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Vacuum Pressure Leads to An Organic Molecular Electronic Response

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ABSTRACT

N,N’bis(n-octyl)-1,6-dicyanoperylene-3,4:9,10-bis(dicarboximide) (PDI8-CN2) organic thin film transistors (OTFTs) was found to exhibit a remarkable change of electrical conductivity when characterized under vacuum pressure in the range from 70 Pa (low vacuum) to 100 KPa (atmosphere). A similar phenomenon was also observed on Pentacene-based OTFTs but not on two dimensional layered MoS$_2$ TFTs. The mechanism to interpret a vacuum pressure response of organic thin film transistors is assumed to be the miniscule change of intermolecular distances under applied pressures. The values of variation of intermolecular distances are theoretically calculated based on a hopping model of the Marcus transfer rate. In addition, the Young’s modulus of PDI8-CN2 thin film evaluated through this model agrees well with the experimental values measured by atomic force microscopy (AFM) characterization using a Peakforce Quantitative NanoMechanics (QNM) mode.

INTRODUCTION

Organic semiconductor materials possess the advantages of soluble-processability, low weight, mechanical flexibility and as well as abundance with numerous varieties, which have broad application prospects, such as the fabrication of large-area photovoltaic devices, flat panel displays, flexible electronic skin and sensors.$^{1-4}$ Especially, since organic molecules are bonded by the weak van der Waals force, the molecular structure is readily sensitive to external conditions. Namely, the intrinsic properties of carrier charge transport in organic semiconductors are strongly dependent on the solid structure,
such as intermolecular distance and molecular stacking. To our knowledge, pressure has an important impact on the electrical performance of organic transistors, such as mobility, drain current and threshold voltage. Recently, the influence of hydrostatic pressure on the charge transport properties and molecular structure of organic single crystal transistors has been widely studied. With applied high pressure, the intermolecular distance decreases and transfer integral increases. Consequently, the mobility increases under applied pressure. Moreover, the pressure can also affect the band gap and phase transition. Hence, pressure is a favorable tool to explore the correlation between the crystal structure and charge transport properties. Kadali et al. have investigated the influence of hydrostatic pressure (up to 10 GPa) on the charge transport properties of 2, 6-diphenylanthracene (2, 6-DPA). They found the lattice constants $a$, $b$ and $c$ under high pressure decreased by 5.23%, 17.26% and 11.34% through density functional theory (DFT) calculations. In addition, a decrease of band gap and increase of mobility were also predicted. Stefano et al. have investigated the reversible phase transition of rubrene single crystals under a pressure range from ambient pressure to 7.1 GPa. Besides, Landi et al. investigated the experimental variation of charge carrier mobility with strain in the three prototypical materials indicating that intrinsic electro-mechanical response of the materials varies by orders of magnitude within the class of organic semiconductors. However, the pressure-dependent mobility obtained in these studies was based only on theoretical calculations under extremely high pressure and the experimental results regarding the electrical performance of organic transistors affected by environment pressure was seldom
reported yet. Specifically, it is demanding to obtain the influence of ambient pressure on the molecular structure under atmospheric pressure range, and it is of great significance to deepen our understanding of the relation between crystal structure and charge carrier transport and to develop new characteristic method to acquire the Young’s modulus of soft materials.

N,N’bis(n-octyl)-1,6-dicyanoperylene-3,4:9,10-bis(dicarboximide)(PDI8-CN2) is a derivative of Perylene Diimides, which is one of the most interesting n-type semiconductor materials due to its air stability arising from the two cyano groups attached to the aromatic core \(^{11,12}\) and good mobility of around 0.1 cm\(^2/\) (Vs). \(^{13-15}\) In this paper, we reported on the fabrication and electric response to pressure in the range from low vacuum (70 Pa) to one atmosphere (100 KPa) of PDI8-CN2, other organic and inorganic 2D thin film transistors. The change of drain current of OTFTs was confirmed by reversibly changing the pressure. Especially, to clarify the mechanism of pressure response of PDI8-CN2 field-effect transistors, Marcus transfer theory based on a hopping model was adopted. In addition, by analyzing the pressure-dependent intermolecular distance, the Young’s modulus of PDI8-CN2 thin film was also calculated and compared with experimental measurement using an Atomic Force Microscopy (AFM) technique.

