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REVIEW

Effect of contact resistance in organic field-effect transistors

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Abstract

Contact resistance ($R_C$) is universally present in organic field-effect transistors (OFETs) and the performance of OFETs can be easily affected by $R_C$, which will result in poor performances such as low mobility ($\mu$), large threshold voltage ($V_T$), and non-ideal transfer/output characteristics. In this article, we provide a comprehensive review on the effects of $R_C$ in OFETs. We start with a brief introduction of the origin of $R_C$ and its effects on OFETs, followed by the commonly used methods for extraction of $R_C$. Then, methods for reducing $R_C$ are thoroughly discussed. Especially, fabricating monolayer molecular crystal (MMC) OFETs is highlighted as one of the key solutions to reduce $R_C$ effectively. The final section describes the challenges in MMCs preparation and concludes with an outlook for further reducing $R_C$ to enhance the performances of OFETs.

KEYWORDS
contact resistances, monolayer molecular crystals, organic field-effect transistors

1 | INTRODUCTION

Organic field-effect transistors (OFETs) based on organic semiconductors (OSCs) have attracted widespread attention for the potential applications in flexible and wearable optoelectronics.[1–11] Although OFETs have many advantages,[12–19] such as flexibility and possibility to be fabricated with a variety of materials in low cost, there are still many unresolved problems that hinder their successful introduction into the commercial market. Contact resistance ($R_C$) is one of the important problems seriously affecting the device performances and ideality of electrical characteristics in OFETs.[20–22] Ideally, Ohmic contacts are required in OFETs for proper operation. However, in most real situations, the injection of charge carriers from the source contacts into OSCs is non-Ohmic because of the mismatch between the orbital energy levels (highest occupied molecular orbital [HOMO] or lowest
unoccupied molecular orbital (LUMO) of OSCs and work function (WF) of source-drain electrodes, which causes significant injection resistance ($R_{\text{Inj}}$). The process of charge carriers transporting from the metal/OSC interface to channel (namely bulk resistance, $R_{\text{Bulk}}$) also contributes to $R_C$. For solution-processed OFETs, the reported common values of $R_C$ are $\sim 10$ kΩ cm up to date. These $R_C$ values are remarkable considering that the $R_C$ of Si metal-oxide-semiconductor field-effect transistors (MOSFETs) generally is less than 0.1 Ω cm. Therefore, the device performances are expected to be significantly enhanced if $R_C$ can be reduced or removed.

The effect of $R_C$ in OFETs not only limits device performance; it also extends to our proper understanding of the electronic performance and device physics of OFETs. In this review, we provide a comprehensive review about the $R_C$ in OFETs. We firstly discuss the origin and the corresponding effects of $R_C$ in OFETs. Following that we introduce the widely used methods for assessing $R_C$. Then we summarize the various methods employed for reducing $R_C$ in OFETs. Finally, the advantages of MMC OFETs in reducing $R_C$ are provided, and the challenges and perspectives of the development of MMC OFETs are discussed.

### 2 ORIGIN AND EFFECTS OF $R_C$ IN OFETs

#### 2.1 Origin of $R_C$ in OFETs

When there is a Schottky barrier (SB) formed at the metal/semiconductor interface, charge injection can be realized in two ways: thermionic emission and field emission (tunneling), which are shown in the energy diagrams Figure 1A and 1B, respectively (taking p-type OSCs as examples). In OFETs, charge is injected from the source electrode and transported to the drain electrode through the channel. The metal/semiconductor contacts at the source and drain electrodes are generally two back-to-back Schottky contacts. The source contact is reverse-biased and dominates the behavior of transistors. The current density injected through a reverse-biased SB is:

$$J = A^* T^\alpha \exp\left(-\frac{-q\Phi_B}{k_B T}\right) \left[1 - \exp\left(-\frac{-qV}{k_B T}\right)\right]$$  \hspace{1cm} (1)

where $A^*$ is the Richardson constant, $T$ is the temperature, $\alpha$ is an exponent parameter, $q$ is the electronic charge, $\Phi_B$ is the Schottky barrier height (SBH), and $k_B$ is the Boltzmann constant. For operating OFETs, there usually is $qV >> k_B T$, so Equation (1) can be simplified to:

$$J = A^* T^\alpha \exp\left(-\frac{-q\Phi_B}{k_B T}\right)$$  \hspace{1cm} (2)

According to Equation (2), SBH is the dominant factor restricting currents at the semiconductor-electrode interfaces in OFETs. This causes $R_{\text{Inj}}$ which is the most important component of $R_C$ in OFETs. Apparently, $R_{\text{Inj}}$ originates from the mismatch between the orbital energy levels of OSCs and WF of source-drain electrodes. Therefore, reducing SBH or realizing Ohmic contact is essential to realize high mobility, low voltage driving, and high frequency operating devices.

In conventional bulk OFETs, total resistance includes three components: $R_{\text{Inj}}$, $R_{\text{Bulk}}$, and $R_{\text{Ch}}$, as shown in Figure 2. Among them, $R_{\text{Ch}}$ is determined by the nature of semiconductors. $R_{\text{Inj}}$ originates from the mismatch between the orbital energy levels of semiconductors and WF of source-drain electrodes. $R_{\text{Bulk}}$ is caused by the charge carriers transporting process from the metal/OSC interface to channel. $R_{\text{Inj}}$ and $R_{\text{Bulk}}$ together constitute $R_C$. In real devices, the values of $R_C$ are also dependent on the device structure. For instance, in the case of bottom-gate (BG) thin film transistors (TFTs), the semiconductor layer in the top-contact (TC) structure is grown uniformly on the dielectric surface, while the morphology of the semiconductor layer is inhomogeneous since it is grown on both the dielectric and source-drain electrodes substrates in the bottom-contact (BC) structure. In addition, the source-drain electrodes would partly screen the gate filed in the BC structure compared with the TC structure. Therefore, BC configuration usually shows or is
predicted to have higher $R_C$ than TC configuration due to the weaker gate field-assisted charge injection and poorer thin-film morphology at the edges of the contacts. The decrease of $R_{ij}$ and $R_{bulk}$ generally exists simultaneously, but the contribution of the two is not distinguished. In addition, the effect of $R_C$ in short channel devices is more obvious due to its domination over $R_{Ch}$.\[^{26–28}\]

According to the components of resistance in OFETs, various methods have been proposed to extract $R_C$, and simultaneously lots of methods have been employed to reduce $R_C$ to improve the performance of OFETs. The importance of reducing $R_C$ in OFETs not only relies on the realization of low driving voltages for optoelectronic devices, but also on low energy consumption.\[^{29}\] Moreover, reducing $R_C$ is helpful for characterizing the intrinsic performance of the OSCs, which is especially critical for understanding the charge transport mechanisms.\[^{30–32}\]

## 2.2 Effects of $R_C$ in OFETs

$R_C$ is a complex issue in OFETs and its values as well as its effect on OFETs have been found to vary with the specific situations, depending on the materials, device architectures and processing methods. As a well-known fact, the parameters of OFETs such as mobility ($\mu$) and threshold voltage ($V_T$) can be easily affected by $R_C$.\[^{33–36}\] Moreover, $R_C$ can have profound effects on the electrical characteristics of OFETs. Thus, it is essential to have a deeper understanding of the properties of $R_C$ and its effects on OFETs.

