

Molecular materials for the transduction of chemical information by CHEMFETs

Jan R. Haak, Peter D. van der Wal and David N. Reinhoudt*

Department of Organic Chemistry and MESA Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede (Netherlands)

Abstract

This paper describes a strategy to overcome the problems associated with the use of MEMFETs as selective chemical sensors. The problems arising from the thermodynamically ill-defined insulator–membrane interface have been eliminated by a new sensor design, viz., the introduction of an intermediate hydrogel layer. Experiments to assess the beneficial effect of such a hydrogel are described. Furthermore, new membrane materials have been designed, synthesized, and characterized. Hence, photopolymerizable polysiloxanes are used which allow both the covalent attachment of electroactive components and the covalent bonding of the sensing membrane to the hydrogel. It is shown that polysiloxanes are versatile materials for the sensing membrane of an ISFET-based chemical sensor. The described technology results in a robust and stable sensor.

1. Introduction

In recent years, interest in chemical sensors has grown rapidly and the use of electrochemical principles is widespread [1]. According to the electrical parameter that they measure, electrochemical sensors can be classified as potentiometric, amperometric, and conductometric. Due to the pioneering work of Bergveld [2, 3] on ion-selective field-effect transistors (ISFETs), transduction on the basis of potentiometry seems very attractive. An ISFET can be considered as a special type of a field-effect transistor; a schematic drawing of this device is given in Fig. 1.

An ISFET consists of a silicon substrate with source and drain diffusions separated by a channel that is covered by SiO_2 as the insulator gate oxide. Changes in the electrical field perpendicular to the gate oxide surface results in a variation of the conductance in the source-drain-channel [4]. When the gate oxide contacts an aqueous solution a change in pH will modify the SiO_2 surface potential, Ψ . Using the site-dissociation model [5] the observed pH-dependence can be related to the state of ionization of the amphoteric SiOH surface groups. Usually an ISFET is operated in a so-called

constant-drain current mode by means of an operational amplifier that controls the gate-source potential using a feedback loop. This can only be achieved when contact with the electrolyte solution is ensured by means of a reference electrode. The output of the amplifier is a direct measure of the developed surface potential.

The use of an ISFET as the transducing element is attractive because it has small dimensions, fast response, and low output impedance. The major disadvantages are the need* for encapsulation [6] and the pH sensitivity of the response [7]. An ISFET exposed to an electrolyte solution not only

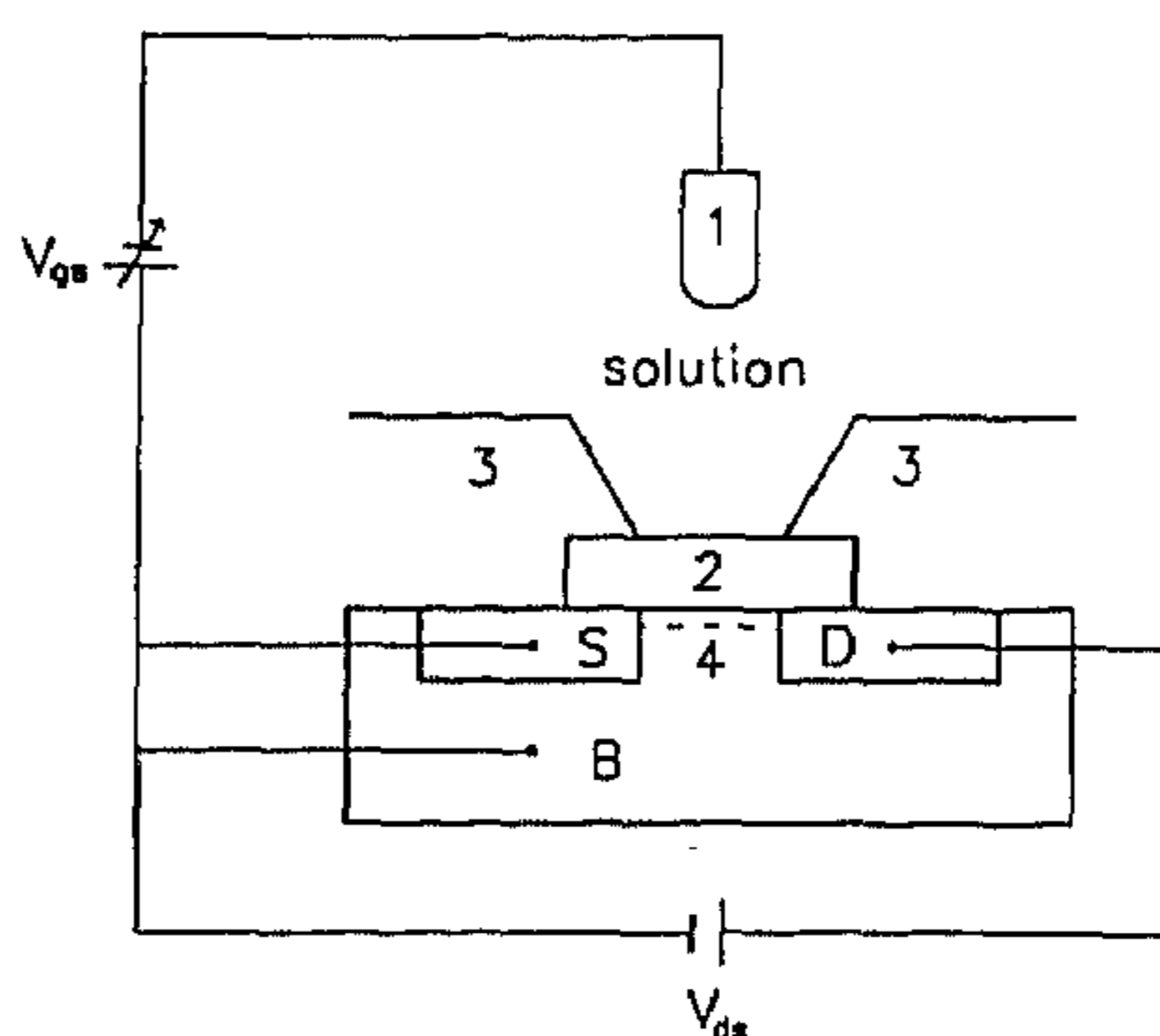


Fig. 1. Schematic representation of an ion-selective, field-effect transistor (ISFET) and measurement set-up. 1, Reference electrode; 2, gate oxide; 3, insulating resin; 4, conducting channel; S, source; D, drain; B, bulk; V_{gs} , gate-source voltage; V_{ds} , drain-source voltage.

*Author to whom correspondence should be addressed.

responds to variations in the pH, but also to changes in the ion-concentrations.

The lack of selectivity of an ISFET might be eliminated by the application of specific ionophores [8]. The discovery by Pedersen [9] that synthetic macrocyclic polyethers form complexes with cationic guest species has tremendously stimulated the molecular design and synthesis of receptor molecules that selectively recognize ions and even neutral molecules. Attachment of these receptor molecules to the gate oxide surface of an ISFET results in a so-called SURFET. Using the dissociation model we have shown [10] that the number of receptor sites would have to be very high, as well as the association constant between receptor and guest. Furthermore, complete coverage of the reactive SiOH groups is difficult to achieve and this will result in a residual pH-sensitivity [11].