**METHODS**

**Device Fabrication and Characterization**

In the fabrication of the PDI8-CN2 OTFT devices, heavily n-doped silicon wafers with a thermally grown layer SiO\(_2\) of 300 nm thickness were employed as substrates.
Before the deposition of the organic layer, the substrates were cleaned in the ultrasonic baths of acetone, ethanol, H2O, and NH4OH (NH3:H2O=1:6) sequentially, the surface modification layer (PS, HMDS, OTS) was applied. Polystyrene with a molecular weight of 100000 was dissolved into toluene to form a polystyrene solution with concentration of 0.5%. The PS modified layer was spin coated onto the silicon substrate with a rotation speed of 6000 rpm for 1 minute. Hexamethyldisilazane and Octadecyltrichlorosilane modified layers were fabricated using self-assembly. The substrate was exposed to HMDS/OTS vapor for 2 h at a temperature of 200 °C. The PDI8-CN2 thin film with 30 nm thickness was deposition by vacuum thermal evaporation (Edwards Co. Auto-306) with a deposited rate of 1nm/min at the specific substrate temperature (Td). Gold electrodes with 50 nm thickness was evaporated on the PDI8-CN2 thin film as metal electrodes using a shadow mask with channel length L=30 μm and width W=210 μm. Similarly, pentacene thin film of 50 nm thickness was deposited on the cleaned substrate by vacuum thermal evaporation. The large area single layer of molybdenum disulfide (MoS2) was fabricated by transfer method using an adhesive-strained metallic layer. The electrical performance of OTFTs including the transfer curves and output curves was measured using a Keithley 4200 system.

The morphology of the thin film was characterized by Bruke multimode-8 AFM at ScanAsyst Mode. The Young’s modulus of PDI8-CN2 thin film was measured by Bruker multimode-8 AFM in Peakforce QNM mode. The spring constant and radius of the used cantilever (type RFESP) were 3 N/m and 10 nm, respectively. Before mechanical mapping on the surface of PDI8-CN2 thin film, the cantilever was
calibrated using a standard sapphire sample. During the scanning of the PDI8-CN2 film by AFM, the Young’ modulus image acquisition failed because of high adhesion force and static electricity on the thin film surface. To avoid these, a PDI8-CN2 film with 300 nm thickness was evaporated with on a highly doped silicon wafer without insulating layers for the measurement of Young’s modulus.

**Vacuum Pressure Sensing**

To test the pressure sensing property, the drain voltage and gate voltage of OFETs were biased at certain value. The drain current was recorded by Keithley 4200 system while the pressure was varied from 70 Pa to 100 KPa. The devices were put on the probe station in a sealed chamber equipped with vacuum pump. To change the pressure, the chamber was pumped off to 70 Pa firstly, and N₂ was purged into the chamber up to 1 atm, then the N₂ in the chamber was pumped off under 70 Pa and purged into the chamber up to 1 atm again. Repeating this process, the drain current of OFETs was detected as the response signal to pressure.
RESULTS AND DISCUSSION

Optimization of PDI8-CN2 Organic Thin Film Transistors (OTFTs)

For preparation of organic thin film transistors, two kinds of molecular materials are selected. One is n-type organic material PDI8-CN2 which can conduct electron with typical mobility around $10^{-3} \sim 10^{-1}$ cm$^2$/Vs under various conditions. The other kind of molecule is p-type organic material pentacene which is ordinarily used for gas sensing and other electronic applications. Film quality and the device performance are routinely optimized for these two kinds of molecular thin film transistors, respectively.

For the PDI8-CN2, a systematical optimization including the substrate heating and surface modification was performed. The electrical curves of PDI8-CN2 organic thin film transistors modified by different modified layers are shown in the Figure 1. The transfer curves of PDI8-CN2 thin film transistors under different substrate modified layers with substrate heating temperature of 90°C in the Figure 1(a). The drain voltage is 60 V, and the gate voltage sweeps from -10 V to 60 V. It can be seen from the transfer curves that PS and HDMS modified layers showed a better effect on the nucleation and
growth of PDI8-CN2 organic small molecules. In addition, the output curves of PDI8-CN2 OFETs are also shown in the Figure 1(b) which reflect the main electrical feature of these devices.

The device results are summarized in the Table 1 with the maximum mobility of 0.064 cm²/(Vs) (Optimization process refers to Supplementary Note 1 in the Supporting Information (SI)). The top-contact bottom-gate device configuration was used for the OTFTs which is shown in Figure 2(a). Besides, inorganic thin film transistor-MoS₂ TFTs was also prepared for the vacuum pressure response test.

