**A CHEMICALLY-SELECTIVE MICROSENSOR FOR ENVIRONMENTALLY-SENSITIVE POLLUTANTS
REALIZED WITH AN INTERDIGITATED GATE ELECTRODE FIELD-EFFECT TRANSISTOR (IGEFET)**

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ABSTRACT

An interdigitated gate electrode field-effect transistor (IGEFET) has been coupled with a chemically-active, electron-beam evaporated copper phthalocyanine (CuPc) thin film to realize a gas-sensitive microsensor. The sensor can selectively detect parts-per-billion concentration levels of nitrogen dioxide (NO_2) and diisopropyl methylphosphonate (DIMP). The sensor is excited with a voltage pulse, and the time- and frequency-domain responses are measured. The envelopes associated with the normalized difference Fourier transform magnitude frequency spectra reveal features which unambiguously distinguish the NO_2 and DIMP challenge gas responses. The area beneath each response envelope can correspondingly be interpreted as the sensor's sensitivity for a specific challenge gas concentration.

INTRODUCTION

In the course of daily activity, the living and working environment exposes humans to a variety of toxic gases and vapors. Two critical groups of environmentally-sensitive contaminants include the oxides of nitrogen, and the organophosphorus pesticides and their structurally affiliated compounds. Today, it is recognized that even trace amounts of these pollutants can pose an adverse effect on many ecological systems. This acknowledgement has motivated the development of sensitive and selective personal monitoring sensors which are capable of detecting sub-threshold levels of these toxic compounds.

The oxides of nitrogen, particularly nitrogen dioxide (NO_2), are unintentionally emitted into the atmosphere from a variety of industrial stacks and the exhaust of automobiles. Because of its environmental impact, nitrogen dioxide was identified as one of the two model compounds investigated.

On the other hand, the organophosphorus pesticides and their structurally related compounds are intentionally synthesized and valued for their deleterious biochemical effect and persistence. Additionally, the distribution of these compounds is essential for their efficacy. Fortunately, a significant portion of the environmentally-sensitive organophosphorus contaminants contain either the phosphoryl or thiophosphoryl group, and the thiophosphoryl pesticides readily oxidize to produce phosphoryl compounds. Consequently, diisopropyl methylphosphonate (DIMP), a phosphoryl-containing compound which has been utilized in prior organophosphorus compound detector research (1-3), was selected as the second model compound investigated.

Recently, coated bulk-wave piezoelectric quartz crystal microbalances (QCMs) (1-5) and surface acoustic wave (SAW) devices (6,7) have been investigated as candidate sensor technologies for detecting NO_2 and the environmentally sensitive organophosphorus compounds. However, significant performance limitations associated with both technologies include the lack of specificity, sensitivity to moisture, and response

reproducibility. These results are not totally unexpected, since the physiochemical sorption of any environmental gas or vapor will increase the mass of the detector's coating and produce a sensor response. Thus, specificity generally remains an elusive performance feature.

In order to achieve specificity with a sensor that is exposed to an ensemble of gases, a more robust, selective, and measurable interaction between the adsorbant of interest and the sensor must occur, and this event must be decipherable from the sensor's response. This paper describes the IGEFET sensor concept and the progress achieved toward satisfying this performance goal.

In contrast to the generally less-specific physiochemical sorption process, this research focused on investigating the electronic properties of an organic semiconductor that are modified when it is exposed to a dehumidified laboratory air atmosphere (typically 2 % r.h.) containing small concentrations of NO_2 or DIMP. In particular, electron-beam evaporated thin films of copper phthalocyanine (CuPc) have been deposited on an interdigitated gate electrode field-effect transistor (IGEFET) to realize a microelectronic integrated circuit sensor which can selectively detect parts-per-billion (ppb) concentration levels of NO_2 and DIMP.

The IGEFET sensor's operation is based on monitoring the variation of the field-effect transistor's drain-to-source current in response to a gas exposure induced change in the thin film which covers the interdigitated gate electrode structure. Molecular and compositional changes in the thin film likely occur as the result of a dipole or charge-transfer electronic interaction with an adsorbed gas. These changes are correspondingly manifested in the gas-sensitive film's dielectric relaxation function, or more succinctly, as a change in the film's electrical impedance.

The concept of utilizing a planar interdigitated electrode chemiresistor to monitor electrical impedance changes caused by a bulk chemical reaction has been reported in the literature (8-13). However, the overwhelming majority of these investigations have focused on measuring the direct current electrical conductivity changes manifested in the chemically-active films. Additionally, a significantly smaller number of studies have examined the film's alternating current impedance behavior, but generally, only at specific frequencies. Consequently, since the interaction between an adsorbant and the thin film produces a distinct change in the film's electrical resistance and reactance at specific frequencies for different challenge gases, the IGEFET sensor concept was motivated, and its response is processed to produce a detailed signature or 'fingerprint' of the resulting chemical interaction in both the time- and frequency-domains. The physical phenomenon which permits this unique perspective is the chemically-active film's dielectric relaxation response. For the IGEFET device, the calculation of the chemically-induced normalized difference Fourier transform magnitude spectrum has been experimentally demonstrated to be unique for the two model gases utilized in this investigation. The unique ensemble of data points

comprising the response signature notably contributes to the sensor's specificity.

By contrast, the QCM, SAW, and interdigitated electrode chemiresistors have most frequently been operated in an attempt to discern sensor specificity by comparing changes associated with a single measured parameter (for example, a resonant frequency shift, a change in the direct current electrical resistance, or an impedance change at a specific frequency); certainly, a near impossible task. That is, the sensor's performance often reveals that, for a given concentration of a specific challenge gas, there often exists a different gas at some concentration which evokes an identical sensor response; hence, the apparent lack of specificity.

SENSOR CONCEPT

As depicted in Figure 1a, the IGEFET sensor consists of a planar interdigitated gate electrode (IGE) structure which forms the gate contact of a conventional MOSFET. The IGE structure is composed of a driven-electrode component which envelopes the entire sensor, and thus, functions as a guard-ring to minimize stray surface-leakage currents. The corresponding floating-electrode component is used to establish the IGE's high input impedance electrical contact with the MOSFET's gate oxide. Prior to the deposition of the chemically-active thin film, the electrical isolation between the driven- and floating-electrodes is typically measured to be on the order of 100 M Ω ; this high degree of electrical isolation is accomplished by supporting the electrodes on a 1 μ m thick silicon dioxide layer whose resistivity is typically greater than 10¹⁴ Ω ·cm. The IGEFET's gas sensitivity is realized by depositing a chemically-active thin film on the surface of, and between, the IGE components. When the chemically-active thin film is exposed to the challenge gas of interest, its electrical impedance is perturbed. These impedance perturbations can be readily measured and quantified when the IGEFET's driven-electrode is excited with a voltage pulse. As a consequence of the floating-electrode component being electrically connected to the MOSFET's gate oxide, charge may be transferred through or polarized in the chemically-active thin film, and this behavior is manifested as a temporally-dependent potential applied to the high-input impedance gate contact of the MOSFET. By biasing the MOSFET to operate as a linear amplifier, the gas exposure induced potential appearing at the MOSFET's gate oxide contact is manifested as a corresponding, temporally-dependent change in the device's drain-to-source current. The external resistor connected to the drain contact illustrated in Figure 1a provides a convenient low impedance port for measuring the sensor's response to a challenge gas. Thus, a critical feature of the IGEFET sensor is the electrical isolation afforded by the dielectric-supported interdigitated electrode structure and the gate oxide combination. These features allow the MOSFET to manifest itself as an *in situ* 'observation window' that is capable of monitoring the electrical behavior of the chemically-active thin film, while correspondingly minimizing its influence on the changes induced by the challenge gas. Finally, because the sensor's response is amplified *in situ*, rather than remotely, the instability associated with electrical noise and long lead lengths is minimized.

The IGEFET sensor's specificity is realized by computing a normalized difference Fourier transform magnitude spectrum. The rationale for this computation was motivated after it was experimentally observed that the long-term excitation pulse characteristics of an unexposed or purged CuPc-coated IGEFET sensor are reproducible and time-invariant (14). The normalized difference Fourier transform magnitude spectra are computed by Fourier transforming the sensor's time-domain volt-

age response due to a challenge gas exposure, and then normalizing it with a factor that is also used to normalize the corresponding Fourier transform of the sensor's unexposed or purged time-domain voltage response. Finally, the overall sensor's response is determined by subtracting the two normalized spectra on a point-by-point basis (at common frequencies), and the magnitude of each difference is used to generate an envelope whose 'signature' reports the detector's sensitivity and specificity. In practice, the area beneath a normalized difference Fourier transform magnitude spectrum can be interpreted to correspond to the sensitivity of the sensor to a specific challenge gas concentration. Correspondingly, the large number of components that define the shape of the spectral response envelope yields valuable guidance for unambiguously specifying the particular challenge gas that the sensor is responding to. That is, although different concentrations of NO₂ and DIMP may manifest an identical change in the direct current resistance of a CuPc-coated IGE structure, the shape of the response envelope defined by the normalized difference Fourier transform magnitude spectrum clearly manifests the unique dielectric relaxation behavior caused by the two challenge gases.

The selection of the chemically-active thin film candidate for the IGEFET sensor is critical for establishing the class of compounds to which the detector will manifest a favorable degree of sensitivity. In this IGEFET sensor investigation, the well-known CuPc organic semiconductor was utilized because it is a member of the metal-substituted phthalocyanine family (which includes Ag, Be, Co, Fe, Mg, Mn, Na, Ni, Pb, Pt, and Zn) whose electrical conductivity has been experimentally reported to increase upon exposure to electron-acceptor challenge gases (for example, BCl₃, BF₃, Cl₂, F₂, and NO₂) (15). Additionally, CuPc is an exceptionally stable compound, as evidenced by its low proton affinity, resistance to dissolution by concentrated mineral acids, and the fact that it can be sublimed at temperatures as high as 580 °C without decomposing. The strong electron donor sites that comprise the planarly-delocalized π -electron bond system in CuPc have been postulated to be responsible for the experimentally observed electron-acceptor gas exposure interaction and the corresponding electrical conductivity changes (15). Since NO₂ is reversibly adsorbed on heated CuPc thin films (typically at temperatures spanning 100-170 °C), the interaction site has been identified to occur at the film's intercrystallite interfaces, rather than being a true bulk diffusion mechanism. The strength of the chemical bond between the CuPc thin film and the electron-acceptor gas is likely to be a strong dipole interaction or weak coordination bond; that is, a bond whose energy is stronger than a purely physical adsorptive interaction (less than 40 kJ/mole), but weaker than a true covalent bond (on the order of 300 kJ/mole). Thus, it is anticipated that the specificity of the interaction between a CuPc thin film and a particular electron-acceptor challenge gas will be strongly influenced by the electronic and steric features of the interaction. In the IGEFET sensor investigation, both NO₂ and DIMP were reversibly adsorbed, and NO₂, being the more robust electron-acceptor challenge gas, induced a correspondingly stronger electrical interaction relative to identical exposure concentrations of DIMP.

SENSOR FABRICATION

The IGEFET sensor design is implemented utilizing the standard 3- μ m, p-well, double-metal, CMOS integrated circuit technology. The p-well feature is incorporated to enhance the electrical isolation between the IGE structure and the MOSFET, and n-channel enhancement-mode devices are utilized.

Aluminum is used as the second-level metal for the IGE array and the sensor's bonding pads. Except for the IGE structure and bonding pads, the surface of the IGEFET is passivated with a 3 μm thick silicon dioxide layer to minimize undesirable environmental interactions. The overall dimensions of the IGEFET sensor are 4466 x 6755 μm . The IGE structure typically consists of 29 floating-electrode fingers and 31 driven-electrode fingers. Each finger is 7.5 μm wide, and the inter-electrode finger spacing is 9 μm . The chemically-active area of the IGE measures 921 x 3792 μm .

In order to couple the chemically-active thin film with the IGEFET, a high-purity CuPc thin film (Fluke Chemical Corp., Ronkonkoma, NY) is deposited at a rate of 10 $\text{\AA}/\text{s}$ on the dielectric-supported IGE structure using a high-vacuum (10^{-6} Torr), cryogenically-pumped (helium), electron-beam thermal evaporation process. An etched metal mask is used to confine the CuPc thin film deposition within the boundaries of the interdigitated electrode structure. As measured with an *in situ* QCM, and later verified with an independent ellipsometric measurement, nominal CuPc film thicknesses on the order of 1000 $\text{\AA}$ can be reproducibly deposited ($\pm 5\%$ thickness variation). To facilitate handling the IGEFET sensor, it is mounted in a standard 64-pin dual-in-line IC package (Figure 1b).

SENSOR OPERATION

The electronic instrumentation configuration for operating the CuPc-coated IGEFET sensor is illustrated in Figure 2. A 4-V peak-amplitude, 50- μs duration, 256 Hz repetition-frequency pulse excitation signal is applied to the IGEFET's driven-electrode. These time-domain excitation pulse characteristics were experimentally determined to produce a corresponding Fourier transform magnitude spectrum possessing frequency components with nearly equal mV-level magnitudes spanning the frequency range corresponding to the 3-dB cut-off frequency of the sensor's *in situ* MOSFET amplifier (Figure 3). The sensor's excitation and response time-domain signals are captured on a dual-trace oscilloscope. To complement the time-domain measurements, a dual-channel Fourier transform analyzer (0-25 kHz bandwidth) is utilized to generate the corresponding sensor excitation and response frequency-domain spectra. For completeness, the direct current resistance of the CuPc-coated interdigitated electrode structure is independently monitored with an electrometer to determine the sensor's equilibrium response during the cyclical challenge gas exposure and purge processes. Data collection is automated using a microcomputer equipped with an IEEE-488 interface plug-in card.

A dynamic gas generation and delivery system incorporating calibrated permeation tubes is utilized to create a broad challenge gas concentration range spanning 20-400 parts-per-billion (ppb) for NO_2 , and 40-4000 ppb for DIMP. A complete description of the thermostated sensor cell design is reported in a related publication (16-17).

SENSOR PERFORMANCE

The electrical transfer function characteristics of the *in situ* MOSFET amplifier portion of the IGEFET sensor and reference transistor (Figure 1b) were periodically monitored throughout the duration of the challenge gas exposure experiments. The low-frequency gain was typically 12 ± 1 dB, and the 3-dB cut-off frequency was approximately 12 kHz.

To illustrate the selectivity feature attributed to the IGEFET sensor when it is excited with a voltage pulse and its response is examined in the time and frequency domains, the corresponding direct current conductivity measurements provide a

useful baseline. To implement the direct current conductivity measurements, the sensor is thermostated to $125 \pm 1^\circ\text{C}$, and the film's exposure and purge dynamics are measured. The conventional film resistance versus time plots for cyclical challenge gas exposures and purges are reported in a related publication (14), and Figure 4 depicts the film's equilibrated resistance values resulting from exposures to NO_2 and DIMP. From the slopes of the least-squares fitted exposure plots, an 800 ppb DIMP challenge concentration produces an equivalent resistance change predicted by the 30 ppb NO_2 challenge; hence, the ambiguity problem in attempting to predict the sensor's specificity.

On the other hand, the corresponding isothermal ($125 \pm 1^\circ\text{C}$) IGEFET sensor's time-domain voltage excitation and response waveforms measured with respect to cyclical exposures and purges with NO_2 and DIMP challenges are illustrated in Figure 5, and this information is further supplemented in a related publication (14). The pre-exposure and purged responses attest to the IGEFET sensor's reversibility (Figure 5b). By contrast, the shape of each time-domain response corresponding to the 100 ppb NO_2 and DIMP challenges are distinctly different (Figures 5c and 5d). That is, by considering the exposed CuPc film to be a lossy-dielectric (the loss component tends to increase upon exposure to increasing concentrations of an electron acceptor gas), the corresponding influence on the film's equivalent electrical RC time-constant, as reflected in the sensor's time-domain response, can be appreciated. In particular, a specific concentration of a challenge gas can be interpreted as the cause for modifying the film's dielectric loss (electrical conductivity). Correspondingly, this change results in the manifestation of a specific ensemble of RC time-constants which simultaneously interact to produce the characteristic exponential rise and decay features in the IGEFET's time-domain response. Rather than implementing the complex analysis required to deconvolve a set of RC time-constants from the sensor's time-domain response, the alternative of directly generating the corresponding frequency-domain equivalent response was implemented. In order to be able to compare the frequency-domain responses with respect to a specific gas and challenge concentration, the sensor's reversibility feature (Figure 5b) is capitalized upon. That is, the Fourier transform of the sensor's purged response is correspondingly measured (Figure 2) and normalized with the same factor used to normalize the sensor's frequency-domain challenge gas induced response. The calculation of the corresponding normalized difference Fourier transform magnitude spectra associated with a set of NO_2 and DIMP time-domain responses are shown in Figure 6. The distinct merit of this signal processing scheme is that it produces a spectral response envelope which unambiguously ascribes a specificity feature to the IGEFET sensor. Since the spectral envelopes only intersect at a very limited number of points; this feature clearly emphasizes the difference between the two challenge gas exposure responses. In particular, the first peak of the NO_2 response occurs at approximately 1000 Hz, while that for DIMP occurs at approximately 3400 Hz. Additionally, the rise and decay rates associated with the primary peaks are more pronounced in the NO_2 spectra. Both challenge gas spectra also contain a secondary peak; the NO_2 secondary peak occurs at approximately 8200 Hz, while that for DIMP occurs in the vicinity of 25 kHz. These low-frequency (acoustic) resonant peaks suggest that a long-range dielectric polarization interaction is being facilitated by the adsorbed challenge gases. Qualitatively, the electronic and steric features of the challenge gases, along with the interstitial crystallite adsorption model discussed earlier, are postulated to

account for the observed interfacial dielectric relaxation behavior. Additionally, considering the 25 kHz spectral bandwidth limitation, the area beneath each response in Figure 6 can be utilized to report the sensor's sensitivity to a particular challenge gas concentration.

CONCLUSION

When compared to the conventional direct current or single-frequency alternating current modes of operating chemically-active, thin film, IGE detection devices, the voltage-pulse mode of operating the IGEFET sensor and the associated Fourier domain signal processing technique yields an ensemble of frequency components which define a unique challenge gas response envelope for small concentrations of either NO₂ or DIMP mixed with a common filtered laboratory air source (diluent). The ambiguity associated with differentiating specific challenge gas responses is minimized with the voltage-pulse excitation mode because the sensor's complete frequency-domain response envelopes are considered, rather than simply comparing the changes associated with a single operand (for example, a change in the direct current electrical conductivity). While the spectral features reported for NO₂ and DIMP unambiguously differentiate between these two challenge gases, it is acknowledged that an interferant likely exists that will yield a spectral envelope that would be statistically unresolvable from those corresponding to either of the two model challenge gases considered. If the ambiguity threshold between sensor responses for several challenge gases manifests itself as a serious limitation, it should be possible to minimize its influence by incorporating a two-dimensional array of IGEFET's on a common substrate where each sensor is coated with a different chemically-active thin film. By utilizing the same signal processing technique and implementing a pattern recognition algorithm with a neural network processor, it is envisaged that the IGEFET sensor concept offers significant promise as an alternative technology for detecting an ensemble of gaseous contaminants. Finally, if a broad spectrum of practical applications is envisaged, this technology must also demonstrate a capacity to selectively detect two or more electron acceptor challenge gas components in a multicomponent mixture.

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REFERENCES

1. E. P. Scheide and G. G. Guilbault, Piezoelectric detectors for organophosphorus compounds and pesticides, *Anal. Chem.*, 44 (1972) 1764-1768.
2. G. G. Guilbault, Y. Tomita and E. S. Kolesar, Jr., A coated piezoelectric crystal to detect organophosphorus compounds and pesticides, *Sens. Actuators*, 2 (1981) 43-57.
3. G. G. Guilbault, J. Affolter, Y. Tomita and E. S. Kolesar, Jr., Piezoelectric crystal coating for detection of organophosphorus compounds, *Anal. Chem.*, 53 (1981) 2057-2060.
4. K. H. Karmarkar and G. G. Guilbault, The detection of ammonia and nitrogen dioxide at the parts per billion level with coated piezoelectric crystal detectors, *Anal. Chim. Acta*, 75 (1975) 111-117.
5. L. M. Webber, J. Hlavay and G. G. Guilbault, Piezoelectric detectors for specific detection of environmental pollutants, *Mikrochimica Acta*, 1 (1978) 351-358.
6. M. S. Nieuwenhuizen, A. Nederlof and A. W. Barendsz, Metallophthalocyanines as chemical interfaces on a surface acoustic wave gas sensor for nitrogen dioxide, *Anal. Chem.*, 60 (1988) 230-235.
7. A. Venema, E. Nieuwkoop, M. J. Vellekoop, W. J. Ghijsen, A. W. Barendsz and M. S. Nieuwenhuizen, NO₂ gas-concentration measurement with a SAW-chemosensor, *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control*, UFFC-34 (1987) 148-155.
8. S. D. Senturia, N. F. Sheppard, S. Y. Poh and H. R. Appelman, The feasibility of electrical monitoring of resin cure with the charge flow transistor, *Polym. Eng. Sci.*, 21 (1981) 113-118.
9. S. L. Garverick and S. D. Senturia, An MOS device for AC measurement of surface impedance with application to moisture monitoring, *IEEE Trans. Electr. Dev.*, ED-29 (1982) 90-94.
10. S. D. Senturia, N. F. Sheppard, H. L. Lee and D. R. Day, In-situ measurement of the properties of curing systems with microdielectrometry, *J. Adhesion*, 15 (1982) 69-90.
11. N. F. Sheppard, D. R. Day, H. L. Lee and S. D. Senturia, Microdielectrometry, *Sens. Actuators*, 2 (1982) 263-274.
12. M. C. W. Coln and S. D. Senturia, The application of linear system theory to parametric microsensors, *Digest of Papers for the 1985 International Conference on Solid-State Sensors and Actuators (Transducers '85)*, Philadelphia, PA, U.S.A., June 11-14, 1985, pp. 118-121.
13. S. D. Senturia and N. F. Sheppard, "Dielectric Analysis of Thermoset Cure", *Epoxy Resins and Composites IV*, K. Dusek (ed.); Springer-Verlag: New York, 1986, pp. 1-48.
14. E. S. Kolesar, Jr. and J. M. Wiseman, Interdigitated gate electrode field effect transistor for the selective detection of nitrogen dioxide and diisopropyl methylphosphonate, *Anal. Chem.*, 61 (1989) 2355-2361.
15. J. D. Wright, Gas adsorption on phthalocyanines and its effects on electrical properties, *Prog. Surf. Sci.*, 31 (1989) 1-60.
16. E. S. Kolesar, Jr. and R. M. Walser, Organophosphorus compound detection with a supported copper + cuprous oxide island film. 1. gas-sensitive film physical characteristics and direct current studies, *Anal. Chem.*, 60 (1988) 1731-1736.
17. E. S. Kolesar, Jr. and R. M. Walser, Organophosphorus compound detection with a supported copper + cuprous oxide island film. 2. alternating current studies and sensor performance, *Anal. Chem.*, 60 (1988) 1737-1743.

(a)

(b)

Figure 1. (a) Interdigitated gate electrode field effect transistor (IGEFET) physical structure and electrical connections. Legend: (1) copper phthalocyanine (CuPc) thin film, (2) driven-electrode conductor, (3) floating-electrode conductor, (4) MOSFET drain contact, (5) MOSFET gate and floating-electrode contact, (6) MOSFET source contact, (7) driven-electrode contact, (8) MOSFET source region, (9) MOSFET drain region, (10) MOSFET drain-to-source channel, and (11) host silicon

substrate. (b) CuPc-coated (darkened region on the IGE structure) IGEFET mounted in a 64-pin dual-in-line IC package. (Two sets of IGE structures are illustrated; the narrower IGE set contains one-half the number of interdigitated electrode finger pairs; the center IGEFET in each set has a solid aluminum gate electrode structure, and this device is utilized to characterize variations in the batch-to-batch MOSFET fabrication process.)

Figure 2. Instrumentation arrangement for measuring the electrical performance of the IGEFET sensor.

Figure 4. Isothermal (125 ± 1 °C) equilibrated electrical resistance of a 1000 Å thick CuPc-coated IGE structure as a function of the challenge gas concentration. (Each data point represents the arithmetic average of the film's resistance measured during the final 3 min of a 20-min duration exposure cycle; 2 % r.h. filtered laboratory air carrier.)

Figure 3. Fourier transform magnitude plot of the IGEFET's voltage excitation pulse.

Figure 5. Time-domain response of the IGEFET sensor when excited with the pulsed-voltage waveform due to 100 ppb NO₂ and DIMP challenge concentrations (CuPc 1000 Å thick film, 125 ± 1 °C operating temperature, and 2 % r.h. filtered laboratory air carrier): (a) pulsed excitation voltage signal, (b) filtered laboratory air response reproducible after purging from either NO₂ or DIMP challenges, (c) NO₂ exposure, (d) DIMP exposure. The horizontal scale in each frame is 50-μs per major division, and the major division vertical scales are 2 V for (a), 0.5 V for (b) and (c), and 0.2 V for (d).

Figure 6. Normalized difference Fourier transform magnitude spectra for the NO₂ and DIMP challenges. (Each data point represents the arithmetic average of six independent measurements.)