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I am submitting herewith a thesis written by Bryan Fagan entitled "Applications of Sol-Gel Materials in Analytical Chemistry." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemistry.

Michael J. Sepaniak, Major Professor

We have read this thesis
and recommend its acceptance:

James R Chambers

Accepted for the Council:

Associate Vice Chancellor and
Dean of the Graduate School

Applications of Sol-Gel Materials in Analytical Chemistry

A Thesis

Presented for the

Master of Science

Degree

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Bryan Christopher Fagan

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Dedication

This thesis is dedicated to my mother, brothers,

and grandparents. Without their love and support,

this work would not have been completed.

Acknowledgements

Throughout the years I have spent here at the University of Tennessee, I have had the opportunity to work with many people to whom I owe my gratitude I would like to begin by thanking my research advisors, Dr. Ziling B. Xue and Dr. Michael J Sepaniak, for their guidance and support throughout the course of my graduate study Special thanks also go to Dr. Panos G. Datskos of Oak Ridge National Laboratory for his input on the work presented in Chapter 3 I would also like to thank Dr. James Q. Chambers for being a member of my graduate committee

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Finally, I am especially grateful for the encouragement and support of my parents, brothers, and grandparents. Without your love and support, this would not have all been possible.

Abstract

This thesis describes the development of sol-gel materials for use in analytical chemistry. An overview of the sol-gel process, as well as an introduction to chemical sensors, are presented in Chapter 1 A novel approach to the use of crown ethers for the removal of Sr^{2+} is discussed in Chapter 2. Disulfonated, dibenzo-18-crown-6 encapsulated within a sol-gel matrix is used for the removal of strontium (II) ions from aqueous systems. Sol-gel materials "doped" with crown ethers are shown to exhibit higher uptake of the target metal (Sr^{2+}) compared to blank, non-ligand containing gels. In Chapter 3, a chemical sensor based on the deflection of a surface modified silicon micro-cantilever is presented. A thin film of sol-gel was applied to one side of the micro-cantilever surface using a spin coating procedure. The sensor has been shown to give different responses to vapor phase analytes of varying chemical composition, as well as to varying concentrations of a given analyte. Ethanol, a highly polar molecule, exhibits a strong affinity for the polar sol-gel coating resulting in a large response, pentane, a non-polar hydrocarbon, shows very little response. The sol-gel coating has also been shown to function as a backbone for the immobilization of chemically selective phases on the cantilever surface. Reaction of the sol-gel film with chlorotriethoxysilane and subsequent capping of the remaining reactive surface silanols with hexamethyldisilizane increase the non-polar nature of the film. This results in an increase in the response of the sensor to non-polar analytes. The effects of film thickness and cantilever structure thickness on response were also investigated.

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Chapter 1

Introduction

With the Japanese bombing of Pearl Harbor on December 7, 1941, the United States of America entered into a new era of nuclear weapons production. Extensive manufacturing efforts to create a stockpile of weapons generated extremely large volumes of waste that subsequently resulted in substantial environmental contamination. The rapid production of nuclear weapons continued in full force until growing concerns about safety and environmental issues emerged in the early 1980's At this point, many of the nuclear weapons production sites were temporarily put on hold. It was not until the fall of the Soviet Union in 1991 that many of the production sites were completely shut down.[1]

Much of the waste generated form the production of nuclear weapons is stored in tanks at a number of the Department of Energy sites throughout the United States. Many of these tanks leak and are contaminating the surrounding soil and groundwater. In 1989, the United States Department of Energy created the Office of Environmental Management solely for the purpose of evaluating and developing methods for remediation of this waste.[1] In this thesis, a few potential applications of sol-gel materials

for the quantification and remediation of hazardous waste are investigated. A novel approach to the use of crown ethers for the removal of Sr^{2+} from bulk waste is discussed in Chapter 2. Sol-gel materials are used as a host matrix for the encapsulation of derivatives of 18-crown-6. The crown ether doped sol-gel materials are shown to exhibit higher uptake of the target metal ion (Sr^{2+}) compared to blank, non-ligand containing gels The potential benefits of encapsulation of crown ethers within sol-gel materials for metals separations are discussed therein. In Chapter 3, sol-gel materials are used to enhance performance and impart selectivity to a micro-scale chemical sensor. Thin films of sol-gel are developed on the surfaces of micro-cantilevers by a spin coating process. The sol-gel coated micro-cantilevers are shown to give different responses to vapor phase analytes of varying chemical composition, as well as to varying concentrations of a given analyte. The sol-gel coating is also shown to function as a backbone for the immobilization of chemically selective phases on the micro-cantilever surface By reacting the sol-gel coating with compounds of varying chemical nature, the selectivity of the chemical sensor can be modified

1.1 Sol-Gel Materials

The sol-gel process, first reported by J J Ebelmen in 1846,[2] has attracted interest in the field of analytical chemistry Much of the recent popularity of this technique stems from the ease with which sol-gel materials can be prepared and the ability to adjust a multitude of variables that affect the physical parameters of the resulting material The use of sol-gel materials in analytical chemistry is attractive for a variety of reasons [3-5]

(a) Sol-gel materials are excellent supports for the encapsulation/immobilization of a variety of molecules Sol-gel materials have been used as a host matrix for many organic and inorganic compounds and have been used extensively in the development of sensors.[6]

(b) Compared to organic polymers, sol-gel materials are chemically and mechanically stable in harsh environments SiO_2 materials have been developed for use in acidic environments of pH below 0.[7] Pure SiO_2 materials tend to break down in basic environments above pH = 13; however, metal oxide blends, such as SiO_2/ZrO_2, have been shown to be stable under these conditions.[8]

(c) The sol-gel process is a low temperature process that occurs under mild conditions. This allows for the encapsulation of a variety of chemical and thermal sensitive molecules, including those of biological origin.

(d) Sol-gel materials can be used in a variety of physical forms. Sol-gels can be cast as monoliths, coated as thin films, or ground into powder

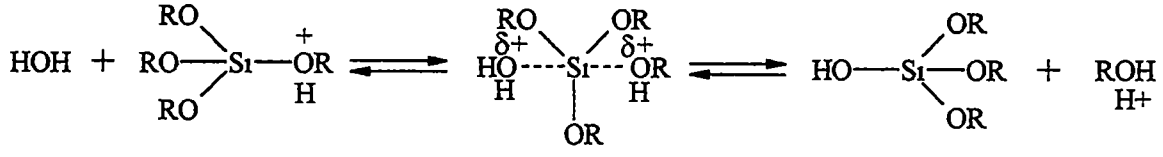
(e) Sol-gel materials are relatively inexpensive to synthesize.

These attributes, along with many others, make sol-gel materials attractive for a wide range of applications The use of sol-gel materials for analytical applications has been reviewed by Collinson.[4]

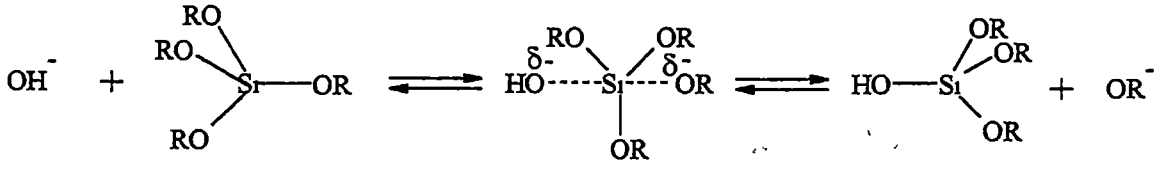
1.2 The Sol-Gel Process

The sol-gel process is a relatively simple technique for the preparation of silicate materials. The process is generally initiated by the hydrolysis of an alkoxide precursor,

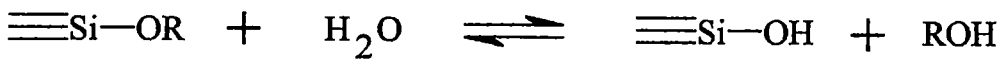
followed by polycondensation reactions to form a cross-linked SiO_2 matrix.[9, 10] Figure 1.1 illustrates the reactions involved in the sol-gel process It is generally argued that both hydrolysis and condensation reactions proceed by bimolecular nuleophilic displacement reactions (S_N2).[5] During hydrolysis, the alkoxide (OR) group attached to the central silicon atom is replaced with hydroxy groups through a bimolecular nucleophilic substitution reaction Due to the relatively low reactivity of silicon alkoxides, a catalyst is often added to increase the rate of hydrolysis [5] Under acidic conditions, the first step of hydrolysis is the protonation of an alkoxide group. The partial charge on the alkoxide group results in the withdrawl of electron density from the central silicon atom, thus making it more electrophilic and more vulnerable to attack by water The water molecule attacks from the rear and forms a penta-coordinated intermediate. The partial positive charge on the alkoxide is reduced, resulting in the loss of alcohol as a good leaving group. This mechanism is illustrated below·



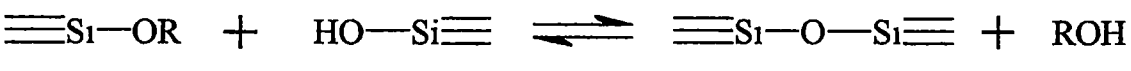
Under basic conditions, the central silicon atom undergoes nucleophilic attack by a hydroxide anion. This also results in a penta-coordinated intermediate, followed by displacement of an alkoxide anion as illustrated below·



Hydrolysis



Condensation



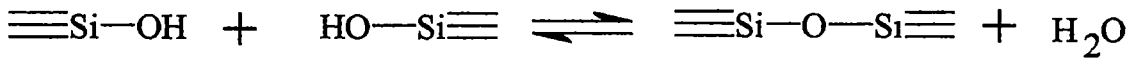


Figure 1.1 Reactions in the sol-gel process

Depending on the extent to which hydrolysis of the alkoxide precursors is complete, two types of condensation reaction can occur.[5] Alcohol condensation occurs when an alkoxide group of a partially hydrolyzed precursor reacts with a hydroxy group of another to form a siloxane bond (Si-O-Si) and generate the corresponding alcohol. When hydrolysis of the precursors is complete, the hydroxy group of one precursor reacts with the hydroxy group of another to produce the siloxane bond and water. This is termed water condensation.

The initial hydrolysis and polycondensation reactions lead to the formation of colloidal particles Once a sufficient quantity of interconnected siloxane bonds form in a region, the siloxane bonds respond cooperatively to form a sol.[9] A sol is defined as "a colloidal suspension of solid particles in a liquid."[5] As time proceeds, the colloidal particles begin to link to form a three-dimensional network As the interconnection between particles increases, the viscosity of the sol continuously increases until a solid gel is formed. As long as the solid gel is not allowed to dry, water and solvent entrapped within the sol-gel matrix allow for polycondensation reactions to continue to occur, thus increasing the degree of cross-linking of the gel This increases the strength of the gel and causes the pores within to become smaller. Eventually, all water and solvent within the gel evaporates or is forced out by the formation of new siloxane bonds or heating. This results in considerable shrinkage of the gel, often reducing the pore volume by a factor of 5-10 compared to the original wet gel. Dried gels, which have lost all water and solvent by evaporation, are called xerogels. Xerogels are considered to be stable with regard to structure [9]

A typical preparation for a sol-gel material might include a silicon alkoxide (tetramethoxysilane) combined with a mixture of water, solvent (usually an alcohol), and a catalyst (acid or base). The physical properties of the resulting sol-gel material are influenced by many parameters. The initial amount of water present in the mixture, often reported as the $H_2O.Si$ molar ratio (r), greatly affects the rates of the hydrolysis and condensation reactions.[11] These reactions, in turn, affect the final properties of the gel. The initial amount of water present determines the extent to which the hydrolysis of the silicon precursors can occur, and thus which condensation reaction will take place. However, because water is a byproduct of the condensation reactions, an initial r value of two is generally sufficient for complete hydrolysis.[5] The alcohol present in the initial mixture is needed due to the fact that alkoxysilanes are not miscible with water.[5] However, the alcohol does not act solely as a solvent. It also plays a major role in the sol-gel process, as it is a byproduct of the condensation reactions. The catalyst is perhaps the most controlling component of the mixture that affects the physical properties of the resulting material. The pH of the sol strongly influences the relative rates of the hydrolysis and condensation reactions.[5, 12] Under acidic conditions, the rate of hydrolysis is large compared to the rate of condensation. Because hydrolysis is essentially complete at an early stage of the sol-gel process, condensation reactions occur between the silanol groups of monomers or the ends of polymers to form a gel of entangled linear chains In general, gels that are formed under acidic conditions with a low r value are dense with small pores.[12] Under basic conditions, condensation reactions occur faster than hydrolysis. Therefore, condensation often occurs between highly branched oligomers to

form particulate gels Gels prepared under basic conditions with a high r value are much more porous compared to their acid catalyzed counterparts [12]

1.3 Sensors

Over the past 20 years, there has been an enormous interest in the development of sensors This is evident in the amount of money invested and the number of articles published in the literature Much of this interest has occurred because of the enormous potential for sensors in industry and environmental monitoring.[13] Increasing concerns with pollution, health, and safety have brought about an escalating desire to monitor potentially hazardous aspects of the environment around us Sensors have been developed for a variety of applications that greatly affect our everyday lives in a multitude of ways. In this section of the thesis, a brief discussion of the fundamentals and applications of sensors will be presented.

A typical sensor consists of three components· the recognition element, the transducer, and the recorder. The recognition element, or selective phase, is used to discriminate between the desired analyte and other species present in the sample. The recognition element is of tremendous importance in the effectiveness of the sensor, as it controls the selectivity and to a degree the sensitivity of the device. The reaction that takes place at the recognition element produces a stimulus, such as the production of heat or a change in mass of the recognition element. The transducer responds to the stimulus, and functions to convert the stimulus into a measurable quantity. The stimulus is often converted to an electrical voltage, charge, or current that can be measured by the

recorder A few common recorders are photomultiplier tubes (PMT's), charge-coupled devices (CCD's), photodiodes, and frequency counters.