<table>
<thead>
<tr>
<th>Modified layer</th>
<th>Mobility (cm²/(Vs))</th>
<th>Threshold Voltage (V)</th>
<th>On/OFF ration</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.005</td>
<td>14</td>
<td>10⁶</td>
</tr>
<tr>
<td>OTS</td>
<td>0.018</td>
<td>-10</td>
<td>10⁶</td>
</tr>
<tr>
<td>PS</td>
<td>0.056</td>
<td>0</td>
<td>10⁶</td>
</tr>
<tr>
<td>HMDS</td>
<td>0.064</td>
<td>4</td>
<td>10⁶</td>
</tr>
</tbody>
</table>

**Table 1** The electric performance parameters of PDI8-CN2 FETs under different modified layers at 90 °C substrate heating

**Pressure Response of Organic Field-Effect Transistors (OFETs)**

The pressure response for three kinds of TFTs was investigated in a home-made gas sensing chamber described as previously. The optimized PDI8-CN2 devices were loaded in a chamber equipped with vacuum pump and electrical characterization system.
(Keithley 4200) (Figure. S1 in the SI). The chamber pressure was controlled by injecting and pumping off the inert gases, mainly nitrogen and argon. The electrical signal was monitored when the pressure was varied with the range from 70 Pa to 100 KPa (one atmosphere) as indicated in Figure 2. The response sensitivity (S) defined as in the following equation (1) was recorded for PDI8-CN2 and Pentacene OTFTs-based pressure sensors:

\[
S = \frac{\Delta I}{I_0 \Delta P}
\]

where \(I_0\) is the initial drain current at 100 KPa while \(\Delta I\) is the change of current and \(\Delta P\) is the change of pressure. The Gate voltage for PDI8-CN2 OTFTs was 15 V and the drain voltage was 5 V. We found the response sensitivity depended very little on the choice of gate and drain bias conditions within a large range of values (As evidenced in Figure. S2 in the SI). Figure 2(b) showed the drain current of PDI8-CN2 OFETs in nitrogen atmosphere varied with the change of pressure repeatedly and reversibly. The drain current decreased immediately once the pressure was reduced, and increased rapidly when pressure was increased to one atmosphere. The relative change in drain current corresponded to 5.0% with background fluctuation of less than 0.5%. This corresponds to a response sensitivity with \(5 \times 10^{-4}\) KPa\(^{-1}\). In addition, there was an overall decline in drain current which was probably due to the bias stress effect in organic OTFTs.
Figure 2 (a) The device structure of PDI8-CN2 OFET (b) The pressure response of PDI8-CN2 OFETs. (c) The pressure response of Pentacene OFETs. (d) The contrast diagram of drain current of Pentacene OFETs under pressure response and gas response (green line represents gas response; red dash part represents pressure response).

The drain current response to argon was also investigated to demonstrate that this is a true pressure response and not a response to a specific gas. By introducing and pumping off with nitrogen and argon alternately within pressure ranged from 70 Pa to 50 KPa, the drain current exhibited similar response to the pressure for both nitrogen and argon atmosphere as shown in Figure 3(a). The response sensitivity to pressure under argon was $2.66 \times 10^{-4}$ KPa$^{-1}$ while the response sensitivity under nitrogen was $2.12 \times 10^{-4}$ KPa$^{-1}$. In addition, the device also showed similar pressure response in the atmosphere of air as evidenced in Figure 3(b). Therefore, the response of drain current was attributed to gas pressure and not the specific gas.

To investigate if this influence of pressure changes was also observed with other organic semiconductors, Pentacene OFETs were also fabricated and analyzed (Figure 4).
The gate voltage was biased at 0 V and drain voltage was biased at -1 V. Figure 2(c) illustrated that the drain current in Pentacene OTFTs reversibly changed when the pressure was varied in the range between 70 Pa and 100 KPa. This was consistent with results of PDI8-CN2 OTFTs. The relative change of the drain current was 9.1\% with a background fluctuation about 0.7\%. This gave a sensitivity of Pentacene OTFTs of $9.1 \times 10^{-4}$ KPa$^{-1}$. Same as PDI8-CN2, Pentacene OFETs showed similar pressure response for both nitrogen and argon. In addition, there was an overall increase in drain current which was can be attributed the same reason as that of PDI8-CN2. Pentacene is an ideal material for gas sensing, and it has been widely applied as gas sensor to detect toxic gases, such as NH$_3$, NO$_2$ and H$_2$S.$^{19-21}$ To compare the ‘gas response’ and ‘pressure response’ of Pentacene thin film transistor, the drain current was continuously recorded while the pressure was varied in the range from 70 Pa to 100 KPa as well as the injection of ammonia gas with 100 ppm (Figure 2(d)). The green line part represented gas response while the part emphasized by red box with dash line represented pressure response. The average change rate of drain current ($\Delta I/I_0$) was 18.6\% and 9.1\% for gas sensing and pressure response, respectively, which indicated that the pressure and gas response can be distinguished within one OFET device at the same time.

