A Microcolumn DC Graphene Sensor for Rapid, Sensitive, and Universal Chemical Vapor Detection

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ABSTRACT: Nearly all existing direct current (DC) chemical vapor sensing methodologies are based on charge transfer between sensor and adsorbed molecules. However, the high binding energy at the charge-trapped sites, which is critical for high sensitivity, significantly slows sensors’ responses and makes the detection of nonpolar molecules difficult. Herein, by exploiting the incomplete screening effect of graphene, we demonstrate a DC graphene electronic sensor for rapid (subsecond) and sensitive (ppb) detection of a broad range of vapor analytes, including polar, nonpolar, organic, and inorganic molecules. Molecular adsorption induced capacitance change in the graphene transistor is revealed to be the main sensing mechanism. A novel sensor design, which integrates a centimeter-scale graphene transistor and a microfabricated flow column, is pioneered to enhance the fringing capacitive gating effect. Our work provides an avenue for a broad spectrum real-time gas sensing technology and serves as an ideal testbed for probing molecular physisorption on graphene.

KEYWORDS: Chemical vapor sensing, Graphene, Direct current detection, Fringing capacitive gating effect, Binding energy

Nanoelectronic sensors based on low dimensional materials benefit from their extremely high surface-to-volume ratio, low power consumption, chemical robustness, and convenient electrical readout. They represent an important emerging technology that potentially has a broad range of applications in environmental protection, industrial safety, and biomedicine.1−7 Particularly, graphene stands out with its high carrier mobility and compatibility with existing semiconductor fabrication technologies that can be explored for developing on-chip sensitive nanoelectronic sensors with large intrinsic gain.2,5,8,9

In a typical nanoelectronic vapor sensor, molecules adsorbed to the sensor surface modify its electronic properties, thus generating the sensing signal. Chemical sensors using the field effect transistor (FET) design stand out due to their high sensitivity, resulting from the intrinsic gain from the electrostatic gating effect. The current voltage relation for an FET-based sensor can be generally expressed as

\[ I = \frac{\mu W}{L} C_g \left( V_g - V_{th} - \frac{1}{2} V_{sd} \right) V_{sd} \]

where \( \mu \) is the charge carrier mobility, \( W \) and \( L \) are the channel width and length, respectively, \( C_g \) is the gate capacitance, \( V_g \) is the gate voltage, \( V_{sd} \) is the source−drain bias voltage, \( V_{th} \) is threshold voltage, and \( C_g \left( V_g - V_{th} - \frac{1}{2} V_{sd} \right) \) gives the charge per unit area within the FET channel induced by the gate voltage.

Most nanoelectronic chemical sensors exploit the charge transfer between the absorbed analyte molecules and the sensor,10−16 directly via the nanomaterial or indirectly via the contact metal. Additional charges to the FET channel thus contribute to the total transistor current:

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interaction between vapor analytes and graphene. All analyte sensing tests were conducted with the back gate, which can be further amplified by graphene’s large mobility and measured conveniently as a DC current change. (b) Schematic showing a Gr-FET covered with a µColumn with a dimension of 40 cm (length) × 400 µm (width) × 370 µm (depth) for enhancing the interaction between vapor analytes and graphene. All analyte sensing tests were conducted with \( V_{g} = 0 \) V and \( V_{sd} = 3 \) V unless stated otherwise. The DC current between the source and the drain was recorded as the sensing signal. (c) DC current responses of µColumn graphene sensor to injections of various masses of four groups of analytes, namely, normal alkanes (left to right: C5–C9), aromatics (left to right: benzene, toluene, ethylbenzene, o-xylene, m-xylene, p-xylene, chlorobenzene), organic polar compounds (left to right: acetone, chloroform, ethanol, DMF, DMMP), and inorganics (left to right: carbon monoxide, carbon dioxide, nitric oxide, and hydrogen sulfide). (d) Temporal response to heptane with the full width at half-maximum \( t_{1/2} = 0.6 \) s (labeled in red arrow).

\[
I_{\text{sensor}} = \frac{\mu W}{L} \left[ C_{g} \left( V_{g} - V_{th} - \frac{1}{2} V_{sd} \right) + Q_{\text{mol}} \right] V_{sd}
\]

where \( Q_{\text{mol}} \) is the charge transfer between the device and molecules per unit area inside the channel. Therefore, depending on whether the adsorbed molecules are electron donors or acceptors, the changes in the detected current signal can give opposite signs. Such charge transfer behavior tends to happen for molecules with high binding energy to the sensor surface, or at low absorption energy sites resulting from defects.\(^{16}\) However, slow defect-mediated charge-transfer processes significantly limit those sensors’ responses to tens to hundreds of seconds. Additionally, most weak polar and nonpolar molecules are inherently weak charge donors or acceptors, which further limits the utility of the charge transfer mechanism. Alternately, analyte binding induced changes in carrier mobility have also been explored for sensing. Previous research has intentionally introduced more defects or functional groups to enhance coulomb scattering and lower sensor mobility.\(^ {17,18}\) Under the framework of this mechanism, all the analytes would consistently give negative current changes. Even though in principle this approach can detect both polar and nonpolar molecules, it generally has low sensitivity.

There are also other limitations to the aforementioned two mechanisms. For example, chemo-selective coating or functionalization\(^ {18–21}\) is often required to increase the sensitivity; post-treatments such as vacuum degassing\(^ {13}\), prolonged heating,\(^ {12,22}\) and ultraviolet radiation\(^ {23}\) are often needed for baseline regeneration. The resulting sensors are impractical for robust on-site vapor monitoring systems, which require rapid real-time responses at low concentrations and fast sensor regeneration.\(^ {24,25}\) Hence, novel sensing mechanisms are needed to resolve these fundamental bottlenecks (i.e., the trade-offs between sensitivity and response time) and take full advantages of nanoelectronic sensors.

Recently, using the intrinsic nonlinearity of a transistor, our groups have pioneered a new sensing technology based on heterodyne mixing to investigate the interaction between the alternating current (AC) drive voltage and the induced oscillating molecular dipole moment.\(^ {26–30}\) By detecting the molecular dipole instead of charge, our heterodyne sensor successfully addresses the fundamental speed-sensitivity trade-off in vapor detection.\(^ {28,30}\) Despite these achievements, this heterodyne sensor cannot detect nonpolar molecules due to its intrinsic dipole moment sensing mechanism; the AC mixing instrumentation is also more complex than traditional DC based circuitry.

This work reports a fringing capacitance change based sensing mechanism by exploiting the incomplete screening of graphene.\(^ {31}\) Unlike sensors made of metals or bulk semiconductors, the binding of molecules on the surface of graphene leads to changes in the gate capacitance of a graphene FET, resulting in current

\[
I = \frac{\mu W}{L} \left( C_{g} + C_{\text{mol}} \right) \left( V_{g} - V_{th} - \frac{1}{2} V_{sd} \right) V_{sd}
\]

\[
= \frac{\mu W}{L} \left[ C_{g} \left( V_{g} - V_{th} - \frac{1}{2} V_{sd} \right) + Q_{\text{mol}} \right] V_{sd}
\]

where \( C_{\text{mol}} \) and \( Q_{\text{mol}} \) are the molecule induced fringing capacitance change and corresponding charge perturbation, respectively. As shown in Figure 1a, fringing capacitance
changes occur when surface molecules alter the local dielectric environment above the graphene channel, which pulls more charges from the metal contacts. Consequently, the molecular fringing gate effect increases the transconductance of the FET by coupling with its back gate voltage. Importantly, instead of being measured directly through impedance spectroscopy, which is usually less sensitive and requires more complicated AC circuitry, this fringing capacitance change ($C_{mol}$) is first amplified in situ by graphene’s high mobility (as shown in eq 3) and then measured conveniently as a DC current change. A unique microfabricated flow column ($\mu$Column) for gas flow is integrated onto the graphene sensor to further enhance the interaction between the analytes and the sensor. Rapid (down to subseconds) and sensitive (down to parts-per-billion) label-free detection of a broad spectrum of vapor analytes, including 13 polar (10 organic and 3 inorganic) and 8 nonpolar (7 organic and 1 inorganic) molecules, was achieved on a centimeter-sized graphene FET (Gr-FET) integrated with a 40 cm long serpentine shaped $\mu$Column.

Figure 1b illustrates the device geometry and measurement setup. The sensor chip consists of two parts, a 2 cm $\times$ 2 cm Gr-FET and a 40 cm long $\mu$Column. Gr-FETs were fabricated using chemical vapor deposition (CVD)-grown graphene on a silicon wafer with thermal oxide (275 nm thick) and atomic layer deposition (ALD) deposited aluminum oxide (50 nm thick) for better gate electrical insulation. Two layers of graphene were transferred to guarantee coverage of graphene in the FET channel area. Next, the Gr-FET was capped with a 40 cm (length) $\times$ 400 $\mu$m (width) $\times$ 375 $\mu$m (depth) $\mu$Column. The bonding of the $\mu$Column and the Gr-FET was designed such that the metal contacts were covered, and only the graphene channel was exposed to the analytes. Details of device fabrication flow are discussed in the Supporting Information.

The as-obtained sensor was connected to a benchtop gas chromatography (GC) system that provides subsecond pulsed injection of analytes (see Methods in Supporting Information). The sensor was then exposed to known amount of analytes, while changes in the source-drain current ($I_{sd}$) were recorded with $V_g$ kept at zero. The sensing response was calculated as the ratio of the transient current change to the baseline current ($\Delta I_{sd}/I_{sd}$). Initial results demonstrated that the sensor showed sharp and strong responses to all tested chemicals, ranging from nonpolar and weak polar to strong polar molecules. Figure 1c lists the DC current response of a typical $\mu$Column graphene sensor to 21 representative chemical species, including normal alkanes ($C_5-C_9$), benzene, toluene, ethylbenzene, xylenes (o-, m-, and p-), 1,2-dichlorobenzene, acetone, chloroform, ethanol, N,N-dimethylformamide (DMF), dimethyl methylphosphonate (DMMP), carbon monoxide, carbon dioxide, nitric oxide, and hydrogen sulfide. All tested devices show instantaneous subsecond response
when exposed to pulsed analytes (i.e., Figure 1d for heptane). Furthermore, the sensor was completely regenerated (i.e., the signal returned to baseline) without any post-treatment.

Next, to evaluate the μColumn graphene sensor sensing performance, its temporal responses to transient exposure to analytes with varying masses were recorded. The sensor responses (i.e., \( \Delta I_d/I_d \)) to three repeated doses of \( n-C_9 \) with an injection mass from 2.3 ng to 90.5 ng are plotted in Figure 2a. To estimate the detection limit, sensor dosage response average is plotted in log−log scale (Figure 2b). The sublinear response reflects the transient behavior of vapor pulses interacting with the graphene surface and is consistent with previous observations from with other optical sensors\(^{32}\) and our heterodyne graphene sensor.\(^{28}\) Using a 3σ noise floor (3σ = 0.016 μA, Figure S2), the limit of detection (LOD) for \( n-C_9 \)

<table>
<thead>
<tr>
<th>analyte</th>
<th>LOD, mass (ng)</th>
<th>concentration at detection limit mass (ppm)</th>
<th>( t_{1/2} ) (s)</th>
<th>OSHA PEL 8 h TWA (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n\text{-}C_5 )</td>
<td>128.5</td>
<td>162</td>
<td>0.6</td>
<td>1000</td>
</tr>
<tr>
<td>( n\text{-}C_6 )</td>
<td>19.7</td>
<td>56.3</td>
<td>1.3</td>
<td>500</td>
</tr>
<tr>
<td>( n\text{-}C_7 )</td>
<td>8.0</td>
<td>13.6</td>
<td>1.4</td>
<td>500</td>
</tr>
<tr>
<td>( n\text{-}C_8 )</td>
<td>4.1</td>
<td>4.3</td>
<td>1.5</td>
<td>500</td>
</tr>
<tr>
<td>( n\text{-}C_9 )</td>
<td>2.1</td>
<td>1.7</td>
<td>1.1</td>
<td>-</td>
</tr>
<tr>
<td>benzene</td>
<td>24.4</td>
<td>46.2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>toluene</td>
<td>39.3</td>
<td>37.0</td>
<td>0.7</td>
<td>200</td>
</tr>
<tr>
<td>ethylbenzene</td>
<td>2.2</td>
<td>5.1</td>
<td>0.8</td>
<td>100</td>
</tr>
<tr>
<td>( o\text{-}xylene )</td>
<td>3.7</td>
<td>2.2</td>
<td>1.7</td>
<td>100</td>
</tr>
<tr>
<td>( m\text{-}xylene )</td>
<td>4.6</td>
<td>4.0</td>
<td>1.3</td>
<td>100</td>
</tr>
<tr>
<td>( p\text{-}xylene )</td>
<td>4.2</td>
<td>3.7</td>
<td>1.6</td>
<td>100</td>
</tr>
<tr>
<td>chlorobenzene</td>
<td>1.7</td>
<td>4.9</td>
<td>0.9</td>
<td>75</td>
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<tr>
<td>acetone</td>
<td>43.5</td>
<td>235.1</td>
<td>0.8</td>
<td>500</td>
</tr>
<tr>
<td>chloroform</td>
<td>33.3</td>
<td>149.4</td>
<td>0.6</td>
<td>100</td>
</tr>
<tr>
<td>ethanol</td>
<td>20.5</td>
<td>19.9</td>
<td>1.1</td>
<td>1000</td>
</tr>
<tr>
<td>DMF</td>
<td>0.43</td>
<td>0.7</td>
<td>1.6</td>
<td>50</td>
</tr>
<tr>
<td>DMMP</td>
<td>0.050</td>
<td>0.02</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>3.5</td>
<td>20.0</td>
<td>0.7</td>
<td>35</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>18</td>
<td>57.4</td>
<td>0.6</td>
<td>5000</td>
</tr>
<tr>
<td>nitric oxide</td>
<td>0.1</td>
<td>0.6</td>
<td>1.1</td>
<td>25</td>
</tr>
<tr>
<td>hydrogen sulfide</td>
<td>0.8</td>
<td>4.2</td>
<td>0.9</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 1. Summary of the μColumn Gr-FET Sensor in Response to 21 Polar and Non-polar Vapor Analytes as well as Their 8 h Total Weight Average (TWA) Permissible Exposure Limits (PEWs) Listed by Occupational Safety and Health Administration (OSHA)

Table 2. Summary of the Experimental Binding Energies, Dipole Moments, and Polarizabilities of Five Tested Alkanes\(^{42}\)

<table>
<thead>
<tr>
<th>analyte</th>
<th>dipole moment (D)</th>
<th>polarizability ( (a\text{,} 10^{-24} \text{cm}^2) )</th>
<th>experimental binding energy (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n\text{-}C_5 )</td>
<td>0</td>
<td>9.88</td>
<td>491 ± 19</td>
</tr>
<tr>
<td>( n\text{-}C_6 )</td>
<td>0</td>
<td>11.63</td>
<td>527 ± 15</td>
</tr>
<tr>
<td>( n\text{-}C_7 )</td>
<td>0</td>
<td>13.37</td>
<td>607 ± 30</td>
</tr>
<tr>
<td>( n\text{-}C_8 )</td>
<td>0</td>
<td>15.24</td>
<td>684 ± 26</td>
</tr>
<tr>
<td>( n\text{-}C_9 )</td>
<td>0</td>
<td>17.37</td>
<td>761 ± 30</td>
</tr>
</tbody>
</table>

Figure 4. μColumn graphene sensor as a testbed for probing alkane–graphene binding energy. (a) μColumn graphene sensor’s temporal response to pentane at 22.9 °C. Exponential fit in red to the desorption part yields the desorption rate \( k_{\text{des}} = 1.27 \text{ s}^{-1} \) \( (\tau_{\text{des}} = 0.79 \text{ s}) \). (b) Desorption rates in the natural log scale plotted against the corresponding measurement temperatures in an Arrhenius plot, with the slope of the linear fit in red giving the binding energy \( E_b \) of 491 meV. The measurement temperatures here are 0.1, 4.9, 9.8, 13.9, 22.9, 30.8, and 37.7 °C, respectively.

Figure 3. Fringing capacitive gating based sensing mechanism. (a) μColumn graphene sensor’s response to chloroform, acetone, \( n\text{-}n\text{-}\text{nonane} \), and nitrobenzene when gated at the p-branch (black) and the n-branch (red). For a given chemical species, the same mass of analyte was injected to the same device with gate bias set in the p- and n-branches, respectively. (b) Illustration of impedance measurement, where the device is configured as a “parallel capacitor” instead of a three-terminal transistor. The graphene together with the metal contact forms one plate, and the underlying p-doped silicon forms the other plate. The impedance was measured by applying AC voltage to the doped Si while both source and drain contacts are grounded. The AC current \( i_{\text{AC}} \) flowing through this capacitor was recorded with a lock-in amplifier. (c) \( i_{\text{AC}} \) response of the “parallel capacitor” to acetone injection with different mass amounts (from left to right: 1317 ng, 2633 ng, and 3950 ng).

