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CHEMICAL TRANSDUCTION THROUGH FIELD-EFFECT TRANSISTORS

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ABSTRACT

Field-effect transistors (FET) are semiconductor devices which have been developed for electronic applications but have found applications in chemical transduction as well. The surface of the FET gate area could be interfaced to a chemically sensitive membrane which generates a potential when placed in contact with a specific chemical species. The current flowing through the transistor can be related to the concentration of the chemical substance. Chemical sensors based on FET are selective, fast-responding and miniature. A number of chemical species had been measured using FET sensors. An overview of the state-of-the-art of FET sensors is presented.

Introduction

The field effect transistor (FET) is a powerful and versatile semiconductor device currently widely used in very large-scale integrated circuits for a number of good reasons. First, the FET has a simple and compact structure which makes it possible to pack more than 100,000 FET units in a single chip. Second, the FET has a high input impedance, which means that the input signal for a FET can be a voltage of practically zero power level. And lastly, FETs may be connected as resistors and capacitors. Thus, it is feasible to design systems consisting entirely of FETs and no other components.

The role of FET in electronics is already well-established. Now, it is steadily gaining ground in another field of application – in chemical transduction. The conversion of chemical information, such as the concentration of chemical species, into an electrical signal allows a simple and rapid method of chemical analysis. This transduction process provides the basis for the development of chemical sensors. chemical sensors are selective, fast-responding devices which can be used for continuous in-situ measurements. They are in demand in industrial, medical and environmental monitoring [24].

The FET has several attractive features which make it suitable for sensing applications. These include its small dimensions, low output impedence, fast response and mass-fabrication ability. Since its introduction in 1970, many chemically-sensitive FETs or ChemFETs have been developed for various substances which includes ions, gases, and organic molecules.

This paper presents an overview of the state-of-the-art in the utilization of FET for chemical transduction, including some results of our work in the development of FET sensors.

Principle

The FET is a three-terminal semiconductor device which depends for its operation on the control of current by an electric field. The configuration of the common FET (Figure 1a) consists of a metallic electrode, the gate, an insulating layer which is usually a silicon dioxide layer, and a silicon semiconductor, the substrate. Because of its structure, this type of FET has also been called MOSFET (metal-oxide-semiconductor FET) or IGFET (insulated-gate FET). Embedded in the substrate are two isolated semiconductors, the source and the drain, which differ in type from the substrate. In the figure, the substrate is a p-type semiconductor, while the source and the drain are n-type.

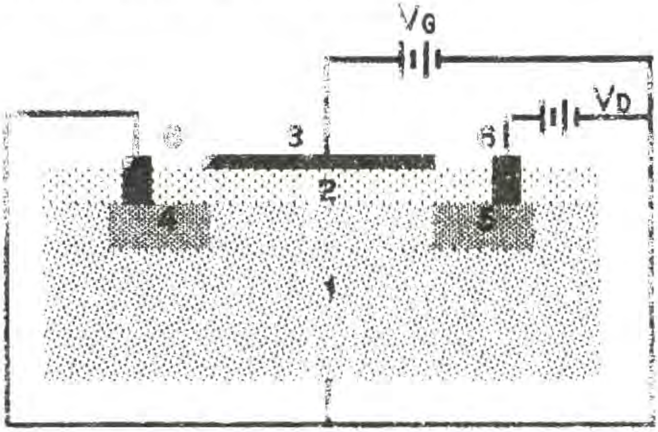

Figure 1a. Diagram of the FET. (1) p-type silicon substrate, (2) insulator, (3) gate metal, (4) n-type source (5) n-type drain, (6) metal contacts to source and drain.

The operation of the FET is based on the control of current flowing through the substrate from source to drain, by means of a voltage applied at the gate. Current is induced in the substrate by applying a voltage between the source and the drain. Normally, no current can pass because there are only few electrons in the p-type substrate. When a positive voltage is applied on the gate, the positive "holes" which are the majority charge carriers in a p-type semiconductor are driven away from the silicon-insulator interface. At a voltage level known as the threshold voltage, the region near the silicon-insulator interface turns from a p-type to an n-type semiconductor, the same type as the source and the drain. This phenomenon, known as inversion, results in the creation of a channel between the source and the drain. The channel allows the conduction of current, and its size determines the level of the current. Since the gate potential controls the channel size, it also influences the level of current in the FET.

The FET can be made to function as a chemical transducer by replacing the metallic electrode with a chemically-sensitive membrane (Figure 1b). When immersed in solution, the FET develops a concentration-dependent potential between the reference electrode and the membrane. Similar to the ordinary FET, this potential controls the current in the semiconductor substrate.

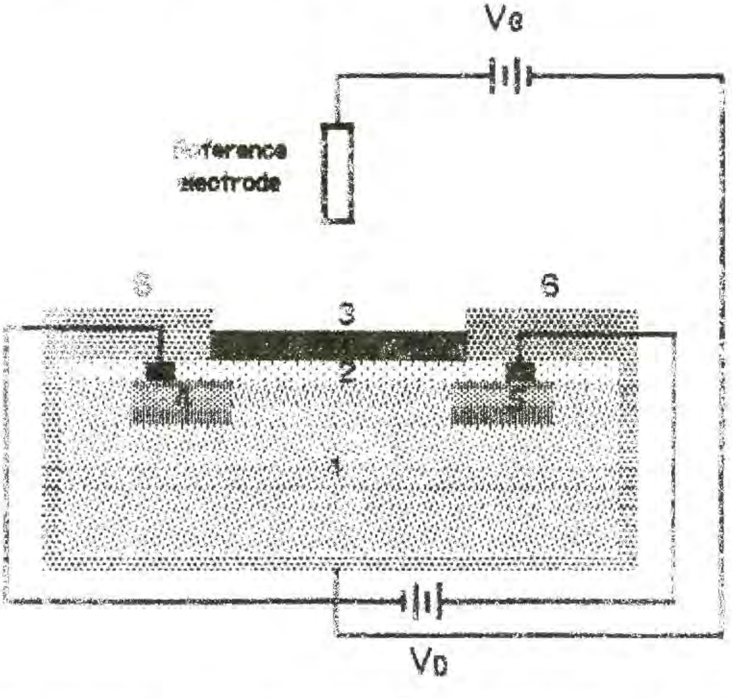

Figure 1b. Diagram of the FET chemical transducer. (1) Silicon substrate, (2) insulator, (3) chemically sensitive membrane, (4) source, (5) drain, and 96) encapsulant.

Instrumentation

Measurements with chemically-sensitive FET can be accomplished in two operating modes. In one mode, the gate voltage is held constant, and in the other, the drain current is kept unchanged. The constant gate voltage operation, however, is the simplest.

The circuit for the constant gate voltage operation is shown in Figure 2. Constant voltages, V_D and V_G, are applied to the drain and reference electrode, respectively. Changes in the potential at the membrane-solution interface manifest as a change in the drain current, I_D. The operational amplifier, A, gives an output voltage which is related to the product of the drain current and the feedback resistor, R_1.

As in potentiometric measurements a reference electrode is required to serve as a baseline for the variable potential of the indicating electrode, or the FET sensor, in this case. Ordinarily, silver-silver chloride or calomel electrodes are used as reference electrodes. These electrodes, however, are bulky and incompatible with the miniature FET sensor. To realize a completely miniaturized sensor system, reference electrodes such as a platinum electrode or a pH-insensitive FET, also known as a RefFET [3], have been used.

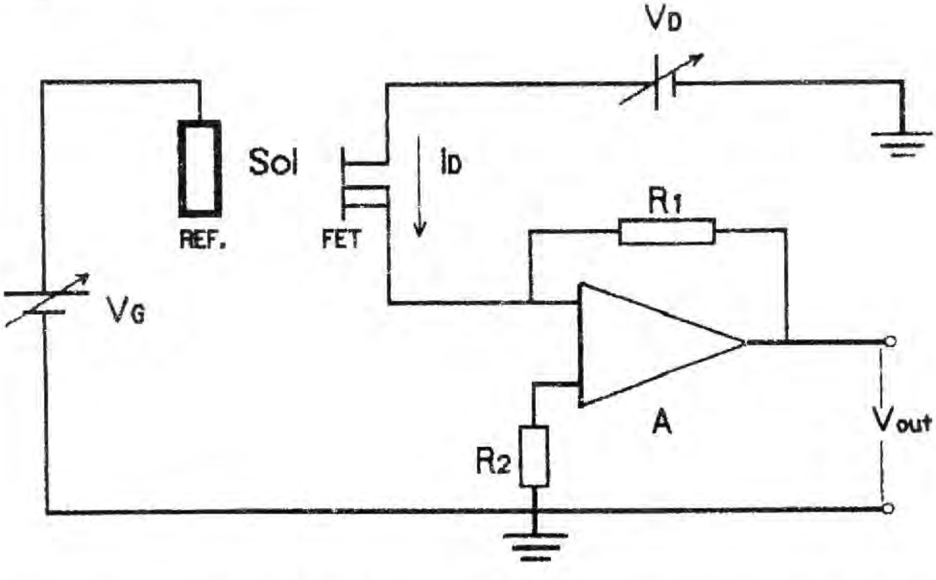

Figure 2. Schematic diagram for measuring ID at constant gate voltage. A, operational amplifier.

