

Organic Chemistry within Ceramic Matrices: Doped Sol–Gel Materials

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1. Background

1.1. The Motivation. Organic chemistry and the chemistry of ceramic materials have had little overlap between them. However, when one considers the unique properties of ceramics on the one hand and the vastness of organic chemistry on the other, it seems almost inevitable that overlapping these domains of chemical research should lead to novel materials and to novel reaction configurations.

I summarize here some aspects of our activities toward that goal in the past decade or so, which indeed began with an intuitive appreciation of the potential usefulness of bridging these two fields,¹ and which have evolved into a self-contained domain, with research activities in many academic and industrial laboratories.^{2–6}

The inherent difficulty in combining organic chemistry with glass and ceramic chemistry was the very wide gap in the typical process temperatures employed: Organic compounds can rarely survive temperatures higher than 200 °C (and biomolecules much less), but typical manipulation temperatures of ceramics and glasses can be well above 1000 °C. It is for this reason that, over the millennia of the history of ceramics and glass production,⁷ one finds additives (e.g., colorants) only such that could withstand the high temperatures, namely, inorganic salts and other oxides.

It has been known for quite some time⁸ that inorganic oxides, with chemical compositions identical to those of glasses and ceramics, can be prepared at room temperatures, by the replacement of the melting procedures with polymerizations and coagulation of metal and semimetal hydroxides or of their organic ethers (alkoxides) or esters.⁹ Compared with the voluminous activity in the field of organic polymers, the study of formation of inorganic oxides by polymerization remained for many years relatively low-key. The late 1970s and early 1980s witnessed a dramatic change: The recognition that better ceramic materials can be obtained through the detailed tailoring of the chemical aspects of the polymerization¹⁰ led to a worldwide burst of activity and to the birth of what became known as “sol–gel science”.^{9,10e,11} Although

sol–gel transitions are, of course, well documented in many polymerization and precipitation phenomena, the terms “sol–gel materials”, “sol–gel process”, etc. are used today in the connotation of the synthesis of inorganic materials from suitable monomers, passing indeed through sol, gel, and xerogel (dry gel) stages.

It became clear that the sol–gel process is a promising candidate for closing the ceramics–organic gap, by virtue of the ambient temperatures employed up to the xerogel stage. Early studies aimed simply at demonstrating that entrapment of organic molecules in sol–gel matrices is at all possible^{1,12} evolved over the years into the following generalizations:

1. Most molecules can be entrapped in sol–gel matrices.
2. The entrapped molecule retains much of its characteristic physical properties.
3. The entrapped molecule retains much of its chemical properties.

1.2. The Sol–Gel Process and Sol–Gel Materials. Practically all of the important oxides MO_n (where M is a metal or semimetal and n is not necessarily an integer), as well as many mixed oxides, have been prepared by the sol–gel process.^{9–11} Many of our studies concentrated on SiO_2 as a model, although for most applications described below, this need not be the optimal matrix, and one should also consider TiO_2 , ZrO_2 , and Al_2O_3 , as well as composites such as SiO_2/ZrO_2 and hybrid organic–inorganic materials (ormosils).¹³

As a synthetic example for the formation of a sol–gel material, we take the hydrolysis–condensation preparation of porous silica. (Most sol–gel prepara-

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(8) (a) Graham, T. *J. Chem. Soc.* **1864**, 618–626. (b) Hatschek, E., Ed. *The Foundations of Colloid Chemistry*; Ernest Benn: London, 1925.

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(10) (a) Livage, J.; Henry, M.; Sanchez, C. *Prog. Solid State Chem.* **1988**, *18*, 259. (b) Hench, L. L.; West, J. K. *Chem. Rev.* **1990**, *90*, 33. (c) Dislich, H. *J. Non-Cryst. Solids* **1985**, *73*, 599. (d) Zarzycki, J. *Heterog. Chem. Rev.* **1994**, *1*, 243. (e) *Better Ceramics Through Chemistry, VI*; Sanchez, C.; Mecartney, M. L.; Brinker, C. J.; Cheetham, A., Eds. *Mater. Res. Soc. Symp. Proc.* **1994**, *346* and earlier volumes in this series.

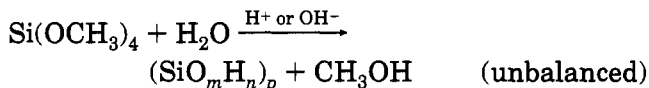
(11) See current issues of the new journal *J. Sol-Gel Sci. Technol.*

(12) (a) Tani, T.; Namikawa, A.; Arai, K.; Makishima, A. *J. Appl. Phys.* **1985**, *58*, 3559. (b) Avnir, D.; Kaufman, V. R.; Reisfeld, R. *J. Non-Cryst. Solids* **1985**, *74*, 395.

(13) For instance: (a) Corriu, R. J. P.; Moreau, J. E. E.; Thepot, P.; Wong-Chi-Man, M. *Chem. Mater.* **1992**, *4*, 1217. (b) Suzuki, T.; Sakae, Y.; Kushibiki, N.; Mita, I. *Chem. Mater.* **1994**, *6*, 692.

