Modelling of coulometric sensor–actuator systems based on ISFETs with a porous actuator covering the gate

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Abstract

The ion-selective field effect transistor (ISFET)-based coulometric sensor–actuator systems have found applications in acid–base titration and in the construction of a low-drift carbon dioxide and a pH-static enzyme sensor. In this paper a brief review is given of the previously developed ISFET-based sensor–actuator systems and the newly proposed system which employs a porous noble metal as the actuator deposited at a short distance over the gate. The advantages and disadvantages of the different systems are compared. Furthermore, an analytical model is proposed for the new system with a porous noble metal as the actuator. Two ways to make the porous gold actuator over the gate of the ISFET are described. The acid–base titration is chosen for the model study. The experimental results are in accordance with the theoretical description. Both the theoretical and experimental results show that devices with a different actuator thickness will behave differently. For a thin porous actuator, an approximately quadratic relationship between the titration time and the concentration of the titrated species is predicted by the model and confirmed by the experiment. For a thick porous actuator, titration of a weak acid shows an approximately linear relationship between the concentration of the titrated species and the titration time, which is predicted by the model. The theoretical calculation of the titration curve of a fully dissociated acid requires the use of a general formula derived from the model. The typical titration times are from 0.5 to 10 s, the corresponding concentrations of the titrated species range from 0.5 mM up to ca. 10 mM.

Keywords: Coulometry, Titrimetry, Acid–base, Ion-selective field effect transistor, Sensor–actuator

The ion-selective field effect transistor (ISFET)-based integrated coulometric sensor–actuator system was introduced in 1985 [1] in order to solve the problem of in situ ISFET calibration and to exploit new applications of the ISFET. Since then a series of developments has been made [2]. The reported applications of the system are typically the acid–base titration [2,3], con-

struction of a low-drift carbon dioxide sensor [2,4] and the introduction of the pH-static enzyme sensor [5]. Progress in the theoretical description of the system has also been achieved recently [6,7].

Generally, the integration of a coulometric actuator with an ISFET has several advantages. In the first place, it provides the ISFET with an easy and rapid way of regular in situ calibration. This is particularly useful in some specific applications such as, for instance, in vivo pH monitoring. Secondly, for an application of the system to the

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acid–base titration, drift is no longer a problem, as the ISFET is used in a dynamic way. In addition, the fast response of the ISFET makes the titration more accurate and rapid. Furthermore, a local pH control in the vicinity of the gate of the ISFET can be achieved, which can lead to new applications of the system as exploited in the pH-static enzyme sensor [5].

The different research projects have shown a promising prospect in the development of coulometric sensor–actuator systems. There are, however, still some disadvantages such as the delay in response existing in the previously developed systems. This is due to the fact that the actuator was a planar electrode closely surrounding the gate, but still at a distance of ca. 15–20 μm . In order to circumvent this problem, a newly designed system has been proposed which employs a porous noble metal as an actuator over the ISFET [8]. In this paper, we will give a brief analysis of the previously developed conventional coulometric sensor–actuator systems and the recently reported new system. The advantages and disadvantages of the different systems are discussed and compared. Afterwards, a model for the recently developed new system is presented and theoretical results are compared with the experimental results.

Closed-cell type microliter coulometric titrator

Figure 1 shows the basic components of the previously developed prototype coulometric sensor–actuator system [1]. The system is made by integrating a large noble metal actuator electrode and a counter electrode on a piece of silicon. A window in the actuator electrode is etched for the gate of the ISFET which functions as a pH indicator. A flow-through cell is constructed by sealing a silicon cover with an etched cavity on the chip. In principle, the operation of the system quite resembles the conventional coulometric titration system. For a titration the sample is first injected into the cavity, the current is then applied to the actuator electrode and the counter electrode. By coulometrically generating protons or hydroxyl ions, an acid or base titration can be performed with high accuracy. The amount of the electrical charge used for a coulometric titration is approximately linearly proportional to the concentration of the sample, because it can roughly be considered as a titration of the whole bulk solution. The main advantage of the system is the exploitation of the fast response of the ISFET as pH sensor for a rapid coulometric titration. Additionally, the system is greatly miniaturized due to the application of the silicon technology and, as a consequence, the required sample volume is sub-

Fig. 1 Schematic representation of the previously developed closed-cell type microliter coulometric titrator.

stantially reduced. The disadvantages of the system are an injection of the sample by a syringe or micropump is necessary, and after each titration the sample has to be flushed out. It is therefore not suitable for an in situ application.

Diffusion-controlled coulometric sensor-actuator system

In order to facilitate the sensor-actuator for in situ applications, a second system was proposed [2,3] of which the basic elements are shown in Fig. 2. It is a modified system of the aforementioned type. The main difference is that the silicon cover of the first system has been omitted, thus allowing the free diffusion of species between the bulk solution and the actuator electrode. In this case the injection of the sample is not necessary, the whole system can be inserted in the analyte solution. The titration is still performed by applying a constant current to the actuator electrode. In this case the square root of the time needed to reach the end-point is linearly proportional to the concentration of the titrated species. This is expected, because the operation of the system is in principle the same as the classical constant-current chronopotentiometry. Except for the delay in response due to the non-zero distance between the gate of the ISFET and the actuator, the Sand equation [9] can be used to describe the behaviour of the system because the diffusion is regarded as one-dimen-

sional due to the use of a large planar actuator electrode around the gate of the ISFET. The significant improvement in this system with respect to the classical chronopotentiometry is the separation of the signals of the indicating electrode from the generating (working) electrode. The pH in the vicinity of the actuator electrode can be selectively measured by the ISFET. This is advantageous especially for the performance of a titration at low concentration. In chronopotentiometry the generating electrode potential is measured, which is in fact the sum of the double layer charging, electrode polarization and redox couple potential change. At low concentrations, the effect of the double layer charging and the polarization will have a relatively strong influence, making it difficult to extract the pH information from the electrode potentials. A main advantage of the system where an ISFET is used for the pH measurement is that it circumvents the problems mentioned above. In addition, the device can be made in a dipstick fashion, so it can be easily used in a continuous way. Furthermore, it permits a continuous local pH control in the vicinity of the ISFET. A disadvantage is the non-linear relation between the amount of the generated titrant needed for a titration and the concentration of the titrated species. In addition, there is a delay in response because of the non-zero distance between the actuator electrode and the gate of the ISFET. Consequently, the pH in

