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Account / Revue

Micro- and nanotechnologies: dullish electrons and smart molecules

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Abstract

The article gives elements to answer a few questions:

- Are Nanotechnologies a logical and rational continuation of Microtechnologies or do they represent a revolution in many aspects of Sciences and Technologies?
- What are the conditions to be able to combine long term basic sciences and innovations which can be rapidly transferred in the industry (or on the ‘market’). ***To cite this article: J. Simon, C. R. Chimie 8 (2005)***.

Résumé

Cette publication tente de donner des éléments de réponse à quelques questions d’actualité :

- Les nanotechnologies ne sont elles qu’une évolution des microtechnologies ou représentent-elles une réelle révolution technologique ?
- Quelles sont les conditions sociétales qui permettent d’allier recherche fondamentale à long terme et innovations transférables vers le « marché » ? ***Pour citer cet article : J. Simon, C. R. Chimie 8 (2005)***.

Keywords: Microtechnology; Nanotechnology; Iono-electronics; Chemical neuron

Mots clés : Microtechnologie ; Nanotechnologie ; Ionoélectronique ; Neurone chimique

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1. Foreword: some aspects of social and industrial revolutions

The advances in Sciences and Technologies did not continuously appear in the past. A society based on a dogma (closed society) cannot yield to significant evolutions of the overall community even though some isolated individualities may propose innovative solutions to problems. As a matter of fact, it seems there is a rather close correlation between social and industrial revolutions. In England, a revolutionary period of time occurred between 1640 and 1653 (Long Parliament).

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The industrial revolution is thought to start in UK around 1780, approximately 100 years afterwards. In comparison, French revolution took place in July 1789 and the industrial revolution started approximately in 1830. During the period 1780–1830, it seems that the French society was enable to follow its English counterpart on the way to progress. A dogmatic society based on hierarchy rather than talent, conservation rather than innovation, money rather than moral can hardly lead to scientific and technological progresses widespread in the mass of the society: decisions are taken as a function of the dogma and not as a function of more relevant criteria. In a way, we entered, in the last decades, in a new type of dogmatic society: the Market replaces the King, you must agree or disagree but always with the same reference.

Electronics and microelectronics represent real technological revolutions made in the last century. Nanoelectronics is even a more revolutionary approach since it concerns more domains of Sciences (Physics, Chemistry, Mathematics, Biology...). One can be however a little bit anxious about the possibilities offered to the researchers to make their work.

2. Electronics, microelectronics, nanoelectronics

2.1. Main steps in electronics and microelectronics

The first vacuum tube has been discovered by J.A. Flemming in 1904, and the corresponding triode in 1906 by Lee de Forest. In 1946, an electronic computer (ENIAC) constituted of 10^4 vacuum tubes and occupying 100 m^3 was built.

In 1925, J.E. Lilienfeld remarked that if a voltage is applied on a “poorly conducting material”, that could change its conductivity and could lead to some “amplification” of the signal. However, at that time, one did not know the very notion of “semiconductors”: these materials were called either “poor metals” or “doped insulators”. In 1931, W. Pauli sent a letter to R. Peierls stating:

“On semiconductor, one should not do any work, that’s a mess, who knows whether they are semiconductors at all”. In fact, until the work of K. Lark-Horowitz on the determination of the dielectric constant of silicon and germanium, these materials were qualified as “bad metals” as quoted by Sir Nevil Mott in 1981. Silicon was already obtained in 1811 by Gay Lussac and Thenard by reduction of silicon tetrafluoride with potassium: they however did not recognize it as an element. A closely related chemical reaction allowed Berzelius in 1823 to recover silicon as a dark powder. The corresponding pellets were obtained by Sainte-Claire Deville in 1857.

In 1947, a point contact germanium transistor was realized by J. Bardeen, W. Schockley and W. Brattain. It was another way to obtain a three terminal electronic device (instead of vacuum triodes) which is necessary to make amplifiers, switches or more generally logic circuits.

Around 1950, Bell Laboratories, which deposited the patent concerning the transistor, decided to offer a license to any company for the moderate sum of $25,000, in order to favor technological efforts in that direction and to replace as soon as possible the vacuum tubes used at that time to make computers.