There are several characteristics that are desirable in a sensor. The following is a list of those characteristics, with a brief explanation of each:[13, 14]

(a) Quantitative - The sensor output should directly correlate to the amount of analyte present in the sample

(b) Sensitive - Sensitivity indicates the response of the sensor to changes in analyte concentration.[15] This determines the ability of the sensor to differentiate between small differences in analyte concentration

(c) Selective - The ability of a sensor to discriminate between the target analyte and other components present in the sample matrix is termed selectivity. Without sufficient selectivity, the sensor can not be used to relate the signal obtained to the amount of analyte present in a sample. This is perhaps the most challenging aspect of sensor development.

(d) Good signal-to-noise (S/N) ratio - Sensors must have a good S/N ratio in order to measure analytes at low concentrations. It is the S/N ratio that determines the limit of detection of the sensor.

(e) Fast response time - This characteristic is not crucial in all sensor applications. However, in some cases, such as real-time monitoring, fast response time is important.

(f) Reversible - It is often advantageous for a sensor to be reversible. This allows for the sensor to be used repeatedly to measure a desired quantity

(g) No Hysterisis - The signal of the sensor after responding to analyte should return to baseline.

It should be pointed out that the "ideal" sensor does not exist. All sensors deviate from ideal behavior to some extent [13] It is also important to note that it is not always necessary for a sensor to possess all of the desired characteristics. The suitable characteristics are often a function of the application What is vital for a senor in one application, may be of no importance in another.

One class of sensors that has received a great amount of attention over the past few years is chemical sensors For the period of 1994-1997, this field experienced a 44% increase in the number of sensors developed.[16] A chemical sensor is defined as "a device which responds to a particular analyte in a selective way through a chemical reaction and can be used for the qualitative and quantitative determination of the analyte "[17] Chemical sensors are often classified according to their mode of transduction into four major categories· electrochemical, optical, thermal sensitive, and mass sensitive sensors. A full overview of the fundamentals and applications of the four classes of sensors in this thesis is not practical. Extensive reviews are available for further reading.[18, 19] However, because the focus of this thesis is on the use of sol-gel materials in analytical applications, a brief introduction to the modes of operation and applications in which sol-gel materials are used for each of the categories is necessary.

Electrochemical sensors, the largest category of chemical sensors, depend upon the exchange and transport of charge for signal generation. This class of sensors includes both potentiometric and amperometric sensors. Sol-gel materials have been used extensively in the development of electrochemical sensors One application that is of

direct relevance to this thesis involves the use of crown ether derivatives encapsulated within sol-gel materials as ion-sensing membranes for neutral carrier type ion-sensitive field effect transistors (ISFETs) [20] Optical sensors include a wide range of sensors that utilize the interaction of light with a targeted analyte to produce an optically detectable signal Often these interactions between light and the target analyte produce or absorb light of characteristic wavelengths that can be used to directly identify and measure analytes at or near the sensor element. Optical sensors that employ sol-gel derived matrices have been developed for a variety of applications, including biological sensors, metal ion sensors, and pH sensors.[21] Recent advances of optical sensors based on sol-gel materials have been summarized by McCraith *et al.*[22] Thermal sensitive sensors, as the name implies, rely upon a change in temperature about the sensing element for signal generation. An example of a thermal sensor involves the use of a ruthenium complex incorporated within a sol-gel matrix The change in the phosphorescence intensity of the ruthenium complex upon heating was used to determine the temperature of the system.[23] To my knowledge, this is the only sol-gel employing thermal sensitive sensor that exists. Mass sensitive sensors, the category to which the sensor presented in this thesis belongs (Chapter 3), respond in proportion to the mass of analyte that interacts with the surface of the sensing element [18] Perhaps the most common type of sensor in this category is the quartz crystal microbalance.[24] Nanto and coworkers have developed a mass sensitive chemical sensor based on a sol-gel coated quartz crystal resonator. The sensor has been shown to identify various alcoholic beverages based upon the ethanol content Sol-gel materials have also been used on surface acoustic wave (SAW) devices to distinguish between various environmental molecules on the basis of size [25]

Chapter 2

Sol-Gel Encapsulated Crown Ethers: A Novel Approach to Heavy Metals Separation

2.1 Introduction

In recent years, the development of new and improved techniques for the separation of metals and ions from complex mixtures has been of intense interest Much of this interest is due to the estimated 25,000 hazardous waste sites that exist in the United States with an estimated cost of remediation approaching $1 billion.[26] Perhaps the best example to illustrate the formidable challenge that researchers face is the Hanford nuclear site near Richland, Washington Hanford is estimated to contain 1 4 billion m^3 of hazardous materials [27] Much of the hazardous waste at these sites exists in complex mixtures that must be separated prior to storage The separation of various highly active radionuclides from the bulk waste is desirable for both economic and environmental reasons.[28] Because methods for disposal of highly active radionuclides are expensive, separation from bulk waste and concentrating the radionuclides into one area would minimize the volume of waste containing the highly active radionuclides. Also, removal of the highly active radionuclides from the tanks where they are stored would prevent introduction of the materials into the environment. Unfortunately, these separations are

often difficult due to the nature of the matrix involved. High concentrations of other metals exist and the pH of the waste material ranges from highly acidic to highly basic [26] An enormous need exists for a selective phase or compound that is capable of removing the metal of interest while leaving behind the undesirable interferents

Crown ethers, a class of macrocyclic compounds first synthesized in 1967 by Charles Pederson,[29] have attracted enormous interest in the field of hazardous waste treatment based upon their unusual ability to recognize cations in a selective fashion This recognition is based upon the match between the size of the inner ring of the crown ether with the diameter of the targeted cation.[30] Crown ethers are best known for their ability to form stable complexes with alkali and alkaline earth metals,[30] both of which are present in high concentrations in hazardous waste.[1] This characteristic has made crown ethers attractive candidates for the remediation of environmentally hazardous waste.

2.1.1 Crown Ethers in Conventional Metals Separations Techniques

There are several separation techniques in which crown ethers have been used as the selective phase for metal separations [31] Solvent extraction is perhaps the oldest and most widely applied separations technique due to its versatility and the high degree of selectivity that can be achieved [32] This method is generally used for the purification of organic compounds, however, it can also be used for quantitative separations of both organic and inorganic species In the solvent extraction of metal ions, an extractant with a known high affinity for the metal of interest is dissolved in an organic solvent and brought into contact with an aqueous solution containing the target metal ions [26] The target metal ions are removed from the aqueous phase into the organic phase for

complexation by the extractant. Crown ethers are currently used in a solvent extraction process for the removal of Sr^{2+} from tank waste. The SREX process utilizes di-t-butyl-cyclohexano-18-crown-6 dissolved in 1-octanol to achieve separation. The process has been shown to remove greater than 99% of the Sr^{2+} from an actual sample of Hanford tank waste.[28] Although solvent extraction with crown ethers is a well developed technique and provides excellent results, it is not without its drawbacks. Firstly, an enormous amount of organic waste is generated which must be disposed of properly. Secondly, many crown ethers have some degree of solubility in water. Because many of these crown ethers are expensive to synthesize, substantial loss of the crown ether could deem a separation unadvantageous on the basis of high cost. In addition to high cost, the introduction of crown ethers, many of which are toxic, into the aqueous phase can offset the advantage gained from the separation.[26]

In an effort to alleviate the problems associated with solvent extraction, crown ethers have been bound to solid supports for the separation of metals. Crown ethers covalently bound to silica gel have been shown successful in the separation and concentration of many metal ions [33-37] The process of using crown ethers immobilized on silica gel to remove, separate, and concentrate metal ions from aqueous systems has been commercialized by IBC Advanced Technologies under the trade name Superlig [33, 38] Crown ethers have also been bound to organic polymers for metal separations [26, 39] Attachment of the selective phase to a solid support eliminates the large volumes of organic waste produced and the potential loss of valuable extractants associated with solvent extraction However, immobilization often requires multi-step syntheses to attach functional groups to anchor the extractant to the solid support In addition,

immobilization can limit the flexibility needed for an extractant to obtain the optimal configuration for complexation of a metal ion.[39]

2.1.2 Our Approach To Metals Separation Using Crown Ethers

Our approach to metals separation involves the use of SiO_2 sol-gel materials as a host matrix for the encapsulation of crown ethers A schematic representation of the principle is shown in Figure 2 1 The ability to control the average pore size of sol-gel materials has made them ideal candidates for the encapsulation of molecules of different sizes. Encapsulation eliminates the time consuming process of functionalizing crown ethers to attach them to solid supports Physical entrapment is also functionally noninvasive and preserves the binding capacity of the crown ether in free solution Avnir and coworkers first illustrated the principle of encapsulation of materials within a sol-gel matrix in their work with Rhodamine 6G.[40] Since then, a variety of compounds have been encapsulated within sol-gel matrices for a multitude of applications.[9, 20, 41-43]

In this work, derivatives of 18-crown-6 are encapsulated within sol-gel matrices to investigate the development of a sol-gel sorbent for the separation of Sr^{2+} from aqueous systems. Derivatives of 18-crown-6 were chosen due to the close match of the inner ring size with the radius of the Sr^{2+} cation. The inner ring of 18-crown-6 has a diameter of 260-320 pm, while the Sr^{2+}cation has a diameter of 236 pm [44] The size of the pores within the sol-gel matrix are tailored to be small enough to prevent excessive leaching, yet large enough to allow diffusion of the target metal into and out of the SiO_2 matrix. Unlike other sorbents that utilize hydrophobic organic supports, hydrophilic inorganic sol-gels are useable in aqueous systems

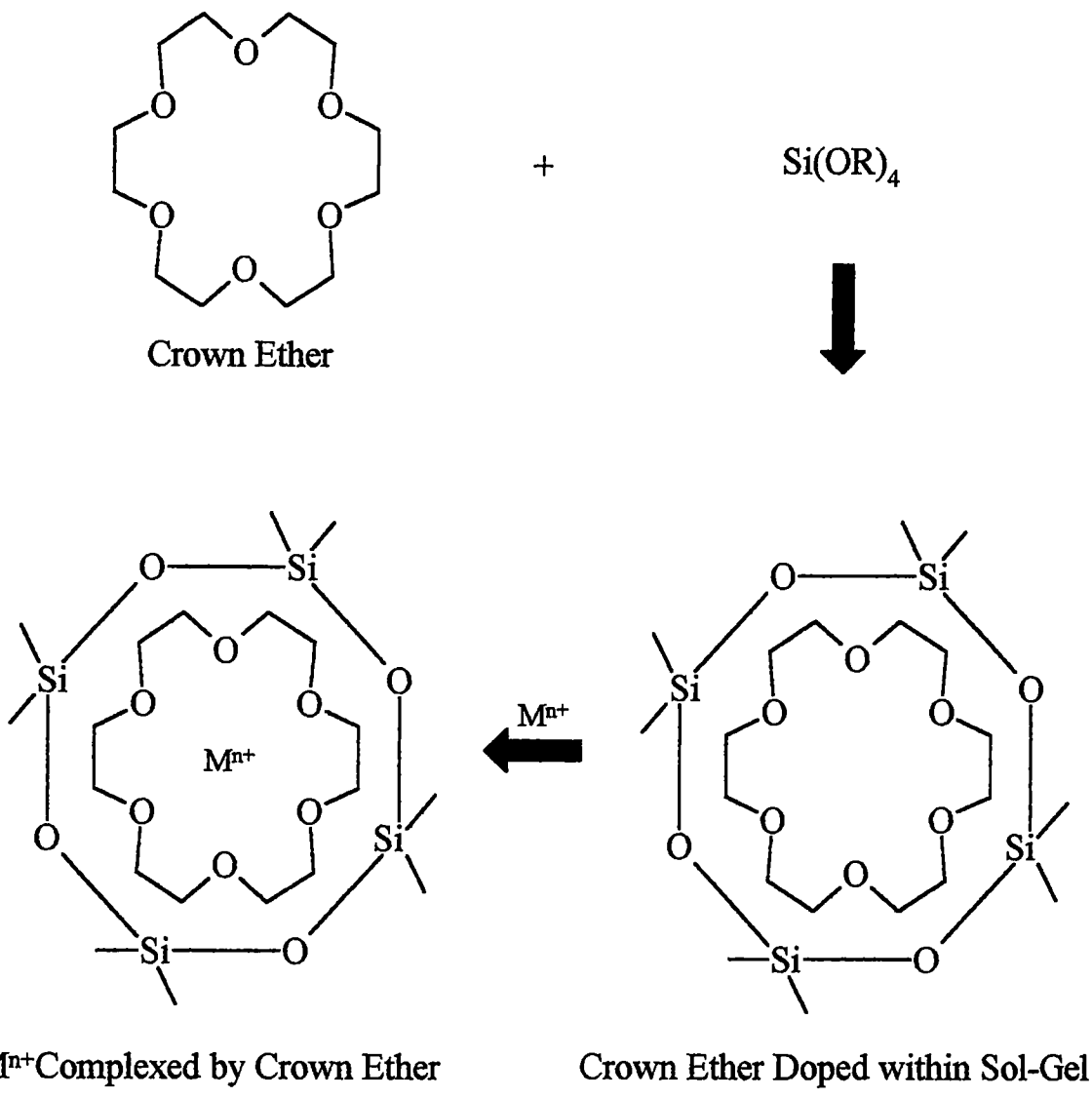


Figure 2.1 Schematic representation of the presented principle

2.1.3 Why Target Strontium (II)?

^{90}Strontium is one of the principal components of waste generated from the production of nuclear power and weapons.[1] As discussed in Chapter 1, much of this highly radioactive waste is stored in tanks at a few DOE sites. Unfortunately, some of these have been found to leak and introduce toxic ^{90}strontium (II) into the environment. ^{90}Strontium in the environment will exist for a long period of time due to its relatively long half-life of 29.1 years [45] Perhaps what is most alarming is the fact that ^{90}strontium is a "bone seeking radionuclide," because of its similarity to calcium.[46] ^{90}Strontium is has been found to incorporate into animals and be stored in the bones The highly penetrating β particles emitted from ^{90}strontium have been shown to totally irradiate the bone marrow of beagle dogs and cause cancerous tumors.[47] Therefore, the separation of ^{90}strontium from hazardous waste is of intense current interest because of the threat it imposes to the environment and humans

2.2 Experimental Section

2.2.1 Chemicals

The chemicals used in this study were used as received from the manufacturers. Tetramethoxysilane (99%) was received from Aldrich Chemical Comapany (Fair Lawn, NJ, USA). $SrCl_2 \bullet 6H_2O$, HCl, H_2SO_4, acetonitrile, lithium hydroxide, 3,5 dimethylphenol, and methanol were received from Fisher Scientific (Fair Lawn, NJ, USA) *cis*-Dicyclohexano-18-crown-6 (mixture of syn-cis and anti-cis isomers) and Dibenzo-18-crown-6 were received from Acros Organics (New Jersey, USA). Deionized water was used in all reactions, preparations of sol-gel materials, and preparations of

aqueous solutions Leaching of *cis*-dicyclohexano-18-crown-6 was determined by ^1H NMR spectroscopy using a Bruker AC-250 spectrometer and 3,5 dimethylphenol as an internal standard. Leaching of Disulfonated-dibenzo-18-crown-6 was determined by UV/VIS spectroscopy on a Hewlett Packard 8452A diode array spectrometer using a 1.0 cm quartz cell

2.2.2 Preparation of Disulfonated, Dibenzo-18-Crown-6

Disulfonated, dibenzo-18-crown-6 was synthesized with slight variations according to the procedure of Sasaki and coworkers [48] The literature procedure was for the preparation of the tetramethylammonium salt of disulfonated, dibenzo-18-crown-6. However, due to solubility problems with this salt in the preparation of sol-gel materials, the lithium salt was prepared. The lithium salt was chosen due to the small size of the Li^+ cation, thus the improbable complexation with the crown ether.

