

The design of durable Na⁺-selective CHEMFETs based on polysiloxane membranes *

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Abstract

The design of durable sodium-selective CHEMFETs based on the covalent attachment of a sodium-selective ionophore and tetraphenylborate anions to a polysiloxane membrane matrix is described. Simulations of the membrane potential of such CHEMFETs using an extended version of the model developed previously in our group, revealed that a membrane with a reduced mobile ionophore and completely immobilized anionic sites should give a sub-nernstian response owing to a counteracting diffusion potential. CHEMFETs with all possible combinations of free and covalently bound ionophore and borate anions were prepared and the effect of covalent binding on the sensing behaviour was studied. The attachment of both electroactive components to a polysiloxane membrane matrix results in CHEMFETs that respond to Na⁺ activities in aqueous solution with good selectivity, and an almost nernstian slope (56.7 mV decade⁻¹). The polarity of the membrane plays a crucial role. The durability is improved by the covalent attachment of the electroactive components (more than 90 days).

1. Introduction

A commonly used method for investigation of the sensing properties of ionophores is the incorporation of these molecules in a plasticized poly(vinyl chloride) (PVC) matrix [1]. Although electrodes modified with plasticized PVC membranes showed major improvements in comparison with liquid membrane electrodes, such as a faster response time, enhanced mechanical strength, and elongated lifetime, it soon became clear that these electrodes suffer from serious limitations with respect to lifetime in various applications [2].

There have been several attempts to solve these problems by the application of various plasticizers [3,4], ionophores [5,6], and anionic sites [7,8] with an increased lipophilicity, and in a few cases by covalent binding of the ionophore to the polymer matrix [9,10]. Membrane materials other than plasticized PVC have

also been investigated, such as poly(methylmethacrylate) [11], polyurethane [11], poly(vinylisobutyl ether) [12], copolymers of poly(bisphenol-A carbonate) and polydimethylsiloxane [13], silicone rubber [14], and poly(vinylidene chloride) [15]. The last three membrane materials have the advantage that no additional external solvent mediator is needed.

Plasticized PVC is also commonly used as the membrane material for ion-sensitive field effect transistors (ISFETs). The limited lifetime of ISEs based on plasticized PVC membranes is also a problem for ISFETs modified with these membranes, even more so because of the much smaller membrane volume. Most of the above mentioned approaches to improve the durability of ISEs have also been applied to ISFETs and they have resulted in an improvement of the lifetime of the device (vide infra). However, ISFETs in which the polymeric sensing membrane is cast directly by physical adsorption onto the hydrophilic SiO₂ or Si₃N₄ gate oxide surface (MEMFETs) suffer from additional problems. An important problem is that the membrane tends to become detached from the surface as a result of water seepage between the membrane and ISFET surface [16].

* In honour of Professor R.P. Buck on the occasion of his 65th birthday.

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In order to obtain Na⁺-sensitive FETs with increased durability based on the commercial oxamide ionophore ETH 227, Wakida and coworkers [17] used Urushi latex as the membrane material. A practical problem encountered using Urushi is the long curing time of 10 days. Johnson et al. [18] showed that the curing time can be reduced to 3 days by the addition of formaldehyde as crosslinking agent. Cha and Brown [19] investigated polymerized imide (PI) matrices, and found that dimethyl phthalate or a diethylene glycol dibenzoate/dipentyl phthalate mixture as plasticizers gave a flexible transparent and mechanically strong membrane with good adhesion to silicon nitride surfaces and sensing behaviour comparable with that using a PVC membrane matrix.

The above described membrane materials which were used to obtain better adhesion to the ISFET surface still need the addition of an external solvent mediator. An example of a solvent-mediator-free membrane that enhances the lifetime of ISFETs is silicone rubber [20,21].

However, none of the MEMFETs described above possess an internal reference solution as is the case for ISEs. Therefore carbon dioxide permeating through the membrane may cause pH changes at the gate oxide|membrane interface resulting in variation of the surface potential leading to an interfering response of the ISFET [22]. The most fundamental problem is that because of the absence of an internal reference solution, the gate oxide|membrane interface is thermodynamically ill defined in terms of a common potential determining species. Consequently, it can be expected that in practice MEMFETs would be inferior to conventional ISEs with respect to stability and drift.

We have previously described a novel architecture for chemically modified field effect transistors (CHEMFETs) in order to solve the problems mentioned above. Firstly, the attachment of the membrane was improved by mechanical [23] or chemical [24,25] anchoring to the surface of the gate oxide. Secondly, we introduced a hydrogel layer (polyHEMA) between the gate oxide and the sensing membrane in which an aqueous pH buffered solution of primary ion salt can be absorbed [26]. This eliminates the interference of CO₂ in the CHEMFET response, and it stabilizes the potential developed in the sensing membrane [26,27].

The limited lifetime of sensors results from the leaching out of electroactive components, i.e. the ligand and the ionic sites, from the membrane phase to the sample solution. To increase the sensor durability, electroactive components with an enhanced lipophilicity could be applied, but a more efficient method is covalent anchoring of these components to the membrane matrix.

In this paper a study of Na⁺-selective CHEMFETs modified with polysiloxane membranes is discussed. Polysiloxane membranes of different polarity, i.e. with different amounts of cyanopropyl siloxane groups, incorporating free or immobilized ionophore and tetraphenylborate anions, were investigated with respect to their performance as sensing membranes. Various ionophore/tetraphenylborate anion combinations, free and attached chemically to the membrane matrix, were studied to reveal the influence of immobilization on the sensing behaviour of the CHEMFET. Given the fact that the ultimate goal is a durable Na⁺-selective CHEMFET with all electroactive compounds immobilized to prevent leaching out of these compounds, the first question addressed is whether a well functioning sensor with this modification can be obtained.

2. Results and discussion

In order to evaluate the influence of the chemical attachment of electroactive components to the membrane matrix on the membrane potential of an ISFET, a theoretical model was developed.

2.1. Model description

This model is a thermodynamic description of the commonly used three-segment membrane model, introduced by Teorell [28], Meyer and Sievers [29], where a membrane of finite dimensions is placed between a reference solution and a sample solution. In this way the two boundary surfaces and the interior of the membrane can be treated separately (Fig. 1). In our group the model has been extended by Van den Berg et al. [30] by including either free or immobilized neutral ligands and immobilized anionic sites in the calculations. Recently, Cobben et al. [31] extended this model to divalent primary and interfering cations and included the possibility of ion-pair formation.

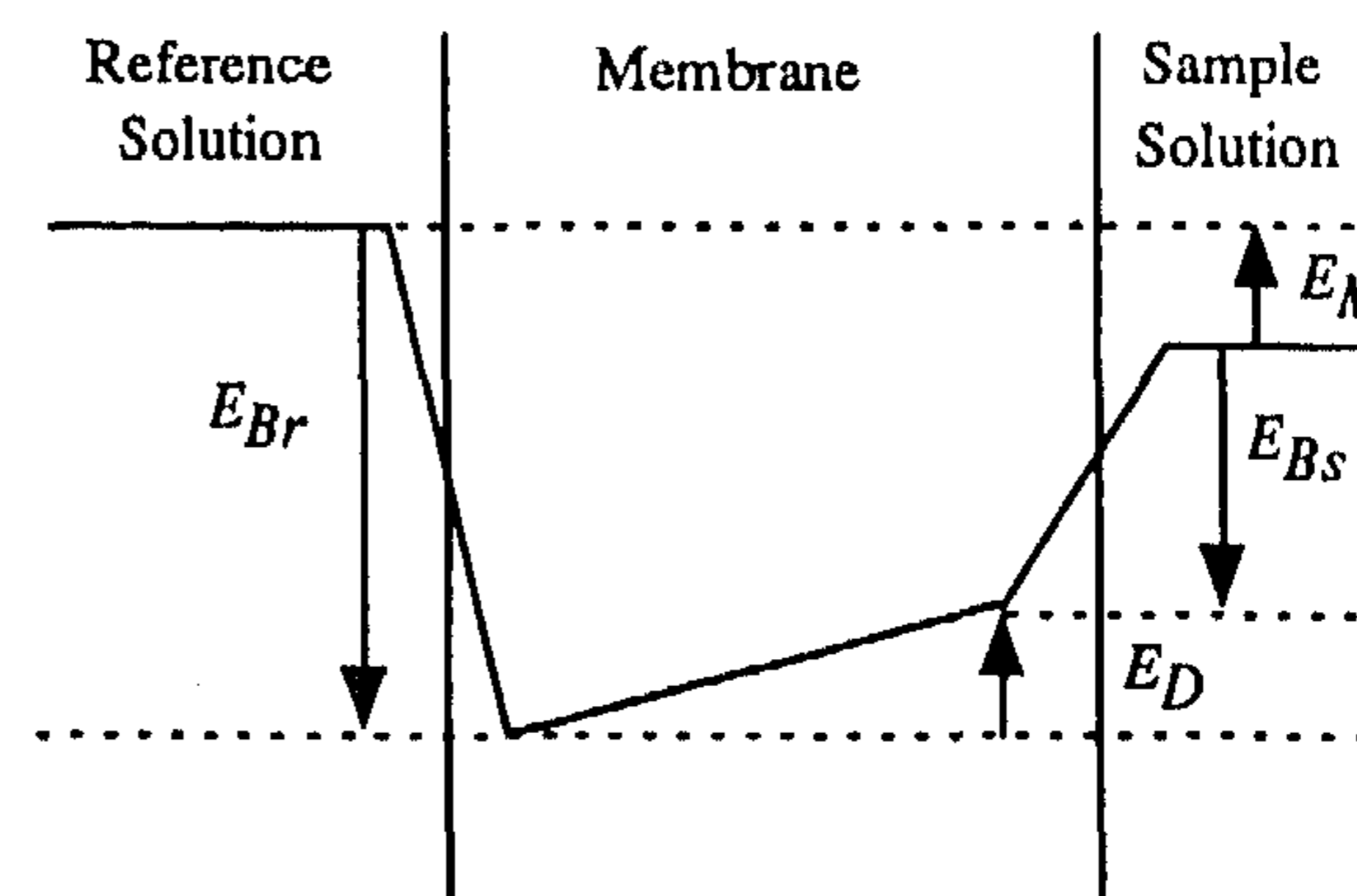


Fig. 1. The membrane potential E_M as a function of the two interfacial potentials E_{Br} and E_{Bs} and the diffusion potential E_D .

The membrane potential E_M is defined as usual in the ion-selective electrode literature, i.e. the difference in the potential of the reference solution ϕ_r and the potential of the sample solution ϕ_s . This membrane potential is determined by the two boundary or Donnan potentials E_{Br} and E_{Bs} , and by a diffusion potential E_D as given in Eq. (1):

$$E_M = \phi_r - \phi_s = -E_{Br} - E_D + E_{Bs} \quad (1)$$

In the model calculations presented here, the activity of the primary ion in the reference solution is kept constant (1×10^{-3} M) and that in the sample solution is varied between 10^{-6} and 10^{-1} M. The boundary potentials E_{Br} and E_{Bs} are calculated from the activities of the ionic species in both solutions and in the membrane phase respectively. The diffusion potential can be calculated from the activities of the charged species at both sides of the membrane and the mobility of these species.

The two boundary potentials, E_{Br} and E_{Bs} , have been calculated by taking into account the equilibria related to (i) the partition of free ions between the membrane and the aqueous phase, and (ii) complexation of free cations by the ligand.

In the description of the model, cation activities are denoted by $a_{+i}(r)$ and $a_{+i}(s)$, and it is considered that one common anion is present with activity $a_-(r)$ and $a_-(s)$, for reference (r) and sample (s) solution respectively. Primary cations are defined by $i = 1$, and interfering cations by $i = 2$. The ligand (L) and anionic sites (Y) are confined to the membrane phase and have activity a_L and a_Y respectively. All parameters belonging to the membrane phase are indicated by tilde (\sim), except for the activity of the ligand L, the activity of the anionic sites Y, and the mobilities m , since these parameters are confined to the membrane phase or are only of interest in the membrane phase.

In the simulations presented here, the primary and interfering cations and the common anion are monovalent and no associates of free cations and ligand-cation complexes with lipophilic anions Y and sample anions are present.

