8.3.2.4 Ion-selective field effect transistor (ISFET) devices

The output signal of the *Ion-Selective Field Effect Transistors* (ISFETs) is usually a potential difference the magnitude of which varies with the change of logarithm of sensed ion activity or concentration in the same way (but not necessarily in sign) as the corresponding ion selective electrode (ISE). It is proposed that the graphical representation of results be in accordance with previous recommendations for ISEs, that is, the output potential difference be plotted versus logarithm of ion activity or concentration so, that the slope of the plot is positive for cation responsive devices and negative for anion-responsive ones.

Here, the notation and terminology of the devices as well as their relation of the performance characteristics to ion-selective electrodes are provided.

Notation and terminology

Not all chemical-sensitive semiconductor devices are based on the *field effect transistor* (FET), *metal oxide semiconductor field effect transistor* (MOSFET), or *insulated gate field effect transistor* (IGFET). Also, not all *chemical-sensitive FETs* (ChemFETs) are ion-sensitive (ISFETs), but considerations are restricted here solely to ISFETs. Generally, ChemFETs are sensitive to gases and to enzyme substrates as well as to ions. Structurally, the ISFET is very similar to the IGFET, and a typical construction of an n-channel IGFET is shown in Figure 8.3.2.4.

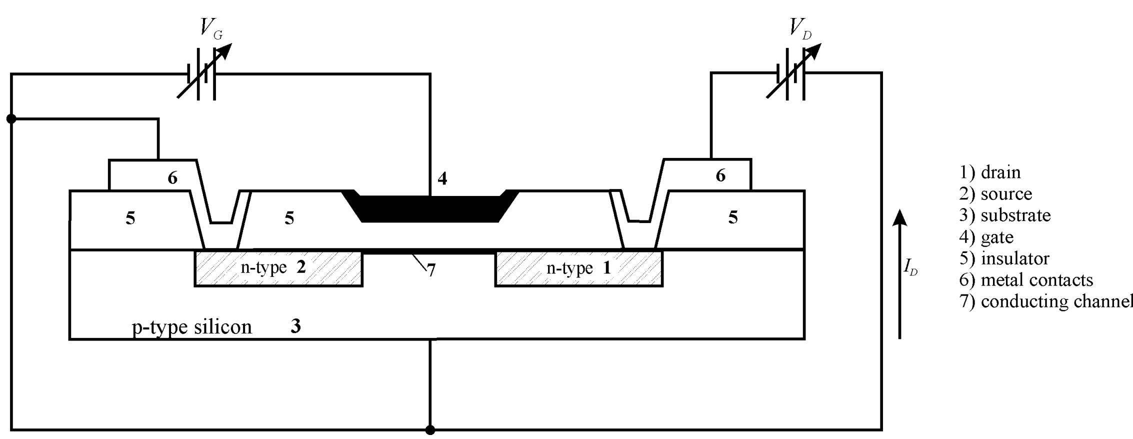

Figure 8.3.2.4 Schematic diagram of an IGFET. (1) drain; (2) source; (3) substrate; (4) gate; (5) insulator; (6) metal contacts; (7) conducting channel.

It consists of a p-type silicon substrate with source and drain diffusions separated by a channel which is overlain by SiO_2 as insulator and a metal gate. The polarity and magnitude of the *gate voltage difference* (V_G) applied between the substrate and the gate are chosen so that an n-type inversion layer is formed in the channel between the source and drain regions. The magnitude of the *drain current* (I_D) is determined by the effective electrical resistance of the surface inversion layer and the *voltage difference* (V_D) *between the source and the drain*.

The ISFET (Figure 8.3.2.5) differs from the IGFET in several respects:

(i) the solution (analyte) is in direct contact with the gate insulator layer(s) and a reference electrode in the solution replaces the metal gate. Previously, it had been thought that the reference electrode was unnecessary, but this is not so.

(ii) silicon nitride, Si_3N_4, overlying the SiO_2 is used to provide a charge blocking interface and an improved pH response.

(iii) other membranes, such as poly(vinyl chloride) containing valinomycin (which is the ion-selective electroactive material used in potassium ion-selective electrodes) can be added to confer other ion selectivities to the ISFET.

(iv) the successful encapsulation of all regions of the device other than the gate region to be exposed to the analyte solutions is mandatory.

