nanostructured ZnO almost doubles that of a flat ZnO layer (C_{dl} = 4.14 µF cm^{-2}), confirming the enhancement of the surface area (Supporting Information, Figure S2).

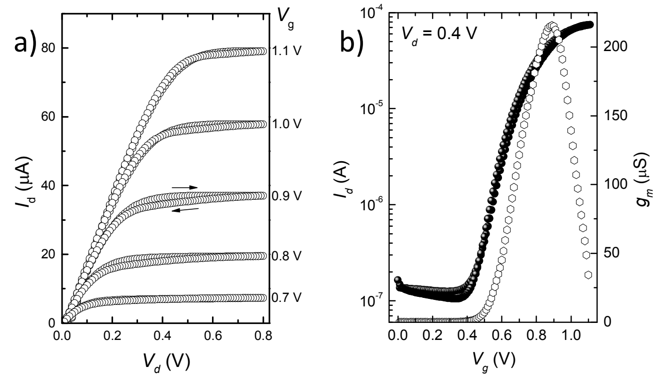

Figure 2. (a) Output characteristics of the EGTs in aqueous electrolyte with V_g varying from 0.7 V to 1.1 V with a step of 0.1 V. (b) Transfer curve for V_d = 0.4 V (full circles) with the associated transconductance (empty hexagons).

The remarkable device performance in water-based electrolytes makes ZnO NPs based EGTs attractive elements for sensors working in aqueous environment. Since the working principle of these devices is based on the displacement of cations in the proximity of the metal oxide surface, their use as ion sensors is the most obvious direct application. Ion-selective EGTs were prepared by integrating a polymer ISM doped with a potassium ionophore, using an architecture recently described for electrochemical transistors based on both semiconducting and conducting polymer.[27, 28] The device structure (Figure 3a) consists of a reference electrolyte (KCl 10^{-2} M) in contact with the ZnO channel, separated from the analyte by the ISM. The ISM consists of a polyvinylchloride matrix containing a plasticizer, an anionic exchanger and the potassium ionophore III. As previously detailed, the solution containing the ISM components was drop-casted on a glass substrate and, after drying, the obtained membrane was transferred onto the EGTs array.[28] Changes in K$^+$ concentration (c_{K^+}) in the sample shift the potential at the electrolyte/membrane interfaces and the resulting electric field drops onto the channel modulating its conductivity.[29] Stock solutions with increasing K$^+$ concentrations were exchanged in the upper chamber while monitoring the consequent variation of the current I_d. Figure 3b shows the response of the transistor $\Delta I/I_0$ (with ΔI being the difference between I_d at a given concentration and I_0, the current at infinite dilution) for c_{K^+} spanning 7 orders of magnitude. The response of the device has been measured 60 s after injecting the saline solution, but we observed that at least 90% of the current response is reached in less than 20 s (Figure S2). The IS-EGTs is capable of sensing K$^+$ with a detection limit of $c_{K^+} = 4.7\cdot10^{-4}$ M and with a thirtyfold increase of the current for the concentration range $10^{-4} \leq c_{K^+} \leq 10^{-1}$ M. The detection limit was estimated as the cross point between the slope of the dataset and a line corresponding to the noise level of the device (I_d at low K^+ concentration). It is important to emphasize again that the ZnO film exposed to the electrolyte is not restricted solely to the channel area, leading to a detection limit which is somewhat higher compared to what is expected by using this particular ISM formulation.

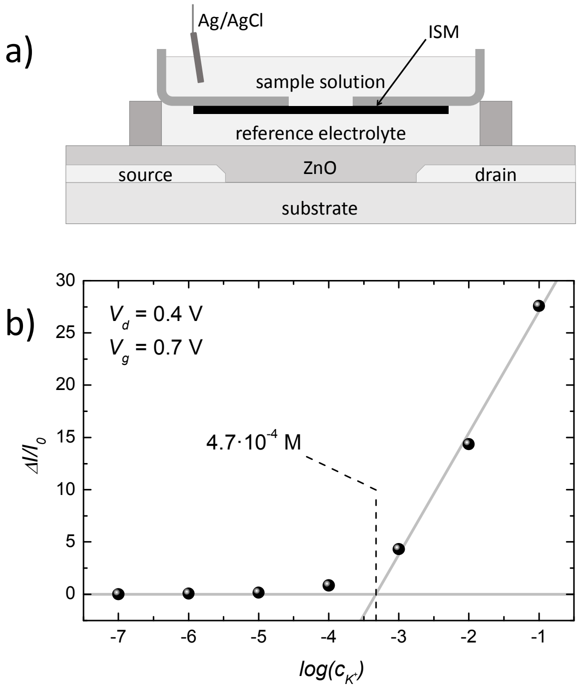

Figure 3. (a) Schematics of the device architecture used in the preparation of ion-selective EGTs. (b) Device response as a function of the c_{K^+} expressed in decades of molar concentration.