Since equilibrium exists between all cations i in the (bulk) membrane phase (\tilde{a}_i^+) and the (bulk) aqueous phase (a_i^+), the electrochemical potential μ of the permeable ions on both sides is equal:

$$\mu_i^{0+} + RT \ln a_{+i} + z_{+i} F \phi = \tilde{\mu}_i^{0+} + RT \ln \tilde{a}_{+i} + z_{+i} F \tilde{\phi} \quad (2)$$

It is assumed that the solutions are very dilute so that all activity coefficients are approximately unity and the osmotic pressure need not be included. In this equation μ_i^{0+} is the standard chemical potential of cation i ,

and all other symbols R , T , and F have their conventional meanings.

The partition coefficient k_{+i} can be defined as the ratio \tilde{a}_{+i}/a_{+i} in the absence of a boundary potential, which gives an expression for k_{+i} from Eq. (2):

$$k_{+i} = \tilde{a}_{+i}/a_{+i} = \exp\left[\left(\mu_i^{0+} - \tilde{\mu}_i^{0+}\right)/RT\right] \quad (3)$$

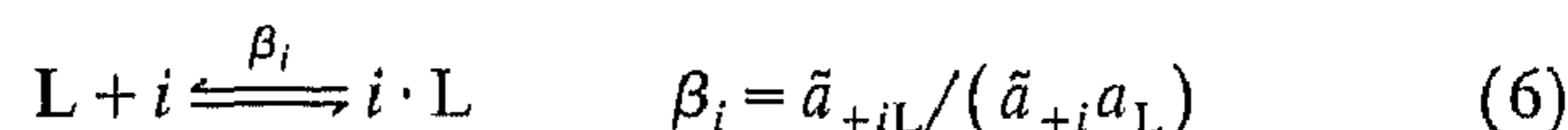
Rearrangement of Eq. (3) and introducing the boundary potential $E_B = \tilde{\phi} - \phi$ gives an expression for the ratio \tilde{a}_{+i}/a_{+i} :

$$E_B = (RT/z_i F) \ln[k_{+i} a_{+i}/\tilde{a}_{+i}] \quad (4)$$

Anion activities in the membrane phase and in the aqueous phase are related in a similar way:

$$E_B = (RT/|z_i| F) \ln[\tilde{a}_-/k_- a_-] \quad (5)$$

Every cation in the membrane can be complexed by the ligand L according to Eq. (6), in which β_i is the association constant of the ligand with cation i :



In addition to the equilibria (2)–(6), the conservation laws for the anionic site Y and ligand L, and the condition of electroneutrality in the bulk of the membrane, apart from the space charge regions at the interfaces, were taken into account in the model calculations.

The mathematical description gives six equations for six variables (\tilde{a}_{+i} , \tilde{a}_- , \tilde{a}_{+iL} , \tilde{a}_L , \tilde{a}_Y , and E_B); an implicit solution for the boundary potential at both interfaces, E_{Br} and E_{Bs} , was obtained by an iterative procedure.

The diffusion potential $E_D = \phi_s - \phi_r$ that arises from the diffusion of charged species with different mobilities inside the membrane was calculated using the Henderson equation [32], which assumes a linear concentration profile of the ions in the membrane:

$$E_D = \frac{\sum |z_+| m_+ \Delta \tilde{a}_+ - \sum |z_-| m_- \Delta \tilde{a}_-}{\sum z_+^2 m_+ \Delta \tilde{a}_+ + \sum z_-^2 m_- \Delta \tilde{a}_-} \times \frac{RT}{F} \ln \frac{\sum z_+^2 m_+ \tilde{a}_+(r) + \sum z_-^2 m_- \tilde{a}_-(r)}{\sum z_+^2 m_+ \tilde{a}_+(s) + \sum z_-^2 m_- \tilde{a}_-(s)} \quad (7)$$

In this equation, m_+ and m_- denote the relative mobilities in the membrane of cationic and anionic species respectively, and $\Delta \tilde{a}_+ = \tilde{a}_+(s) - \tilde{a}_+(r)$, $\Delta \tilde{a}_- = \tilde{a}_-(s) - \tilde{a}_-(r)$. After calculation of E_D the total membrane potential $E_M = E_{Bs} - E_D - E_{Br}$ can be evaluated.

Immobilization of ligand and anionic sites

The simulations described in this paper were intended to extend the understanding of the effects that

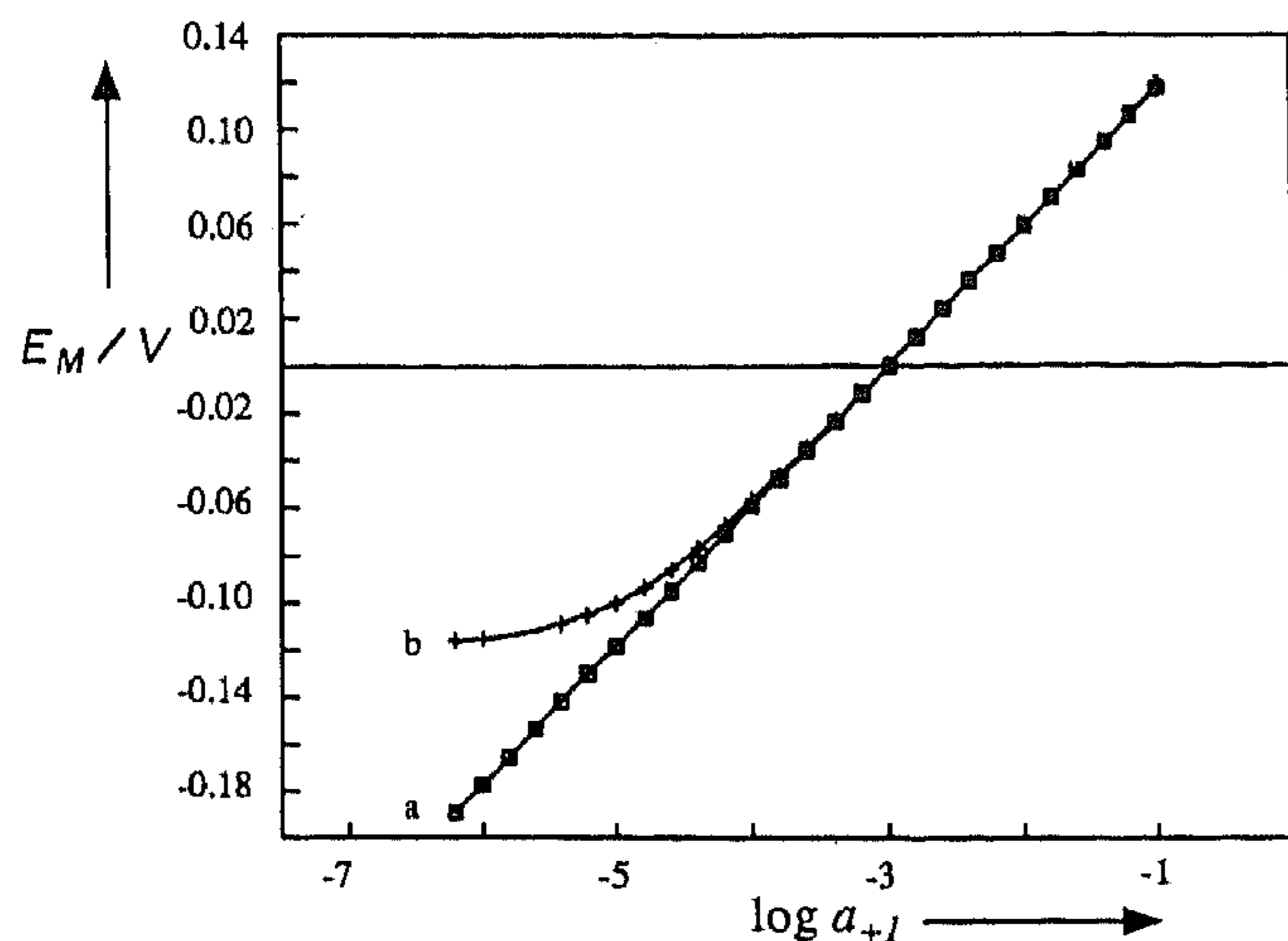


Fig. 2. The influence of the association constant β_i on the potentiometric response of monovalent cations, $m_L = 1$, $m_Y = 0$: (a) $\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $a_{+2} = 0 \text{ M}$; (b) $\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $\beta_2 = 1 \times 10^5 \text{ M}^{-1}$, $a_{+2} = 1 \times 10^{-1} \text{ M}$.

determine the membrane potential by study of the situation when the electroactive components become increasingly restricted in their mobility. The simulations were performed with an association constant $\beta_1 = 1 \times 10^9 \text{ M}^{-1}$ for the primary ion–ligand complex. This value is chosen because it gives a good response in the simulations described previously [31]. The concentration of the ligand in the membrane phase L_{tot} is $1 \times 10^{-3} \text{ M}$ and that of the anionic sites Y_{tot} is $5 \times 10^{-4} \text{ M}$. Cation i and the sample anion have the same partition to the membrane phase ($k_{+i} = k_- = 1 \times 10^{-6}$). The relative mobilities of charged species in the membrane ($m_{+i} = m_-$) is unity but the relative mobilities m_L of the ionophore L (and the cation–ionophore complex $i \cdot L$) and m_Y of the anionic sites Y were varied.

In the first simulation in this series the mobility of the ionophore m_L was kept unity and the anionic sites were totally immobilized ($m_Y = 0$). In the case when no interfering cation is present, no effect of the immobilization of the anionic sites was observed (Fig. 2(a)). The introduction of an interfering cation with $a_{+2} = 1 \times 10^{-1} \text{ M}$ and association constant $\beta_2 = 1 \times 10^5 \text{ M}^{-1}$ in the simulation results in a reduction of the response to primary cation activity at low activities of 10^{-6} – 10^{-4} M . The response behaviour is similar to that obtained from the simulation where both electroactive components are mobile (Fig. 2(b)).

Subsequently the situation was simulated where the ionophore was restricted in its mobility and the anionic sites were completely mobile. Consequently $m_Y = 1$ and the mobility of the ionophore was restricted to $m_L = 0.1$ and 0.01 respectively. When no interfering

ion is present, in both simulations no effect of the restriction of ionophore mobility was observed. A Nernstian response is found for the whole activity range (Fig. 2(a)). The introduction of an interfering cation in the above simulations with an activity $a_{+2} = 1 \times 10^{-1} \text{ M}$ and association constant β_2 of $1 \times 10^5 \text{ M}^{-1}$ yields the same response behaviour as was observed for the simulation with completely mobile electroactive components (Fig. 2(b)).

The next step in the simulations was a reduction in the mobility of the ligand to $m_L = 0.1$, with completely immobilized anionic sites ($m_Y = 0$). First the situation was simulated for the case where no interfering cation is present in solution. As is shown in Fig. 3, the response is nernstian ($59.0 \text{ mV decade}^{-1}$) in the primary cation activity region, $a_{+1} = 10^{-6}$ – 10^{-2} M . In the region of primary cation activity 10^{-2} – 10^{-1} M , a sub-nernstian response of $53.9 \text{ mV decade}^{-1}$ is found. The values for the diffusion potential E_D , the boundary potential at the sample solution side E_{Bs} , and the overall membrane potential E_M show that where the response of E_{Bs} remains nernstian, E_M becomes sub-nernstian owing to an increased counteracting diffusion potential E_D . (See Tables A1 and A2 in Appendix A).

