Modification of Microelectrode Arrays: New Microelectrochemical Devices for Sensor Applications [and Discussion]

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Modification of microelectrode arrays: new microelectrochemical devices for sensor applications

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Microelectrode arrays consisting of two or eight closely spaced (*ca.* 1 μm) gold or platinum microelectrodes (approximate dimensions 2 μm wide × 50 μm long × 0.1 μm high) can be modified with a variety of redox-active materials in a way that leads to microelectrochemical devices that may be useful as sensors. In general, a pair of microelectrodes connected by a redox-active material represents a device, because the current, I_d, passing from one microelectrode (source) to the other (drain) at a fixed potential between them, V_d, can be modulated by electrically or chemically induced changes in the state of charge of the redox material. The fundamental issues associated with pH-sensitive devices based on poly(3-methylthiophene), poly(4-vinylpyridine), a viologen–quinone redox polymer and WO_3 are described to illustrate generic concepts that underlie the development of microelectrochemical sensors.

Introduction

This paper describes several molecule-based microelectrochemical devices that respond to pH. The details of microelectrochemical devices based on platinized poly(3-methylthiophene) (Thackeray 1986; Thackeray & Wrighton 1986), poly(4-vinylpyridine) (Bélanger & Wrighton 1987), the polymer derived from scheme I, $[(BV\text{-}Q\text{-}BV)^{6+}]_n$ (Smith *et al.* 1986, 1987), and WO_3 (Natan 1986; Natan *et al.* 1987*b*) in connection with response to variation in pH, have been elaborated elsewhere. An interesting overview of new kinds of electronic devices based on macromolecular materials has also appeared (Chidsey & Murray 1986). The aim of this article is to provide a summary of some approaches to the development of small, sensitive and specific sensors of biological and chemical substances that stem from modification of microelectrode arrays. Results from the four systems mentioned above will be used to illustrate concepts of generic significance to the development of new kinds of sensor.

Research on molecule-based microelectrochemical 'devices' in the research group headed by M.S.W. has been inspired by developments in chemistry, biology and microfabrication technology (Wrighton 1985). The ability to carry out solid-state microfabrication with sizes of the order of a few micrometres makes it possible to exploit synthetic and naturally occurring molecular materials to achieve device-like 'functions' that depend on the properties of the molecular material(s) that make up the device. Recent research has demonstrated that molecule-based transistors (Kittlesen *et al.* 1984; White *et al.* 1984; Paul *et al.* 1985; Thackeray *et al.* 1985) and diodes (Kittlesen *et al.* 1985; Kittlesen & Wrighton 1986) can be fabricated with crucial dimensions of significantly less than 1 μm. Although a polyaniline-based transistor

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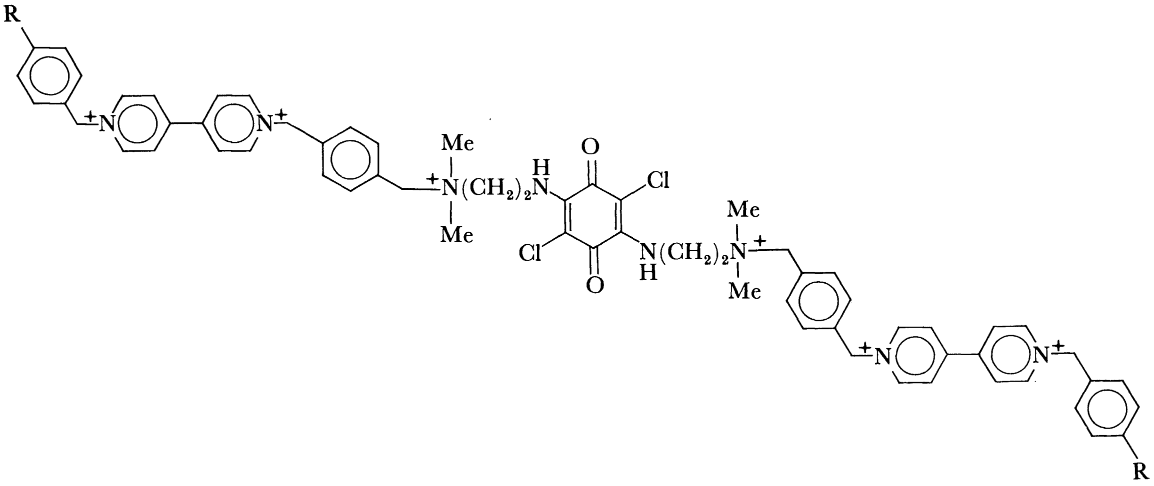


Scheme 1. Compound A (R = $-Si(OMe)_3$).

has been shown to amplify power up to a frequency of 1 kHz (Lofton *et al.* 1986) the applications of molecule-based transistors in the near future are not likely to be in conventional electronic systems, where solid-state semiconductor devices are presently used. Rather, molecule-based devices are likely to find use in those situations where the properties of the molecular material are crucial to the desired function. Applications for molecule-based devices as sensors are, therefore, a realistic practical opportunity.

MICROELECTRODE ARRAYS

Conventional microfabrication techniques used in the manufacture of microelectronic devices (Elliott 1982) can be used to prepare microelectrode arrays. Figure 1 shows a cross-sectional view of a typical array fabricated and used by the Wrighton group, and figure 2 shows a typical 'chip', consisting of an eight-electrode array and contact pads. The array consists of eight closely spaced electrodes, each of which can be individually addressed and can be regarded as a 'microelectrode', because the width of each electrode is only about 2 μm. There has been much recent interest in microelectrodes (Howell & Wightman 1984). Our focus has been on the exploitation of electrode modification techniques leading to the connection of two or more closely spaced microelectrodes to achieve microelectrochemical devices that have

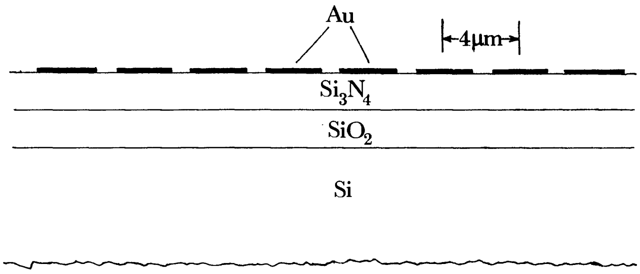


Figure 1. Cross-sectional view of a typical eight-electrode microelectrode array used in the demonstration of microelectrochemical devices described in the text. (See also figure 2).