In a 3-neck roundbottom flask, 2.59 g of dibenzo-18-crown-6 was dissolved in 40 mL of acetonitrile. The solution was mechanically stirred for 10 min. After adding 1.62 g of H_2SO_4 from a dropping funnel, the solution was refluxed at 80 °C for 1 h. A dark, oily substance formed on the bottom of the flask. The solvent was then slowly distilled away at 96 °C until no solvent remained. To the flask containing the viscous, brown substance, 100 mL of a 0.5% (w/w) solution of LiOH in methanol was then added. The solution was allowed to stir for 12 h to ensure complete reaction of Li^+ with the sulfonate groups of the crown. The product was then twice recrystallized from methanol/acetone solutions.

2.2.3 Preparation of Sol-Gel Materials

2.2.3.1 Acid Catalyzed Preparation of *cis*-Dicyclohexano-18-Crown-6 Containing Gels (Gel 1)

cis-dicyclohexano-18-crown-6 (0.1208 g) was dissolved in a mixture of 250 μL of methanol and 100 μL of H_2O. To this mixture, 400 μL of TMOS was added, followed by 50 μL of 0.01 M HCl to catalyze the reaction. The solution was mechanically stirred for 30 min to ensure proper mixing. The solid gel formed in ~60 h. The gel remained in the capped vial for 1 week to continue polymerization. The gel was then placed in a 45 °C oven for 48 h to dry.

2.2.3.2 Acid Catalyzed Preparation of *cis*-Dicyclohexano-18-Crown-6 Containing Gels (Gel 2)

cis-dicyclohexano-18-crown-6 (0.1208 g) was dissolved in a mixture of 250 μL of methanol and 100 μL of H_2O. To this mixture, 400 μL of TMOS was added. 150 μL of 0.01 M HCl was then added to catalyze the reaction. The solution was mechanically stirred for 30 min to ensure proper mixing. The solid gel formed in ~95 h. The gel remained in the capped vial for 1 week to continue polymerization. The gel was then placed in a 45 °C oven for 48 h to dry.

2.2.3.3 Acid Catalyzed Preparation of Disulfonated, Dibenzo-18-Crown-6 Containing Gels (Gel 3)

Disulfonated, dibenzo-18-crown-6 (0.1791 g) was dissolved in a mixture of 250 μL of methanol and 100 μL of H_2O To this mixture, 400 μL TMOS was added 50 μL of 0.01 M HCl was added to catalyze the reaction. Time of gelation was ~ 96 h The gel remained in the capped vial for 1 week to continue polymerization. The gel was then place in a 45 °C oven for 48 h to dry.

2.2.3.4 Base Catalyzed Preparation of Disulfonated, Dibenzo-18-crown-6 Containing Gels (Gel 4)

Disulfonated, dibenzo-18-crown-6 (0 0417 g) was dissolved in a mixture of 335 μL of methanol and 420 μL of H_2O. To this mixture, 400 μL of TMOS was added 150 μL of 0 5 M NaOH was added to catalyze the reaction. The gel was mechanically stirred for 30 min to ensure mixing A solid gel was formed after 3 5 h. The gel remained capped for 20 hours to continue polymerization, and was then placed in a 45 °C oven for 12 h to dry

2.2.4 Determination of cis-Dicyclohexano-18-Crown-6 Leaching

A known amount of *cis*-dicyclohexano-18-crown-6 containing gel was weighed into a glass vial and soaked in 3 mL of deionized water for 24 h After 24 h, the supernatant from above the gel was removed with a syringe and replaced with a fresh 3 mL aliquot of deionized water. This procedure was repeated until the gel had undergone four leaching cycles. Once the leaching cycles were complete, the supernatant solutions were combined in a roundbottom flask and the solvent was evaporated off A known amount of 3,5 dimethylphenol was added as an internal standard The contents of the

flask were then dissolved in 5 mL of $CDCL_3$. The amount of *cis*-dicyclohexano-18-crown-6 in this solution was determined by ^1H NMR spectroscopy. By comparing the integration of the peaks from the cis-dicyclohexano-18-crown-6 at ~δ 3.8 ppm (20 protons) to that of the peak from the internal standard at ~δ 6.61 ppm (1 proton), the amount of ligand leached from the gel could be determined according to the following equation:

$$\frac{\dfrac{\text{Integration of Ligand}}{\text{\# of Protons}}}{\dfrac{\text{Integration of Standard}}{\text{\# of Protons}}} = \frac{\dfrac{\text{mg of Ligand}}{\text{Molecular Weight of ligand}}}{\dfrac{\text{mg of Standard}}{\text{Molecular Weight of Standard}}}$$

The NMR spectra of Gel 1 after the first leaching cycle is shown in Figure 2.2.

2.2.5 Determination of Disulfonated, Dibenzo-18-Crown-6 Leaching

A known amount of disulfonated, dibenzo-18-crown-6 containing gel was weighed into a glass vial and soaked in 30 mL of deionized water for 24 h After 24 h, the supernatant from above the gel was removed with a syringe and replaced with 30 mL of fresh deionized water. This procedure was repeated until no ligand was detected in the supernatant A UV/VIS spectra was obtained for each supernatant solution The concentration of disulfonated, dibenzo-18-crown-6 was determined according to Beer's law. The molar absorbtivity for disulfonated, dibenzo-18-crown-6 was determined experimentally to be 4860 ± 4%.

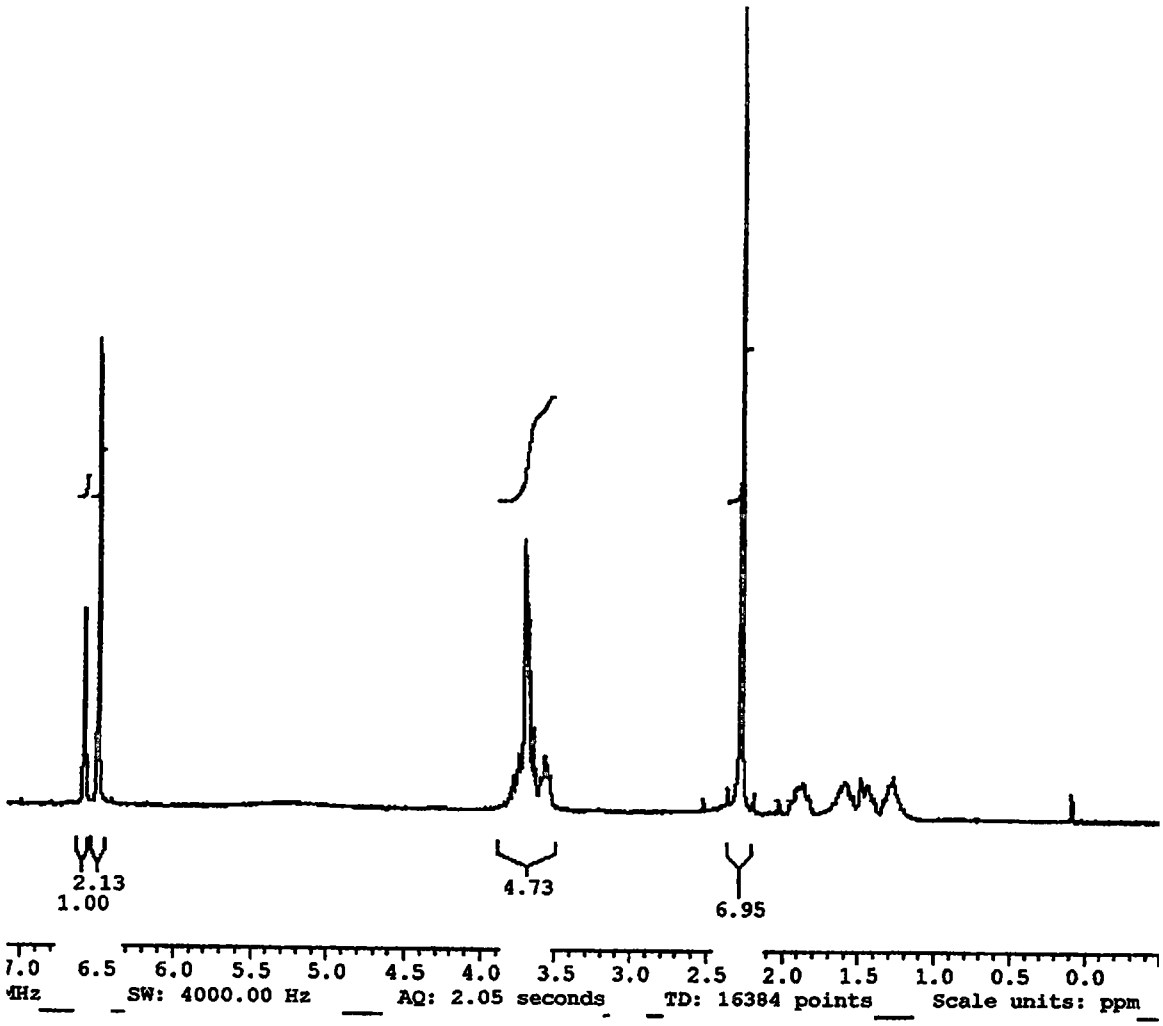


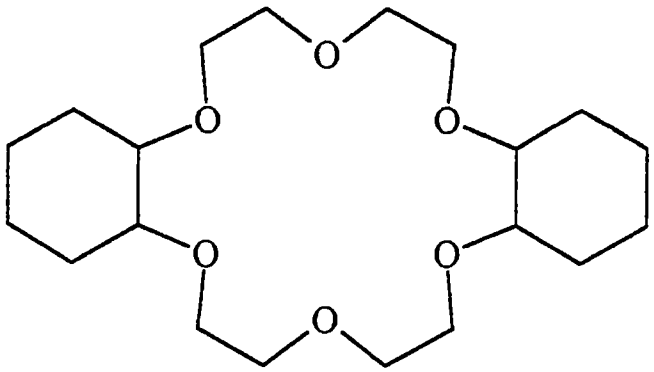
Figure 2.2 NMR spectra of first leaching cycle for Gel 1

2.2.5 Extraction of Sr^{2+}

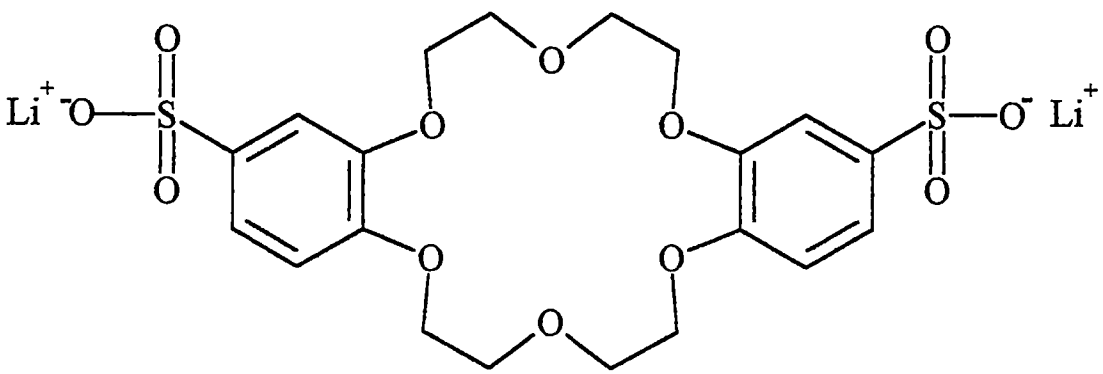
A known amount of dry sol-gel sorbent was weighed into a glass vial To the vial, a known volume of a standard $SrCl_2$ solution was added The gel remained in the $SrCl_2$ solution for a period of 24 h. A portion of the supernatant was then removed for Sr^{2+} analysis by atomic emission spectroscopy The amount of Sr^{2+} absorbed by the sol-gel was determined by the difference in concentrations of the initial stock solution and the Sr^{2+} concentration after extraction

2.2 Results and Discussion

A primary goal of this work was to demonstrate the efficacy of encapsulation of crown ethers within sol-gel materials for Sr^{2+} separation. Encapsulation within a sol-gel matrix is an attractive alternative to other separations techniques in which crown ethers have been used, such as solvent extraction and solid-phase extraction In these preliminary studies, attempts were made to encapsulate derivatives of 18-crown-6, namely *cis*-dicyclohexano-18-crown-6 and disulfonated, dibenzo-18-crown-6, within sol-gel matrices The chemical structures of these compounds are shown in Figure 2.3. These compounds exhibit moderate affinity for Sr^{2+}, with log K values of 3 and 1, respectively.[49] It should be pointed out that other crown-ethers with higher affinities for Sr^{2+} exist; however, many of these compounds are expensive and/or require lengthy syntheses. The compounds used in this work are commercially available or require simple modifications of a commercially available compound. Although the affinities of these compounds for Sr^{2+} are moderate, these compounds should be sufficient to demonstrate the presented principle



(a) Dicyclohexano-18-crown-6



(b) Lithium salt of disulfonated, dibenzo-18-crown-6

Figure 2.3 Chemical structures of compounds used in this work.