On one hand, $R_C$ is known to be gate-dependent, which was experimentally characterized by Hu et al. using scanning Kelvin probe microscopy (SKPM).\[^{37}\] This gate-dependence of $R_C$ affects the shape of the transfer characteristics. For instance, the “double-slope” feature has been frequently observed in OFETs, which is considered as a sign of overestimation of mobility and has aroused widespread concern and interest in the OFET community.\[^{38–40}\] Early in 2014, Sirringhaus et al. pointed out that one possible explanation for “double-slope” effect is due to $R_C$, namely the conductivity of the accumulation layer increases when the gate voltages is high enough, and thus the current becomes contact-dominated.\[^{41}\] Bittle et al. extracted the gate dependence of $R_C$ and $R_{Ch}$ from the impedance spectroscopy data in combination with modeling, and showed that “double-slope” effect appears when the gate dependence of $R_C$ is much stronger than that of $R_{Ch}$, which results in overestimation of mobility when only the $I_d$-$V_{gg}$ characteristic at low $V_g$ is considered (Figure 3A, B).\[^{34}\] Furthermore, Hu et al. directly extracted and compared the gate-dependence of $R_C$ and $R_{Ch}$ using SKPM, and discussed their correlation with “double-slope” effect.\[^{37}\] In this case, compared with $R_{Ch}$, the gate dependence of $R_C$ is smaller and the “double-slope” feature was not observed in the transfer curve. As a result, the $R_C$ causes underestimation of the mobility (Figure 3C, D). Therefore, the gate-dependent $R_C$ may affect the values of extracted mobility and lead to improper evaluation of the intrinsic property of semiconductor. The “double-slope” effect in OFETs can be found in an excellent review by Bazan and Nguyen.\[^{35}\]

On the other hand, $R_C$ was also found to be temperature-dependent, and so it has influence on the temperature-dependent properties of OFETs. A few researches have been illustrated that $R_C$ is non-linearly dependent with temperatures\[^{30–32}\]. How the $R_C$ affects temperature-dependence of mobility is important to reveal the charge transport mechanisms of OSCs. As an example shown in Figure 4,\[^{32}\] $R_C$ was achieved by SKPM in operating C$_8$-BTBT OFETs and the influence of it on the temperature dependence of mobility was revealed. As shown in Figure 4C, if $R_C$ was not taken into account, the calculated linear mobility ($\mu_{lin}$) shows almost independence with temperature in the range of 240–300 K, indicating very weak band-like transport. However, when the effect of $R_C$ on mobility was taken into account, which leads to the corrected intrinsic mobility ($\mu_{int}$), it is actually seen that the $\mu_{int}$ increases obviously with decreasing temperatures, indicating a strong band-like transport. This study very well illustrates that the existence of $R_C$ would lead to a non-intrinsic temperature dependence of mobility and hinder the proper understanding of charge transport mechanism in OFETs.

To sum up, since $R_C$ is gate and temperature dependent, reducing $R_C$ is not only useful for achieving improved OFET performance, but also important for revealing the intrinsic characteristics of semiconductors and studying the charge transport mechanism in OFETs.

## 3 METHODS FOR EXTRACTION OF RC IN OFETS

There are many methods for extracting $R_C$ in OFETs. For example, transmission line method (TLM)\[^{42,43}\] Y-function method (YFM)\[^{44–48}\] gated four-point probe method (gFPP method)\[^{49–51}\] and SKPM \[^{37,52–58}\] are the most commonly used methods. Meanwhile some other methods for obtaining $R_C$ have been provided in certain cases.\[^{34,59–64}\] Here we mainly concentrate on the above-mentioned four methods.

### 3.1 TLM

The most widely used method to obtain $R_C$ in OFETs is the TLM, which was first proposed for amorphous silicon thin film transistors by Luan and Neudeck in 1992.\[^{65}\] When the space charge-limited conduction (SCLC) is neglected...
in FETs, the ON resistance, $R_{ON}$, in the linear regimes, can be expressed as follows:

$$R_{ON} = \frac{\partial V_d}{\partial I_d} \bigg|_{V_d=0} = R_{Ch} + R_C = \frac{L}{W \mu_i C_1 V_g - V_T} + R_C$$

(3)

where $R_{Ch}$ is the channel resistance, $W$ is the channel width, $L$ is the channel length, $C_1$ is the capacitance of the gate dielectric, $I_d$ is the drain current, $V_d$ is the drain voltage, $\mu_i$ is the intrinsic mobility, $V_g$ is the gate voltage, and $V_T$ is the intrinsic threshold voltage. $R_C$, which is associated with the contacts between source-drain electrode and semiconductor layer, can be extracted by measuring $R_{ON}$.
from the linear region of the OFETs output characteristics with different channel lengths and by plotting $R_{ON}W$ as a function of $L$. The intercept of the $R_{ON}W$ versus $L$ plot is exactly the $R_C W$.

However, the deviation of key parameters in OFETs, such as $\mu$ and $V_T$, severely affects the application of TLM. In TLM the main concern is the large deviation of the extracted $R_C$ values, especially when gate voltages are slightly low and the devices are only made with a few different channel lengths. Sometimes TLM cannot work due to the large dispersion of parameters. Take these issues into account, a modified TLM (M-TLM) was reported in 2010. Conventional TLM (C-TLM) can also be elaborated as follows:

$$R_{ON} \times W = (R_{Ch} + R_C) \times W = \frac{L}{\mu C_i (V_g - V_T)} + R_C \times W$$  \hspace{1cm} (4)

And M-TLM reads as follows:

$$\frac{R_{ON} \times W}{L} = \frac{1}{\mu C_i (V_g - V_T)} + (R_C \times W) \frac{1}{L}$$  \hspace{1cm} (5)

In Equation (3), the short of precision is because the slope has several parameters in the $R_{Ch}$ part. Based on Equation (5), when we draw $\frac{R_{Total} \times W}{L}$ relative to $1/L$, the slope is now dominated by the $R_C \times W$ part, which usually shows small changes between devices. So, the $R_C$ can be obtained more reliably since the slope which is less dispersive.

