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Selective Surface Acoustic Wave-Based Organophosphonate Chemical Sensor Employing a Self-Assembled Composite Monolayer: A New Paradigm for Sensor Design

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INTRODUCTION

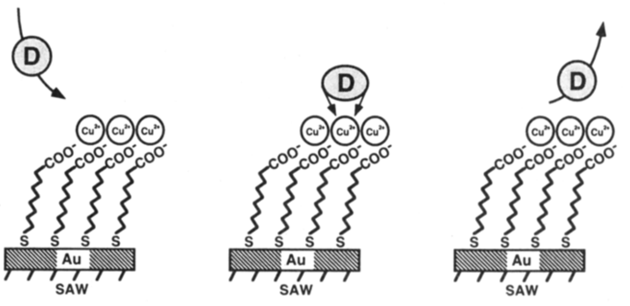
We report the first example of a chemical sensor that derives a degree of selectivity, sensitivity, reversibility, and durability from a rationally designed, composite monolayer consisting of simple molecular components. This approach to sensor design has a number of advantages, including (1) prediction of sensor response based on known bulk-phase intermolecular interactions, (2) rapid response times resulting from ultrathin coatings, and (3) simplicity of fabrication. In this correspondence we show how each of these desirable characteristics results from simple sequential self-assembly chemistry.

Chemical sensors usually consist of a chemically sensitive coating supported by an inert physical transducer.[1] Because the exact nature of the intermolecular interactions between the coating and the target analyte are often ambiguous, the design of selective sensor coatings is based largely on trial and error. A more appealing approach to sensor fabrication relies upon rational design based on known, bulk-phase interactions between the analyte and the selective coating. Three elegant examples that employ this design strategy have recently been reported, and they serve to summarize the state of the art.[2-4] Although all three are viable, these sensing schemes suffer from various practical difficulties. For example, all rely on complex and difficult-to-synthesize molecules.

The device described in this report derives its selectivity, reversibility, and durability from a simple, self-assembled monolayer and its sensitivity from a mass-sensitive surface acoustic wave (SAW) device. The coating design takes advantage of the interaction between organophosphonate nerve-agent simulants and a composite monolayer, consisting of Cu^{2+} tethered to the SAW device by an ordered, carboxylate-terminated *n*-alkanethiol monolayer. The rationale for this design is that Cu^{2+} and some of its chelates are hydrolysis catalysts for certain nerve agents.[5] Thus, a surface layer of coordinatively unsaturated Cu^{2+} might be expected to provide selective and reversible binding sites for organophosphonates. The general approach is illustrated in Chart I, where the analyte (D) is the nerve-agent simulant diisopropyl methylphosphonate (DIMP).

The selective coating responds proportionally and reversibly to DIMP, in a manner readily distinguishable from its response to common organic solvents and water. Moreover, the sensor is both sensitive and durable.

Chart I



1. Approach 2. Binding 3. Desorption

The details of organomercaptan self-assembly on Au, Ag, and Cu substrates have been widely studied and will not be recapitulated here, except to note that, under certain conditions, highly ordered monolayers of organomercaptans spontaneously adsorb onto Au surfaces from the vapor phase[6] and from solution.[7] Carboxylic acid-terminated monolayers are more disordered than methyl-terminated *n*-alkanethiols, and they undergo extensive intramonolayer hydrogen bonding.[6c,7b,c,8] For the purposes of this preliminary report, it is sufficient to visualize the organomercaptan monolayer acting only as scaffolding for the Cu^{2+} surface.

A number of transducers have been used as platforms for sensing organophosphorus compounds.[9-12] We have used SAW devices because of their extreme mass sensitivity.[1,13-15] Because of their high operating frequency and confinement of the acoustic wave energy to within one wavelength of the surface, the SAW devices we used are sensitive to the presence of as little as 100 pg/cm^2 of surface adsorbates (ca. 1.5×10^{-3} monolayers of DIMP).[1,16] In the uncomplicated case, the velocity of the SAW is perturbed in direct proportion to adsorbed mass-per-area, which is measured as a shift in the

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(16) The frequency shift corresponding to one monolayer of DIMP was calculated from eq 1 and the density of bulk liquid DIMP. Substrate surface roughness was not taken into account, but previous studies have shown roughness factors to be about 1.5–2.1 (see ref 6a).