2.3.1 Results of Leaching Studies

Perhaps the main concern with encapsulation of crown ethers within sol-gel matrices is that of leaching Usually, the average pore size of the sol-gel material can be tailored to retain the majority of the doped material within the sol-gel matrix It is expected that some of the dopant will leach from the host matrix; however, if too much dopant leaches from the sol-gel, the gel will be inefficient in metal uptake

In the initial experiments, *cis*-dicyclohexano-18-crown-6 was chosen as the dopant material The first gel made (Gel 1) was prepared with a small amount (50 μL) of acid as a catalyst As previously mentioned, acid catalyzed systems result in materials with smaller average pore sizes as compared to those that are base catalyzed. Therefore, it was expected that the bulk of the crown ether would remain within the sol-gel matrix when soaked in water. However, it was determined that 86% of the crown ether leached from the sol-gel matrix after 96 h. In an effort to increase the amount of crown ether retained within the gel, a second gel (Gel 2) was prepared with a larger volume of acid (150 μL) Upon soaking Gel 2 in water for 96 h, it was once again determined that nearly total leaching had occurred, as only 2% remained. Table 2.1 shows the amount of crown ether leached from the *cis*-dicyclohexano-18-crown-6 containing gels in increments of 24 h.

After unsuccessful attempts to dope *cis*-dicyclohexano-18-crown-6 within a sol-gel matrix, attempts were made to dope disulfonated, dibenzo-18-crown-6. Although disulfonated, dibenzo-18-crown-6 has less affinity for Sr^{2+} than *cis*-dicyclohexano-18-crown-6, the increase in size, along with the electrostatic attraction of the charged sulfonate groups for the sol-gel matrix should result in an increase the amount of ligand

Table 2.1 Percentage of ligand leached from *cis*-dicyclohexano-18-crown-6 containing gels

Time (h)	Gel 1	Gel 2
24	49.5	29 8
48	68.5	65 1
72	83.4	89 9
96	85 9	99.1

retained within the host matrix This is in fact what was observed The acid catalyzed gel (Gel 3) was found to retain 71% of the crown ether As expected, the based catalyzed gel (Gel 4) retained less, 35%. Once again, the average pore size associated with base catalyzed systems is larger than that of acid catalyzed systems, thus more leaching occurs. Figure 2.4 illustrates the amount of crown ether leached from both the *cis*-dicyclohexano-18-crown-6 and disulfonated, dibenzo-18-crown-6 containing gels.

2.3.2 Results of Strontium (II) Uptake Studies

Due to the excessive leaching of *cis*-dicyclohexano-18-crown-6 from the gels mentioned above, no Sr^{2+} uptake studies were performed However, the results obtained for the disulfonated, dibenzo-18-crown-6 containing gels were encouraging The results of the Sr^{2+} uptake studies for the disulfonated, dibenzo-18-crown-6 containing gels are summarized in Table 2 2 Although the acid catalyzed Gel 3 retained 71% of the crown ether after leaching, Gel 3 (0 0272 g) showed little or no uptake of Sr^{2+} when soaked in a 10.6 ppm solution of Sr^{2+} Less than 1% of the available crown ether was used for metal ion complexation This is more than likely due to the average pore size of the material being too small to allow diffusion of the metal ion into the sol-gel matrix. Brunauer-Emmett-Teller (BET) nitrogen adsorption analysis indicated an average pore radius of 16.5 Å and a total pore volume of 2 11 x 10^{-3} cc/g. A low pore volume such as that obtained for Gel 3 is indicative of an extremely non-porous material. In an effort to increase the porosity of the material to allow better diffusion of the metal ion into the sol-gel matrix, base catalyzed Gel 4 was prepared BET analysis of Gel 4 indicated an average pore radius of 23.1 Å with a total pore volume of 2 042 x 10^{-3} cc/g. Although the

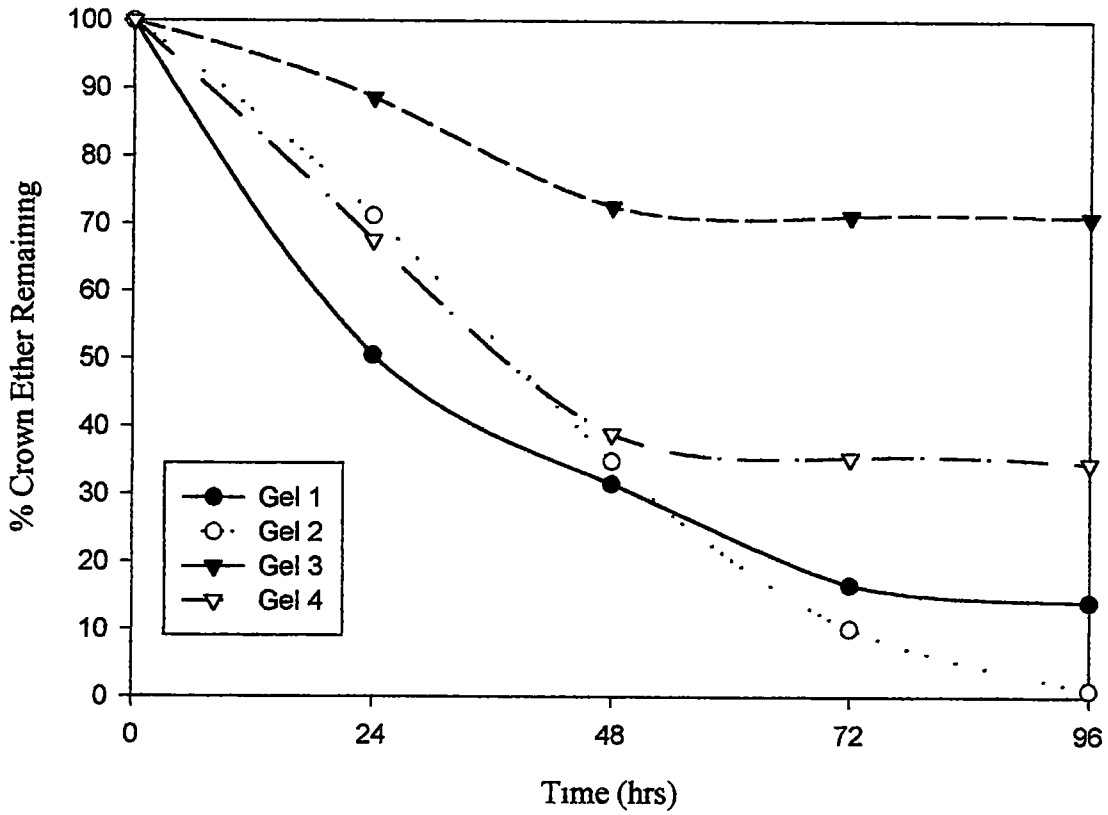


Figure 2.4 Leaching profiles of crown ether containing gels

Table 2.2 Results of Sr (II) uptake studies.

	Initial $[Sr^{2+}]$ [a]	Final $[Sr^{2+}]$ [a]	Capacity [b]	K_d [c]	% Removed
Gel 3	10 6	10 48	5.88×10^{-4}	4.75	2
Gel 4	11.0	2.65	$3\ 07 \times 10^{-2}$	1.01×10^{3}	76
Gel 4 (Blank)	11.0	8.75	8.31×10^{-3}	323	20
Gel 4	50.0	17.9	3.42×10^{-2}	168	64
Gel 4 (Blank)	50 0	50 0	0	0	0

a – Concentration in ppm.

b – Capacity in mmol of Sr^{2+}/ g of gel

c – K_d in [µg of Sr^{2+} / g of gel] / [ppm of Sr^{2+} remaining]

pore volume remains low, the average pore radius increased. Upon soaking Gel 4 (0 0256 g) in 10 mL of 11.0 ppm Sr^{2+}, the concentration of the soak solution was reduced to 2.6 ppm Approximately 33% of the available crown ether was used for metal ion complexation A blank gel, prepared in the same manner as Gel 4 without ligand, only reduced the Sr^{2+} concentration to 8.75 ppm. It was believed that Gel 4 would uptake more Sr^{2+} if placed in a more concentrated solution. A fresh sample of Gel 4 (0.1071 g) in 10 mL of 50.0 ppm Sr^{2+} was shown to reduce the Sr^{2+} concentration to 17 9 ppm In this case, approximately 10% of the available crown ether was used for metal ion complexation. No detectable Sr^{2+} uptake was observed for the blank gel.

2.4 Conclusions

In this work, we have shown that sol-gel materials can function as a host matrix for the encapsulation of crown ethers for metal separations. Encapsulation within sol-gel materials is an attractive alternative to other metal separations techniques in which crown ethers are currently being used, such as solvent extraction and solid phase extraction Because the 18-crown-6 derivatives used in this work exhibit only moderate affinity for the target metal ion, the efficiency of the separation is not that good However, by choosing a dopant with a high affinity, the efficiency should increase The use of 1,4,10,13-tetraoxa-7,16-diazaycloocatadecane-7,16-bis(malonate) encapsulated within a sol-gel matrix for Sr^{2+} separation has been investigated in our lab. This ligand has a high affinity for Sr^{2+}, with a log K value of 9.[50] Sol-gels doped with this ligand have been shown to selectively remove >99% of Sr^{2+} from an aqueous solution in the presence of Ca^{2+}.[51] There are a variety of compounds known to selectively bind certain metal

cations. Encapsulation of these compounds within sol-gel materials could provide a mean for the separation of toxic metals from hazardous waste

Chapter 3

Modification of Micro-Cantilever Sensors with Sol-Gels to Enhance Performance and Immobilize Chemically Selective Phases

3.1 Introduction

Recently, much of the effort in the development of chemical sensors has been focused upon miniaturization of chemical sensors, including those employing micro-cantilevers as the sensing element Micro-cantilever chemical sensors have several advantages over traditional mass-sensitive chemical sensing techniques These sensors have been shown to exhibit over two orders of magnitude greater chemical sensitivity compared to other currently available sensors[18, 52, 53] such as quartz crystal microbalances (QCM)[53], surface acoustic wave (SAW) devices[18, 54], acoustic plate mode (APM) devices[54], chemiresitors[52], and flexural plate wave (FPW) oscillators [54] This increase in sensitivity can somewhat be attributed to the extremely small size of the sensing element With an active area of 10^{-5} cm^2, the micro-cantilevers used in this work have approximately five orders of magnitude smaller area than QCM, SAW, and FPW devices. The inherent advantages of smaller size include faster response time, lower cost of fabrication, the possibility of sensor arrays with small overall dimensions, the ability to explore microenvironments, and improved portability for field applications

To facilitate selective detection of diverse chemical analytes, a chemically selective layer can be deposited onto one side of the micro-cantilever to create a bimaterial actuator. Due to the difference in affinity of the two surfaces for the target analyte, a differential response is achieved causing the cantilever to bend A variety of coatings have been applied to the surface of micro-cantilevers to enhance the chemical sensitivity of the sensor. Micro-cantilevers coated with polydimethylsiloxane[55] and thin films of polymeric chromatographic stationary phases[56] have been used for the detection of volatile organic compounds Gold coatings have been used for the detection of alkanethiols.[57] A sensor for the detection of cesium ions based upon ion-selective self-assembled monolayers on the surface of micro-cantilevers has been developed.[58] Phosphoric acid and bovine skin gelatin have been used for the detection of water vapor.[59] An "artificial nose" based on an array of silicon cantilevers coated with a variety of materials has been developed for the detection of hydrogen, primary alcohols, natural flavors, and water vapor [60, 61] Each of these coatings has been successful in enhancing the sensitivity of the chemical sensor, however, the level of selectivity achievable with chemically modified micro-cantilevers has not been adequately established or investigated.

The use of sol-gel materials for the development of chemical sensors and biosensors is of intense current interest [3, 6, 21, 22] In most applications, the sol-gel material functions as a porous support matrix in which analyte-sensitive species are entrapped.[5] The sol-gel process is attractive because gelation can occur at low temperatures which allows for the encapsulation of a variety of molecules that are temperature sensitive, including biological reagents [9, 62] A glucose sensor based on the entrapment of the

protein glucose oxidase within a sol-gel matrix has been developed.[63] An optical sensor based on the entrapment of high pKa dyes within a sol-gel matrix has been developed for the determination of pH in highly acidic and highly alkaline environments.[7, 8] Raiteri *et al.* have used thin films of sol-gel coated onto silicon nitride micro-cantilevers via a dip coating process to show the change in response of the micro-cantilever to different mixtures of ethanol and water.[64] In the work presented herein, we modify and evaluate silicon micro-cantilevers with thin films of sol-gel Thin films of sol-gel are deposited onto micro-cantilevers using a spin coating procedure. This method of film formation requires less equipment and is less expensive than conventional techniques such as CVD, evaporation, or sputtering.[5] Adsorption of analyte onto the sol-gel coating causes a differential stress ($\Delta s = s_c - s_{si}$, where s_c and s_{si} are the stresses on the coated and uncoated Si surfaces) on the micro-cantilever due to the additional mass and change in the spring constant of the coated micro-cantilever. This results in stress-induced bending and/or changes in the resonance frequency of the micro-cantilever.[65-67] In this work, bending is monitored based on deflection of a laser beam that is reflected from the micro-cantilever surface onto a position sensitive detector The bending, z, depends linearly on the differential stress (Δs) and is given by

$$z = \frac{31}{t_1 + t_2}\left[\frac{1+(t_1/t_2)^2}{3(1+t_1/t_2)^2 + (1+t_1E_1/t_2E_2)(t_1^2/t_2^2 + t_2E_2/t_1E_1)}\right]\frac{\Delta s}{E^*}$$

where t_1 and t_2 are the thickness of the coating and micro-cantilever substrate, l is the micro-cantilever length, E_1 and E_2 are the Young's moduli of the coating and the micro-cantilever, and $E^* = [(E_1E_2/(E_1+E_2)]$ is the effective Young's modulus of the coated

micro-cantilever. This bending is depicted in Figure 3 1. By obtaining calibration plots for the test analytes, the bending of the micro-cantilever can be correlated to the concentration of analyte in a sample We evaluate the effect of the sol-gel coating on the sensitivity of the micro-cantilever to analytes of varying chemical composition. The selectivity of the micro-cantilevers is also evaluated by modifying the chemical nature of the surface of the sol-gel film by reaction with organosilanes. The influence of sol-gel film thickness and micro-cantilever structure thickness on sensor response are also investigated.