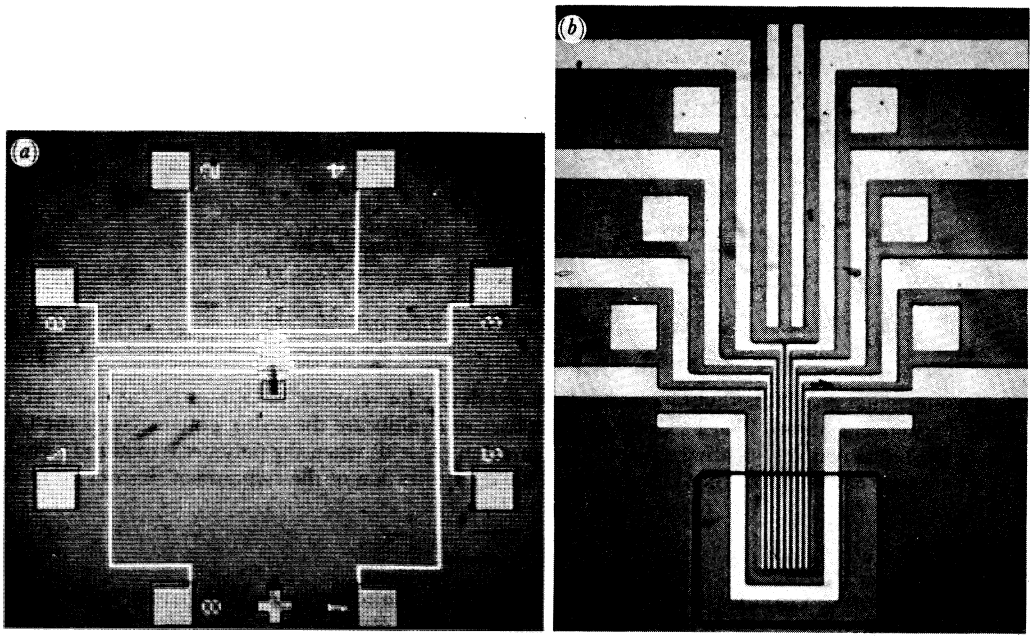


Figure 2. Typical 'chip' consisting of an array of eight gold microelectrodes. (*a*) The entire chip, *ca.* 3 mm × 3 mm. The large, numbered squares are the contact pads. (*b*) An enlargement of the microelectrode array; the active area is *ca.* 50 μm × 50 μm.

functions analogous to solid state diodes or transistors. Details concerning microfabrication of microelectrode arrays have been published elsewhere (Kittlesen 1985; Kittlesen *et al.* 1985). The small size of the individual electrodes is important, but the close spacing between them is crucial to making microelectrochemical devices, because the magnitude of the current that passes between two microelectrodes connected with electroactive material is inversely proportional to their separation. All of the devices to be described in the following sections involve the use of electroactive materials with modest maximum conductivity to connect two microelectrodes. Accordingly, smaller electrode spacings would be desirable to increase the signal derived from the device and to improve the response time. These issues will be of greatest concern for devices based on conventional redox materials, as opposed to so-called conducting polymers, as described below. Technology exists to fabricate microelectrode arrays with electrodes spaced closer than the *ca.* 1 μm employed so far.

Catalysis: a key to specificity, speed and sensitivity

Figure 3 illustrates a two-terminal poly(3-methylthiophene)-based device that has recently been described (Thackeray 1986; Thackeray & Wrighton 1986). The device is responsive to variation in $[O_2]$,$[H_2]$ and pH. There are several important features that lead to the response. First, poly(3-methylthiophene) (Tourillon & Garnier 1982) undergoes a dramatic change in conductivity when it is cycled between its reduced (insulating) and oxidized (conducting) form (Thackeray *et al.* 1985). Second, a Pt catalyst will equilibrate the poly(3-methylthiophene) with H_2O–H_2 and O_2–H_2O redox couples and is effective at a loading sufficiently low for the poly(3-methylthiophene) still to undergo a dramatic change in conductivity on oxidation or

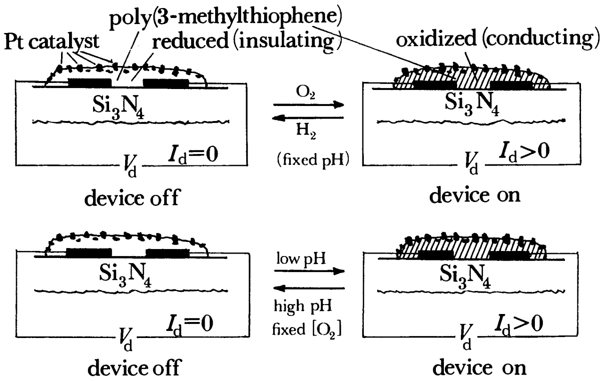


FIGURE 3. Two-terminal poly(3-methylthiophene)–Pt-based device for response to O_2 and H_2 (at fixed pH) or pH (at fixed O_2 concentration). The Pt serves as a catalyst to equilibrate the redox polymer with the O_2–H_2O and H_2O–H_2 redox couples, yielding a device that turns on ($I_d > 0$) when the polymer is oxidized (Thackeray 1986; Thackeray & Wrighton 1986). See figure 5 for an illustration of the response of this device to O_2 and H_2.

reduction (Tourillon & Garnier 1984; Thackeray 1986; Thackeray & Wrighton 1986). Finally, the changes in conductivity of the poly(3-methylthiophene) are sharpest in a range of electrochemical potentials accessible by variation in the O_2 or H_2 concentration (at fixed pH) or by variation in pH (at fixed O_2 concentration).

Properties of the poly(3-methylthiophene)-based device of importance in the sensor function can be established by measurements of the electrical characteristics of the microelectrochemical transistor illustrated in figure 4 (Thackeray *et al.* 1985). The range of electrochemical potentials where variation in drain current, I_d, can be achieved is established by measuring I_d (at fixed drain potential, V_d) as a function of the gate potential, V_g. The I_d–V_g characteristic stems from intrinsic properties of the molecular material. The shape of the curve, the region of significant I_d, and the maximum and minimum values of I_d all depend on the molecular material. Thus, in principle, the I_d–V_g characteristic can be manipulated by purposeful alteration of the molecular material. The electrical characteristics of the poly(3-methylthiophene) are such that the device begins to turn on at $V_g \approx +0.4$ V and is completely on at $V_g \approx +0.9$ V (measured against a saturated calomel electrode). The resistance between the 'source' and 'drain' (figure 4) can be altered from greater than $10^{10}\,\Omega$ to *ca.* $10^2\,\Omega$ in CH_3CN–0.1 M [*n*-Bu_4N]ClO_4

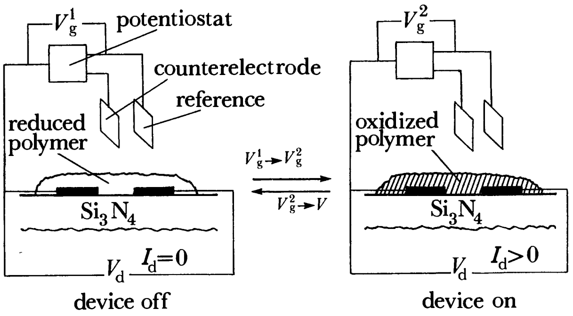
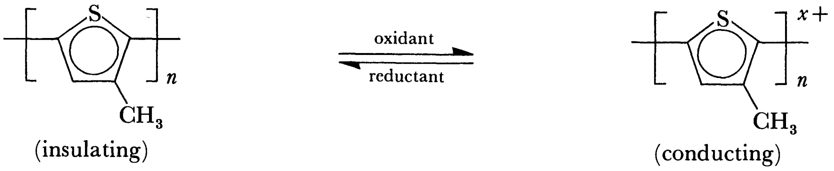


FIGURE 4. A microelectrochemical transistor based on poly(3-methylthiophene). Variation in V_g from V_g^1 to V_g^2 causes the polymer to be switched from its reduced and insulating state to its oxidized and conducting state (Thackeray *et al.* 1985).

for a source–drain separation of *ca.* 1 μm and a polymer coverage of *ca.* 10^{-7} mol cm^{-2}. The exposed area of such a device is about 10^{-6} cm^2. In H_2O–electrolyte, electrical characteristics similar to those in CH_3CN–electrolyte are found. The devices are typically durable in a pH range from 0 to 12 and a V_g range from -0.1 to $+0.8$ V and show similar electrical characteristics in all media. The poly(3-methylthiophene)-based transistor can be rapidly switched on and off by cycling V_g between a potential where the polymer is reduced (and insulating) and one where the polymer is oxidized (and conducting); the time required to turn on to over 90 % of the steady-state I_d value is less than 50 ms, and the time required to turn off the device to less than 10 % of the maximum steady-state I_d value is less than 50 ms. The electrical characteristics of the device in figure 4 suggest that a good redox sensor can be achieved; there is a large change in I_d in a useful potential range, the response is rapid, and the active material is durable over a wide range of conditions.