Apart from the organic semiconductor devices, inorganic transistors were also fabricated to explore the influence of pressure. A large area single layer of molybdenum disulfide (MoS$_2$) was fabricated by the transfer method using an adhesive-strained metallic layer.$^{22}$ The transfer curve of MoS$_2$ transistors (Figure S3(a) in the SI) showed
a mobility of 1.77 cm²/(Vs) and on/off ratio of 10⁷. The pressure response measurements were shown in Figure S3(b) in the SI. The drain current kept constant during the pressure variation within the measurement uncertainty, which confirmed that MoS₂ transistors had no response to pressure.

Many factors might influence the drain current delicately, such as electrode contact. We have explored the output curves of PDI8-CN2 OFETs under 70 Pa and 100 KPa, respectively, as indicated in Figure S4 in the SI. It is obvious that during the changing of vacuum pressure the Ohmic contacts are kept steadily, indicating the change of drain current does not originate from the contact issue.

![Figure 3](image_url)  
**Figure 3** The vacuum pressure response of PDI8-CN2 OFETs under (a) Ar and N₂, (b) under air atmosphere.

**Analysis of Gas Pressure Sensing Mechanism**

Since holes transport as band-like behavior in most Pentance films, we here focus only on the low mobility material PDI8-CN2 using a Marcus hopping model. In order to further understand the pressure response mechanism, a semi-quantitative calculation was applied to figure out the relationship between pressure, intermolecular distance and mobility. The Marcus transfer rate based on hopping transport gives the equation (2) of mobility when the electric field is close to zero.
\[
\mu = \frac{q}{k_B T \hbar} \left( \frac{\pi}{4E_a k_B T} \right)^{\frac{1}{2}} \exp \left( -\frac{E_a}{k_B T} \right) t^2 d^2
\]  
(2)

Where \(\mu\) is mobility, \(q\) is the elementary charge, \(K_B\) is Boltzmann’s constant, \(T\) is the absolute temperature, \(E_a\) is the reorganization energy, \(\hbar\) is the reduced Planck constant, \(t\) is the intermolecular transfer integral, and \(d\) is the effective hopping distance. To simplify the calculation, we assume the transfer integral decays exponentially with hopping distance\(^{26}\)

\[
t \propto \exp(-2\alpha d)
\]  
(3)

Where \(\alpha\) is inverse localized length. We therefore got

\[
\mu = g \exp(-4\alpha d) d^2
\]  
(4)

Where \(g\) is unknown constant. By rewriting equation (4), the relationship between the variation of mobility \((\Delta\mu/\mu)\) and hopping distance \((\Delta d/d)\) can be obtained. As we know the drain current is proportional to the mobility, therefore

\[
\frac{\Delta I}{I} = \frac{\Delta d}{d}(2 - 4\alpha d)
\]  
(5)

From the experimental results, Figure 2(b) showed a change of current \(\Delta I/I_0\) of 5% as the pressure changed from 70 Pa to 100 KPa. The structure of PDI8-CN2 thin film was reported triclinic unit cell with parameters of \(a=9.399, b=5.028, c=20.57\) Å.\(^{27}\) For simplification, the middle lattice constant 9.4 Å of PDI8-CN2 was chosen to be equivalent to hopping distance in our theoretical calculation. In general, the inverse localized length \(\alpha\) was reported to be the order of \(10^{10}\) m\(^{-1}\).\(^{26}\) Using equation (5), this corresponds to the variation of intermolecular distance \(\Delta d/d\) of \(1.4 \times 10^{-3}\). If one instead uses the Bohr radius of 0.053 nm as the minimum limit localized length,\(^{28}\) the corresponding \(\Delta d/d\) was \(7.3 \times 10^{-4}\).
Estimation of Young’s Modulus of PDI8-CN2 Film

The shortening and elongation of the intermolecular distance in the organic thin film during pressurization and decompression was schematically indicated in Table of Contents Image (TOC). According to above simple model, the change in intermolecular distance is associated with the change of drain current of PDI8-CN2 OFETs. Refer to Young’s modulus definition in the mechanics of materials:

\[ E = \frac{\sigma}{\varepsilon} = \frac{F/S}{\Delta d/d} \]  

Where \( E \) is young’s modulus, \( \sigma \) is stress, \( \varepsilon \) is strain.