### 3.2 YFM

YFM is a method of extracting the parameters of Si MOSFETs proposed by Ghibaudo for the first time. Later, in 2010 the YFM was introduced into the BC and TC OFET configurations by the same group. Based on a direct analysis of the drain current $I_d$ in the linear region, it is a simpler and more powerful $R_C$ extraction method than the TLM. Considering that the additional potential drops at the contacts are caused by $R_C$, the transfer characteristics in the linear regime are

$$I_d = G_m V_d (V_g - V_T) / [1 + \theta (V_g - V_T)]$$  \hspace{1cm} (6)

Here,

$$G_m = (W/L) \mu_0 C_i$$  \hspace{1cm} (7)

is the transconductance parameter, where $\mu_0$ is the low-field mobility, $V_T$ is the threshold voltage, and $\theta$ is the mobility attenuation factor including $R_C$ contribution.

Assuming that $R_C$ is constant, the transconductance, $g_m$, can be obtained from Equation (6):

$$g_m = \frac{dI_d}{dV_g} = G_m V_d / [1 + \theta (V_g - V_T)]^2$$  \hspace{1cm} (9)

The $Y$ function is

$$Y = \frac{I_d}{\sqrt{g_m}} = \frac{\sqrt{WC_i \mu_0 V_d}}{L} \times (V_g - V_T)$$  \hspace{1cm} (10)

According to Equation (8), the $Y$ function is independent of $R_C$, and so $\mu_0$ and $V_T$ can be obtained. It is an important sign to assess the inherent property of OFETs. It can be seen that $\theta$ could be extracted by Equation (9) and $G_m$ could be extracted by Equation (6). Once $\theta$ and $G_m$ are known, the $R_C$ could be calculated by Equation (8). Note that if $R_C$ is almost independent with $V_g$, this method allows us to obtain the $R_C$ from a single transistor. The YFM allows for analysis of variable parameters of OFETs. Compared with the other methods presently used in OFETs, the simplicity of the method has great advantages. However, the assumption that $R_C$ is constant relative to $V_g$ limits its further application.

### 3.3 gFPP method

The gFPP adopts the bottom-gate top-contact (BGTC) or bottom-gate bottom-contact (BGBC) transistor architectures, and two additional “inductive” probes are evenly distributed in the channel, as shown in Figure 5. With the assumption that the potential is linearly distributed in the channel, the voltages of the inductive probes are allowed for calculation of the $R_C$. The potential drop at the source contact is

$$\Delta V_s = V_1 - \frac{V_2 - V_1}{L_2 - L_1} L_1 - V_s$$  \hspace{1cm} (11)

where $L_1$ and $L_2$ are the distances from the source electrode to the first and the second inductive probe, respectively, and $V_s$ is the potential at the source electrode, which is generally grounded ($V_s = 0$ V). So the potential drop at the drain contact is

$$\Delta V_d = V_d - \left( V_2 + \frac{V_2 - V_1}{L_2 - L_1} (L - L_2) \right)$$  \hspace{1cm} (12)
where $L$ is the channel length, and $V_d$ is the drain voltage. So the potential drop across the all conductive channel is

$$\Delta V_{ch} = \frac{V_2 - V_1}{L_2 - L_1} L$$  \hspace{1cm} (13)$$

which can be obtained by subtracting $\Delta V_s$ and $\Delta V_d$ from drain voltage. By using Ohm’s law, the resistance is:

$$R_i = \frac{\Delta V_i}{I_D}, \ i = s, d, Ch$$ \hspace{1cm} (14)$$

Note that superiority of the gFPP method is that it can obtain $R_s$ and $R_d$ separately, which is particularly helpful in the research of OFETs with different source and drain electrode materials.

### 3.4 SKPM method

Another method of measuring $R_C$ is using SKPM to probe the surface potential of a biased device across the channel. The drain current and the potential drop at the source-drain contacts can be obtained directly by this measurement, and so the $R_C$ can be easily obtained, with the corresponding equations $R_s = \frac{\Delta V_s}{I_d(V_g)}$ and $R_d = \frac{\Delta V_d}{I_d(V_g)}$. Different from other methods which are based on the assumption of linear channel voltages and linear increase of $R_{Ch}$ with the channel length, SKPM can extract $R_C$ and $R_{Ch}$ under any conditions. An example is shown in Figure 6, which shows a schematic of the SKPM measurement on a BGBC DPPT-TT device (Figure 6A). The potential distribution detected by SKPM under various gate voltages is shown in Figure 6B. It is clear that significant voltage drops at the source-drain contacts, and that the potential distribution are linear across the channel only at high gate voltages. Figure 6C and Figure 6D show potential drop and resistance at the source/drain contacts at different gate voltages, respectively. The results demonstrate that the $R_s$ and $R_d$ have different values and also very different gate dependence. The disadvantage of this method is that it can be used only in devices where the contacts and the channel are exposed to the SKPM tip, namely BG devices.

### 4 STRATEGIES FOR REDUCING R_C IN OFETS

As illustrated above, $R_C$ in OFETs includes two components, $R_{Inj}$ and $R_{Bulk}$, which are mainly determined by the energy barrier between energy levels of OSCs and WF
of source-drain electrodes, morphology of semiconductors as well as device configuration. The general guideline for reducing $R_C$ is to decrease the energy barriers between the WF of source-drain electrodes and the frontier orbital levels of semiconductors or decreasing $R_{\text{Bulk}}$. Various methods for reducing $R_C$ have been developed and can be classified as: (1) exploiting proper electrodes, (2) modifying electrodes with self-assembled monolayers (SAMs)/buffer layers or contact doping at source-drain electrodes/semiconductor interface, (3) passivating semiconductor/dielectric interface, (4) tailoring molecular structures or constructing monolayer molecular crystal (MCC) OFETs. Among them, the most facile way to decrease $R_C$ is to fabricate OFETs based on MCCs, in which $R_{\text{Bulk}}$ is directly eliminated without some other complex and tedious procedures. In the following parts, we will discuss these methods for reducing $R_C$ in detail.