An alternative approach is to deposit a membrane, incorporating the receptor molecule, on top of the gate oxide. A schematic representation of such a MEMFET is given in Fig. 2. With this device the measured potential is a membrane potential which can be regarded as the sum of three contributions, i.e., two boundary potentials at the two membrane interfaces and a diffusion potential in the bulk of the membrane. This concept has been applied by Moss and co-workers [12] to obtain a potassium sensitive device. To this end, a plasticized PVC membrane containing valinomycin as the receptor was physically attached onto the gate oxide of an ISFET. Although a response to variations in the potassium concentrations was observed there are some serious drawbacks that, until now, have prevented such devices competing or even replacing the conventional ion-selective electrode. First, the physical attachment of the hydrophobic PVC polymer on the hydrophilic gate oxide results in an inferior binding. In addition, seepage of water between the membrane and the gate oxide weakens the adhesion between the

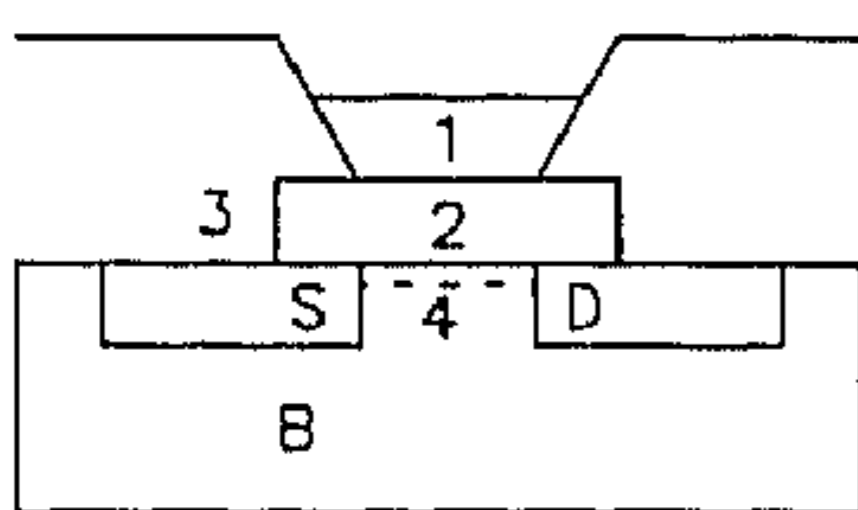


Fig. 2. Schematic representation of a membrane field-effect transistor (MEMFET). 1, PVC membrane; 2, gate oxide; 3, insulating resin; 4, conducting channel; S, source; D, drain; B, bulk.

membrane and the ISFET [13]. This results in the loosening of the membrane which limits the lifetime of the sensor. Another problem that may arise with the use of thin membrane layers is the leaching out of electroactive components (solvent mediator, receptor, and anionic sites), which may result in an increased drift and noise and, ultimately, in deterioration of the sensor performance. A third problem associated with PVC as the membrane phase is the perfusion of CO_2 through the membrane. The casting of the membrane does not remove the amphoteric SiOH groups from the oxide surface. Hence, the acid properties of CO_2 modify the ionization state of the surface and result in an interfering response of the ISFET [14]. However, the most fundamental problem is the fact that the interface between the gate oxide and the organic matrix is not defined in terms of common species. In the case of the pH-sensitive ISFET this potential is thermodynamically defined by the (de)protonation equilibrium of the SiOH surface groups. Such an equilibrium does not exist in the case of a MEMFET that is sensitive for other ions, leading to irreproducible and unstable membrane potentials.

This paper describes our strategy to overcome the above mentioned problems with the MEMFET. This strategy was the first to change the design in such a way that the problems of the thermodynamically ill-defined membrane-insulator interface and the residual pH-sensitivity would be eliminated. In addition, different membrane materials had to be developed for the covalent attachment of electroactive components in the membrane matrix. These membrane materials should also have the intrinsic property that they can be anchored onto the gate oxide of the field-effect transistor via covalent bonds. These chemical modifications of the ISFET should result in a robust and stable sensor.

2. The architecture of the sensor

Because the various interfaces should be thermodynamically well-defined, a common potential-determining species in the two phases in contact at an interface should be in equilibrium. Another requirement is the elimination of the pH-sensitivity, and because a complete removal of the amphoteric SiOH groups has been proven impossible, our

TABLE 1. Effect of polyHEMA hydrogel on the peak-to-peak noise level (V_{pp}) for modified ISFETs with different hydrophobic membranes containing valinomycin^a

Hydrophobic membrane	V_{pp} (mV)	
	Without polyHEMA	With polyHEMA
PVC	0.10	0.030
ACE/Epocryl ^b	> 10	0.020
Silopren	0.50	0.030
Silicone rubber	0.20	0.040

^aMeasured in 0.1 M KCl.

^bPolyacrylate.

layer which was conditioned with a buffered potassium chloride solution. The results in Table 1 reveal that for all the investigated polymers the peak-to-peak level is decreased drastically. The most pronounced effect is observed for the ACE-Epocryl polyacrylate membrane. The large instabilities observed with this material in the absence of the polyHEMA might be due to the low water content of the membrane.

The second experiment concerned the interference by CO₂ [15]. When the polyHEMA layer was equilibrated with a buffered potassium chloride solution and subsequently covered with a plasticized PVC membrane, complete elimination of CO₂ interference was observed (Fig. 5, curve 1). In the absence of the hydrogel layer, introduction of CO₂ into the sample solution gave rise to a fast response of the output signal (Fig. 5, curve 2).

The third experiment shows the beneficial effect of the introduction of the polyHEMA layer on the