Fig. 2 Schematic representation of the basic components of the dipstick ISFET-based coulometric sensor-actuator system

the vicinity of the ISFET is not uniformly distributed not only because of the delay time, but also because of the concentration gradient in the diffusion layer

Another application of the second system worthwhile to mention here is the construction of a pH-static enzyme sensor [5], which utilizes specifically the ability of the local pH control of this system. With a membrane containing an immobilized enzyme mounted on top of the ISFET-based sensor-actuator device, the pH in the membrane can be adjusted to a desired value for an optimal operation of the enzyme. The catalytic products from the enzymatic reaction can be continuously titrated to keep the pH inside the membrane constant by applying a current to the actuator electrode, of which the current is in turn a measure of the concentration of the substrate. However, the aforementioned disadvantages of the second system such as the delay in response and the not uniformly distributed pH inside the membrane will limit the possibilities of this application

Coulometric sensor-actuator system with a porous noble metal as the actuator

The recently proposed ISFET-based coulometric sensor-actuator system [8] employs a porous noble metal, for instance porous gold, as an actuator closely shaped around and over the gate of

the ISFET. The basic components of this system are shown in Fig. 3. This system is expected to keep the advantages of the aforementioned two systems and to get rid of the disadvantages. The preliminary results have shown that the delay in response of the system is considerably reduced because the distance from actuator to the gate of the ISFET is minimized. Since the gate is fully surrounded by the porous actuator, the titration of the internal volume of the porous actuator will give rise to a smaller concentration gradient, which limits the diffusion of the species from the bulk solution to the gate of the ISFET. As a result, the amount of generated titrant needed for a coulometric titration is expected to be approximately linearly proportional to the concentration of the titrated species. Another advantage is that the system is less sensitive to convection. This makes the system more suitable for on-line applications. The other advantages such as ease of operation and possibility for a design of a dipstick device still remain.

The behaviour of the previously developed systems has already been extensively studied [6,7]. A semi-quantitative description of the system delay in response has also been presented [6]. For the new system with a porous noble metal as the actuator, preliminary results have shown that the delay in response is considerably reduced, whilst also the expected approximately linear relation-

Fig. 3 Schematic representation of the basic components of the coulometric sensor-actuator system based on an ISFET with gate-covered porous gold actuator

ship between the amount of the generated titrant used for titration and the concentration of the titrated species was found [8]. In the following part of this paper, we will propose an analytical model to describe the behaviour of the new system, combined with improved technologies in making the devices. The model will be verified with corresponding experimental results.

MATHEMATICAL MODEL

General considerations

For a coulometric titration of an acid or base, the titrant generated at the actuator electrode by electrolysis of water depends on the direction of the applied current. The reactions at the electrodes are as follows:

When a current is applied to the porous actuator, the continuously titrated species inside the pores of the actuator will generate an electrochemical potential gradient between the internal volume of the porous actuator and the bulk solution. Mass transport will then occur. For the system used here, only diffusion is considered in the mass transport. Convection is assumed to be absent for two reasons: firstly, the titration is performed in a stagnant solution and secondly, in the relatively short time of titration convection caused by a change in density or thermal effect is excluded. The effect of migration can be eliminated by adding excess of supporting electrolyte. For the derivation of the model some extra assumptions are made:

(1) The diffusion is considered to be one-dimensional only, because the geometric area of the actuator is much larger than its thickness. This assumption means that there is only a concentration gradient perpendicular to the ISFET inside the porous layer and in the bulk solution. The concentration profiles of the species can then be divided into two parts as shown in Fig. 4, where x is the distance from the gate to the bulk and l is the thickness of the porous actuator.

Fig. 4. Illustration of the concentration profiles inside and outside the porous actuator for $t > 0$.

$C_1(x, t)$ and $C_2(x, t)$ represent the concentration profiles of the species inside and outside the porous actuator, respectively.

(2) The porosity of the porous actuator is assumed to be homogeneous, and the applied current is assumed to be uniformly distributed at the active surface of the porous actuator, i.e., the current density is assumed to be constant over the whole active surface. As a consequence of this assumption, the titrant is uniformly generated inside the porous actuator.

(3) Since the pH is measured by an ISFET, it is not necessary to determine the current density at the electrode for the calculation of the electrode potential. The internal volume of the actuator to be titrated can then be considered as a homogeneous source or sink. In the following calculations a parameter, ρ , defined as the apparent titrant production rate per unit volume is introduced:

$$\rho = \frac{I}{FV_{\text{act}}} = \frac{I}{FSl} \quad (2)$$

where I is the applied current and F the Faraday constant, V_{act} is the total volume of the porous actuator, S and l are the geometric area and thickness of the porous actuator, respectively. Owing to a reasonably high porosity of the actuator the volume taken up by the gold itself is ignored. Since only the faradaic portion of the

current is significant for the faradaic process, the subscript f will further be used to denote the faradaic portion of the current and the corresponding value of ρ , $\rho_f = I_f / FSl$, representing the real titrant production rate per unit volume. In the case of an applied constant current, the titrant production rate per unit volume is also a constant.

(4) The diffusion coefficients of the species inside the porous actuator are considered to be the same as in the bulk solution because of the relatively large pore size.

With the above assumptions, the equations governing the mass transport inside and outside the porous actuator are then derived as follows.