Substitution of the activities of the mobile, charged species in the membrane phase, listed in Tables A1 and A2, in the Henderson equation leads to the following conclusions. With mobile anionic sites Y ($m_Y = 1$), these anions and the slightly mobile primary cation–ligand complex ($m_L = 0.1$) are the main diffusion potential determining species. This results in a negligible diffusion potential because of the absence of a concentration gradient of this species. On immobilization of the anionic sites Y ($m_Y = 0$) the sample anions and the

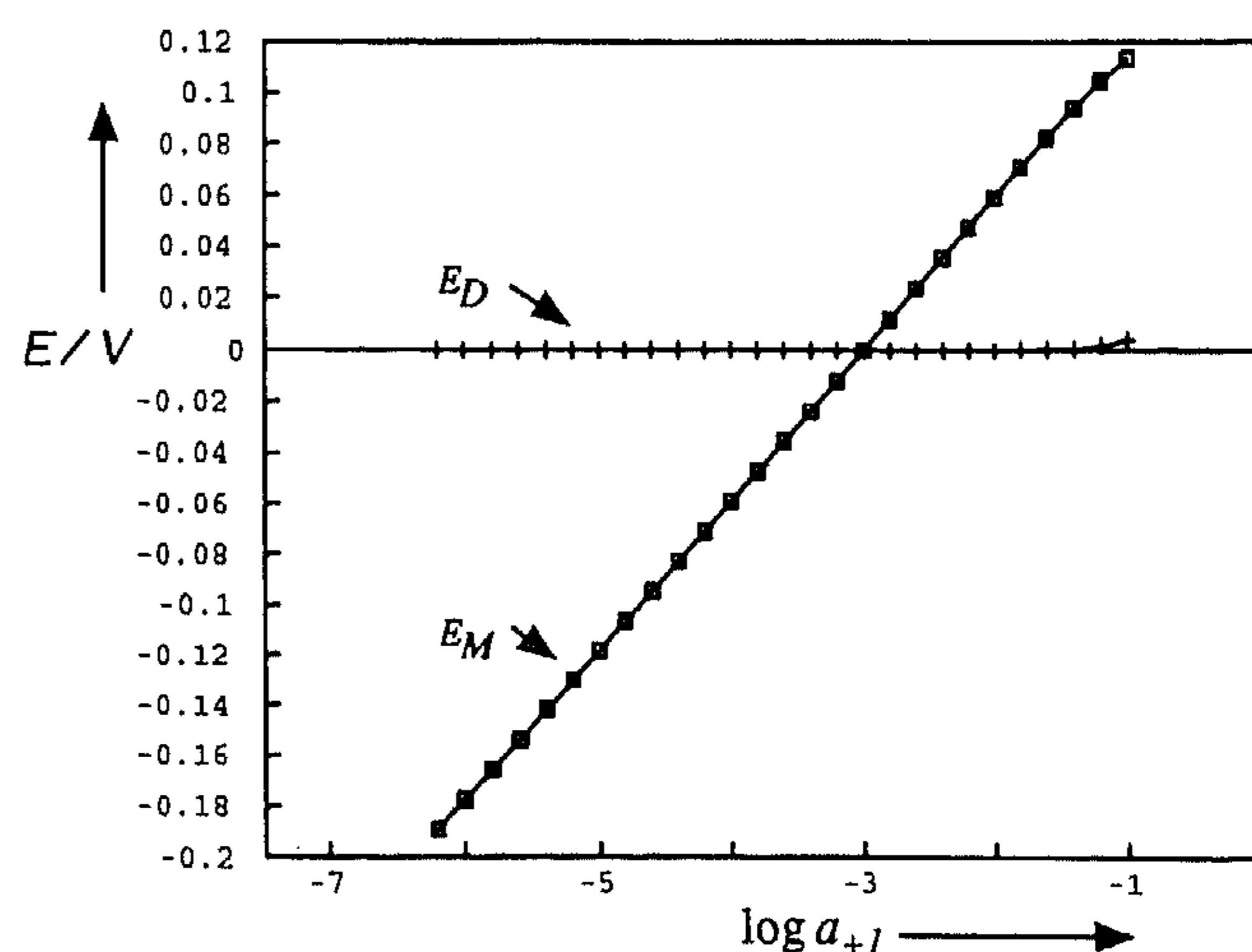


Fig. 3. The influence of the immobilization of electroactive components on the potentiometric response of monovalent cations ($\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $m_L = 0.1$, $m_Y = 0$).

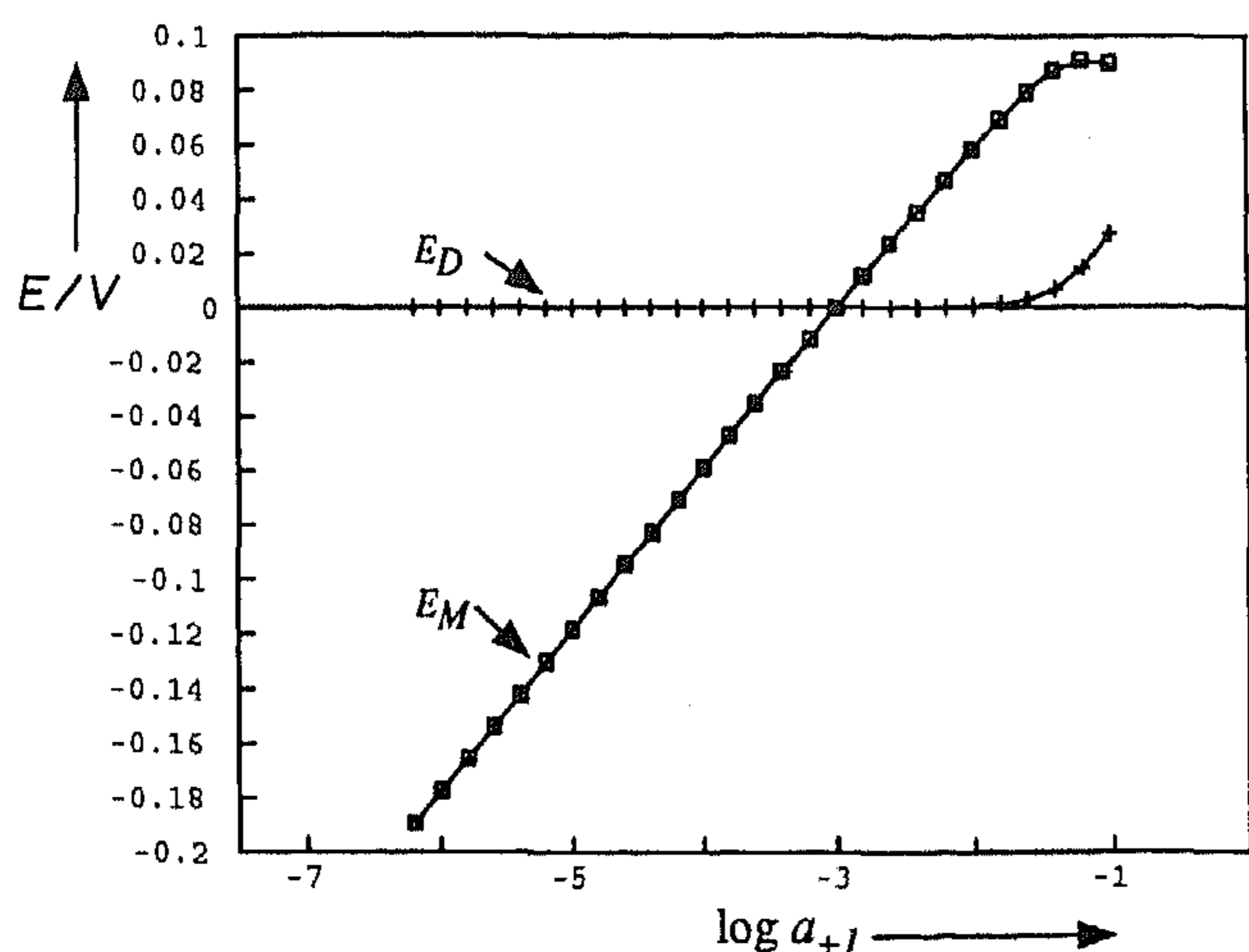


Fig. 4. The influence of the immobilization of electroactive components on the potentiometric response of monovalent cations ($\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $m_L = 0.01$, $m_Y = 0$).

slightly mobile primary cation–ligand complex ($m_L = 0.1$) become the main diffusion potential determining species. On an increase in the activity of the primary cation in the sample solution, the activity of sample anions in the membrane increases more strongly, owing to the combined effect of partition equilibrium and an increase in the boundary potential E_{Bs} . A tenfold increase in the primary cation activity (and anion activity) in the sample solution results in an hundredfold increase in the activity of sample anions in the membrane phase \bar{a}_- , owing to the partition equilibrium (tenfold increase in the sample anion activity) and the Nernst relation (59 mV increase of the boundary potential). This increase in anion activity in the membrane results in an increase in the diffusion potential. A diffusion potential of 4.03 mV is calculated at $a_{+1} = 10^{-1} \text{ M}$.

A further decrease in the mobility of the ligand to $m_L = 0.01$ with immobilized anionic sites ($m_Y = 0$) in the absence of interfering ions shows a further increase in the diffusion potential E_D . The response to the increase in the primary cation activity is only 31.5 mV between $a_{+1} 10^{-2}$ – 10^{-1} M owing to the counteracting diffusion potential (Fig. 4 and Table A3 in Appendix A). The diffusion potential E_D is higher in this case because the relative contribution of the sample anions becomes larger owing to the lower mobility of the primary cation–ligand complex. From the Henderson equation a value for E_D of 27.2 mV at $a_{+1} = 10^{-1} \text{ M}$ is calculated. An even lower response is found for E_M on a further decrease in the ligand mobility m_L to 0.001 owing to the strongly increasing diffusion potential (Fig. 5). This shows a possible origin of anion response at high concentration levels. Buck and coworkers [33,34]

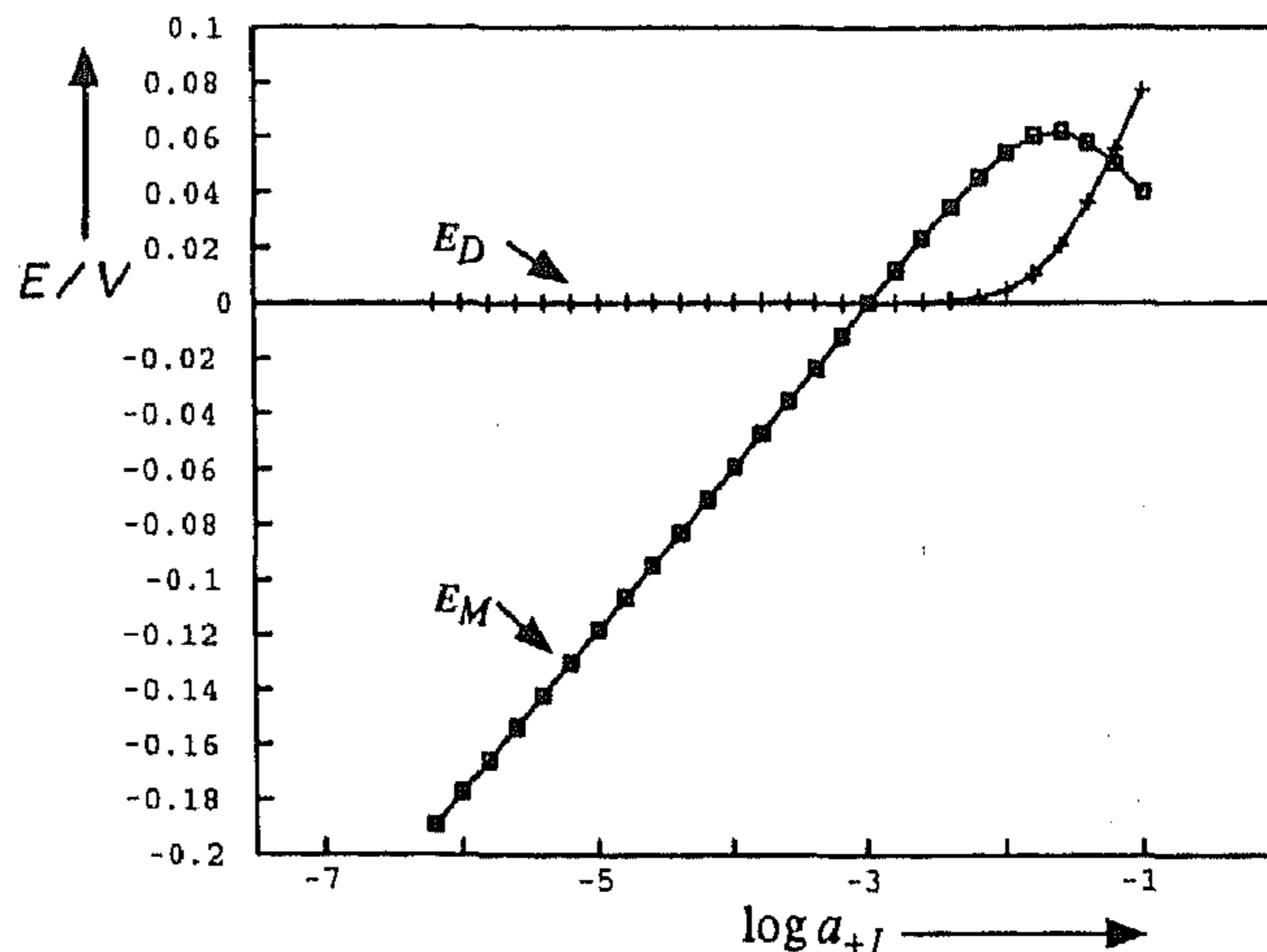


Fig. 5. The influence of the immobilization of electroactive components on the potentiometric response of monovalent cations ($\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $m_L = 0.001$, $m_Y = 0$).

have observed Donnan exclusion failure for high carrier loadings of potassium-selective electrodes in the presence of lipophilic sample anions, e.g. thiocyanate.