David Avnir is a chemistry professor at the Institute of Chemistry, The Hebrew University of Jerusalem. He joined the University in 1980 as a lecturer and was promoted to full professor in 1988. He was appointed chairman of the School of Chemistry in 1991 and held that position for three years. In 1992 he founded *Heterogeneous Chemistry Reviews*, now in volume 2, and is its editor-in-chief. His scientific activities include sol–gel materials, fractal theory and its applications in surface science and catalysis, surface photoprocesses, far-from-equilibrium phenomena, and symmetry and chirality in chemistry. He has coauthored more than 175 scientific papers on these topics and edited the highly cited book *The Fractal Approach to Heterogeneous Chemistry*. He has been a member of numerous scientific committees and is on the editorial boards of several journals. He was often cited for his excellence in teaching.

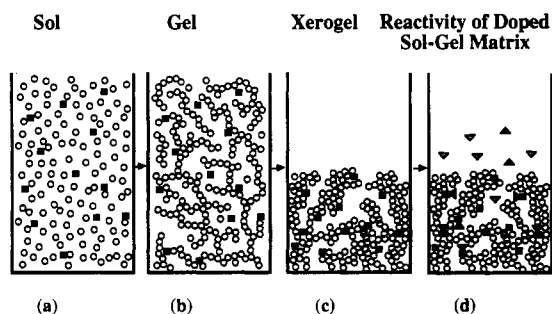
tion procedures are aqueous, but a very interesting nonaqueous sol-gel chemistry is being developed.)¹⁴ The following reaction is with the methoxide of silicon (TMOS), but many other alkoxides, aryl oxides, and acyl oxides can be used, as well as Si-N and Si-Cl compounds.



Here, all of the oxygen in the silicon oxide comes from the water molecules. The underlying details of the chemistry are extremely complex,^{9,15} the values of m , n , and p being dictated by a host of parameters. These include the water/silane ratio ($=r$), concentration of H^+ or OH^- , cosolvent, temperature, method and rate of drying, existence of dopants, size and shape of the product (thin film, monolith, powder), and even chemical nature of the surface of the reaction container or thin film support. Typically, $(\text{SiO}_m\text{H}_n)_p$ are highly porous materials with pore size distributions which vary from broad to narrow, centered around several tens of angstroms, with surface areas usually in the range of several hundreds of m^2/g .¹⁶ As for the values of m and n , the theoretical minimal composition is m close to 2 and n close to 0, for completely nonporous SiO_2 . However, the surface of the porous product is densely coated with various types of silanols (SiOH , $\text{Si}(\text{OH})_2$), so that the other hypothetical extreme (all Si is at the surface) is about SiO_3H_2 . Adsorbed water molecules, which are always there, affect the n/m ratio as well. It is the fact that the silica has actually the SiO_mH_n composition (and not the commonly cited SiO_2) that is crucial for many of the special properties listed below. The value of p in the general formula can also be very high: Since the monomer has four arms, the resulting polymer is extremely branched and a monolithic sol-gel block can in principle be one huge molecule with p approaching Avogadro's number.

The complexity of the polymerization process has two levels. The first one is the competition between the hydrolysis rate of the SiOR groups, forming $\text{SiOH} + \text{ROH}$, and the rate of the polymerization/condensation steps. The second one is that, in small oligomers, each of the SiOH and SiOR groups has a distinctly different electronic and steric environment, resulting in distinct hydrolysis and condensation rates for each of these groups. It is not surprising therefore that, although theoretical input does exist,¹⁷ the control of the physical properties of porous sol-gel materials is still a matter of art and of trial and error. It should be noted, however, that the very ability to control it is an important advantageous property of this class of materials.

1.3. Entrapment of Organic and Bioorganic Molecules in Sol-Gel Matrices. The introduction of a host molecule is done by adding its solution to

Scheme 1. The Entrapment Process^a

^a(a) A sol of inorganic oxide particles (○) is prepared by polymerization of metal alkoxides in the presence of the desired dopant molecules (■). (b) The sol turns into a gel, which then dries and shrinks, forming a porous xerogel (c), within which the dopant molecules are trapped. The pores are sufficiently narrow to render the matrix transparent, allowing optical applications. (d) The pore network allows external molecules (▼) to diffuse into the matrix and react with the trapped dopant (■). Sensing, catalysis, photochemistry, and biocatalysis have been demonstrated.

the polymerizing mixture. When the polymerization is completed, the dopant molecules are entangled in the inorganic polymeric network (Scheme 1). The nature of the entrapment is yet not fully understood, and it is really remarkable to see how many applications of the entrapment have been developed, without fully understanding the picture at the molecular level. I return to this point in section 3.

The two most important properties of the entrapment are as follows.

I. The entrapped molecules are accessible to external reagents through the pore network: Chemical reactions and interactions are possible.

II. Sol-gel materials such as monolithic silicas or silica films are transparent well into the UV: Optical applications are possible.