Derivation of the model

In the bulk solution, i.e., $l < x < \infty$, the change of the concentration of the sample is only caused by diffusion. The diffusion equation for $C_2(x, t)$ is

$$\frac{\partial C_2(x, t)}{\partial t} = D \frac{\partial^2 C_2(x, t)}{\partial x^2} \quad l < x < \infty \quad (3)$$

The change of the concentration of the sample inside the porous actuator is caused by both its diffusion and the reaction with the generated titrant. The change of the concentration of the sample by diffusion can be written immediately as

$$\frac{\partial C_1^d(x, t)}{\partial t} = D \frac{\partial^2 C_1(x, t)}{\partial x^2} \quad 0 < x < l \quad (4)$$

where the superscript d denotes the change of concentration by diffusion. If the rate of charge transfer, i.e., the electrolysis of water as described by Eqn 1, and the related dissociation kinetics are not taken into account, the change of the concentration of the sample by the reaction with the generated titrant is

$$\frac{\partial C_1^f(x, t)}{\partial t} = -\rho_f \quad 0 < x < l \quad (5)$$

Combining the two processes, the diffusion equation for $C_1(x, t)$ is expressed as

$$\begin{aligned} \frac{\partial C_1(x, t)}{\partial t} &= \frac{\partial C_1^f(x, t)}{\partial t} + \frac{\partial C_1^d(x, t)}{\partial t} \\ &= D \frac{\partial^2 C_1(x, t)}{\partial x^2} - \rho_f \quad 0 < x < l \end{aligned} \quad (6)$$

Eqns 3 and 6 govern the mass transport inside and outside the porous actuator. The initial and boundary conditions are

$$t = 0, C_1(x, 0) = C_2(x, 0) = C_0 \quad (7)$$

$$x = 0, \frac{\partial C_1(0, t)}{\partial x} = 0 \quad (8)$$

$$x = l, \begin{cases} \frac{\partial C_1(l, t)}{\partial x} = \frac{\partial C_2(l, t)}{\partial x} \\ C_1(l, t) = C_2(l, t) \end{cases} \quad (9)$$

$$x \rightarrow \infty, C_2(x, t) = C_0 \quad (10)$$

where C_0 is the initial bulk concentration of the species. Equation 8 is based on the fact that there is no flux flowing through the ISFET which is positioned at the edge of the actuator ($x = 0$). Equation 9 reflects the conservation and continuation of matter. Applying the initial condition (Eqn 7) and boundary condition (Eqns 8, 9 and 10) to Eqns 6 and 3, expressions for $C_1(x, t)$ and $C_2(x, t)$ can be obtained (cf. appendix A)

$$\begin{aligned} C_1(x, t) &= C_0 - \rho_f t + \frac{\rho_f}{2} \left\{ \left[t + \frac{(l+x)^2}{2D} \right] \right. \\ &\quad \times \operatorname{erfc} \frac{l+x}{2\sqrt{Dt}} - (l+x) \sqrt{\frac{t}{\pi D}} \\ &\quad \times \exp \left[-\frac{(l+x)^2}{4Dt} \right] \\ &\quad + \left[t + \frac{(l-x)^2}{2D} \right] \operatorname{erfc} \frac{l-x}{2\sqrt{Dt}} - (l-x) \\ &\quad \times \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(l-x)^2}{4Dt} \right] \left. \right\} \quad (11) \end{aligned}$$

$$\begin{aligned} C_2(x, t) &= C_0 - \frac{\rho_f}{2} \left\{ \left[t + \frac{(x-l)^2}{2D} \right] \operatorname{erfc} \frac{x-l}{2\sqrt{Dt}} \right. \\ &\quad - (x-l) \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(x-l)^2}{4Dt} \right] \\ &\quad - \left[t + \frac{(x+l)^2}{2D} \right] \operatorname{erfc} \frac{x+l}{2\sqrt{Dt}} + (x+l) \\ &\quad \times \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(x+l)^2}{4Dt} \right] \left. \right\} \quad (12) \end{aligned}$$

The end-point is detected by the gate of the ISFET, and because the gate is closely surrounded by the porous actuator, the position of the gate is considered to be located at $x = 0$. This assumption is acceptable for two reasons. One is that the real distance from the gate to the actuator is only $3 \mu\text{m}$ which is much smaller than the thickness of the actuator. The other reason is that the space volume around the gate is negligible compared to the volume of the porous actuator. The concentration at $x = 0$ is

$$C_1(0, t) = C_0 - \rho_f t + \rho_f \left[\left(t + \frac{l^2}{2D} \right) \operatorname{erfc} \frac{l}{2\sqrt{Dt}} - l \sqrt{\frac{t}{\pi D}} \exp \left(-\frac{l^2}{4Dt} \right) \right] \quad (13)$$

For the sake of clarity an auxiliary variable θ is introduced $\theta = l/2(Dt)^{1/2}$. Then Eqn 13 becomes

$$\begin{aligned} C_1 &= C_0 - \rho_f t + \rho_f t \\ &\times \left[(1 + 2\theta^2) \operatorname{erfc} \theta - \frac{2\theta}{\sqrt{\pi}} \exp(-\theta^2) \right] \\ &= C_0 - \rho_f t + \rho_f t * 4t^2 \operatorname{erfc} \theta \\ &= C_0 - \rho_f t * [1 - 4t^2 \operatorname{erfc} \theta] \end{aligned} \quad (14)$$

where

$$t^2 \operatorname{erfc} \theta = \frac{1}{4} (1 + 2\theta^2) \operatorname{erfc} \theta - \frac{2\theta}{\sqrt{\pi}} \exp(-\theta^2) \quad (15)$$

At the time the end-point is reached, $C_1(0, t)$ equals zero. The titration time τ can be obtained from Eqn 14 by letting $C_1(0, \tau) = 0$

$$\tau = \frac{C_0}{\rho_f [1 - 4t^2 \operatorname{erfc} \theta]} \quad (16)$$

Equation 16 is the formula to calculate the time to reach the end-point for an acid or base titration. From Eqn 16 it can be seen that the titration time is proportional to the initial bulk concentration of the titrated species, but it must be pointed out that in a general case $t^2 \operatorname{erfc} \theta$ may also be a function of τ , resulting in a titration time that is not a linear function of the initial

bulk concentration. The situation can, however, be simplified in some specific circumstances which will be discussed later.

