Reliable Mobility Evaluation of Organic Field-Effect Transistors with Different Contact Metals

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Abstract—The reliability of mobility evaluation for organic field-effect transistors (OFETs) has recently been a serious issue since numerous overestimated and underestimated mobilities have been reported. A reliable approach to accurately evaluate the OFET mobility is highly desirable. Under this background, two commonly used methods and the Y function method (YFM) are used to extract the mobility of indacenodithiophene-co-benzothia-diazole (IDT-BT) OFETs with four different contact metals. It is observed that the mobilities extracted by other methods vary greatly with the contact metal and the channel length, while the mobility extracted by YFM is very stable and approaches the inherent mobility of IDT-BT. Our results show that YFM can be a precise alternative to be widely used for OFET mobility evaluation.

Index Terms—Mobility, characterization, OFETs, contact resistance.

I. INTRODUCTION

Mobility, determining how quick the charges move through the channel and thus the output driving current, is a key performance parameter of organic field-effect transistors (OFETs). Typically, OFET mobility is extracted by the conventional method based on the saturation transfer characteristics [1], [2]. However, that model was initially developed for silicon metal-oxide-semiconductor field-effect transistors (MOSFETs), which is for gradual channel approximation with ohmic contacts and band transport [3].

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OFETs, on the other hand, are generally with disordered organic semiconductor and mismatched energy levels for charge injection. This gives rise to variable-range hopping charge transport and very high contact resistance [4], [5], leading to severe deviations from the ideal model. As a consequence, the mobilities of those OFETs can be significantly overestimated or underestimated [1], [6], [7]. It is thus highly desirable to find a reliable approach to evaluate the inherent carrier mobility.

The Y function method (YFM) was first established for MOSFET parameter extraction [8], in particular, the low-field mobility and contact resistance. Differing from the conventional method, YFM applies in the linear regime (i.e. in the low-field regime) and, most importantly, it takes into account the influence of the contact resistance. So, YFM is free from extrinsic effects and has demonstrated much superior reliability [9]. Nevertheless, a work reporting how to reliably extract mobility without the contact metal effect is still lacking.

In this letter, polymer OFETs using state-of-the-art polymer semiconductor of indacenodithiophene-co-benzothiadiazole (IDT-BT) are fabricated with various contact metals. Three different extraction methods are adopted to evaluate their mobilities. Different trends are observed when plotting the corresponding mobilities against contact metal. The dependence of mobility on the contact resistance and the channel length are discussed. The mobility extracted by YFM proves to be more accurate and inherent as compared to other mobilities extracted by the commonly used methods. Thus, YFM turns out to be a reliable approach to evaluate OFET mobility.

II. DEVICE FABRICATION AND CHARACTERIZATIONS

In this work, top-gate staggered IDT-BT transistors were fabricated (Fig. 1(a)). The drain and source electrodes were formed by thermal evaporation with four different contact metals (Au, Ag, Cu, and Ni) on the pre-cleaned glass substrate via designed shadow masks. The channel width (W) was fixed to 1000 μm with the length (L) varying from 60 μm to 350 μm . IDT-BT was dissolved in dichlorobenzene (10 mg/ml) and was spin-coated at 2000 rpm for 60 s, and then the samples were annealed at 100 $^{\circ}\text{C}$ for 1 hour in a nitrogen-filled glovebox. Subsequently, the IDT-BT layer was patterned by lithography to suppress the leakage. Afterward, polystyrene, as the first dielectric layer, dissolved in n-butyl acetate (80 mg/ml) was

spin-coated at 2000 rpm for 60 s and then annealed at 80 °C for 2 hours. The second dielectric layer of Cytop™ was spin-coated at 2000 rpm for 60 s and then annealed at 80 °C for 1 hour. Finally, the top-gate Au electrode was made by thermal evaporation by using shadow masks. The electrical characterizations were performed in nitrogen atmosphere using a semiconductor parameter analyzer (Keithley 4200-SCS).

Fig. 1. (a) Schematic illustration of the top-gate staggered IDT-BT OFETs. The contact metal is Au, Ag, Cu, and Ni, respectively. (b) Chemical structure of IDT-BT. (c) Linear and (d) saturation transfer characteristics of the IDT-BT OFETs with four different contact metals.