3.2 Experimental Section

3.2.1 Chemicals and Materials

The chemicals used in this study were used as received from the manufacturer Reagent grade methanol, hydrochloric acid, sulfuric acid, hydrogen peroxide, and toluene were purchased from Fisher Scientific (Fair Lawn, NJ, USA) Absolute ethanol was supplied by Aaper Alcohol and Chemical Co (Shelbyville, KY, USA). Tetramethoxysilane (TMOS), chlorodimethyloctadecylsilane (CDOS), and octadecyltriethoxysilane(OTEOS) were purchased from Aldrich Chemical Co. (Milwaukee, WI, USA) and hexamethyldisilizane (HMDS) from Petrarch Research Systems (Bristol, PA, USA).

The silicon micro-cantilevers were purchased from Park Scientific Instruments (Sunnyvale, CA, USA). The 600 nm thick, V shaped, silicon micro-cantilevers had a 120 μm height, 90 μm base, and legs with a width of 26 μm As supplied, the micro-cantilevers had a 50 nm coating of gold on the underneath side.

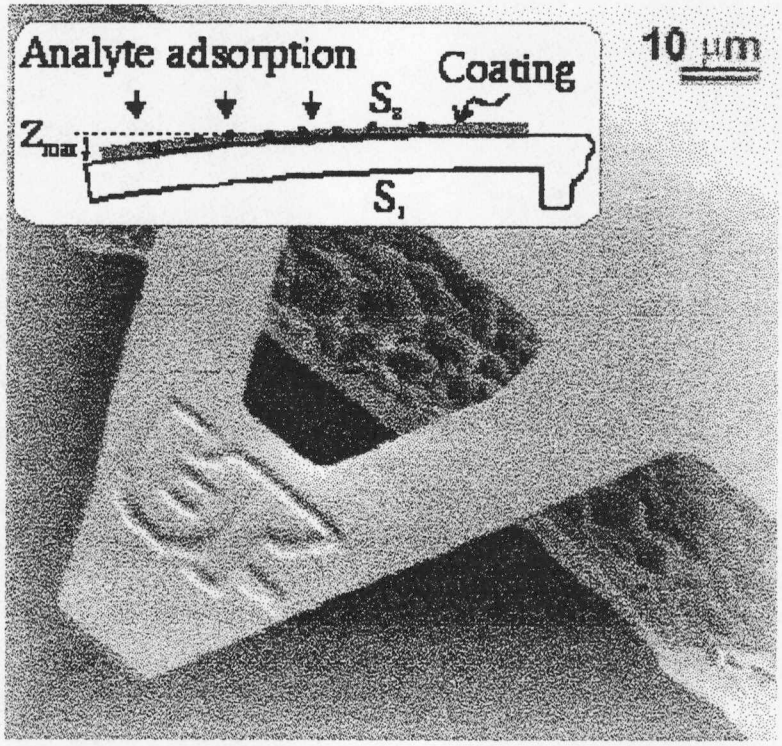


Figure 3.1 Depiction of micro-cantilever bending (z).

3.2.2 Sol-Gel Film Preparation

The sol solution from which the films were cast was prepared by adding 300μL of tetramethoxysilane (TMOS) to a mixture of 125 μL of H_2O, 15 μL of 0.01 M HCl, and 250 μL of methanol. After waiting six hours for crosslinking to occur, thin films of sol-gel were created on the micro-cantilevers using a spin coating procedure Before deposition of the sol-gel film onto the topside of the micro-cantilever, the micro-cantilevers were cleaned by immersion in piranha solution (75% H_2SO_4, 25% H_2O_2) for 3 h. The sol was deposited onto the center of a spinning circular Teflon mount that secured the micro-cantilevers in place. The mount continued to spin at a rate of 500 rpm for 5 s after deposition. The spin rate was then increased at 30000 rpm/s to a final spin rate of 6000 rpm at which the spin rate was held constant for 2 min to evaporate all remaining solvent After spin coating, the micro-cantilevers were placed in a 110 °C oven for 12 h to cure the sol-gel coating Finally, to remove any sol-gel from the underneath side of the micro-cantilever, the micro-cantilevers were soaked in aqua regia (75% HCl, 25% HNO_3) for 6 h. This mixture of hydrochloric and nitric acids is known to dissolve gold. By dissolving the gold coating from the underneath of the micro-cantilever, the aqua regia functioned to remove any sol-gel that may have coated the underneath of the micro-cantilever

3.2.3 Determination of Sol-Gel Film Thickness

The thickness of the sol-gel films on the cantilever surfaces were determined by profilometry (Dektak 8000, Veeco/Sloan Technology, Santa Barbara, CA, USA) Due to bending of the micro-cantilever under the profilometer stylus, direct measurement of film thickness was not possible. Therefore, film thickness was measured on films cast onto silicon wafers under the same conditions used to apply the films to the micro-cantilevers. Scanning electron micrographs were obtained using a Hitachi S-800 Scanning Electron Microscope (Hitachi Instruments, Inc., San Jose, CA, USA) located in the Division of Biology, Electron Microscopy Facility, University of Tennessee, Knoxville.

3.2.4 Modification of Sol-Gel Film

In some cases, the sol-gel films were treated with organosilanes In the first attempt, the sol-gel coated micro-cantilever was immersed in a 5% w/w solution of CDOS in absolute ethanol with gentle heat The micro-cantilever was allowed to remain in solution for 25 min The micro-cantilever was then removed and rinsed thoroughly with absolute ethanol. In an attempt to increase the amount of bonded phase on the sol-gel film surface, a second sol-gel coated micro-cantilever was immersed in a 5% w/w solution of OTEOS in toluene for 2 5 h The solution was kept at 90 °C. The cantilever was then removed from solution and rinsed with toluene followed by absolute ethanol. To cap the remaining reactive silanols, the micro-cantilever was placed in a 3% w/w solution of HMDS in toluene for 1 h The solution was kept at 110 °C The micro-cantilever was removed and rinsed with toluene and absolute ethanol

The effect of sol-gel film thickness on cantilever response is discussed within this work The sol-gel film was thinned using a focused ion (Ga ion) beam milling (FIB) machine (FIB 200, FEI Co., Hillsboro, OR, USA). FIB was also used to determine the effect of micro-cantilever structure thickness on sensor response

3.2.5 Optical Instrumentation

The micro-cantilevers were mounted into an optical system similar to that used for atomic force microscopy. A block diagram of the optical setup is shown in Figure 3 2 A 5 mW diode laser (Coherent Laser Corp , Auburn, CA, USA) operating at 635 nm was spatially filtered using a 10 μm pin hole. The laser was then columnated and focused onto the tip of the micro-cantilever The diameter of the laser beam was controlled by an iris at the end of the laser rail. The reflected beam was focused using a bi-convex lens onto a segmented position sensitive photodiode (PSD) detector built in house. The segmented PSD was divided into four segments, separated by a gap or a dead region When centered at the center of the PSD, a symmetrical optical beam generates equal photocurrents in all segments The relative position is obtained by measuring the output current of each segment. A diagram of the PSD and the equations for signal generation both in the horizontal and vertical planes are shown in Figure 3.3 Deflection of the micro-cantilever caused by adsorption of analyte on the micro-cantilever surface was measured using the output of the PSD that corresponded to vertical beam deflection. The amplified voltage from the PSD was monitored using a lock-in amplifier (Stanford Research Systems, Sunnyvale, CA, USA) The signals in this work are reported in voltage output of the detector. The relationship between micro-cantilever displacement

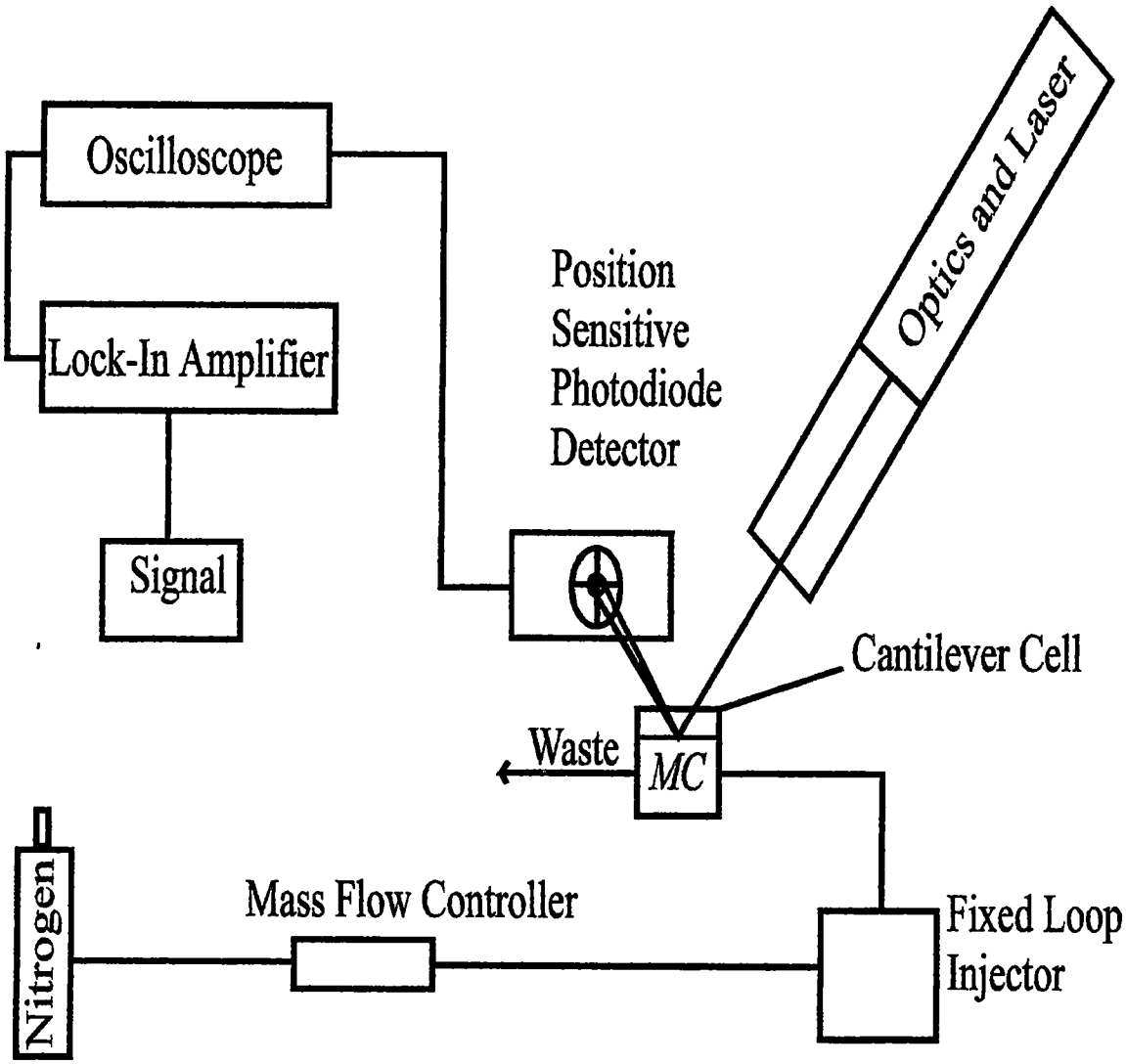
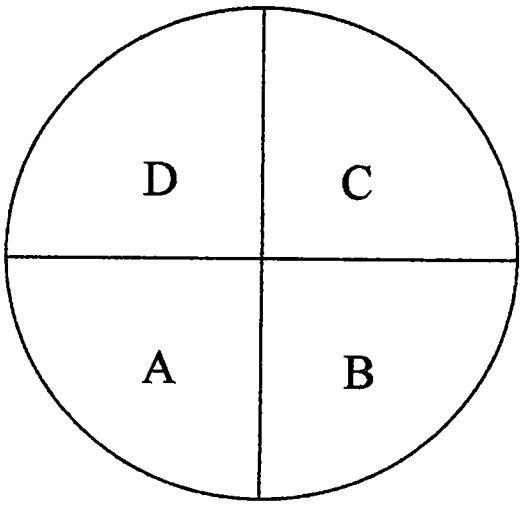


Figure 3.2 Block diagram of optical setup



$$\text{Horizontal} = \frac{(A + D) - (B + C)}{A + B + C + D}$$

$$\text{Vertical} = \frac{(A + B) - (C + D)}{A + B + C + D}$$

Figure 3.3 Schematic diagram of PSD and equations for signal generation

and output voltage was not determined However, for a typical optical configuration used in these studies, the conversion between deflection of the micro-cantilever tip and detector voltage is roughly 80 nm/volt.[56, 68]

3.2.6 Sample Preparation

Samples were created from headspace above analyte solutions developed in 40 mL headspace vials that were fitted with Teflon septa Prior to the development of analyte headspace, the vial headspace was purged with nitrogen to ensure that the analyte and the nitrogen carrier gas were the only components to enter the flow cell. Sampling and subsequent injection into the fixed loop injector was accomplished using a gas-tight syringe For preparation of different analyte vapor concentrations, the analyte vapor was diluted with N_2 within the sampling syringe.

A 3 mL flow cell was mounted over the micro-cantilever to allow for the flow of gaseous analytes across the micro-cantilever surface. A constant flow of ultra high purity nitrogen at a rate of 1.0 mL/min was achieved using a digital mass flow controller (MKS Instruments, Inc., Andover, MD, USA). Nitrogen flow was directed first through a 1 mL fixed loop sample injection valve (Model 5020, Rheodyne, Inc., Cotati, CA, USA) and then through the flow cell Transient signals due to micro-cantilever bending where observed upon injection of headspace samples Considerable dilution of the sample occurred due to the large volume and flow configuration of the flow cell, which was not designed for optimum sensitivity.