A poly(3-methylthiophene)-based redox sensor can be based on the dramatic change in conductivity of the polymer that can be brought about chemically. Any chemical system, comprising a signal that equilibrates with the redox polymer can, in principle, be 'detected' by virtue of the change in I_d (at fixed V_d) in a two-terminal configuration, as illustrated in figure 3. However, *large* changes in I_d will occur only when the chemical signal is in the redox potential régime established (by electrical characterization) to give large I_d variation. For poly(3-methylthiophene)-based devices, the I_d–V_g characteristic shows dramatic change between $+0.4$ and $+0.9$ V. Because the electrical characteristics of the poly(3-methylthiophene)-based device are essentially independent of the medium in which it operates, any chemical oxidant capable of oxidizing the reduced poly(3-methylthiophene) will be detected as an increase in I_d (turn on), and any reductant capable of reducing oxidized poly(3-methylthiophene) will be detected as a decrease in I_d (turn off), as shown in scheme 2. Thus the I_d–V_g characteristic, which stems from the redox properties of the molecular material, is the basis for an important degree of specificity. For example, the strong oxidant $[Fe(\eta^5\text{-}C_5H_5)_2]^+$ ($E^{\ominus\prime} = 0.307$ V) (Bard & Faulkner 1980) would turn on a two-terminal poly(3-methylthiophene) device, but the weak oxidant $[Co(\eta^5\text{-}C_5H_5)_2]^+$ ($E^{\ominus\prime} = -0.90$ V) (Sheats 1979) would not, because of the ability of the former, but not the latter, to serve as an oxidant for the chemistry represented by scheme 2.



Scheme 2

Although the I_d–V_g characteristic of the device in figure 4 does provide an important and useful degree of specificity, two oxidants of the same ozidizing power will, in principle, both be detected. However, differences in the kinetics of the redox processes represented by scheme 2 for two different oxidants can provide a basis for specificity. For example, the oxidant $IrCl_6^{2-}$ in H_2O will turn on the two-terminal poly(3-methylthiophene)-based device, but O_2 will not (Thackeray 1986; Thackeray *et al.* 1985). Similarly, $Fe(CN)_6^{4-}$ will turn off the device, but H_2

will not. The point is that O_2 is *thermodynamically* capable of serving as an oxidant, and H_2 as a reductant, for the redox processes represented in scheme 2, but the kinetics are poor. The kinetics for the O_2 oxidation and H_2 reduction can be improved dramatically by using a catalyst: Pt electrochemically deposited onto the polymer (figure 3) will equilibrate the polymer with the O_2–H_2O and the H_2O–H_2 redox couples to yield a device that can be turned on with O_2 and off with H_2 (figure 5). Further, because $E^{\ominus\prime}$ (O_2–H_2O) depends on pH, the device can be turned off and on by variation in pH at fixed O_2 concentration. The Pt catalyst functions to improve the rate of equilibration with O_2–H_2O and H_2O–H_2, but does not alter the essential I_d–V_g (electrical) characteristic of the device. The catalyst provides a mechanism to improve the specificity of the sensor system by rapidly equilibrating the active device material with the chemical signal of interest. A simple example would be to distinguish between O_2 and $IrCl_6^{2-}$ by having two poly(3-methylthiophene)-based devices on a chip with one device made responsive to O_2 by selective deposition of a Pt catalyst. Exposure of the two devices to $IrCl_6^{2-}$ would turn on both devices, whereas O_2 would only turn on the device with Pt. The deposition of Pt onto poly(3-methylthiophene) establishes that catalysis can be useful in bringing about a response at a microelectrochemical device that is unresponsive without the catalyst. Owing to the catalytic activity of Pt, the poly(3-methylthiophene)–Pt 'composite' material system in H_2O has a conductivity that is reproducibly dependent on the O_2 concentration at fixed pH or on the pH at fixed O_2 concentration.

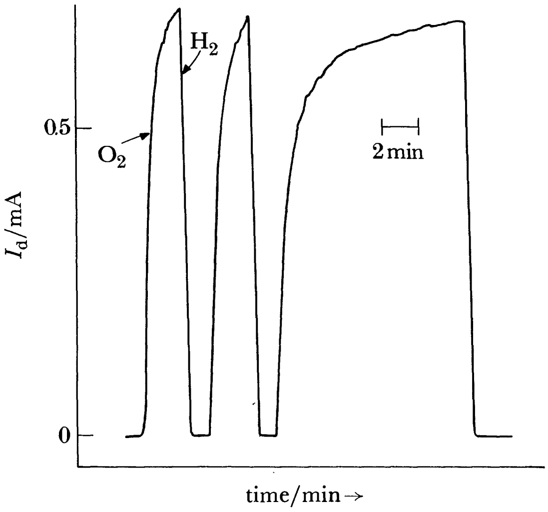


FIGURE 5. Drain-current (I_d) response of the device illustrated in figure 3 to O_2 and H_2 at 298 K with alternate cycling of 1 atm (10^5 Pa)O_2 and H_2 in 0.1 M $HClO_4$–H_2O; V_d = 0.200 V. In the absence of the Pt catalyst the device is unresponsive to O_2 or H_2 (Thackeray & Wrighton 1986).

A two-terminal device that can be turned on by a chemical, as in the turn-on of the poly(3-methylthiophene)–Pt device by O_2 illustrated in figure 5, can be regarded as an amplifier of the chemical signal, in one sense. The amount of charge transferred in effecting the turn-on can be much less than the amount of charge passed between the two microelectrodes. The notion of amplification in this sense can be appreciated by considering the two-terminal device to be in a flowing stream of solvent–electrolyte with an electrochemical potential where the device is off ($I_d = 0$) but into which are introduced repetitive injections of a redox reagent such that the device can be turned on ($I_d > 0$). The amplification of the repetitive signal can then be measured by determining the charge passed in the drain circuit against the charge passed in effecting turn-on of the device. In this sense, amplification of $IrCl_6^{2-}$ injected into a flowing stream has been demonstrated using a poly(3-methylthiophene)-based device. The charge passed in the drain circuit was more than 10^4 times the charge needed to turn on the device (Thackeray 1986; Thackeray *et al.* 1985). The amplification factor depends on many factors, including the signal frequency (controlled by flow rate of the flowing stream), the kinetics for turn-on and turn-off, and the nature of the redox material that makes up the device.