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oscillation frequency of the device when it is used as the feedback element of an appropriate oscillator circuit.[13] In real systems, such as those described here, the SAW velocity may also be affected by changes in the mechanical properties of the coating.[6a,10b,17]

EXPERIMENTAL SECTION

Chemicals. The following chemicals were used as received: diisopropyl methylphosphonate, DIMP (98%, Alfa), dimethyl methylphosphonate, DMMP (Aldrich), 11-mercaptoundecanoic acid, MUA (Aldrich); $Cu(ClO_4)_2{\cdot}6H_2O$ (98%, Aldrich); absolute ethanol, EtOH (Midwest Grain Products); H_2SO_4 (J. T. Baker); H_2O_2 (30%, J. T. Baker). Water was purified with a Milli-Q (Millipore) deionization system or was double distilled. For vapor testing, a number of reagent-grade solvents were used as received. The vapor pressure of a sample of fractionally distilled DIMP, measured using the Knudsen effusion method, was found to be 0.7 ± 0.3 mmHg at 25 °C.

Substrate Preparation. Au-coated substrates were cleaned in freshly prepared "piranha" solution (**Caution**: "Piranha" solution, 1:3 $H_2O_2{:}H_2SO_4$, reacts violently with many organic materials and should be used with extreme care, and it should not be stored in sealed containers) for about 10 s, rinsed with deionized water, and dried under N_2 gas. The freshly cleaned Au substrates were immersed in a 1 mM MUA/EtOH solution for 8–12 h, rinsed with EtOH and water, then immersed in a 2 mM $Cu(ClO_4)_2{\cdot}6H_2O$/EtOH solution for 5–10 min to yield the composite monolayer depicted in Chart I. Best results were obtained when all of these procedures were performed in inert-atmosphere glovebags.

FTIR-External Reflection Spectroscopy (FTIR-ERS). Polished Si (100) wafers (1.3- × 2.5-cm) were coated by electron-beam evaporation of 300 Å of Ti and 2000 Å of Au and then modified as described above. Measurements were made using a Digilab FTS-40 FTIR spectrometer equipped with a Harrick Scientific Seagull reflection accessory and a liquid N_2-cooled MCT detector. All spectra were obtained using p-polarized light incident on the substrate at 85° from the surface normal. Each spectrum is the sum of 256 individual spectra, acquired over the course of 3.5 min.

SAW Experiments. SAW devices (98-MHz) on ST-quartz with Al or Au-on-Cr transducers were designed at Sandia National Laboratories (SNL) and fabricated by SNL or Crystal Technologies, Inc. (Palo Alto, CA). In the active surface region between the transducers, 2000 Å of Au was either electron-beam evaporated over a Ti adhesion layer or thermally evaporated over a Cr adhesion layer. Composite monolayers were prepared according to the procedure described above. Experiments were conducted at 25 °C.

SAW experiments were performed according to previously described procedures.[6a,b,13] DIMP, DMMP, organic solvents, and water were entrained in a stream of high-purity N_2 using gas washing bottles. Vapor-saturated streams were diluted as necessary with pure N_2 to give desired concentrations. The relationship between the changes in frequency (Δf) and mass-per-area (m_A) is given by eq 1. Here, κ is the fraction of the

$$\Delta f/f_o = -\kappa c_m f_o m_A \qquad (1)$$

center-to-center distance between the transducers covered by the Au film. In the present case, its value is 0.57. The mass sensitivity, c_m, is 1.33 $cm^2/(g\ MHz)$ for ST-quartz; f_o is the oscillator frequency.

Ellipsometric Experiments. The substrates prepared for FTIR-ERS measurements were also used for ellipsometric thickness measurements. The method used for determining film thickness has been described previously.[8a] The value used for the refractive index of the films was 1.50.

RESULTS AND DISCUSSION

The formation of a carboxylate/Cu^{2+}-terminated monolayer, such as that illustrated in Chart I, was confirmed by FTIR-ERS, X-ray photoelectron spectroscopy (XPS), and ellipsometry. Figure 1a shows the FTIR-ERS spectrum for a monolayer of the protonated form of MUA prior to Cu^{2+} adsorption. The asymmetric and symmetric methylene stretching frequencies at 2925 and 2854 cm^{-1}, respectively, are typical for a monolayer of acid-terminated *n*-alkanethiols and indicate liquidlike packing of the methylene chains.[6c,7b,c,8a] The carbonyl stretching peaks at 1740 and 1717 cm^{-1} indicate that the acid groups are protonated and present as a mixture of free monomers and laterally hydrogen-bonded dimers, respectively.[6c,7b,c,8] Figure 1b was obtained after immersing the acid-terminated surface in a dilute Cu^{2+}/EtOH solution. The methylene stretching region is essentially identical to that shown in Figure 1a, but significant changes are apparent in the carbonyl stretching region. The peaks for the carbonyl stretch have disappeared, and two new absorbances, which represent the asymmetric and symmetric C–O stretches of the carboxylate groups, are present at about 1609 and 1450 cm^{-1}, respectively. These peaks strongly suggest that the surface has been deprotonated and is complexed to Cu^{2+}.[8b,18]