Fet Sensors

FET sensors can be divided into direct or indirect sensing devices. The difference between the two is illustrated in Figure 3. In a direct sensing device, the substance of interest (the primary chemical variable) directly causes the change in the electrical parameter of the FET through a chemically-sensitive interface. In an indirect sensing device, the primary chemical variable is first converted by an intermediate layer into a secondary chemical variable which is sensed directly by the underlying FET chemical transducer.

Examples of direct sensing FET sensors include all membrane-covered and chemically-modified FET sensors since they do not involve any secondary chemical variable. The gas-sensitive FETs as well as the FETs sensitive to organic compounds, BioFETs, are indirect sensing devices.

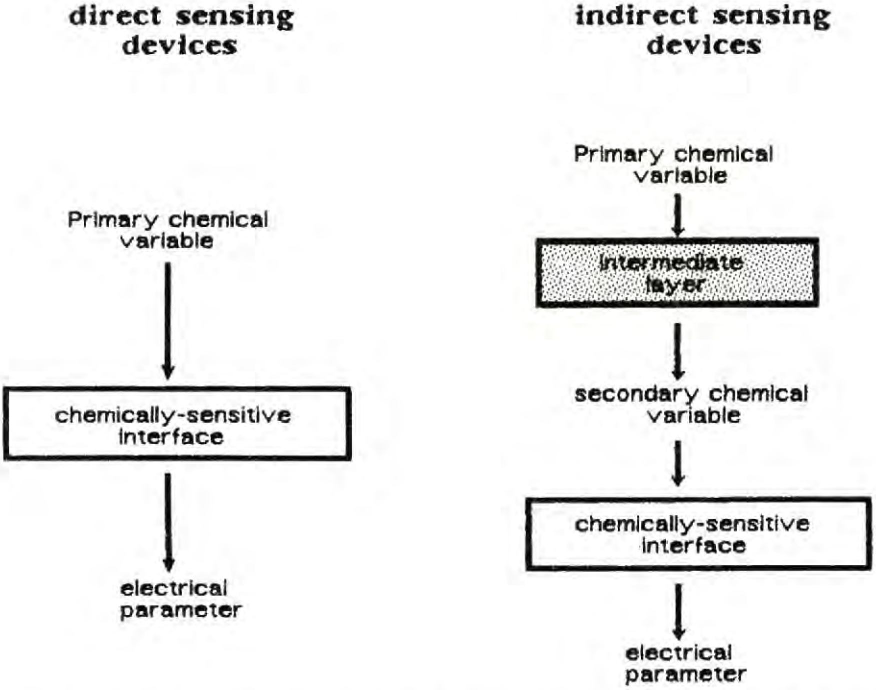

Figure 3. Schematic representation of direct and indirect sensing FET devices.

pH-sensitive FETs

The pH-sensitive FET is the most widely investigated sensor because of the importance of pH measurement, as well as, the nature of the gate materials commonly used in it. The first FET chemical sensor that was developed had a Si02 membrane which was naturally sensitive to pH [2]. Although this mateiral showed some pH sensitivity, the response was nonlinear, it drifted highly, and suffered considerable sodium interference [8]. Much of the work that followed tried to improve on the first by employing other gate materials, such as Si_3N_4 [17], $A1_2O^3$ [18], and Ta_2O_5 [18]. Commerical pH-sensitive FETs are already available.

In our laboratory, we investigated the behavior of a pH-sensitive FET containing a Si_3N_4 gate. The FET was obtained from advanced Biotechnology Corporation (Germany). We have fabricated a robust and compact pH sensor based on this semiconductor device (Figure 4). The calibration curve of this sensor is shown in Figure 5.

The potential-generating mechanism of an FET chemical transducer is described by the site-binding model (Figure 6). According to this model, the response results from the presence of silanol groups at the surface of hydrated silica, the ionization state of which changes with pH. The resulting electrical surface charge of the dielectric leads to modulation of the channel' conductace which becomes the analytical signal. This model has also been applied to the other pH-sensitive materials.

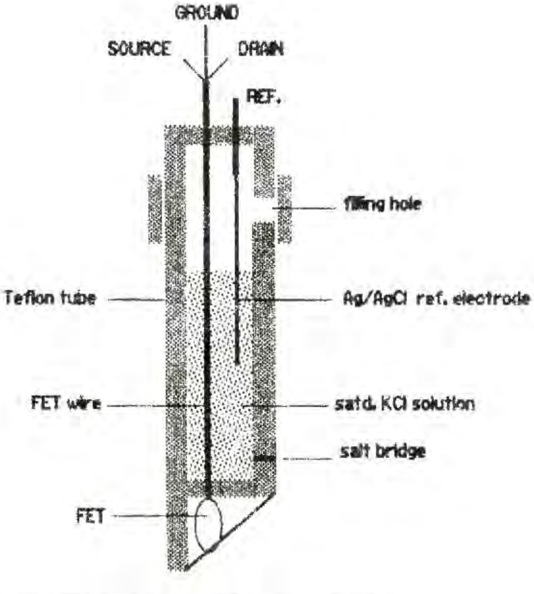

Figure 4. Diagram of the pH sensor based on FET

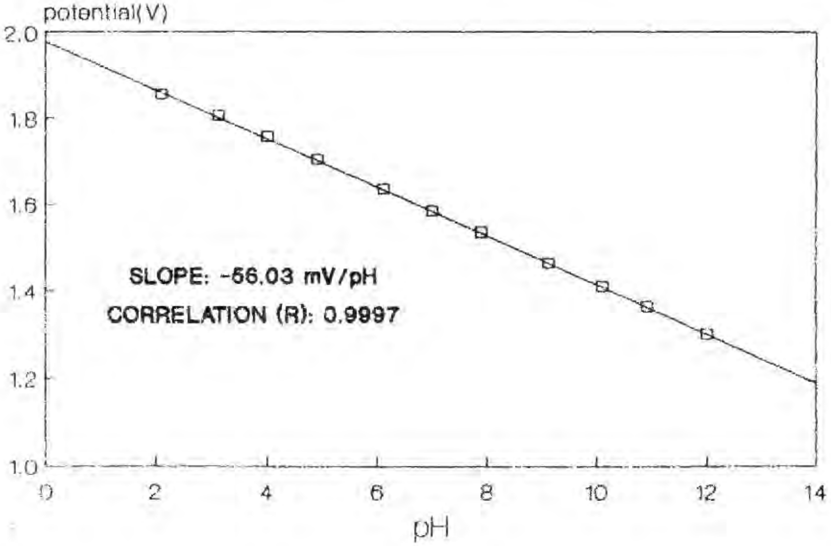

Figure 5. **Calibration curve of the FET-based pH sensor**

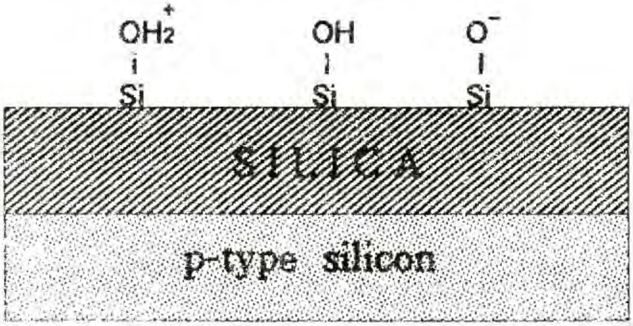

Figure 6. **Ionization states of silanol with different pH values.**

Ion-sensitive FETs

FET sensors for ions other than the hydrogen ion have been developed through chemical modification of the gate membrane. Modification has often been done either by deposition of ion-sensitive membranes or by chemical grafting, i.e. by covalently binding ion-sensitive molecules to the silanol groups of the silicon dioxide gate insulator [9].

Deposition of inorganic membranes, such as films of aluminosilicate glass [11] and calcium fluoride [12], allowed the detection of sodium and fluoride ions, respectively. A more versatile material for deposition are polymers doped with ionophores which may be complexing and chelating agents. FET sensors for potassium [20] and ammonium ions [21] have been fabricated by depositing polymer mebranes containing valinomycin and nonactin, respectively, as ionophores. A recent development is the use of Langmuir-Blodgett films which can be as thick as the strand of a molecule but can nevertheless include ionophores [23].

Gas-sensitive FETs

Sensors for gases have been developed using the Severinghaus electrode configuration (Figure 7), which consists of a pH-sensitive electrode, configuration (Figure 7), which consists of a pH-sensitive electrode, a reference electrode, an internal electrolyte, and a gas permeable membrane. The internal electrolyte contains a solution of the weak salt of the gas to be detected. During measurement, the gas diffuses through the membrane until the final equilibrium distribution of dissolved gas molecules is attained throughout the membrane and the internal electrolyte layer. The chemical processes involved in the CO_2 and NH_3 gas sensor are shown in Figure 8.

Severinghaus electrodes for CO_2, NH_3, SO_2 and other gases have been made. Most of them, however, are still using the fragile and bulky glass electrode, the most common pH electrode. So far, only the CO_2 severinghaus electrode has been fabricated with a pH-sensitive FET [22]. Currently, we are working on an ammonia gas sensor (Figure 9) using a FET. The response curve shown in Figure 10 is the result of a preliminary study.

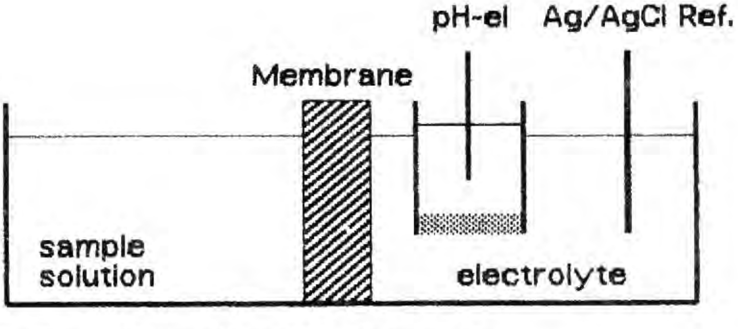

Figure 7. Severinghaus cell assembly for gas sensing

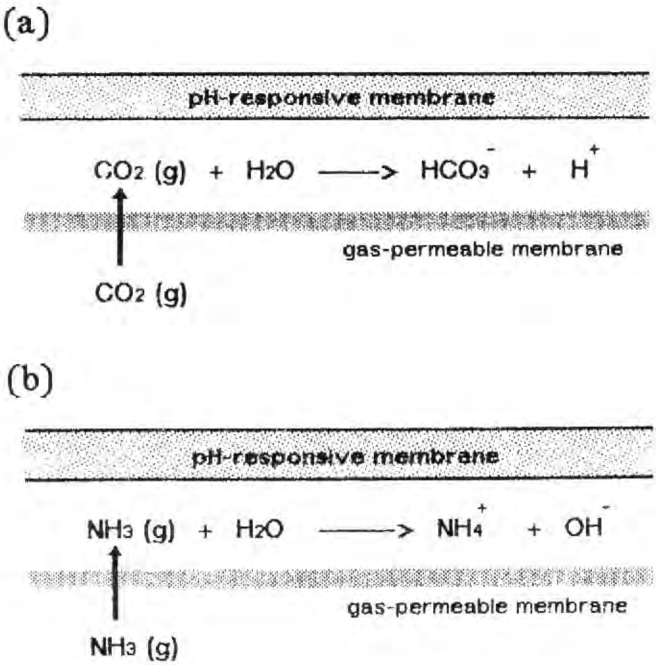

Figure 8. Chemical processes that lead to the potentiometric response of (a) CO_2 and (b) NH_3 gas sensor.

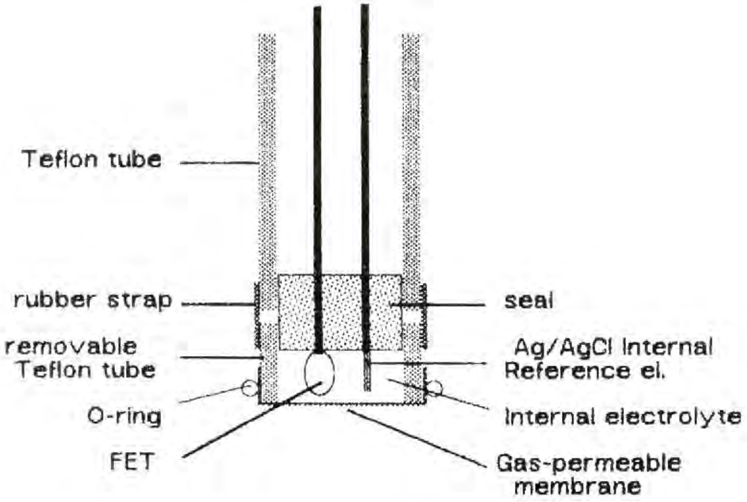

Figure 9. Ammonia gas sensor based on FET.

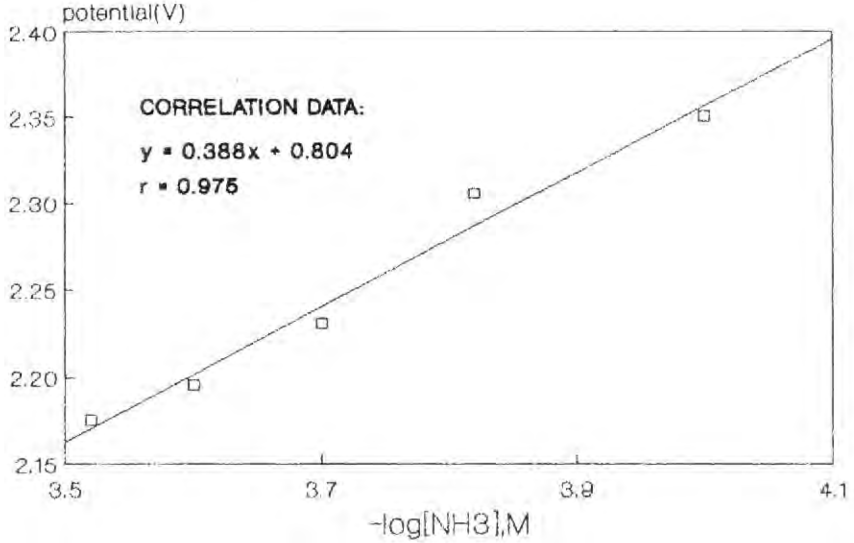

Figure 10. Calibration curve of ammonia gas sensor based on FET.

BioFETs

A pH-sensitive FET becomes more versatile as an indirectly sensing device, when it is coupled with a biological element. Adding intermediate layers containing immobilized enzymes, antibodies, or microorganisms on the gate membrane of the FET (Figure 11) expands the range of substances it can analyze. In this way, many FET sensors for organic substances have been developed. Collectively, these sensors have been called BioFETs because of the biological origin of their intermediate layers.

Most BioFETs were developed for medical applications. The substances often determined include glucose [7] [15], urea [1], and penicillin [6]. BioFETs for acetylcholine [12], penicillin G [5], hypoxanthine [13], inosine [14] and alcohol [16] have been devised, as well.

A BioFET sensor for lactose based on co-immobilized galactosidase and glucose dehydrogenase was also developed by the authors. The chemical reactions leading to the transduction are as follows:

$$\text{Lactose} \xrightarrow{\text{galactosidase}} \text{Glucose} + \text{Galactose}$$

$$\text{Glucose} + \text{NAD} \xrightarrow[\text{}]{\substack{\text{glucose} \\ \text{dehydrogenase}}} \text{Gluconic acid} + \text{NADH} + \text{H}^+$$

The sensor displayed a highly reproducible and relatively rapid response. The response of the sensor is shown in Figure 10.

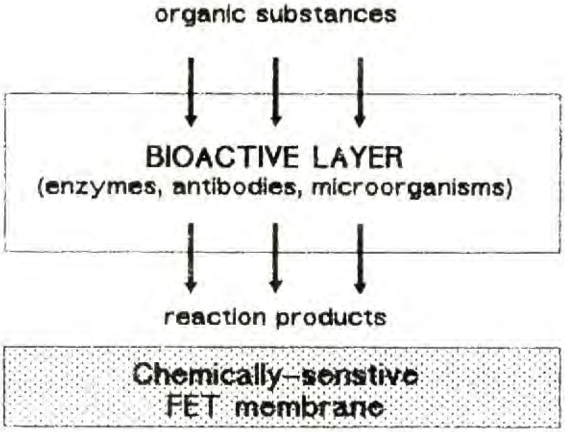

Figure 11. Mechanism of the response of BioFETs

Conclusion

The FET has not only been useful as an electronic device but also as a transducer for chemical species. The potential advantages of FET transducers over conventional ion-selective electrodes have been realized. Its applications in flow-through and flow-injection analytical systems have been recognized and are being investigated [4]. Novel methods of sensitizing the gate dielectric of FETs will further enhance the capabilities of FETs for chemical transduction [9]. Progress in electronic microcircuitry and microphotolitography will lead to a highly efficient and IC-technology compatible sensors for the detection and measurement of chemical substances [10].

Acknowledgements

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