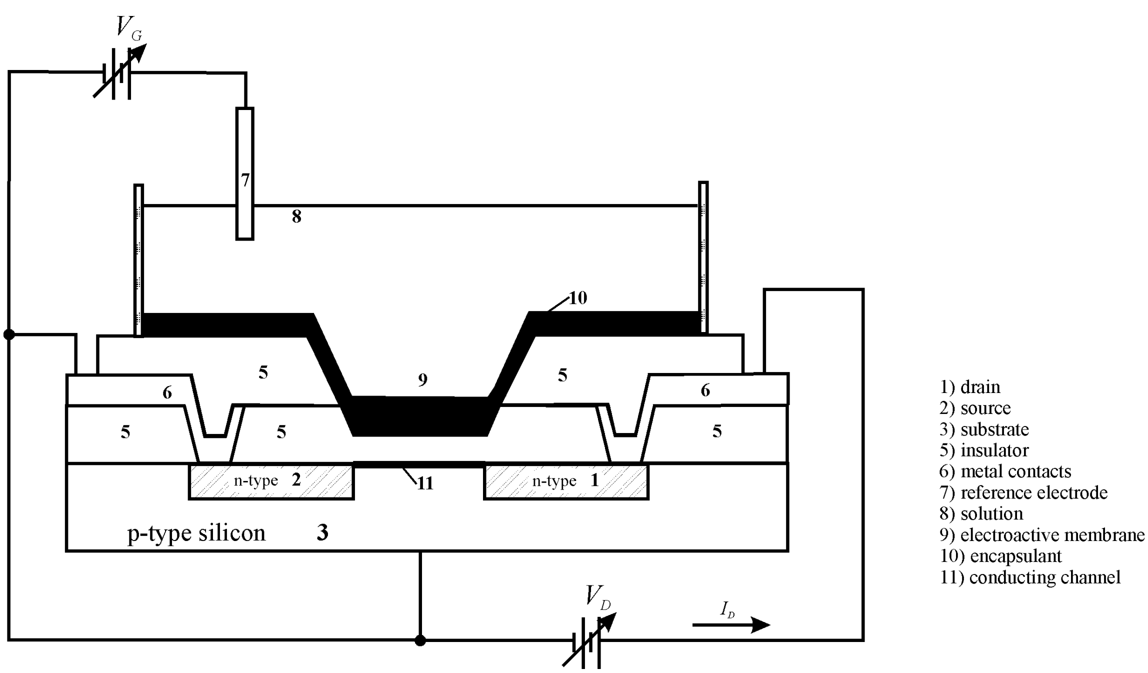

Figure 8.3.2.5 Schematic diagram of a composite gate, dual dielectric ISFET. (1) drain; (2) source; (3) substrate; (5) insulator; (6) metal contacts; (7) reference electrode; (8) solution; (9) electroactive membrane; (10) encapsulant; (11) conducting channel.

A diagram of the complete electrochemical system, together with the relevant electrical potentials (i.e. differences in inner potentials between the bulk phases), is shown in Figure 8.3.2.6. By analogy with the IGFET gate voltage difference (V_G), it is possible to define an *equivalent ISFET gate voltage difference* (V_G^*) as the electrical potential difference between the bulk phases of the semiconductor and gate material

$$V_G^* = E_I + V_{ref} + V_B$$

where V_B is an additional series polarising potential (*gate bias potential*), E_I is the *interfacial membrane-solution potential difference* generally given by the Nernst or Eisenmann-Nikolsky equations, and V_{ref} is the *reference electrode potential*.

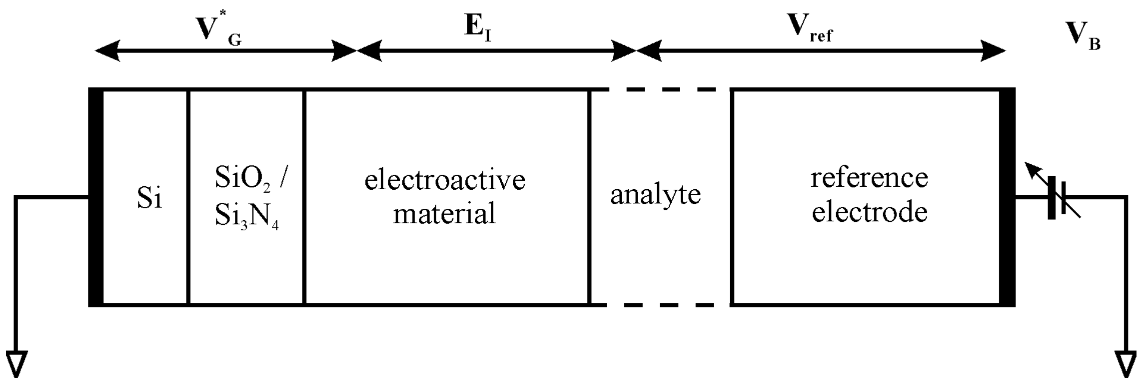

Figure 8.3.2.6 Schematic diagram of composite gate, dual dielectric ISFET showing potential difference contributions.