3.3 Results and Discussion

The sol-gel coating applied to the micro-cantilever surface (i) enhances the sensitivity of the sensor by creating an adsorptive coating, (ii) increases the binding capacity by introducing a mesoporous-structured surface, (iii) and provides a reactive surface for the covalent attachment of a variety of analyte binding reagent phases A primary goal of this work was to develop a chemical sensor based on sol-gel coated micro-cantilevers that would be capable of distinguishing between vapor phase analytes of varying chemical composition, as well as to varying concentrations of a given analyte. The sol-gel film on the micro-cantilever surface allows for modification of the selectivity of the sensor by immobilizing chemically selective phases on the sol-gel backbone. By altering the chemical nature of the phase bonded to the sol-gel matrix, the selectivity of the sensor can be tailored for a certain class of compounds. The following analytes, all monitored in the vapor phase, and potential modes of molecular interaction with the sol-gel film were employed: ethanol (very weakly acidic compound with strong H-bonding capabilities), aniline (aromatic weakly basic compound with H-bonding capabilities), toluene (aromatic system with high polarizability), and pentane (very non-polar compound, dispersive interactions only). The structures of the test analytes are shown in Figure 3.4, and a few relevant physical properties of the test analytes are listed in Table 3.1.

3.3.1 Determination of Optimal Spin Coating Conditions

Because the viscosity of the sol solution changes with time, 50 μL of sol was deposited onto the spinning silicon wafers at 5,6,7, and 8 h into the gelation process to

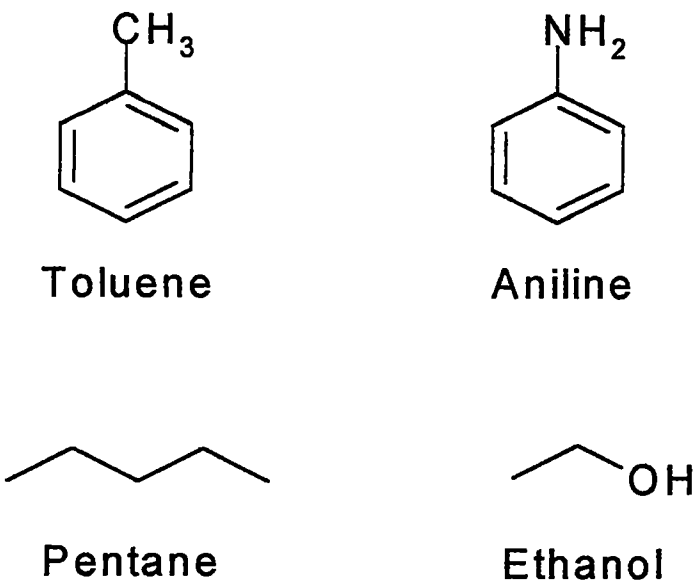


Figure 3.4 Chemical Structures of the test analytes.

Table 3.1 Relevant physical properties of the test analytes.

Analyte	Molecular weight (g/mol)	Boiling point (° C)	Vapor density (Air = 1)	Vapor pressure @ 20 ° C (mm Hg)
Toluene	91	111	3.14	22
Aniline	93	184	3.22	0.6
Ethanol	46	78	1.6	44
Pentane	72	36	2.5	426

determine the optimal time to achieve the desired film thickness. The velocity at which the silicon wafers were spun was also varied to determine the effect of the spin rate on the thickness of the cast films. Table 3.2 shows the sol-gel film thickness for the respective gelation times at 2 different spin rates It was determined that films cast at times early in the gelation process with the faster spin-rate give thinner films. In order to allow sufficient time for cross-linking to occur, it was determined that all films would be cast 6 h into the gelation process This would produce films of approximately 50-100 nm in thickness. Scanning electron micrographs of an uncoated micro-cantilever and a sol-gel coated micro-cantilever are shown in Figure 3.5. SEM images indicate that the coating on the micro-cantilever is non-uniform thus creating a rough surface. Profilometry measurements are also indicative of this trend.

3.3.2 Response of Native Sol-Gel Coating

The responses of a sol-gel coated micro-cantilever to analytes of different polarity and varying chemical composition are quite different as illustrated in Figure 3 6. Because the gaseous analytes have different vapor pressures, the concentrations of the injected headspace were determined by GC/MS. Standard solutions of various concentrations were prepared for each analyte and a calibration plot was obtained The concentration of the injected headspace was determined by comparison to the calibration plot. The response factors (signal/concentration) relative to toluene set to 1.0 appear in Table 3.3. The sharp increase in signals seen in Figure 3.6 is due to the adsorption of analyte onto the sol-gel film surface Due to the polar nature of the sol-gel film, the response of the sensor to polar and polarizable analytes is much greater than the response

Table 3.2 Sol-gel film thickness at various times during the gelation process and at two different spin rates.

Time during gelation process	**Sol-gel film thickness at a final spin rate of 4000 rpm**	**Sol-gel film thickness at a final spin rate of 6000 rpm**
5 hours	289 nm	58 nm
6 hours	114 nm	82 nm
7 hours	104 nm	92 nm
8 hours	180 nm	120 nm

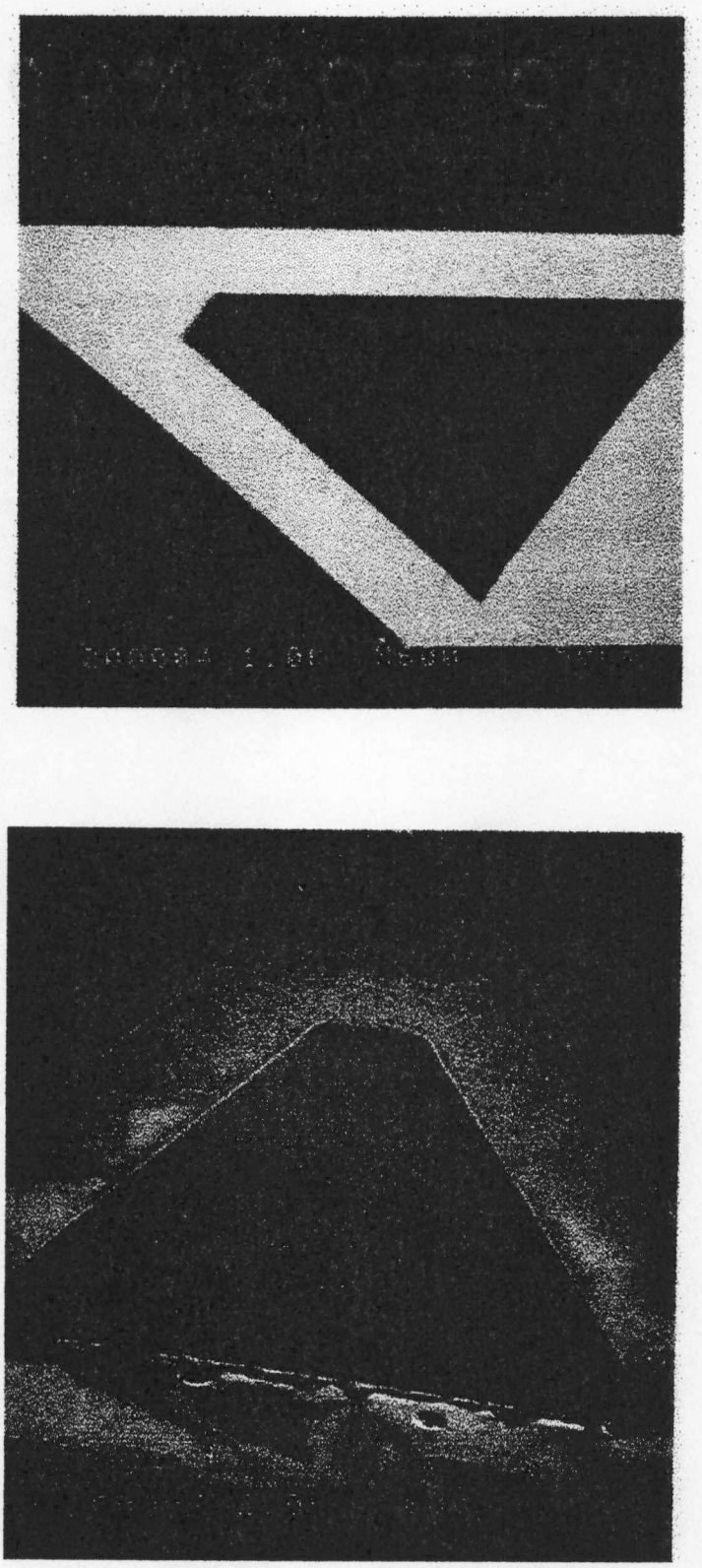


Figure 3.5 Scanning Electron Micrographs of an uncoated silicon micro-cantilever (top) and a sol-gel coated silicon micro-cantilever (bottom).

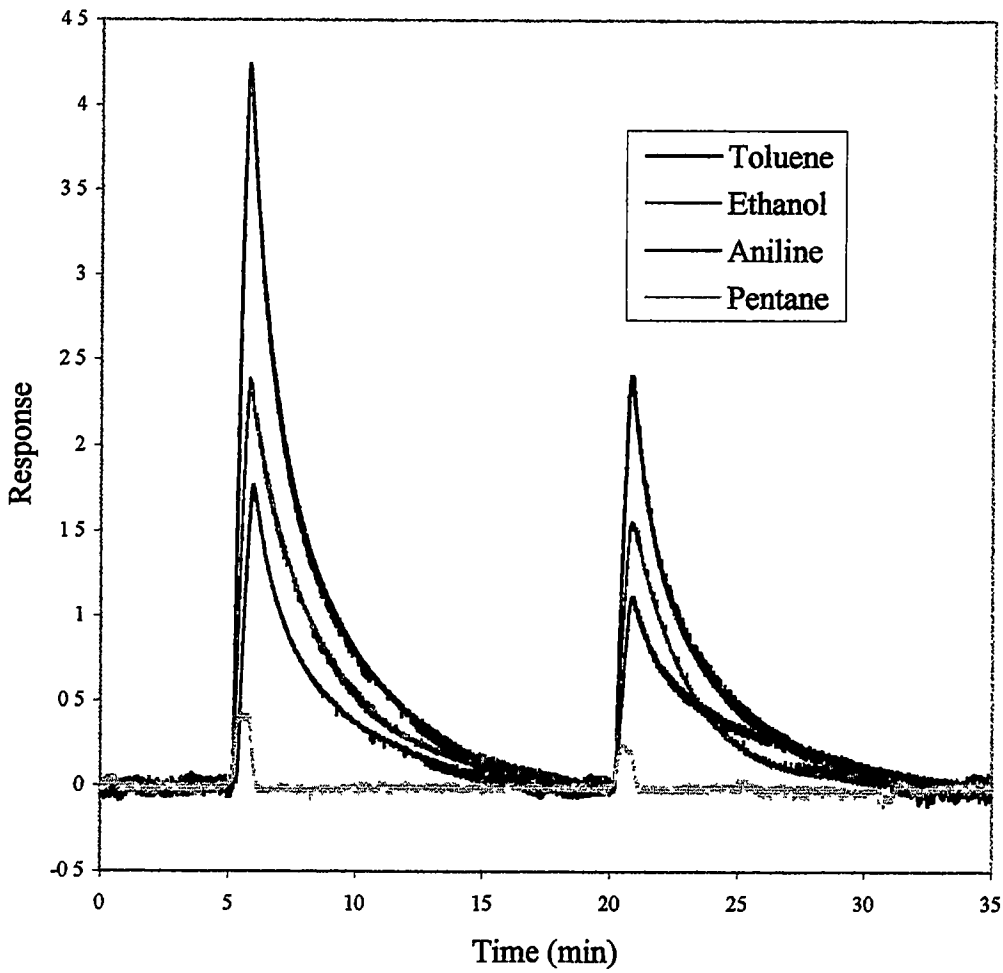


Figure 3.6 Response of sol-gel coated micro-cantilever to toluene, ethanol, aniline,and pentane in order of decreasing sensor resonse at injected concentrations of 100% and 50% of the developed neat headspace, respectively

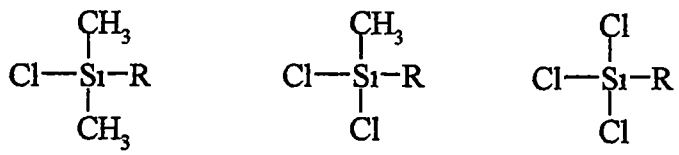
Table 3.3 Headspace concentrations and micro-cantilever response relative to toluene.

Analyte	Headspace concentration (M)	Response relative to toluene
Toluene	1.02×10^{-4}	1 0
Aniline	$6\ 40 \times 10^{-6}$	7.21
Ethanol	1.35×10^{-4}	0.51
Pentane	1.74×10^{-3}	$6\ 19 \times 10^{-3}$

to non-polar analytes. Also, the desorption of the polar or polarizable analytes from the film is relatively slow due to the affinity of the polar sol-gel film for the analytes. Pentane, a non-polar hydrocarbon, shows little affinity for the sol-gel film and completely desorbs in a short period of time The reproducibility of peak responses is currently limited by the crude method of preparing these gas phase samples and is generally about 10%

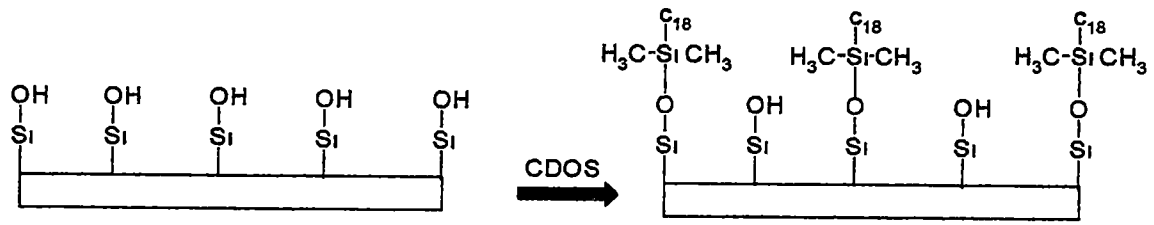
3.3.3 Response of Sol-Gel Coating Modified with CDOS

Perhaps the most desirable feature in an effective sensor is the ability to target a certain analyte or class of compounds The pursuit of better selectivity has become the main focus of chemical sensor research. In an effort to alter the selectivity of sol-gel modified micro-cantilevers, the polarity of the sol-gel film was modified by treating the film with organosilanes. Organosilanes may have as many as three groups that can react with the sol-gel surface. Depending on the number of reactive groups, the organosilanes are termed monofunctional, difunctional, or trifunctional:



Monofunctional Difunctional Trifunctional

Difunctional and trifunctional organolsilanes are often referred to as multifunctional organosilanes in the literature. Initially, the film was treated with CDOS as described above. CDOS is a monofunctinoal silane that reacts with the sol-gel film surface in the following manner·



The addition of non-polar C_{18} chains to the surface of the sol-gel film should enhance the response of the chemical sensor to non-polar analytes However, the amount of bonded phase attached to the silanol groups (Si-OH) of the sol-gel film is limited For the reaction of the monofunctional silane with the sol-gel film, steric hindrance can limit the number of silanol groups (SiOH) on the surface that react. In one report, at least half of the original silanols are still present on the sol-gel film surface after reaction [69] These remaining surface silanols can interact with analytes and contribute to the adsorptive properties of the chemical sensor. Therefore, the sensor maintains some of its polar nature Figure 3.7 shows the response of the sensor to the test analytes both before and after surface modification with CDOS The signal for pentane after modification is more than twice the signal obtained from the native sol-gel coating. The non-polar phase bonded to the sol-gel surface exhibits an increased affinity for non-polar analytes, as also indicated by an increased desorption time of pentane on the modified film (not shown). The presence of the non-polar alkyl chains on the sol-gel film surface caused the signals for toluene and aniline to dramatically decrease The relatively constant signal for ethanol may be due to the affinity of the short alkyl group for the bonded phase, as well

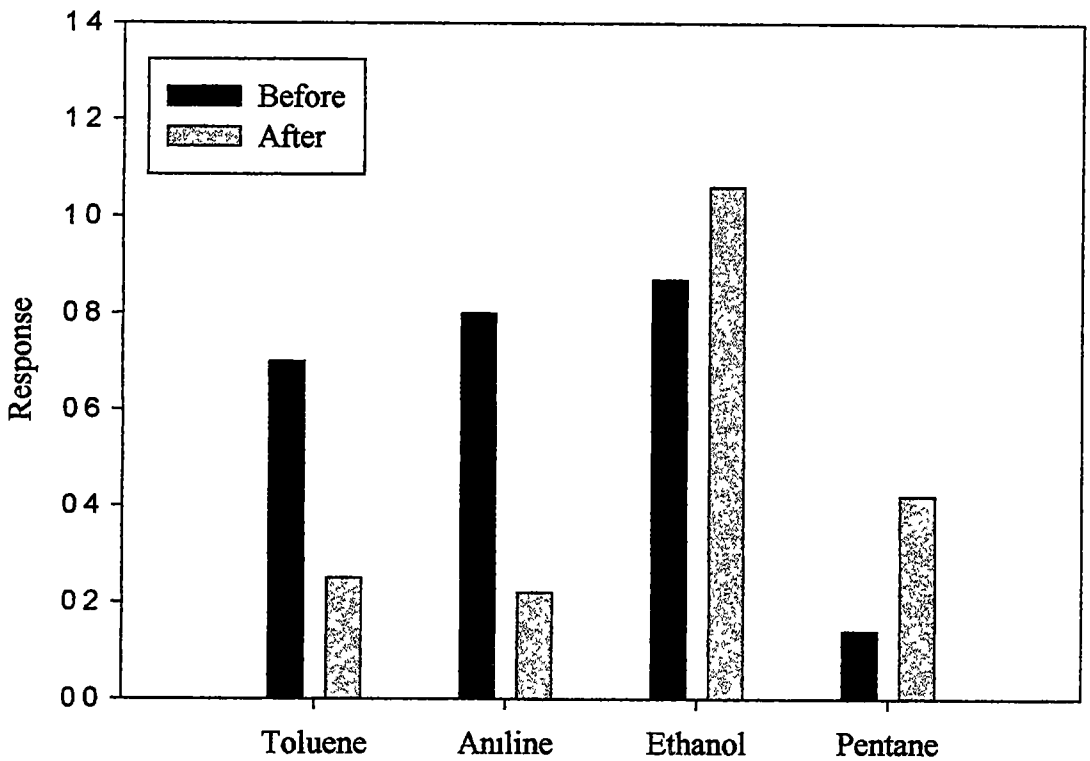
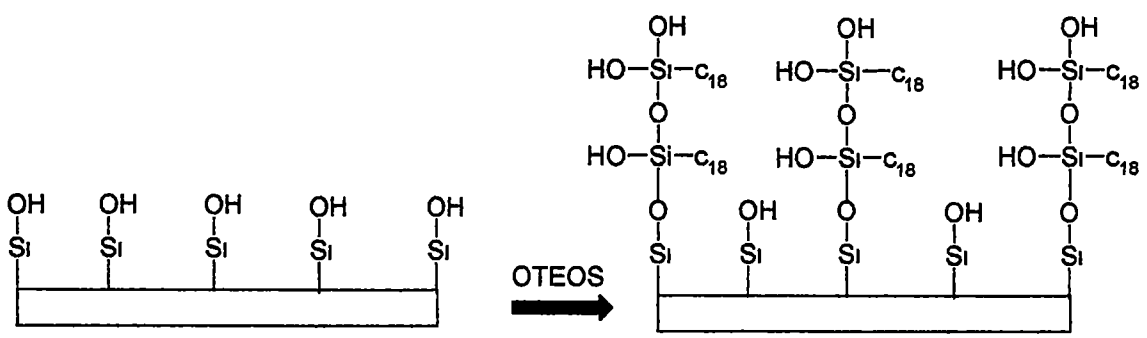


Figure 3.7 Sensor Response to the test analytes both before (native sol-gel coating) and after treatment with CDOS

as the ability of the hydroxy group to hydrogen bond with the oxygens of the siloxane bonds

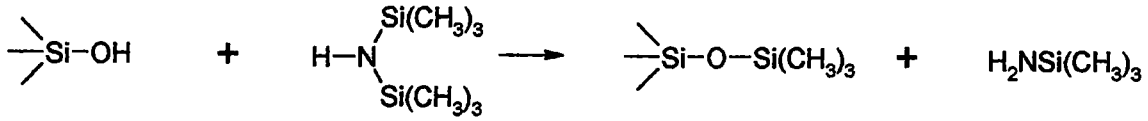
3.3.4 Response of Sol-Gel Coating Modified with OTEOS and Capped with HMDS

While the surface coverage obtainable with monofunctional silanes is limited by steric hindrance, the reaction of multifunctional silanes results in a significantly higher content of bonded phase.[69] Also, the presence of water on the surface of the sol-gel can result in the formation of additional silanols and thus increase the amount of bonded phase substantially.[69] In an attempt to increase the amount of bonded phase on the surface of the sol-gel film, the micro-cantilever was immersed in boiling deionized water for 30 min before modification of the sol-gel film. The micro-cantilever was then treated with OTEOS, a trifunctional organosilane. This reagent reacts with the sol-gel film in the following manner



This reagent with three reactive ethoxy groups functions to increase the non-polar nature of the sol-gel film by building a polymer-like matrix that contains non-polar C_{18} chains. The presence of the ethoxy groups on the silane allows for hydrolysis and polycondensation reactions to occur and thus build the polymer-like matrix. The micro-

cantilever was subsequently placed in HMDS, a reagent often used in column preparation in liquid chromatography to "cap" remaining reactive silanols [69, 70] This reagent reacts with the unreacted silanols on the sol-gel film surface, as well as the silanols produced from the OTEOS, according to the following reactions:



The end result is the replacement of silanols with $Si(CH_3)_3$. The response of the sensor to analytes on the native sol-gel coating, the coating treated with OTEOS, and the final end-capped coating are shown in Figure 3.8. The increase in signal for ethanol following the treatment of the sol-gel surface with OTEOS is possibly due to the increase in the number of silanol binding sites created by the polymerization reaction The signal for pentane remained relatively constant following this treatment. After capping the remaining reactive silanols with HMDS, the signal for pentane increased nearly five-fold. This indicates a much greater presence of non-polar constituents on the surface of the sol-gel film.

3.3.5 Native Sol-Gel Coated Micro-Cantilever as a Means To Determine Analyte Concentration

The micro-cantilever chemical sensor is also capable of providing quantitative information by differentiating between varying concentrations of a given analyte. By

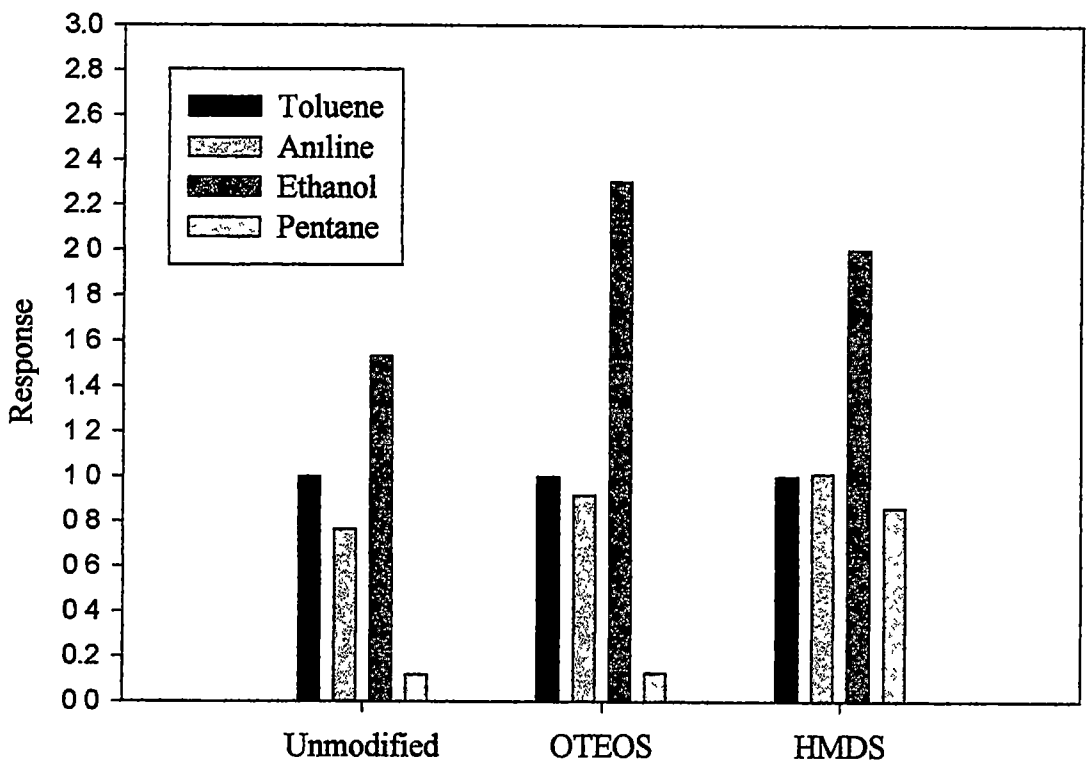


Figure 3.8 Sensor response to the test analytes for native sol-gel coating (Unmodified), coating reacted with OTEOS, and final end-capped surface modified coating after reaction with HMDS Each response is normalized to the response of the native sol-gel coating to toluene.

diluting analyte headspace within the gas-tight sampling syringe with N_2, calibration plots were obtained for the test analytes on the native sol-gel coating as shown in Figure 3.9. The response of the micro-cantilever decreased with decreasing concentration. The calibration plots for pentane are shown for the native sol-gel coating (a) and the surface modified coating (b). A linear calibration plot for pentane was unattainable for the native sol-gel coating. An estimation of the limit of detection for each of the test analytes was determined. After removing the high frequency baseline noise with a 250 point square polynomial fit, the estimated signal for a S/N value of 2 was determined. The estimated signal was then converted into analyte concentration by comparison to the calibration plots shown in Figure 3 9 The estimated limits of detection for the test are shown in Table 3.4. The limits of detection range from 550 µg/L for pentane down to 1 4 µg/L for aniline. The % analyte shown in Table 3.4 corresponds to the percentage of developed headspace that can be detected when diluted with nitrogen.

3.3.6 The Effect of Sol-Gel Film Thickness on Sensor Response

The effect of sol-gel film thickness on micro-cantilever response was also investigated. Bending occurs because of analyte-induced, differential stress between the bare silicon and sol-gel coated sides of the legs of the micro-cantilever The thickness of the silicon legs of the micro-cantilever was held constant at 560 nm and FIB was used to decrease the thickness of the sol-gel film. The depth of material removed (d) was determined according to the following equation·

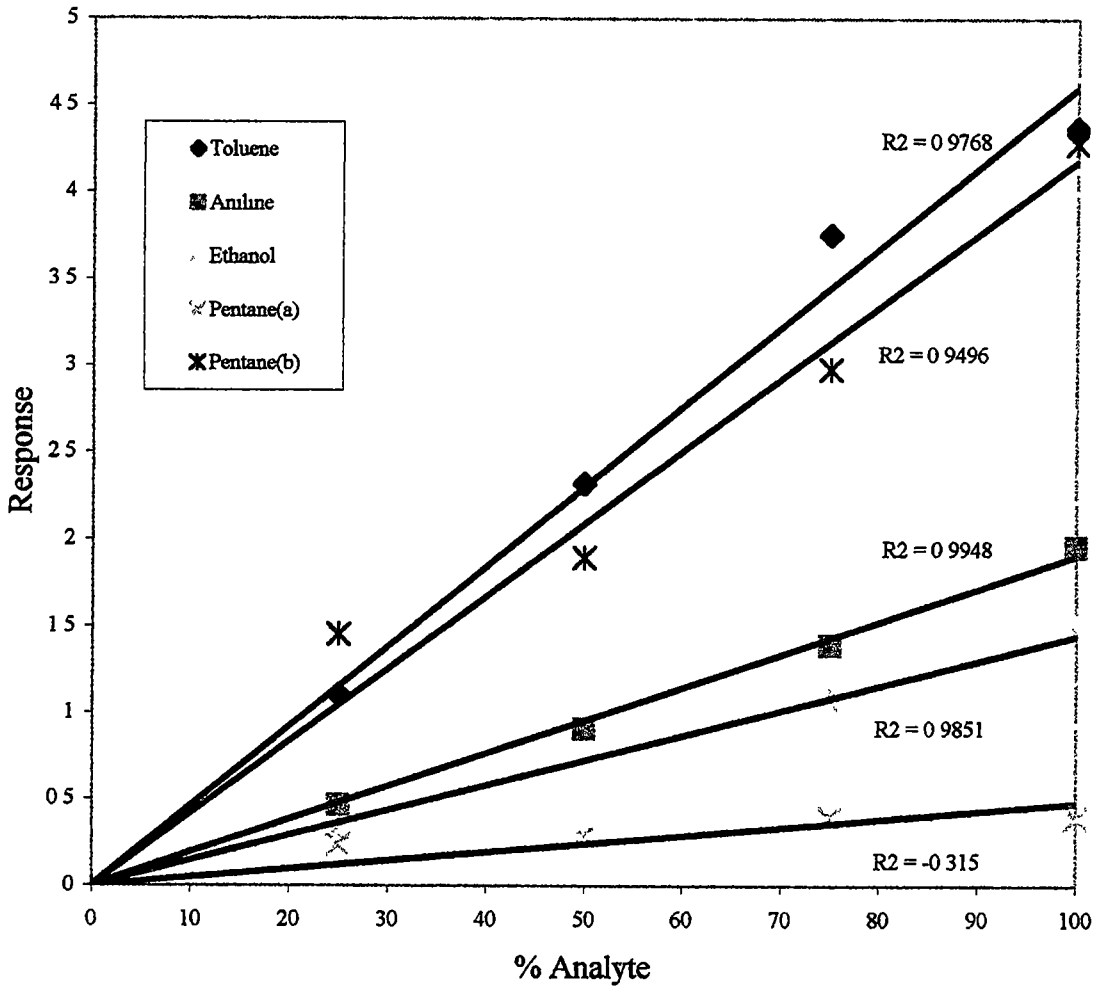


Figure 3.9 Calibration plots for the native sol-gel coating exposed to the test analytes.

Table 3.4 Estimated limits of detection for the test analytes.

Analyte	Estimated LOD in % analyte	Estimated LOD in µg/L
Toluene	0.25	23
Aniline	0.24	1.4
Ethanol	0.40	24
Pentane*	0 47	566

* after modification with OTEOS and subsequent capping with HMDS

$$d = \frac{(t)(I)(S_r)}{(l)(w)}$$

t = time exposed to focused-ion beam (s)
I = beam current (nA)
S_r = sputtering rate for SiO_2 ($\mu m^3/nC$)
l = length of the area removed (μm)
w = width of the area removed (μm)

An area 27 μm by 130 μm was milled on each leg for 130 sec using a beam current of 2.7 nA. The sputtering rate for the sol-gel was assumed to be 0.20 $\mu m^3/nC$, the sputtering rate for SiO_2 (Ion Tech, Inc., Fort Collins, CO, USA). Under the stated conditions, the depth of material removed was roughly 20 nm. The initial film thickness was estimated by profilometry to be ~50 nm After exposing the micro-cantilever to toluene vapor at the initial film thickness, the sol-gel film on the legs of the micro-cantilever was thinned in increments of ~20 nm. Figure 3.10 shows the response of the micro-cantilever at varying sol-gel film thickness. The response of the sensor dramatically decreased after the first milling and noticeable after the second. No noticeable change was observed in the sensor response between the second and third millings. This may indicate that the sol-gel film had been nearly completely removed and also supports the preliminary estimate of the initial sol-gel film thickness It should be noted that both SEM (Figure 3.5) and profilometry experiments indicate the sol-gel thickness is rough (thickness is not uniform) Figure 3 5 also provides evidence that the sol-gel thickness on the legs

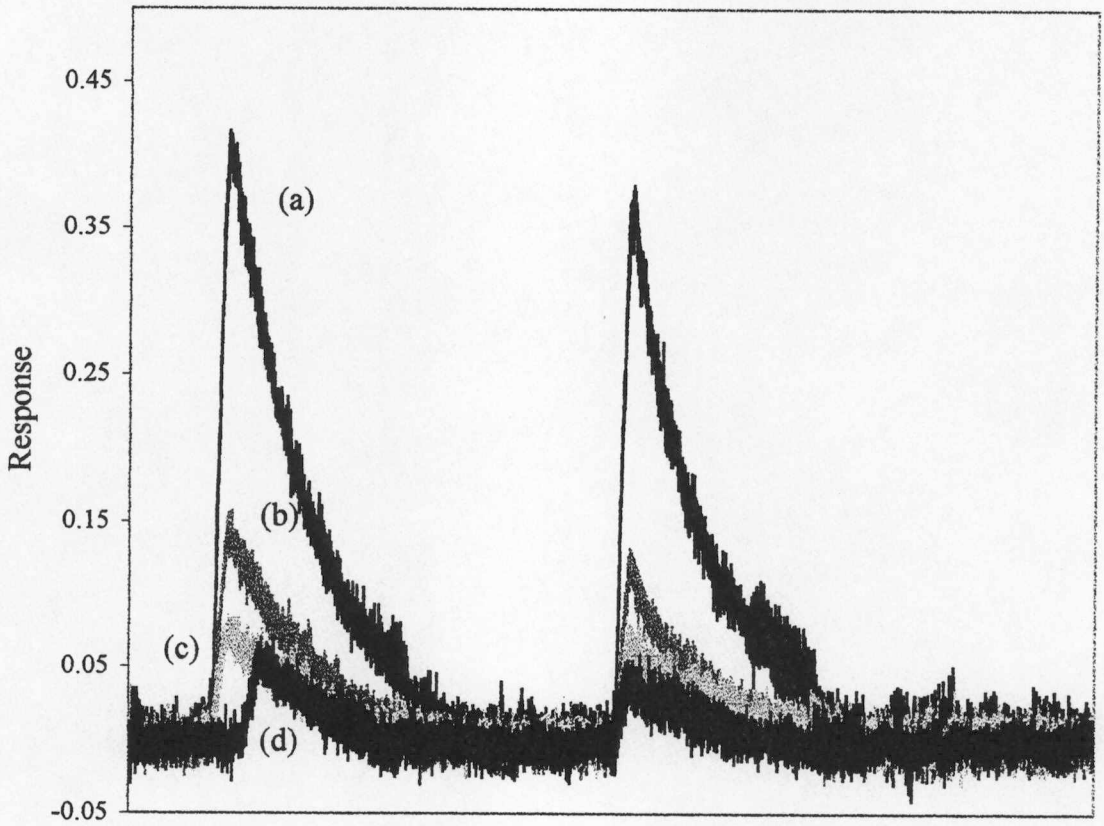


Figure 3.10 Sensor response to toluene at varying sol-gel film thickness (a) initial film thickness (b) after first milling (c) after second milling (d) after third milling.

decreases (at least for the one shown) as one moves from the base toward the pad of the cantilever An attempt was made to determine the effect of a much thicker sol-gel film on the micro-cantilever. However, due to the insulating properties of the sol-gel film, FIB was unable to thin the thicker film. As the positively charged gallium ions bombard the sol-gel film, a positive charge begins to build on the surface. Eventually, the charge becomes large enough to repel the ions from the ion gun and no ablation of the sol-gel film can be accomplished.

3.3.7 The Effect of Micro-Cantilever Structure Thickness on Sensor Response

The micro-cantilever structure thickness also has an effect on the response of the sensor. The initial thickness of the micro-cantilevers as received from the manufacturer is 600 nm. The legs of the sol-gel coated micro-cantilever were thinned in increments of 80 nm according to the same equation used above to determine the amount of sol-gel material removed. The S_r for silicon is 0 15 μ^3/nC. Figure 3.11 depicts the response of the sensor to toluene vapor at varying micro-cantilever structure thickness. As the legs were thinned, the response of the sensor increased up to an optimal leg thickness of ~280 nm. Beyond that point, the response began to decrease This trend is consistent with prior studies involving micro-cantilevers modified with GC polysilane phases [56]

3.4 Conclusions

In the work presented, we have shown that sol-gel coatings can function to enhance the sensitivity and selectivity of micro-cantilevers. Immobilization of chemically selective phases on the surface of sol-gel films provides a method for altering

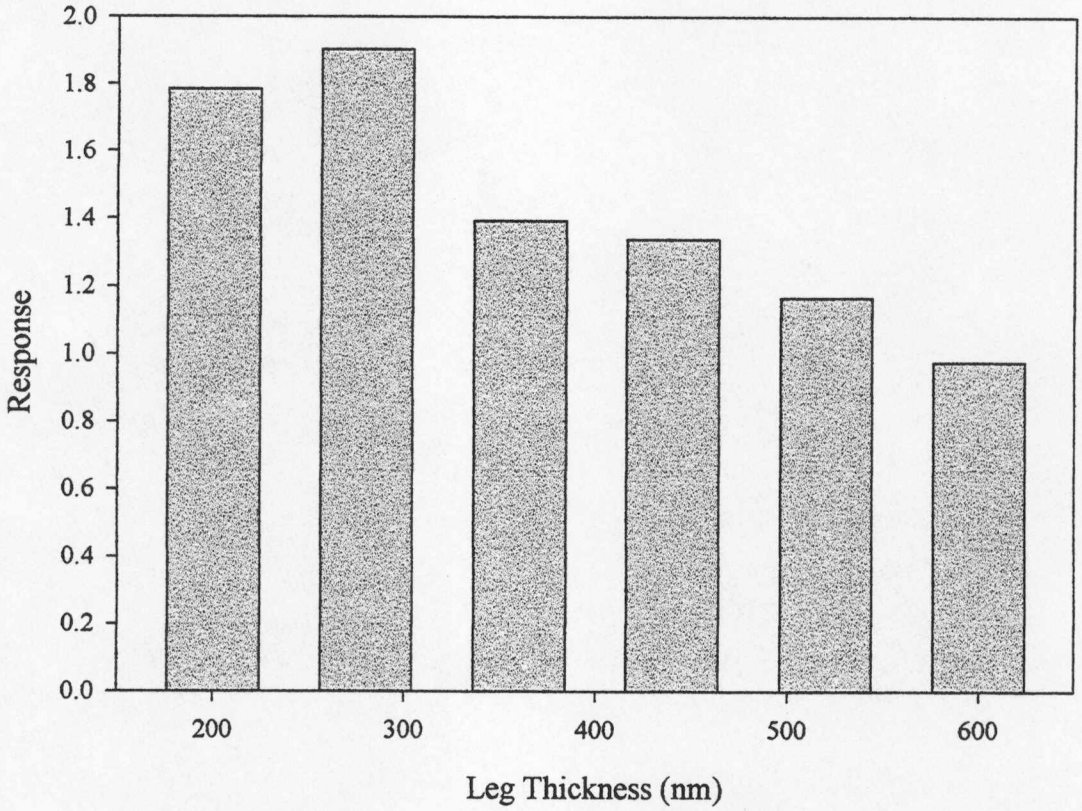


Figure 3.11 Sensor response to toluene at varying micro-cantilever structure thickness.

the selectivity of micro-cantilever chemical sensors. There are a variety of organosilanes that may serve to achieve this purpose. Ideally, an array of cantilevers, each coated with a sol-gel film modified with an organosilane specific for a class of compounds, could be used to identify the chemical nature of an unknown analyte. Also, the use of sol-gel matrices for the entrapment of analyte-sensitive species could provide a means for the development of micro-cantilever sensors for a wide variety of analytes.

3.5 Future Studies

As mentioned in section 3.3.1, the films created on the micro-cantilever surfaces by the spin-coating procedure are generally non-uniform and rough. It should also be pointed out that the films are difficult to reproduce from micro-cantilever to micro-cantilever. Therefore, it is necessary to investigate other mechanisms of film deposition to create reproducible, uniform films It is believed that a more complete, uniform coverage of the micro-cantilever would improve the response of the sensor There are several film deposition techniques available. Spraying the sol onto the surface of the micro-cantilever is one option The sol can be aspirated through a nebulizer and sprayed onto the micro-cantilever surface. The size of the droplets generated from the nebulizer would determine if this approach is feasible. Another approach is to dip coat the micro-cantilevers. This is the method used by Raiteri *et al.*[63] The main concern with dip coating is coating both sides of the micro-cantilever. However, the unwanted sol-gel that coats the underneath side of the micro-cantilever can be removed by treatment with aqua regia, as discussed in section 3.2.2. Another concern would be filling in the open triangle of the micro-cantilever with the sol-gel film and thus limiting the flexibility of the micro-

cantilever. This problem could be alleviated by changing the shape of the micro-cantilever Micro-cantilevers of different shapes are commercially available or can be fabricated using FIB. These methods of film deposition are currently under investigation in our laboratories

Once a technique is established for creating uniform films, efforts will be made to continue to modify the selectivity of the micro-cantilever chemical sensor. A more complete coverage of the micro-cantilever surface would create more sites for the immobilization of selective phases. In the work presented, an aliphatic C_{18} chain immobilized on the surface of the sol-gel film increased the response of the sensor to non-polar analytes. By increasing the density of C_{18} chains immobilized on the surface of the film, the response of the sensor to non-polar analytes should likewise increase. There are a variety of silanes that can be used to modify the selectivity of the micro-cantilever chemical sensor. For example, immobilization of silanes with aromatic substituents, such as phenyldimethylchlorosilane, could enhance the response of the sensor to aromatic analytes Many silanes exist that possess substituents of varying chemical nature and can be used for tailoring the selectivity of the sensor for a certain class of compounds. Ideally, an array of sol-gel coated micro-cantilevers, each modified with a selective phase that targets a certain class of compounds, could be used to determine the identity of an unknown analyte. The micro-cantilever array would produce a "fingerprint" of the unknown analyte. Using pattern recognition methods and a library of array responses, it may be possible to identify an analyte or even a combination of analytes that are present in a sample.

Immobilization of selective phases on the sol-gel films is not the only technique available for imparting selectivity on the micro-cantilever chemical sensor. Encapsulation of selective compounds, as discussed in Chapter 2 of this thesis, is also a viable approach. Entrapment of analyte-sensitive species within the sol-gel matrix could provide a means for the development of micro-cantilever sensors for a wide variety of analytes There are a wide variety of macrocyclic receptors that exhibit high selectivity for certain compounds Cyclodextrins possess a relatively non-polar interior cavity and can accommodate many classes of compounds. Inclusion of the target analyte into the interior cavity of the cyclodextrin is influenced by the physiochemical properties of both the analyte and the cyclodextrin. Calixarenes also exhibit this type of guest/host interactions. Therefore, these compounds are attractive candidates to increase the selectivity of the micro-cantilever sensor.

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