Consideration of the double layer charging

As the porous actuator has an enormously large active surface area, the charging of the double layer capacitance cannot be neglected. On the other hand, for the calculation of τ by Eqn 16 the faradaic portion of the current has to be known. In practice, only the applied current is known. If both faradaic and double layer charging effects play a role the applied current to the actuator has to be separated into two parts: the faradaic current, I_f , and the current used to charge the double layer, I_d . Generally, these currents are not constant during the titration. At the beginning of the titration and at the time around the end-point, the actuator potential changes rapidly and the current for the charging of the double layer capacitance is significant, so most of the current is used to charge the double layer. After the double layer is charged to the redox couple potential and before the end-point is reached, the applied current is nearly faradaic. The exact expression for the double layer charging current is difficult to obtain, so that an approximation is often made by means of a simplified calculation or estimation in practical situations. Here we will apply the constant double layer charging current approximation [9]. In this case the current for the charging of the double layer is assumed to be constant during the whole titration and therefore the total applied current is simply expressed as

$$I = I_f + I_d \quad (17)$$

where I_f is the faradaic current, I_d is the current used to charge the double layer. Substitution of Eqn 17 into Eqn 16 yields

$$\tau = \frac{C_0}{\rho_f [1 - 4t^2 \operatorname{erfc} \theta]} + \frac{I_d \tau}{I} \quad (18)$$

where $I_d \tau$ is the total number of coulombs needed to charge the double layer capacitance. Note that now the apparent titrant production rate per volume ρ appears in Eqn 18 instead of ρ_f . This means that the calculation of τ can now be easily

performed. According to the assumption, $I_d \tau \approx C_{dl} \Delta E$, where C_{dl} is the average double layer capacitance and ΔE the actuator potential difference during titration, Eqn 18 can be written as

$$\tau = \frac{C_0}{\rho[1 - 4i^2 \operatorname{erfc} \theta]} + \frac{C_{dl} \Delta E}{I} \quad (19)$$

Comparing Eqn 19 with Eqn 16, the second term of the right-hand side of Eqn 19 represents the contribution of the double layer charging to the titration time.

Applicability of the model to practical systems

Equation 19 expresses the relation of the time needed to reach the end-point at the gate of the ISFET as a function of the initial bulk concentration of the species for an acid or base titration. The first term of Eqn 19 represents the contribution of the faradaic process. As is already mentioned before, the titration time is not a linear function of the initial bulk concentration in a general case, because $i^2 \operatorname{erfc} \theta$ is also a function of the titration time. Thus Eqn 19 is not convenient for practical use. However, the parameter θ and the function $i^2 \operatorname{erfc} \theta$ have their real physical meanings, so that in some specific circumstances, the function $i^2 \operatorname{erfc} \theta$ can be approximated by a linear function of θ . Equation 19 can then be simplified. This is done by evaluating the value of $i^2 \operatorname{erfc} \theta$ as a function of θ as follows.

The expression $(2Dt)^{1/2}$ is conventionally used as a measure of the average displacement of the species due to diffusion after a time t . By its definition, $\theta (= l/2\sqrt{Dt})$ divided by a factor of $\sqrt{2}$ is the ratio of the thickness of the actuator to the diffusion distance of the species from the bulk solution into the porous actuator. It can thus be reasoned that before the diffusing species reach the gate of the ISFET, the change of the concentration of the species in the vicinity of the gate is caused only by the generated titrant. The titration can then be considered as a volumetric titration inside the porous actuator. When the diffusing species reaches the gate of the ISFET ($x = 0$) after time t , the change of the concentration of the species at this point will of course be influenced by the diffusion in addition to the generated titrant. After this moment the diffusion pro-

Fig. 5. Plot of $1 - 4i^2 \operatorname{erfc} \theta$ as a function of θ .

cess will also determine the titration time τ . Therefore, θ can be considered as a parameter to evaluate the time for the species to reach the gate of the ISFET by diffusion and consequently the value of $i^2 \operatorname{erfc} \theta$ can be used as a measure of the contribution of the diffusion to the time of titration. In other words, the value of θ and $i^2 \operatorname{erfc} \theta$ are expected to be suitable criteria to distinguish whether the titration is a diffusion-controlled titration or a volumetric titration inside the porous actuator. Based on this consideration, the function $1 - 4i^2 \operatorname{erfc} \theta$ is evaluated as a function of θ as shown in Fig. 5. From this figure it can be seen that if θ approaches zero or infinity, $1 - 4i^2 \operatorname{erfc} \theta$ will approximate two asymptotic lines. If one of these two extreme cases applies, $i^2 \operatorname{erfc} \theta$ can be replaced by a simple linear expression of θ , which is independent of τ or is only a simple function of τ . Hence, the applications of Eqn 19 to an acid or base titration can be generally classified into the following three cases.

Case 1 If the actuator is very thick and the time for a titration is short, i.e., $l > 2(Dt)^{1/2}$ or $\theta > 1$, the value of $i^2 \operatorname{erfc} \theta$ will be very small. If $\theta \rightarrow \infty$, $i^2 \operatorname{erfc} \theta$ will ultimately approach zero. In this case the diffusion can be ignored and the titration can be regarded as a bulk titration inside the porous actuator. Then, Eqn 19 becomes

$$\tau = \frac{C_0}{\rho[1 - 4i^2 \operatorname{erfc} \theta]} + \frac{C_{dl} \Delta E}{I} \approx \frac{C_0}{\rho} + \frac{C_{dl} \Delta E}{I} \quad (20)$$

It can be seen that τ is now linearly proportional to the initial bulk concentration of the species. The limit to neglect the $i^2 \text{erfc}\theta$ depends on the required precision. For instance if $\theta = 1$, then $4i^2 \text{erfc}\theta = 0.06$. It means that if the titration is treated as a titration of the internal volume of the porous actuator only, the diffusion caused deviation of the calculated titration time is ca 6%.