Other properties which have contributed to the attractiveness and versatility of the sol-gel doping approach are the chemical, photochemical, electrochemical inertness as well as the thermal stability of the matrix; the ability to induce electrical conductivity;¹⁸ the richness of ways to modify chemically the matrix and its surface as well as the above mentioned controllability of matrix structural properties; the enhanced stability of the entrapped molecule;^{1,19} the ability of employing the chromatographic properties of the matrix for enhanced selectivity and sensitivity of reactions with the dopant;³ the simplicity of the entrapment procedure; the ability to obtain the doped sol-gel material in any desired shape (powders, monoliths, films, fibers; and the ability to miniaturize it.^{20,21}

2. Reactions within Sol-Gel Matrices

2.1. Light-Induced Reactions: Photochemical Lenses.²² **2.1.1. Isomerizations.** The first family of reactions we studied in detail were the photochromic isomerizations of Aberchrome 670²³ and of various spiropyrans.^{24,25} The motivation was to develop novel materials for information processing and for other optics applications, and it serves as a good illustration of what the organically doped sol-gel methodology can

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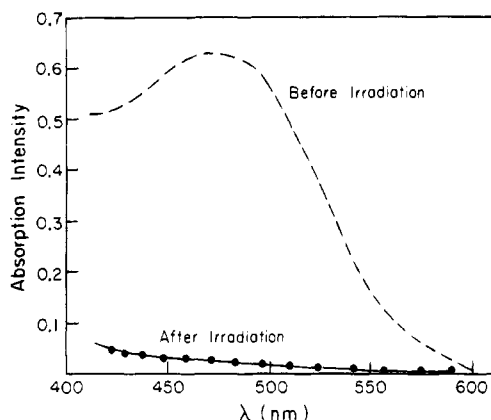


Figure 1. Sol-gel optics. The entrapment of organic photochromic dyes, here 6-nitrospiropyran, opens the way for a variety of optical applications. By careful tailoring of the properties of the ceramic cage, the directionality of the photochromic act can be influenced. Shown is a reversed photochromism (colored in the dark; colorless upon illumination) achieved in a sol-gel matrix prepared from tetramethoxysilane and poly(dimethylsiloxane).²⁵

offer: traditionally, photochromic glass preparations have been limited to a few dopants that can withstand the high temperatures of glass melting; by contrast, organic photochromism offers several tens of thousands of molecules with which one can tailor the shade of color change, the direction of the photochromism (Figure 1), the rate of change in color intensity, reversibility (optical gates), or unidirectionality (information recording). I return to this class of reactions in section 3.

2.1.2. Photoinduced Electron Transfer. The ability to separate reactive species that otherwise annihilate each other is another feature which the sol-gel methodology allows by virtue of the entrapment isolation. This was best demonstrated in a study aimed at storage of light energy in the form of a photogenerated ionic radical pair.²⁶ A notorious problem in this field of research has been the dissipation of the absorbed energy through fast back reaction of the radical pair. An exceedingly long-lived (several hours!) charge-separated pair was obtained in an SiO₂ sol-gel between the photogenerated pyrene cation (Py⁺) and methylviologen cation (MV²⁺): Py* + MV²⁺ ⇌ Py⁺ + MV^{•+}.

This is a very reactive pair which under free diffusing conditions would immediately quench each other with the back reaction. The back reaction was inhibited by entrapment of both Py and MV²⁺ while allowing them to communicate chemically with a mobile charge carrier, *N,N'*-tetramethylene-2,2'-bipyridinium, TV²⁺, which diffused freely in the aqueous solution within the porous network.

(20) Samuel, J.; Strinkovski, A.; Shalom, S.; Lieberman, K.; Ottolenghi, M.; Avnir, D.; Lewis, A. *Mater. Lett.* **1994**, *21*, 431.

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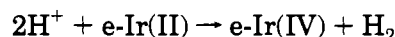
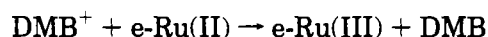
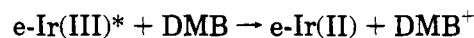
(23) Kaufman, V. R.; Levy, D.; Avnir, D. *J. Non-Cryst. Solids* **1986**, *82*, 103.

(24) Levy, D.; Avnir, D. *J. Phys. Chem.* **1988**, *92*, 4734.

(25) Levy, D.; Einhorn, S.; Avnir, D. *J. Non-Cryst. Solids* **1989**, *113*, 137.

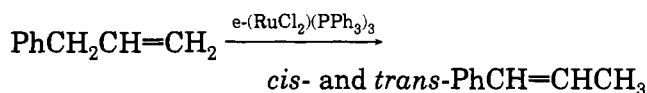
(26) Slama-Schwok, A.; Ottolenghi, M.; Avnir, D. *Nature* **1992**, *355*, 240.