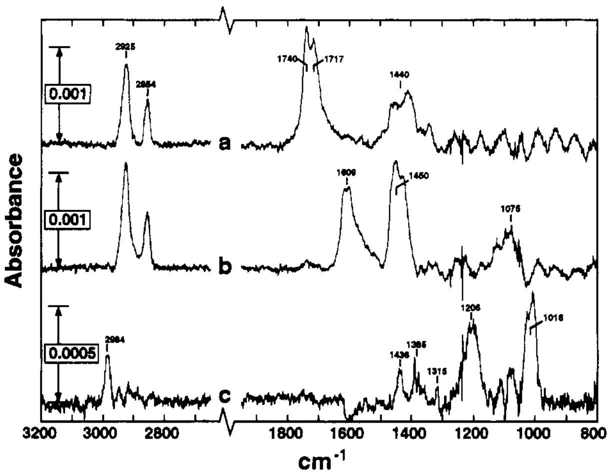

Figure 1. FTIR–ERS spectra of (a) a monolayer of the acid form of MUA confined to a Au substrate, (b) the carboxylate form of a MUA monolayer complexed to Cu^{2+}, and (c) DIMP adsorbed to a Cu^{2+}/carboxylate-terminated monolayer.

A prominent Cu 2p doublet in the XPS spectrum of the composite monolayer confirms the presence of Cu^{2+} on the monolayer surface. Film thicknesses calculated from ellipsometric data verify that only a single composite monolayer is generally present on the Au surface prior to analyte exposure.

Figure 1c shows the difference spectrum obtained by subtracting Figure 1b from a spectrum recorded 2–5 min after exposing the composite monolayer to DIMP/N_2 vapor for 20 min. Several peaks characteristic of DIMP are present: the P—O stretch at 1016 cm^{-1}; the hydrogen-bonded P=O stretch at 1206 cm^{-1}; the symmetric deformation of the P-bound CH_3 groups at 1315 cm^{-1}; the resonance-split symmetric deformation of the isopropyl methyl groups centered at 1385 cm^{-1}; and the asymmetric C—H stretch of the isopropyl methyl groups centered at 2984 cm^{-1}.[18] Unfortunately, these data do not conclusively prove the phosphonate interacts with the unsaturated Cu^{2+} sites, although they are not inconsistent with this hypothesis. The frequencies and magnitudes of the peaks in Figure 1c do conclusively demonstrate that, under these conditions,[19] approximately one monolayer of DIMP adsorbs onto the carboxylate/Cu^{2+} surface.

Figure 2 shows the SAW response for a MUA/Cu^{2+}-modified SAW device upon exposure to pure N_2 and mixed DIMP/N_2

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(19) FTIR-ERS experiments were performed ex situ, and as a result, there is significant DIMP desorption from the substrate prior to spectral acquisition. In situ SAW experiments discussed later in the text indicate multilayer DIMP adsorption.

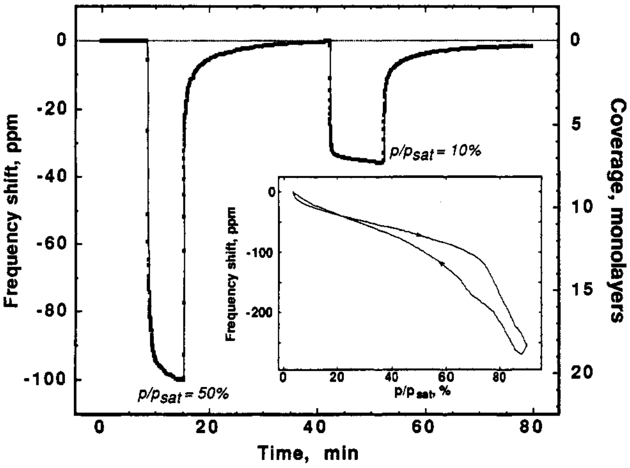

Figure 2. Response of a Cu^{2+}/MUA-modified SAW device to 50%- and 10%-DIMP-saturated N_2 vapor streams. Inset: Frequency shift of the same device as a function of the gas-phase concentration of DIMP. The isotherm was obtained over the course of 2 h.

vapor streams. Between 0 and 8 min the sensor was exposed to pure N_2. These data were used to establish a linear correction for a very slight baseline drift of 0.07 ppm/min. Between 8 and 15 min, the sensor was exposed to 50%-saturated DIMP vapor in N_2. Between 15 and 42 min the sensor was again exposed to pure N_2, and then between 42 and 52 min it was exposed to 10%-saturated DIMP. Several points are worth noting. First, the negative frequency shifts, which correspond to a mass loading of about 20 and 6 monolayers[16] of DIMP for 50% and 10% DIMP streams, respectively, are approximately proportional to the partial pressure of DIMP. Second, the sensor has rapid response time: for 10% saturated DIMP, 90% of the maximum frequency shift is attained in 35 s. Third, DIMP reversibly binds to the chemically sensitive surface: when the 50%-saturated stream is replaced by pure N_2, 90% of the DIMP desorbs in just over 2 min. Similar responses have also been obtained for DMMP. The sort of response illustrated in Figure 2 was obtained consistently over a period of several months, during which the sensor was repeatedly exposed to a range of common organic solvents and the laboratory ambient.