Catalysis of the sort illustrated with Pt can be extended to systems that involve the use of immobilized enzymes as the catalyst. The use of enzymes could bring about response to specific biological redox agents (Carr & Bowers 1980). Catalysis can obviously be useful, too, in improving the speed (response time) of a sensor device, by improving the rate of redox reaction of the active device surface with the chemical to be detected. The fastest response possible, of course, depends on the diffusion of the chemical to be detected. The electrically driven turn on–turn off (on the timescale of 50 ms) establishes that the poly(3-methylthiophene)-based device can be fast, but slow response to chemical signals may be found, because of poor kinetics. There is one other significant point to be made concerning catalysis: a catalyst can provide a way to bring about amplification of a chemical signal. The amplification provided by an enzyme can enhance the sensitivity beyond that associated with the amplification by the two-terminal device described above. For example, an enzyme that can be activated by a chemical signal can serve as an amplifier of that signal in the sense that, once activated, the enzyme can catalytically produce a species that can be detected. There are several possible ways to exploit enzyme catalysts with a view to improving speed, sensitivity, and specificity of microelectrochemical devices

WO_3-CONNECTED MICROELECTRODES: USE OF AN ELECTROACTIVE INORGANIC MATERIAL WITH AN INTRINSIC pH-DEPENDENCE

Catalysis of the equilibration of the O_2–H_2O and H_2O–H_2 redox couples with redox polymers is clearly a way to prepare a composite material system that has an O_2- or H_2-dependent conductivity (at fixed pH) or pH-dependent conductivity at fixed O_2 or H_2 concentration. However, there are redox-active materials that have an intrinsic pH dependence; such materials include electroactive metal oxides. WO_3 is known to be such a redox-active material and has been widely studied in connection with electrochromic display devices (Dautremont-Smith 1982). Figure 6 illustrates a WO_3-based microelectrochemical device that shows a pH-dependent I_d–V_g characteristic. Unlike the poly(3-methylthiophene)-based device, which has the same I_d–V_g characteristic over a wide pH range, the WO_3-based device shows a pH-dependence such that the device turns on at more negative values of V_g at higher pH (figure 7). Thus the WO_3-based device shows a variation in I_d on variation in pH at a fixed V_g (Natan 1986; Natan *et al.* 1987*b*).

At fixed pH, the WO_3-based device of figure 6 is like the poly(3-methylthiophene)-based device of figure 4, except that a negative potential excursion turns on the WO_3-based device. Thus, in a two-terminal mode at fixed pH, the WO_3-based device can be turned on by reducing agents and off by oxidizing agents. From the I_d–V_g characteristic at pH ≈ 7 the WO_3-based device begins to turn on at $V_g \approx 0.0$ V and turns on to the maximum extent by $V_g \approx -1.2$ V.

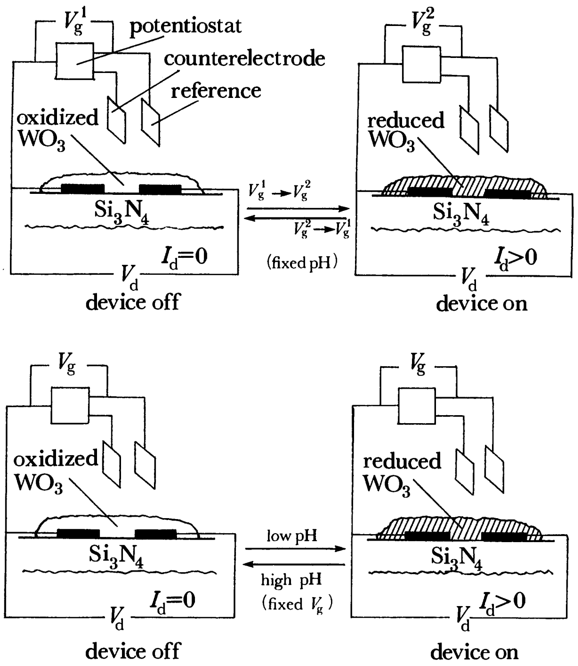
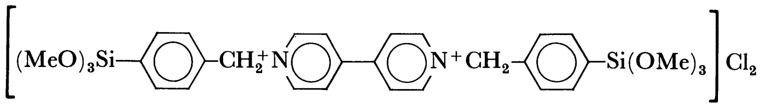


FIGURE 6. A WO_3-based transistor that turns on ($I_d > 0$) when V_g is moved from $V_g{}^1$, where WO_3 is oxidized and insulating, to $V_g{}^2$ where WO_3 is reduced and conducting. The WO_3-based device can also be turned on and off by varying the pH at fixed V_g. (See figure 7.) (Natan 1986; Natan *et al.* 1987*b*.)

A variety of biological reducing agents can therefore turn on the WO_3-based device. Interestingly, at pH ≈ 7 the I_d–V_g curve shows its sharpest change in the vicinity of -0.6 V, close to the formal potential of the cofactor NAD^+–NADH (Burton & Wilson 1953; Rodkey 1955). This potential is also close to that of the well-known viologen mediator system (Kuwana & Heineman 1976; Heineman 1978) for equilibrating electrode surfaces with various redox enzymes. The WO_3 has the additional intrinsic virtue that it is an oxide. As well as being extremely rugged, oxides are known to be easily modified with redox molecules having $-Si(OR)_3$ functionality (Murray 1984) as for the viologen derivative B, shown in scheme 3. (Dominey *et al.* 1983). Modification of WO_3-based transistors with this chemical may yield rapid equilibration of WO_3 with a variety of enzymes of significance in connection with biological sensors.



SCHEME 3. Compound B.

The WO_3-based transistor (figures 6 and 7) exemplifies the behaviour of a microelectrochemical device based on a material with an intrinsic pH-dependence. There are many other oxides that are electroactive and pH-dependent, such as iridium oxide (Katsube *et al.* 1982) or nickel oxide (Barnard *et al.* 1981). These active materials, like WO_3, are rugged and may comprise the basis for pH sensors that function over a wide pH range. Each material is expected to give a device with a unique I_d–V_g characteristic, since the electrochemical behaviour of each

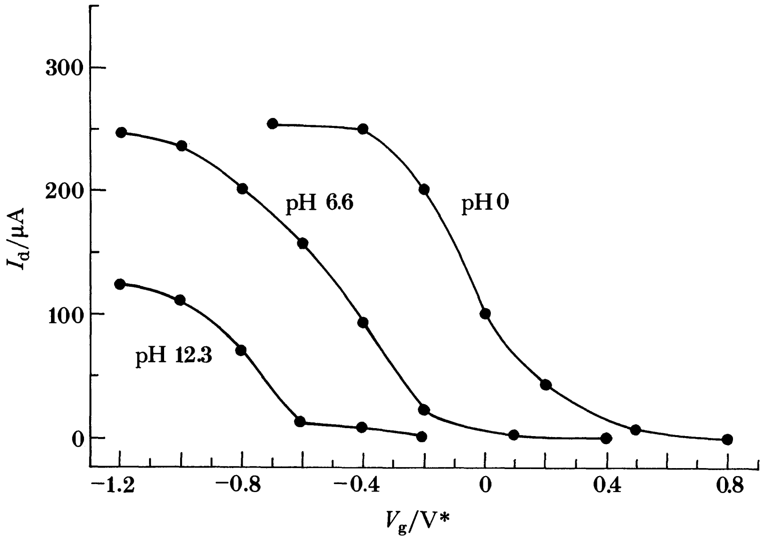


FIGURE 7. Electrical characteristics of a WO_3-based transistor (figure 6), as a function of pH at 298 K and fixed V_d (100 mV) (Natan *et al.* 1987*b*). (* Voltages measured against a saturated calomel electrode.)

differs. For example, nickel-oxide-based transistors are pH-responsive, like those based on WO_3 but turn on at positive, not negative, potentials (Natan *et al.* 1987*a*). Metal-oxide-based devices are analogous to the chemically sensitive field-effect transistors (ChemFETs) that respond to pH (Janata & Huber 1985). Whether devices based on the electroactive oxides are superior in practical terms is not clear, but it is clear that the electroactive oxides do provide an entry to a wide variety of new microelectrochemical devices.