Photoinduced charge separations of this type can be used for subsequent useful reactions.²⁷⁻²⁹ An example is the series of reactions in which H₃O⁺ was reduced to H₂: A donor, Ru(bpy)₃²⁺ (Ru(II)), and an acceptor, Ir(bpy)₂(C,³N')bpy³⁺ (Ir(III)), were coentrapped in an SiO₂ sol-gel matrix, and dimethoxybenzene (DMB) was used as the redox shuttler between the Ir and Ru (Here and below, I use the symbol "e-compound" to mark the entrapped species and to distinguish it from the diffusible one).

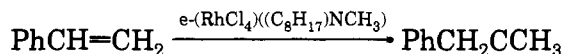


2.2. Organometallic Catalysis. The sol-gel approach has been used in catalysis in three main directions: preparation of inorganic oxide catalysts;³⁰ entrapment of metal microcrystallites;³¹ and polymerization of trialkoxysilyl derivatives of metal ligands.^{32,33} In accordance with our general theme, we have experimented with a fourth direction, namely, straightforward entrapment of organometallic catalysts in sol-gel matrices.³⁴ These catalysts include RuCl₂(PPh₃)₃, RhCl(PPh₃)₃, IrCl(CO)(PPh₃)₃, and their sulfonated analogues, where Ph₂-3-C₆H₄SO₃Na replaces a PPh₃ ligand; dirhodium complexes; and, in particular, quaternary organic ammonium salts of Ru, Ph, Ir, and Pt which have been shown to be versatile catalysts under homogeneous and phase transfer conditions. These were prepared from the chlorides of the metals and from a wide variety of ammonium salts, including (Bu₄N)Br, ((C₇H₁₅)₄N)Br, ((C₈H₁₇)₄N)Br, and others.

The sol-gel doped ion-pair catalysts proved to be versatile and recyclable, and they undergo little or no leaching. Some of the reactions carried out with these heterogeneous catalysts included double-bond isomerizations,



hydrogenations, e.g.,



hydroformylations, e.g.,

(27) Slama-Schwok, A.; Avnir, D.; Ottolenghi, M. *J. Phys. Chem.* **1989**, *93*, 7544.

(28) (a) Slama-Schwok, A.; Avnir, D.; Ottolenghi, M. *J. Am. Chem. Soc.* **1991**, *113*, 3984. (b) Slama-Schwok, A.; Avnir, D.; Ottolenghi, M., *Photochem. Photobiol.* **1991**, *54*, 525.

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(34) (a) Rosenfeld, A.; Avnir, D.; Blum, J. *J. Chem. Soc., Chem. Commun.* **1993**, 583. (b) Blum, J.; Rosenfeld, A.; Polak, N.; Israelson, O.; Schumann, H.; Avnir, D. *J. Mol. Catal.*, in press. (c) Rosenfeld, A.; et al. Manuscript in preparation.

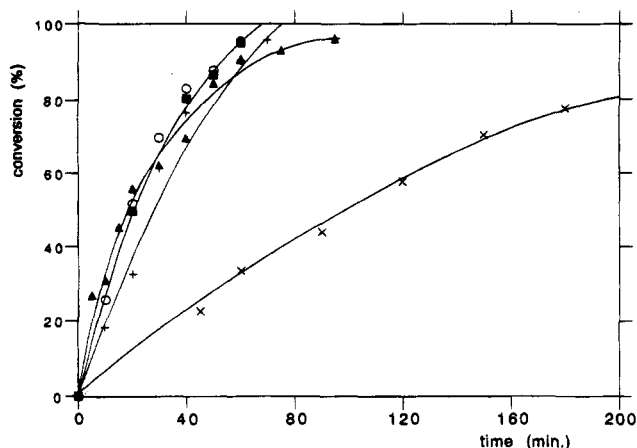
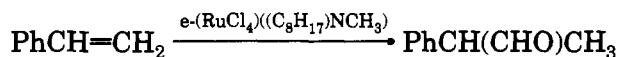
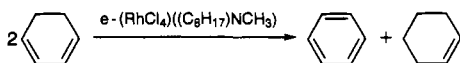


Figure 2. Catalytic sol-gel matrices. Doped sol-gel matrices are convenient heterogeneous catalysts. These range from the well-known dispersed metals and oxides to the novel entrapment of photocatalysts, of biocatalysts, and, shown here, of organometallic catalysts for organic synthesis. An efficient, recyclable catalyst for a variety of disproportionation reactions was obtained^{34b,c} by the entrapment of $(\text{RhCl})((\text{C}_8\text{H}_{17})\text{CH}_3)$ in an SiO_2 sol-gel matrix. The conversions for four cycles (1, O; 2, ■; 3, ▲; 4, +) of disproportionating 1,2-dihydronaphthalene to naphthalene and 1,2,3,4-tetrahydronaphthalene at 110 °C in toluene are seen to be practically the same in each cycle. The catalyst had to be activated by boiling water, to open somewhat the pores; prior to activation, the reaction is much slower (x).



and disproportionations such as with 1,2-dihydronaphthalene (Figure 2) or with 1,2-dihydrobenzene:



In many of these reactions, significant acceleration over homogeneous conditions was observed, and product distribution altered. Thus, while the homogeneous catalyst promoted only very slow hydroformylation of styrene under phase transfer conditions, and not at all in water-free toluene, the heterogeneous reaction mentioned above resulted in full conversion to the aldehyde with high selectivity of the addition to the double bond.