### 4.1 Selection of proper electrodes

Metals with WF close to the HOMO of p-type semiconductors or LUMO of n-type semiconductors are usually adopted as the source-drain electrodes for better energy level alignments to reduce $R_{\text{Inj}}$. Gold electrode [70,71] is most widely used for charge injections. Other metals, such as silver, [72,73] aluminum, [74] copper, [75] and flexible transparent electrodes [76] are also usually used in OFETs. Gold is commonly used as electrodes because of its high WF and chemical stability, which matches the HOMO of p-type OSCs in most cases, thus lowering the $\Phi_B$. Moreover, we can change the WF of Au by O$_2$ plasma [77] and optimize crystallite morphology by O$_2$ plasma [78] UV/ozone [79,80] treatment or using nanopore-structure gold electrodes. [81] However, some organic materials have been employed to substitute Au and other metals as source-drain electrode materials in OFETs. For example, dinonylnaphthalene sulfonic acid doped polyaniline/single-walled carbon nanotube (DNNSA-PANI/SWNT) electrode [82] can result in large grain size of pentacene in contact area; Multi-walled carbon nanotubes silver nanoparticles (Ag-MWNT) electrode [83] has better contact and energy alignment at the electrode/semiconductor interface for poly(3hexylthiophene) (P3HT) semiconductor; (Tetrathiafulvalene) (tetra-cyanooquinodimethane) [(TTF)(TCNQ)] electrode has smaller interfacial potential at the OSC/organic electrode interface than that at the OSC/metal electrode interface [84] or forms interface dipoles at the OSC/organic metal interface for dibenzo-tetrathiafulvalene (DBTTF) semiconductor. [85] Transistors using organic electrodes may have low $R_C$ and high mobility due to the difference of contact properties between organic/metal and organic/organic interface. [86,87] Here we concentrate on several examples of selection of proper source-drain electrodes for reduced $R_C$ in OFETs.

Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) semiconducting polymer is solution processable and transparent, having great potential in flexible optoelectronics. [88] In 2017, Kostianovskii et al. used patterned PEDOT:PSS films as source-drain electrodes for ambipolar OFETs. [47] A copolymer semiconductor DPPT-TT was used for this study. The $R_C$ of PEDOT:PSS electrodes extracted by YFM was 10 times smaller (9.8 × 10$^2$ Ω cm) compared with that of Au counterparts (1.0 × 10$^4$ Ω cm), although the hole mobility of both devices was 0.29 cm$^2$ V$^{-1}$ s$^{-1}$ (Figure 7A and B). On the contrary, the electron mobility decreased from 0.075 ± 0.008 to 0.048 ± 0.004 cm$^2$ V$^{-1}$ s$^{-1}$ as the electrode material changes from gold to PEDOT:PSS (Figure 7A,B). Thus, PEDOT:PSS-based OFETs have improved hole injection and lowered electron injection performance, which may be attributed to p-doping of PEDOT:PSS to the semiconductors. [89]

Another study also confirmed that PEDOT:PSS electrodes are good candidates for enhanced hole injection. Sanyoto et al. compared several solution processed conductive inks, including bare, MeOH treated PEDOT:PSS, single wall carbon nanotubes, and hybrid PEDOT:PSS-AgNW, as contact electrodes for printed p-type OFETs with DPPT-TT as semiconducting layer. The highest field-effect mobility of 0.49 ± 0.03 cm$^2$ V$^{-1}$ s$^{-1}$ was achieved using hybrid AgNW-PEDOT:PSS electrodes due to the lowest $R_C$. [46]

MXene materials have attracted intensive attention in recent years. In 2018, pentacene BGC OFETs with Ti$_2$CT$_x$ electrodes were fabricated (Figure 7C). [44] The WF of Ti$_2$CT$_x$ is about 5.1 eV according to SKPM measurements. Superior device performance with mobility up to 1.1 cm$^2$ V$^{-1}$ s$^{-1}$ was obtained with a low $R_C$ of 3 kΩ cm. The $R_C$ is even smaller than that in devices with Au electrodes (Figure 7F). [90] Temperature-dependent electrical measurement showed that the injection barrier for holes (0.17 eV) between pentacene and Ti$_2$CT$_x$ is smaller than that between Au and pentacene (0.45 eV) (Figure 7D,E). Due to strong interactions at metal–organic interface, pentacene molecules have a face-on orientation on Au surfaces. [89] Although the WF of Au is close to the HOMO of pentacene, the strong dipole effects produced a large hole injection barrier height at the Au/pentacene interface. [33] However, due to the edge-on arrangement of pentacene molecules at the Ti$_2$CT$_x$/pentacene interface, there may not be strong interface dipole effects [91], and the WF of Ti$_2$CT$_x$ is not seriously affected. Therefore, according to the energy level alignment between Ti$_2$CT$_x$ and pentacene (HOMO ≈ 5.2 eV), a low $\Phi_B$ is expected.
FIGURE 7 Selection of proper source-drain electrodes in OFETs. Transfer curves of DPPT-TT devices with (A) PEDOT:PSS and (B) Au electrodes. (C) Transfer curves of a pentacene device with Ti$_2$CT$_x$ electrodes. D, Arrhenius plot and (e) extracted $\Phi_B$ at various gate voltages (inset of (E): energy levels diagram). (F) Drain current and corresponding Y-function at different gate voltages.

4.2 Electrode/semiconductor interface engineering

Besides exploiting proper electrodes, there are other methods for better energy level alignment to reduce $R_{\text{Inj}}$ in OFETs at the electrode/semiconductor interface. Engineering the electrode/semiconductor interface can not only provide better energy level alignments but also yield better morphology of semiconductors in BC OFETs for reducing $R_{\text{Inj}}$ and $R_{\text{Bulk}}$ simultaneously. We would discuss the three main ways of electrode/semiconductor interface engineering: self-assembled monolayer (SAM)-modified electrodes, buffer layer modified electrodes, and contact doping.

4.2.1 SAM-modified electrodes

In general, modification of the electrodes with SAMs of polar molecules allows the optimization of their physical and electrical properties, such as $\Phi$ and surface energy. Various types of chemical groups have been introduced to form SAMs on metal electrodes to reduce the $R_{\text{C}}$ and thereby enhancing the device performances, such as the widely used alkanethiols and perfluorinated alkanethiols. Since alkanethiols and perfluorinated alkanethiols have opposite dipoles, they can be used to decrease and increase the WF of metal electrodes, respectively. Besides their ability to tune the WF, recently the interface dipole formed...
by SAMs was proved effective to reduce the trap sites at the metal/organic interface in OFETs[108] and to improve the crystallinity and grain sizes of the semiconductor films[95,97,109] Thus, SAM-modified electrodes would significantly influence the value of \( R_C \) in OFETs.