When in the simulations the ligand mobility $m_L = 0.1$ and the anionic sites are immobilized ($m_Y = 0$) in the presence of an interfering cation with activity $a_{+2} = 1 \times 10^{-1} \text{ M}$ and association constant $\beta_2 = 1 \times 10^5 \text{ M}^{-1}$, a similar behaviour is found as in the absence of interfering cation. A considerable reduction in response is observed owing to the occurrence of a diffusion potential E_D of 7.20 mV (Fig. 6 and Table A4 in Appendix A). The diffusion potential becomes as high as 39.2 mV when the mobility of the ligand m_L is reduced further to 0.01 (Fig. 7 and Table A5 in Appendix A). The fact that the diffusion potential E_D is

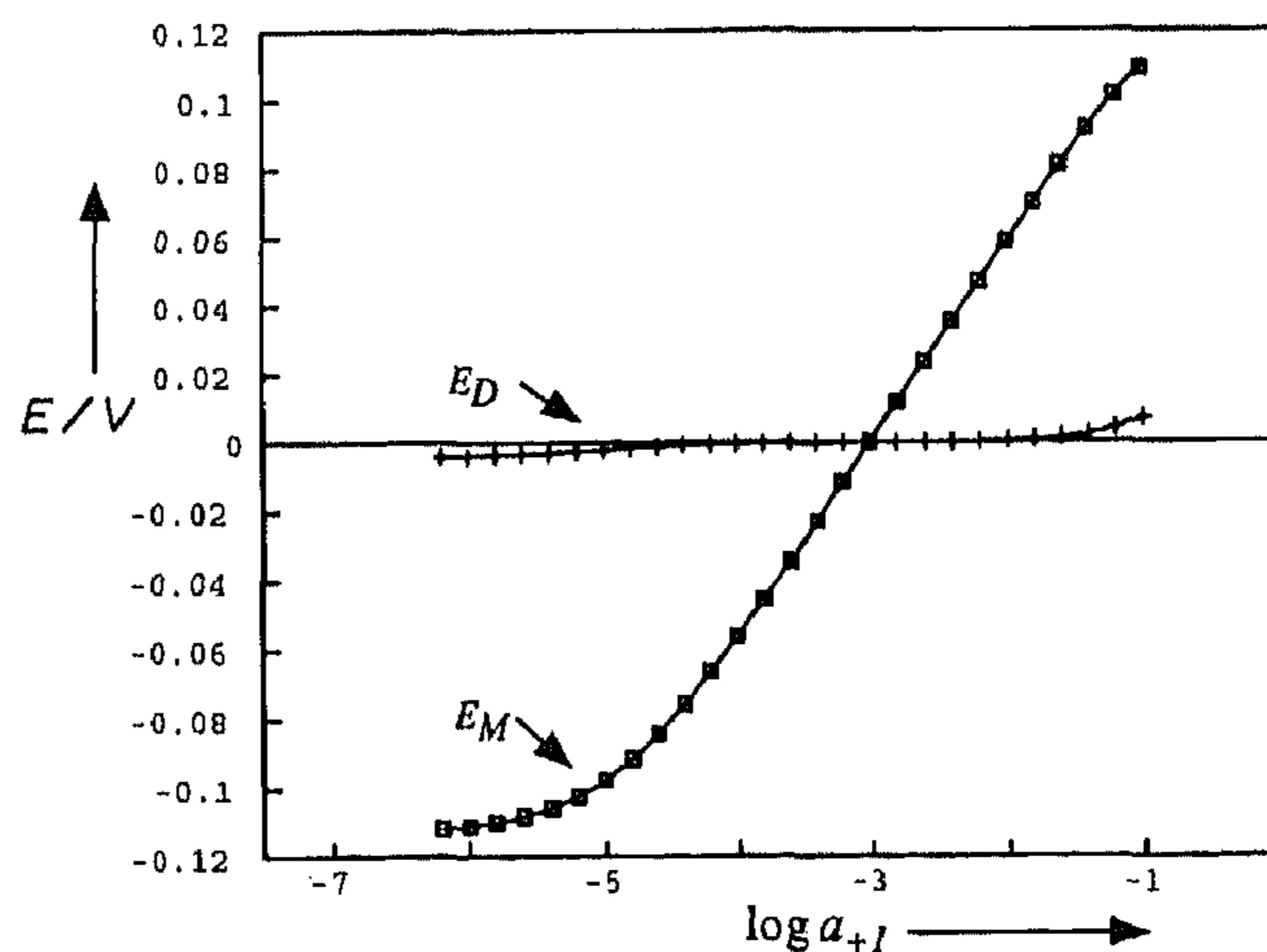


Fig. 6. The influence of the immobilization of electroactive components on the potentiometric response for monovalent cations ($\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $\beta_2 = 1 \times 10^5 \text{ M}^{-1}$, $a_{+2} = 1 \times 10^{-1} \text{ M}$, $m_L = 0.1$, $m_Y = 0$).

larger in these cases, resulting in a more pronounced deviation from a nernstian response, can be explained by the higher activity of sample anions in the membrane owing to the presence of interfering salt in the sample solution.

In summary, the simulations of a membrane phase with a partly immobilized ionophore ($m_L = 0.1$) and mobile anionic sites Y ($m_Y = 1$) in the absence of an interfering salt in the sample solution show a slight increase in the diffusion potential at high primary cation activities. On a total reduction in the mobility of the anionic sites ($m_Y = 0$), and keeping the mobility of the ionophore the same, a distinct diffusion potential of 4.03 mV was calculated at a primary cation activity of 10^{-1} M. The calculated increase in the diffusion potential is a consequence of the immobilization of the anionic sites. Owing to this immobilization these anionic sites lose their diffusion potential determining role and the main diffusion potential determining species now becomes the sample anions in combination with the reduced mobile primary cation–ligand complex ($m_L = 0.1$). In the case when an interfering salt is present in the sample solution, the reduction in the response due to the counteracting diffusion potential becomes even larger as a consequence of a higher activity of the sample anions in the membrane. The same behaviour is observed on further immobilization of the ionophore ($m_L = 0.01$ and $m_L = 0.001$). In this case the compensating behaviour of the cationic species to the diffusion potential is reduced further.

2.2. Construction of a durable sodium CHEMFET

From the literature [35] it is known that for ISEs and ISFETs with neutral ionophores, the selectivity for

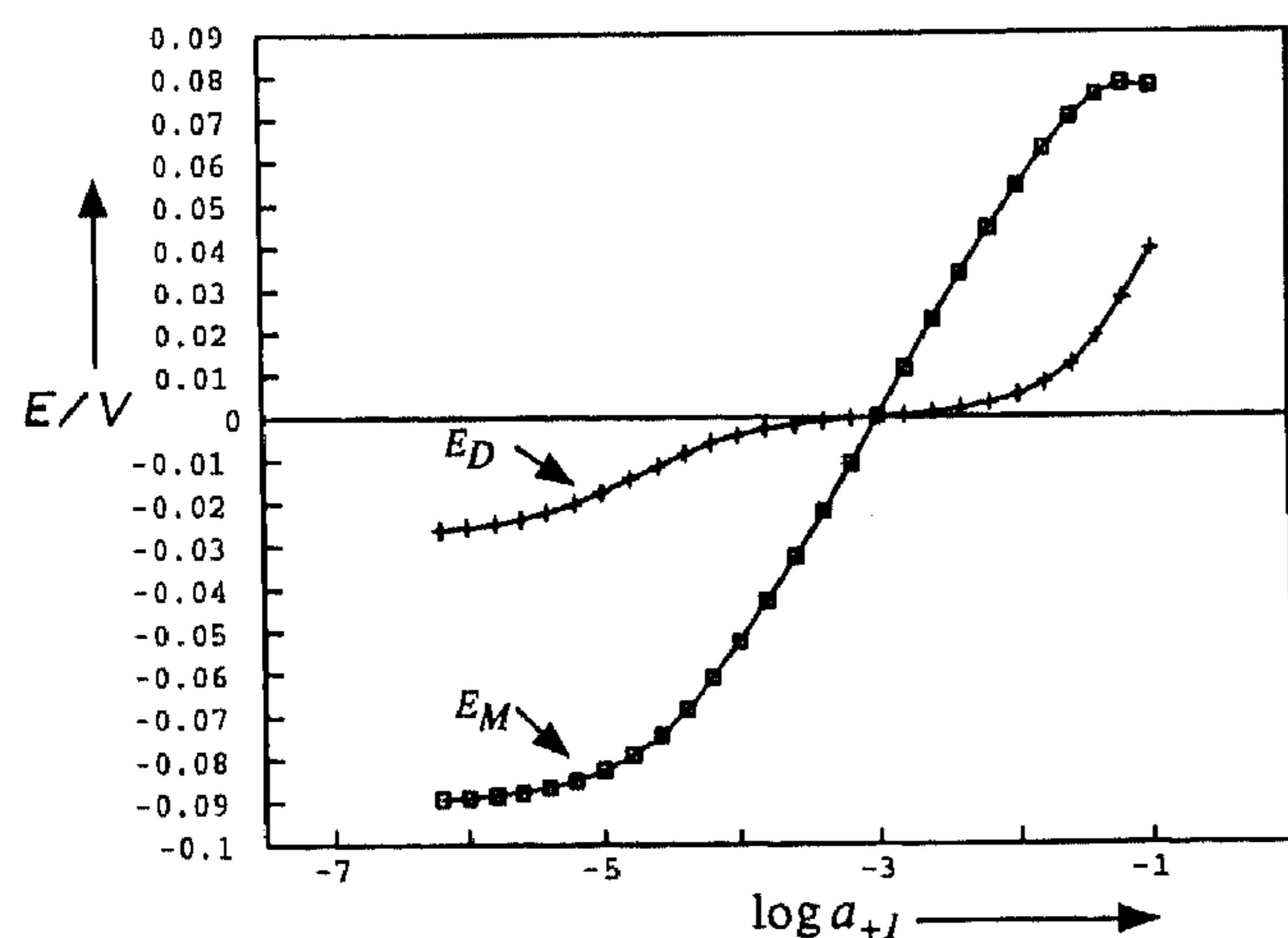
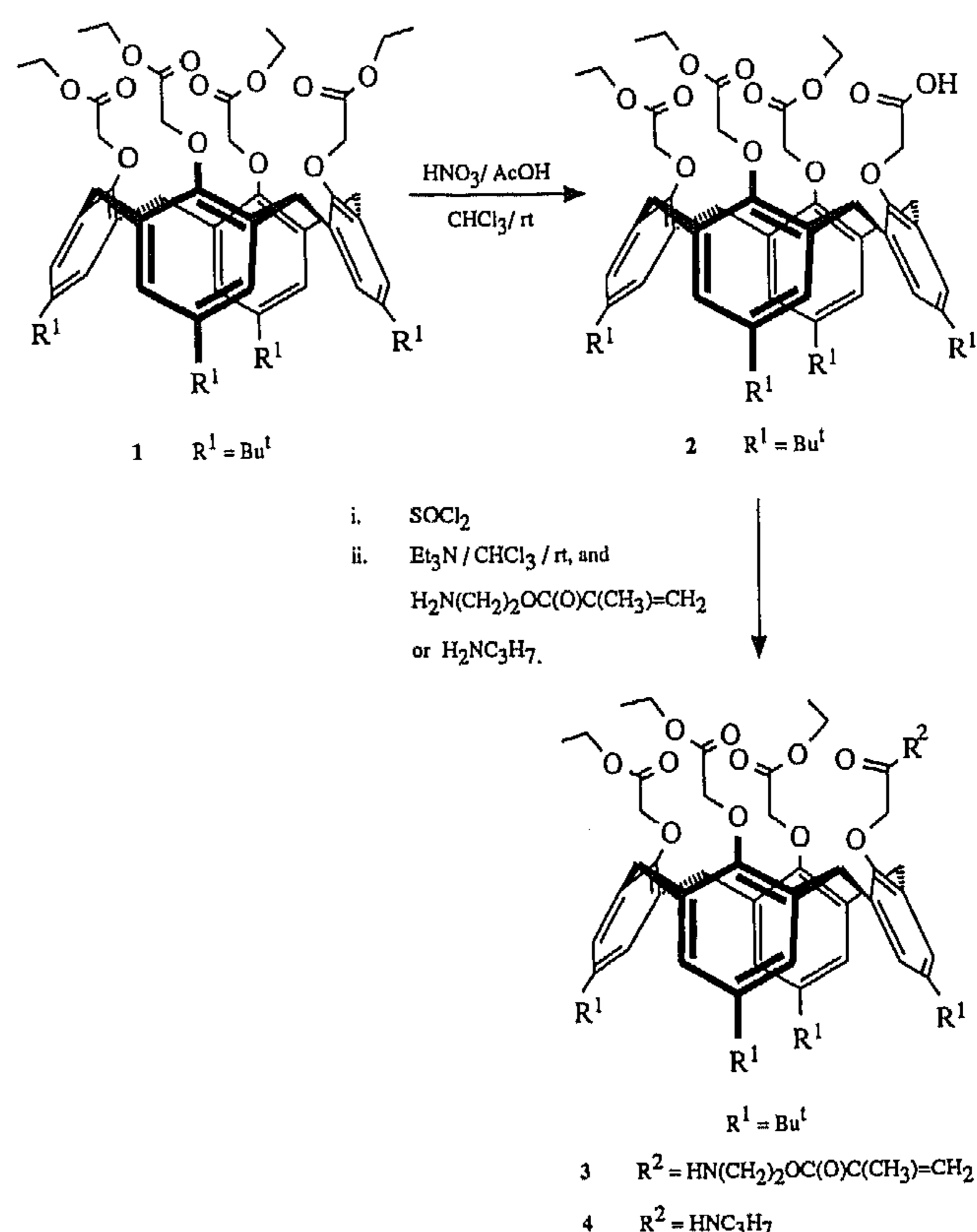