III. RESULTS AND DISCUSSIONS

The typical transfer characteristics are shown in **Fig. 1(c)** and **1(d)** for the four contact metals. One can observe a large discrepancy even though the semiconductor and dielectric are unchanged. An obvious kink, which has been considered to be a sign of the nonideality, exists in the OFETs with Cu and Ni contact metals, especially in the linear regime [10]. It means that these transistors suffer from extrinsic effects when contact metal varies. The reliability of the mobilities extracted simply by the transfer characteristics can be disturbed.

To further investigate the mobility, three extraction methods are discussed for comparison. They can be expressed by the following three equations [8], [11]: for the saturation mobility $\mu_{SAT} = 2L/WC_{OX} \cdot (\partial(I_{DSSA})^{1/2}/\partial V_{GS})^2$, and for the effective mobility $\mu_{LIN} = L/V_{DS}WC_{OX} \cdot \partial I_{DSL}/\partial V_{GS}$, and for the low-field mobility by the Y function method $\mu_Y = L/V_{DS}WC_{OX} \cdot \partial(I_{DSL}(\partial I_{DSL}/\partial V_{GS})^{-1/2})/\partial V_{GS}$, where I_{DSSA} , I_{DSL} , V_{DS} , V_{GS} , L , W , and C_{OX} are the drain current in the saturation regime, the drain current in the linear regime, the drain voltage, the gate voltage, the channel length, the channel width, and the areal gate dielectric capacitance. The three mobilities extracted by these methods are plotted in **Fig. 2**, where the error bars represent the standard deviation calculated from more than 10 samples. Obviously, μ_Y is stable and independent of the contact metal.

By contrast, the mobilities extracted by the other two methods (μ_{SAT} and μ_{LIN}) vary greatly with the contact metal. Especially, μ_{SAT} decreases nearly two orders of magnitude from 2.116 cm²/V·s to (0.03 ?) cm²/V·s when the contact metal changes from Au to Ag, Cu, and Ni. Compared to the previous

mobility values reported for IDT-BT OFETs [12], [13], which are around 1 cm²/V·s, so the mobility here is overestimated for Au contacted OFETs while is severely underestimated for Cu or Ni contacted OFETs.

Fig. 2. The mobilities extracted by different methods with the Au, Ag, Cu, and Ni contact metal, respectively.

Differing from the other two mobilities, μ_{SAT} is extracted only from the saturation regime (i.e. at high drain voltages). High drain voltage can produce high output driving current thus alleviating the mobility underestimation induced by contact resistance, and sometimes very high mobility can be obtained [14]. However, such superficial values can be affected by the channel length modulation [15], hopping barrier lowering [16] etc., which exist in the OFETs under very high lateral field. The former effect can lead to misestimated channel length owing to the source-oriented shift of the pinch-off point. The latter effect causes a reduced hopping barrier and thus the extracted mobility deviates from the inherent value [16], [17]. These may account in part for the higher μ_{SAT} when the OFETs use Au as contact metal.

Fig. 3. The contact resistance (R_C) and channel resistance (R_{CH}) estimated at different gate voltage.

On the other side, the underestimated μ_{SAT} for Cu and Ni contacted OFETs, and the variation of μ_{LIN} extracted from the linear regime, are also observed. Actually, these results stem from the contact resistance, as reported extensively before [2], [18], [19]. Due to the lack of a matured doping technique for organic semiconductor, ohmic contacts are difficult to form in OFETs. As a result, the contact resistance (R_C) that often comes from very high Schottky barrier has been a main reason for the non-ideal characteristics of many OFETs. We thus extract R_C by the transfer-length method (TLM) and compare it with the channel resistance (R_{CH}), as seen in **Fig. 3**.