QUINONE–VIOLOGEN CONNECTED MICROELECTRODES: USE OF AN ELECTROACTIVE MOLECULAR MATERIAL WITH AN INTRINSIC pH-DEPENDENCE

WO_3 is an example of an electroactive inorganic material with an intrinsic pH-dependence that can be exploited in microelectrochemical devices. Molecular materials can also be found, with an intrinsic pH-dependence, which can be exploited in microelectrochemical devices. Polyaniline-based transistors show a pH-dependent characteristic (Paul *et al.* 1985), but there is only a relatively narrow pH range over which polyaniline is durable. In principle, any molecule with a pH-dependent redox potential can be the basis for a polymeric material with a pH-dependence. For example, quinones (Q) undergo reversible 2e–2H⁺ reduction to the dihydroxy form, QH_2:

$$Q + 2e^- + 2H^+ \rightleftharpoons QH_2. \qquad (1)$$

For pH values below the pK_a of QH_2, the formal potential, $E^{\ominus\prime}$, of the Q–QH_2 redox couple is expected to vary by 59 mV per pH unit. If a polymer of Q (or any other molecule with a pH-dependent $E^{\ominus\prime}$) were used in a microelectrochemical transistor, the significance of the pH-dependence would be that the polymer-based transistor would have a pH-dependent I_d–V_g curve.

Polymers based on conventional redox reagents differ in some important practical ways from the so-called conducting polymers like poly(3-methylthiophene), polyaniline, and polypyrrole.

The differences stem from the fact that the conventional redox polymers, such as polyvinylferrocene (Merz & Bard 1978) or the viologen polymer from hydrolysis of B (scheme 3) (Dominey *et al.* 1983) can be regarded as merely an assembly of highly concentrated (*ca.* 2–3 M) redox centres that do not interact strongly. In the conventional redox polymers, the charge carriers are well localized. Reduction of the viologen polymer from compound B results in formation of localized viologen radicals, and likewise oxidation of polyvinylferrocene results in formation of localized ferrocenium (radical) centres. The conducting polymers differ in the sense that oxidation of poly(3-methylthiophene), for example, gives rise to a material where the radical is delocalized over several monomer units. Whereas the conductivity of the conducting polymers is limited by chain-to-chain charge transfer, every charge-transfer process in the conventional polymer is a kind of self-exchange redox event between an oxidized unit and a reduced unit of the polymer. A major practical consequence of the conjugation of monomer units in the conducting polymer, compared with the lack of electronic interaction in the conventional redox polymer, is a large difference in the maximum conductivity. The conducting polymers can have conductivity more than five orders of magnitude higher than the conventional redox polymers.

Conventional redox polymers are only 'conductors' by virtue of the high concentration of redox subunits in the polymer and reasonably large rate constants for the self-exchange electron transfer process, k_{se}. The 'conductivity' of conventional redox polymers is related to the value of k_{se} and the concentrations of oxidized, [ox], and reduced, [red], sites by the following equation:

$$\text{`Conductivity'} \propto k_{se}[\text{ox}][\text{red}]. \tag{2}$$

A conventional redox polymer shows maximum conductivity when [ox] = [red]; this condition occurs whenever the polymer is at its formal potential, $E^{\ominus\prime}$. In a transistor based on a conventional redox polymer, the I_d–V_g (at fixed V_d) plot will thus show a maximum at $V_g = E^{\ominus\prime}$. Moreover, the above equation also predicts that I_d will only be significant over a narrow range of V_g (for small V_d) because the [ox]:[red] ratio depends sharply on potential. The sharp I_d peak at $V_g = E^{\ominus\prime}$ for a transistor based on conventional redox polymers is an electrical characteristic that is very different from that for solid-state transistors, which show a region of V_g, where $I_d = 0$ (off) and a region of V_g where $I_d > 0$. In principle, all redox polymers could show a peak in the I_d–V_g plot, but the so-called conducting polymers show a large region of V_g, where $I_d > 0$. In fact, the poly(3-methylthiophene)-based devices behave in a manner similar to solid-state devices. The polyaniline-based devices show a broad peak in the I_d–V_g plot, but in general the conventional redox polymers will give rise to devices with the smallest 'on' regions. To exploit the narrow region of conductivity of the conventional redox polymers, small values of V_d must be used; values of V_d of less than 100 mV are typically appropriate, because there is a significant amount of both oxidized and reduced centres for $V_g = E^{\ominus\prime} \pm 100$ mV.

The fact that conventional redox polymers can be used to produce transistors where I_d maximizes at $V_g = E^{\ominus\prime}$ means that specific sensors can be made. A two-terminal microelectrochemical device will only turn on when the electrochemical potential of the contacting medium brings the polymer to a potential where [red] ≈ [ox]. Further, a transistor device configured as in figure 4 can be a useful sensor whenever the polymer has an $E^{\ominus\prime}$ that depends on the chemical environment. A pH-dependent $E^{\ominus\prime}$ means, for example, that at fixed V_g and V_d, I_d will depend on pH. The device will only turn on in a narrow pH range (figure 8). The WO_3-based device of figure 6, in contrast, has a range of pH where the device is off and a range

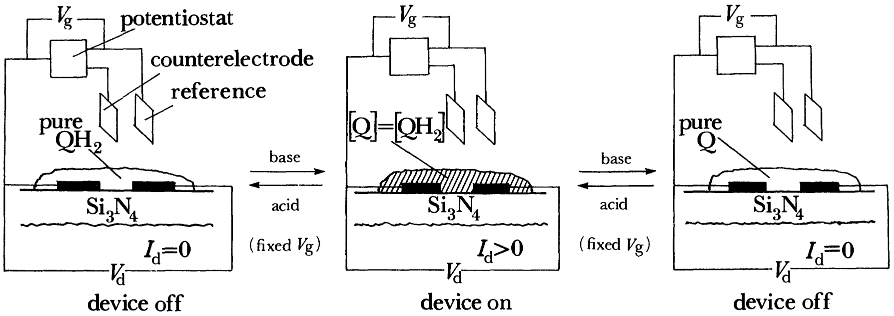


FIGURE 8. Q-based device operated at a fixed V_g and V_d, which responds to pH. Because $E^{\ominus\prime}$ (Q–QH_2) becomes more negative with increasing pH, the device is expected to turn on to maximum extent at a pH where $V_g = E^{\ominus\prime}$, as outlined in the text.

where the device is on. Likewise, the two-terminal pH-responsive poly(3-methylthiophene)–Pt-based device of figure 3 is off or on depending on pH. With the pH-dependent conventional redox polymer, there is the prospect of devices that can be truly 'tailored' with a turn-on only in a certain pH range.

The specificity possible with devices based on conventional redox polymers represents a genuine advantage. However, the low conductivity of conventional redox polymers means that the magnitude of I_d will be very modest in comparison with I_d values for devices based on conducting polymers or oxides. Further, the charge transport properties of conventional redox polymers make the devices slower in response time. The diffusion coefficient for charge transport in polyvinylferrocene is only *ca.* 10^{-10} $cm^2\ s^{-1}$ (Daum & Murray 1981); this results in a switching time of the order of several seconds for a transistor configured as in figure 4 (*ca.* 1 μm source–drain separation) whereas the poly(3-methylthiophene)-based device (with the same dimension) switches in less than 50 ms. Despite the relatively low values of I_d and the relatively slow response, devices based on conventional redox polymers offer a rational path to very specific devices. It is now clear that conventional redox polymers can be made responsive to a wide variety of interesting reagents (gases such as N_2, CO, CO_2 or ions such as Li^+, Na^+ or Ca^{2+}) which are not themselves electroactive. The viability of this claim stems from the fact that the 'binding' of such species to electroactive centres can influence $E^{\ominus\prime}$ just as pH variation affects the $E^{\ominus\prime}$ of Q. Moreover, low values of I_d and slow response can be overcome by making devices with a smaller source–drain separation. For the geometry given in figure 4, the switching time, t, is given approximately by the equation $t \approx x^2/2D_{ct}$, where x is the source–drain separation and D_{ct} is the diffusion coefficient for charge transport in the polymer. The maximum value of I_d is given approximately by:

$$I_d\,(\max) \approx \frac{(nD_{ct}\mathrm{F}AC)}{x}, \tag{3}$$

where n is the number of electrons transferred, F is the Faraday, A is the area of the drain electrode and C is the concentration of redox centres in the polymer. With electron-beam writing, it should be possible to prepare devices with crucial dimensions (source–drain separation) of the order of a few tens of nanometres. Such dimensions will generally lead to substantially improved microelectrochemical devices, and will make possible the use of redox polymers that exhibit only modest conductivity.