Fig. 7. The influence of the immobilization of electroactive components on the potentiometric response for monovalent cations ($\beta_1 = 1 \times 10^9 \text{ M}^{-1}$, $\beta_2 = 1 \times 10^5 \text{ M}^{-1}$, $a_{+2} = 1 \times 10^{-1} \text{ M}$, $m_L = 0.01$, $m_Y = 0$).



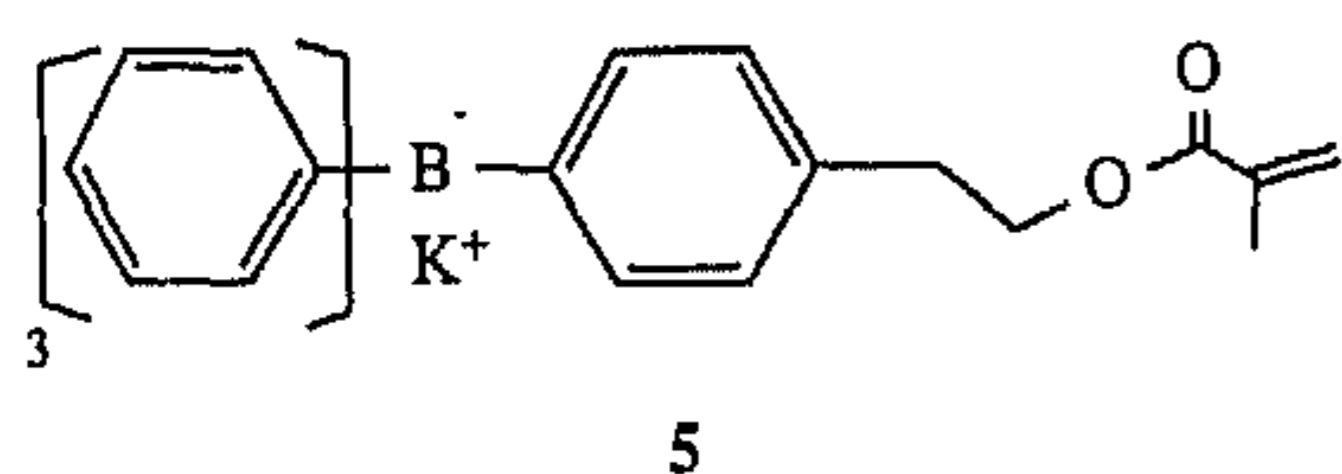
Scheme 1.

monovalent cations is favoured by a membrane of low polarity. However, too low a polarity may lead to noisy sensors because of insufficient conductance of the membrane. In order to obtain the optimal polarity of polysiloxane membranes, CHEMFETs modified with polysiloxane membranes incorporating either 2.8 mol% or 10 mol% cyanopropyl siloxane groups were investigated. The abbreviations PS(2.8)CN-CHEMFET and PS(10)CN-CHEMFET are used for CHEMFETs modified with these polysiloxane membranes.

Synthesis of methacrylated ionophores and anionic sites

In this section the synthesis of calix[4]arene derivatives and tetraphenylborate anions both with a methacrylate functionality (Scheme 1) is discussed. The methacrylate functionality is introduced to immobilize these compounds.

The synthesis of the calix[4]arene derivatives 3 and 4 was started from the triester monoacid 2 (Scheme 1). Triester monoacid 2 was obtained by selective hydrolysis of one of the ester groups of the tetraethyl ester of *p*-*tert*-butylcalix[4]arene 1 under the influence of an acid. In the first experiments trifluoroacetic acid was used, according to the procedure described by Böhmer et al. [36], and triester monoacid 2 was obtained in



79% yield after reaction for about 6 days. Since this reaction needed such long reaction times, catalysis by other acids was also investigated. Better results were obtained with hydrolysis in the presence of a mixture of acetic acid and nitric acid, which gave the desired compound **2** in 84% yield in a reaction time of only 1.5 h. Monoacid **2** readily gave the acid chloride on reaction with thionyl chloride, under the conditions described by Harris et al. [37]. Reaction of the acid chloride with the appropriate agent, i.e. 2-aminoethyl methacrylate or *n*-propylamine, gave the desired products **3** and **4** respectively, in a moderate yield of 60%.

The tetraphenylborate anion with a methacrylate functionality **5** (Chart 1) was synthesized starting from 4-(2-hydroxyethyl) bromobenzene, according to known procedures [38]. The hydroxyl group of 4-(2-hydroxyethyl) bromobenzene was protected first by reaction with *tert*-butyldimethylsilyl chloride. Subsequently, this silyl ether was reacted with magnesium to give the corresponding Grignard reagent which was reacted with triphenylborane at room temperature. On treatment with a saturated potassium chloride solution the potassium tetraphenylborate salt precipitated. The desired borate anion **5** was obtained by deprotection of the hydroxyl group with tetramethylammonium fluoride, followed by reaction of the free hydroxyl group with methacryloyl chloride.

Low polar polysiloxane membrane

The first experiments were performed with CHEMFETs [38,39] based on polysiloxane membranes with standard compositions: 2 wt.% ionophore and 50 mol% anionic sites. PS(2.8)CN-CHEMFETs with the tetraethyl ester of calix[4]arene **1** as Na⁺-selective ionophore and the commercial tetraphenylborate anion (KTCPB), i.e. with both electroactive components mobile, show a nernstian response, 59.5 (±1.0) mV decade⁻¹ (Table 1, entry 2). The selectivities over all interfering cations studied are comparable to those of the CHEMFETs modified with plasticized PVC membranes containing these electroactive compounds (Table 1, entry 1). This result indicates that polysiloxane membranes of this compositions can be used to introduce sodium sensitivity and selectivity.

In the following series of experiments the effect of immobilization of one or both electroactive compounds on the response characteristics was studied.

CHEMFETs with free ionophore **1** and covalently attached borate anion **5** were first investigated. After deposition of the solution of polysiloxane membrane in THF onto the CHEMFET surface the mixture became cloudy on evaporation of the THF. After photopolymerization, optical inspection of the membranes with a microscope revealed the presence of small particles in the membrane. The lower solubility of the methacrylated borate anion **5** limits the total amount of electroactive components that can be added to the polysiloxane membrane. PS(2.8)CN-CHEMFETs with cloudy membranes containing a (too) high amount of electroactive components gave erratic responses and noisy signals. Transparent polysiloxane membranes were obtained by reducing the amount of electroactive

TABLE 1. Response characteristics to various ions *j* of CHEMFETs modified with polysiloxane membranes containing 2.8 mol% cyanopropyl copolymer [PS(2.8)CN]

Entry	Ionophore, borate anion	log K _{Na,j} ^{pot} [Slope/mV decade ⁻¹]					
		Cs ⁺	Rb ⁺	K ⁺	Li ⁺	Ca ²⁺	Mg ²⁺
1 ^a	1 , KTCPB	-3.8 [62.0]	-3.6 [60.9]	-2.7 [60.3]	-3.7 [61.3]	-3.4 [58.8]	≤ -4.2 [59.2]
2	1 , KTCPB	-3.8 [60.5]	≤ -3.9 [60.3]	-2.6 [58.1]	≤ -3.8 [60.0]	-3.5 [58.5]	≤ -4.3 [59.6]
3	1 , 5 ^b	≤ -3.8 [60.4]	≤ -3.8 [60.5]	-2.5 [60.1]	≤ -3.8 [59.5]	≤ -3.4 [58.9]	≤ -4.4 [59.0]
4	3 ^b , KTCPB	≤ -3.1 [58.4]	≤ -3.4 [58.6]	-2.6 [58.3]	-3.4 [58.9]	-3.2 [57.4]	≤ -3.8 [58.9]
5	3 ^b , 5 ^b	- ^c [53.0]	- ^c [55.8]	-2.0 [56.5]	- ^c [56.8]	- ^c [56.6]	- ^c [55.9]

^a CHEMFET modified with PVC/DOS membrane [38]. ^b Bound to the polymer matrix by photopolymerization. ^c Severe drift at low Na⁺ activities (Fig. 8).

components to 0.5 wt.% tetraethyl ester **1** and 25 mol% borate anion **5**. This composition was used throughout all further experiments with polysiloxane-modified CHEMFETs. PS(2.8)CN-CHEMFETs with this membrane composition show the same response characteristics (Table 1, entry 3) as the PS(2.8)CN-CHEMFETs with both electroactive components mobile (Table 1, entry 2).

Subsequently, PS(2.8)CN-CHEMFETs based on covalently bound methacrylated calix[4]arene **3** and mobile KTCPB showed only a slight decrease in the nernstian response. However, a distinct reduction in Na⁺-selectivity with respect to all interfering cations was found, except for potassium where a good Na⁺/K⁺-selectivity of 10^{-2.6} was determined (Table 1, entry 4).

Finally, PS(2.8)CN-CHEMFETs with both methacrylated calix[4]arene derivative **3** and borate anion **5** immobilized responded with severe drift at low Na⁺ activities of 10^{-5.5}–10^{-3.5} M for all interfering cations (Fig. 8 and Table 1, entry 5). The response slope at higher Na⁺ activities is sub-nernstian and varies between 53.0 and 56.8 mV decade⁻¹. An exception was the titration performed in K⁺-solutions with a response slope of 56.5 mV decade⁻¹ for the entire activity range of Na⁺. However, the selectivity for Na⁺ over K⁺ was distinctly reduced to log K_{Na,K}^{pot} = -2. When these CHEMFETs were stored in 0.1 M NaCl for 2 months no improvement of response characteristics was observed.