Case 2 If the porous actuator is very thin and the time for a titration is long, i.e., $l \ll 2(Dt)^{1/2}$ or $\theta \ll 1$, $1 - 4i^2 \text{erfc}\theta$ will approach $4\theta/\sqrt{\pi}$. After substitution of $1 - 4i^2 \text{erfc}\theta$ by $4\theta/\sqrt{\pi}$, Eqn 19 becomes

$$\begin{aligned} \tau &= \frac{C_0}{\rho[1 - 4i^2 \text{erfc}\theta]} + \frac{C_d \Delta E}{I} \\ &\approx \frac{FSl\sqrt{\pi}}{4\theta I} C_0 + \frac{C_d \Delta E}{I} \\ &\approx \frac{FS\sqrt{\pi D\tau}}{2I} C_0 + \frac{C_d \Delta E}{I} \end{aligned} \quad (21)$$

or

$$\sqrt{\tau} \approx \frac{FS\sqrt{\pi D}}{2I} C_0 + \frac{C_d \Delta E}{I\sqrt{\tau}} \quad (22)$$

The titration can now thus be regarded as a diffusion-controlled titration. In fact, the first term of the right-hand side of Eqn 22 is exactly the same as the Sand equation which was derived in the classic chronopotentiometry [9]. The square root of the titration time is linearly proportional to the bulk concentration of the titrated species if the double layer charging is omitted. The precision for the approximation can also be calculated. As an example, for $\theta = 0.05$, $[1 - 4i^2 \text{erfc}\theta - 4\theta/\sqrt{\pi}]/[1 - 4i^2 \text{erfc}\theta] = -0.045$. This indicates that $1 - 4i^2 \text{erfc}\theta$ can be replaced by $4\theta/\sqrt{\pi}$ for the calculation if an error of 4.5% is allowed in this example.

Case 3 If the above two extremes do not apply, Eqn 19 has to be used to calculate the titration time as a function of the concentration of the titrated species. The calculation can be done by means of a computer or by consulting tabulated values of the error function.

EXPERIMENTAL

Technology to make the device

The procedure to make the sensor-actuator devices is comparable to the previously reported one [8] and as shown in Fig 6. There are two improvements. First, the structure of the ISFET was modified in order to enhance the ability of

Fig 6 Procedure to make the device (a) Flat ISFET with a thin layer of evaporated gold around the gate, (b) deposition of a sacrificial layer of SiO₂ by PECVD, (c) deposition of a layer of porous gold, (d) etching of the sacrificial layer

the ISFET to withstand the hydrofluoric acid etching, because the etching of the sacrificial layer by hydrofluoric acid is very aggressive and the etching usually takes a rather long time to guarantee a complete removal of both the sacrificial layer and the glass compounds in the thick-film paste, which is used for the fabrication of the porous actuator electrode. During the manufacture micro cracks in the upper-layer of tantalum pentoxide have been found at the edge of the

field silicon dioxide [10]. The cracks result from the volume expansion of the tantalum during oxidation to become tantalum pentoxide. The etchant can slowly penetrate from the crack part into the field silicon dioxide and consequently cause a damage of the ISFET. The ISFET will finally have an abnormally large leakage current. The new type of ISFET has a completely flat surface, so that the cracking in the top layer of tantalum pentoxide is avoided. The flat structure

Fig. 7. Microstructure of the porous gold made by (a) sintering of thick-film paste at 600°C and (b) sintering of black gold at 550°C.

is achieved by etching of the whole field silicon dioxide layer after finishing the diffusion process [10]. An extra thick layer of tantalum pentoxide with an open window for the gate area is made after the first tantalum pentoxide is formed. It functions as a protection layer to prevent migration of gold into the silicon. The second improvement is the simplification of the sacrificial layer. Since the flat structured ISFET can withstand a long time of hydrofluoric acid etching without damage, a single silicon dioxide layer as the sacrificial layer, made by plasma enhanced chemical vapour deposition (PECVD), was applied instead of a sandwich layer of $\text{SiO}_2/\text{Si}/\text{SiO}_2$ that has been used before [8]. The thickness of the sacrificial layer is $3\text{ }\mu\text{m}$.

Gold was chosen as the material for the porous actuator. The porous gold was made in two ways. The first way was by sintering of thick-film paste (DuPont 9910) at 600°C , which has previously been reported [8]. The second way was by sintering of black gold. The black gold was made by vapour deposition of gold onto a substrate at a certain pressure in a nitrogen atmosphere. The pressure used for deposition was ca. 0.5 Torr , the distance from the source of gold evaporation to the substrate is ca. 5 cm . The obtained black gold was sintered at 550°C also in a nitrogen atmosphere. The microstructure of the porous actuators made by sintering of thick-film paste and sintering of black gold is shown in Fig. 7a, b by means of scanning electron microscopy (SEM) photographs. Due to a low efficiency of the vapour deposition at high pressure, the thickness of the porous gold actuator made by sintering of black gold is usually thinner than that made by sintering of gold thick-film paste. The thickness of the porous actuator made by sintering of black gold is in the range of $10\text{--}30\text{ }\mu\text{m}$, while a porous actuator made by sintering of thick-film paste is $100\text{--}200\text{ }\mu\text{m}$.

Determination of the geometric parameters and estimation of the total double layer capacitance

For the theoretical calculation of the titration times for an acid or base titration, the apparent titrant production rate per unit volume ρ and the total double layer capacitance should be known

first. These two parameters are related to the dimension of the actuator. The calculation of ρ requires the determination of the geometric area and the thickness of the porous actuator. The total double layer capacitance of the actuator is dependent on the total active area of the actuator and the specific capacitance. Unfortunately, these parameters are difficult to determine exactly. This is because the dimension of the actuator is not always well defined due to the difficulty in applying photolithography. The difficulty in packaging the devices gives rise to an imprecisely defined area, too. Thus the geometric area, S , and the thickness of the porous actuator, l , for each device are measured individually by an optical microscope. The production rate per unit volume is then calculated by its definition (see Eqn. 2). Another geometric parameter that is difficult to determine is the total active area of the actuator. Its value is related to the grid size and the pore size of the porous gold, both of which are dependent on the way of preparing the actuator and are also not well defined. In fact, exact determination of the total surface area of the actuator is insignificant in this case, because the specific double layer capacitance is actually a function of the electrode potential and the ionic strength [11]. However, estimation is often adequate for the application of the derived model as long as the accuracy for calculation is within the experimental error and the correctness of Eqn. 19 still holds. Normally, these conditions are fulfilled. The estimation for the total double layer capacitance is made as follows. The specific double layer capacitance is estimated as $20\text{ }\mu\text{F cm}^{-2}$ as ordinarily accepted [12]. The total surface area of the actuator was estimated according to the measured grid size and thickness of the porous actuator from the SEM photograph. The porous gold actuator is considered as a composition of laminated layers of gold with layer thicknesses of average grid size. Since the actuator is rather porous, i.e., the gold particles are not tightly packed, each layer of gold is assumed to have the same area as the geometric area. The number of layers is determined by dividing the total actuator thickness by the grid size of the gold. The total active area is assumed to be equal to the geometric area times the

Fig. 8 Measuring set-up for an acid–base titration

number of layers. The total double layer capacitance is then calculated as

$$C_{dl} = SNC_{dl}^* \quad (23)$$

where S and N are the geometric area and the number of layers of the gold particles, respectively and C_{dl}^* is the specific capacitance of the double layer, being $20 \mu\text{F cm}^{-2}$.

Acid to base titration

A nitric and an acetic acid titration were chosen for a model study of the system. The set-up for the titration is shown in Fig. 8. The output of the ISFET amplifier as well as the actuator potential are registered by the computer. The titration was performed in a 25-ml plastic container. After each titration, a reversed current was applied and the solution was stirred for homogenizing the solution inside and in the vicinity of the actuator. There was ca. one minute pause after stirring and before the start of each titration in order to get rid of convection effects.

RESULTS AND DISCUSSIONS

In order to examine the reduction of the delay time, the titration with a previously developed sensor–actuator device with planar actuator is performed first as a comparison. Because the

porous actuator made in different ways has different thicknesses, the titration with various devices will, according to the model, show different behaviour. Therefore, the titration with various devices, of which the porous actuator is made in different ways, will be discussed separately.

Titration with a planar type sensor–actuator device

Titration of nitric acid using the previously developed prototype device with a planar structure of the actuator was carried out. Figure 9 shows the typical registration curves of the ISFET amplifier output voltage as well as the actuator potential and the corresponding first derivatives. The times to reach the end-points at the ISFET and the actuator are determined by the minima of the corresponding first derivatives. This method applied to the actuator is in fact the classic chronopotentiometry. From the upper curves of Fig. 9, the time to reach the end-point at the ISFET can be found at $t = 1.72 \text{ s}$. From the lower curves of the actuator potential and the first derivative, the time to reach the end-point at the actuator is at $t = 1.02 \text{ s}$. The delay time can be calculated by a simple subtraction, which results for this example in 0.7 s .

Fig. 9 Registration curves and the first derivatives (dashed lines) for a nitric acid titration. The actuator is a planar structure. $[\text{KNO}_3] = 0.1 \text{ M}$, $[\text{HNO}_3] = 2.0 \text{ mM}$, applied current density is $20 \mu\text{A mm}^{-2}$.

Titration using a device with a porous actuator made by sintering of black gold

A series of titration of nitric acid was also carried out using a device with a porous gold actuator made by sintering of black gold. Figure 10 shows the registration curves and the first derivatives recorded from the titration. From Fig. 10 it can be seen that the times to reach the end-points at the ISFET and the actuator are about the same. Compared to Fig. 9, it can be concluded that the delay time is considerably reduced.

The dimension of the porous gold actuator made by sintering of black gold was measured. The geometric area is ca. 0.5 mm^2 and thickness is ca. $30 \mu\text{m}$. The average grid size of the porous is roughly estimated to be in the order of $1 \mu\text{m}$ from Fig. 6b. The number of layers for calculation is then 30. The total double layer capacitance is calculated to be ca. $3 \mu\text{F}$. The titration times are typically from 0.5 to 10 s. The corresponding θ can be calculated to have a value from 0.2 to 0.05 for this device. According to the model and calculated values of θ , the device with such a thin porous actuator should show a quadratic relation between the titration time and the initial bulk concentration of the titrated

Fig. 10 Registration curves and the first derivatives (dashed lines) for a nitric acid titration. The porous actuator was made by sintering of black gold. The applied current is $30 \mu\text{A}$, $[\text{KNO}_3] = 0.1 \text{ M}$, $[\text{HNO}_3] = 2.7 \text{ mM}$.

Fig. 11 Relation of the titration time and the concentration of titrated nitric acid. Dashed line is theoretically calculated, marks and solid line are experimental results with linear fitting. The applied current is $20 \mu\text{A}$. The porous actuator was made by sintering of black gold.

species. The titration can be regarded in this case as diffusion controlled, and consequently Eqn. 21 can be applied for a simplified calculation. Figure 11 shows the theoretical and experimental results. For the sake of accuracy, the theoretical values were calculated by Eqn. 19. The experimental results show a good agreement with the theoretical calculation. The concentration of the titrated nitric acid is ca. $0.5\text{--}3 \text{ mM}$, and the applied current was $20 \mu\text{A}$.

Titration using devices with porous actuator made by sintering of thick-film paste

The titration of both nitric acid and acetic acid was performed using the devices with a porous gold actuator made by sintering of thick-film paste. Because the porous actuator made in this way is very thick, the time for the diffusion of the species to reach the gate of the ISFET will be long. The behaviour of this device will therefore be quite different from that of the devices described in the previous section. It can be expected that the diffusion starts at the interface between the actuator and the bulk electrolyte, so the depletion of the titrated species can be assumed to take place gradually from inside the actuator towards the boundary. Theoretical calculation of

Fig 12 Registration curves and the first derivatives for a nitric acid titration. The porous actuator was made by sintering of thick-film paste. The applied current is $30 \mu\text{A}$, $[\text{KNO}_3] = 0.1 \text{ M}$, $[\text{HNO}_3] = 0.5 \text{ mM}$

the concentration profile can be based on Eqn 11. Figure 12 shows the registration curves using this device for a nitric acid titration. It can be seen that the time to reach the end-point at the actuator is later than at the gate of ISFET, implying that the species are gradually titrated and depleted at different locations inside the actuator and that the depletion of the species in the vicinity of the gate is always prior to the depletion of the whole volume of the actuator.

The thickness of the actuator made by sintering of thick-film paste is between 100 and 200 μm . The average grid size of the porous gold is estimated to be 2 μm from Fig 6a. The number of layers for calculation is then 50–100. The geometric area was designed to be ca. 0.5–1 mm^2 . The total double layer capacitance can then be calculated to be ca. 5–20 μF .

The typical titration times of the system are from 0.5 to 10 s. For a titration of acetic acid, the dominant diffusion species is the acetic acid molecule, of which the value of θ is calculated to be 2.2–0.58 (100 μm) and 4.3–0.96 (200 μm). For a titration of nitric acid, the dominant diffusion species being the protons, the value of θ is calculated to be 0.17–0.34 (100 μm) and 0.33–0.68 (200 μm). The smaller values of θ for a nitric

acid titration with respect to the acetic acid titration are due to the fact that a proton has a much higher mobility than an acetic molecule. According to the model and calculated values of θ , the titration of the weak acid or base permits the use of Eqn 20 for simplified calculation, while titration of a fully dissociated acid or base requires the use of Eqn 19. Figures 13 and 14 show the results of the titration of acetic acid and nitric acid. The titration times are presented as function of the concentration of the acids. The concentration of the titrated species is from 0.5 up to ca. 10 mM. The dashed lines in Figs 13 and 14 are calculated from Eqn 19. The geometric area and thickness of the actuator are measured to be 0.68 mm^2 and 100 μm for the result of Fig 13, and 0.6 mm^2 and 200 μm for the result of Fig 14. The corresponding total double layer capacitances are calculated, according to Eqn 23, to be 68 and 12 μF .

From the experimental results shown in Fig 13, a linear relation between the titration times and the concentration of the titrated species can be seen for the acetic acid titration, which is in agreement with the model prediction. In that case, Eqn 20 can be applied for simplified calculation. The slopes of the curves from the theoretic

Fig 13 Titration time as a function of the concentration of acetic acid. Dashed lines are theoretically calculated, marks and solid lines are experimental results with linear fitting. The applied currents are (●) 10 μA , (■) 20 μA , (◆) 30 μA . The porous actuator was made by sintering of thick-film paste.

Fig. 14 Titration time as a function of the concentration of nitric acid. Dashed lines are theoretically calculated, marks and solid lines are experimental results and linear fitting. The applied currents are (●) 10 μA , (■) 20 μA , (◆) 30 μA . The porous actuator was made by sintering of thick-film paste.

cal calculation (dashed lines) are larger than the experimental ones. One direct reason is the negligence of the volume of the gold. In a real situation, the volume of the electrolyte inside the actuator is smaller than the total volume of the actuator. This means that the experimental titration of the species will actually be faster than theoretically predicted. The actual slope can be determined before application by calibration in a well-defined acid. For practical applications, this is always necessary because the pore size of the actuator cannot be accurately determined. Also due to the technological difficulties the thickness and the geometric area of the porous actuator are not precisely controlled. These geometric parameters will ultimately determine the slope of the calibration curves.

The calibration curves in Fig. 14 from the experimental results are found to be more linear than theoretical ones in Fig. 14. A possible reason is that the concentration gradient of C_2 is in practice less than C_1 at the boundary of the actuator because the internal solution-filled volume of the actuator is less than its total volume, through which the flux of the diffusing species into the porous actuator will be less than assumed. Another reason may be the different ef-

fective diffusion coefficients (normally smaller values) of the species inside the pores [13]. In addition, the gases originating from the electrolysis of water may form a diffusion barrier for mass transport. These effects will limit the diffusion process, which means that more linear calibration curves will be obtained in practice. An experimental support for these explanation is that the system is found not to be very sensitive to stirring during titration. This diffusion-limiting process is in fact an advantage and will improve the applications of the coulometric sensor-actuator system, for instance, the application to the pH-static enzyme sensor. If an enzyme is immobilized in the pores of the actuator, the controlled pH inside the porous actuator will be more uniformly distributed due to a smaller concentration gradient.

It should be noted that in both Fig. 13 and Fig. 14, none of the extrapolations of the linear fitting curves intersects the origin of the axis. This shift of the curves along the time axis is mainly due to the existence of a large total double layer capacitance resulting from a very large active surface area of the porous actuator. Apart from the double layer charging, if the generated titrant is not uniformly distributed inside the porous actuator, it will probably also cause partly a shift of the calibration curves. For instance if the current density gradually decreases from the outside of the actuator to the inside of the actuator [14], and consequently the species near the gate of the ISFET will be titrated slower than expected, this will result in a longer titration time and a subsequent shift of the calibration curves along the time axis. As with the delay time of the previous system [6], this effect will also cause a difficult in the application.