Through precise patterning of the channel together with insulation of the ITO contacts and interconnects, we expect the device to show sensitivity and detection limit in agreement with similar ion-sensing structures.[28] A key advantage of metal oxides over conducting polymers or molecular semiconductors is the possibility of tuning their properties as well as introducing tailored functionalities by direct surface modifications.[30] As in most metal oxides, the surface of ZnO is rich in -OH groups, which can be readily functionalized by electrostatic or covalent binding of virtually any type of molecule.[31] For this reasons, ZnO has been widely used as electroactive substrate in the preparation of amperometric enzymatic sensors.[32] As a proof of principle, we prepared simple glucose-sensing EGTs by covalent binding of the enzyme glucose oxidase (GOD) on the ZnO NPs surface. GOD was grafted on the metal oxide by using (3-glycidyloxypropyl)-trimethoxysilane (GOPS) as the covalent linker. The methoxy silane functionality of the GOPS binds on the ZnO surface, while the epoxide group allows the formation of a secondary amine bond with the enzyme (Figure 4a).[33, 34] A 10 wt% GOPS solution in isopropanol (iPrOH) was deposited by spin coating on the ZnO channel and annealed at 100 °C for 10 minutes. The layer was subsequently rinsed with 0.1 M KCl in water to remove the excess of unbounded GOPS. Afterwards, an aqueous GOD solution was added on the transistor and was allowed to dry at RT overnight. Before the device characterization, the functionalized ZnO films were rinsed gently with 0.1 M KCl in water to remove any excess of unattached GOD. For the sensor characterization, a Pt wire was used as the gate electrode in order to avoid the necessity of adding a redox mediator.[4] We observed an increased V_{th} of 0.83 V and a reduction of the *on*/*off* ratio to about 2 order of magnitude (Figure 4b), in accordance with the increased electrode work function of Pt.[35] In this case, the achievement of current saturation (and thus higher *on*/*off* ratio) is limited by the electrochemical window of water. The current response $\Delta I/I_0$ of the sensor was measured 60 s after the injection of stock 0.1 M KCl aqueous solutions with increasing D-glucose concentrations [Glc], and is reported in Figure 4c.

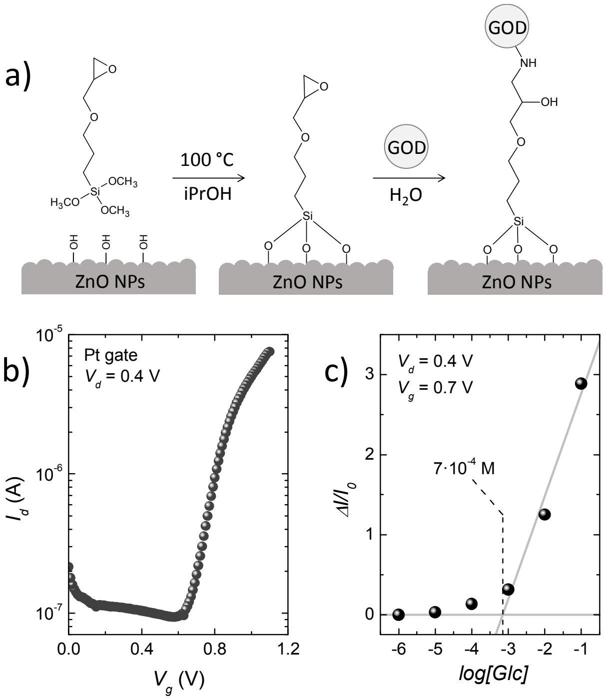

Figure 4. (a) Reaction scheme for the functionalization of the ZnO NPs surface with the enzyme GOD. (b) Transfer curve of the GOD-functionalized EGTs employing a Pt gate electrode. (b) Device response to increasing glucose concentration, expressed in decades of molar concentration.

The device operation as glucose sensor confirms that the biological activity of the enzyme is preserved after covalent bonding on the ZnO NPS. The functionalized EGT is capable of sensing Glc in the range $10^{-4} \leq [\mathrm{Glc}] \leq 10^{-1}$ M, with the highest sensitivity (slope of the response curve) above 10^{-3} M, which matches to the physiological concentration of glucose in humans (1-20 mM).[4] The correspondent detection limit, calculated as in the case of the ion-selective transistor, is $7\cdot10^{-4}$ M. As a final test, we evaluated the overall stability of the EGT by continuously cycling it between V_g=0 V and V_g=0.9 V (maximum of transconductance) at V_d=0.4 V. The *on/off* ratio readily reaches and stabilizes at 60% of its maximum value for at least 2.5 h (Supporting Information, Figure S4), indicating a remarkable lifetime of the water-gated ZnO transistor.

Conclusions

In summary, we have shown electrolyte gated transistors (EGTs) prepared by simple solution processing of commercial ZnO NPs suspension. The device can work in aqueous environment at biases as low as 1 V, and shows electron mobility of 0.81 cm^2/Vs. Of great importance is the versatility of such devices for the realization of a variety of biosensors. Ion-selective membranes can be integrated with the electrolyte-gated transistors leading to sensitive ion sensors capable of determining K$^+$ over a wide range of concentrations. On the other side, ZnO is an extraordinary platform for further chemical modifications, since virtually any type of chemical transducer (electrochemical and even optical) can be bonded on its surface leading to a variety of different functionalities. Through the use of a functional alkoxysilane, we covalently attached glucose oxidase on the surface of the transistor channel, resulting in a simple sensor for physiological monitoring of glucose. These results clearly show the potential of metal oxides electrolyte-gated transistors in environmental and biomedical applications, and pave the way for a new generation of low-cost, disposable and even flexible biosensors.

Notes and references

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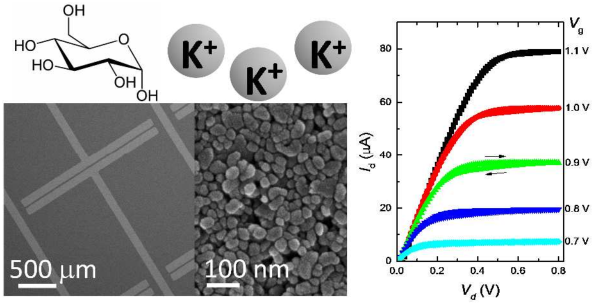

A water-gated transistor based on a nanostructured ZnO channel is a simple, versatile and low-cost biosensor.