The I_D/V_G^* characteristics of ISFET devices are essentially those of the FET substructure on which it is based and depend on device design (in particular channel geometry and structure), materials and processing conditions. Several methods can be used to determine the I_D/V_G^* characteristics. If the applied gate bias potential (V_B) is fixed, then changes at the solution-electroactive material interface are reflected in changes of I_D. However, if the drain current is maintained at a constant value by means of an operational amplifier, which directly controls the applied gate bias potential with a negative feedback loop (Figure 8.3.2.7), then the output, V_{out}, is a potential difference which varies with change in activity of the sensed ion (a_i) in accordance with the Nernst equation. The output is therefore effectively the same as that of an ISE. Problems of representation and comparison arise, however, because the sign of V_{out} may or may not be the same.This is associated with that the ion-selective electrode output depends on the inverting characteristics of the operational amplifier(s) used. Therefore, a uniform method of result presentations obtained with ISFETs and ISEs is recommended below.

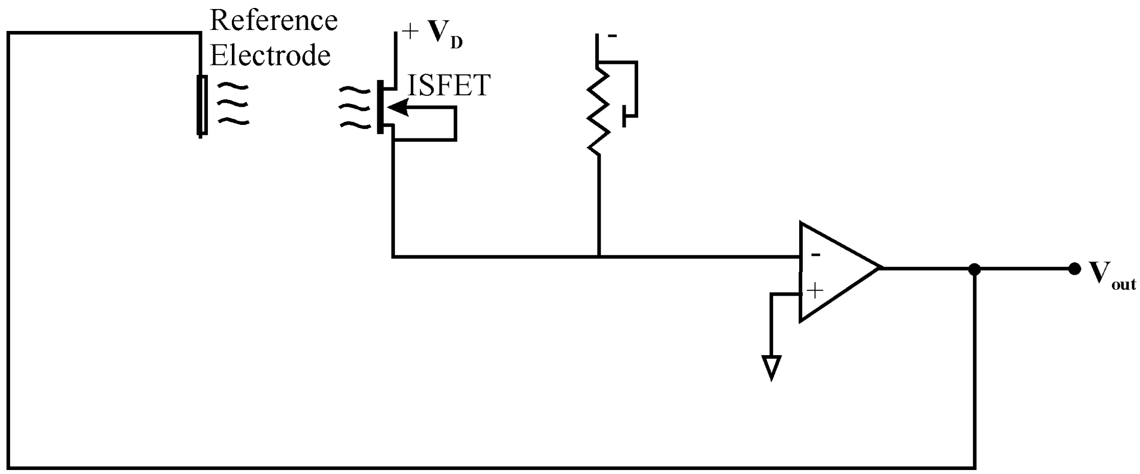

Figure 8.3.2.7 Schematic circuit of constant drain current (I_D) operating mode with negative feedback to the reference electrode.

Relation of ISFET performance characteristics to that of ion-selective electrodes

For uniformity of the ISE calibration curves, it is recommended that the potential difference (emf) of an ion-selective electrode cell (ISE combined with a reference electrode) be plotted at the ordinate (vertical axis) with the positive potentials increasing to the top of the graph and that -lg[activity of species measured] or -lg[concentration of species measured] be plotted at the abscissa (horizontal axis) with increasing activity (concentration) to the right. Essentially, this leads to a cation-responsive ISE having a calibration curve with a positive slope and an anion-responsive ISE a calibration curve with a negative slope. It is recommended that the ISFETs calibration curves should be in accord with this convention for the slopes, so that the way of plotting on the ordinate of experimental values of output potential difference is chosen appropriately, and that the modulus of the values of experimental output derived from ISFETs is regarded as equivalent to potential differences from ISEs, as used in the Nernst or Eisenman-Nikolsky equations.

Other symbols and techniques related to the performance of ISFETs with regard to determination of ions in solution should be in accordance with the recommendations for ISEs. Recommended procedures for calibration of ISFETs are those recommended for ISEs. For instance, the selectivity coefficient ($K_{A,B}^{pot}$) should preferably be determined by the mixed solution method.