Unfortunately, pure Q-based polymers appear to have such poor charge-transport properties

(Miller *et al.* 1984) that preparing devices with *ca.* 1 μm source–drain separation is impractical, even at the research laboratory stage. However, results for a device based on the pH-sensitive polymer derived from A (scheme 1) have been obtained. Figure 9 shows the values of I_d (at $V_g = -0.7$ V) at varying pH, establishing that the device is responsive to pH (Smith *et al.* 1987). For the polymer derived from A, however, the pH-dependence is not straightforward, as would be the case in a pure Q-based polymer. In fact, the $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ polymer does not transport charge to a significant extent via Q–QH_2 self-exchange events, as would be necessary to give a straightforward pH-dependence. The composition (one Q, two BV^{2+}) and structure (hydrolysis of $-\mathrm{Si(OMe)_3}$ on BV^{2+}) of the polymer, and the relatively small value of k_{se}, prevent the Q centres from carrying charge via Q–QH_2 self-exchange. At all pH values where the polymer is durable (pH <9) the $BV^{2+/+}$ redox couple transports charge. Whenever the pH is such that $E^{\ominus\prime}$ (Q–QH_2) (at pH = 7, -0.35 V vs. SCE) is close to the pH-independent $E^{\ominus\prime}$ ($BV^{2+/+}$) (-0.45 V vs SCE), a contribution may be made to the charge transport-process by the cross-redox process represented by:

$$2BV^{+} + 2H^{+}Q \rightleftharpoons QH_2 + 2BV^{2+}. \qquad (4)$$

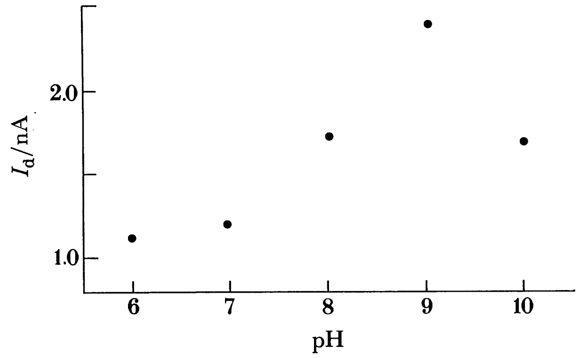


FIGURE 9. Change in I_d with variation in pH for a transistor based on the polymer derived from A (scheme I), $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$, at 298 K (Smith *et al.* 1986*b*). $V_d = 0.7$ V; $V_g = -0.7$ V.

At low pH, the $BV^{2+/+}$ system only carries the charge, with the Q–QH_2 system behaving passively as a concentration diluent. At low pH ($\leqslant 5$) the reduction process given by equation (4) is effectively irreversible, because QH_2 does not have the (thermodynamic) reducing power to return charge to the BV^{2+} centres. As figure 9 illustrates, the $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$-based device does show a pH-dependent value of I_d. Devices based on $[(\mathrm{BV}^{2+})]_n$, from B (Scheme 3), do not show a pH-dependence; this result is consistent with the above arguments (Smith *et al.* 1987). Further, the decline of approximately 30% in the maximum value of I_d on lowering the pH from 8 to 5 is consistent with the dilution of charge-carrying species, considering that one third of the redox subunits (Q–QH_2) are effectively removed by lowering the pH from 8 to 5. It is tempting to conclude that the ‘dilution effect’ accounts entirely for the pH dependence of the $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$-based device. However, this cannot be verified because the rate constant for the cross-reaction according to equation (4) is not known.

The $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ polymer is clearly not ideal as a device material in configurations considered to this point. However, the pH-dependent behaviour of single electrodes modified with $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ suggests that useful pH-sensitive devices can be made. The intriguing property of electrodes modified with $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ is that, when pH $\leqslant 5$, reduction of the polymer occurs by $4e^-$–$2H^+$, $1e^-$ into each of the BV^{2+} centres and $2e^-$ and $2H^+$ into the Q centre, but only the $2e^-$ added to the BV^{2+} can be electrochemically withdrawn. In contrast, at higher pH, $4e^-$ can be added and withdrawn. The 'rectification' at low pH is due to the fact that the Q centres do not equilibrate directly with the electrode and the reduction of the Q centres occurs only via equation (4). The point is that complete reduction of $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ can occur at low pH, but the charge used to reduce Q to QH_2 is 'trapped', because at low pH the QH_2 is incapable (thermodynamically) of delivering the charge back to the BV^{2+} centre; the only path to deliver the charge from QH_2 back to the electrode is thus blocked. In principle, the rectification exhibited by an electrode modified with $[(\mathrm{BV\text{-}Q\text{-}BV})^{6+}]_n$ can be exploited in pH sensors based on the charge recoverable from the $4e$–$2H^+$ reduced polymer; at low pH, $2n\,e^-$ can be recovered, whereas at high pH $4n\,e^-$ can be recovered. Considering that the rectification is observed with electrodes modified with only *ca.* 2×10^{-10} mol cm^{-2} of A (scheme 1) (Smith *et al.* 1986*a*), there is the prospect of making devices with very small source–drain separation. The ultimate goal is a pair of microelectrodes connected by an array of single molecules. Because rectification can be observed on a single electrode at a coverage not too different from that expected for a monolayer coverage, there appears to be no fundamental limitation to preparing such a device; rather, the significant problem that emerges is one of microfabrication.

POLY(4-VINYLPYRIDINE)-CONNECTED MICROELECTRODES: TWO-STIMULUS RESPONSE TRANSISTORS

In the previous sections, three different types of pH-dependent device have been described. Poly(4-vinylpyridine)-connected microelectrodes provide yet another kind of pH-responsive system: a device where turn-on (at fixed V_g and fixed V_d) depends on the presence of *two* chemicals; neither reagent alone is effective. Although the applications for such a device are not obvious, there is considerable interest in sensor arrays where different device functions can be useful in providing a 'signature' for a given environment. Multistimulus-response electronic devices are of interest in a variety of contexts. Two-stimulus, poly(4-vinylpyridine)-based transistors are based on the reversible protonation of the pyridine nitrogen (5) to yield a cationic polymer capable of reversibly (electrostatically) binding electroactive anions, such as $\mathrm{Fe(CN)_6^{4-}}$ (6):

$$\mathrm{PVPy + H^+ \rightleftharpoons PVPyH^+}; \tag{5}$$

$$\mathrm{PVPyH^+ + \mathit{n}Fe(CN)_6^{4-} \rightleftharpoons [PVPyH^+(Fe(CN)_6^{4-})_\mathit{n}]}. \tag{6}$$

The electrostatic binding of electroactive species to charged polymers was first studied with the system represented by equations (5) and (6) (Oyama & Anson 1980) but such systems are now relatively common. Interestingly, the protonated poly(4-vinylpyridine) polymer can effectively concentrate the electroactive anion from very dilute solutions.