Applying the calculation of Young's modulus equation (6) to the pressure response of PDI8-CN2 thin film, the \( \sigma \) corresponds to the pressure change \( \Delta P \), \( \varepsilon \) corresponds the change of hopping distance \( \Delta d/d \). The Young’s modulus of PDI8-CN2 organic thin film was evaluated as

\[ E = \frac{\Delta P}{\Delta d/d} = \frac{\Delta P(2-4\alpha d)}{\Delta l/l} \]  

Applied the varied pressure of 100 KPa and the relative change of hopping distance in the range of \( 7.3 \times 10^{-4} \) to \( 1.4 \times 10^{-3} \), the Young’s modulus \( E \) of PDI8-CN2 thin film could be evaluated to be in the range of 71 MPa to 138 MPa. The evaluation of Young’s modulus in organic thin film opened a path for the rough estimation of Young’s modulus, since the Young’s modulus of thin film of soft materials is very difficult to measure through experimental characterization (Refers to Supplementary Note 2 in the SI). To verify the results of of theoretical calculation, we carried out measurements of Young’s modulus for PDI8-CN2 thin film by Peakforce Quantitative NanoMechanics (QNM) mode of AFM.

A PDI8-CN2 film with thickness of 300 nm was prepared by vacuum thermal
evaporation on a highly doped silicon wafer without insulating layers. The high doping
density ensured that noise arising from static electricity on the surface of the film was
not present. In addition, the thick film of several hundred nanometers prevented the
Young’s modulus measurement from being affected by the substrate. The morphology
and Young’s modulus images with scanning area of 2 μm×2 μm and digital resolution
of 256 pixels×256 pixels were showed in Figure 4. The peak force was 9.82 nN and the
average indentation depth was 20 nm. The average DMT Young’s modulus was 400 (±
200) MPa. However, the Young’s modulus obtained by AFM has been reported to be
overestimated when the tip is sharp. In combination with the experimental conditions,
the tip radius of 10 nm was rather sharp, so the measured Young's modulus might be
higher than the practical modulus. Therefore, the Young's modulus of PDI8-CN2 film
was found to be quite close to the theoretical calculation, which supports our theoretical
estimation.

![Figure 4](image)

**Figure 4** Representative maps of morphology and Young’s modulus of PDI8-CN2 film (300 nm) By the Peakforce Quantitative NanoMechanics (QNM) mode of AFM. (a) peak force error image, (b) DMT modulus image, (c) AFM topography

It should be noted that the crystal structure is a key factor to influence the drain
current when we deal with the evaluation procedure. Compared with the MoS₂ film of
single crystal, PDI8-CN2 and Pentacene film formed polycrystalline films. Hence, lattice distortion and grain boundary should also be considered in the above evaluation. However, the strict consideration containing this detailed information is beyond the extent of this article and perhaps will be continuously performed in the future. As a first primary quantitative calculation we propose that, the present method has provided enough sufficient results.

**CONCLUSIONS**

In conclusion, PDI8-CN2 and Pentacene OFETs were fabricated and optimized using substrate heating and modification method. The reversible vacuum pressure response of PDI8-CN2 and Pentacene OFETs were observed and their response sensitivities were found to be $5.0 \times 10^{-4}$ KPa$^{-1}$ and $9.1 \times 10^{-4}$ KPa$^{-1}$, respectively. The response mechanism of intrinsic organic thin films to pressure was attributed to the change of intermolecular distance under applied pressure. Through theoretical calculations, the variation of intermolecular distance ($\Delta d/d$) under pressure changing within 100 KPa was estimated in PDI8-CN2, which was in the range of $7.3 \times 10^{-4}$ to $1.4 \times 10^{-3}$. Based on this, the corresponding Young’s modulus for PDI8-CN2 organic thin film was estimated to be in the range of 71 MPa to 138 MPa, which is in relatively good agreement with practical AFM measurement of Young’s modulus. This work gives experimental evidence for the influence of atmosphere pressure on the electric performance of OTFTs, which deepens our understanding about the relationship between the electric performance and crystal structure. In addition, it also provides a feasible evaluation method for Young’s modulus evaluation of soft molecular thin films.
ASSOCIATED CONTENT

Supporting Information

The optimization of PDI8-CN2 organic thin film transistor, The photographs of optimized PDI8-CN2 devices, The vacuum pressure response of PDI8-CN2 FETs, The pressure-dependent output curve of PDI8-CN2 OFETs under different gate voltage, The vacuum pressure response of PDI8-CN2 OFETs, Electrical performance characterization and pressure response of MoS2 inorganic thin film transistors, and characteristic technology of Young’s modulus.