There are two nearly linear regions in the complete adsorption isotherm for the DIMP sensor, as shown in the inset of Figure 2, suggesting two simple, single-energy equilibrium constants relating gas-phase to surface-adsorbed DIMP concentrations. We are able to detect DIMP at concentrations as low as 100 ppb.

Useful chemical sensors must be selective as well as reversible and sensitive. To investigate selectivity, we exposed the sensor used to obtain the data shown in Figure 2 to 10%-saturated streams of polar and nonpolar solvents (Figure 3). The frequency shifts observed for these vapors, and for several other common organic solvents, are all in the opposite direction to the shifts resulting from DIMP or DMMP exposure. Also, the sensor responds much more slowly to water and the organic solvents than to the organophosphonates. These data demonstrate this sensor's selectivity for organophosphonates relative to typical interferants, though the sensor response to ligands likely to strongly coordinate the Cu^{2+} remains to be examined.

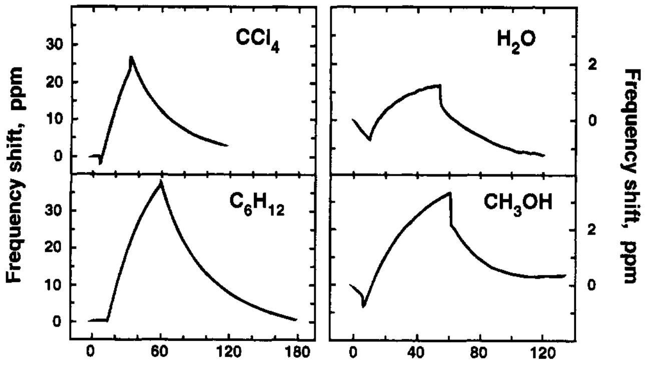

Figure 3. Plots of frequency shift versus time for a MUA/Cu^{2+}-coated SAW device exposed to flowing N_2 streams of pure vapor-phase solvents. Shortly after $t = 0$ min, the sensor was exposed to a 10% solvent-saturated stream of N_2. All solvents caused positive frequency shifts, in contradistinction to the negative frequency shifts obtained for DIMP and DMMP. Nonpolar solvents resulted in a substantially larger response than polar solvents, suggesting that interactions with the hydrocarbon chains of the MUA monolayer are important.

It is somewhat surprising that positive frequency shifts result from exposure of the device to common organic solvents. Since no mass loss is apparent after N_2 purging, we conclude that the positive frequency shifts correspond to changes in the viscoelastic properties of the film.[6a,10b,17] Anecdotal support for this conclusion is provided by the small magnitude of the shifts for polar molecules compared to the shifts for nonpolar molecules. We speculate that the solvents insert between the methylene chains of the MUA monolayer, most likely at defects which must occur at boundaries between adjacent Au crystallites, effectively stiffening the film. Such an effect would be most pronounced for nonpolar solvents, consistent with our data. We are presently investigating this interesting result.

As control experiments, SAW devices having bare quartz, bare Au, and Cu^{2+}-free MUA self-assembled films were examined. Quartz and Au surfaces yielded measurable response to DIMP, but in both cases, a significant fraction of the response was irreversible, irreproducible, and apparently dependent on surface cleanliness. Moreover, responses to organic solvents were not generally distinguishable from responses to DIMP in these control experiments, since all frequency shifts were negative. The Cu^{2+}-free MUA films gave responses similar to those of the Cu^{2+}-terminated films, including positive frequency shifts for organic solvents, but the repeatability and reversibility of the DIMP responses were inferior to those of the Cu^{2+}-terminated films.

CONCLUSIONS

The most important result of this study is that straightforward self-assembly chemistry can be used to fabricate surfaces that are chemically sensitive to important analytes. This implies that rational development of selective coatings need not involve tedious synthesis of complex and fragile "active sites". Moreover, since this sensor is based on a simple monolayer, rapid responses are obtained. Finally, we have demonstrated that this simple fabrication procedure incorporates all of the essential features of an ideal sensor: (1) it is selective for organophosphonates; (2) it is sensitive to 100 ppb of an important nerve-gas simulant; (3) it provides a reversible and proportional response to target analytes; (4) it is durable for periods of months.

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