UC San Diego

UC San Diego Previously Published Works

Title

Crystal Clear? Microspectroscopic Imaging and Physicochemical Characterization of Indoor Depositions on Window Glass

Permalink

<https://escholarship.org/uc/item/7nw879cv>

Journal

Environmental Science and Technology Letters, 5(8)

ISSN

2328-8930

Authors

Or, VW
Alves, MR
Wade, M
et al.

Publication Date

2018-08-14

DOI

10.1021/acs.estlett.8b00355

Peer reviewed

Crystal Clear? Microspectroscopic Imaging and Physicochemical Characterization of Indoor Depositions on Window Glass

Victor W. Or,[†] Michael R. Alves,[†] Michael Wade,[‡] Sarah Schwab,[†] Richard L. Corsi,[‡] and Vicki H. Grassian^{*,†,§}

[†]Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California 92093, United States

[‡]Department of Civil, Architectural and Environmental Engineering, Cockrell School of Engineering, The University of Texas at Austin, Austin, Texas 78712, United States

[§]Scripps Institution of Oceanography and Department of Nanoengineering, University of California, San Diego, La Jolla, California 92093, United States

Supporting Information

ABSTRACT: Deposition and surface-mediated reactions of adsorbed species can play a role in the level of exposure of occupants to indoor pollutants, which include gases and particles. Detailed molecular-level descriptions of these processes occurring on indoor surfaces are difficult to obtain because of the ever-increasing types of surfaces and their proximity to a variety of different indoor emission sources. The results of an investigation of interactions of glass surfaces in unique indoor environments are described here. Window glass, a ubiquitous indoor surface, was placed vertically in six different locations to assess differences in particle and coating depositions. Atomic force microscopy–photothermal infrared (AFM–PTIR) spectroscopic analysis of these glass surfaces reveals differences in morphology and chemical composition, which reflects the diversity of surface processes found in local environments indoors. Overall, this detailed microspectroscopic imaging method shows deposition of particles and the formation of organic thin films that increase the surface area and surface roughness of the glass surface. PTIR spectroscopy demonstrates that depositions can be linked to primary emitters intrinsic to each of the different local environments.

INTRODUCTION

A large number of studies focused on understanding atmospheric chemistry and its impact on human health have been undertaken in the past decade. High-impact discoveries in this field maintain a strong focus on atmospheric aerosols, heterogeneous and multiphase chemistry, greenhouse gas emissions, and overall air quality.^{1–3} Although atmospheric chemistry and outdoor air quality remain important, the average person reportedly spends a large majority of their lives (~87%) indoors. Oxidative gases and airborne particulate matter exist indoors at concentrations comparable to, if not higher, than those outdoors.^{4–9} In addition, because of differences in lighting conditions, air circulation, and unique chemical sources and sinks, the impact of indoor air quality on human health is poorly understood.^{10–12} Because a high surface to volume ratio is in indoor environments,¹⁰ indoor surfaces play an important role in defining levels of exposure of occupants to a wide range of indoor pollutants.^{13,14} In particular, complex multiphase and heterogeneous processes have been proposed to occur on indoor surfaces;¹⁵ however, analyzing these complex surfaces to better understand these processes remains a challenge, and there is a current lack of knowledge of various indoor materials.^{11,13,14} Furthermore, the local indoor environments within which materials exist can

alter the types of primary emitters and transformative processes that are most likely to occur on material surfaces.^{16–19}

Building on this need to understand more details of surfaces in indoor environments, we placed window glass, a surface ubiquitous to the indoor environment, in different indoor locations, including a copier room, office, kitchen, and garage. Each of these offers unique local environments with their distinct characteristic primary emitters that can interact with glass surfaces.^{6,16,17,20–23} Herein, microspectroscopic imaging and chemical analysis of these glass surfaces demonstrate that the chemical and morphological evolution of the surface reflects emissions characteristic to a specific indoor environment.

MATERIALS AND METHODS

Glass specimens were placed in the field for 6 months at four field locations: a photocopy room on the campus of The University of Texas at Austin (UT Austin) (copier room), on

Received: July 12, 2018

Revised: July 17, 2018

Accepted: July 17, 2018

Published: July 17, 2018

Figure 1. (A) AFM amplitude images of the glass surfaces placed in different indoor environments with scale bars set to $10 \mu m$. Box-and-whisker plots (close-up) of AFM-measured changes in (B) surface area and (C) R_q roughness following exposure in each location for 6 months using 10 images ($50 \mu m \times 50 \mu m$). Lines show 20 and 80th percentiles. A full view of the plot is available in Figure S1.

Figure 2. (A) Organic film (thickness $> 10 nm$) coverage on glass surfaces after exposure in each local environment for 6 months taken from the 10 AFM images ($50 \mu m \times 50 \mu m$). (B) AFM amplitude image of the organic film coating on kitchen glass after exposure for 6 months. (C) Height profiles taken at lines marked in panel B for a particle (top) and film (bottom). Note the difference in the scale of the height axis.

the desk of a graduate student office at UT Austin (office), on a refrigerator in a residential kitchen (kitchen), and in a residential garage (garage) (see Table S1 for details). Laboratory (control) blanks were left unexposed and used as a reference control.

Samples were analyzed using a commercial nanoIR2 microscopy system (Bruker Nano Instruments/Anasys, Santa Barbara, CA). Atomic force microscopy (AFM) imaging of authentic indoor surfaces was conducted at 298 K and a relative humidity (RH) of $\sim 40\%$ at ambient pressure. For AFM studies, $50 \mu m \times 50 \mu m$ images were collected per surface at a scan rate of 0.25 Hz, using silicon nitride probes (tip radius of $< 30 nm$) with a $33\text{--}77 N m^{-1}$ spring constant and a 200–400 kHz resonant frequency in tapping mode. Images were collected with a 1–2 mm separation between scanned regions. Image processing and measurements were conducted using Gwyddion software.

For AFM–PTIR spectroscopy studies, images were collected at a scan rate of 0.5 Hz using gold-coated silicon nitride probes (tip radius of $< 30 nm$), a $1\text{--}7 N m^{-1}$ spring

constant, and a $75 \pm 15 kHz$ resonant frequency in tapping mode. Spectra were collected by averaging 256 laser pulses at each wavenumber with a spectral resolution of $4 cm^{-1}$ and a spatial resolution of $< 30 nm$. All spectra shown were recorded on a single point within a particle or film without additional averaging between spectra or smoothing filters applied.

Inductively coupled plasma mass spectrometry (iCAP RQ-ICP-MS, ThermoFisher), operated in standard mode, was used to quantify the elemental content of these surfaces. Samples from UT Austin used in this analysis include blank nonexposed, kitchen, office, copier room, garage, and an additional blank containing only the adhesive backing present on all samples.

RESULTS AND DISCUSSION

AFM amplitude images of glass surfaces placed in four different indoor environments are shown in Figure 1A along with a control sample. It is clear from these images that glass surfaces, after being placed in these different environments, show unique features and characteristics. The images shown in

Figure 3. Box-and-whisker plot of the number of particles (thickness > 30 nm) deposited per square micrometer on glass surfaces from 10 AFM images ($50\ \mu\text{m} \times 50\ \mu\text{m}$) for each indoor location. Lines show 20 and 80th percentiles. Particles are categorized by volume equivalent diameter into three size bins: <500 nm, between 500 and 1000 nm, and >1000 nm (with total particle counts shown at the far left). Insets show close-ups of the particle counts for the larger-sized particle bins.

Figure 1A are representative of the images obtained for the different environments. To quantify the differences in these surface features, panels B and C of Figure 1 show an analysis of surface properties readily quantifiable from AFM images that include the change in surface area and surface roughness, represented by the root-mean-square roughness (R_q). An increase is observed in both surface properties because of deposition. Deposition of particulate matter is expected to cause increases in surface area and roughness, especially on window glass, a relatively flat indoor surface. The large spread in surface properties within a single piece of glass indicates that these indoor surfaces are far from exhibiting homogeneous depositions. The surface area increases across all exposed glass, most exemplified in the garage and kitchen glass, with increases of up to 50 and $770\ \mu\text{m}^2$, respectively, indicating indoor surface to volume ratios naturally will increase with time as deposition of particulate matter continues. The surface roughness increased upon exposure to various environments. The roughest surfaces were the garage and kitchen glass, with R_q values reaching 220 and 500 nm, respectively. Changes in surface roughness are of interest to the indoor environment as the surface structure of the indoor materials will govern the mechanical interaction of the surface with airborne gaseous compounds and particulate matter, where rougher surfaces alter particle adhesion or change rates of surface-mediated reactions.²⁴

In addition to particle deposition, thin organic films were observed on the glass surfaces placed in the various locations. Film surface coverages were calculated by taking the fraction of the coating surface area over the total surface area. This analysis is summarized in Figure 2A. In the control, office, copier, and garage samples, the surfaces experienced film coatings ranging from 0 to 11%. In contrast, glass exposed to kitchen conditions was heavily coated, ranging from 70 to 99% coverage. Film formation on impervious indoor surfaces has been observed in past studies and has been demonstrated to be largely comprised of organic matter.^{25–27} These films are expected to form in indoor locations with elevated levels of organic compound emissions, exemplified in the kitchen where large quantities of oils and fats are regularly emitted during cooking and cleaning. Shown in Figure 2B is an AFM

amplitude image of a typical film on kitchen glass. Height profiles are shown at the corresponding line colors in Figure 2C. These films are not homogeneous, nor do they completely engulf the surface, where regions of bare silica are visible in the AFM image shown. With films reaching thicknesses in the tens of nanometers, relative to the other locations, in an organic emission-rich indoor environment such as a kitchen, the presence of these coatings confirms that surfaces, when left unattended, act as sizable reservoirs for organic and inorganic compounds. Organic film formation on indoor surfaces is of great interest as coatings will affect surface properties and subsequent interactions with the local environment. Film coatings can be expected to alter the electrostatic, hydrophobic, and other properties of the surface, altering the adsorption efficiency of the surface toward other molecular species.²⁸ Films consisting of unsaturated organic compounds can also lead to increases in the levels of surface reactions with ozone.^{29–31} For indoor environments with higher humidity levels such as faucets, baths, and toilets, surface coatings alter the water content of indoor surfaces because of differences between the hygroscopicity of the organic film and underlying building material. Formation of water films on these hygroscopic coatings enables aqueous phase reactions, which are suggested production pathways of very important indoor gases, including the OH radical and HONO.³²

The data plotted in Figure 3 show the particle depositions across all images on the window glass held in various locations, grouped by diameter into three size bins: <500 nm, between 500 and 1000 nm, and >1000 nm. Relative to the control glass, there is an increase in the number of particles deposited across all particle sizes for each location. In all locations, particle depositions were predominantly in the submicrometer size range with many particles being <500 nm in diameter, the largest being that of copier glass (avg. $0.449\ \text{particle}/\mu\text{m}^2$). In contrast, kitchen glass was covered in significantly fewer sub-500 nm sized particles (avg. $0.108\ \text{particle}/\mu\text{m}^2$). The absence of smaller particles on kitchen glass can be attributed to the heavy coating of organic films, which mask or engulf smaller particles. Exposure of the glass to all indoor locations resulted in a higher level of deposition of the larger-sized particles, the most significant being kitchen and garage glass. The deposition

Figure 4. (A) Three-dimensional (3D) AFM height image (left) and PTIR spectrum (right) for a deposited particle on the copier glass. The inset shows a comparison with carbon black (black) and CaCO_3 (gray) PTIR spectra. (B) 3D AFM height image (left) and PTIR spectrum (right) for a particle and film on the kitchen glass. The inset shows a comparison with nonyl aldehyde (black) and palmitic acid (gray) PTIR spectra. The region from 800 to 1200 cm^{-1} has been omitted because of the presence of a large Si–O vibrational mode from the underlying glass.

of the smallest particles had a weaker impact on the surface area and roughness. The glass specimens in the photocopy room had the largest fraction of sub-500 nm sized particles but experienced smaller changes in surface area and roughness. In contrast, kitchen and garage surfaces had the largest deposition of particles in the size range of 500–1000 nm, 0.0096 and 0.0124 particle/ μm^2 , respectively, and >1000 nm and subsequently produced the roughest surfaces. The kitchen glass experienced near double the deposition of supermicrometer-sized particles, 0.0044 particle/ μm^2 , in comparison to garage glass, 0.0024 particle/ μm^2 , but produced surfaces with comparatively lower surface areas and roughness, which can be attributed to the morphology of the depositions. Kitchen emissions tended to form smoother mounds of coatings, potentially pools of organic compounds arising from aggregation of smaller organic matter over the sampling period, while garage emissions formed coarser particles with significantly lower levels of organic coatings (see Figure S2).

AFM–PTIR enables acquisition of spectra from depositions with spatial resolution in the tens of nanometers, allowing for microspectroscopic imaging and characterization of depositions.^{33,34} Shown in Figure 4 are the PTIR spectra from 1200 to 3600 cm^{-1} taken from the corresponding images of organic depositions found on the kitchen and copier room glass surfaces. Spectra of pure glass are dominated by peaks corresponding to the SiO_2 matrix at $\nu(\text{Si–O})$ (942, 1018, and 1092 cm^{-1}) and $\nu(\text{OH})$ (3390 cm^{-1}) (see Figure S3A). In comparison, spectral features from deposited particles can be correlated to primary emissions characteristic of a particular indoor location. Most notably, the kitchen particle shown in Figure 4B contains a carbonyl stretching frequency associated with an aldehyde compound, identified by $\nu(\text{C=O})$ (1734 cm^{-1}). Carbon–hydrogen stretching motions were identified

as CH_2 and CH_3 groups with peaks at 2874 and 2944 cm^{-1} , respectively. We propose these films formed from deposition of aldehydes and long chain fatty acids, the two abundant classes of organic emissions found during cooking.^{17,28,35} PTIR spectra of palmitic acid and nonyl aldehyde are shown as representatives for these compounds commonly emitted during cooking. Shown in Figure 4A is a particle deposited from the copier room with organic content, as indicated by $\nu(\text{CH}_2, \text{CH}_3)$ (2870, 2940 cm^{-1}). Spectral features suggest a mixture of CaCO_3 from $\nu(\text{CO}_3^{2-})$ (1466 cm^{-1}), a major component of paper, and carbon black from $\nu(\text{C=C})$ (1540, 1580 cm^{-1}), the primary coloring component of black toners.¹⁶

To complement the microspectroscopic imaging and physicochemical characterization of AFM–PTIR spectroscopy, analysis of elements present in the different samples was also performed. Shown in Figure 5 are the ICP–MS concentrations measured for selected ions. All components detected in the blank sample were measured as the lowest concentration in this study. The relatively high background signal of calcium and potassium in the blank is due to interfering species, ^{40}Ar and $^{38}\text{Ar}^{1}\text{H}$ respectively, present in the sample matrix. Copier room, garage, and kitchen samples show relatively similar metal concentrations for most elements analyzed. Copier room samples exhibit higher levels of copper, barium, and zinc. Barium and zinc are among the number of metals that can be used as a ferromagnetic composite carrier (for example, barium ferrite), whereas copper is found in many dye compositions.¹⁴ Other commonly found elements in printing toners such as potassium, magnesium, lead, nickel, and others are found at similar concentrations compared to those of the other samples, possibly suggesting selective particulate formation or deposition pathways. A stark difference is seen in the office sample where elevated levels of iron, chromium, nickel, cobalt,

Figure 5. ICP-MS analysis of an ~ 1.27 cm $\times$ 1.27 cm piece of window glass exposed to various indoor locations showing the nine most abundant elements found. Selected elements for detection include chromium, nickel, iron, aluminum, phosphorus, zinc, magnesium, potassium, calcium, vanadium, cobalt, manganese, copper, lead, and barium. A similar plot of the less abundant elements and a full list of elements screened is available in the [Supporting Information](#).

vanadium, and manganese are observed. This can be attributed to the office sample being in the proximity of a stainless steel heating vent, whose composition includes iron, chromium, nickel, molybdenum, and manganese, with trace amounts of vanadium, cobalt, copper, and other elements.³⁶

Overall, these data taken together provide a unique look at the impact of local environments on glass surface physicochemical properties. A comprehensive understanding of the chemistry occurring on indoor surfaces and its subsequent impact on the quality of indoor air requires knowledge of the nature of these surfaces. Unsurprisingly, the different environments to which indoor surfaces are exposed play a large role in the composition of particles deposited on the surface and the nature and amount of organic coatings. Understanding changes in indoor surfaces over time will enhance our understanding of how these surfaces interact with other gases that are present, including water vapor. Hydrocarbon depositions are expected to increase surface hydrophobicity, whereas water-soluble organic films and salts would enhance surface hygroscopicity. The variance in the distinct indoor emitters will be reflected by differences in the surface properties and chemical composition of the exposed surface. Examination of indoor surfaces under realistic conditions is essential for obtaining a crystal clear understanding of “authentic” indoor surfaces, and this will be only further enhanced with the emergence of new methods to better understand indoor surfaces, which provides insights into their physicochemical characteristics.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the [ACS Publications website](#) at DOI: [10.1021/acs.estlett.8b00355](https://doi.org/10.1021/acs.estlett.8b00355).

Additional methods, Tables S1 and S2, and Figures S1–S4 ([PDF](#))

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: vhgrassian@ucsd.edu. Phone: (858) 534-2499.

ORCID

Victor W. Or: [0000-0002-6831-575X](https://orcid.org/0000-0002-6831-575X)

Michael R. Alves: [0000-0003-1434-5483](https://orcid.org/0000-0003-1434-5483)

Vicki H. Grassian: [0000-0001-5052-0045](https://orcid.org/0000-0001-5052-0045)

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the Alfred P. Sloan Foundation (G-2017-9692) and the National Science Foundation Graduate Research Fellowship Program (DGE-1650112). The authors also thank Dr. Richard Cochran for helpful discussions.

■ REFERENCES

- (1) Weschler, C. J. Chemistry in Indoor Environments: 20 Years of Research. *Indoor Air* **2011**, *21* (3), 205–218.
- (2) Reinmuth-Selzle, K.; Kampf, C. J.; Lucas, K.; Lang-Yona, N.; Fröhlich-Nowoisky, J.; Shiraiwa, M.; Lakey, P. S. J.; Lai, S.; Liu, F.; Kunert, A. T.; et al. Air Pollution and Climate Change Effects on Allergies in the Anthropocene: Abundance, Interaction, and Modification of Allergens and Adjuvants. *Environ. Sci. Technol.* **2017**, *51* (8), 4119–4141.
- (3) Shiraiwa, M.; Ueda, K.; Pozzer, A.; Lammel, G.; Kampf, C. J.; Fushimi, A.; Enami, S.; Arangio, A. M.; Fröhlich-Nowoisky, J.; Fujitani, Y.; et al. Aerosol Health Effects from Molecular to Global Scales. *Environ. Sci. Technol.* **2017**, *51*, 13545–13567.
- (4) Zhang, J.; Li, P. J. Ozone in Residential Air: Concentrations, I/O Ratios, Indoor Chemistry, and Exposures. *Indoor Air* **1994**, *4* (2), 95–105.
- (5) Weschler, C. J.; Hodgson, A. T.; Wooley, J. D. Indoor Chemistry: Ozone, Volatile Organic Compounds, and Carpets. *Environ. Sci. Technol.* **1992**, *26* (12), 2371–2377.
- (6) Lee, S. C.; Lam, S.; Kin Fai, H. Characterization of VOCs, Ozone, and PM10 emissions from Office Equipment in an Environmental Chamber. *Build. Environ.* **2001**, *36* (7), 837–842.
- (7) Ormstad, H. Suspended Particulate Matter in Indoor Air: Adjuvants and Allergen Carriers. *Toxicology* **2000**, *152* (1–3), 53–68.
- (8) Fromme, H.; Twardella, D.; Dietrich, S.; Heitmann, D.; Schierl, R.; Liebl, B.; Ruden, H. Particulate Matter in the Indoor Air of Classrooms - Exploratory Results from Munich and Surrounding Area. *Atmos. Environ.* **2007**, *41* (4), 854–866.
- (9) Balasubramanian, R.; Lee, S. S. Characteristics of Indoor Aerosols in Residential Homes in Urban Locations: A Case Study in Singapore. *J. Air Waste Manage. Assoc.* **2007**, *57* (8), 981–990.
- (10) Weschler, C. J.; Carslaw, N. Indoor Chemistry. *Environ. Sci. Technol.* **2018**, *52* (5), 2419–2428.
- (11) Nazaroff, W. W.; Goldstein, A. H. Indoor Chemistry: Research Opportunities and Challenges. *Indoor Air* **2015**, *25*, 357–361.
- (12) Zhang, Y.; Xiong, J.; Mo, J.; Gong, M.; Cao, J. Understanding and Controlling Airborne Organic Compounds in the Indoor Environment: Mass Transfer Analysis and Applications. *Indoor Air* **2016**, *26* (1), 39–60.
- (13) Morrison, G. Interfacial Chemistry in Indoor Environments. *Environ. Sci. Technol.* **2008**, *42*, 3495–3499.
- (14) Uhde, E.; Salthammer, T. Impact of Reaction Products from Building Materials and Furnishings on Indoor Air Quality-A Review of Recent Advances in Indoor Chemistry. *Atmos. Environ.* **2007**, *41* (15), 3111–3128.
- (15) Sleiman, M.; Gundel, L. A.; Pankow, J. F.; Jacob, P.; Singer, B. C.; Destailats, H. Formation of Carcinogens Indoors by Surface-Mediated Reactions of Nicotine with Nitrous Acid, Leading to Potential Thirdhand Smoke Hazards. *Proc. Natl. Acad. Sci. U. S. A.* **2010**, *107* (15), 6576–6581.
- (16) Pirela, S. V.; Pyrgiotakis, G.; Bello, D.; Thomas, T.; Castranova, V.; Demokritou, P. Development and Characterization of an Exposure Platform Suitable for Physico-Chemical, Morphological and Toxic-

logical Characterization of Printer-Emitted Particles (PEPs). *Inhalation Toxicol.* **2014**, 26 (7), 400–408.

(17) Abdullahi, K. L.; Delgado-Saborit, J. M.; Harrison, R. M. Emissions and Indoor Concentrations of Particulate Matter and Its Specific Chemical Components from Cooking: A Review. *Atmos. Environ.* **2013**, 71, 260–294.

(18) Destailats, H.; Lunden, M. M.; Singer, B. C.; Coleman, B. K.; Hodgson, A. T.; Weschler, C. J.; Nazaroff, W. W. Indoor Secondary Pollutants from Household Product Emissions in the Presence of Ozone: A Bench-Scale Chamber Study. *Environ. Sci. Technol.* **2006**, 40 (14), 4421–4428.

(19) Abt, E.; Suh, H. H.; Catalano, P.; Koutrakis, P. Relative Contribution of Outdoor and Indoor Particle Sources to Indoor Concentrations. *Environ. Sci. Technol.* **2000**, 34 (17), 3579–3587.

(20) Vuković, G.; Aničić Urošević, M.; Razumenić, I.; Kuzmanoski, M.; Pergal, M.; Škrivanj, S.; Popović, A. Air Quality in Urban Parking Garages (PM₁₀, Major and Trace Elements, PAHs): Instrumental Measurements vs. Active Moss Biomonitoring. *Atmos. Environ.* **2014**, 85, 31–40.

(21) Batterman, S.; Jia, C.; Hatzivasilis, G. Migration of Volatile Organic Compounds from Attached Garages to Residences: A Major Exposure Source. *Environ. Res.* **2007**, 104 (2), 224–240.

(22) Dodson, R. E.; Levy, J. I.; Spengler, J. D.; Shine, J. P.; Bennett, D. H. Influence of Basements, Garages, and Common Hallways on Indoor Residential Volatile Organic Compound Concentrations. *Atmos. Environ.* **2008**, 42 (7), 1569–1581.

(23) He, C.; Morawska, L.; Taplin, L. Particle Emission Characteristics of Office Printers. *Environ. Sci. Technol.* **2007**, 41 (17), 6039–6045.

(24) Kohli, R.; Mittal, K. L. *Developments in Surface Contamination and Cleaning*; Elsevier: Amsterdam, 2013; Vol. 6.

(25) Butt, C. M.; Diamond, M. L.; Truong, J.; Ikononou, M. G.; Ter Schure, A. F. H. Spatial Distribution of Polybrominated Diphenyl Ethers in Southern Ontario As Measured in Indoor and Outdoor Window Organic Films. *Environ. Sci. Technol.* **2004**, 38 (3), 724–731.

(26) Diamond, M. L.; Gingrich, S. E.; Firtuck, K.; McCarry, B. E.; Stern, G. A.; Billeck, B.; Grift, B.; Brooker, D.; Yager, T. D. Evidence for Organic Film on an Impervious Urban Surface: Characterization and Potential Teratogenic Effects. *Environ. Sci. Technol.* **2000**, 34, 2900–2908.

(27) Lam, B.; Diamond, M. L.; Simpson, A. J.; Makar, P. A.; Truong, J.; Hernandez-Martinez, N. A. Chemical Composition of Surface Films on Glass Windows and Implications for Atmospheric Chemistry. *Atmos. Environ.* **2005**, 39 (35), 6578–6586.

(28) Liu, Q.-T.; Chen, R.; McCarry, B. E.; Diamond, M. L.; Bahavar, B. Characterization of Polar Organic Compounds in the Organic Film on Indoor and Outdoor Glass Windows. *Environ. Sci. Technol.* **2003**, 37 (11), 2340–2349.

(29) Cros, C. J.; Morrison, G. C.; Siegel, J. A.; Corsi, R. L. Long-Term Performance of Passive Materials for Removal of Ozone from Indoor Air. *Indoor Air* **2012**, 22 (1), 43–53.

(30) Weschler, C. J.; Shields, H. C. Production of the Hydroxyl Radical in Indoor Air. *Environ. Sci. Technol.* **1996**, 30 (11), 3250–3258.

(31) Zhou, S.; Forbes, M. W.; Katrib, Y.; Abbatt, J. P. D. Rapid Oxidation of Skin Oil by Ozone. *Environ. Sci. Technol. Lett.* **2016**, 3 (4), 170–174.

(32) Duncan, S. M.; Sexton, K. G.; Turpin, B. J. Oxygenated VOCs, Aqueous Chemistry, and Potential Impacts on Residential Indoor Air Composition. *Indoor Air* **2018**, 28 (1), 198–212.

(33) Dazzi, A.; Prater, C. B. AFM-IR: Technology and Applications in Nanoscale Infrared Spectroscopy and Chemical Imaging. *Chem. Rev.* **2017**, 117 (7), 5146–5173.

(34) Dazzi, A.; Glotin, F.; Carminati, R. Theory of Infrared Nanospectroscopy by Photothermal Induced Resonance. *J. Appl. Phys.* **2010**, 107, 124519.

(35) Zhao, Y.; Hu, M.; Slanina, S.; Zhang, Y. The Molecular Distribution of Fine Particulate Organic Matter Emitted from

Western-Style Fast Food Cooking. *Atmos. Environ.* **2007**, 41 (37), 8163–8171.

(36) Cristobal, M.; San-Martin, D.; Capdevila, C.; Jiménez, J. A.; Milenkovic, S. Rapid Fabrication and Characterization of AISI 304 Stainless Steels Modified with Cu Additions by Additive Alloy Melting (ADAM). *J. Mater. Res. Technol.* **2018**, n/a.