Once bound into the polymer, the $\mathrm{Fe(CN)_6^{3-/4-}}$ redox system represents a mechanism for propagating charge through the polymer. Thus, when the $\mathrm{Fe(CN)_6^{3-/4-}}$ system is bound into the protonated polymer, there is a degree of conductivity of the type associated with conventional redox polymers. Accordingly, a two-stimulus-response transistor can be fabricated as shown in figure 10 (Bélanger & Wrighton 1987). The device only turns on ($I_d > 0$) when

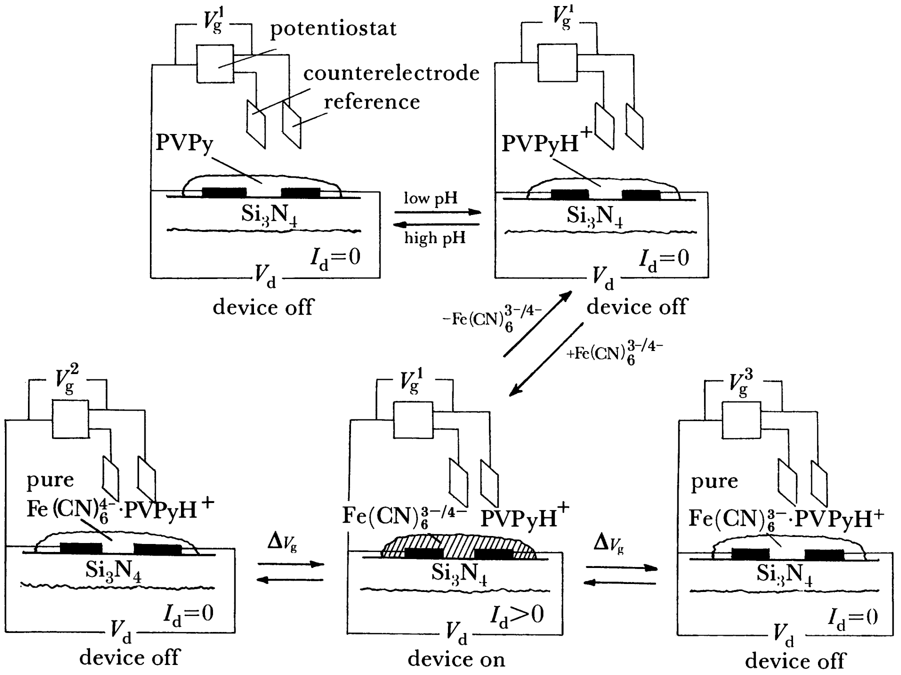


FIGURE 10. Configuration and behaviour of a device based on the protonation of poly(4-vinylpyridine), PVPy, and the subsequent electrostatic binding of $Fe(CN)_6^{3-/4-}$ (cf. figure 11) (Bélanger & Wrighton 1987).

the pH is in a certain range, below the pK_a of poly(4-vinylpyridine), *and* when the $Fe(CN)_6^{3-/4-}$ concentration is sufficient to be bound in the charged polymer at a level that gives significant conductivity. Figure 11 illustrates the I_d–V_g characteristic for the two-stimulus-response device in an acidic solution of $Fe(CN)_6^{3-/4-}$ showing the sharp region of V_g where $I_d > 0$ expected for a conventional redox polymer. Note also the small maximum value of I_d that is a consequence of the small value of D_{ct} for $Fe(CN)_6^{3-/4-}$ when bound in the protonated poly(4-vinylpyridine). An appreciation for the low value of D_{ct} in the polymer can be gained by comparing I_d with the value of the maximum steady-state current that will flow between two adjacent gold microelectrodes (not modified with polymer) immersed in a solution of only 1 mM $Fe(CN)_6^{3-}$ and 1 mM $Fe(CN)_6^{4-}$. In such a case the steady-state current is associated with the reduction of $Fe(CN)_6^{3-}$ at one microelectrode and oxidation of $Fe(CN)_6^{4-}$ at the other. The mass-transport-limited current is *ca.* 10 nA, compared with the I_d value of *ca.* 1.5 nA for the polymer-confined system in figure 11. The value of the diffusion coefficient for the $Fe(CN)_6^{3-/4-}$ system is 6.5×10^{-6} cm^2 s^{-1}, more than three orders of magnitude larger than D_{ct} for $Fe(CN)_6^{3-/4-}$ in the protonated poly(4-vinylpyridine) (Oyama & Anson 1980). The fact that the current for the solution and polymer-confined systems are similar, then, stems from the high concentration of redox centres in the polymer (*ca.* 1 M) compared with the 1 mM solutions.

As shown in figure 11 the [$PVPyH^+ . Fe(CN)_6^{3-/4-}$]-based transistor responds as expected for a system based on a conventional redox polymer. The key is that I_d(peak) occurs at $V_g = E^{\ominus\prime}$ for the electrostatically bound $Fe(CN)_6^{3-/4-}$. Note that the absolute value of I_d is well below that associated with the WO_3-based transistor (figure 7) or the poly(3-methylthiophene)-based device (figure 5). The data in figure 11 establish that microelectrochemical transistors can have a narrow turn-on region that may be useful in an array of microelectrochemical sensors. For

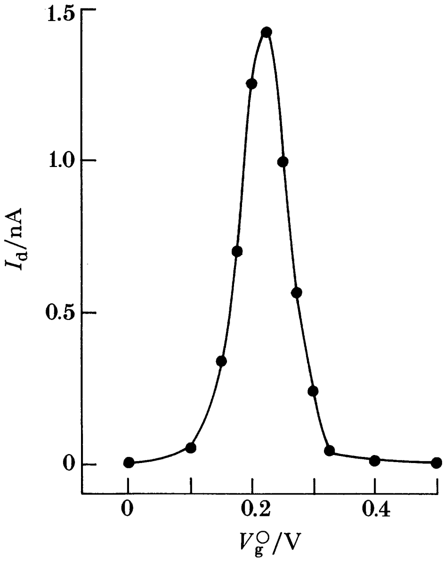


FIGURE 11. Electrical characteristic of a $[PVPyH^+ . Fe(CN)_6^{3-/4-}]$-based transistor (figure 10) at pH = 1.8, at 298 K; V_d = 20 mV. The coverage of $Fe(CN)_6^{3-/4-}$ for this device was 1.5×10^{-7} mol cm^{-2}. I_d values shown are steady-state values recorded at *ca.* 2–3 min after setting V_g.

the example shown, the additional principle is established that transistors can be designed to turn on only when two chemicals are present. In sensor applications, specificity may be achieved by exploiting both the narrow region of turn-on, associated with the use of conventional redox polymers, and the multistimulus response.

CONCLUSIONS

Modification of pairs of closely spaced microelectrodes with electroactive materials has been shown to give rise to a variety of chemically responsive microelectrochemical devices. In this paper we have introduced the principles associated with the operation of devices which are analogous to solid-state transistors where the active material is one whose resistance changes as a function of its state of charge. In solid-state transistors, such as a M–SiO_2–Si field-effect transistor (MOSFET) (Sze 1981), the function of the device depends on movement of capacitive charge in the gate circuit to effect a change in the carrier distribution of the Si between source and drain and just below the oxide of the gate. In the microelectrochemical devices, the function depends on actual oxidation–reduction of the active material connecting the source and drain. Thus, faradaic charge must be moved in the gate circuit to effect turn-on or turn-off. This leads to intrinsically slower responses for the microelectrochemical devices, compared with solid-state transistors, because faradaic processes require the movement of ions.