2.3. Doped Sol-Gel Matrices as Chemical Sensors. The widest array of chemical reactions which has been carried out within sol-gel matrices was revealed while the doped sol-gel methodology for chemical sensing purposes was being developed.^{3,35,36} They include proton transfer reactions (such as pH indicators), redox reactions, complexations, ligand exchanges, enzymatic reactions, and more.³ Common to these reactions is their ability to sense chemical changes in the environment of the entrapped molecule, revealing it through color-developing reactions between the entrapped reagent and an external diffusible chemical species or through emission of light. The chemical inertness and the optical transparency of SiO_2 sol-gel matrices have made the doping method-

ology quite attractive for sensor developments. References 3 and 36 summarize various sensing reactions that have been demonstrated successfully with the sol-gel methodology. These include many toxic metal cations, anions, and various pollutants.

An attractive feature for sensing purposes is that sol-gel materials can be made in various forms, as the analytical or optical method requires. Thus, one can prepare the sensing materials as a monolithic block,³⁷ as a microscopic grain,^{20,21} as a thin film on a flat support,³⁸ as an optical fiber coating,^{39,40} and in chromatographic capillary tubes.⁴¹

Extremely high sensitivities are achievable with sol-gel sensors. An example is the sensing of Fe^{2+} ,³⁵ detected through its red-colored complex with three molecules of *o*-phenanthroline. This color evolution is far from being obvious: *three* entrapped phenanthroline molecules must complex with the penetrating Fe^{2+} in order to form a color which is identical to the one formed in aqueous solution, as indeed is the case^{36,42} (I return to this point in section 3). The response curve of an *e-o*-phenanthroline (0.025%) SiO_2 porous glass to various concentrations of Fe^{2+} revealed an exceedingly high sensitivity with a detection limit of about 100 ppt (about 2 orders of magnitude better than conventional solution absorption spectroscopy).^{36,42} This very high sensitivity is due to a unique feature of the sol-gel matrix: being actually a high-surface area adsorbent, it *concentrates* by adsorption the impurity and then detects it. Facile detection of Fe^{2+} was also demonstrated by Lev et al., who developed the use of doped sol-gel particles as sensing chromatographic materials, packed within capillaries.⁴¹ The idea is simple and convenient: the capillary is immersed in a given volume of solution containing the analyte; the solution is driven up by capillary forces, leaving behind a stain, the length of which is proportional to the concentration of the analyte. Besides Fe^{2+} , this approach was demonstrated for other analytes.⁴¹

The development of sol-gel pH sensors (Figure 3) attracted several laboratories, employing various indicators and various techniques based both on light absorption^{37,41} and on fluorescence emission.^{40,43} Techniques included, as mentioned above, simple monolithic disks embedded with various routine indicators,^{35,37} thin film,³⁹ various fluorescent fiber optics configurations,^{39,40} the capillaries,^{41,44} and prototype pH-meters constructed with some of these techniques.^{37,40} For continuous, long-term, reversible applications, leaching must be eliminated, and so doping with trialkoxysilyl derivatives of the pH indicators may become desirable. One such example is methylred, which was derivatized through its carboxylate moiety with (trimethoxysilyl)propylamine²¹ (shifting the pK_i from 5.2 to 3.0). Doping with trialkoxy

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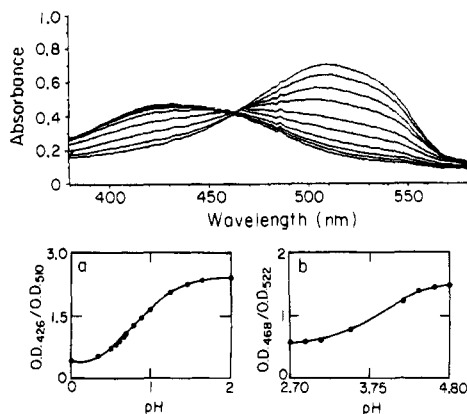


Figure 3. Sol-gel sensors. The optical properties of the sol-gel matrix and its inertness make it an ideal choice as a host for sensing reactions. In most cases, the known chemistry of the entrapped indicator remains basically unchanged, although a shift in the range of activity may be observed, due to cage effects, as in the example shown here: methyl-orange, a pH indicator, exhibits its characteristic isosbestic point (top) and sigmoid titration curve (a) when entrapped in SiO_2 , but the pK_a is shifted to lower values, compared with solution (b).³⁷

derivatives is a general solution for cases which are hampered by leaching.

An important future aspect for the development of useful applications of doped sol-gel sensors is miniaturization. One step toward that goal was recently undertaken^{20,21} with the fluorescent pH probe pyranine.⁴⁵ A pH-meter based on a 10 μm piece of doped sol-gel was constructed by incorporating it in a near-field optical microscopy configuration, which consists of metal-coated micropipet tips: a good, reversible titration curve was obtained. Further miniaturizing to $\sim 1 \mu\text{m}$ was achieved as well, with subsecond response time.

