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Highly Flexible Chemical Sensors Based on Polymer Nanofiber Field-Effect Transistors

O Young Kweon, a Moo Yeol Lee,a Teahoon Park,b Hanbit Jang,a Ayoung Jeong,a Moon-Kwang Um b and Joon Hak Oh c

Soft electronic devices are key components of flexible or wearable smart electronics. Chemical sensors based on organic field-effect transistors (OFETs) show great promise because of their high sensitivity, low cost, fast response, flexible applications, and signal amplification via gate voltage tuning. In addition, the sensor response can be made highly selective by incorporating specific functional groups or recognition elements. The response magnitude of an OFET sensor depends strongly on the surface area of the active layer that interacts with the analyte. In this study, two strategies including nanostructuring and surface functionalization have been explored to enhance the performance and sensitivity of OFET sensors. We describe the fabrication of highly flexible, electrospun poly[3,3-didodecylquaterthiophene/calix[8]arene (PQT-12)/C[8]A] sensors employing semiconducting polymer nanofibers (NFs) as the active layer. The resulting bendable and flexible PQT-12/C[8]A OFET sensors show highly sensitive to ethanol (192%) and toluene (229%) and moderately sensitive to n-hexane (121%) with a minimum detectable level of 10 ppm. In addition, the PQT-12/C[8]A NF sensors works electrically stable under typical operating conditions with a bending radius down to 0.5 mm. This work demonstrates a viable approach to the fabrication of flexible OFETs for use as wearable sensors and health-monitoring devices.

Introduction

Soft electronic devices are key components of flexible or wearable smart electronics.1-3 Recently, extensive research has focused on developing flexible or stretchable organic electronics using conducting polymers,4 carbon-based nanomaterials,5 and metal nanostructures6 and hybrids thereof. Due to their high flexibility and elasticity, conducting polymers are particularly promising candidates for wearable electronic components, including organic field-effect transistors (OFETs),7-9 organic photovoltaics (OPVs),10,11 and organic light-emitting diodes (OLEDs).12,13 Several polymers have been used in flexible device applications, including polypyrrole,14 polyaniline,15 PEDOT,16 PBTTT,17-18 P3HT,14 and poly(3,3-didodecylquaterthiophene) (PQT-12).19-20 Most chemical or photometric sensors made with conducting polymers are based on changes in the resistance/conductance of the conductive sensing layer upon the application of external stimuli, e.g., certain chemicals or light intensities.

Sensors based on OFETs boast several advantages, including high sensitivity, low cost, fast response, physical flexibility, and signal amplification via gate voltage. The semiconducting polymer can also be modified with specific functional groups, allowing for a high degree of response specificity.1 OFETs undergo changes in current upon exposure of the active organic semiconductor layer to the ambient environment or an analyte stream. This modulation occurs as the analyte interacts with the transport region of the OFET, typically the first few layers of the film, or within grain boundaries formed during thin-film growth.21 Analytes can influence thin-film conductivity as dopants or as traps for charge carriers, through bulk resistive effects on inter-grain transport, or through accumulated electrostatic dipole interactions. In addition, sensor response depends strongly on the surface area of the active layer that interacts with the analyte.22 In this respect, herein we have used two main strategies to enhance the mechanical flexibility and sensing performance of OFET sensors. The first is to increase the surface to volume ratio of the active layer through the formation of 1-dimensional (1D) nanofibers (NFs). The second is the development of semiconducting materials with specific functional groups that enable a selective response toward a target analyte. In general, 1D organic semiconducting nanomaterials are suitable for use in flexible and stretchable sensors due to their high elasticity and high surface-to-volume ratios. Both of these factors result in higher sensitivity than is generally attainable with film-type materials. Electrospinning is a simple and powerful method for fabricating long and uniform 1D nanomaterials, such as single and coaxial nanofibers.15 The second strategy involves the incorporation of calix[8]arene (C[8]A) container molecules into the surface of existing OFETs for selective molecule uptake.