Microelectrochemical transistors function in the same way as solid-state devices, including the function of power amplification (Lofton *et al.* 1986). Operational frequencies of solid-state transistors exceed 10^9 Hz (Sze 1981) whereas the microelectrochemical devices have only been demonstrated up to 10^3 Hz (Lofton *et al.* 1986) in the best of circumstances. At the other extreme, even 1 Hz operation is not possible with the $[PVPyH^+ . Fe(CN)_6^{3-/4-}]$-based devices (Bélanger & Wrighton 1987) because the charge-transport properties of conventional redox polymers are so poor. Considering that the microelectrochemical devices are currently much slower than their solid-state analogues, there is no realistic prospect of microelectrochemical transistors displacing conventional solid-state devices. However, the microelectrochemical devices do function in chemical environments, and indeed require exposure to chemical systems. Thus, sensors based on microelectrochemical transistors represent an application area that is realistic and where solid-state devices may not be competitive.

Principles associated with several chemically responsive microelectrochemical devices have been presented in this paper: catalysis of equilibration of redox reagents with conducting polymers (poly(3-methylthiophene–Pt)); use of intrinsically chemically sensitive, electroactive materials (WO_3 and the polymer $[(BV\text{-}Q\text{-}BV)^{6+}]_n$; and multistimulus response systems ($[PVPyH^+ . Fe(CN)_6^{3-/4-}]$). These systems show that modification of microelectrodes in the *ca.* 1 μm size range with the proper combinations of active materials can lead to interesting device properties. Elaboration of the examples to practically significant sensor systems depends on the ability to synthesize multicomponent systems with the desired function (Wrighton 1985). The accomplishments so far would appear to justify a substantial effort to (1) make devices with dimensions well below 1 μm; (2) synthesize new molecular materials with chemically dependent redox properties; and (3) synthesize new redox catalysts and investigate the use of enzymes as catalysts in microelectrochemical devices. Considering the emerging capabilities in microfabrication technology, the growing understanding of biological systems, and the prowess of synthetic chemists, there is a possibility of designing and making a variety of new microelectronic devices, and especially sensors, from the level of the molecule upwards.

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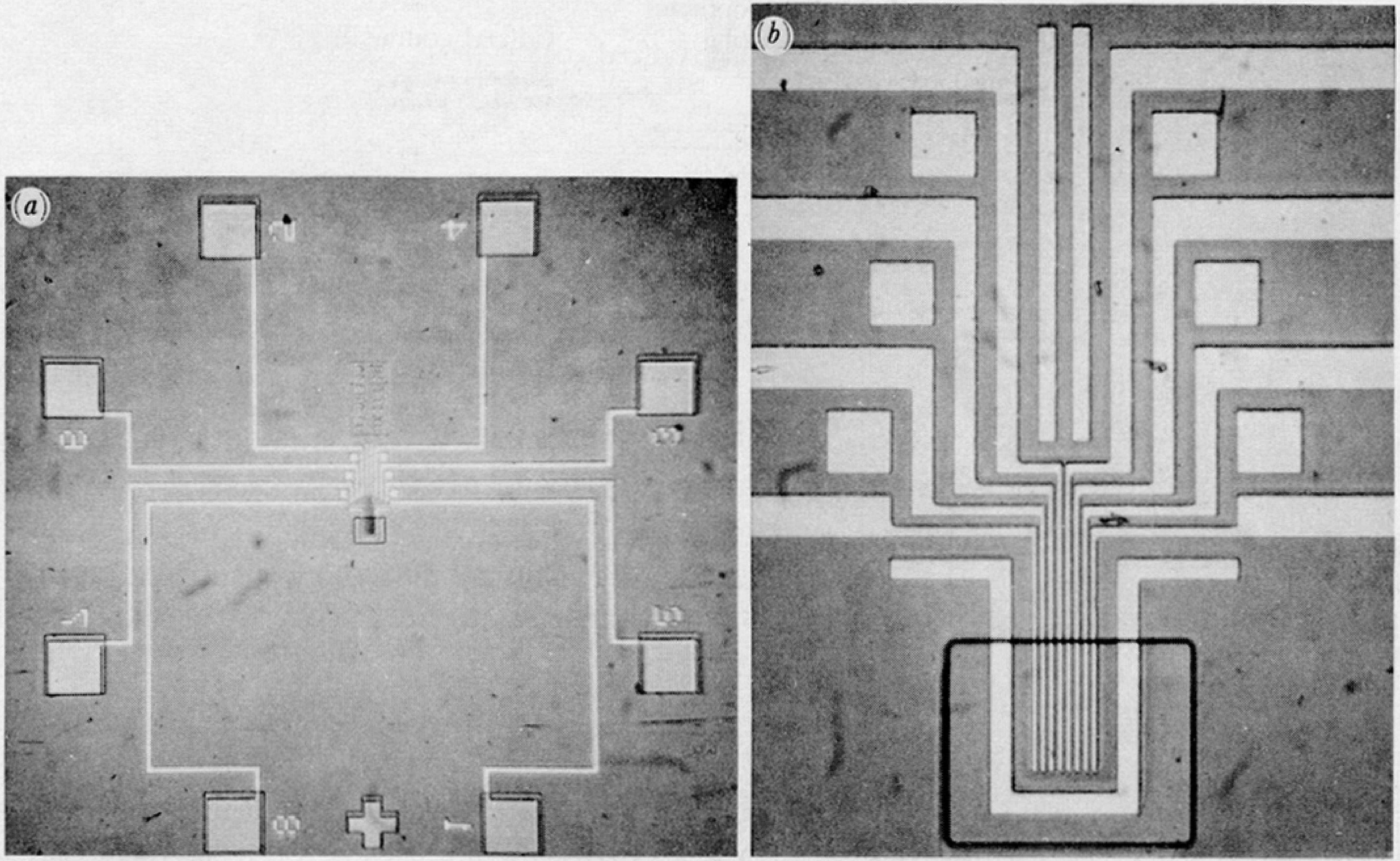
Discussion

W. J. Albery, F.R.S. (*Department of Chemistry, Imperial College of Science & Technology, London, U.K.*). Professor Wrighton has shown us that the switching time for his current transients is about 50 ms. From our own work on conducting polymers I would agree with this time scale. I therefore find it hard to see how one can achieve frequencies as high as 1 MHz. It will be difficult to charge the double layers and the conducting polymer at such a high frequency.

M. S. Wrighton. The switching speed of our molecule-based transistors depends on the rate at which the redox active material can be oxidized and reduced to modulate its conductivity.

Ultimately, the switching speed is then limited by the diffusion of ions in solution. For a 1 μm source–drain separation (present device dimensions) and diffusion coefficients of 10^{-6}–10^{-5} cm^2 s^{-1}, the switching time would be approximately 5×10^{-4} s to 5×10^{-3} s. At a source–drain separation of 50 nm (achieveable with electron-beam lithography) a switching time of approximately 10^{-6} s to 10^{-5} s can be expected. Devices with *ca.* 1 μm spacing have already been demonstrated to switch within about 10^{-3} s. It should be recognized that the double-layer charging of small electrodes can occur in a very short time; for a single electrode, potentiostatic control may be realized in a period as short as *ca.* 10^{-8} s for a sufficiently small electrode.



IGURE 2. Typical 'chip' consisting of an array of eight gold microelectrodes. (*a*) The entire chip, *ca*. 3 mm × 3 mm. The large, numbered squares are the contact pads. (*b*) An enlargement of the microelectrode array; the active area is *ca*. 50 μm × 50 μm.