2.4. Sol-Gel Matrices Doped with Enzymes and Antibodies. This remarkable aspect of doped sol-gel chemistry had been discovered fairly recently⁴⁶ and already has motivated intensive activity (which was recently reviewed in detail in refs 47 and 48d; so only some highlights are summarized here). "Remarkable", because a priori there was no reason to believe that sol-gel encapsulation of enzymes would keep them alive. When one considers the ability of the alkoxide to react with the enzyme surface and active site, the pressure buildup on the protein as the matrix shrinks, the release of toxic alcohol during polymerization, and the need to have the active site of the entrapped protein exposed to the pore network, one appreciates the nontriviality of that result.

An intensively studied entrapped enzyme has been glucose oxidase,^{48,49,55b} which catalyzes the oxidation of D-glucose. That reaction is of appreciable diagnostic value, and this application is classically carried out

by utilizing the released H_2O_2 , which is a reaction product (if oxygen is used as an oxidant). H_2O_2 forms then a secondary colored product via a peroxidase-catalyzed oxidation of aromatic aza compounds. Performing this procedure in a sol-gel matrix demonstrated the ability to carry out a multiple-enzyme network of reactions. Actually, enzymes that are hostile to each other and destructive in solution can be brought together in a harmless way when entrapped in the sol-gel matrix. For instance, trypsin autodigests itself completely in solution; by contrast, SiO_2 -entrapped trypsin retained its full activity for several months when incubated at pH 7.5.⁴⁹ Returning to glucose oxidase, a reversible optical glucose sensor was constructed by Braun et al.,⁵⁰ employing the decoloration of the isoalloxazine moiety in the enzyme upon reductive complexation with glucose. Electrochemical detection of glucose with sol-gel enzymatic electrodes was carried out by several research groups.⁵¹

Some of the entrapped enzymes show remarkable enhancement in stability.^{46,52} Thus, acid phosphatase, which in solution at 70 °C and pH 5.6 lived for less than 0.1 min, had a 2 orders of magnitude jump in its half-life to 12 min in the entrapped form.⁵² Since denaturation of enzymes involves folding-unfolding of the peptide chain, we attribute the enhanced stability to the rigidity of the SiO_2 cage, which apparently restricts such motions. It has been demonstrated in a number of experiments that the geometric accessibility of the entrapped enzyme to incoming substrate molecules is perhaps the most important parameter which dictates its activity.^{49,52} For instance, the efficiency of trypsin inhibitors, a set of benzoyl arginine derivatives, was found to be linked to their size.⁴⁹

Many enzymes have been entrapped successfully in sol-gel matrices.^{47,48d} The entrapment of parathion hydrolase,^{47,53} which is capable of detoxifying and detecting the pesticide parathion, demonstrates the potential of the sol-gel methodology in environmental applications.

Of special interest are the entrapments of antibodies. Although this field is still in its infancy, a number of promising recent reports point to the great potential of this direction. These reports include the covalent bonding of antibodies to functionalized sol-gel films,⁵⁴ the entrapment of polyclonal fluorescein,^{55a} the development of a sol-gel enzyme-linked immunosorbent assay (ELISA) test for antigenic parasitic protozoa,⁵⁶ and our own study of the entrapment of *anti-2,4-*

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dinitrobenzene, a common moiety in many polluting pesticides.²¹ Finally, various nonenzymatic proteins, whole cell extracts, and whole intact cell were also entrapped successfully in sol-gel matrices,⁵⁷ and these are reviewed in ref 47, as well.

3. Properties of the Sol-Gel Cage

Understanding the reactivity of doped sol-gel glasses is intimately linked with understanding the nature of the entrapment and the cage properties. Various spectroscopies were used for studying the dopant cage properties and their evolution in time along the monomer → oligomer → sol → gel → xerogel transition. The main tools have been UV-visible absorption and emission spectroscopies, and to a lesser extent other spectroscopies such as EPR.⁵⁸ Following the evolution of the sol-gel process and the evolution of various cage properties was first done with pyrene^{23,59} (Py) because of its relatively long singlet lifetime (~100 ns), its distinct vibronic peaks in the fluorescence spectrum, and its ability to form an excited state dimer, i.e., the excimer, Py^*_2 , and because of the sensitivity of these parameters to changes in environmental conditions. With this probe, the changing polarity and the changing structure around the probe, from adsorption onto the surface of the growing SiO_2 particles up to the complete isolation in microporous cages, were detected and monitored.⁵⁹ Many sol-gel studies have utilized that useful probe.⁶⁰