In 1951, W. Schockley realized a P–N junction transistor. Around 1952, mainly germanium based transistors were fabricated and studied. C.S. Fuller in 1952 proposed to “dope” germanium by introducing foreign atoms using a vapor phase diffusion process.

A very important technological advance was made in 1955 when C.J. Frosh and L. Derick superficially oxidized silicon into silicon dioxide and showed that this layer could be used as a mask to avoid dopant diffusion within silicon. The same year (1955) J. Andrus and W.L. Bond used a photoresist as a mask preventing oxide etching allowing to use photograving processes for the fabrication of transistors.

In 1958, Jack St Clair Kilby realized a very simplified version of an integrated circuit with a resistor, a capacitor and one transistor on a single slice of silicon. He still used wires for the connections of the different electronic components. However, the same year, J. Hoerni proposed the fabrication of silicon transistors in a planar geometry in which the lateral extent was controlled by oxide masking and optical lithography. In 1959, B. Noyce used “photodefined” interconnections by selectively etching vapor deposited metallic layers. The integrated circuits with structures very close to those known nowadays were realized.

In 1960, D. Kahng and M. Atalla fabricated a Metal Oxide Field Effect Transistor (MOSFET) with SiO_2 as a gate insulator. It took however several years before the MOSFET could compete with bipolar transistors.

P.K. Weimer realized an insulated gate *thin film* transistor 1 year later.

In 1961, the company Fairshild and Texas Inst. industrially produced integrated circuits, but they were 10 times more expensive than the conventionally made electronic circuits. Fortunately, the Apollo programme was launched in 1961 and by the end of the sixties the NASA bought several millions of integrated circuits for its own use: accordingly, the prices decreased considerably and became financially competitive.

An integrated circuit was realized by INTEL to fulfill the needs for pocket size computers. They chose the name 'processor' to call this type of integrated circuits. In 1971, the number of transistors within a processor was of the order of 2×10^3 (so approximately the same number of vacuum tubes in the computer built in 1946). The now well known Personal Computer (PC) was launched in 1972. In 1985, the number of transistors per (micro) processor reached already 3×10^5 to attain 42×10^6 in 2000. A typical microprocessor therefore contains several millions transistors; however, only of the order of 200 connections are sufficient to connect the microscopic world of the transistor circuits to the macroscopic world of the users.

2.2. Towards nanoelectronics

It is possible to decrease the size of the device (the electronic component and the wires) down to the nanoscopic scale.

Single crystals nanowires [1] (diameter: 5–30 nm) have been obtained by chemical vapor deposition using SiH_4 as starting compound and gold clusters as catalysts. The crystalline silicon core is surrounded by a 1–3 nm thick sheath of amorphous oxide. The average energy to create e^-/h^+ pairs in SiO_2 is of the order of 18 eV as determined by energy loss of fast electrons in solids [2]: SiO_2 is consequently a very good insulating material for the silicon core.

The corresponding field effect transistor (FET) has been fabricated [3,4]. The micrometric long nanowires are oriented on an insulating substrate using a flow-directed alignment method. Source and drain electrodes (distance: 5 µm) are then deposited. The FET characteristics are measured for about 100 nanowires. Standard MOSFET equations yield hole mobilities of the order of 120 cm^2/V s comparable to reported values of polysilicon FET. Detection of chemical and biological species using nanowire sensors has been described [5].

Carbon nanotubes [6] have also been used to form FET [7–9].

The discovery of scanning tunneling microscopy (STM) in 1982 [10] followed by atomic force microscopy a few years later allowed molecular controls and measurements at nanoscopic scales [11][1].

Self assemblies in two-dimension of nanometer diameter gold clusters linked with bifunctional (dithiol or diisonitrile) aromatic compounds have been described [12]. The conductivity of single molecular wires anchored on a gold surface and diluted with another thiol derivative has been studied using a STM tip [13]. A review is given in Ref. [14].