High polar polysiloxane membrane

To elucidate the role of the polarity of the polysiloxane membrane, polysiloxane membranes of 10 mol% cyanopropyl siloxane were also included in this series. PS(10)CN-CHEMFETs with both electroactive components mobile show excellent response characteristics

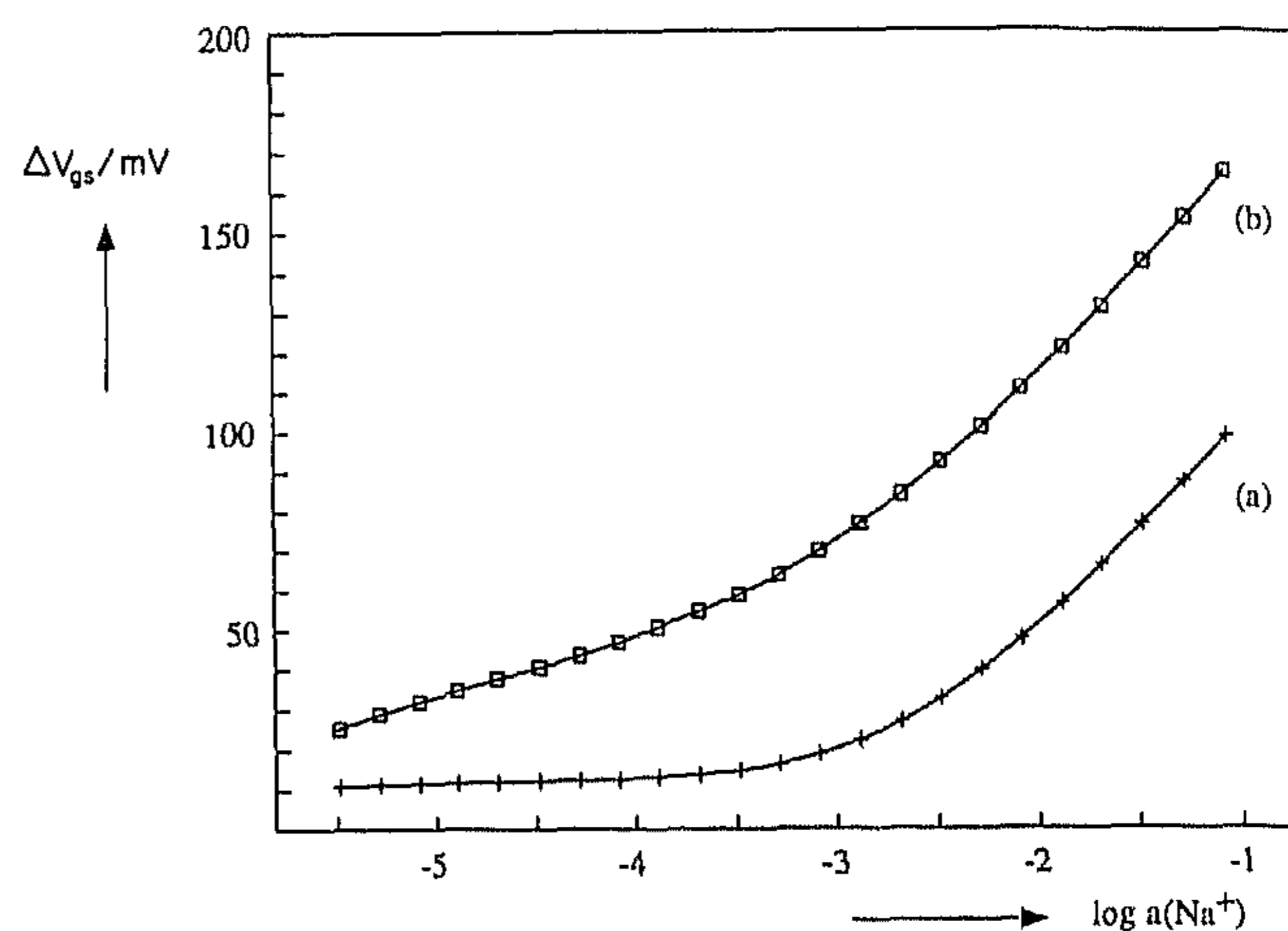


Fig. 8. Response curves of CHEMFETs modified with polysiloxane membranes containing 2.8 mol% of the cyanopropyl copolymer [PS(2.8)CN] with both covalently bound calix[4]arene **3** and borate anion **5**: (a) in 0.5 M KCl, (b) in 0.5 M MgCl₂.

(Table 2, entry 1). Proper Nernstian responses were observed and the Na⁺-selectivities with respect to interfering cations, except for K⁺, are similar to those for PS(2.8)CN-CHEMFETs (Table 1, entry 2). With respect to K⁺ a very good selectivity of log K_{Na,K}^{pot} = -3.0 was found. This is within the range of experimental error equal to the best Na⁺/K⁺-selectivity (-3.1) found for CHEMFETs with PVC/DOS membranes, including the bis(syn-distally)-*O*-functionalized diethyl ester-dimethyl amide calix[4]arene [38].

Immobilization of the tetraphenylborate anion in polysiloxane membrane using compound **5** together with the free tetraethyl ester **1** results in PS(10)CN-CHEMFETs with the same response characteristics as found for membranes with both electroactive components mobile, only a small reduction in Na⁺-selectivity over K⁺ was found (Table 2, entry 2).

TABLE 2. Response characteristics to various ions *j* of CHEMFETs modified with polysiloxane membranes containing 10 mol% cyanopropyl copolymer [PS(10)CN]

Entry	Ionophore, borate anion	log K _{Na,j} ^{pot} [Slope/mV decade ⁻¹]						
		Cs ⁺	Rb ⁺	K ⁺	Li ⁺	Ca ²⁺	Mg ²⁺	
1	1, KTCPB	≤ -3.8 [58.8]	≤ -3.8 [58.7]	-3.0 [59.2]	≤ -3.8 [58.0]	-3.4 [57.5]	≤ -4.1 [58.6]	
2	1, 5 ^a	-3.7 [59.9]	-3.7 [58.8]	-2.7 [58.0]	-3.8 [57.7]	-3.4 [57.2]	-4.0 [56.7]	
3	3 ^a , KTCPB	-3.2 [58.4]	-3.4 [58.6]	-2.5 [58.3]	-3.5 [58.9]	-3.4 [57.4]	-3.8 [58.9]	
4	3 ^a , 5 ^a	-2.6 [58.0]	-2.9 [57.9]	-2.3 [56.9]	-2.9 [55.7]	-3.1 [56.1]	-3.3 [55.6]	
5	4, KTCPB	≤ -3.4 [59.8]	≤ -3.5 [60.2]	-2.5 [56.3]	≤ -3.4 [59.4]	-3.1 [58.1]	≤ -4.2 [57.9]	
6	4, 5 ^a	-2.7 [59.6]	-2.8 [57.2]	-2.4 [54.6]	-3.0 [59.0]	-3.0 [57.0]	-3.9 [57.6]	

^a Bound to the polymer matrix by photopolymerization.

For the PS(10)CN-CHEMFETs with immobilized calix[4]arene derivative **3** in combination with mobile tetraphenylborate anion KTCPB, the same effect was observed as for the CHEMFETs based on low polar polysiloxane (Table 2, entry 3). A good nernstian response in all interfering cation solutions, together with a reduction in selectivity for Na⁺ over interfering cations is observed, although the reduction in this case is smaller than was found for the PS(2.8)CN-CHEMFETs, e.g. $\log K_{\text{Na,K}}^{\text{pot}} = -2.5$.

Finally, we studied a membrane in which both the methacrylated calix[4]arene derivative **3** and the methacrylated borate anion **5** were immobilized. These PS(10)CN-CHEMFETs showed good response curves, although with a slightly decreased response of 56.7 mV decade⁻¹ (Table 2, entry 4). Further, an improvement in the Na⁺/K⁺-selectivity (from -2.0 to -2.3) of this membrane was found compared with the low polar analogue. The PS(10)CN-CHEMFETs with both electroactive components immobilized by photopolymerization show reasonable Na⁺-selectivity to all interfering ions.

Based on the model calculations, serious anion interference was predicted in the case of both covalently attached ionophore and borate anions (cf. Fig. 5). The results presented above show that in practice this effect is limited. This can probably be explained by (i) a lower partition than $k_- = 10^{-6}$ of the anion to the membrane phase (lower polarity of the membrane), and (ii) higher mobilities of the ionophore and the borate anions (higher flexibility of the membrane matrix), than $m_L = 0.001$ and $m_Y = 0$ used in the model calculations.

Effect of the nature of the ionophore cavity

The PS(10)CN-CHEMFETs with immobilized ionophore **3** and borate anion **5** show a decreased selectivity for Na⁺ and a slightly reduced nernstian response compared with CHEMFETs based on the free ionophore **1**. The cavity of the calix[4]arene derivative **3** with the methacrylate functionality is composed of one amide and three ester carbonyl oxygen coordinating sites, whereas tetraethyl ester **1** has a cavity composed of four ester carbonyl oxygen coordinating sites. This difference could possibly be responsible for the observed differences in selectivity.

In order to compare **3** with an ionophore with the same coordinating sites, the monoamide triethyl ester calix[4]arene **4** was synthesized and studied on CHEMFETs. Comparison of the response characteristics of PS(10)CN-CHEMFETs with this monoamide triester calix[4]arene **4** and KTCPB (Table 2, entry 5) and with tetraethyl ester **1** and KTCPB (Table 2, entry 1) shows that the nature of the cavity indeed has a distinct effect

on the selectivity, whereas the sensitivity of CHEMFETs with both ionophores is comparable. Compared with tetraester **1**, the selectivity of monoamide-triester **4** is decreased towards all interfering cations, except for Mg²⁺. The observed selectivities for **4** are the same as found for the CHEMFETs with immobilized calix[4]arene **3** and KTCPB (Table 2, entry 3). This allows the conclusion that the lower selectivity of immobilized **3** compared with **1** is not only due to immobilization of the ionophore but also to differences in the two cavities. CHEMFETs with immobilized borate anion **5** in combination with free monoamide-triethyl ester **4** also show a reduction in selectivity (Table 2, entry 6) similar to PS(10)CN-CHEMFETs with both ionophore and borate anion immobilized, i.e. **3** and **5** (Table 2, entry 4). Remarkably, this effect was not observed for tetraethyl ester **1**; for this ionophore the selectivities towards interfering cations are the same, irrespective of whether **1** is combined with free borate anion KTCPB or with immobilized borate anion **5**. This result suggests that improved results could probably be obtained with immobilized *tetraester* calix[4]arenes.

Time dependence of the sensor response

In order to study the sensing behaviour of CHEMFETs modified with both polysiloxane matrices including immobilized ionophore **3** and immobilized borate anion **5**, step titrations were performed. In these titrations the response of a CHEMFET on an ion activity jump is monitored in time. Using this technique it is possible to discriminate in the CHEMFET signal between the real response on a change in activity of the primary ion, and the possible drift present on top of this response. The results of these experiments are shown in Figs. 9 and 10. Titrations were performed