Some other photophysical probes which were used for following the sol-gel transitions include 7-azaindole,⁶¹ 1- and 2-naphthols,⁶² pyrene-3-carboxaldehyde,⁶³ $\text{ReC}(\text{CO}_3)\text{bipyridine}$ (as a probe for cage rigidity),⁶⁴ thymol-blue,⁶⁵ and Rhodamine B.^{19b} Photochromic compounds were also used by us for the investigation of the sol-gel xerogel transition in $\text{Si}(\text{OCH}_3)_4$,²³⁻²⁵ and substituent effects on the point of the change from normal to reversed photochromism (Figure 1) were analyzed in terms of Hammett parameters.²⁴

A pyrene derivative, 8-hydroxy-1,3,6-pyrenesulfonic acid (pyranine), was successfully used⁴⁵ for the detection of water during the early stages of the polymerization of $\text{Si}(\text{OCH}_3)_4$ (Figure 4). The idea of using this probe molecule is based on the fact that its excited state is a short-lived strong acid, capable of efficient proton transfer to neighboring water molecules, leaving behind the anion of pyranine in its excited state. Pyranine was also used by Pouxviel et al. for studying aluminosilicate sol-gels: here, too, that probe proved to be a highly sensitive probe to changes in water content.⁶⁶

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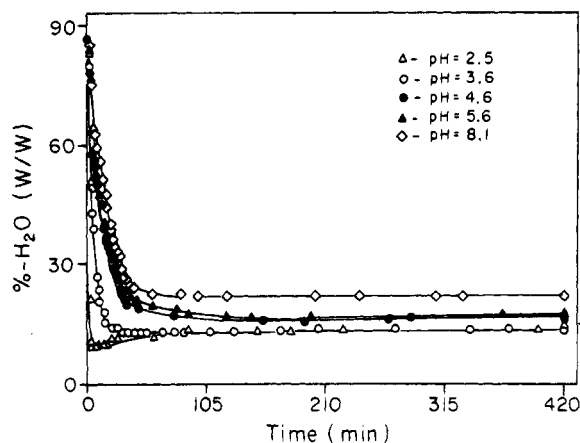


Figure 4. The sol-gel-xerogel transitions. The use of photo-probes for following the structural changes that the matrix undergoes during its formation proved to be particularly informative. Shown here is the use of an excited state acid, pyranine, to follow the kinetics of water release and water consumption during the first several hours of a water/silane = 4 gel formation, at various pH's. The very fast consumption of water at the lowest pH (the hydrolysis stage), followed by its slow release (the condensation stage), is clearly seen.⁴⁵

In addition to the spectroscopic follow-up of the sol-gel process, much research was devoted to the analysis of the cage properties at the final xerogel stage. Early detailed spectroscopic analysis of absorption and emission spectra of R6G, a laser dye, in SiO_2 sol-gel¹ indicated that the polarity of the immediate environment of the dopant is high and due to hydroxyls, although less polar than water (as obtained also with Py as a probe). The ability of the matrix to isolate efficiently one molecule from the other, even at high concentration, first observed for that dopant,¹ led to an intensive study of doped sol-gel materials for a variety of optical uses, notably, as dye laser components.^{4,5,67} We know today, however, that this is not universal and that high concentrations may lead eventually to some aggregation. This was found for proteins⁴⁷ and for $\text{Ru}(\text{bpy})_3^{2+}$.^{12b} Dopant aggregation may also be the way in which three doped *o*-phenanthroline ligands find their way to complex a single Fe^{2+} ion.³⁵

An indication as to the homogeneity of the entrapment comes from the analysis of a decay profile of the excited state in the final xerogel. First-order decays point to homogeneity of distribution and were found, for instance, in $\text{e-Ru}(\text{bpy})_3^{2+}/\text{SiO}_2\text{-TiO}_2$ (films)^{12b} and in $\text{e-biphenylcarboxylic acid}/\text{SiO}_2$.⁶⁸ The protective nature of the sol-gel cage has been clearly evident in these two cases and later on in many other studies. For instance, in the case of $\text{e-Ru}(\text{bpy})_3^{2+}$, the observed lifetime in solution at a concentration of 1×10^{-3} M is 0.3 μs , but at the same concentration in a sol-gel matrix, there is a 6-fold increase to 1.9 μs .^{12b} Photostability to prolonged irradiation is another indication for the protective nature of the cage.^{1,19b} For instance, the degradation half-life of oxazine-4 increased 4-fold by entrapment, compared to solution.^{12b} One of the most striking manifestations of the special protective

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properties of the sol-gel caging has been the ability to obtain room temperature phosphorescence (RTP), under regular atmospheric conditions, from a very wide range of organic molecules,⁶⁸ many of which reveal that emission only at cryogenic temperatures and in vacuum. Examples include polycyclic hydrocarbons,^{23,68} dyes like eosin-y, bases like quinine, and acids such as 4-biphenylcarboxylic acid.