In 2015, Samori and coworkers studied SAMs modification on gold using 2,3,4,5,6-pentafluorothiophenol (PFBT) and (S-(2′,3′,4′,5′,6′-pentafluoro-[1,1′-biphenyl]-4-yl) ethanethioate) (PF2BT).[98] The WF of Au increased largely when modified with the two SAMs, while slightly larger change was obtained for the PFBT. This can be attributed to the repulsion effect of the fluorine atoms on the terminal phenyl group. The PFBT molecule has a shorter length than PF2BT molecules, and so the PF2BT SAMs are oriented perpendicular to the surface, with their terminal (fluorinated) phenyl groups arranged by the same orientation (Figure 8A). The calculations indicated that, although free-standing of the two monolayers have nearly the same dipoles, the bond dipoles on the gold surface are quite different, which has been shown to account for the fact that the PFBT-modified gold has a higher WF. This work underlines the consideration of the bond dipole in the design of SAMs for WF modification in the future.

To test effects of SAMs in transistors, BGBC devices made of three p-type polymers with different energy levels (HOMO\(_{\text{P3HT}}\) = -4.86 ± 0.02 eV, HOMO\(_{\text{IIDDT-C3}}\) = -5.34 ± 0.02 eV, and HOMO\(_{\text{F8T2}}\) = -5.55 ± 0.02 eV) were exploited as shown in Figure 8B. The \( R_C \) of the three devices made with gold or SAM-modified gold electrodes are illustrated in Figure 8C. For IIDDT-C3 transistors, the \( R_C \) for gold electrodes is about 60% higher than that for the two SAM-treated electrodes, which is consistent with the effect of energy injection barrier. It is expected there is no energy barrier for the SAM-modified electrodes due to its higher WF. In the case of F8T2, the \( R_C \) for the two SAM-modified electrodes is lower than that of gold electrodes, and moreover, the \( R_C \) is significantly lower for the PF2BT devices than that for the PFBT devices due to the smaller injection barrier in the former. Finally, in the case of P3HT, no matter which kind of electrodes is used, \( R_C \) is smaller than that of the two above-mentioned devices, since there is no injection barrier due to the much lower HOMO levels of P3HT. However, it is also noted that the gold electrodes result in smaller \( R_C \) than the two SAM-modified electrodes, which indicates that the energetics are not the only factors. Two other impacts need to be noted: (1) the surface energy of the modified electrode can affect the morphology of films at the contacts and thus the carriers transport from the bulk to the active layer of semiconductors;[70,110] (2) the tunneling caused by SAMs.[33,957,111] The indiscernible \( R_C \) values of the PFBT and PF2BT devices and similar terminal units of the two SAMs indicate that the morphology of films may play a dominant role in this small \( R_C \). In fact, it is found that the water contact angles for PF2BT (95.5 ± 1.9°) are
4.2.2 Buffer layer modified electrodes

The insertion of a charge injection layer, namely buffer layer, at source-drain electrode-semiconductor interface is another common method to improve contact performance. Various materials have been used as buffer layers to date such as aryl-functionalized graphene oxides (GOs), molybdenum oxide (MoO3), vanadium oxide (VOx), tungsten oxide (WO3), and some inorganic salts. Also organic compounds like TCNQ, (deoxyribonucleic acid (DNA)), poly(methyl methacrylate) (PMMA), subphthalocyanine chloride (SubPc), triphenylamine derivative (TPD), 4,4,40,40-tris[3-methylphenyl(phenyl)amino] triphenylamine (m-MTDATA), radical polymer poly(2,2,6,6-tetramethylpipеридин-1-окси мETHАCryлат) (PTMMA) etc. are used as insertion layers. The mechanism of injection improvement for insertion of buffer layer is the introduction of a tunneling barrier for reducing \( R_{\text{inj}} \). Besides that, it may also change the morphology of semiconductor at the source-drain electrodes edges to influence the \( R_{\text{bulk}} \) in BC OFETs.

For example, MoO3 modified Au electrodes are often used to enhance the efficiency of hole injection in OFETs. Huang et al. prepared heterojunction TC OFETs with/without MoO3 modified electrodes based on copper phthalocyanine/hexadecafluorophtholocyaninatocopper (CuPc/F16CuPc) in 2015 (Figure 9A). In comparison with F16CuPc devices, the electron mobility of the heterojunction devices without MoO3 buffer layer increased from \( 3.1 \times 10^{-3} \) to \( 8.7 \times 10^{-3} \) \( \text{cm}^{2} \text{V}^{-1} \text{s}^{-1} \), but they did not obtain effective hole mobility. By introducing a MoO3 buffer layer to modify the source-drain electrodes, the hole injection of the heterojunction devices was effectively improved with electron and hole mobilities of 2.5 \( \times 10^{-3} \) and 3.1 \( \times 10^{-3} \) \( \text{cm}^{2} \text{V}^{-1} \text{s}^{-1} \), respectively. Compared with bare Au electrode devices, the electron-injection barrier height between the inserted MoO3 layer and the OSC layers increases 0.2 eV (Figure 9B), which makes it difficult to inject electrons into the F16CuPc. However, \( R_{\text{C}} \) in p-type regimes in the F16CuPc/CuPc heterojunction devices with MoO3 buffer layer get reduced by one order of magnitude compared with that of OFETs without the MoO3 buffer layer, which resulted in the enhancement of the hole current. Thus, ambipolar charge transportation was successfully achieved.

Most researches focused on looking for buffer layers with only better hole- or electron-injections properties. However, there are few studies on the improvement of hole and electron injection simultaneously. Low cost metal electrodes prepared by using poly(9,9diocytfluorene) wrapped semiconducting single-wall carbon nanotubes (PFO:s-SWNT) as buffer layer to enhance ambipolar injection (Figure 9C) was proposed by Lee et al in 2017. In this work, compared with the Mo OFETs, the Mo/PFO:s-SWNT buffer layer BC OFETs based on the ambipolar semiconductor poly(thiénylenëvinylene-co-phthalimide)s (PTVPhl-Eh) showed higher hole and electron mobilities, lower \( V_T \), and lower trap density. It was due to reduced \( R_{\text{C}} \) in both p- and n-type regions for Mo/interlayer OFETs compared to Mo OFETs (Figure 9D), indicating that there are many charge traps at the contacts for Mo OFETs.
In addition, in this work, they also verified that the PFO:s-SWNT buffer layer can be used when different metal such as Ni was used as electrodes (Figure 9E,F) or when different semiconductor like (PNDI2ODT2) was employed (Figure 9G,H), indicating the universality of the buffer layer.

4.2.3 Contact doping

Contact doping is another important approach that can improve carrier injection to reduce $R_{\text{inj}}$ by tailoring the fermi levels of semiconductors.\cite{125} It is similar to buffer layer method except that contact doping changes the orbital energy levels of semiconductors, and introduces narrow barriers at the metal/semiconductor interface for tunneling.\cite{2,28,119,126–128} For example, MoO$_3$-deposited Mo electrodes exhibited better performance than Au electrodes for P3HT and DPPT-TT FETs, which can be attributed to the doping of the semiconductors at the contacts.\cite{48} Sulfuric acid and hydrogen peroxide mixture (SPM) treated Au electrodes reduce $R_C$ by absorbing sulfate ions, which act as acceptors in pentacene OFETs and reduce the HOMO level and/or improve the morphology of pentacene films, thus lowering the height of the injection barrier.\cite{129} Therefore, the device performances such as $V_T$ and $R_C$ can be modified by introducing dopants to dope semiconductors intentionally.