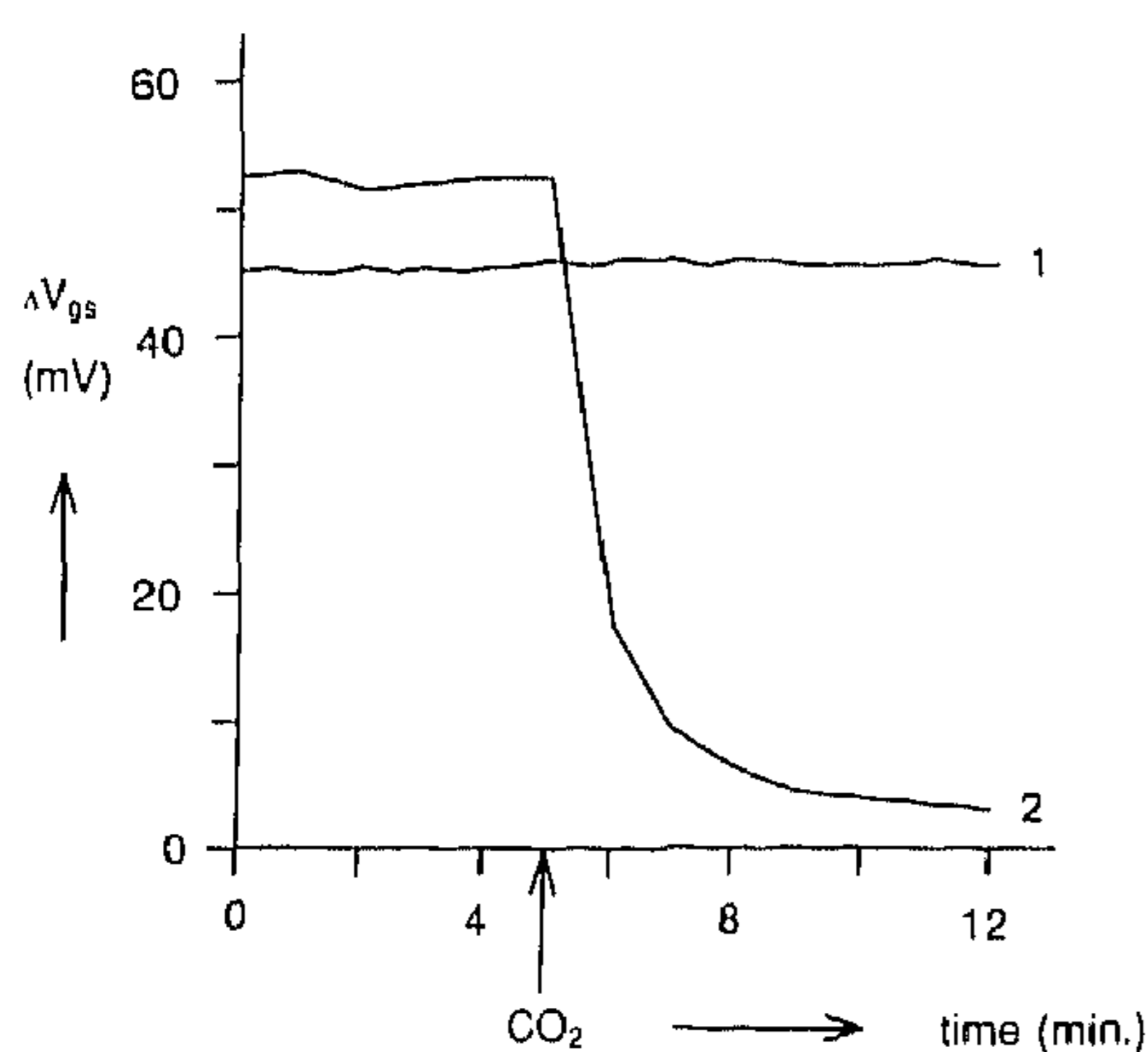


Fig. 5. Amplifier output voltage (ΔV_{gs}) using PVC-modified SiO₂ ISFETs on saturation of a 0.1 M KCl solution with CO₂. Curve 1, with a buffered (pH 4.0) 0.1 M KCl intermediate polyHEMA layer; curve 2, PVC membrane deposited directly on the gate oxide.

TABLE 2. Effect of polyHEMA hydrogel on the sensitivity of a sodium-selective sensor^a

Interfering ion	$dE/da(\text{Na}^+)$ (mV/pNa)	
	Without polyHEMA	With polyHEMA
Li ⁺	45–50	58
K ⁺	37–44	58
Mg ²⁺	57–60	58
Ca ²⁺	56–58	58

^a. Measured in the presence of 0.1 M interfering ion.

sensitivity and reproducibility of a sodium-sensor [17]. The results (Table 2) reveal that the sensitivity for sodium in the presence of different interfering ions is near-Nernstian, i.e., approximately 59 mV/pNa. This can be observed for a set of ten sensors measured simultaneously. This observation is contrasted with the results for sensors without an intermediate hydrogel layer. In all cases the measured sensitivity scatters over a much larger interval. Furthermore, the averaged sensitivity is lower when alkali ions are used as the interfering ion.

In conclusion, it is noted that the introduction of an intermediate hydrogel layer results in an improvement in the sensor characteristics. Since the hydrogel is formed *in situ* on the device by photopolymerization, this technique is compatible with IC technology. The surface of the hydrogel contains hydroxyethyl functional groups, which can be easily chemically modified to render possible covalent anchoring of the hydrophobic membrane to the hydrogel.

3. New materials for sensing membranes

Having solved the problems associated with the architecture of the sensor we set out to study new polymeric materials to be used as the matrix for the sensing membranes. We have investigated both (meth)acrylates and polysiloxanes. In earlier studies [18, 19] it was found that the commercial acrylic ester ACE and the methacrylic Epocryl DRH 370 perform well as membrane materials in the preparation of reference field-effect transistors (REFETs). The chemical structures of the monomeric units are shown in Fig. 6. All acrylate- and methacrylate-based membranes were obtained

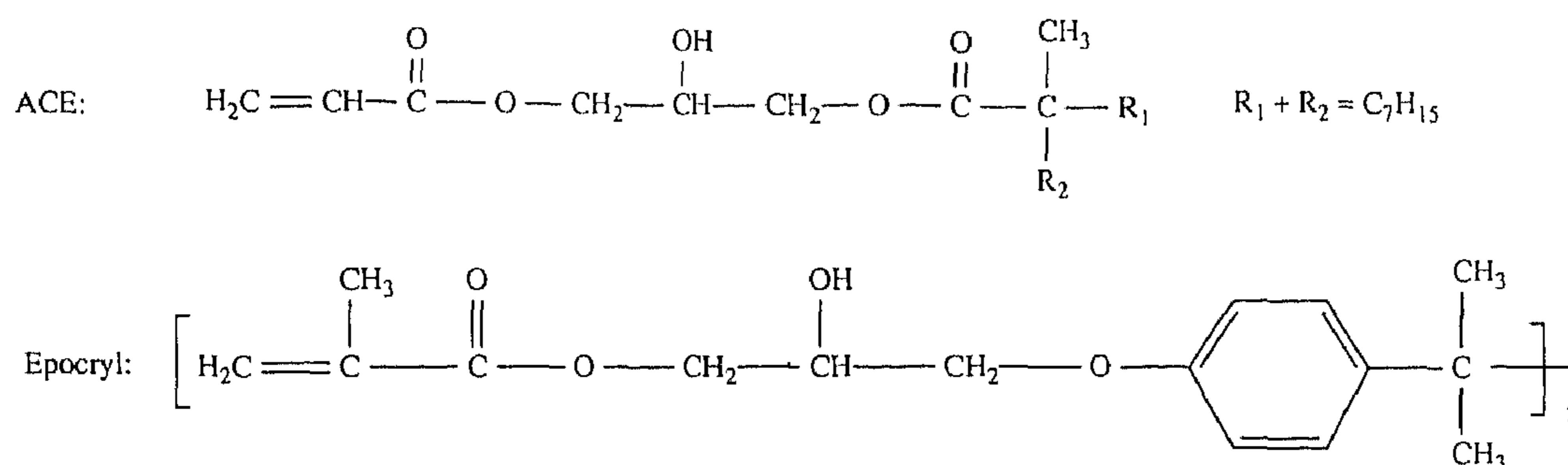


Fig. 6. Chemical structures of (meth)acrylate monomeric units.

by photopolymerization on top of a polyHEMA interlayer. Using these materials, the construction of a potassium sensor was investigated.