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REFERENCES


SUPPORTING INFORMATION

Vacuum Pressure Leads to An Organic Molecular Electronic Response

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Supplementary Note 1. The optimization of PDI8-CN2 organic thin film transistor

In order to improve the electrical performance of PDI8-CN2 organic thin film transistors, we optimized devices through substrate heating and surface modification.

For substrate heating, six growth temperatures were designed to choose the most favorable conditions for nucleation and growth of small organic molecules, which were 25 °C, 50 °C, 70 °C, 90 °C, 110 °C, 130 °C. The polystyrene (PS) films as modified layer was prepared by solution spin coating, and the PDI8-CN2 films was deposited by vacuum thermal evaporation with 30 nm. The gold electrode was evaporated with 50 nm. Through the measurement of electrical performance, the device with growth temperature 90 °C showed the best mobility. Therefore, the substrate heating temperature of 90 °C is used in the subsequent substrate modification experiments.

For substrate modification, it is important to choose the modified layers to reduce the influence of the hydroxyl groups on the surface of silicon dioxide on the charge transport of carriers and to improve the surface roughness. We use three kinds of organic materials which are polystyrene (PS), hexamethyldisilane (HMDS) and octadecyltrichlorosilane (OTS) to modify the substrate surface. The PS with a sub-weight of 100,000 is dissolved in toluene solution to obtain the PS solution with the concentrate of 0.5%. Then the modified PS film was prepared on the surface of silicon dioxide by the method of solution spinning at the speed of 6000 rpm for 1 min. Besides, HMDS and OTS are prepared as self-assembled modified layer by vacuum vapor method. We exposed the clean silicon wafers to the vapor of HMDS and OTS for 2 hours, and keep the chamber temperature to 200 °C. After modification, organic thin film with growth thickness of 30 nm was evaporated with the substrate heating at 90 °C. And gold electrode of 50 nm is deposited by vacuum thermal evaporation.
Figure S1  The photographs of optimized PDI8-CN2 devices which loaded in a chamber equipped with vacuum pump. (a) Photograph of PDI8-CN2 OFETs on PCB board, (b) Photograph of PDI8-CN2 OFETs connecting with vacuum pressure chamber.

Figure S2  The vacuum pressure response of PDI8-CN2 FETs under different gate voltage and drain voltage. (a) Gate Voltage=3 V, DrainVoltage=1 V, (b) Gate Voltage = 15V, DrainVoltage = 5 V.
Figure S3  Electrical performance characterization and pressure response of MoS$_2$ inorganic thin film transistors. (a) Transfer curve of MoS$_2$ inorganic thin film transistors, (b) vacumn pressure response curve of MoS$_2$ inorganic thin film transistors.

Figure S4 The pressure-dependent output curve of PDI8-CN2 OFETs under different gate voltage. (a) the pressure=70 Pa, and (b) the pressure=100 KPa.
Supplementary Note 2. Characteristic technology of Young’s modulus

The measurement of Young’s modulus of soft materials has always been a challenge because of their fragile structure and high adhesion force. In general, the techniques used in Young’s modulus measurement consist of dynamic mechanical analyzer (DMA), Nanoindenter and atomic force microscopy (AFM). DMA method which measures the Young’s modulus of bulk materials by applying load to stretch materials is hard applicable for the materials in micron and nano scale.\textsuperscript{1-2} It is conventionally preferred to evaluate the rigid materials for its Young’s modulus by using Nanoindenter, while AFM is more convenient to measure soft materials with high accuracy as it can detect with very tiny force (< 0.1 nN) and indentation depth (< 1 nm).\textsuperscript{3} Nevertheless, with the existing of large adhesion force and the complex substrate effect, AFM approach obtains low resolution images and thus leads to a large measurement error in most of the soft materials. Therefore, it is of great significance for the Young’s modulus of soft materials to create a characteristic method.
Supporting Reference