In 2016, the effect of ammonium hydroxide solution (NH$_4$OH (aq)) and iodine (I$_2$) on device properties was reported through chemical vapor treatments on poly(4,4-dihexadecyl-4H-cyclopenta[1,2-b:5,4-b']dithiophen-2-yl)-alt-[1,2,5] thiadiazolo-[3,4-c]pyridine (PCDTPT) (Figure 10A).\cite{130} By comparing device properties, it was found that there were trapped holes at the metal/semiconductor interfaces in pristine devices, which may have been caused by water or oxygen accidentally, resulting in a positive $V_T$. When treated by ammonia (NH$_3$) vapor (N-PCDTPT), charge density of the device decreased (at zero gate bias) and $V_T$ shifted to $\approx$ 0 V. In comparison, when the device was treated by I$_2$ vapor (I-PCDTPT), the charge density increased and $V_T$ shifted to $\approx$ 14 V (Figure 10B). The $R_C$ for N-PCDTPT, PCDTPT and I-PCDTPT devices are 65.2 k$\Omega$, 30.9 k$\Omega$ and 14.7 k$\Omega$, respectively (Figure 10C)\cite{131} It should also be noted that the slopes of the linear fittings in Figure 10C are almost the same for all the three cases, which indicates that the $R_{\text{Ch}}$ of the N-PCDTPT, PCDTPT, and I-PCDTPT thin films are almost the same, implying that doping only occurs near the metal electrodes.\cite{132}

Through XPS measurements, it can be concluded that the device properties of PCDTPT were controlled by oxidation and reduction of nitrogen of the pyridyl unit (Figure 10D).

Generally, the off-currents would increase when channel doping occurred during contact doping process. It has adverse effects on the on-off ratio and mobility in OFETs. Therefore, the selective contact doping away from channel is important for enhancing device performance. In 2019, Kim et al. reported improving charge injection by doping with $F_4$-TCNQ while keeping low off-currents by introducing an argon plasma etching treatment in PBTTT OFETs.$^{133}$ By this method, they can effectively control the amount of neutral dopants and significantly suppress the
dopants diffusion into the channel layers of the PBTPT (Figure 10E) OFETs. It is found that the extracted value of the $R_C$ (by YFM) of the pristine device is 24.5 kΩ cm while that of the doped PBTPT transistors is 5.1 kΩ cm, which is equivalent to the lowest reported value.\[128,134\] The improved charge injection properties are due to the transition of the main charge injection mechanism from thermionic emission to tunneling at the contact, which was verified through the low-temperature measurement and the band diagram analysis (Figure 10F, G). This study shows that the doping method is an effective approach to solve the $R_C$ problems in OFETs.

### 4.3 Dielectric engineering

The active layer of transistor channel exists in the several layers at the semiconductor/dielectric interface, and so the dielectric material can significantly affect the morphology of the semiconductor to reduce $R_{Bulk}$.\[135,136\] For example, poly(imide-siloxane) combining siloxane units with various molecular weights and contents in a polyimide mainchain were used as gate dielectrics for pentacene OFETs.\[137\] It is found that when gate dielectrics with a smaller surface energy are used, the growth of pentacene is mainly in the Volmer-Weber growth mode (three-dimensional growth), while pentacene grows in Stranski-Krastanov mode (island growth) on gate dielectrics with a larger surface energy. Similarly, pentacene thin-film transistors were demonstrated by using different dielectrics including thermal oxide SiO$_2$, bilayer dielectrics of polymethyl methacrylate (PMMA)/SiO$_2$, polycarbonate (PC)/SiO$_2$, and polystyrene(PS)/SiO$_2$.\[138\] Among them, the PS dielectrics result in larger grain sizes in the first layer due to its lower surface energy, which makes the fabricated transistors have higher mobility. In addition, the nonpolar dielectric lacking -OH groups such as PMMA and perfluoro(1-butenyl vinyl ether) polymer (Cytop) can effectively eliminate the trapping sites, which leads to a lower $R_C$ in C$_8$-BTBT devices.\[139\] Meanwhile, biocompatible PMMA/silk fibroin (SF) bilayer dielectric and hexamethyldisilazane (HMDS)\[140–143\] can improve the crystallization of semiconductors and decrease the interface trap density to improve the device performances.

Cytop dielectric is commonly used to decrease the trap density in TG OFETs. In 2015, Diemer et al. compared the OFET performances based on 2,8-difluoro-5,11-bis (triethylsilylthiethyl) anthradithiophene (dif-TES ADT) in two different devices structures: BG device with SiO$_2$ as dielectric and TG device with Cytop as dielectric (Figure 11A).\[144\] The TG Cytop device displays a $R_C$ of 4.5 kΩ cm, compared to 17.7 kΩ cm for the BG SiO$_2$ device. According to Grünewald’s method, the density of traps at the SiO$_2$ interface is ~50 times higher than that at the Cytop interface (Figure 11B). Temperature dependent measurements results indicated Cytop devices have a smaller
activation energy for charge injection (Figure 11C). So, Cytop based OFETs outperformed those made on SiO$_2$ due to lower trap density at the dielectric/semiconductor interface and reduction in the $R_C$.

Besides the surface properties of dielectric materials, dielectric thickness also has close relation to $R_C$. Zojer et al. predicated that BC TFTs may have exhibit lower RC than otherwise equivalent TC TFTs by performing drift-diffusion-based simulations when the energy barrier is sufficiently low between the semiconductor and source electrode and the dielectric is sufficiently thin.\(^{[145]}\) In 2019, Borchert et al. fabricated BC and TC 2,9-diphenyl-dinaphtho-[2,3b:2′,3′-f]thieno[3,2-b]thiophene (DPh-DNTT) transistors with the gate dielectrics of various thickness of aluminum oxide (Al$_2$O$_3$) modified by (n-tetradecylphosphonic acid (TDPA)) (Figure 11D) in order to verify this predication.\(^{[146]}\) It is found that the $R_C$ in the BC TFTs is smaller than that in the TC TFTs on the doped Si wafer substrate as long as the gate-dielectric thickness is small enough (3 nm) (Figure 11E). In addition, for BC OFETs, when the dielectric thickness is 5.3 nm, smaller $R_C$ of 29 Ω cm can be obtained on flexible PEN substrates (Figure 11F), which is a record-low $R_C$ value for organic thin film transistors.

4.4 | Semiconductor engineering

In general, the molecular structures of OSCs determine their optical and electronic properties. By tailoring molecular structure of semiconductors, different fermi-level and morphology can be achieved, leading to different optical and electronic properties and thus modulating the value of $R_{\text{finj}}$ and $R_{\text{bulk}}$ at the same time in OFETs.

In 2015, Nketa-Yawson et al. reported the influence of an electron-donating unit containing thienoisooindigo (TIIG) groups on morphology of semiconductors and charge transport in OFETs.\(^{[147]}\) By introducing different electron-donor units (benzene [Bz], naphthalene [Np], and benzofuran [Bf]) onto TIIG, TIIG-Bz, TIIG-Np, and TIIG-Bf were obtained (Figure 12A), having different energy levels, film morphologies and OFET performance. GIWAXS results show that TIIG-Np films have higher crystallinity (Figure 12B). AFM images show that the TIIG-Bz and TIIG-Np films have the nano-rod crystals, whereas TIIG-Bf shows nano-rods and salt-like crystals (Figure 12C), and polarized optical microscopy images confirmed surface morphological microstructures (Figure 12D). The best hole mobilities of TIIG-Np, TIIG-Bz and TIIG-Bf OFETs with TG/BC geometry are 0.019, 0.012,
and 0.004 cm$^2$ V$^{-1}$ s$^{-1}$, respectively and the $R_C$ increased accordingly (Figure 12F). Morphology measurements and energy level alignment analysis reveal that, the lowest HOMO of TIIG-Np caused the lowest $R_C$ since it owned the lowest injection barrier height from Au (Figure 12E) and improved morphology of films near the Au contacts. This research provides a useful guidance for achieving smaller $R_C$ in OFETs through molecular design.

In 2017, Bhargava et al. explicitly explored the effect of alkyl side chains length on tailoring the performance of OFETs. Poly(3-hexylthiophene) (P3HT) and Poly(3-octylthiophene) (P3OT) are semiconductors with different length of alkyl side chains. The value of $R_C = 2 \times 10^9 \Omega$ extracted in P3OT OFETs is significantly larger than that of P3HT counterpart, where $R_C = 9 \times 10^7 \Omega$ was obtained (Figure 12G). It was found that the torsional and energetic disorder were decreased in the main chain of the polymer with the decrease of alkyl side chains length, as seen through UV-vis spectroscopy and PL spectroscopy (Figure 12H, I). XRD and Raman spectra analysis showed that the crystallinity of P3OT film was lower than that of P3HT film because of the larger alkyl side chain (Figure 12J, K). The larger $R_C$ of P3OT OFETs verified that the existence of larger alkyl chain resulted in the increase of injection barrier at the contacts, thus leading to poorer performance of P3OT OFETs than that of P3HT OFETs. These results provide information about reducing $R_C$ by tailoring of the polymer molecule structures.

### 4.5 Utilization of MMCs

The first MMC OFETs were demonstrated by Hu et al. in 2011. In this work millimeter scale monolayer film of 1,4-bis((50-hexyl-2,20-bithiophen-5-yl)ethynyl)benzene (HTEB) was obtained via drop-casting method. MMC OFETs exhibited even better performance than OFETs based on multilayers, which confirmed the fact that charge transport occurs in the first layer closing to the dielectric. Inspired by this work, we realize that if bulk OSCs are replaced by MMCs, the $R_{\text{bulk}}$ would be vanished and thus greatly reduce $R_C$. Therefore, fabricating OFETs based on MMCs is one of the most facile way to decrease $R_C$ since it does not need other complex and tedious procedures. In addition, the fully exposed charge transport layer in MMC OFETs is also beneficial to directly probing the intrinsic property of OSCs, which is important to fundamental studies in organic electronics.

Solution process is commonly used for preparing MMCs. In 2018, Jiang et al. prepared centimeter scale n-type MMCs of dicyanomethylenesubstituted fused tetrathienoquinoid (CMUT) on polymer substrates using
the gravity-assisted 2D spatial confinement method. The saturation mobility of the MMC OFETs is up to 1.24 cm² V⁻¹ s⁻¹ which is better than those of thick films (about 40 nm). \( R_C \) extracted in thick film OFETs by TLM are 30 times of that for MMC OFETs. This clearly demonstrates MMC OFETs have lower bulk/contact resistance than devices based on thick crystals. In 2019, Jiang et al. further studied the dependence of the \( R_C \) on crystal thickness of HTEB. The \( R_C \) of devices based on MMCs, 4-layer and 15-layer single-crystal devices extracted by TLM are 1.77 kΩ cm, 26.9 kΩ cm and 5.15 MΩ cm, respectively (Figure 13A-C). The channel length dependence of \( R_C/R_{\text{Total}} \) ratio is smallest for MMC devices (Figure 13D). The linear mobilities of MMC devices are more stable under different \( V_d \) due to the lower \( R_C \), and the linear and saturation mobility showed smaller differences. In addition, a low-voltage operating (-2 V) MMC device was realized with an ultra-low \( R_C \) of 540 Ω cm by using a 30 nm HfO₂ insulating layer. In 2020, Peng et al. also managed to prepare C₈-BTBT crystals with thickness ranging from monolayer to a few layers on BN substrates. In 2017, they systematically investigated the performance of 1L, 2L and 3L C₈-BTBT OFETs. Compared to conventional OFETs, monolayer device exhibited significant electrical property with high mobility over 30 cm² V⁻¹ s⁻¹, Ohmic contact with \( R_C \) values of 100 Ω cm was extracted from gFPP measurements. Compared with monolayer devices, the 2L and 3L devices exhibited strong nonlinearity at low \( V_d \) (Figure 14A). The low temperature experiments indicated that 2L and thicker C₈-BTBT devices exhibited thermally activated behavior with strong Schottky contacts (Figure 14B). The \( \Phi_B \) was 140 meV for this 2L-OFETs (Figure 14C,D). When graphene buffer layers were inserted between Au electrodes and C₈-BTBT semiconductors, the nonlinear output characteristics of 2L-FETs were eliminated to a great extent and \( \Phi_B \) was reduced by ∼0.1 eV compared with bare Au contacts.
However, the contact property of Au/graphene/2L-C$_8$-BTBT was not as good as that of the monolayer devices. Therefore, monolayer OFETs have distinctive advantages in lowering $R_C$.

All above results indicate that MMC OFETs show significantly lower $R_C$. Thus, MMC OFETs in combination with properly modified source-drain electrodes may further reduce $R_C$, which can be beneficial to short channel devices and high-speed circuits. In Table 1, the $R_C$ values in OFETs reported in literatures are summarized, with the corresponding semiconductor materials as well as the extraction method of $R_C$ included.

5 | CONCLUSION AND OUTLOOK

In summary, this article provides a comprehensive review of the understanding and characterization of $R_C$ in OFETs. Meanwhile, the various methods for reducing $R_C$ in OFETs are included. Great efforts have been devoted to the interfacial engineering by tuning the WF of metal electrodes and energy levels of semiconductors to lower the SBH for a low $R_{\text{inj}}$ and improving morphology of semiconductor to reduce $R_{\text{Bulk}}$. Using MMC OFETs also emerged as the most effective approach to improve the performances of OFETs by lowering the $R_{\text{Bulk}}$.

Although several OFETs based on MMCs have been reported with $R_C < 100 \ \Omega \ \text{cm}$, there are some challenges impeding the developments of MMC OFETs with small resistance or even Ohmic contact: (1) Preparation of large-area and uniform MMCs is still difficult. There is no common rule for directing the growth of MMCs. It is therefore urgent to develop basic laws to direct the growth of MMCs. (2) Some MMCs prepared so far maybe defective. How to control the growing conditions to obtain perfect MMCs without defects is a question in urgent need to answer. (3) Since the directly exposed conducting channel is susceptible to external environments in MMC OFETs, how to prepare MMC OFETs with no damages and prevent the conducting channel from being affected by external environments is still a challenging issue. Therefore, it is extremely important to study the growth of MMCs in depth and invent new methods and techniques for fabricating MMC OFETs. We believe that the combination of MMC OFETs with other engineering methods would promote the development high performance of OFETs with low $R_C$ and facilitate the application of OFETs in organic circuits and other optoelectronic devices.
**TABLE 1** The ever reported $R_C$, the corresponding semiconductor materials as well as the extraction method of $R_C$ in OFETs

| Year | Material     | Device configuration; Dielectric; Source-drain electrodes | $R_C$  | Method | Reference |
|------|--------------|------------------------------------------------------------|--------|--------|-----------|
| 2020 | C$_{10}$-DNTT | BGTC; PTS/ SiO$_2$ Au                                      | 40 Ω cm| TLM    | [157]     |
| 2019 | HTEB         | BGBC; HfO$_2$ Au                                           | 540 Ω cm| TLM    | [155]     |
| 2019 | DPhe-DNTT    | BGBC; Al$_2$O$_3$ Au/SAMs                                  | 29 Ω cm| TLM    | [146]     |
| 2019 | PBTHT        | BGBC; SiO$_2$ Au/F$_4$-TCNQ                                 | 5.1 kΩ cm$^{-1}$| YFM    | [133]     |
| 2018 | C$_{5}$-DNBDT-NW | BGTC; SiO$_2$/SAMs Au/F$_4$-TCNQ                            | 46.9 Ω cm| TLM    | [156]     |
| 2018 | C$_{12}$-BTBT | BGTC; PS/SiO$_2$ Au                                        | <10 kΩ cm| TLM    | [2]       |
| 2018 | pentacene    | BGBC; SiO$_2$ Ti$_2$CT$_x$                                  | 3 kΩ cm| YFM    | [44]      |
| 2018 | pentacene    | BGTC; Al$_2$O$_3$ Au/Al                                     | 0.3 MΩ cm| TLM    | [71]      |
| 2017 | DPPT-TT      | TGBC; PMMA PEDOT:PSS                                       | 980 Ω cm| YFM    | [47]      |
| 2017 | C$_{5}$-BTBT | BGTC; BN Au                                                | 100 Ω cm| gFPP   | [160]     |
| 2017 | diF-TES ADT  | TGBC; Cytop Au/TFBT                                         | 2.5 kΩ cm| TLM    | [91]      |
| 2017 | heptazole    | BGTC; Al$_2$O$_3$/Cytop Au/Guanine                         | 25.5 kΩ cm| TLM    | [120]     |
| 2016 | DNTT         | BGTC; SiO$_2$/AlOx/SAMs Au                                  | 130 Ω cm| KPFM   | [58]      |
| 2016 | DPPT-TT      | BGBC; SiO$_2$ PEDOT:PSS+DMSO+AgNW                           | 26.7 kΩ cm| YFM    | [46]      |
| 2016 | pentacene    | BGBC; SiO$_2$ Au/PTMA                                       | 1.2 MΩ cm| TLM    | [123]     |
| 2016 | N2200        | TGBC; ParyleneC Ag/Jul                                      | 50 kΩ cm| TLM    | [90]      |

(Continues)
| Year | Material   | Device configuration; Dielectric; Source-drain electrodes | \( R_C \) | Method | Reference |
|------|------------|----------------------------------------------------------|----------|--------|-----------|
| 2016 | PCDTPT     | BGBC SiO\(_2\) Au/Ni                                      | 14.7 KΩ | TLM    | [130]     |
| 2015 | P3HT       | TGBC PMMA Mo/MoO\(_3\)                                    | 1.2 MΩ cm | YFM    | [48]      |
| 2015 | CuPc       | BGTC SiO\(_2\) Au/MoO\(_3\)                               | 31500 MΩ | TLM    | [112]     |
| 2015 | pentacene  | BGTC PMMA Au/m-MTDATA                                    | 0.02 MΩ cm | TLM    | [122]     |
| 2014 | pentacene  | BGBC PI Ag/TCNQ                                          | 0.4 MΩ cm | TLM    | [79]      |
| 2014 | pentacene  | BGTC PMMA Al/WO\(_3\)                                     | 0.045 MΩ | TLM    | [115]     |
| 2014 | pentacene  | BGTC PS Au/DNA                                           | 4.134 MΩ cm | TLM    | [119]     |
| 2014 | pentacene  | BGTC PMMA Au/PMMA                                        | 0.02 MΩ cm | TLM    | [121]     |
| 2013 | rubrene    | BGTC Air gap Au                                          | 466 Ω cm | TLM    | [26]      |
| 2011 | DNTT       | BGTC AlO\(_x\)/SAMs Au/contact doping                   | 390 Ω cm | TLM    | [28]      |
| 2007 | pentacene  | BGBC SiO\(_2\) Au/ UV/ozone treatment                    | 80 Ω cm  | TLM    | [79]      |
| 2006 | pentacene  | BGBC SiO\(_2\) Au/O\(_2\) plasma                         | 0.22 MΩ cm | TLM    | [78]      |
| 2004 | PTCDI-C\(_5\) | BGTC C\(_{15}\)-Al\(_2\)O\(_3\) Ca               | 60 KΩ cm | gFPP   | [31]      |

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