In this study, we describe the fabrication of flexible PQT-12/C[8]A NF sensors using organic semiconducting polymer nanofibers (NFs) as the active layer. Chemical sensors were prepared by electrospinning a mixture of PQT-12 NFs in a viscous polymer

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material (poly(ethylene oxide) (PEO)) onto interdigitated Au electrodes to form an OFET structure. An additional dielectric layer of silicon dioxide (SiO$_2$) or SU-8 (thickness ≈ 300 nm) was introduced in a bottom-gate, top-contact device configuration. The resulting PQT-12/C[8]A NF-based layers were bendable and elastic. Exposure to solvent vapors such as ethanol, n-hexane, and toluene produced concentration-dependent current changes. PQT-12 OFET sensors functionalized with C[8]A were particularly sensitive and selective with a minimum detectable level (MDL) of approximately 10 ppm. The sensors were both electrically and mechanically stable with a minimum bending radius ($R_b$) of 0.5 mm. To demonstrate the potential of this system for use in portable or wearable sensors for on-site detection of volatile gases, we incorporated PQT-12/C[8]A NF-based sensors into wireless devices with an associated smartphone application. Despite rapid advancements in OFET-based flexible sensor technology, organic sensors based on a PQT-12/C[8]A NF platform have not previously been demonstrated. Our work provides a viable approach for fabricating flexible OFET devices for use in wearable sensors or health-monitoring devices.

**Experimental section**

**Materials and device fabrication**

The PQT-12/C[8]A NF-based OFETs were constructed in a bottom-gate, top-contact configuration. PQT-12 (M.W. 50,000–150,000, Solaris Chem Inc.), PEO (M.W. =600,000, Aldrich), and C[8]A (Aldrich) were dissolved in chlorobenzene at a ratio of 2:1:0–0.1 (w/w/w) (total polymer concentration =10 wt%). The blended solution was stirred at 60°C for 24 h. OTS-modified SiO$_2$/Si substrates (n-type, <0.004 Ω cm) and PET substrates were used when measuring electrical performance and flexibility of PQT-12/C[8]A NFs, respectively. Details on the fabrication of OTS self-assembled monolayers (SAM) are provided in the Supporting Information (Section S1). SU-8 was used as a flexible dielectric layer and was spin-coated onto thermally deposited Au/PET substrates at 5000 rpm. The Cr/Au source and drain electrodes (thickness, ≈4/40 nm) were patterned through a shadow mask by thermal evaporation onto a dielectric layer. Electrospinning of NFs was performed at a 15.0 kV nozzle, 0.33 mm). The tip was connected to the positive terminal of a power supply. The tip to collector distance was 10 cm and the flow rate of the solution was 6–8 μL min$^{-1}$. To uniaxially align the NFs, PQT-12/C[8]A NFs were deposited directly onto substrates attached to a drum collector rotating at 1500 rpm. The average diameter of the electrospun nanofibers was about 500 nm.

**Characterization of Flexible OFET Devices**

OFET devices and electrospun NFs were characterized using optical microscopy, field-emission scanning electron microscopy (FE-SEM), and grazing incidence X-ray diffraction (GIXD) analyses. The electrical characteristics, including current–voltage (I–V) curves, of PQT-12/C[8]A OFETs were measured with a Keithley 4200-SCS semiconductor parameter analyzer (US) in a N$_2$-filled glove box. Sensing/bending tests were performed in ambient atmosphere. Chemical sensitivity was characterized using a customized microfluidic controller. Field-effect mobility ($\mu_{\text{FE}}$) and threshold voltage ($V_{\text{TH}}$)

**Results and discussion**

**Electrospinning of PQT-12/C[8]A NFs**

The overall experimental procedure for the fabrication of PQT-12/C[8]A NF-based sensors is illustrated in Fig. 1a. The basic concept combines a high-mobility conjugated polymer with calixarene container molecules. The conjugated polymer, PQT-12, is a commercial p-type semiconductor with high crystallinity. It is stable in air and boasts a higher charge mobility than other conjugated polymers. Sensors based on PQT-12 also exhibit lower response times than most other conducting polymer-based chemical sensors. 24-25 Semiconducting NFs, which served as the active channel in our OFET device, were produced by electrospinning a mixture of PQT-12 and PEO, a processing aid polymer (Fig. 1b).
Fig. 2 (a) A schematic showing a PQT/C[8]A OFET device with an interdigitated S/D electrode. (b) Optical micrograph and SEM image (inset) of a PQT/C[8]A NFs. (c) Transfer characteristics of PQT-12/C[8]A 5 wt% NFs ($V_{DS} = -100$ V). The red/dotted line is an extrapolation used for mobility calculations. (d) Transfer characteristics of PQT-12/C[8]A OFETs during a $V_{DS}$ sweep (-5 V to -50 V).

are difficult to obtain from a pure solution of conjugated polymer due to the low solubility, relatively low average molecular weight, rigid backbone, and high crystallinity of most conjugated polymers. The addition of a high-molecular-weight polymer, such as PEO, poly(ε-caprolactone) (PCL), poly(methyl methacrylate) (PMMA), polystyrene (PS), or poly(vinyl pyrrolidone) (PVP), to the electrosprining solution provides sufficient fluid viscosity for the continuous spinning of semiconducting NFs. In this study, a blended solution of PQT-12, PEO, and C[8]A in chlorobenzene (CB) (2:1:0–0.1 by weight, total concentration, = 10 wt%) was used to obtain uniformly electros spun PQT-12/C[8]A NFs 1 wt%, 3 wt%, and 5 wt%.

Fig. 2a illustrates the configuration of the OFET sensor. PQT-12/C[8]A NFs were electrospun from a mixed solution of PQT-12, C[8]A, and PEO into an OTS-modified silicon wafer (contact angle to deionized water, $=109^\circ$) was utilized as a dielectric and gate electrode. The thickness and capacitance of the PDMS dielectric layer were approximately 1.5 μm and 1 nF cm$^{-2}$, respectively. PQT-12/C[8]A NFs comprised the active material and were directly electros spun on the prepared device substrate. The active channel dimensions of a single PQT-12/C[8]A NF were estimated from the width ($W$) and length ($L$) of an NF crossing the S/D Au electrodes, and that of multiple NFs was obtained from the sum of $W/L$ ratios of NFs located in the channel region. The dimensional calibration of the PQT-12 component was difficult, because PQT-12/C[8]A NFs were electros spun from a mixed polymer solution. Therefore, our estimated field-effect mobility may have been underestimated because the insulating properties of PEO were not taken into account. The electrical characteristics of PQT-12/C[8]A OFETs measured in the saturation region are shown in Fig. 2c (see also Fig. S1 and Table S1). The maximum hole mobility ($\mu_{h,max}$) and on/off current ratio ($I_{on}/I_{off}$) of PQT-12/C[8]A OFETs were $7.1 \times 10^{-2}$ cm$^2$ V$^{-1}$ s$^{-1}$ and 1.7 $\times 10^{2}$, respectively (Table 1). PQT-12 OFETs with C[8]A exhibited slightly higher values of the drain currents ($|I_D|$) with a lower turn-on voltage compared with those without C[8]A in the forward sweep, most likely a result of p-type doping effects and preferential interaction of C[8]A with PQT-12. The p-type doping effect of the semiconducting layer is related to the induced polarization by contact with the polar C[8]A molecule with PQT-12 fibers. The $V_{TH}$ of the OFETs shifted from 0.8 to 3.9 V after introduction of the C[8]A molecule, revealing the easier turn-on due to the electron withdrawing characteristics of the C[8]A. In addition, the slight increase of $\mu_h$ and $V_{TH}$ of calixarene incorporated OFETs can also be attributed to the preferential interactions of the aryl groups with the semiconductor layers. Under ambient conditions, the PQT-12/C[8]A OFETs exhibited a high on/off current ratio ($I_{on}/I_{off}$) of more than $10^3$. OFET operation in the linear regime showed obvious field-effect behaviors (Fig. 2c), which were stable enough to achieve signal.

