Biosensors and Bioelectronics 98 (2017) 437–448

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

Detection principles of biological and chemical FET sensors

Matti Kaisti

University of Turku, Department of Future Technologies, FI-20014 Turun yliopisto, Finland

ARTICLE INFO

Keywords:
Biosensor
Chemical sensor
FET
ISFET
Detection
Electrochemistry

ABSTRACT

The seminal importance of detecting ions and molecules for point-of-care tests has driven the search for more sensitive, specific, and robust sensors. Electronic detection holds promise for future miniaturized in-situ applications and can be integrated into existing electronic manufacturing processes and technology. The resulting small devices will be inherently well suited for multiplexed and parallel detection. In this review, different field-effect transistor (FET) structures and detection principles are discussed, including label-free and indirect detection mechanisms. The fundamental detection principle governing every potentiometric sensor is introduced, and different state-of-the-art FET sensor structures are reviewed. This is followed by an analysis of electrolyte interfaces and their influence on sensor operation. Finally, the fundamentals of different detection mechanisms are reviewed and some detection schemes are discussed. In the conclusion, current commercial efforts are briefly considered.

1. Introduction

Among various potentiometric techniques, sensing based on field-effect transistors (FETs) has attracted considerable attention because of its potential for miniaturization, parallel sensing, fast response time, and seamless integration with electronic manufacturing processes, such as complementary metal-oxide semiconductors (CMOS) Chen (2013); Schoning and Poghossian (2002); Poghossian and Schöning (2014). The concept of an ion-sensitive FET (ISFET) was introduced in the early 1970s and it was derived from a metal-oxide-semiconductor FET (MOSFET) Bergveld (2003). It was realized that a MOSFET with the metal gate removed and the underlying gate oxide inserted in an aqueous solution along with a reference electrode could be used detect ions. Given the importance of the hydrogen ion, most early research focused on its detection through experimental and modeling developments Bergveld (2003), whereas more recent efforts emphasize various gate-modification techniques towards the detection of biomolecular interactions Schoning and Poghossian (2002); Poghossian and Schöning (2014). Interestingly, the coated-wire electrode, analogous to the ISFET technology, was invented at the same time Cattrall and Freiser (1971). It was designed to simplify the conventional ion-selective electrode (ISE) that requires internal filling solutions in conjunction with an ion-selective membrane (ISM). The coated-wire arrangement consists of either a metal wire or a disk electrode directly coated with an ISM. This results in a much simpler, smaller, inexpensive, and robust sensor compared to the conventional ISE. The potential of the electrode is measured against a reference electrode using a high-impedance voltmeter. There are no ohmic potential drops in the system because it operates (ideally) in zero-current condition. The measured potential is the sum of many interfacial potentials, but only the interfacial potential between the sample and the gate material varies depending on the target analyte activity Hu et al. (2016). This principle also applies to FET-based sensors. In fact, the input terminal of the voltmeter is simply a FET, and only the surrounding circuit and biasing are different compared to conventional potentiometric setup. Additionally the used electrodes are different, but the reason is mostly practical.

There are many different FET sensor structures and sensing materials. Along with different target analytes, it results in a myriad of different sensor system combinations. These systems share the same overall construction that is illustrated in Fig. 1. The information obtained from the sample corresponds to either the concentration/activity of the target analyte or the presence/quantity of a biomolecule, which is transduced to an electrical signal via the field effect. Then, the signal can be amplified, processed, and displayed Schoning and Poghossian (2002) or sent to the cloud Nemiroski et al. (2014) depending on the application.

This review focuses on different transistor structures and on the interfacial behavior at the electrolyte-solid interface. I omit structures such as silicon nanowire (SiNW) FETs and graphene FETs because they are extensively covered elsewhere. For recent reviews beyond the scope of this work, the reader can refer to the following: broad and general electrochemical sensor reviews Privett et al. (2010); Ronkainen et al. (2010); Perumal and Hashim (2014), CMOS-based sensing Arya et al.

E-mail address: mkaist@utu.fi.

http://dx.doi.org/10.1016/j.bios.2017.07.010
Received 12 April 2017; Received in revised form 21 June 2017; Accepted 4 July 2017
Available online 05 July 2017

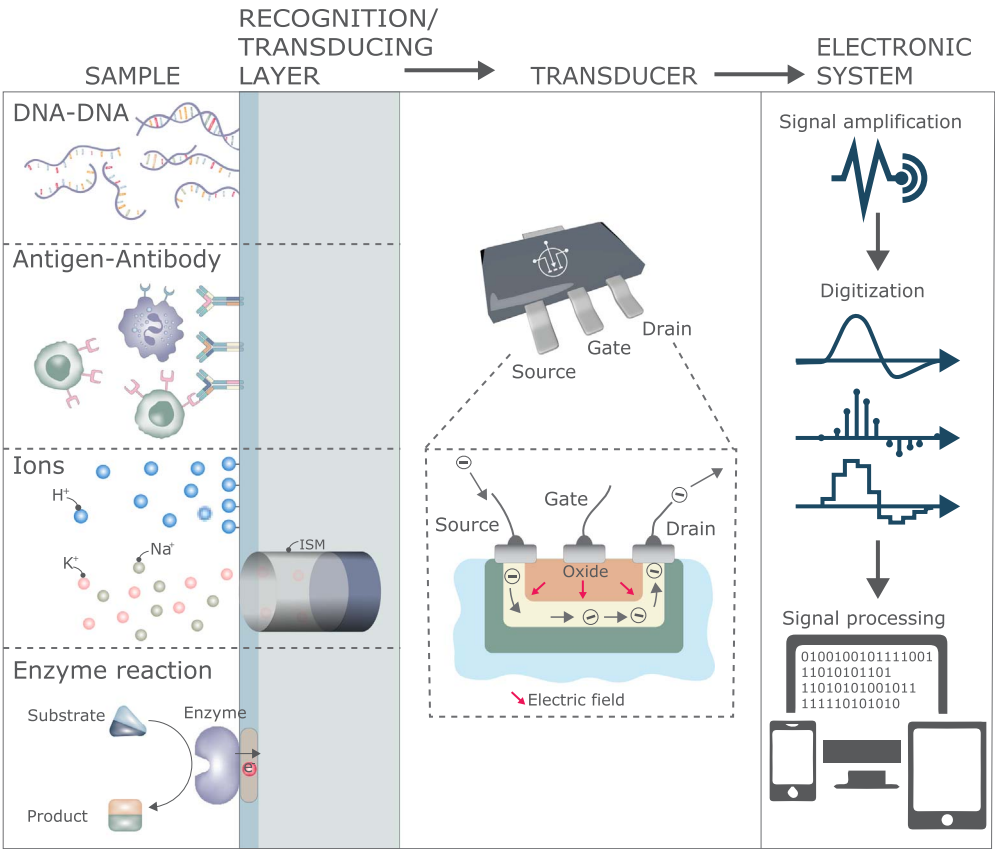

Fig. 1. Illustration of a biological and chemical FET sensor.

(2015); Lei et al. (2016), label-free detection Poghossian and Schöning (2014); Mehrabani et al. (2014), electrochemical immunosensors for point-of-care diagnostics Wan et al. (2013), nucleic acid diagnostics Ahmad and Hashsham (2012), wearable chemical sensors Matzeu et al. (2015); Bandodkar et al. (2016), lab-on-chip applications Lafleur et al. (2015), and SiNW biosensors Zhang and Lieber (2016).

1.1. Biological and chemical FET sensors

A simplified potential diagram of a generalized (bio)chemical sensor is shown in Fig. 2, which conveys the necessary information required to understand the basic detection principle. Shoorideh and Chui (2014). The observed responses originate from charge σ_0 resting at the sensing surface. This charge sees capacitances on both of its sides with signal grounds that follow. The capacitance is presented as a parallel combination of the double-layer and sensor (i.e., FET) capacitances, C_{DL} and C_{FET}, respectively, where the latter comprises the gate oxide, C_{OX}, and depletion, C_b, capacitances. The potential change at the sensing surface can be approximated by

$$\Psi_0 = \frac{\Delta\sigma_0}{C_{DL} + C_{FET}}. \quad (1)$$

Depending on the transistor biasing, either of these capacitances can dominate. In weak inversion, C_b will clearly be smaller and determine the overall sensor capacitance, in contrast to strong inversion, where C_b can be omitted and C_{OX} is relevant Streetman and Banerjee (2006). In either case, these capacitances are usually clearly smaller than the double-layer capacitance. Thus, the double layer strongly couples the potentials and, in many cases, it can be omitted from Eq. (1). Hence, we can conclude that in these cases the transistor capacitance has a negligible effect on the sensitivity at the sensing interface.

An attempt has been made to dissect the biosensor into indepen-

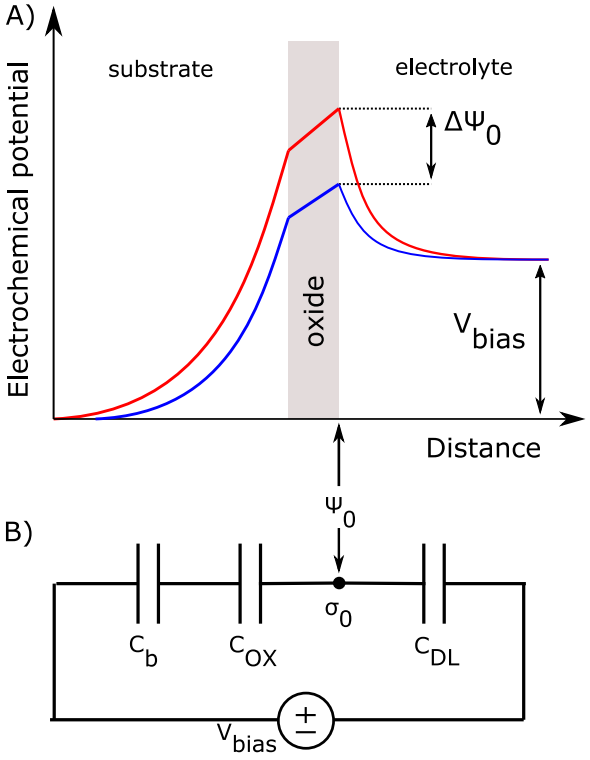

Fig. 2. A) Potential over a simplified model of electrochemical cell with an oxide as the interfacial material. The charge binding in the surface creates a potential shift, denoted by $\Delta\Psi_0$, at the interface. The effect of Debye screening is observed in both the electrolyte solutions and semiconductor regions. B) Equivalent circuit model of the sensor where C_{DL}, C_{OX}, C_b are the double-layer, gate oxide, and depletion capacitances, respectively. The interfacial charge, σ_0, is shared by capacitors on both sides. Adapted from Shoorideh and Chui (2014).