In the absence of a receptor the ACE membrane shows cationic permselective behaviour of 44 mV/pK. The addition of valinomycin did not introduce the desired potassium selectivity. This means that although a potassium permselectivity of about 44 mV/pK is observed, no selectivity is observed in the presence of 0.1 M of interfering ions such as sodium and lithium. This prompted the investigation of the polymer system in more detail [20]. The parameters studied included the addition of different external plasticizers (dibutyl phthalate and *n*-octanol), changing the ACE to Epocryl monomer ratio, and the addition of lipophilic anionic sites. The results (Table 3) reveal that these variations did not significantly improve the potassium *sensitivity*. More disappointing was the

fact that, despite all the changes made, only occasionally could potassium *selectivity* be observed. The ACE monomer was also modified by reaction of the hydroxyl group to give acetyl-, pentanoyl- and hydroxypentanoylACE. Membranes of these modified ACE monomers containing valinomycin, when prepared on an ISFET device, show a sub-Nernstian potassium sensitivity of 45 mV/pK and no potassium selectivity.

Polysiloxane membranes can easily be obtained from commercially available starting materials. Three different types were studied [20], i.e. the addition type Wacker RTV-ME 625 and the condensation types Dow Corning 3140 RTV and Silopren (Bayer). In contrast to the (meth)acrylate membranes, the polysiloxanes investigated can be deposited directly onto the gate oxide of the ISFET, but also in these cases the introduction of a polyHEMA interlayer will reduce the noise level and eliminate the interference by CO₂ (*vide supra*). The siloxane membranes formed have elastomeric properties and therefore they do not need an external plasticizer. The Wacker RTV-ME 625 material is a two-component addition-type silicone rubber. The curing reaction involves the addition of SiH groups to vinyl moieties using a platinum catalyst (Fig. 7). Dow Corning 3140 RTV undergoes polycondensation by the uptake of water from the atmosphere, catalysed by a titanium catalyst. The Bayer Silopren material undergoes polycondensation in the presence of an organotin catalyst. Both condensation-type curing reactions use a tetraalkoxysilane as a cross-linker. These latter types of materials have also been used in the preparation of conventional ion-selective electrodes [21–23].

The CHEMFETs with these materials all reveal potassium selective responses (Table 4). The lifetime

TABLE 3. Effect of a polymeric membrane composition on the potassium sensitivity of CHEMFETs containing valinomycin^a

Polymer	Plasticizer	Lipophilic salt	dE/da(K ⁺) (mV/pK)
ACE	–	–	44
ACE	DBP ^b	–	48
ACE/Epocryl (1:1)	DBP ^c	–	36
ACE	Ocl ^d	–	54
HydroxypentanoylACE	–	–	45
AcetylACE	–	–	45
PentanoylACE	–	–	45
ACE	–	KB(PhCl) ₄ ^e	44
ACE	–	KDNNS ^f	45

^aSensitivity measured in pure water. ^bDibutyl phthalate, 50 wt.%. ^cDibutyl phthalate, 67 wt.%. ^d*n*-Octanol, 50 wt.%. ^ePotassium tetrakis(4-chlorophenyl)borate. ^fPotassium dinonylnaphthalene sulphonate.

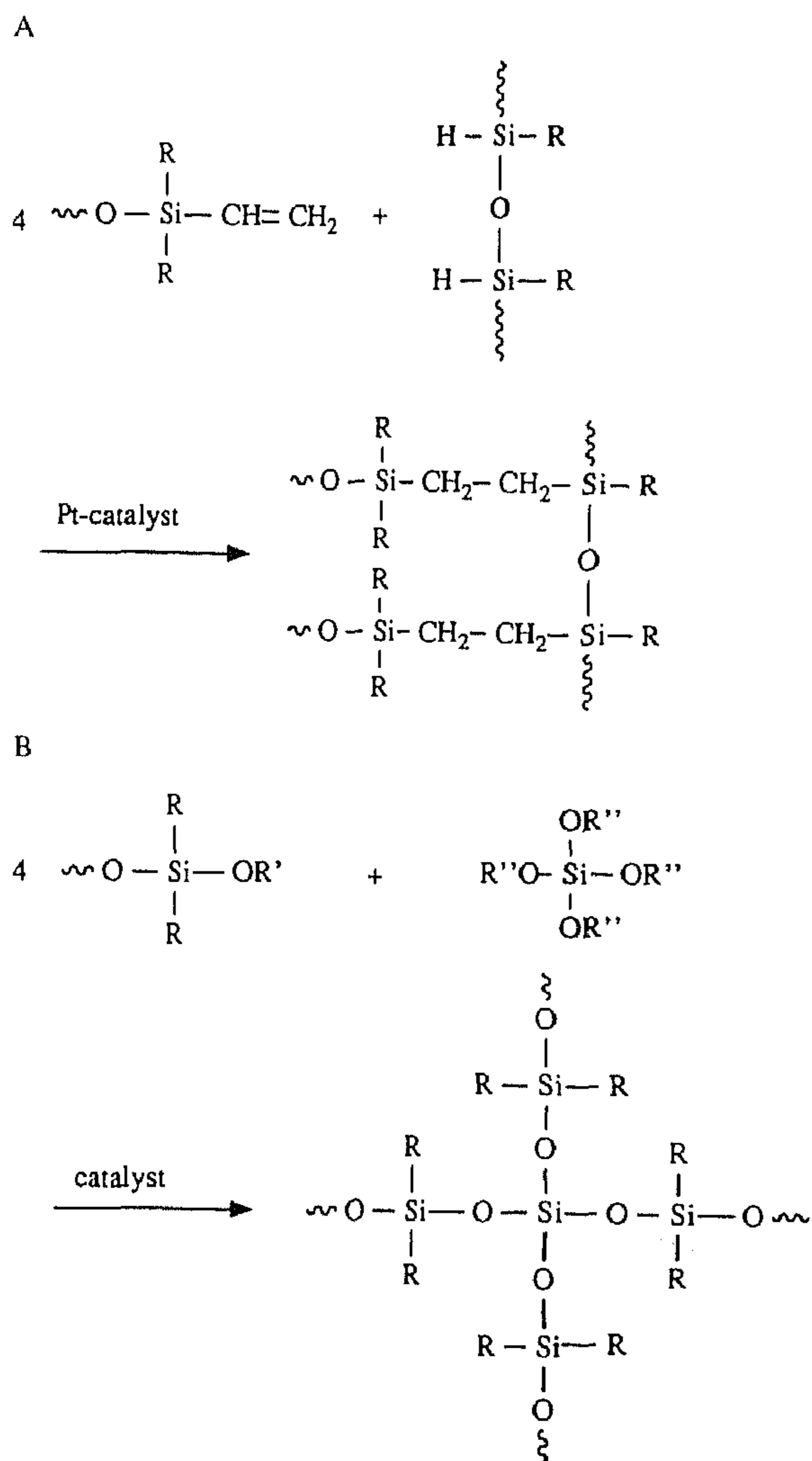


Fig. 7. Curing reaction scheme for commercial polysiloxanes. A, Addition-type curing reaction: Wacker RTV ME 625; R = methyl. B, Condensation-type curing reaction: Dow Corning 3140 RTV; R = R' = R'' = methyl, water from the atmosphere and a titanium catalyst are needed; Bayer Silopren; R = methyl, R' = H, R'' = ethyl, an organotin catalyst is used.