Even-numbered clusters of carbon atoms in the range C_{30}–C_{60} have been shown to be present in carbon vapor [15]. Afterwards, conditions were found for which a C_{60} molecule could be made dominant in fractions of vaporized graphite [16]. A model was proposed, represented schematically by a soccer ball, to understand the stability of the C_{60} molecule [16]. The C_{60} molecule could allow to realize a single molecule FET: the tip of a STM was used as a drain, the C_{60} molecule (diameter approximately 2 nm) as the electroactive part, the gold substrate as a source [17–19]. The gate voltage can be considered to be the potential applied to the piezoelectrical crystals employed to vary the tip to substrate distance. The drain-to-source current was varied by changing this distance and by correlatively modifying the 'pressure' applied on the C_{60} molecule.

3. Molecular and iono-electronics

3.1. Introduction

Molecular and iono-electronics cannot be considered to be only the continuation of conventional electronics by merely decreasing the size of the constitutive parts.

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[1] The cantilever was fabricated by a student: T.R. Albrecht. It is indicated in this article that stylus profilometer was previously able to give three-dimensional images of surfaces with a lateral resolution of 100 nm and a vertical resolution of 1 nm: B.P. Williamson, Proc. Inst. Mech. Eng. 182 (1967) 21.; K.H. Guenther, P.G. Wierer, J.M. Bennett, Appl. Optics 23 (1984) 3820.; E.C. Teague, F.E. Scire, S.M. Backer, S.W. Jenssen, Wear 83 (1982) 1.

By considering the electron effective mass in silicon, it can be calculated that approximately 10^4 atoms of silicon are concerned with the transport of a single charge carrier [20]. In iono-electronics [21] single ions (Na^+, K^+...) are the active elements allowing to transfer and store the energy. In molecular electronics [22], it is thought that single molecules can achieve all the functions of one or several devices. The number of atoms to be taken into account is therefore different by several orders of magnitude. All the equations conventionally used have been established for a large number of species. As an example, the notion of temperature can be hardly understood for a small number of elements. In consequence, most of the mathematical and physical treatments must be revisited at the nanoscopic scale at least as to the basic hypotheses made.

Chemists and Biologists work with molecules rather than with crystals where macroscopic properties may be demonstrated. However, Chemistry involves mainly systems at equilibrium and non-cooperative reactions or complexations. In Biology, the same type of chemical reactions occurs but a huge amount of cross reactions and feed back processes are effective and the system is never at equilibrium. Moreover, numerous biochemical processes involve cooperative processes. All oxidizing reactions are exoergonic and the stable state in air of any organic matter should tend to the formation of CO_2 and H_2O. Fortunately, the system is 'open': the sun continuously delivers energy caught by various photosynthetic processes allowing to make reactions very far from the equilibrium. This is a necessary condition to be able to form highly structured entities which should be entropically unfavorable.

The microscopic and nanoscopic worlds are also fundamentally different from a technological point of view. In the first case, the architecture is imposed by a rational design followed by a stepwise fabrication. In the second case, self organization may occur and the elementary processes are interconnected leading to a difficult understanding of the whole system.

The concepts necessary to establish a way from three terminal devices (vacuum triode, transistor) to a device allowing a treatment of information (i.e. a microprocessor in present days) have not fundamentally changed in the last 40 or 50 years. The main advances have been brought by the progresses in Technology. A binary logic constitutes (with a very few exceptions) the basis of the information processing [23]. A completely different approach is possible in molecular electronics and iono-electronics.

3.2. Colored charge carriers

Organic molecules or more generally molecular units can be reduced and/or oxidized. However, the energy required for the disproportionation reaction:

$$2A \text{ in equilibrium with } A^+, A^-$$

A: molecular unit is too large to give significant amounts of cations or anions (which can act as charge carriers) at least at room temperature [24]. Lutetium bisphthalocyanine (Pc_2Lu) and lithium phthalocyanine (PcLi), due to their radical nature, have been shown to be exceptions to that respect [25–27]. More recently [28], a single component charge transfer compound has been synthesized and shown to yield a metallic conductivity from room temperature down to 0.6 K. In the case of Pc_2Lu, it can be considered that 'colored charge carriers' are formed since Pc_2Lu^- is blue (in solution) and Pc_2Lu^+ is red. Electrochemical studies on Pc_2Lu solutions [30] or thin films [29] have demonstrated the exceptional reversibility of the redox processes. Charge transfer in a Pc_2Lu thin film by application of a constant current and by using an electrolytic contact was studied [31]. When Pc_2Lu thin films is fully reduced (or oxidized), they behave as 'new materials' possessing their own electrical and electrochemical properties. A single molecule can therefore yield many different states which can be written as:

$$Pc_2Lu^{2+},\ Pc_2Lu^{+},\ Pc_2Lu,\ Pc_2Lu^{-},\ Pc_2Lu^{2-},\ Pc_2Lu^{3-} \ldots$$

together with the corresponding materials. It is consequently possible to consider a logic based on more than two states.