Conclusions

In this paper, we have described and compared the previously developed two ISFET-based coulometric sensor-actuator systems and the newly designed coulometric sensor-actuator system which is based on an ISFET with a gate-covering porous noble metal as the actuator electrode. The porous gold actuator has been successfully made in two ways: sintering of the applied gold thick-film paste and sintering of the

vapour deposited black gold. From the point of technological consideration, the advantage of the former is the ease of making a thick porous gold actuator, a disadvantage is the incompatibility with integrated circuit (IC) technology. The latter production method is more compatible with IC technology, but the disadvantage is the very low efficiency for vapour deposition of gold.

A model characterizing the system has been proposed, which quantitatively describes the behaviour of the system. For a very thin porous actuator, the titration time is proportional to the squared concentration of titrated species. This is predicted by the model and confirmed by the experimental results. For a thick porous actuator, the titration time is linearly proportional to the titrated species in the case of a weak acid titration, in the case of a fully dissociated acid titration, the behaviour is also described by the model. However, the measured calibration curve is found to be more linear than expected from theory. Meanwhile, a deviation in slopes of the calibration curves exists. This deviation is ascribed to the poor reproducibility of the geometric parameters, e.g., the thickness, geometric area and the active surface area of the porous actuator during processing of the devices.

Experimental results have also shown that the delay of the system response, which existed due to the distance between the gate of the ISFET and planar actuator, has been considerably reduced after introduction of a porous actuator closely surrounding the gate of the ISFET. Another advantage is that the system is less sensitive to the convection, which makes the system more suitable for on-line application. The disadvantage of the new system is a more significant double layer charging effect, which will result in a shift of the calibration curves along the time axis and will cause an error for some specific applications of the new systems.

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APPENDIX

Solution of the diffusion Eqns 6 and 3

Applying the Laplace transform to Eqns 6, 3, and 7, we obtain

$$C_1(x, s) = A_2 \exp(-\sqrt{s/D}x) + A_2 \times \exp(\sqrt{s/D}x) + C_0/s - \rho_f/s^2 \quad (\text{A } 1)$$

$$C_2(x, s) = B_1 \exp(-\sqrt{s/D}x) + B_2 \times \exp(\sqrt{s/D}x) + C_0/s \quad (\text{A } 2)$$

where s is the Laplace plane variable. If boundary Eqn 8 is substituted into Eqn A 1, we obtain $A_1 = A_2$. It can be inferred from Eqn 10 that $B_2 = 0$. Let $A_1 = A_2 = A$, $B_1 = B$, then Eqns A 1 and A 2 become

$$C_1(x, s) = A [\exp(-\sqrt{s/D}x) + \exp(\sqrt{s/D}x)] + C_0/s - \rho_f/s^2 \quad (\text{A } 3)$$

$$C_2(x, s) = B \exp(-\sqrt{s/D}x) + C_0/s \quad (\text{A } 4)$$

Applying the boundary condition Eqn 9 to the Eqns A 3, A 4 and their derivatives, the coefficients A and B are obtained

$$B = -\frac{\rho_f}{2s^2} [\exp(\sqrt{s/D}l) - \exp(-\sqrt{s/D}l)] \quad (\text{A } 5)$$

$$A = \frac{\rho_f}{2s^2} \exp(-\sqrt{s/D}l) \quad (\text{A } 6)$$

Substituting A and B into Eqns A 3 and A 4 yields

$$C_1(x, s) = \frac{C_0}{s} - \frac{\rho_f}{s^2} + \frac{\rho_f}{2s^2} \exp(-\sqrt{s/D}l) \times [\exp(\sqrt{s/D}x) + \exp(-\sqrt{s/D}x)] \quad (\text{A } 7)$$

$$C_2(x, s) = \frac{C_0}{s} - \frac{\rho_f}{2s^2} + [\exp(\sqrt{s/D}l) - \exp(-\sqrt{s/D}l)] \exp(-\sqrt{s/D}x) \quad (\text{A } 8)$$

By inverting the Laplace transforms [15], the solutions are obtained

$$C_1(x, t) = C_0 - \rho_f t + \frac{\rho_f}{2} \left\{ \left[t + \frac{(l+x)^2}{2D} \right] \times \operatorname{erfc} \frac{l+x}{2\sqrt{Dt}} - (l+x) \sqrt{\frac{1}{\pi D}} \times \exp \left[-\frac{(l+x)^2}{4Dt} \right] + \left[t + \frac{(l-x)^2}{2D} \right] \operatorname{erfc} \frac{l-x}{2\sqrt{Dt}} - (l-x) \times \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(l-x)^2}{4Dt} \right] \right\} \quad (\text{A } 9)$$

$$C_2(x, t) = C_0 - \frac{\rho_f}{2} \left\{ \left[t + \frac{(x-l)^2}{2D} \right] \operatorname{erfc} \frac{x-l}{2\sqrt{Dt}} - (x-l) \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(x-l)^2}{4Dt} \right] - \left[t + \frac{(x+l)^2}{2D} \right] \operatorname{erfc} \frac{x+l}{2\sqrt{Dt}} + (x+l) \times \sqrt{\frac{t}{\pi D}} \exp \left[-\frac{(x+l)^2}{4Dt} \right] \right\} \quad (\text{A } 10)$$

or

$$C_1(x, t) = C_0 - \rho_f t + 2\rho_f t \times \left(i^2 \operatorname{erfc} \frac{l+x}{2\sqrt{Dt}} + i^2 \operatorname{erfc} \frac{l-x}{2\sqrt{Dt}} \right) \quad (\text{A } 11)$$

$$C_2(x, t) = C_0 - 2\rho_f t \left(i^2 \operatorname{erfc} \frac{x-l}{2\sqrt{Dt}} + i^2 \operatorname{erfc} \frac{x+l}{2\sqrt{Dt}} \right) \quad (\text{A } 12)$$

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