Analyte selective response in solution-deposited tetrabenzo porphyrin thin-film field-effect transistor sensors

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A B S T R A C T

Organic thin film transistor (OTFT) chemical sensors rely on the specific electronic structure of the organic semiconductor (OSC) film for determining sensor stability and response to analytes. The delocalized electronic structure is influenced not only by the OSC molecular structure, but also the solid state packing and film morphology. Phthalocyanine (H2Pc) and tetrabenzo porphyrin (H2TBP) have similar molecular structures but different film microstructures when H2Pc is vacuum deposited and H2TBP is solution deposited. The difference in electronic structures is evidenced by the different mobilities of H2TBP and H2Pc OTFTs. H2Pc has a maximum mobility of 8.6 × 10−3 cm2 V−1 s−1 when the substrate is held at 250 °C during deposition and a mobility of 4.8 × 10−3 cm2 V−1 s−1 when the substrate is held at 25 °C during deposition. Solution deposited H2TBP films have a mobility of 5.3 × 10−3 cm2 V−1 s−1, which is consistent with better long-range order and intermolecular coupling within the H2TBP films compared to the H2Pc films. Solution deposited H2TBP also exhibits a textured film morphology with large grains and an RMS roughness 3–5 times larger than H2Pc films with similar thicknesses. Despite these differences, OTFT sensors fabricated from H2TBP and H2Pc exhibit nearly identical analyte sensitivity and analyte response kinetics. The results suggest that while the interactions between molecules in the solid state determine conductivity, localized interactions between the analyte and the molecular binding site dominate analyte binding and determine sensor response.

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1. Introduction

Organic thin film transistors (OTFTs) have attracted interest as chemical sensing platforms for vapor and liquid phase detection of explosives, toxins and biochemicals [1–7]. OTFTs offer numerous advantages over inorganic oxide and polymer chemiresistors, such as tailored chemical selectivity, room temperature operation, and multimetered response [8–12]. Several reports demonstrate novel device structures using inexpensive, robust materials providing a low cost fabrication pathway for selective, single use sensing applications [13–15]. However, the organic semiconductor layer is often deposited by vacuum evaporation in order to control film thickness and microstructure, which are key parameters governing sensitivity and stability [16–19]. A potential advantage of organic materials is the possibility of fabricating solution processed sensors using low cost, high throughput deposition methods, such as inkjet printing and spin-coating. However, for practical devices, the high sensitivity and mobility of vacuum deposited sensors must be retained with solution processing methods.

Porphyrins (Por) and phthalocyanines (Pcs) are a well studied group of sensor materials, characterized by their good thermal stability, high optical absorbance and functionality [20–23]. Porphyrins are structurally related to phthalocyanines, with the four –CH groups in the inner porphyrin ring replacing the four meso nitrogens of phthalocyanine. Several studies have investigated differential chemical sensing by changing the central metal atom in the Por/Pc core or by changing the peripheral substituents [24–27]. Sensing mechanism studies for metal-free phthalocyanine (H2Pc) thin-films have correlated sensor response with a selective molecular chemisorption event, determined by the hydrogen bond basicity of the analyte [28,29]. The present work expands on the selective
response mechanism of H2Pc thin-film sensors by demonstrating nearly identical sensor response for H2Pc and H2TBP OTFTs with dramatically different film morphologies and bulk electronic structures.

The film morphology and bulk electronic structures of H2Pc and H2TBP films were modified using different deposition methods. H2TBP is deposited with the use of a soluble precursor and thermally converted to form a textured polycrystalline film with large grains and large surface roughness. H2Pc is deposited by vacuum evaporation while holding the substrate at different temperatures which allows growth of films with significantly different grain size and surface roughness. In general, for H2Pc at higher substrate deposition temperatures (Tsub), there is increased ordering leading to larger grains and increased mobility [30]. Similar correlations between mobility and grain size have been noted for spin-coated H2TBP films; however the mobilities are often higher than vacuum evaporated H2Pc films which suggests better intermolecular coupling and long-range order within the grains [31,32]. The present study shows that solution processed H2TBP and vacuum deposited H2Pc OTFTs exhibit nearly identical analyte sensitivity and analyze response kinetics despite large differences in the film morphology and bulk electronic structure. The H2TBP OTFTs have greater than 3× larger RMS roughness, greater than 3× larger grain size and greater than 100× higher mobility than room temperature vacuum deposited H2Pc OTFTs; yet the analyte sensitivities are equal to within a factor of two for most analytes. The results suggest that sensing properties are determined by selective molecular chemisorption via hydrogen-bonding at the binding site and have little dependence on film microstructure.

2. Materials and methods

H2TBP and H2Pc TFT sensors were fabricated using an inverted bottom contact device geometry using a modified bilayer resist lift-off method [33,34]. Briefly, resist layers of PMGI SF8 (Microchem) and S1818 (Shipley) are employed to create an undercut resist profile so that metal deposition yields a tapered electrode geometry. Electrodes consisted of a 5 nm Ti adhesion layer followed by 45 nm of Au deposited under high vacuum on 100 nm thermally grown SiO2/n+Si (100) substrates (Silicon Quest). The soluble H2TBP precursor 1:4:8:11:15:18-22,25-tetraethano-29H,31H-tetrabenzo[b,g,l,q]porphine (CP) was spin-coated in air from a 0.7 wt% chloroform solution and annealed at 200 °C in a N2 purged oven. Prior to spin coating, the substrates were rinsed in acetone and isopropanol, treated with UV-ozone for 20 min, and soaked in ethanol. Synthesis of CP followed the literature procedure [35]. H2Pc was purchased from Sigma–Aldrich and purified 3 times by multiple zone sublimation before loading into the deposition chamber. Prior to H2Pc deposition, the substrates were sonicated in isopropanol and in deionized water. H2Pc was thermally evaporated in ultra-high vacuum at rates of 0.9–1.0 Å s−1 onto rotating substrates held at constant substrate temperature. An H2Pc film thickness of 100 nm was chosen, which is similar to the estimated thickness of the H2TBP film [36].

Current–voltage measurements were recorded in air in the dark, immediately following removal from a vacuum storage chamber, using an Agilent B1500 semiconductor parameter analyzer. The mobility and threshold voltage were calculated based on the equation for TFT saturation mode operation. \( I_T = (W/C_L) \mu V_T \) where \( C_L \) is the gate oxide capacitance \( \mu \) is the field-effect mobility, \( V_T \) is the threshold voltage, \( W \) is the channel width and \( L \) is the channel length. Before chemical sensing, the samples were wire bonded on a ceramic DIP and mounted on a printed circuit board. In order to minimize the effect of device aging, the devices were stored in a chemical free vacuum desiccator for one day prior to chemical sensing.

AFM measurements were performed with a Nanoscope IV scanning microscope in tapping mode using a Nanosensors SSS-NCHR-20 ultra-sharp Si probe. SEM measurements were performed on a field emission SEM, JSM-2007 from JEOL.

Sensing experiments were performed under zero grade air (Praxair, <2 ppm H2O, <0.02 ppm NOx) at 25 °C. A 2% duty cycle pulse train operated at 0.02 Hz was applied for both the gate and drain bias. Transient measurements were recorded using a National Instruments 6211-DAQ by recording the voltage drop across a 1.2 kΩ resistor. Prior to sensing measurements, the devices were operated under zero grade air using the gate pulse sequence to equilibrate the bias stress effect. Analyte vapors were introduced to an enclosed, thermally regulated chamber with electrical feedthroughs by bubbling zero grade air through the liquid analyte. The concentration of analyte introduced was controlled by mixing the saturated vapor with a separate dilution line in a manifold prior to the chamber.

Recovery analysis was performed by comparing \( t_{60} \) values, where \( t_{60} \) is defined as the time required to recover 60% of sensor response with respect to the baseline current. The \( t_{60} \) values were calculated following subtraction of residual baseline current drift. The drift was fit to a linear regression and subtracted from the raw signal to prevent drift from skewing the \( t_{60} \) values.

3. Results and discussion

To determine appropriate test parameters for sensor operation, TFTs based on H2Pc and H2TBP were electrically characterized. Fig. 1 shows typical current–voltage (I–V) characteristics of H2Pc (Tsub = 25 °C) and solution processed H2TBP TFTs, with the molecular structures of H2Pc and H2TBP as insets in Fig. 1b and d. The mobilities and threshold voltages range from \( (3.0 \pm 0.8) \times 10^{-3} \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) and \( -4.1 \pm 0.4 \text{V} \) for H2Pc to \( (5.3 \pm 0.9) \times 10^{-3} \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) and \( -2.9 \pm 0.4 \text{V} \) for H2TBP, which is comparable to previously reported H2Pc and H2TBP OTFTs [30,36]. The mobilities, threshold voltages and \( I_{on}/I_{off} \) ratios for H2Pc and H2TBP OTFTs with different Tsub and spin-coated H2TBP OTFTs are summarized in Table 1. The non-linear behavior of the drain current at low drain voltage in Fig. 1c is consistent with significant source/drain contact resistance and could be attributed to poor step coverage of the H2TBP at the Au/H2TBP channel edge [37]. Vapor deposited H2Pc devices exhibit slightly better contact resistance, as evidenced by the distinct linear region in Fig. 1a, possibly due to enhanced film coverage at the contact interface. Torsi et al. demonstrated that contact resistance cannot be neglected during chemical sensing when the device is operated at low bias conditions [38]. In this work, the devices are operated at sufficiently high drain voltage (\( V_D = -10 \text{V} \)) and gate voltage (\( V_G = -8 \text{V} \)) that differences in contact resistance will not affect the sensing properties.

Stable operating conditions for OTFT sensors require careful control of both electrical and environmental test parameters. Stable operation was achieved using dry synthetic air flow and a pulsed gate bias with a 2% duty cycle. The pulsed gate method has been demonstrated as an effective operating method to reduce bias

<table>
<thead>
<tr>
<th>Tsub (°C)</th>
<th>( \mu ) ( \times 10^{-3} \text{cm}^2\text{V}^{-1}\text{s}^{-1} )</th>
<th>( V_{th} ) (V)</th>
<th>( I_{on}/I_{off} )</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>0.30 ± 0.08</td>
<td>-4.1 ± 0.4</td>
<td>(2.3 ± 0.4) × 10^4</td>
</tr>
<tr>
<td>80</td>
<td>1.57 ± 0.04</td>
<td>-3.3 ± 0.1</td>
<td>(6.4 ± 0.4) × 10^4</td>
</tr>
<tr>
<td>125</td>
<td>5.50 ± 0.43</td>
<td>-4.0 ± 0.5</td>
<td>(2.5 ± 1.2) × 10^4</td>
</tr>
<tr>
<td>200</td>
<td>5.76 ± 0.07</td>
<td>-4.9 ± 0.4</td>
<td>(2.0 ± 0.1) × 10^4</td>
</tr>
<tr>
<td>250</td>
<td>8.37 ± 1.30</td>
<td>-5.1 ± 0.5</td>
<td>(4.2 ± 0.9) × 10^4</td>
</tr>
<tr>
<td>Spin-coated H2TBP</td>
<td>53.7 ± 9.9</td>
<td>-2.9 ± 0.4</td>
<td>(3.7 ± 1.5) × 10^4</td>
</tr>
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</table>

Table 1: H2TBP and H2Pc device properties. Calculated mobility (\( \mu \)), threshold voltage (\( V_{th} \)) and \( I_{on}/I_{off} \) parameters for vacuum evaporated H2Pc at different substrate temperatures (Tsub) and solution deposited H2TBP.
stress effects for both polymer and small molecule OTFTs [39,40]. By reducing the gate “on” time via pulsing, it is possible to minimize bias induced shifts in threshold voltage during chemical sensing. Following stabilization, the H$_2$BP and H$_2$Pc devices were operated with current drift as low as 0.1% per hour.

Fig. 2 shows the H$_2$TBP, H$_2$Pc ($T_{sub}$ = 25 °C) and H$_2$PCP ($T_{sub}$ = 250 °C) sensor responses to acetonitrile (Fig. 2a) and dimethyl methylphosphonate (Fig. 2b) when operated in the saturation region ($V_{ds}$ = 10 V, $V_{gs}$ = −8 V) using a pulsed gate bias with a 2% duty cycle. The drain currents ($I_d$) for both devices are normalized and plotted with respect to the initial currents ($I_0$). The stable baseline allows a well defined response ($\Delta I/I_{baseline} \times 100$), where $\Delta I$ is defined by the current change over a 20 min dose period and $I_{baseline}$ is the drain current measured immediately before analyte doses (see Supplementary Data). Five analytes were tested to assess a range of sensor binding affinities where trimethylphosphate (TMP), isophorone (ISO) and dimethyl methylphosphonate (DMMP) are considered strong binders and acetonitrile (ACN) and methanol (MeOH) are considered weak binders [28]. Sensor response was linear with dose concentration, and drain current decreases were observed for all analytes tested. Sensor response for MeOH, TMP and ISO doses can be found in the Supplementary Data (Figs. S1–S3). The sensitivities (%ppm$^{-1}$) for each analyte are plotted in Fig. 2c, where sensitivity is defined by the slope of the linear fit of the sensor responses versus analyte concentrations (Figs. S4 and S5). For H$_2$TBP, the sensitivity (S) was greatest for DMMP and lowest for MeOH, with a response ratio ($S_{DMMP}/S_{MeOH}$) of ~85. The corresponding response ratios for H$_2$PCP ($T_{sub}$ = 250 °C) and H$_2$Pc ($T_{sub}$ = 25 °C) were ~53 and ~32. For all sensors, the response ratios between DMMP and weak binding analytes exceeded 30 (Table 2). The high response ratio makes H$_2$TBP suitable for use in cross-reactive sensor arrays where discriminatory analysis can be used to identify analytes [29]. Although some of the response ratios differ by more than 2× between the H$_2$PCP and H$_2$TBP sensors, the relative analyte sensitivities ($S_{H2TPP}/S_{H2PCP}$) differ by less than 2× for all analytes (Tables S1 and S2). This suggests that molecular chemisorption between the analyte and the semiconductor dominates sensor response even though morphological effects may provide slightly enhanced analyte discrimination for H$_2$TBP.

By analyzing the transient recovery in OTFT chemical sensors, the analyte binding kinetics can be elucidated. Average $t_{60}$ values for each sensor are presented in Table 2. The $t_{60}$ values are normalized with respect to MeOH to illustrate the consistent relative recovery times for each sensor. The relative recovery time normalizes the $t_{60}$ for each recovery with respect to the $t_{60}$ for MeOH. This eliminates run-to-run variations in flow rate or temperature which could influence recovery rates. Both H$_2$PCP and H$_2$TBP sensors

**Fig. 1.** $H_2$PC and $H_2$TBP OTFT characteristics. Output characteristics of (a) 100 nm vacuum deposited $H_2$PC with $T_{sub}$ = 25 °C and (c) solution processed $H_2$TBP OTFTs. Transfer characteristics of the same (b) $H_2$PC and (d) $H_2$TBP OTFTs. The solid lines indicate fits used to extract threshold voltage and mobility. Gate oxide capacitance ($C_g$) × 3.45 × 10$^{-6}$ F/cm$^2$, channel length ($L$) = 5 μm, channel width ($W$) = 10$^5$ μm for both devices, $V_{gs}$ sweep using −1 V steps for (b) and (d).
exhibit rapid recovery following doses of weak binding analytes such as MeOH and ACN (Fig. 2a), whereas for strong binding analytes such as TMP and DMMP there is a slower recovery (Fig. 2b). The H₂TBP sensor recovery immediately following a 15.8 ppm DMMP exposure and a 1174 ppm ACN exposure is presented in Fig. 2d to illustrate the extended recovery time required for DMMP.

The results for H₂TBP and H₂Pc OTFTs are analogous to those for previously reported H₂Pc thin-film chemiresistors [28]. The analyte sensing mechanism is attributed to hydrogen-bonding at the inner N₄H₂ group. OTFT on-current decreases are observed during exposure to hydrogen bond acceptor analytes due to electron density donation from the analyte to the interior N–H protons in H₂TBP and H₂Pc. Therefore, analytes which are better hydrogen-bond acceptors such as DMMP and TMP are also stronger Lewis bases [41]. The sensitivities and relative recovery times for H₂TBP and H₂Pc OTFT sensors correlate with the analyte hydrogen-bond basis.

The distinction in response between strong and weak binding analytes is consistent with a selective molecular chemisorption event between the analyte and semiconductor. Molecular chemisorption between the analyte and semiconductor is due to electron density transfer upon hydrogen-bonding. The magnitude of electron density transfer and binding energy (Eₜₐₜ) distinguishes weak binding analytes as physisorbates (Eₜₐₜ < 0.3 eV) and strong binding analytes as chemisorbates (Eₜₐₜ ~ 1 eV) [42]. The distinction between chemisorbing and physisorbing analytes on H₂TBP and H₂Pc OTFTs is evident not only by the high sensitivities noted above, but also by the relative recovery times. Although taken

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Spin-coated H₂TBP</th>
<th>H₂Pc (Tₘₐₓ = 25 °C)</th>
<th>H₂Pc (Tₘₐₓ = 250 °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMMP</td>
<td>4.8 (0.3)</td>
<td>4.0 (1.1)</td>
<td>4.4 (0.1)</td>
</tr>
<tr>
<td>TMP</td>
<td>2.6 (0.1)</td>
<td>1.8 (0.2)</td>
<td>2.9 (0.3)</td>
</tr>
<tr>
<td>ISO</td>
<td>2.2 (0.6)</td>
<td>0.7 (&lt;0.1)</td>
<td>0.8 (0.1)</td>
</tr>
<tr>
<td>ACN</td>
<td>0.3 (&lt;0.1)</td>
<td>0.7 (&lt;0.1)</td>
<td>0.9 (0.1)</td>
</tr>
<tr>
<td>MeOH</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>DMMP/MeOH</td>
<td>45.5</td>
<td>32</td>
<td>53</td>
</tr>
<tr>
<td>DMMP/ACN</td>
<td>68</td>
<td>50</td>
<td>126</td>
</tr>
</tbody>
</table>

Fig. 2. H₂TBP and H₂Pc OTFT sensing. Transient response of H₂Pc (Tₘₐₓ = 25 °C and 250 °C) and H₂TBP OTFTs to (a) acetonitrile (ACN) and (b) dimethyl methylphosphonate (DMMP). (c) Calculated sensitivities for H₂TBP, and H₂Pc OTFT sensors. Calculations are based on the slope of the linear fit of the sensor responses versus analyte concentration, averaged for three devices. (d) Recovery of H₂TBP sensors following exposure to 1174 ppm ACN and 15.8 ppm DMMP.
for a small set of analytes, the data shows a significant difference between $t_{50}$ values for strong and weak binding analytes. Strongly hydrogen-bonding analytes such as DMMP and TMP have longer recovery times and higher sensitivities; consistent with the inner N$_2$H$_2$ ring acting as the preferential binding site. This demonstrates that the different processing methods and film morphologies for H$_2$TBP and H$_2$Pc OTFTs do not significantly alter the analyte-semiconductor hydrogen-bonding characteristics that govern chemical sensing.

H$_2$Pc sensors show significantly shorter $t_{50}$ for isophorone than DMMP and TMP despite having a high sensitivity to isophorone; however, anomalous recovery characteristics for isophorone in H$_2$Pc chemiresistors have been reported previously [29]. It has been suggested that physisorbing analytes can interact with MPC films by preferential binding or by weak van der Waals interactions with the conjugated π system of H$_2$TBP and H$_2$Pc [29]. Therefore, it is possible that the meso nitrogens present in H$_2$Pc, and absent in H$_2$TBP, contribute to sensor response and recovery. However, the fast recovery and low sensitivity for each sensor to doses of MeOH and ACN suggest that the molecular structure of the extended π system does not significantly alter sensor response.

OTFT device properties are highly dependent on fabrication methods which influence film electronic structure by affecting grain size and intermolecular coupling [43]. The different surface morphologies of 100 nm H$_2$Pc films with $T_{sub} = 25$–250 °C and a solution processed H$_2$TBP film are shown in atomic force microscopy (AFM) images presented in Fig. 3a–e. Line profiles of a 500 nm segment are shown as insets for each image. The height scale on the line profiles is held constant to demonstrate the larger surface roughness for H$_2$TBP films.

Vacuum deposited H$_2$Pc has a film morphology which depends on substrate temperature. At $T_{sub} = 25$ °C, H$_2$Pc forms small, densely packed grains (Fig. 3a) with an average grain size of 34 ± 12 nm and RMS roughness of 8 nm. As $T_{sub}$ increases, the grains become large elongated crystallites with an average long-axis length of 187 ± 87 nm and aspect ratio of ~3. The large crystallite growth enhances the layer-to-layer connectivity as evidenced by a smaller RMS roughness of 5 nm. To illustrate the effect of grain size and film morphology on the H$_2$Pc film electronic properties, the mobility was plotted for OTFTs deposited with $T_{sub}$ ranging from 25 °C to 250 °C (Fig. 3f). The increase in mobility with grain size is often observed for phthalocyanine OTFTs [30,44].

Following spin-coating, the bicycloroporphyrin precursor forms an amorphous film with thicknesses between 100 and 200 nm. After thermal conversion to H$_2$TBP, large crystallites form (Fig. 3e) and create a highly textured film with average grain size of 107 ± 47 nm and root-mean-square (RMS) roughness of 28 nm. The H$_2$TBP OTFTs in this work have mobilities exceeding any of the H$_2$Pc OTFTs even though the H$_2$TBP films do not have the largest grain sizes. The higher mobility in H$_2$TBP OTFTs is consistent with enhanced intermolecular coupling and better long-range order though the H$_2$TBP grains.

Several reports for OTFT sensors using different molecular semiconductors note the importance of controlling grain size and surface roughness to optimize sensitivity [18,45,46]. However, the nearly identical chemical sensor response in this study suggests...
that film microstructure differences do not significantly alter the 
H2TBP and H2Pc molecular interactions with analytes. The data 
presented are consistent with grain growth affecting the elec-
tronic delocalization and field-effect mobility of the film, but 
not affecting the hydrogen-bonding event that governs the relative 
sensor response. The data suggests that the film intermo-
molecular interactions influence the mobility and are independent 
from the intramolecular interactions between the film and analyze that 
control chemical sensing.

4. Conclusion

In summary, OTFT sensors based on solution processed H2TBP 
were found to have enhanced mobilities while yielding chemical 
sensing properties nearly identical to OTFT sensors based on vapor 
deposited H2Pc. The mobilities of the films were strongly affected 
by differences in film microstructure, but this had little influence on 
chemical sensor behavior. This is consistent with analyze binding 
being chiefly a function of interactions with individual molecules 
of the sensor film. This study suggests the feasibility of preparing 
nonvolatile metal coordination complex sensor arrays with solu-
tion processed films. Consistent chemical sensor response can be 
obtained despite dramatic changes in field-effect mobility, which 
implies that relative chemical sensor response is a more robust 
property than field-effect mobility in OTFT sensors.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in 

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Biographies

James Royer received his B.S. degree in chemistry from the University of Maryland, College Park and is a Ph.D. candidate in chemistry at the University of California, San Diego. His current research interests include chemical sensing in organic thin film transistors and molecular adsorption on organic monolayers studied by scanning tunneling microscopy.

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Jerzy Kanicki received the Ph.D. degree in sciences from the Free University of Brussels, Brussels, Belgium, in 1982. He subsequently joined the IBM Thomas J. Watson Research Center, Yorktown Heights, NY, as a Research Staff Member working on hydrogenated amorphous silicon devices for photovoltaic and flat panel display applications. In 1994, he moved to the University of Michigan where he did leading work on various flat panel display technologies and on a variety of fundamental problems related to organic and molecular electronics. He is the author and coauthor of over 250 publications in journals and conference proceedings.

William Trogler graduated from Johns Hopkins University in 1974, obtaining both B.A. and M.A. and B.A. degrees in chemistry before moving to Caltech for his Ph.D. with Harry Gray. In recent years, his research interests have centered on luminescent polymer sensors for explosives, thin film resistive chemical vapor sensors, and biomedical applications of nanoparticles. He is the author of over 180 papers.

Andrew Kummel graduated from Yale University in 1981 with a B.S. in chemical engineering. He received an M.S. degree in chemical engineering and Ph.D. in chemistry from Stanford University in 1988. Since 1996 he has been full professor of chemistry and biochemistry and an affiliated faculty member in materials science, nanoscience, and electrical engineering. He is the author of over 120 papers. His current research interests include (a) atomic and electronic structure of oxide–semiconductor interfaces using STM/STS probes; (b) chemically sensitive thin-film effect transistor sensors; and (c) nanoshell and microshell-based drug delivery, drug detection, and cancer detection.