TABLE 4. Potassium sensitivity ($dE/da(K^+)$) and potassium-sodium selectivity ($\log K_{ij}^{pot}$)^a of polysiloxane modified ISFETs

Membrane material	Ionophore ^b	KB(PhCl) ₄ (mol%) ^c	$dE/da(K^+)$ (mV/pK)	$\log K_{ij}^{pot}$
3140 RTV	1	-	56	< -3.7
3140 RTV	1	67	56	< -3.7
Silopren	1	-	56	< -3.7
Silopren	1	67	55	< -3.7
Silopren	2	-	55	≤ -3.3
Silopren	3	-	56	≤ -3.1

^aFixed interference method, 0.1 M NaCl. ^b3 wt.% of ionophore. For chemical structures see Fig. 8. ^cWith regard to ionophore.

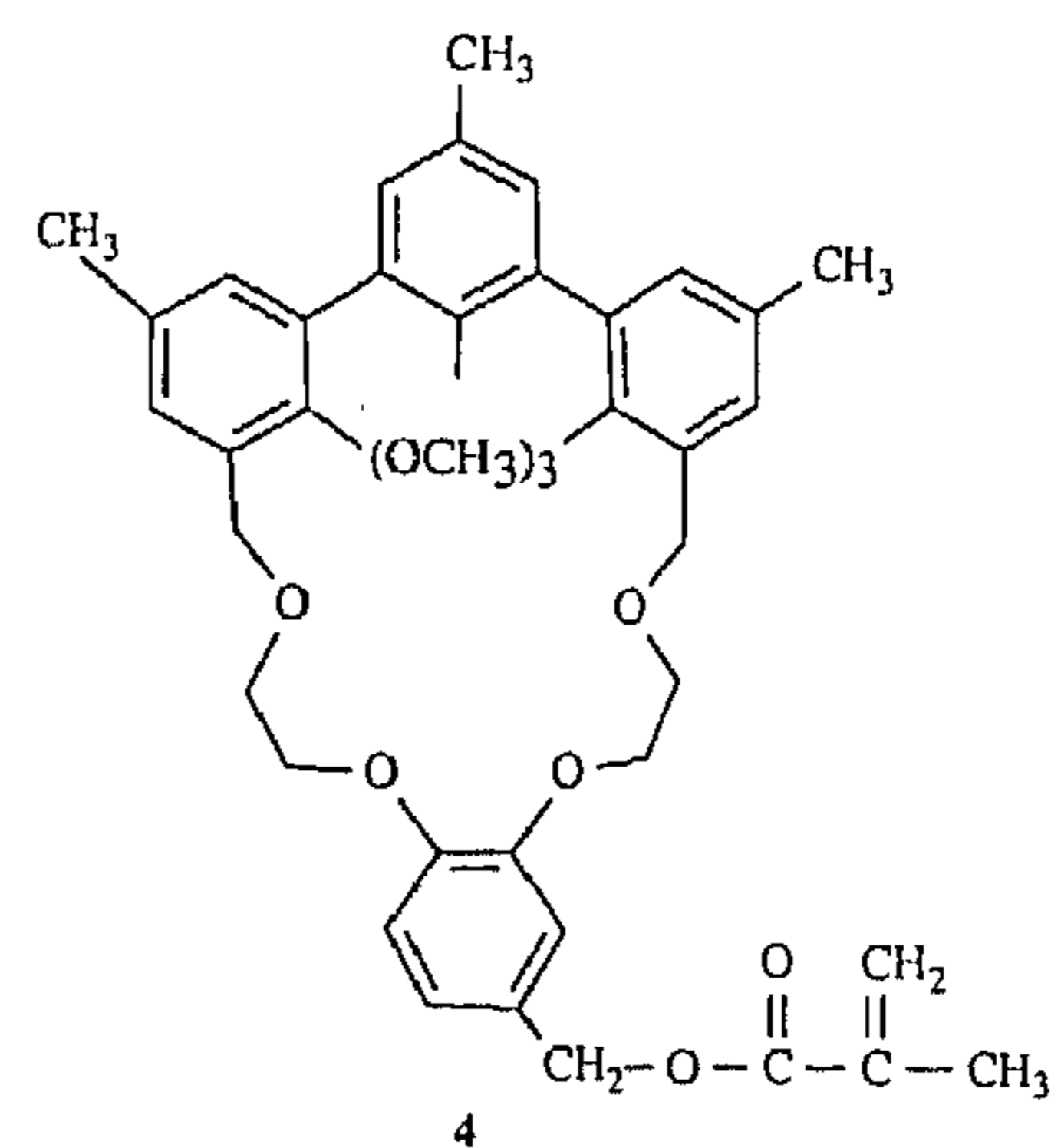
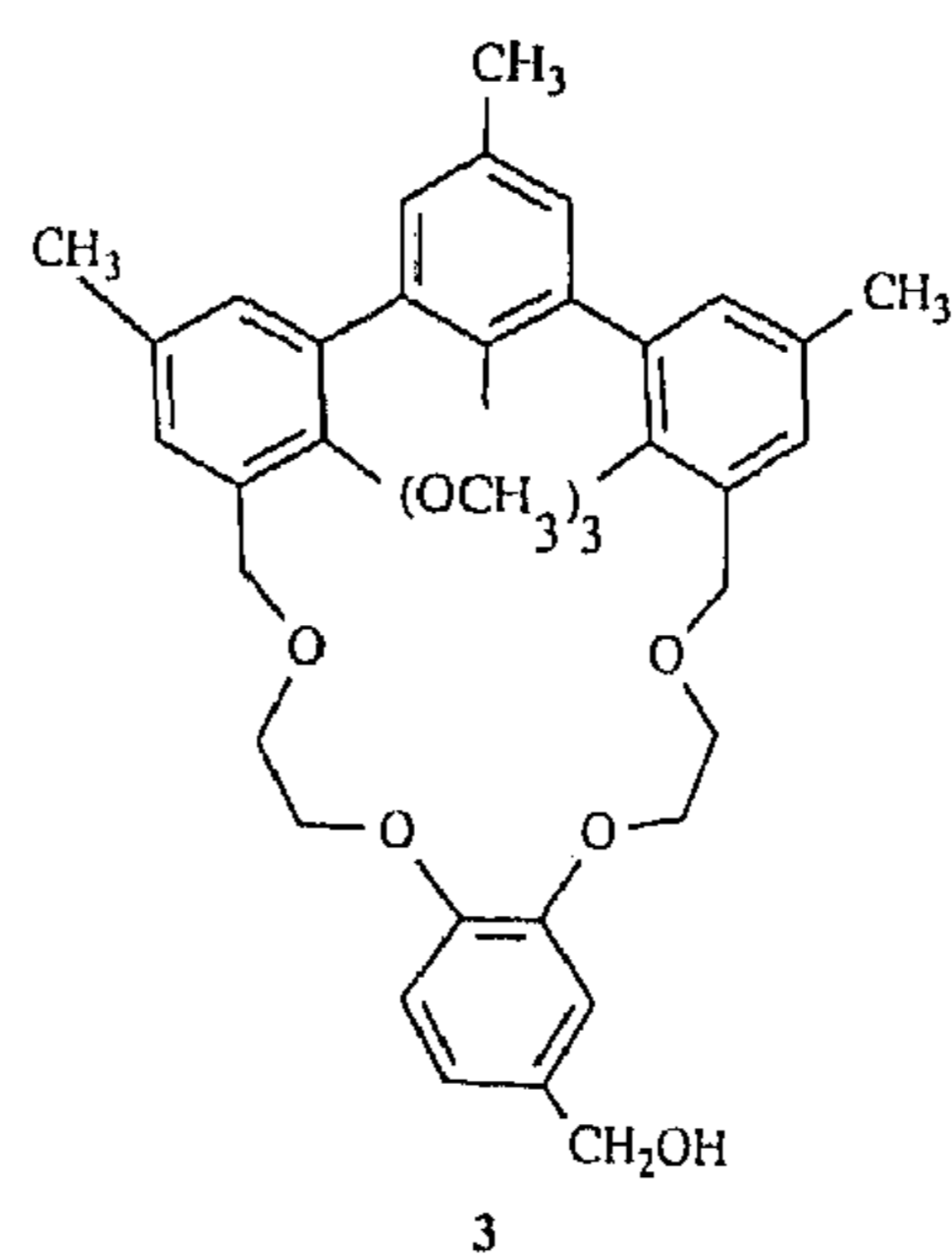
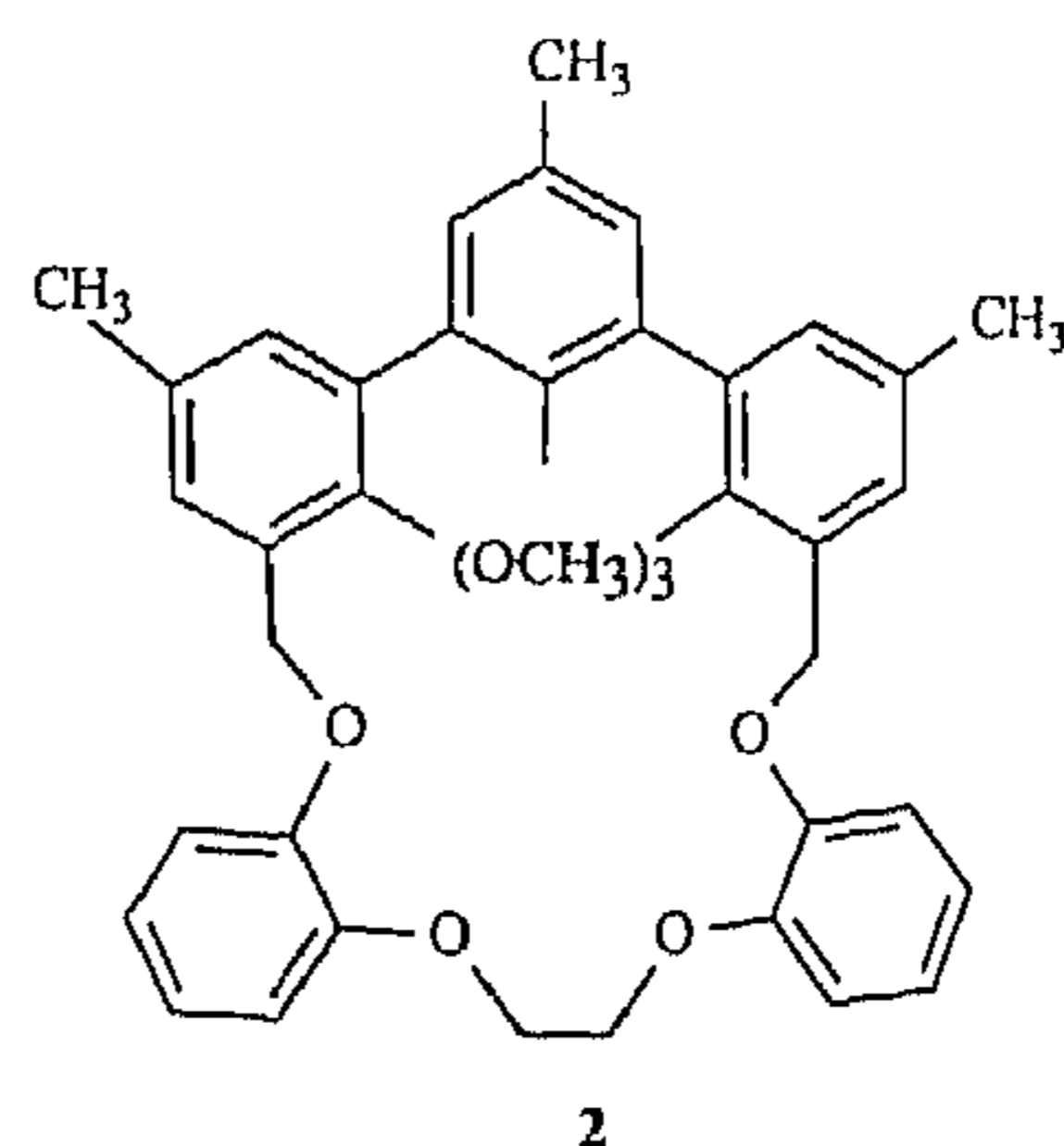
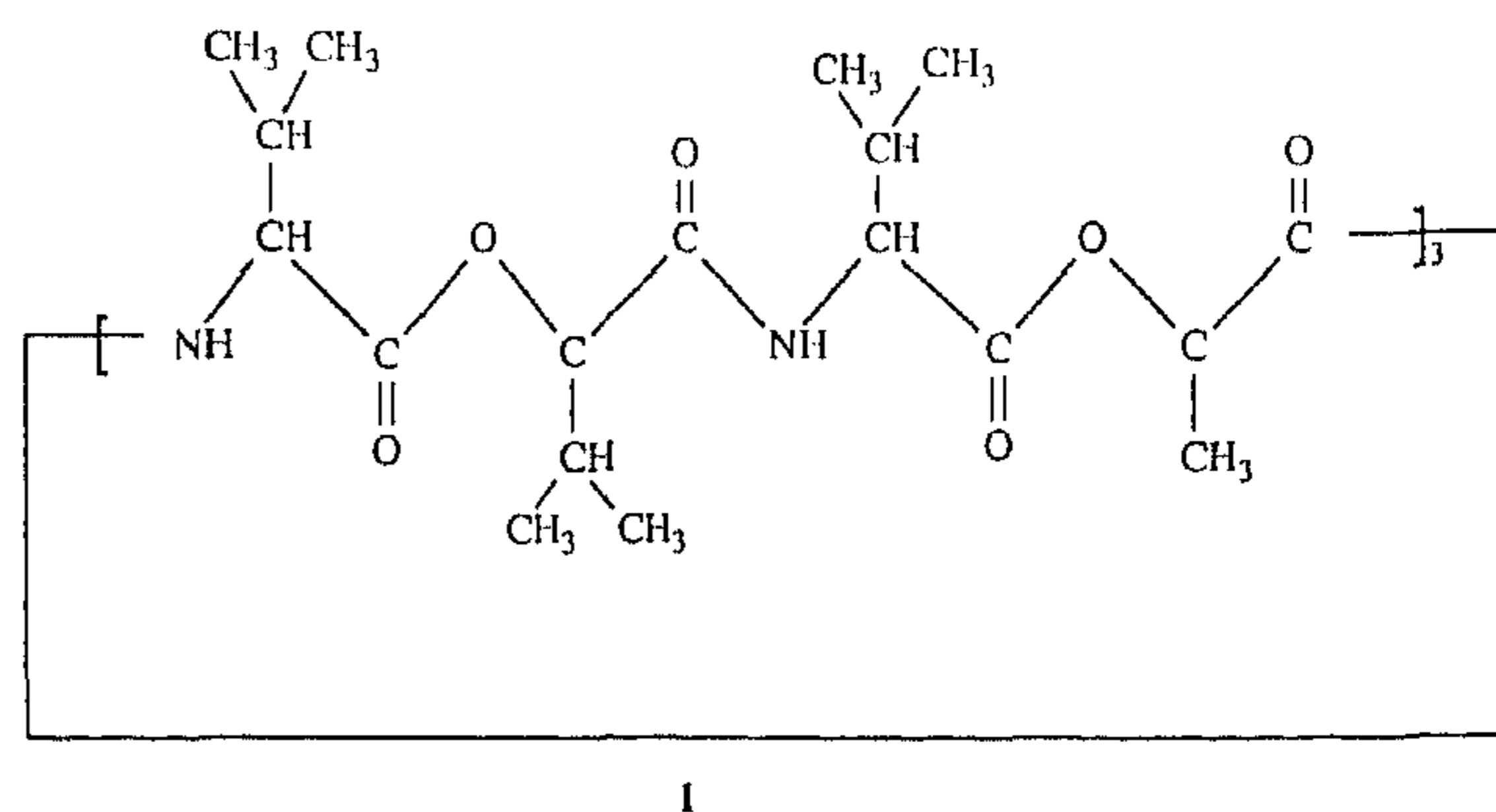