For better illustration, an empirical formula is employed to fit the extracted R_C and the fitting is illustrated by red line [11]. One can see that, the R_C decreases more rapidly than R_{CH} for Au contacted transistors, while R_C is always dominant in Ni contacted OFETs. The resistance evolvement of Cu contacted transistors is similar to Ni (not shown here). Combined with the mobility summarized in **Fig. 2**, our result is consistent with the

model proposed by Liu *et al.* about gate-voltage dependent resistance [2], where the Au contacted situation corresponds with the overestimated mobility and the Ni contacted situation is vice versa. It also proves that μ_{SAT} and μ_{LIN} extracted from R_C -dominant OFETs ($R_C > R_{CH}$ or $R_C \approx R_{CH}$) are seriously disturbed, and therefore the correspondingly extracted mobility are not reliable. Only the mobility extracted from the R_{CH} -dominant OFETs ($R_C \ll R_{CH}$) like Ag contacted OFETs here are relatively reliable. Interestingly, the mobility of Ag contacted OFETs is almost independent of the extraction method (Fig. 2).

Fig. 4. The channel length dependence of the different method extracted mobility with respect to Au (a), Ag (b), Cu (c) and Ni (d) contact metal.

Numerous extrinsic effects have been examined to shed light on the unreliability of mobility evaluation, yet YFM is insusceptible. Is the stable low-field mobility reliable? In general, if all the extrinsic effects are removed, the mobilities extracted by different methods should be close and approach the inherent mobility of the applied semiconductor. According to Fig. 2, only the mobilities extracted by R_{CH} -dominant transistor, i.e., Ag contacted OFETs satisfy this inference. It means that the mobility extracted from Ag contacted OFETs is free from extrinsic effects. From another point of view, the μ_Y is very stable with the contact metal. Note that, this mobility is almost identical to the value of Ag-contacted OFETs and agrees with the literature for IDT-BT OFETs [12], [16]. These results suggest that the μ_Y extracted by YFM is reliable.

To explore μ_Y reliability, the channel mobility (μ_o) is investigated to compare with μ_Y . Here, μ_o is derived from the OFETs with various channel lengths by using TLM(not shown). Thus, μ_o is free from the influence of contact resistance. As expected, one observes a contact independent μ_o whose value is about 0.9 - 1 cm²/V·s for the four metal contacted OFETs, very close to μ_Y . This result indicates that, the intrinsic mobility can be evaluated by YFM. However, YFM requires only a single OFET.

Another notable characteristic of YFM is shown in Fig. 4. μ_Y always remains the inherent value while μ_{SAT} and μ_{LIN} significantly vary with the channel length (L) and then approach the constant μ_Y . It implies that the mobilities are gradually independent on their extraction methods, i.e., more intrinsic mobilities can be obtained. This is because the contact

effect plays an important role in limiting the apparent mobility of the short-channel devices, in which R_C is much higher than R_{CH} since R_C is almost constant with L while R_{CH} decreases proportionally with shortening L . Mobility underestimation is thus inevitable for the short-channel transistors [22], [23]. To further verify this inference, the previous μ_{LIN} is corrected for R_C , which can be done by correcting the measured drain current with the R_C and R_{CH} , i.e., $I_{DSCOR} = I_{DSL}(1 + R_C/R_{CH})$ [21], where I_{DSCOR} represents the drain current without contact effects. The corrected mobility (μ_{COR}) is replotted in Fig. 4, where μ_{COR} and μ_Y are nearly identical and independent of the contact metal as well as the channel length. Given this result, it can be concluded that the largely varying μ_{LIN} with the contact metal is due to the contact resistance. Only the long-channel transistors are reliable for extracting mobility if the contact resistance is high. From a practical point of view, one does not know what is the adequate channel length for this purpose. A better way is to apply YFM that directly offers the inherent μ_Y independent of the contact metal and the channel length, .

IV. CONCLUSIONS

Three mobility extraction methods are employed to analyze the OFETs with four different contact metals. YFM proves to be the most reliable method to evaluate mobility since it directly provides the inherent mobility independent of the contact metal and the channel length. By contrast, the widely used methods give μ_{LIN} and μ_{SAT} that greatly vary with the contact metal and the channel length, leading to large mobility misestimation. Therefore, YFM can be a reliable alternative to extract OFET mobility.

REFERENCES

- [1] A. F. Paterson, S. Singh, K. J. Fallon, T. Hodsden, Y. