Fluorographene as a Mass Spectrometry Probe for High-Throughput Identification and Screening of Emerging Chemical Contaminants in Complex Samples

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Supporting Information

ABSTRACT: Mass spectrometry techniques for high-throughput analysis of complex samples are of profound importance in many areas such as food safety, omics studies, and environmental health science. Here we report the use of fluorographene (FG) as a new mass spectrometry probe for high-throughput identification and screening of emerging chemical contaminants in complex samples. FG was facilely synthesized by one-step exfoliation of fluorographite. With FG as a matrix or probe in matrix-assisted or surface-enhanced laser desorption/ionization time-of-flight mass spectrometry (MALDI- or SELDI-TOF MS), higher sensitivity (detection limits at ppt or subppt levels), and better reproducibility were achieved than with other graphene-based materials due to the unique chemical structure and self-assembly properties of FG. The method was validated with different types of real complex samples. By using FG as a SELDI probe, we could easily detect trace amount of bisphenol S in paper products and high-fat canned food samples. Furthermore, we have successfully identified and screened as many as 28 quaternary ammonium halides in sewage sludge samples collected from municipal wastewater treatment plants. These results demonstrate that FG probe is a powerful tool for high-throughput analysis of complex samples by MS.

Emerging chemical contaminants (ECCs) are defined as chemicals that are not covered by standard monitoring and regulatory programs but may adversely affect the environment and human health.^{1–3} The list of ECCs is expanding with more and more chemicals' environmental occurrence and biological impacts being revealed. However, research into ECCs is limited by the lack of proper analytical methods.⁴ Due to their emerging nature, extremely low concentration (usually at parts per trillion to billion levels) and complex sample matrices, identification and quantification of ECCs in the environment is a great challenge. Current methods largely rely on chromatography coupled to mass spectrometry (MS), which however are laborious, low throughput, and require complicated sample preparation procedures.⁵

Matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS) offers a high-throughput technique for analysis of large molecules. Surface-enhanced laser desorption/ionization (SELDI) is a variant mode of MALDI that uses a probe for simultaneous extraction, enrichment, desorption, and ionization of target analytes.^{6–10}

Recent exploration of new MALDI matrices and SELDI probes also extends their application to small molecule analysis.^{11–15} Specifically, graphene has shown great promise for the use as MALDI matrix or SELDI probe due to its excellent adsorption capacity, strong optical absorption properties, efficient electron–phonon coupling, and unique two-dimensional structure.^{16–19} In practical applications, graphene usually needs to be chemically modified, such as oxidation^{20,21} and sulfonation,^{22–25} to prevent its aggregation that may greatly compromise its performance in LDI MS. Graphene can also be used synergistically with other materials or derivatized with functional groups to further improve the analytical sensitivity and selectivity.^{17,26}

Fluorographene (FG) is an important derivative of graphene.^{27–30} Fluorination can tune the bandgap of graphene by converting the C–C bonds from sp^2 to sp^3 configu-

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Figure 1. Scheme showing the procedures for the identification and screening of ECCs in complex samples by SELDI-TOF MS with FG as a probe.

ration.^{31,32} Compared with pure graphene, the introduction of F atoms may offer additional opportunity for FG to form hydrogen bonding with target compounds due to the high electronegativity of F atoms.^{33,34} Furthermore, theoretical calculations have predicted that FG is more thermodynamically stable than other graphene derivatives,³⁵ suggesting that FG may produce fewer fragments and less background noises in the LDI process. Therefore, FG may serve as a good SELDI probe for a wide variety of analytes. However, to the best of our knowledge, the application of FG in LDI MS is so far unexplored.

Inspired by the intriguing properties of FG, we here show the use of FG as a new SELDI probe for high-throughput identification and screening of ECCs in complex samples. We found that FG could self-assemble into a honeycomb-like film and showed better performance than other graphene-based materials in MALDI- and SELDI-TOF MS. High sensitivity and good reproducibility were obtained with the FG probe. More importantly, the method was validated with different types of real complex samples. By using FG as a SELDI probe, we could detect trace amount of bisphenol S (BPS) in thermal receipt paper and canned food samples. We have also identified and screened over 20 quaternary ammonium halides in sewage sludge samples collected from municipal wastewater treatment plants. These results demonstrate that FG is a powerful tool for MS screening of small molecules in extremely complex samples.

EXPERIMENTAL SECTION

Chemicals and Materials. Chemically converted graphene and graphene oxide (GO) were bought from XFNANO (Nanjing, China). Fluorographite (F% > 56%) was purchased from CarFluor Chemicals (Shanghai, China). BPS, tetradecyldimethylbenzylammonium chloride hydrate (TDBAC), and tetrabromobisphenol A (TBBPA) were from TCI (Tokyo, Japan). 2,2',4,4'-Tetrabromodiphenyl ether (BDE-47) was from AccuStandard (New Haven, CT, U.S.A.). Arsenic(III) standard solution at 1000 $\mu\text{g}/\text{mL}$ in 0.5% (v/v) $\text{HCl}/0.3\%$, (w/v) $\text{NaOH}/0.06\%$, (w/v) NaHCO_3 solution was purchased from Inorganic Ventures (Christiansburg, VA). Estradiol (E2) and pentachlorophenol (PCP) were from Dr. Ehrenstorfer (Augsburg, Germany). Hexadecyldimethylbenzylammonium chloride (HDBAC), dodecyldimethylbenzylammonium chloride (DDBAC), cetyltrimethylammonium bromide (CTAB), tetradecyltrimethylammonium bromide (TTAB), perfluorooctanesulfonate (PFOS), and α -cyano-4-hydroxycinnamic acid (CHCA) were from Sigma (St. Louis, MO). Dichloromethane and acetone of HPLC grade were from J.T. Baker (Phillipsburg, NJ). Chlorosulfonic acid (HSO_3Cl , 99.0%) and sodium

peroxide (Na_2O_2 , 95%) were from SinoPharm (Shanghai, China). *N*-Methyl-2-pyrrolidone (NMP, 99.0%) was from Alfa Aesar (Ward Hill, MA). Ultrapure water was prepared by a Millipore Milli-Q system (Billerica, MA). All chemicals were of analytical grade unless otherwise noted.

Synthesis of FG. FG was synthesized by exfoliating fluorographite with sodium peroxide and chlorosulfonic acid as described previously.³⁶ First of all, 0.1 g of fluorographite powder and 1 g of Na_2O_2 were added to a corundum crucible and ground evenly. Then, 5 mL of HSO_3Cl was added dropwise to the mixture under stirring. After cooling down at room temperature, 100 mL of water was added to dilute the mixture. The obtained solution was filtered through a 0.22 μm poly(vinylidene fluoride) membrane. The solids were collected and washed with water three times followed by drying at 60 $^\circ\text{C}$ overnight. Finally, a black powder of FG was obtained. Note: the reaction of Na_2O_2 with HSO_3Cl is violent and this step of operation should be carried out very carefully.

Characterization of Materials. SEM images were obtained by using a Hitachi S-3000N scanning electron microscope (Tokyo, Japan). FTIR spectra were obtained on a JASCO FT/IR Fourier transform infrared spectrometer (Victoria, B.C., Canada). The samples were pressed into transparent disks with KBr for the measurement. XPS spectra were obtained using a Thermo Scientific Escalab 250Xi X-ray photoelectron spectrometer (Massachusetts, U.S.A.) with Al $K\alpha$ X-ray radiation as the X-ray source excitation.

MALDI- and SELDI-TOF MS. For direct MALDI-TOF MS measurement, the sample solution and the matrix dispersion were mixed at a ratio of 1:1 (v/v), and then 1 μL of the mixture was dropped to a stainless steel MTP target frame III (Bruker Daltonics) followed by air drying.

For SELDI-TOF MS measurement (see Figure 1), the FG probe was dispersed in water at 10 mg/mL under ultrasonication. Then, 500 μL of the probe was added to 2 mL of sample solution to enrich target analytes. The solution was incubated at room temperature for 48 h. The probe was then collected by centrifugation at 9000 rpm for 15 min. The supernatant was discarded and the precipitate (2 μL) was deposited on the MALDI target for analysis.

The LDI-TOF MS was performed on a Bruker Daltonics Autoflex III Smartbeam MALDI-TOF mass spectrometer equipped with a 337 nm nitrogen laser working at a frequency of 100 Hz and controlled by the FlexControl software. The measurement was performed in reflector mode. The mass spectra were recorded by summing 200 laser shots. The FlexAnalysis 3.4 software was used for data processing.

Analysis of Real Samples. The thermal receipt paper samples were collected from supermarkets, grocery stores, and restaurants in Beijing ($n = 9$). The spam and canned sardines samples were bought from three supermarkets in Beijing. Each sample was homogenized and extracted with 15 mL of ultrapure water by the aid of sonication for 90 min. The mixture was centrifuged at 9000 rpm for 10 min and the supernatant was used for the analysis.

The sewage sludge samples were collected during Oct 2010 to May 2011 from 12 municipal wastewater treatment plants in 6 provinces and municipalities in China. Approximately 500 g wet weight of the freshly digested sludge sample obtained from the dehydration process was freeze-dried, homogenized, and stored at $-20\text{ }^{\circ}\text{C}$. Then, 0.2 g of solid sample was extracted with 8 mL of ultrapure water under sonication for 90 min. The sample was centrifuged at 9000 rpm for 10 min, and then the supernatant was subjected to the SELDI-TOF MS analysis.

RESULTS AND DISCUSSION

Characterization of FG. Before testing the performance in MS, we characterized the materials by different techniques. FG was synthesized by one-step exfoliation of fluorographite.³⁶ The as-synthesized FG showed a good water-dispersibility. SEM measurement showed that the FG could form a homogeneous and flat film on the MALDI target (Figure 2A). Interestingly, we found that when the aqueous dispersion of FG was incubated exceeding 48 h before being dropped to the MALDI target, the formed FG film could turn into a honeycomb-like three-dimensional (3D) structure (Figure 2B). The reason was ascribed to the self-assembly of FG sheets driven by strong

hydrophobic interaction and hydrogen bonding.³⁷ Theoretical studies have predicted that fluorination may transform the sp^2 -bonding planar crystal structure of graphene into a sp^3 -bonding 3D structure.^{37,38} The phenomenon observed here provides an evidence for this prediction. Such a 3D structure was not observed when the incubation time was 1 h (Figure 2A), indicating that the self-assembly of FG was a relatively slow process. For comparison, pure graphene formed an inhomogeneous and rugged film on the MALDI target, leaving a considerable part of the MALDI target surface being exposed (Figure 2C). When prolonging the incubation time from 1 to 48 h, the graphene film tended to aggregate due to its strong hydrophobic nature rather than forming any ordered structures (Figure 2D), suggesting that the F atoms played a critical role in the self-assembly of FG.

Figure 2E compares the C 1s XPS spectra of graphene, GO, and FG. FG yielded four main components at 284.8, 288.1, 290.3, and 292.2 eV, assigning to C–C, C–F, F–C–F, and CF_3 bonds, respectively. The strong peak of F–C–F bond indicates a high degree of fluorination in FG. The peaks of oxygen functionalities for FG were much lower than those for GO and graphene, indicating that C–F bonds were the major functionality in FG. EDX measurement showed that the ratio of C to F atoms in FG was 1.1:1 (Supporting Information, Figure S1), indicating that the FG was nearly fully fluorinated. The materials were also characterized by FTIR (Figure 2F). FG exhibited a sharp peak at 1218 and 1352 cm^{-1} , which are ascribed to the feature absorption of the C–F and F–C–F stretch.³¹ The peaks at 2933 and 2853 cm^{-1} are assigned to the asymmetric and symmetric C–H stretching vibration, respectively.³⁹ Graphene and GO had a broad peak at $\sim 3428\text{ cm}^{-1}$ due to the O–H stretching vibration and showed no C–F absorption peaks. The peaks at 1734, 1618, and 1050 cm^{-1} are assigned to the C=O stretching vibration, the skeletal ring vibrations, or the stretching vibration of the C–O bond.³⁹ Solid absorption spectra showed that the optical absorption of FG at 337 nm (the wavelength used in MALDI) was close to GO but less than graphene (Figure S2).

Use of FG as a MALDI Matrix. In order to be used as a SELDI probe, the material must be able to serve as an efficient MALDI matrix. So we first investigated the performance of FG as a MALDI matrix. A variety of chemical contaminants with molecular weight below 1000 Da were used as model analytes (see Table 1), including two flame retardants (TBBPA and BDE-47), a synthetic fluorosurfactant (PFOS), an endocrine disrupter (E2), an organochlorine pesticide (PCP), an

Figure 2. Characterization of materials. (A–D) Typical SEM images of FG film after incubation for 1 h (A), FG film after incubation for 48 h (B), graphene film after incubation for 1 h (C), and graphene film after incubation for 48 h (D). (E) C 1s XPS spectra of graphene (G), GO, and FG. (F) FT-IR spectra of G, GO, and FG.

Table 1. Feature Peaks and LODs ($S/N = 3$) of Typical Chemical Contaminants Obtained with FG as a SELDI Probe

negative ion			positive ion		
compound	m/z	LOD ^a (pg/mL)	compound	m/z	LOD ^a (pg/mL)
BPS	248.4	0.7	As ^{III}	152.4	1.5×10^3
BDE-47	250.2	0.03	TTAB	255.9	0.07
PCP	264.2	0.06	CTAB	284.0	0.07
E2	270.5	38	DDBAC	304.0	3.8
PFOS	498.5	6×10^{-3}	TDBAC	332.1	0.4
TBBPA	542.4	0.6	HDBAC	360.1	5.0×10^2

^aThe LODs were obtained based on the highest feature peaks of the analytes.

industrial adhesive (BPS), two linear surfactants (CTAB and TTAB), three aromatic surfactants (HDBAC, TDBAC, and DDBAC), and inorganic As^{III}. These chemicals have been widely used in industrial and consumer products but pose potential risks to human health and ecosystems (see section 1.1 in Supporting Information for details).

The performance of different materials (including FG, graphene, GO, and conventional organic matrix CHCA) as MALDI matrices was compared in detection of these typical contaminants. As shown in Figure 3A,B, when using FG as a

Figure 3. Comparison of performance of different materials as matrices in MALDI-TOF MS detection of typical ECCs (BPS, BDE-47, PCP, E2, PFOS, TBBPA, As^{III}, HDBAC, TDBAC, DDBAC, CTAB, and TTAB): (A, B) FG, (C, D) graphene, (E, F) GO, and (G, H) CHCA. The left and right column represent the spectra obtained in negative and positive ion mode, respectively. The samples were incubated with the matrix for 48 h before the analysis. Analyte concentration: BPS, 10 $\mu\text{g/mL}$; BDE-47, 5 $\mu\text{g/mL}$; PCP, 10 $\mu\text{g/mL}$; E2, 50 $\mu\text{g/mL}$; PFOS, 1 $\mu\text{g/mL}$; TBBPA, 10 $\mu\text{g/mL}$; As^{III}, 15 $\mu\text{g/mL}$; HDBAC, 5 $\mu\text{g/mL}$; TDBAC, 5 $\mu\text{g/mL}$; DDBAC, 5 $\mu\text{g/mL}$; CTAB, 1 $\mu\text{g/mL}$; and TTAB, 1 $\mu\text{g/mL}$.

matrix, all compounds could be readily detected by MALDI-TOF MS with strong peak intensities. Notably, we found that the incubation time of matrix dispersion with sample solution significantly affected the MS signals. With an incubation time of 1 h, the peak intensities with FG were relatively low (Figure S3). When increasing the incubation time to 48 h, the peak intensities significantly increased and FG showed the best performance in both negative and positive ion mode (Figure 3). Such a remarkable increase in MS signals could be well explained by the structural transformation of the FG film. As shown in Figure 2A,B, FG could self-assemble to form a

honeycomb-like structure upon increasing the incubation time. This structure not only could increase the surface area of the film for laser energy absorption and transfer, but also effectively avoided the aggregation of FG sheets. In contrast, the peak intensities obtained with graphene and GO decreased with the increase in the incubation time (Figures 3 and S3) probably due to the aggregation of the materials. It should be noted that the graphene matrix incubated for 1 h could also generate high peak intensities in negative ion mode, but in positive ion mode the peak intensities were lower than those obtained with the FG matrix incubated for 48 h (Figure S3). For CHCA (Figure 3G,H), only weak peaks of $[M - H]^-$ of PFOS in negative ion mode, $[M - \text{Br}]^+$ of CTAB and TTAB, and $[M - \text{Cl}]^+$ of DDBAC and TDBAC in positive ion mode were detected, confirming that conventional organic matrices were not suitable for analysis of small molecules.

The fluorination of graphene also greatly affected the reproducibility of analysis. MALDI-TOF MS often suffers from the reproducibility due to the inhomogeneous cocrystallization process of the matrix with analytes. With a short incubation time (1 h), the shot-to-shot ($n = 20$) and sample-to-sample RSDs ($n = 15$) obtained on the FG matrix were in the ranges of 22.2–95.1% and 38.0–91.7%, respectively (Table S1). When the incubation time was increased to 48 h, the shot-to-shot and sample-to-sample RSDs were significantly improved to 12.6–29.4% and 14.5–32.3%, respectively (Table S2). This reproducibility was satisfactory for MALDI-TOF MS analysis and also better than that obtained on graphene and GO matrices, e.g., the shot-to-shot and sample-to-sample RSDs on the graphene matrix were in the ranges of 34.6–90.6% and 36.6–91.4%, respectively (Tables S1 and S2). The good reproducibility of FG should result from the relatively stable and uniform structure of the FG film. The limits of detection (LODs) for the typical contaminants by direct MALDI-TOF MS measurement on the FG matrix ranged from 0.5 to (7.5×10^5) pg/mL (Table S3), which were lower than those obtained with graphene and GO (Table S3). Overall, FG has been demonstrated to be a highly efficient matrix for MALDI-TOF MS.

Use of FG as a SELDI Probe. After demonstration of the capability of FG as a MALDI matrix, we further attempted to use FG as a SELDI probe. The probe was added to sample solution to enrich target compounds, and then the probe was collected and directly subjected to LDI-TOF MS analysis. We first tested the method with spiked water samples with spiking concentrations at ppb levels and compared the performance of FG with graphene and GO. As shown in Figure 4A,B, all 12 typical contaminants could be detected by using the FG probe and the peak intensities were significantly higher than those using other materials. With graphene as a probe (Figure 4C,D), BPS, PCP, PFOS, BDE-47, and E2 could be detected in negative ion mode, and TTAB and TDBAC could be detected in positive ion mode. However, their peak intensities were low and the peaks for other compounds were absent. When using GO as a probe (Figure 4E,F), only PFOS was detected in negative ion mode. These results support our hypothesis that FG is a good SELDI probe due to its special fluorinated structure, which can enhance the affinity of FG for a wide range of compounds via hydrophobic interaction and hydrogen bonding.

Table 1 lists the LODs for the typical contaminants obtained by SELDI-TOF MS with the FG probe. The corresponding mass spectra are given in Figure S4. For most of compounds

Figure 4. Comparison of performance of different materials as SELDI probes in detection of typical ECCs (BPS, BDE-47, PCP, E2, PFOS, TBBPA, As^{III}, HDBAC, TDBAC, DDBAC, CTAB, TTAB) in spiked water samples. The left and right column represent the spectra obtained in negative and positive ion mode, respectively. (A, B) FG, (C, D) graphene, (E, F) GO. Spike concentration: TBBPA, 6.6 ng/mL; PFOS, 0.66 ng/mL; E2, 33.1 ng/mL; PCP, 6.6 ng/mL; BDE-47, 3.3 ng/mL; and BPS, 6.6 ng/mL; As^{III}, 9.9 ng/mL; HDBAC, 3.3 ng/mL; TDBAC, 3.3 ng/mL; DDBAC, 3.3 ng/mL; CTAB, 0.66 ng/mL; and TTAB, 0.66 ng/mL.

(except for As^{III}), the LODs were at ppt or subppt levels (0.006–500 pg/mL). These LODs can satisfy the demands for routine screening of these contaminants. For As^{III}, an additional enrichment procedure may be required to meet the “action level” of 10 ppb set by the U.S. EPA.⁴⁰ Comparing the LODs obtained by SELDI- and MALDI-TOF MS (Tables 1 and S3), the LODs were significantly lowered by $7.1 - (8.3 \times 10^5)$ -fold by the FG enrichment (except for HDBAC). It is worth mentioning that the LOD for PFOS was low to 6 fg/mL, probably because PFOS is also a fully fluorinated compound, and thus, FG has a particularly strong affinity for PFOS. We also compared the present method with previously reported methods such as HPLC or GC coupled to MS in terms of LOD. For most of compounds (except for As^{III} and HDBAC), the present method yielded lower or comparable LODs than previously reported methods (see Table S4).