Fig. 8. Chemical structures of potassium selective ionophores.

of the sensor based on the Dow Corning material is about two weeks and can be increased to at least four weeks by the incorporation of a lipophilic salt, but the best results are obtained with Silopren. In the presence of valinomycin (**1**) or hemispherand ionophores **2** and **3** (see Fig. 8), excellent potassium–sodium selectivity is observed. Both materials show a good adhesion to the SiO₂ gate oxide, probably originating from bond formation between the surface SiOH groups and the terminating OH groups of the polysiloxanes. This results in a good durability of the sensor. For a Silopren-modified ISFET, continuous immersion of the device in an analyte solution for eight weeks showed only a minor decrease in the sensitivity to 54 mV/pK. The limited lifetime of the Dow Corning-based CHEMFET is probably due to the leaching out of the anionic sites. Since this does not occur with Silopren material it is concluded that this membrane must contain intrinsically anionic groups.

The success of these commercial polysiloxanes as elastomeric materials in the preparation of potassium-selective ISFETs stimulated the design and synthesis of new polysiloxanes which can be cross-linked upon radiation by u.v. light. Such materials are a prerequisite for the production of CHEMFETs on a wafer scale using IC compatible technology. Therefore, random terpolymers have been synthesized by emulsion polymerization of octamethylcyclotetrasiloxane (D4), a mixture of the cyclic trimer and tetramer of (3-cyanopropyl)methyl siloxane (D'3 and D'4), and methacryloxypropylmethyl dichlorosilane (MS) (Fig. 9). The relative amounts of the three different components can be varied to tune the properties of the polymer. The dimethyl siloxane building block is used to obtain a sufficiently low glass transition temperature. The function of the cyano-containing grafts is to modify the dielectric constant. The methacrylate functionality is incorporated to cross-link the polysiloxane to form the hydrophobic membrane. Furthermore, this reactive group can be used to anchor an adequately modified receptor molecule covalently in the membrane matrix. The composition of a membrane that detects monovalent cations selectively has the following molar ratio: D4:(D'3 + D'4):MS = 10:1:2, with a molecular mass exceeding 20 000 D [24]. Polymers for the detection of divalent cations should have a higher dielectric constant