The question of rigidity of the sol-gel cage^{58a,64} accompanied the research in this class of materials from its very beginning.¹ Both the rigidity and polarity of the cage can be altered by changing the monomer, by the incorporation of suitable additives, and by copolymerization. A nice example is the encapsulation of photochromic spiropyrans mentioned above.²³⁻²⁵ When the entrapment is in pure SiO₂, the photochromism is observable only up to the wet-gel stage.²⁴ Beyond it, the cage becomes so rigid that the isomerization between the closed spiro form (colorless) and the open merocyanine colored zwitterion stops at the final dried xerogel stage. A straightforward method to relax the rigidity is to use a three-dentate monomer, rather than the normal tetraalkoxy monomer, thus reducing the degree of cross-linking. Indeed, entrapment of the spiropyrans in a sol-gel matrix prepared from ethyltriethoxysilane provided the needed flexibility for lasting photochromism.²⁵ A marked effect of an additive on cage properties was observed in the case of entrapped pH indicators:³⁷ Addition of a surface active agent, such as cetyltrimethylammonium bromide, shifted the pK_i by 2 units to a more acidic indicating action.

For practical applications, a delicate balance should be found between good isolation and protection on one hand and sufficient accessibility of the entrapped molecule to external reactants on the other. Evidence is accumulating that high acidity and low water/silane ratio do the trick, at least in some cases (for example, in the entrapment of pyranine^{20,21} as a fluorescent pH sensor and in the entrapment of Py^{16,21} as a fluorescent sensor for oxygen). However, these need not be necessary conditions: the entrapped quaternary ammonium metal catalysts mentioned above do not leach out even though prepared under neutral conditions,³³ and enzymes and antibodies do not leach out because of their sheer size.⁴⁷

The last cage property I would like to comment on is symmetry. We have studied that property by entrapment of Eu³⁺ (as its chloride, obtained in situ from Eu₂O₃/HCl) in SiO₂ sol-gel,⁶⁹ and although it is an inorganic dopant, I am describing it here because that report led to many studies of Eu³⁺-doped sol-gel matrices, including both organic and inorganic ligands,⁷⁰ as well as to many studies of doping with

other transition-metal cations.⁷¹ Symmetry in the chemical sciences is a rather complex issue,⁷² and the cage symmetry of sol-gel materials is no exception, especially since it involves a population of cages with varying degrees of symmetries (for the concept of degree of symmetry, see ref 72). Yet Eu³⁺, which is known to be an excellent indicator for site symmetry,⁴ allows at least an average picture of that property. The basis of this symmetry probe is that the lowering of local symmetry enhances radiative transitions in that cation, and particularly sensitive is the ⁵D₀ → ⁷F₂ emission at 615 nm. In general, we found that the symmetry around Eu³⁺ resembles the solvation shell found in a polar solvent, up to the nonheated, mature wet-gel stage. Upon heating to 100 °C, solvent leaves the gel and the fluorescence spectrum reveals this change by an overall increase in intensity and by a relative increase in the ⁵D₀ → ⁷F₂ transition intensity. Thus, as the amount of OH groups is reduced, the symmetry around the cation decreases.

4. Concluding Remarks

I have selected to concentrate in this brief review on the special cage properties of the sol-gel matrix and on reactive sol-gel materials. However, the activity in organically doped sol-gel materials in optics (Figure 2) and photophysics (without a chemical reaction) is at least as voluminous and has spanned a longer period. References 4 and 67 contain many examples. Other important and interesting studies with doped sol-gel materials which did not find their way into this review for lack of space are doped sol-gel electrochemistry,¹⁸ sol-gel chromatographic and ion-exchanging materials,⁷³ chemiluminescence of doped sol-gel matrices,⁷⁴ the formation of Belousov-Zhabotinskii spirals in a sol-gel matrix,⁷⁵ and fractal analyses of sol-gel structures.⁷⁶

It is my hope that this brief overview of a new family of materials, at the crossroads of organic and inorganic chemistry, will stimulate researchers and students to consider this new frontier of materials chemistry for solving problems of their own scientific endeavors, and as a potential solution for the design of useful devices.

I set sail on this project in 1982 with Prof. R. Reisfeld and Dr. David Levy, then an M.Sc. student, and have continued to collaborate with them for many years. The results of this collaboration are summarized mainly in section 3. The material presented in section 2 has been developed as a joint project in collaboration with the research groups of Prof. J. Blum (catalysis), Dr. S. Braun (biochemistry), Dr. O. Lev (sensors and environmental issues), and Prof. M. Ottolenghi (reactivity of sol-gel materials and especially photoreactivity). This being an interdisciplinary project, none of it could have been achieved without these collaborations. Special thanks are due to Dr. M. Altstein, Prof. D. Huppert, Dr. V. R. Kaufman, Prof. L. C. Klein, Prof. A. Lewis, Dr. D. Pines-Rojanski, Y. Polevaya, A. Rosenfeld, C. Rottmann, Dr. J. Samuel, H. Sertchook, Prof. H. Schumann, Dr. A. Slama-Schwok, A. Turniansky, and Dr. R. Zusman. The Sol-Gel project is currently funded by the U.S.-Israel Binational Science Foundation, by the Volkswagen Foundation, by the Israel National Council for Research and Development, and by the Research Institute of Innovative Technology for the Earth-RITE (Kyoto).

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