3.3. Examples of ternary logic operations

A brief description of a ternary logic truth table will be given to illustrate that approach [32][2]. In a binary logic, one generally considers:

1	ON	TRUE (T)
0	OFF	FALSE (F)

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[2] Mr D. Bureau is thanked for his help.

In a ternary logic, a new possibility appears : PERHAPS:

1	TRUE (T)
0	FALSE (F)
2	PERHAPS TRUE/PERHAPS FALSE (Pe)

The corresponding truth tables may then be built:

Inverter	**F**	Pe	**T**
	T	Pe	**F**
AND	**F**	Pe	**T**
F	**F**	F	**F**
Pe	F	Pe	Pe
T	**F**	Pe	**T**
OR	**F**	Pe	**T**
F	**F**	Pe	**T**
Pe	Pe	Pe	T
T	**T**	T	**T**

The truth tables based on a ternary logic include the conventional binary logic ones with additional options (the elements found in both binary and ternary logics are figured in bold face). In a binary logic 3 variables yield 256 logic functions whereas 7×10^{12} logic functions are generated in a ternary logic. The very structure of the information processing is therefore modified.

3.4. Self-assembling properties

Molecular compounds can form a huge number of condensed phases from perfectly organized single crystals to mesophases and isotropic liquids [33]. A hint can be found in the way the molecular units organize themselves by applying the motto "like as like goes together": rigid parts segregate from flexible ones, hydrophobic from hydrophilic. It is not possible to give even a very naïve overview of the various self-assembling processes involved in chemical or biochemical systems. A closer look will be taken on phthalocyanine based mesophases which have been shown to form nanometric wires and transistors.

3.4.1. Nanometric wires and transistors

Chandrasekhar et al. [34] proposed in 1977 a new type of mesophases based on a hexa-alkyl-substituted benzene ring. The versatile phthalocyanine subunit has been used as a central rigid core instead of benzene [35]. The phthalocyanine can lead to a very large variety of four to six coordinated metal complexes having importantly different chemical and physicochemical properties (see for instance [24,33,36].

Nanometric wires with a phthalocyanine central rigid core of approximately 1.5 nm diameter surrounded by a medium constituted of flexible paraffinic side chains in a quasi-molten state, have been synthesized and studied. The difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) generally defines the energy needed to generate charge carriers. It is not the case for Pc_2Lu since the unpaired electron occupies a semi-occupied molecular orbital (SOMO). The difference in energy between the oxidation and the reduction processes is related to the 'pairing energy' associated with electron–electron repulsion within a same orbital. In the case of Pc_2Lu this energy is of the order of 0.5 eV [27]. The HOMO–LUMO difference for polyethylene —a close model for the paraffinic chains—has been calculated to be 9.3 eV [37]. The phthalocyanine central core which can yield charge carriers by disproportionation or doping is consequently mantled by an insulating layer. The synthesis of bis (octaalkyloxyphthalocyaninato) lutetium was published in 1985 [35]. The electrical properties of the columnar mesophases have been studied in the frequency range 10^{-3}–10^{5} Hz and at 10 GHz [38,39].

In the case of monophthalocyanine derivatives of general formula $(C_nO)PcM$ (M = divalent metal ion or two H-atoms; C_n: alkyl chain C_nH_{2n+1}), the energy needed to generate charge carriers is of the order of 2 eV and the intrinsic conductivity at room temperature is not observable because minute amounts of impurities are sufficient to dominate the charge transport process (see for instance [24] and references therein). It has been proposed to irradiate the mesophases derived from these molecular units by 3 MeV electron pulses (5–50 ns) [40,41]. It is postulated that such irradiations produce electron/hole pairs (probably s-PcM^+, s-PcM^-; s- standing for substituted) 100 nm apart. Microwave conductivity after irradiation was studied in the range 29–38 GHz [40,41].