![Image](https://example.com/image.png)

**Fig. 3** The relative responses of PQT-12 based OFET sensors are shown upon exposure to 100 ppm (a) ethanol, (b) n-hexane, and (c) toluene vapor. The bar values in y-axis indicate the normalized current change of PQT-12 and PQT-12/C[8]A OFET sensors as a function of $V_{GS}$, respectively.

**Table 1** Summary of electrical characteristics of PQT-12 based OFETs with and without C[8]A.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\mu_{h,max}$ ($cm^2 V^{-1} s^{-1}$)</th>
<th>$\mu_{h,max}$ ($cm^2 V^{-1} s^{-1}$)</th>
<th>$I_{on}/I_{off}$</th>
<th>$V_{TH}$ [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQT-12</td>
<td>$3.2 \times 10^{-2}$</td>
<td>$5.1 \times 10^{-2}$</td>
<td>$1.1 \times 10^{2}$</td>
<td>0.8</td>
</tr>
<tr>
<td>PQT-12/C[8]A 5 wt%</td>
<td>$4.3 \times 10^{-2}$</td>
<td>$7.1 \times 10^{-2}$</td>
<td>$1.7 \times 10^{2}$</td>
<td>3.9</td>
</tr>
</tbody>
</table>

**Electrical Characteristics of PQT-12/C[8]A OFETs**

To investigate the electrical performance of PQT-12/C[8]A OFETs, an OTS-modified silicon wafer (contact angle to deionized water, $=109^\circ$) was utilized as a dielectric and gate electrode. The thickness and capacitance of the PDMS dielectric layer were approximately 1.5 μm and 1 nF cm$^{-2}$, respectively. PQT-12/C[8]A NFs comprised the active material and were directly electros spun on the prepared device substrate. The active channel dimensions of a single PQT-12/C[8]A NF were estimated from the width ($W$) and length ($L$) of an NF crossing the S/D Au electrodes, and that of multiple NFs was obtained from the sum of $W/L$ ratios of NFs located in the channel region. The dimensional calibration of the PQT-12 component was difficult, because PQT-12/C[8]A NFs were electros spun from a mixed polymer solution. Therefore, our estimated field-effect mobility may have been underestimated because the insulating properties of PEO were not taken into account. The electrical characteristics of PQT-12/C[8]A OFETs measured in the saturation region are shown in Fig. 2c (see also Fig. S1 and Table S1). The maximum hole mobility ($\mu_{h,max}$) and on/off current ratio ($I_{on}/I_{off}$) of PQT-12/C[8]A OFETs were $7.1 \times 10^{-2}$ cm$^2$ V$^{-1}$ s$^{-1}$ and 1.7 $\times 10^{2}$, respectively (Table 1). PQT-12 OFETs with C[8]A exhibited slightly higher values of the drain currents ($|I_D|$) with a lower turn-on voltage compared with those without C[8]A in the forward sweep, most likely a result of p-type doping effects and preferential interaction of C[8]A with PQT-12. The p-type doping effect of the semiconducting layer is related to the induced polarization by contact with the polar C[8]A molecule with PQT-12 fibers. The $V_{TH}$ of the OFETs shifted from 0.8 to 3.9 V after introduction of the C[8]A molecule, revealing the easier turn-on due to the electron withdrawing characteristics of the C[8]A. In addition, the slight increase of $\mu_h$ and $V_{TH}$ of calixarene incorporated OFETs can also be attributed to the preferential interactions of the aryl groups with the semiconductor layers. Under ambient conditions, the PQT-12/C[8]A OFETs exhibited a high on/off current ratio ($I_{on}/I_{off}$) of more than $10^3$. OFET operation in the linear regime showed obvious field-effect behaviors (Fig. 2c), which were stable enough to achieve signal.
amplification and a fast response in sensing conditions. To assess the potential of our PQT-12/C[8]A OFETs in low-voltage sensors, we investigated their transfer characteristics with various operating conditions varying $V_{DS}$, which is applied voltage between drain and source (Fig. 2d). One side of the electrode was pegged to ground (0 V) and current flow was measured while the voltage applied to the other side was gradually increased from –5 to –50 V. PQT-12/C[8]A OFETs showed stable field-effect operation behavior under low $V_{DS}$ less than –10 V, indicating reasonable transfer characteristics. Grazing incidence X-ray diffraction (GIXD) analyses were performed to further investigate the electrical characteristics and molecular orientation of the PQT-12:PEO NFs. Diffraclograms were obtained from thin films of both pristine PQT-12 NFs and PQT-12/C[8]A NFs after thermal annealing at 150°C for 30 min. The PQT-12-base NFs diffraction indicated the existence of two-phase polymorphs, which is in agreement with previous reports.28-29 The first crystalline phase of the PQT-12 NFs was characterized by well-defined (100) lamellar peaks, which are indicative of an edge-on orientation that would facilitate charge transport between the source and drain electrodes. In addition, the presence of polymorphic (100)′ lamellar peaks indicate the formation of another highly crystalline phase (Fig. S2 and Table S2). Compared to films prepared without C[8]A, electrospun PQT-12/C[8]A NF films exhibited smaller (100) and (100)′ lamellar spacing (by approximately 0.97 Å). This may be attributed to denser molecular packing and preferential interactions between the aryl groups of C[8]A and the PQT-12 semiconductor layers.21

Chemical Sensing Characteristics of PQT-12 NF-based OFET Sensors

PQT-12/C[8]A NF-based OFETs were exposed to vapors of various volatile organic compounds (VOCs) to evaluate their sensing performance as chemical sensors. The normalized current change ($\Delta I/I_{BASE}$) of a given sensor was monitored in real time at room temperature and after exposure to a chemical vapor. Figure 5 displays the relative sensitivity (defined as the normalized current change) of flexible PQT-12/C[8]A OFETs as a function of the concentration of ethanol, n-hexane, and toluene vapor. All of the analytes elicited negative sensing behaviors, where the $|I_0|$ decreased with analyte exposure. In its electrically conductive state, PQT-12 is a p-type semiconductor. The exposure of PQT-12 NFs to electron-donating molecules, such as those bearing hydroxyl groups (–OH), can result in a reversible redox reaction.30 In addition, the proximity of such electron-rich groups would decrease the number of holes ($h^+$) which function as charge carriers at channel region of NF-base OFETs, resulting in a decrease of $|I_0|$ in a p-channel PQT-12 OFET-based sensor.27 In other words, introducing ethanol to PQT-12 NFs effectively neutralizes the polymer backbone and decreases the number of charge carriers, resulting in a drop in conductivity.31-32 The intensity of signal response of OFET-based sensors increased with increasing analyte concentration from 10 to 100 ppm. This is because the diffusivity of analyte vapor into the active material depends strongly on the concentration of analyte in the surrounding environment.27 Our OFET sensors showed the highest sensing performance to ethanol vapor, in terms of response and recovery times, among the tested chemical vapors. Here, response time is defined as the time required for the sensor signal to reach from baseline to 90% of its maximum response. Similarly, recovery time is the time required for the sensor signal to drop from its maximum response to 10% above its baseline level. The response and recovery times of our OFET sensors to ethanol vapor were approximately 1 and 2 s, respectively. Moreover, the MDL of these sensors, which were operated at $V_{DS} = -100$ V and $V_{GS}$ (applied voltage between gate and source) = $-10$ V, was 10 ppm of VOCs.

OFET devices incorporating C[8]A demonstrated higher signal responses for concentrations at 100 ppm. The sensitivity of the PQT-12/C[8]A OFET response rate, $-\Delta I/I_{BASE}$ (%), is given in Fig. 3 and Fig S4. Devices incorporated with C[8]A 5 wt% showed drastic increases in selectivity and sensitivity for ethanol (ca. 192%), and toluene (ca. 229%), and a moderate increase in sensitivity to n-hexane (ca. 121%) than those of PQT-12 OFET (Table S3). Upon exposure to VOCs, the sensitivity of sensors showed proportional increase depending on the increasing concentration of C[8]A. We hypothesize that the calixarene layer facilitates selective gas adsorption on surface of the semiconducting polymer. Cavity-like structures formed by calixarene

Fig. 4 (a) The selective sensing mechanisms of C[8]A incorporated into PQT-12 OFET sensors are illustrated. (b) Changes in the normalized current ($\Delta I/I_{BASE}$) of PQT-12/C[8]A OFET sensors in response to periodic exposures to various VOCs (100 ppm) are shown in the left panel. For clarity, the first response signals to certain VOCs are enlarged in the right panel.
can trap analyte molecules, resulting in surface-dipole interactions that induce changes in $|I_0|$ and increased sensor sensitivity. The charge transfer and output characteristics of PQT-12/C[8]A and PQT-12 NFs sensors, shown in Fig. 55, confirm these changes. Moreover, calixarene cavities preferentially capture molecules that are compatible with the chemical environment and physical dimensions of the cavity framework, thus incorporating a degree of selectivity into the sensor. Molecular dynamics simulations presented in our previous work show the steric effects, calculated charge transfer, binding energies and induced dipole moments of C[8]A when exposed to various VOCs. The results given here indicate that ethanol and toluene fit within the calixarene framework and molecular dynamics of C[8]A, resulting in significant signal amplification relative to n-hexane.

In addition to steric effects, we recognized that the signal intensity of our PQT-12/C[8]A NF-based OFETs to various VOCs depended on the protonation state, oxidation state, swelling, and conformational alignment of the active polymer layer (Fig. 4a and 4b). Charge-carrier trapping effects can also occur in the presence of various VOCs. In all cases, the amphiphilic nature of the C[8]A container is significant, selecting those molecules that can most effectively bind through both lipophilic (e.g., C-H⋯n) and hydrophilic (e.g., O-H⋯O) interactions with both the aromatic core and hydrophilic rim of the C[8]A container. Hydrophilic and lipophilic interactions between C[8]A and ethanol or toluene allowed for effective electron donation into the OFET active layer, resulting in increased electron density. This decreased the number of $h^+$, resulting in a lower $|I_0|$ and a faster response time compared with those without C[8]A. As mentioned above, the response and recovery times of our OFET sensors to ethanol vapor were approximately 1 and 2 s, respectively. In the case of n-hexane and toluene, response and recovery times were around 14 and 32 s, 8 and 71 s respectively. Both molecular dynamics including steric effects and interaction between C[8]A and analytes can affect the intensity of amplification, response and recovery times, and cause the difference shape of signals, providing helpful information to discriminate unknown volatile analytes (Fig. 4b).