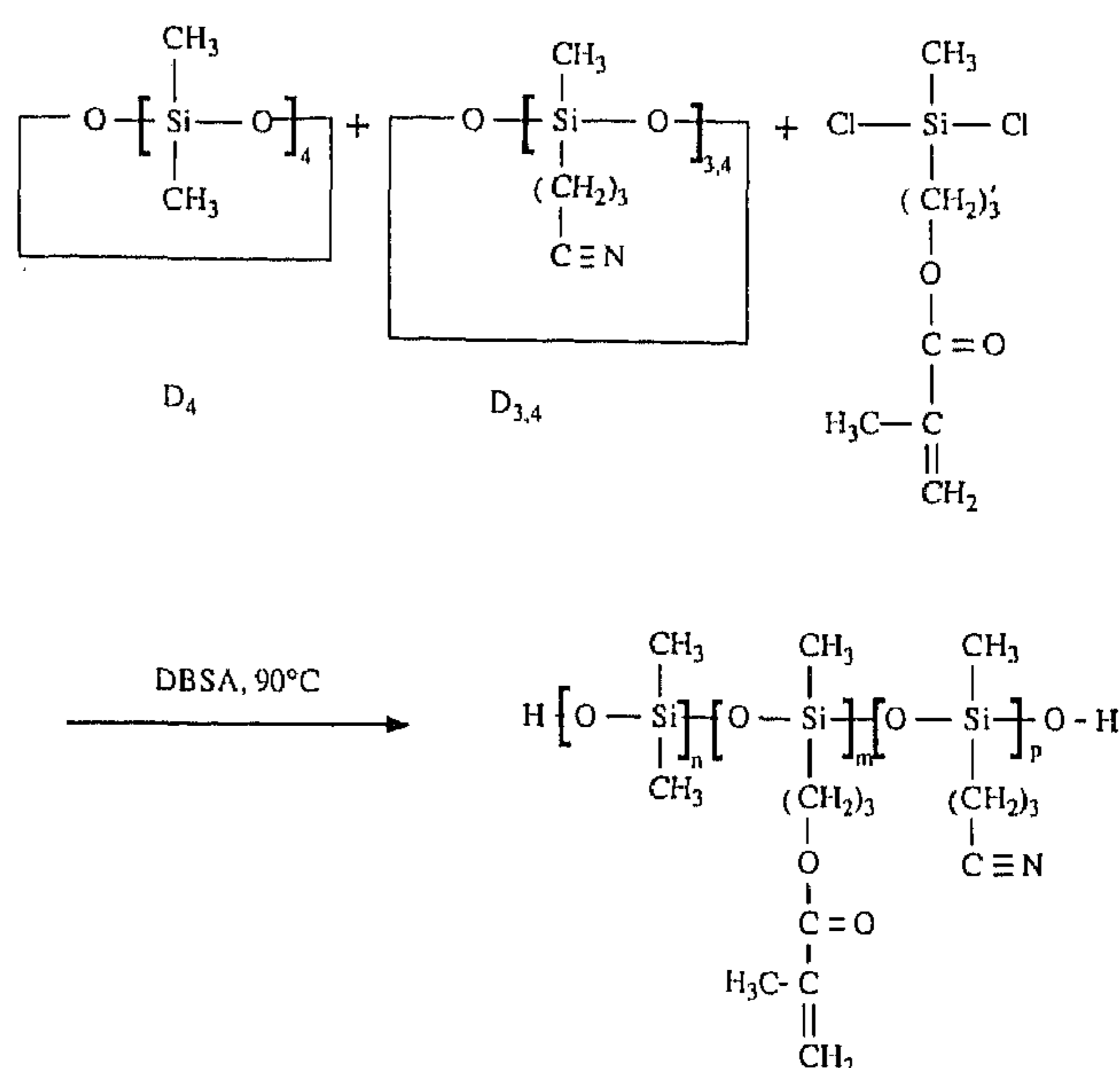


Fig. 9. Reaction scheme for the synthesis of photopolymerizable polysiloxanes.

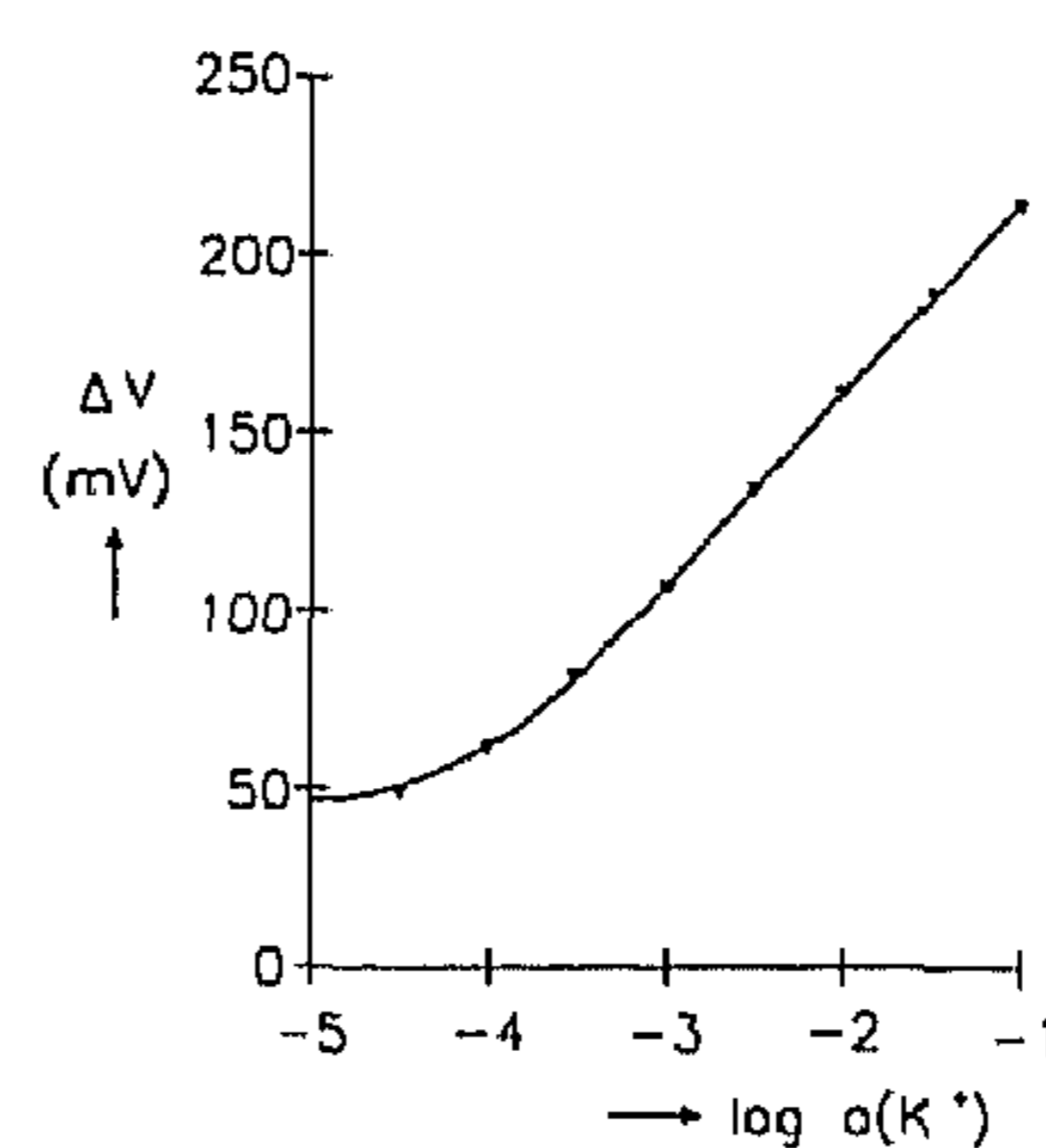


Fig. 10. Typical response curve for a polysiloxane-based CHEMFET.

[25]. This can be achieved by increasing the cyano content of the polymer. The various materials can be easily cross-linked upon irradiation using 4 mol% of 2,2-dimethoxy-2-phenylacetophenone as a photoinitiator.

The photopolymerizable polysiloxane was used for the construction of a CHEMFET in which the receptor molecule is covalently anchored via a methacryl moiety. The response to a change in the potassium concentration in the presence of 0.1 M NaCl is given in Fig. 10. The potentiometric selectivity coefficient ($\log K_{ij}^{pot}$), as determined by the fixed interference method, (0.1 M) is excellent. The long-term stability of this CHEMFET is unprecedented and exceeds 200 days [26].

4. Conclusions and outlook

Using the architecture of the CHEMFET, a stable, potentiometric sensor based on the ISFET as the transducing element can be obtained which selectively detects cations. The basic problem of ill-defined thermodynamic interfaces is eliminated by the introduction of a buffered hydrogel layer between the gate oxide and the sensing membrane. This option also suppresses the CO₂ interference. This intermediate layer is covalently anchored to the gate oxide. For the sensing membrane functionalized polysiloxanes are promising materials. Membranes made from these polymers show good sensing properties. There is no longer any need for an external plasticizer and the receptor molecule can be covalently attached to the membrane matrix. In principle, the same concept can be used for the anionic sites present in the membrane. The lifetime of the obtained sensor is long enough to be practically applicable.

With the described technology in hand we will focus our research on the extension of the ions which can be detected. This pertains both to the detection of cations and anions. To this end, receptor molecules which selectively bind the desired ion will be incorporated into the membrane matrix. The optimum composition, both with regard to the electroactive components and to the membrane matrix itself, will be investigated.

Acknowledgements

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