A recent publication described with some details the fabrication of a FET based on a molecular unit having a rigid conjugated core substituted with paraffinic chains. The nanometric wires were oriented by using a polytetrafluoroethylene (PTFE) striated layer (thickness: 10 nm) obtained by friction [42,43] on a silica layer used as a gate dielectric [44]. Source and drain electrodes (distance: 25 μm) were then deposited on the top of the aligned columnar phase.

A crown ether substituted bisphthalocyaninato-lutetium compound has been synthesized in 1989 [45] which allows to couple the generation of electronic charge carriers with the binding (complexation) of alkali or alkaline earth cations with crown ether substituents. As a consequence the charge carriers may be perturbed by a chemical reaction completely independent of the nature of the carrier itself.

The self-assembling process to form nanowires can be used for many applications. Already in 1986 [46] magnetic coupling of substituted Cu(II) phthalocyanine in columnar mesophases were studied. Ion channels with crown ether substituted phthalocyanine were described in 1987 [47]. Irradiation with photons followed by a quasi-one dimensional energy migration within the aromatic core was reported in 1987 [48]. The extent of the migration was determined by adding different amounts of quenchers (the corresponding copper complex) within the columns. The same year [49], antiferroelectric couplings between out-of-plane lead phthalocyanine derivatives, $(C_8OCH_2)_8PcPb$, were studied.

3.4.2. Chemical neurons

The only similarity between ‘artificial’ electricity (standard current of electrons) and ‘natural’ electricity (migration of cations or anions) is the unit used: the millivolt. All the physicochemical characteristics are different.

A chemical neuron may be represented in a schematic way as:

Chemical input → Non-linear treatment →

Chemical output.

The non-linear treatment of the information delivered by the chemical inputs must be able to generate chemical outputs described by discrete states. A conventional FET structure where Pc_2Lu is used as electroactive material could be suitable for such a chemical neuron. Proper V_{gs} voltages allow to generate charge carriers within the molecular material (Pc_2Lu). The conduction will decrease whenever approximately 50% of the molecular units are oxidized (or reduced). Afterwards the fully oxidized (reduced) material can be considered to be a new material with its own electrical and FET properties. The gate can be constituted by receptors able to selectively bind desired species; this constitute the chemical input of the neuron. The non-linear treatment is furnished by the transistor: the delivered source-to-drain current can in turn oxidize (or reduce) an organic material containing an ion pair. The oxidation will lead to the delivery of a cation within the surrounding medium. This is the chemical output of the neuron.

As previously seen, the molecular transistor is not constrained to a binary logic. Moreover, the chemical inputs and outputs possess a much richer information content than a mere electrical current. The ‘chemical neurotransmitters’ may be stretched, bound, protonated...before they reach the neighboring chemical neurons. In ‘natural neurons’, the neurotransmitters diffuse over only 20–50 nm.

3.4.3. New architectures

It is possible to design new architectures by using ions and/or molecules as information vectors. In one of the possibilities we explored, two criteria seem necessary:

- a cooperative (non-linear) process must govern the chemical mechanism in the active element used instead of the conventional transistor;
- a connection between numerous active elements must be found.

A solution to this problem has been already proposed [50–52]. A more elaborated version is given below.

When working at a nanoscopic level, a major challenge is to be able to individually address the nanometric active elements. Is it however a necessary condition?

Let us consider a phthalocyanine moiety substituted statistically with 12-crown-4, 15-crown-5, 18-crown-6 and 21-crown-7 macrocycles. The various crown-ethers form complexes with many cations but we will consider only alkali and alkaline earth cations [53]. Depending on the relative sizes of the cation and the macrocycle 1:1 complexes or 2:1 complexes are formed. In these latter, the cations are bound to two crown ether moieties in a sandwich like geometry. In the case lutetium bisphthalocyanine derivatives are used columnar structures may form depending on the concentrations of the various cations present in the solution.

Porphyrin [54,55] and phthalocyanine [56] derivatives substituted with crown ether macrocycle of only a single type have been described. The previously described compounds are still to be prepared.