Figure 2a. To estimate the detection limit, sensor dosage response average is plotted in log−log scale (Figure 2b). The sublinear response reflects the transient behavior of vapor pulses interacting with the graphene surface and is consistent with previous observations from with other optical sensors\(^{32}\) and our heterodyne graphene sensor.\(^{28}\) Using a 3σ noise floor (3σ = 0.016 μA, Figure S2), the limit of detection (LOD) for \( n\text{-}C_9 \)
is estimated to be 2.1 ng (or 1.7 ppm by volume) at an S/N of 3.

To demonstrate the versatility of our µColumn graphene vapor sensor, we characterized the sensor’s repeated dosage response to an additional 20 analytes, including four other alkanes from n-C4 to n-C10 (Figure 2c), seven aromatics (Figure 2d), four other organic polar molecules (Figure 2e), and four inorganic compounds (Figure 2f). Table 1 summarizes the extracted LOD in both mass and volume concentrations for all 21 analytes, together with full width at half maxima (FWHM) at minimum injection amounts and corresponding OSHA standard for 8 h total weight-average (TWA) permissible exposure limits (PELs). In particular, the LOD for DMMP (Figure 2d) is estimated to be ~0.050 ng (0.02 ppm in concentration), which represents an improvement of several orders of magnitude over most existing DC-based nanoelectronic sensors.13,16,20,22,23,33,34 Critically, the µColumn graphene sensor is not only capable of detecting most common hazardous air pollutants (e.g., benzene, toluene, ethylbenzene, and xylenes) but also achieves sensitivities exceeding the OSHA requirement for long-term exposure limits for nearly all 21 analytes. Therefore, these initial results already demonstrate its great potential for practical applications in real-time industrial safety monitoring.

The sensing mechanism for µColumn graphene sensors can be explained as follows. The change in carrier density in the graphene channel can be induced by either direct charge transfer between graphene and the adsorbate or fringing capacitive gating, in which the analyte changes the local transfer between graphene and the adsorbate or fringing graphene channel can be induced by either direct charge transfer, is the dominant sensing mechanism in our present work. Assuming negligible direct charge transfer between graphene and adsorbed molecules, $C_{\text{null}}$ is solely responsible for the current perturbation after analyte injection. $C_{\text{null}}$ and molecule induced charge perturbation $Q_{\text{mol}}$ can be estimated as follows,
CVV V

10 mV to 5 V, the signal-to-noise ratio (S/R) of the sensor in sensitivity enhancement. When the bias was increased from the previous DC sensing work,\textsuperscript{33,35} where sensitivity shows molecules do not have enough time to fully interact with the sensitivity because it has a very wide channel. Given the high the smaller sensing area, which can also be seen in Figure S7 (Figures S4c and S6). Control 1 has a lower sensitivity due to length and wider in width than the prototype \(\mu\)Column (Figures S4c and S6). Control 1 has a lower sensitivity due to the smaller sensing area, which can also be seen in Figure S7 where the graphene channel area was further reduced from a centimeter scale to 2 \(\mu\m\times 2\ \mu\m\). Control 2 has a lower sensitivity because it has a very wide channel. Given the high volumetric rate (8.5 mL/min) in our experiments, the molecules do not have enough time to fully interact with the graphene surface if the channel is too wide.

We also notice that for our prototype \(\mu\)Column graphene sensor, the source–drain bias voltage plays an important role in sensitivity enhancement. When the bias was increased from 10 mV to 5 V, the signal-to-noise ratio (S/R) of the sensor increased from \(\sim 1\) to 27 (Figure S8). It is noticed that the conductance change toward injection of a given analyte with the same amount remains constant (Figure S8), and none of the detection peaks have any tailing issue; this is different from the previous DC sensing work,\textsuperscript{33,35} where sensitivity shows significant dependence on \(V_{sd}\) and the signal does not emerge until above a threshold of applied voltage. In those works, the sensitivity and reversibility of the sensors were enhanced by a change in the charge transport mode, as in the Poole–Frenkel conduction regime electrons "jump" through the defects instead of bypassing them. In order to limit current going through the device, bias voltage of 3 V was adopted for all sensing performance characterizations in this work, which is sufficient to provide a decent S/N.

Unveiling the van der Waals (vdW) interactions between small molecules and sp\(^2\) carbon allotropes is important for surface physics and sensor design, as well as in studying the related biological processes. Particularly, the behavior of rigid hydrocarbon chains on \(\pi\) systems is of special interest in organic synthesis, biochemistry, drug delivery, and hydrocarbon gas storage. To date, most studies are based on theoretical simulations,\textsuperscript{36,37} or thermal desorption spectroscopy measurements on graphite.\textsuperscript{38–40} However, these methods might result in deviation of the molecular binding energies compared to those on graphene surfaces. A nanoelectronic chemical vapor sensor offers a more suitable platform to study the interactions between small molecules and the nanomaterials with their sensitive response and electrical readout.\textsuperscript{1,3,4} However, as previously discussed, the response of conventional nanoelectronic sensors is based on charge transfer (covalent binding), which does not represent the physicochemical nature of noncovalent vdW interactions near the pristine surface of graphene. Using the heterodyne mixing detection technique, we have recently quantified the binding affinity between graphene and five polar molecule species.\textsuperscript{29} However, the graphene heterodyne sensor is only responsive to polar molecules and unable to probe nonpolar molecules.

Unlike other graphene nanoelectronic sensors, the \(\mu\)Column graphene sensor in the present work offers a testbed for characterizing the binding energy of adsorbed nonpolar molecules at the graphene surface. The high speed, high sensitivity, and reversible performance enables real-time monitoring of the rapid molecular physiosorbtion behavior. Additionally, this sensor’s design keeps both metal contacts and graphene edges outside the flow column, thus allowing the detection signal to unveil the true vdW interaction between the molecules and graphene.

To investigate the hydrocarbon/sp\(^2\)-carbon interaction, temperature-dependent measurements were conducted on the \(\mu\)Column graphene sensor for five alkanes (from \(n\)-C\(_6\) to \(n\)-C\(_9\)). The detailed testing method has been discussed in our previous paper.\textsuperscript{29} Briefly, the device was kept on a Peltier cooler/heater to allow for device temperature control; for each analyte, time-domain measurements were conducted at different temperatures. The desorption rates are extracted at the first exponential decay of the curve (Figure 4a) and plotted against corresponding temperatures (Figure 4b). The binding affinity is then extracted by fitting the slope in Arrhenius scale, according to transition state theory.\textsuperscript{41} The experimentally extracted binding energies of the four alkane chains on graphene are provided in Table 2. We notice that the binding energy between \(n\)-alkanes and graphene increases with increased chain length, in agreement with increased polarizability. These experimentally extracted values resemble the simulation results on graphene–alkane interactions.\textsuperscript{36} However, compared to the modeling work on graphite, the corresponding binding energies of the same alkanes are lowered by \(\sim 200\ \text{meV} \).\textsuperscript{40}

In conclusion, we report a new nanoelectronic sensing mechanism by exploring the fringing capacitance change resulting from molecules binding to the graphene transistor surface. Unlike conventional impedance or capacitance sensing approaches, the dielectric response change is intrinsically amplified by the large transconductance of the graphene transistor and measured conveniently using DC readout. Our label-free \(\mu\)Column DC graphene sensor demonstrates high speed, high sensitivity, and low power consumption and can detect a wide spectrum of analytes including polar/nonpolar and organic/inorganic molecules. The performance metrics of our \(\mu\)Column graphene sensor in conjunction with other types of electronic sensors are summarized in Table 3. Furthermore, the \(\mu\)Column design is compatible with existing \(\mu\)GC platforms, enabling the integration of this electronic sensor with \(\mu\)GC system for portable and wearable sensing applications.

\section*{ASSOCIATED CONTENT}

\subsection*{Supporting Information}
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.1c03416.

Methods (device fabrication and measurement setup), addition experimental data, figures, and tables (PDF)

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W.Z., Z.Z., and X.F. conceived the experiments. W.Z. and Z.L. fabricated the devices, developed the electrical measurement setup, and performed the measurements. G.S.K., Y.W., and K.L. provided support for fabrication and electrical measurement setup. H.Z. and M.W.-H.L. contributed to calibration of the GC system. All authors analyzed the data and cowrote the paper.

Notes

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