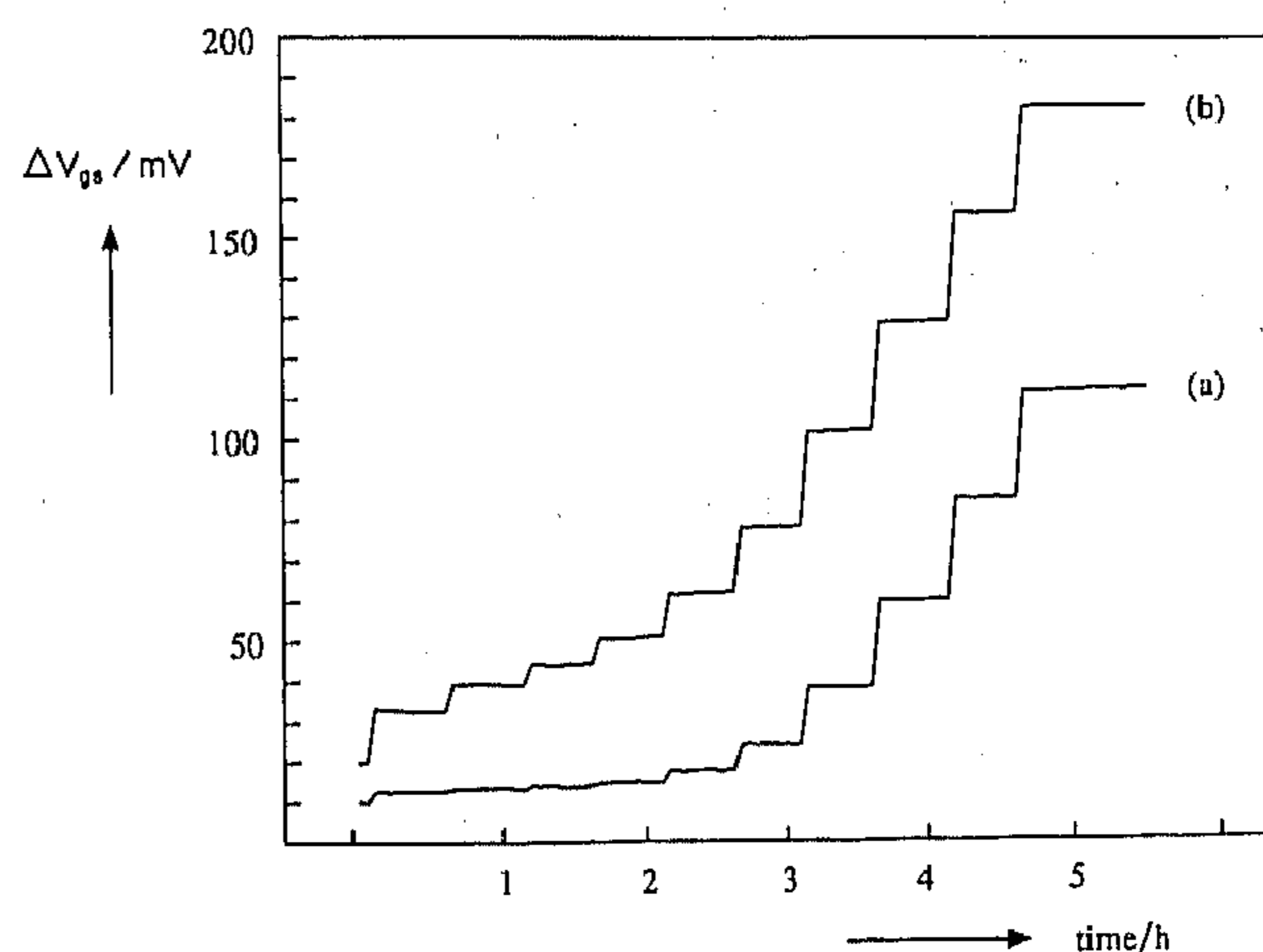


Fig. 9. Response curves for step titrations with PS(10)CN-CHEMFETs with both covalently bound calix[4]arene **3** and borate anion **5**: (a) in 0.5 M KCl, (b) in 0.5 M MgCl₂.

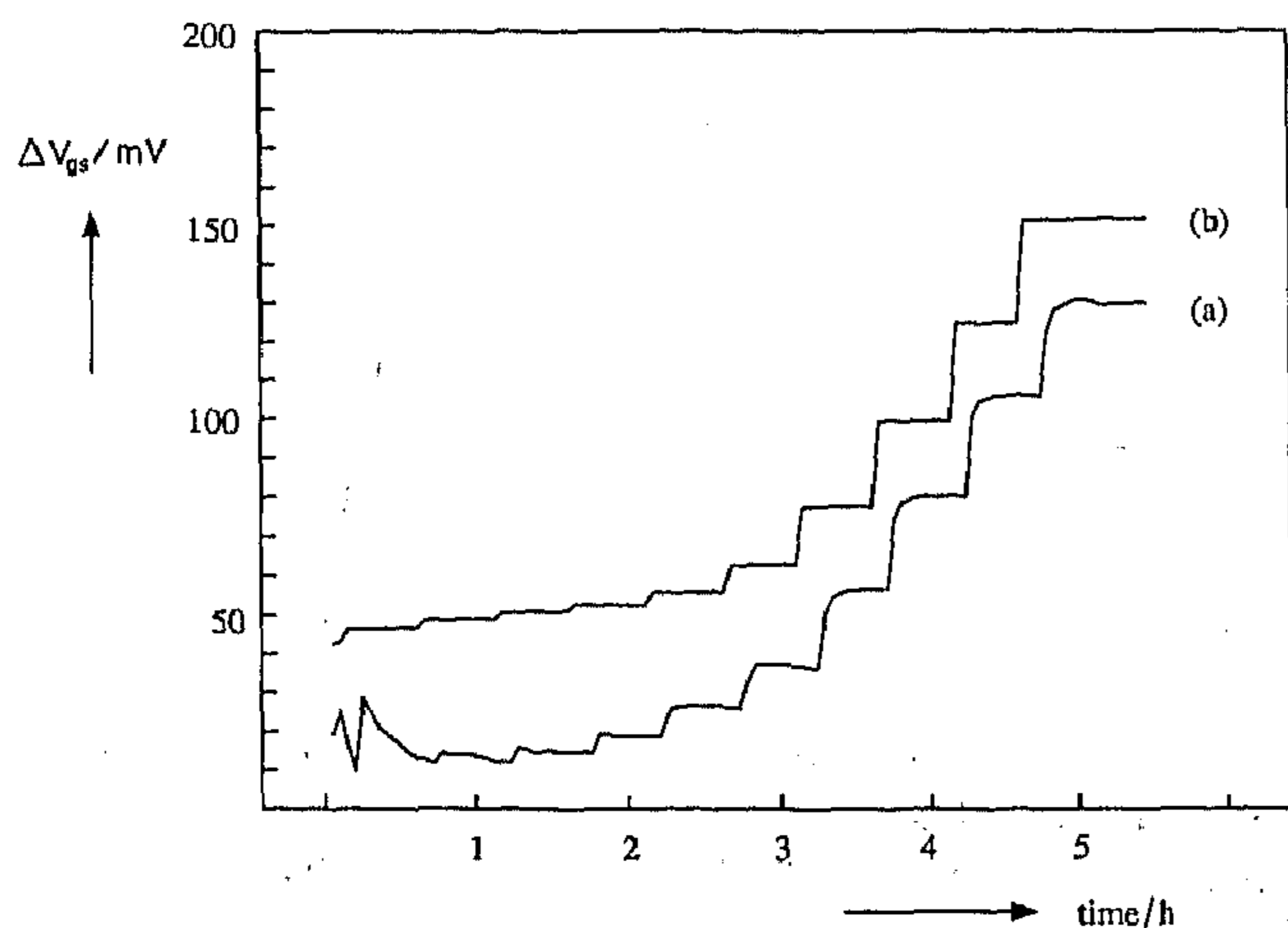


Fig. 10. Response curves for step titrations with PS(2.8)CN-CHEMFETs with both covalently bound calix[4]arene **3** and borate anion **5**: (a) in 0.5 M MgCl₂, (b) in 0.5 M KCl.

with activity jumps of half a decade in the Na⁺-activity region 10⁻⁶–10⁻¹ M. After every activity jump the CHEMFET signal was measured for 30 min with time intervals of 0.5 min. The step titrations were performed in solutions of K⁺ and Mg²⁺, since these are the most and least interfering ions respectively. As can be seen in Fig. 9, the PS(10)CN-CHEMFETs gave the expected response on an Na⁺-activity jump. A fast response to the change in Na⁺-activity occurs and the CHEMFET signal remains stable during the following 30 min. In contrast, the PS(2.8)CN-CHEMFETs show drift at low Na⁺-activities, which becomes less severe in the activity range 10⁻³–10⁻¹ M (Fig. 10).

Durability study of polysiloxane CHEMFETs

Durability studies were carried out with CHEMFETs with PS(10)CN membranes in which the ionophore and borate anions were either free or attached covalently. The CHEMFETs were exposed continuously to a 0.1 M NaCl solution. This solution was refreshed every 7 days. The response characteristics after a 90 day time period of exposure to 0.1 M NaCl of PS(10)CN-CHEMFETs with the mobile tetraethyl

ester **1** and the mobile tetraphenylborate anion KTCPB, the tetraethyl ester **1** and the immobilized borate anion **5**, and the immobilized calix[4]arene **3** and immobilized borate anion **5** are presented in Table 3.

By comparing the response characteristics in Table 3 with the initial response characteristics (Table 2 entries 1, 2, and 4 respectively) some conclusions can be drawn. The PS(10)CN-CHEMFETs with both electroactive components mobile show a distinct decrease in the response slopes after 90 days. This effect is strongest for potassium and caesium as the interfering ions, where the slopes decrease from 59.2 to 54.3 and from 58.8 to 54.3 mV decade⁻¹ respectively (Table 2 and Table 3, entries 1). The selectivity for Na⁺ with respect to all interfering cations is not influenced significantly during this period for this CHEMFET.

For the PS(10)CN-CHEMFETs with the mobile tetraethyl ester **1** and the immobilized borate anion **5** a similar effect was found, although less pronounced than for the PS(10)CN-CHEMFETs with **1** and KTCPB (Table 2 and Table 3, entries 2). The largest reduction in response slope is also observed in this case for potassium and caesium. For both interfering ions the initial response slope is reduced by 4 mV decade⁻¹ after exposure of the CHEMFETs to 0.1 M NaCl for 90 days. Also in this case no significant change in Na⁺-selectivity with respect to interfering ions was observed.

In contrast to the two former PS(10)CN-CHEMFET configurations, CHEMFETs based on both immobilized electroactive components (ionophore **3** and borate anion **5**) did not show a significant decrease in the response slope after the 90 day time period (Table 2, entry 4 and Table 3, entry 3). The Na⁺-selectivities after 90 days of exposure to 0.1 M NaCl are the same as the initially determined Na⁺-selectivities.

3. Conclusions

Polysiloxane membranes including Na⁺-selective calix[4]arene derivatives are suitable sensing membranes for the construction of Na⁺-selective CHEM-

TABLE 3. Response characteristics to various ions *j* of PS(10)CN-CHEMFETs after continuous exposure to 0.1 M NaCl for 90 days

Entry	Ionophore, borate anion	log K _{Na,j} ^{pot} [Slope/mV decade ⁻¹]					
		Cs ⁺	Rb ⁺	K ⁺	Li ⁺	Ca ²⁺	Mg ²⁺
1	1 , KTCPB	-3.7 [54.3]	-3.6 [55.8]	-2.9 [54.3]	-3.9 [56.8]	-3.4 [56.1]	-3.9 [56.4]
2	1 , 5 ^a	-3.7 [55.9]	-3.9 [56.9]	-2.7 [54.0]	-3.8 [55.9]	-3.3 [56.1]	-3.8 [55.6]
3	3 ^a , 5 ^a	-2.4 [55.0]	-2.7 [56.3]	-2.4 [57.1]	-2.8 [55.1]	-3.0 [55.4]	-3.6 [55.3]

^a Bound to the polymer matrix by photopolymerization.

FETs. These CHEMFETs show nernstian responses and a good Na⁺-selectivity with respect to the interfering ions, regardless of whether the electroactive components are free or bound covalently to the membrane matrix. However, in the case where both ionophore and borate anions are bound to the membrane matrix, the polarity of the membrane should not be too low. CHEMFETs with polysiloxane membranes containing 2.8 mol% cyanopropyl function showed in this case severe drift at low Na⁺-activities. However, when the polarity of the membrane was increased to polysiloxanes with 10 mol% cyanopropyl function, the CHEMFETs showed a normal response.

The slightly reduced Na⁺-selectivity found for the durable Na⁺-CHEMFETs is induced mainly by a decrease in the selectivity of complexation of the ionophore in these cases, and an improvement may be expected using an immobilizable calix[4]arene with four ester groups.

The durability experiments, which are being continued, indicate strongly that chemical binding of the electroactive components results in improved durability. On exposure to 0.1 M NaCl for 90 days of CHEMFETs with one or both electroactive components mobile, a distinct reduction in the sensitivity was observed, whereas for the CHEMFET with both electroactive components chemically bound to the polysiloxane matrix no change in response characteristics was observed¹. No decrease in the Na⁺-selectivity was observed during the evaluation period. This is a clear indication that this membrane architecture, in which both electroactive components are bound covalently to the membrane matrix, is very promising for the further development of stable, durable CHEMFETs.

4. Experimental

Synthesis

Melting points (mp) were determined with a Reichert melting point apparatus and are uncorrected. ¹H NMR and ¹³C NMR spectra were recorded with a Bruker AC 250 spectrometer in CDCl₃ with Me₄Si as internal standard. Positive or negative ion FAB spec-

tra, with the use of *m*-nitrobenzyl alcohol (NBA) as a matrix, were obtained using a Finnigan MAT 90 spectrometer.