In a second step, a crown ether phthalocyanine may be combined in the presence of Lu(III) with another phthalocyanine substituted with functional groups able to react with the surface states of silica [57]. An unsymmetrical lutetium bisphthalocyanine is thus obtained [57]. A mixture of variously substituted compounds is used to graft randomly the surface of silica.

It is now possible to study the formation of pillar-like aggregates [50–52] in the presence of various cations and the crown ether lutetium bisphthalocyanine previously described. It is however necessary to characterize the amount of pillar-like aggregate formed at the surface of silica. This could be done individually by using a nanoscopic measurement (AFM, STM). A simpler method is proposed below.

The grafted surface can be a part of a device on which a periodic deformation could be applied (as a cantilever). It would then be possible to determine the corresponding frequency of resonance. This frequency will be related to the amount of columnar aggregates attached to the surface and also to their distribution on the silica surface. A 'calibration' experiment is carried out with known amounts of cations. A second experiment is carried out in the presence of unknown concentrations of cations. The single output, the frequency of resonance, is compared to the previous one. If the two values are in the same range it must be reasonably considered that the concentrations of cations are the same in the two cases. This comparison is meaningful because the complexation processes within each active elements are highly cooperative and because all the active elements are connected with each others by ion diffusion. This protocol is voluntarily naïve, its merit is only to demonstrate that a very complicated system where cooperative complexations are effective may be characterized by a single parameter.

In summary, this proposition is made to demonstrate that:

- a mastered organization of the active nanoscopic non-linear elements is not a prerequisite for an information processing;
- the use of cooperative complexation reactions may be employed as active elements (or plug);
- the writing or the lecture of the device does not compulsory involve nanoscopic measurement methods such as STM, AFM or more recently described scanning electrochemical microscope [58][3].

3.5. Applications

This section is devoted to a brief description of widely used commercially available devices (ion selective electrodes) and to others that present decisive advantages in terms of technology and even of costs compared to the previous ones but which are surprisingly only marginal on the 'market'.

3.5.1. Ion selective electrodes

In 1873 F. Kohlrausch was the first to apply an alternating voltage on electrodes in order to avoid their polarization. A former PhD student of F. Kohlrausch, W.H. Nernst proposed in 1889 the well known relationship relating the concentration of an oxidant [Ox] and a reductant [Red] to the voltage on the electrodes:

$$E = E_o + R\,T/n\,F \log[\mathrm{Ox}]/[\mathrm{Red}]$$

In 1906 M. Cremer proposed to use glass electrodes to measure the concentrations of protons in solution: the glass electrodes possess surface states which can be more or less ionized depending on the solution studied.

A potentiometric measurement allows the determination of the surface voltage and, in consequence, the pH of the solution. The voltmeter used in the experiment must have an input impedance at least 10^4 times higher than the resistance of the glass electrode [59].

Addition of Al_2O_3 and/or B_2O_3 to the sodium glass silicates allowed to detect other types of univalent ions such as Na^+, K^+, Li^+ in addition to H^+ [60].

In 1964, Moore and Pressmann [61] described the action of valinomycin on mitochondria. Stefanac and Simon [62,63] made cells of the type:

Ag–AgCl (inner solution)//membrane//
sample//calomel electrode.

In these cells nonactin or related compounds (gramicidin, valinomycin) were used to impregnate various

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[3] In a previous publication a micropipette is used to inject electroactive species: it allows to measure the local electrode activity. By moving the micropipette a 'Faradaic map' is obtained at a micronic resolution.

supports such as sintered glass, filter paper, polyethylene film, nylon mesh or thixotropic gel formers. These constituted the ‘membrane’ of the previous cell. The selectivity in favor of K^+ over Na^+ reached 750 to be compared with 30 in the case of potassium sensitive glass electrodes [62,63]. Nonactin and related compounds were also used within nujol/2-octanol [64] or within tris(2-ethylhexyl)phosphate [65].

In 1928, Corten and Estermann used the system:

$$M_1/C_1A_1(\text{insoluble})/$$
$$C_2A_1(\text{insoluble})/C_2A_2(\text{soluble})$$

with M: metal; C: cation; A: anion (the subscripts 1 or 2 designate the nature of the element)

for the determination of Ca^{2+} (see references mentioned in [66]).

In 1967 [67], a Ca^{2+} ion selective electrode based on a calcium salt of $(C_{10}O)_2PO_2H$ dissolved in $(C_8O)_2PO\Phi$ was realized. A major improvement was made [68] by incorporating a liquid ion exchanger into a PVC matrix.

Neutral ligands such as valinomycin have been incorporated into cross-linked silicon rubber to form potassium selective electrodes [69].

Ion selective electrodes represent a huge market. It has been quoted [70] that every year (in 1991), in the US, 2×10^8 clinical assays have been carried out with valinomycin based ion selective electrodes.

3.5.2. Ion selective field effect transistors (ISFET)

In an ISFET, the metallic gate electrode of a classical MOSFET is replaced by a solution containing the ions and/or molecules to be analyzed (analyte). The ionization state of the interface SiO_2/solution influences the drain-to-source current in the same way as the electrical potential applied on a conventional metallic gate electrode.

The ISFET device has been proposed in 1970 by Bergveld [71]. The title of the publication mentions: “ion sensitive solid state device for neurophysiological measurements”. The original intention of the author was to measure the sodium and potassium fluxes at nerve membranes [72]. However, experimentally, the studies were limited to pH measurements using the different ionization states of the silanol groups to modify the surface potential of the insulator.

The original paper led to a discussion whether or not a reference electrode is necessary for using ISFET [73]; all present measurements do use a reference electrode.

The mechanism arising at the SiO_2/solution interfaces were detailed by considering electrical double layers involving colloidal oxide [74].

Already in 1975 [75], a K^+ sensor was proposed in which the gate was constituted by a layer containing a mixture: valinomycin/plasticizer/PVC. This membrane was deposited on SiO_2/Si_3N_4. The same year, a H_2 sensitive ISFET was described [76], in which the gate insulator was recovered by a 10-nm-thick Pd thin film.

The originally designed ISFET could, at least in principle, detect any charge or dielectric changes arising at the insulator surface. In 1976, the concept of an ISFET able to detect the presence of biological molecules was proposed [77] and subsequently fabricated [78].

Penicillinase mixed with albumin and cross-linked with lysine was deposited on the gate insulator. In the presence of penicillin, a hydrolysis reaction occurs which is detected by the corresponding pH change liberated during the reaction.

Inorganic gate thin films (SiO_2, Si_3N_4, Al_2O_3, sodium aluminosilicate...) deposited by chemical vapor deposition have been described for fabricating pH or Na^+ sensitive FET [79]. Ta_2O_5 and borosilicate glasses have also been proposed [80].

Already in 1980, the detection of H^+, K^+, Ca^{2+} with a membrane ISFET in 20 µl samples of blood was described [81].

In 1986, a dielectric polymer, Parylene, which can be vacuum deposited and polymerized from [2.2] paracyclophane[4] was deposited on the gate insulator. It was then superficially oxidized to produce $–CO_2H$ reactive groups which were reacted after activation with an amino-benzo-18-crown-6 derivative [82].

Step by step the membrane became more elaborated and, in one version [83], all the apparently necessary ingredients were gathered:

- a silicone matrix;
- a cyanopropyl-side chain to increase the dielectric constant of the membrane;

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[4] Pyrolysis of *p*-xylene (producing xylylene) was used by M.M. Swarc to obtain the first polymeric material. W.P. Gorman proposed instead to employ the stable [2.2] paracyclophane as starting compound. An announcement was made in 1965 revealing that new polymeric coating materials (the Parylenes) were available with a new method for depositing them under vacuum.

- a calixarene subunit susceptible to selectively bind molecules;
- a grafted highly delocalized and bulky anion.

In 1995, double stranded DNA could be detected by using SiO_2 as gate dielectric [84]. A label free detection of DNA by ISFET whose insulating layer was functionalized with simple strand DNA was described [85]. Genetic variations have been detected by a transistor array coupled with a polymerase chain reaction (PCR) [86].

4. Conclusion

Microelectronics and associated technologies have invaded the industrial world. Most of the basic innovations were made decades ago. More developments are expected in other domains as smart sensors.

Molecular and iono-electronics offer a new field of research for the Chemists, the ultimate goal being to be able to fabricate artificial neural systems.

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