**Bending Properties of PQT-12/C[8]A NF-based OFETs**

Electrical characterization and chemical sensitivity were investigated as a function of $R_b$ (Fig. 5a) using a layer of SU-8 (thickness $= 300$ nm) as the dielectric in a bottom-gate, top-contact device configuration. Bending tests were performed with the OFETs bent into cylinders with $R_b$ of 12.5, 10.5, 7.0, 3.5, or 0.5 mm as shown in Fig. 5b. The resulting transfer curves are shown in Fig. 5c, including the initial and recovered status, and average on- and off-currents are shown in Fig. 5d as a function of $R_b$. Note that the PQT-12/C[8]A 5 wt% OFET devices were electronically stable at $R_b$ as small as 0.5 mm, where the estimated tensile strain was 10.0%, calculated as $\varepsilon = d/R_b$, where $\varepsilon$ represents the strain and $d$ is the thickness of the device. This clearly indicates the effectiveness of one-dimensional PQT-12/C[8]A NF platforms in terms of flexibility. OFETs made with films of 100 $\mu$m thickness were stable at $R_b$ of 12.5 mm ($\varepsilon = 0.40\%$), 10.5 mm ($\varepsilon = 0.48\%$), 7.0 mm ($\varepsilon = 0.71\%$), and 3.5 mm ($\varepsilon = 1.43\%$). On- and off-currents were stable, even after repeated and severe bending, indicating outstanding mechanical flexibility and operational stability. PQT-12/C[8]A NF OFETs prepared on SU-8-
coated polyethylene terephthalate (PET) substrates exhibited an on-current retention of up to 86.96% (±0.19%). Under bent conditions, the bottom layer of the OFET experiences compressive stress while the top layer experiences tensile stress. It is likely that the SU-8/PET substrate helps dissipate the compressive stress in the bottom layer while alleviating tensile stress in the top PQT-12/C[8]A OFET layer, resulting in the elongation of PQT-12 chains and the constraint of transporting h+.34

Demonstration of Wearable Chemical Sensor with IoT Platform
Because our sensing platform is made with polymeric materials, it is well-suited for use in wearable and/or lightweight sensing devices. To assess the potential of our sensors in human–machine interfaces and environmental monitoring, a PQT-12/C[8]A OFET sensor was fabricated with a wireless module and embedded in a wearable band. Fig. 6a provides an illustration showing the sensor design. Then, the chemical sensing abilities of wearable device were assessed as a function of $R_s$. Fig. 6b shows the relative variation in PQT-12/C[8]A OFET on-current in response to 100 ppm ethanol at $R_s$ down to 0.5 mm. While the off-currents of OFET-based sensors were independent of $R_s$, on-currents decreased with decreasing $R_s$ because of constraint of transporting h+.

Then a PQT-12/C[8]A OFET was incorporated into a simple chemical sensor Internet of Things (IoT) platform on a flexible plastic substrate (PET) (Fig. 6c) with a customized sensing board with an mA current read (operating voltage: $V_{DS} = -5$ V and $V_{DS} = -10$) and a custom-made Bluetooth module. An as-prepared PQT-12/C[8]A-based sensor was connected to a wireless board using copper cables and tape. Real-time exposure of the device to ethanol vapor yielded well-resolved signals on a smartphone screen through a customized user interface. As shown in Fig. 6d, the normalized OFET current decreased linearly with decreasing ethanol concentration.

Conclusions
PQT-12 NF-based OFETs incorporating calixarene container molecules (C[8]A) were fabricated in the order of gate electrode, dielectric, S/D electrodes, and electrospun PQT-12/C[8]A NFs as an active channel. The resulting PQT-12/C[8]A OFETs showed remarkable chemical sensitivity with reasonable flexibility. Sensor response increased with increasing analyte concentrations from 10 to 100 ppm, with an MDL of approximately 10 ppm VOC when operated at $V_{DS}$ and $V_{DS} = -100$ V. Incorporating C[8]A into the active layer drastically increased the sensitivity and selectivity of the sensor for ethanol (ca. 192%) and toluene (ca. 229%) and afforded a moderate improvement in sensitivity for n-hexane (ca. 121%). The PQT-12/C[8]A OFETs were electronically stable and maintained an on-current retention of up to 86.96% (±0.19%) at $R_s$ as small as 0.5 mm. This report also details a facile process for fabricating practical sensors for use in IoT platforms and demonstrated this process with a wearable, wireless device for monitoring ambient VOCs. The developed method represents a new route for fabricating polymer-based, high-performance OFET sensors with mechanical flexibility and operational stability. The sensing platform described herein is suitable for a wide range of applications in biomedical diagnostics and environmental monitoring and is a promising candidate for the fabrication of low-cost flexible circuits and wearable electronics.

Conflicts of interest
There are no conflicts to declare.

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References
Electrospun semiconducting polymer nanofibers functionalized with specific container molecules have been used for flexible and high-performance chemical sensors.