The monoacid triester derivative **2** [36] was prepared from *p*-*tert*-butylcalix[4]arene tetraethyl ester **1** [41] according to literature procedures. Tetrahydrofuran (THF) was freshly distilled from sodium/benzophenone ketyl; acetonitrile (CH₃CN) and *N,N*-dimethylformamide (DMF) were stored over molecular sieves (3 and 4 Å respectively), and used without further purification. Silica gel 60 (particle size 0.040–0.063 mm, 230–400 mesh) was purchased from Merck. All commercially available chemicals were of reagent grade quality from Janssen Chimica or Aldrich, and were used without further purification unless otherwise stated. All reactions were carried out under an argon or nitrogen atmosphere. The presence of solvent in the analytical samples was confirmed by ¹H NMR spectra of the samples in CDCl₃. When water was present in the analytical samples the water content was determined by Karl–Fischer titration. For reasons of clarity the Gutsche convention [42] is followed, using the name calix[4]arene instead of the official IUPAC name pentacyclo[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]octacosa-1(25), 3,5,7(28),9,11,13(27),15,17,19(26),21,23-dodecane-25,26,27,28-tetrol.

25-Carboxylic acid-26,27,28-triethyl-ester-p-tert-butylcalix[4]arene (2). Recrystallization from methanol afforded a white solid in 79% yield in the case where the reaction of *p*-*tert*-butylcalix[4]arene tetraethyl ester **1** was performed with trifluoroacetic acid, and in 84% yield in the case where the reaction was performed with an acetic acid + nitric acid mixture: mp 125–126°C (literature value 166–169°C [36]).

General procedure for the synthesis of monoamide-triester calix[4]arenes **3** and **4**

A solution of triester monoacid **2** (2.0 g, 2.07 mmol) dissolved in thionyl chloride (7 ml) was refluxed for 2.5 h. Subsequently, thionyl chloride was removed under reduced pressure and the obtained acid chloride was dissolved in chloroform (70 ml). To this solution the different reagents (2.48 mmol, 1.2 eq), i.e. 2-aminoethyl methacrylate (0.33 g) for **3**, or *n*-propylamine (0.15 g) for **4**, and triethylamine (0.84 g, 8.21 mmol) were added. The reaction mixture was stirred for 3 h at room temperature, with the exclusion of light in the case where reagents were used with a methacrylate functionality. The reaction was quenched by the addition of acetic acid (70 ml, 5 vol.%), and after washing the mixture twice with deionized, doubly distilled water it was dried over MgSO₄. The residue obtained after

¹ After 90 days of exposure to a 0.1 M NaCl solution the sensitivity of CHEMFETs in which either one or both electroactive components are mobile is reduced 2.4–2.9 mV decade⁻¹ on average, whereas the reduction in sensitivity of CHEMFETs with both electroactive components immobilized is only 1.0 mV decade⁻¹. For potassium-selective CHEMFETs which have ionophores of lower lipophilicity [40], it was observed that in the case when one or both electroactive components were mobile the response for potassium was lost even after approximately 40 days of exposure to a 0.1 M KCl solution.

removal of chloroform was recrystallized from acetonitrile.

25-Methacryloyloxyethylamide-26,27,28-triethyl-ester-p-tert-butylcalix[4]arene (3). Following the general procedure, a white solid was obtained after recrystallization from acetonitrile (1.40 g, 61.9%): mp 78–80°C; ¹H NMR δ 8.51 (bs, 1H, NH), 6.76, 6.67 (s, 2H, ArH), 6.72 (s, 4H, ArH), 6.06, 5.48 (bs, 1H, C(CH₃)=CH₂), 4.68, 4.54, 3.17, and 3.16 (ABq, 8H, *J* = 13.2 Hz, ArCH₂Ar), 4.85, 4.79, 4.34, 4.30 (s, 2H, ArOCH₂), 4.28 (t, 2H, *J* = 6.6 Hz C(O)OCH₂CH₂NH), 4.13 (q, 6H, *J* = 7.1 Hz, OCH₂CH₃), 3.64 (q, 2H, *J* = 6.5 Hz, NHCH₂), 1.86 (s, 3H, C(CH₃)=CH₂), 1.19 (t, 9H, *J* = 7.1 Hz, OCH₂CH₃), 1.04, 0.98 (s, 9H, C(CH₃)₃), 1.00 (s, 18H, C(CH₃)₃); ¹³C NMR δ 170.7, 170.4 (s, C(O)OEt), 167.1 (s, C(O)NH), 74.3 (t, OCH₂C(O)NH), 71.8, 71.4 (t, OCH₂C(O)OEt), 62.9 (t, C(O)OCH₂CH₂NH), 60.8, 60.5 (t, OCH₂CH₃), 37.9 (t, CH₂NH), 33.9, 33.8 (s, C(CH₃)₃), 32.0 (t, ArCH₂Ar), 31.3 (q, C(CH₃)₃), 18.3 (q, C(CH₃)=CH₂), 14.2, 14.1 (q, OCH₂CH₃); FAB mass spectrum, *m/e* 1076.6 [(M + H)⁺, calculated 1076.6]. Analysis calculated for C₆₅H₈₅NO₁₃ and 1.40 wt.% H₂O: C, 70.41; H, 8.03; N, 1.28. Found: C, 70.04; H, 7.87; N, 1.11.

25-n-Propylamide-26,27,28-triethyl-ester-p-tert-butylcalix[4]arene (4). Following the general procedure, a white powder was obtained after recrystallization from acetonitrile (1.29 g, 61.8%): mp 80–82°C; ¹H NMR δ 8.39 (bs, 1H, NH), 6.83, 6.73 (s, 2H, ArH), 6.80 (s, 4H, ArH), 4.87, 4.72, 4.68, 4.53 (s, 2H, ArOCH₂), 4.78, 4.65, 3.26, and 3.23 (ABq, 8H, *J* = 13.0 Hz, ArCH₂Ar), 4.20 (q, 6H, *J* = 7.1 Hz, OCH₂CH₃), 3.39–3.31 (m, 2H, NHCH₂), 1.72–1.63 (m, 2H, NHCH₂CH₂), 1.27 (t, 9H, *J* = 7.1 Hz, OCH₂CH₃), 1.11, 1.04 (s, 9H, C(CH₃)₃), 1.08 (s, 18H, C(CH₃)₃), 0.96 (t, 3H, *J* = 7.4 Hz, NHCH₂CH₂CH₃); ¹³C NMR δ 170.3, 170.1 (s, C(O)), 74.5 (t, CH₂C(O)NH), 71.7, 71.4 (t, CH₂C(O)OEt), 60.6, 60.5 (t, OCH₂CH₃), 41.1 (t, C(O)NHCH₂), 33.9 (s, C(CH₃)₃), 32.0 (t, ArCH₂Ar), 31.4 (q, C(CH₃)₃), 23.1 (t, NHCH₂CH₂CH₃), 14.2 (q, OCH₂CH₃), 11.5 (q, NHCH₂CH₂CH₃); FAB mass spectrum, *m/e*

1006.5 [(M + H)⁺, calculated 1006.6]. Analysis calculated for C₆₁H₈₃NO₁₁ and 1.34 wt.% H₂O: C, 71.83; H, 8.35; N, 1.37. Found: C, 71.26; H, 8.33; N, 1.48.

CHEMFETs

Reagents

Potassium tetrakis(4-chlorophenyl)borate (KTCBPB) was purchased from Fluka, potassium triphenyl 1-(4-methacryloyloxymethyl phenyl) borate **5** was synthesized by ourselves [38]. All silane and siloxane reagents were purchased from Petrarch Systems. The polysiloxane copolymers used were synthesized according to Sudhölter et al. [26,43]. The variation in the ratio of the reactant is given in Table 4. The amount of cyanopropyl(methyl) siloxane and methacryloxypropyl(methyl) siloxane in the copolymer was determined from ¹H NMR and elemental analysis data. As a photoinitiator 2,2'-dimethoxy-2-phenylacetophenone, obtained from Janssen Chimica, was used. The pH 4 buffer was purchased from Yokogawa. Tetrahydrofuran (THF) was freshly distilled from sodium/benzophenone ketyl before use. The chloride salts of the alkali and alkaline earth metals used were of analytical grade (Merck-Schuchardt), except for sodium and potassium which were of even higher purity (Suprapur, Merck-Schuchardt). All solutions were made with deionized, doubly distilled water.

Fabrication of CHEMFETs

The ISFETs used in this study had dimensions 1.2 × 3.0 mm². The SiO₂ gate oxide (or insulator layer) was grown thermally in an oxygen atmosphere for 10 min at 1150°C (thickness approximately 700 Å). Further details of the fabrication are as described previously [44]. The ISFETs contained an intermediate hydrogel of poly(hydroxyethyl methacrylate) (polyHEMA) between the gate oxide and the sensing membrane which was anchored chemically to the gate oxide using the photolithographic procedure described earlier [26,43]. ISFETs are referred to by the acronym CHEMFETs. Subsequently, the CHEMFETs were mounted on a support, a printed circuit board, wire bonded, and

TABLE 4. Composition of the polysiloxane copolymer in the reaction mixture and in the product (in mol% of the corresponding siloxane unit)

Siloxane copolymer code	Cyano-siloxane in reaction mixture	Cyano-siloxane found in the product	Methacryl-siloxane in reaction mixture	Methacryl-siloxane found in the product
PS(2.8)CN	2.8	2.1	1.3	1.0
PS(10)CN	10.0	8.7	2.0	1.5

encapsulated with epoxy resin (Hysol H-W796/C8 W795). CHEMFETs used to study photopolymerizable polysiloxane membranes were encapsulated with silicone rubber (Dow Corning 3140 RTV). The composition of the polysiloxane membranes was as follows: polysiloxane copolymer (98.4 ± 0.2 wt.%), ionophore (0.5 ± 0.05 wt.%), tetraphenylborate (25 ± 2.5 mol%, with respect to the ionophore), and photoinitiator (1 wt.%). This mixture with a total weight of around 100 mg was dissolved in 600 μ l THF. On top of the polyHEMA layer, which was conditioned by immersion in a buffered (pH 4) 0.1 M NaCl solution for 3–6 h, 2–3 μ l of the polysiloxane membrane solution was cast by means of a micropipette. These CHEMFETs were placed on a developing plateau under a nitrogen atmosphere and left for 15–20 min at room temperature to evaporate the solvent. Subsequently, the membranes were photocured by exposure for 2.5 min to UV light (100 W high pressure mercury lamp, Blak-Ray B-100A). The CHEMFETs were stored overnight under an atmosphere of nitrogen. Before starting the measurements the membranes were conditioned in a 0.1 M NaCl solution for 2 days.

CHEMFET measurements

The output signal of the CHEMFETs was measured in a constant drain-current mode ($I_d = 100 \mu\text{A}$), with a constant drain-source potential ($V_{ds} = 0.5$ V) [45]. This was achieved using a CHEMFET amplifier of the source-drain follower type (Electro Medical Instrumentation, Enschede, The Netherlands). The developed membrane potential was compensated by an equal and opposite potential ΔV_{gs} via the reference electrode. A saturated calomel electrode (SCE) was used as a reference, connected to the sample solution via a salt bridge, filled with 1.0 M LiOAc. Ten ISFETs were monitored simultaneously and the data were collected and analysed using an Apple IIGS microcomputer. Computer controlled switches allowed disconnection of CHEMFETs which showed a too high leakage current ($I_d \geq 50$ nA). All equipment was placed in a dark and grounded metal box in order to eliminate any effects from static electricity and photosensitivity of the ISFETs.

The potentiometric selectivity coefficients K_{ij}^{pot} were determined by the fixed interference method (FIM) [46]. The constant background concentration of the interfering ions was 0.5 M unless stated otherwise. All concentrations were converted to single-ion activities using the Debye-Hückel convention [32]. The mean activity coefficient was obtained by the extended Debye-Hückel equation [32]. The response characteristics obtained were analysed according to the Nicolsky-Eisenman equation [32].

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TABLE A5. Calculated potentials and activities of membrane components: $m_L = 0.01$, other parameters as for Table A4

	log a_{+1}					
	-6	-5	-4	-3	-2	-1
E_M/mV	-89.1	-82.5	-52.4	2.47×10^{-1}	54.1	77.1
E_{Bs}/mV	-115	-100	-56.6	2.55×10^{-1}	59.0	116
E_D/mV	-25.9	-17.4	-4.18	1.01×10^{-2}	4.98	39.2

For $\tilde{a}_{+1}(s)$, $\tilde{a}_{+1L}(s)$, $a_{+2}(s)$, $\tilde{a}_{+2L}(s)$, $a_L(s)$, $\tilde{a}_-(s)$, and $a_Y(s)$ see Table A4.