Screening of BPS in Real Complex Samples. To demonstrate the application potential in analysis of complex samples, we used the FG probe to screen BPS in different types of real samples. As a substitute of bisphenol A (BPA), BPS is widely used as fixing and anticorrosive agents in epoxy glues, but it has also been identified as a potential endocrine disruptor and immunotoxicant.⁴¹ Recently, the occurrence of BPS in paper products and foods has been reported.^{42–44} So in this study we selected thermal receipt papers, spams, and canned sardines as target sample matrices. The analysis of food samples like spams and canned sardines is normally regarded as a very challenging task due to their high fat contents, and complicated

sample preparation procedures are required to analyze these samples.

Here the FG probe was used to detect BPS at ppt levels in thermal receipt papers, spams, and canned sardines. Direct analysis of these samples by MALDI-TOF MS without enrichment produced no signals corresponding to BPS due to its low concentrations present in these samples (Figure S5). When using FG as a SELDI probe, peak of $[M - H]^-$ of BPS was detected at m/z 248.8 in all samples with few interferences caused by sample matrices (Figure 5). The concentration was

Figure 5. Screening of BPS in real complex samples by SELDI-TOF MS with FG as a probe: (A) thermal receipt paper samples, (B) spam samples, and (C) canned sardines samples.

determined by the standard addition method ($R^2 > 0.988$; see Table S5). High concentration of BPS was found in thermal receipt paper samples (1.4–2.8 $\mu\text{g/g}$; $n = 9$), which was within the range that reported in previous reports (Table S6).^{42,43} Based on the obtained concentration, the daily intake of BPS is estimated to be 0.08–0.16 ng/day for the generation population and 6.1–12.2 ng/day for occupationally exposed individuals (see section 1.2 in Supporting Information for estimation method). The BPS was also detected in canned food samples at lower concentrations (0.011–0.17 $\mu\text{g/g}$ for spam ($n = 3$) and 0.0015–0.048 $\mu\text{g/g}$ for canned sardines ($n = 3$); see Table S5). These results demonstrate that FG is a sensitive probe for screening of trace amount of ECCs in high-fat complex samples.

Identification and Screening of ECCs in Sewage Sludge Samples. We then applied the FG probe in identification and screening of ECCs in sewage sludge samples collected from 12 municipal wastewater treatment plants. The sewage sludge is considered as a major sink of urban contaminants and is recycled by the application of bio-solids.^{45–48} In this study, we focused on quaternary ammonium halides as target ECCs. Quaternary ammonium halides, as a class of cationic surfactants, are widely used in commercial products. They have shown potential persistency in the environment^{49,50} and can affect the bioavailability and mobility of hydrophobic organic contaminants.⁵¹ The SELDI-TOF MS analysis was carried out in positive ion mode. In control experiments, no ECCs were identified in blank water samples (Figure S6). In sewage sludge samples, a large number of peaks were detected from m/z 200 to 610 (Figure 6A). Among them, we have successfully identified the feature peaks of as many as 28 quaternary ammonium halides (Figure 6A). This number

Figure 6. Identification and screening of quaternary ammonium halides in municipal sewage sludge samples collected from 12 municipal wastewater treatment plants. (A) A typical mass spectrum of sewage sludge samples. (B) Correlation of analytical results of ATMAC-10, ATMAC-22, BAC-18, and DADMAC-16:16/14:18 obtained by SELDI-TOF MS with concentrations determined by HPLC-ESI-MS/MS. Note that the lines in (B) just show the comparison results between the two methods but are not calibration curves for the compounds.

was the same as that obtained in a previous work using HPLC-ESI-MS/MS.⁴⁷ The names, molecular formulas, and feature peaks of the identified compounds are listed in Tables 2 and S7. For comparison, we have also analyzed the sewage sludge samples by using graphene as a SELDI probe with an incubation time of 1 h, but only two types of quaternary ammonium halides could be identified (see Figure S7).

To verify the results obtained by the FG-based SELDI-TOF MS, we also measured the concentrations of the quaternary ammonium halides in sewage sludge samples by HPLC-ESI-MS/MS (see section 1.3 in Supporting Information for experimental details). Excellent linear correlations ($R > 0.929$) was found between the peak intensities of quaternary ammonium halides in SELDI-TOF MS and the concentrations obtained by HPLC-ESI-MS/MS. Figure 6B shows the results for ATMAC-10, ATMAC-22, BAC-18, and DADMAC-16:16/14:18 as examples ($R > 0.974$). Data for other quaternary ammonium halides are given in Figure S8. The good consistency between these two techniques proves the accuracy of the identification results and demonstrates that SELDI-TOF MS is a reliable method for identification and screening of ECCs in complex samples. The comparison results also show that quaternary ammonium halides are present in sewage sludge at relatively high concentrations, e.g., the concentration of DADMAC-18:18 could reach 157 $\mu\text{g/g}$ (Figure 6B). This calls for more attention paid to these compounds present in the environment. Finally, it should be stressed that sewage sludge is a highly complex matrix. The conventional analytical methods involves complicated and laborious sample preparation procedures.⁴⁷ As an alternative, the FG-based SELDI-TOF MS technique provides a much more facile, high-throughput, and sensitive tool for the analysis of low-mass compounds in complex samples.

CONCLUSIONS

In summary, we have shown that FG can be used as a new MALDI matrix and SELDI probe for identification and screening of ECCs in complex samples. The FG was facilely prepared using a one-step exfoliation method from fluorographite. In LDI MS, FG could form a honeycomb-like film by self-assembly, which could facilitate the MS detection. Using FG as a MALDI matrix or SELDI probe, higher sensitivity and better reproducibility than other graphene-based materials were obtained. The method was successfully applied to identify and screen ECCs in different types of real complex samples, including thermal receipt paper, canned foods, and sewage sludge samples. This work not only provides a new promising tool for high-throughput identification and screening of low-mass compounds, but also further fulfils the capability of LDI

Table 2. Acronyms, Molecular Formulas, and Feature Peaks of the Identified Quaternary Ammonium Halides in Sewage Sludge Samples by Using the FG Probe^a

compound	molecular formula	<i>m/z</i>	compound	molecular formula	<i>m/z</i>
ATMAC-10	C ₁₃ H ₃₀ NBr	200.7	DADMAC-8:8	C ₁₈ H ₄₀ NBr	270.1
ATMAC-12	C ₁₅ H ₃₄ NBr	228.1	DADMAC-8:10	C ₂₀ H ₄₄ NBr	298.1
ATMAC-14	C ₁₇ H ₃₈ NBr	256.1	DADMAC-10:10	C ₂₂ H ₄₈ NBr	326.2
ATMAC-16	C ₁₉ H ₄₂ NBr	284.8	DADMAC-12:12	C ₂₆ H ₅₆ NBr	382.5; 214.7
ATMAC-18	C ₂₁ H ₄₆ NBr	312.4	DADMAC-14:14	C ₃₀ H ₆₄ NBr	438.4; 242.8
ATMAC-20	C ₂₃ H ₅₀ NBr	340.2	DADMAC-16:16	C ₃₄ H ₇₂ NBr	494.8
ATMAC-22	C ₂₅ H ₅₄ NCl	368.2	DADMAC-18:18	C ₃₈ H ₈₀ NBr	550.9
ATMAC-24	C ₂₇ H ₅₈ NCl	396.4	DADMAC-20:20	C ₄₂ H ₈₈ NBr	606.9
BAC-8	C ₁₇ H ₃₀ NCl	248.1	DADMAC-10:12	C ₂₄ H ₅₂ NBr	354.2
BAC-10	C ₁₉ H ₃₄ NCl	276.1	DADMAC-12:14	C ₂₈ H ₆₀ NBr	410.4
BAC-12	C ₂₁ H ₃₈ NCl	304.8	DADMAC-14:16	C ₃₂ H ₆₈ NBr	466.1
BAC-14	C ₂₃ H ₄₂ NCl	332.9	DADMAC-14:18	C ₃₄ H ₇₂ NBr	494.8
BAC-16	C ₂₅ H ₄₆ NCl	360.2	DADMAC-16:18	C ₃₆ H ₇₆ NBr	522.9
BAC-18	C ₂₇ H ₅₀ NCl	388.9	DADMAC-18:20	C ₄₀ H ₈₄ NBr	578.9

^aThe full names and chemical structures are given in Table S7.

MS in small molecule analysis by extending its application to more complex sample matrices than before. Future efforts will be made to understand whether other functionalities of graphene (e.g., sulfonation) can bring new benefits in the MS analysis.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.analchem.6b04167.

Supporting experimental details, supporting tables, supporting figures, and supporting references (PDF).

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Notes

The authors declare no competing financial interest.

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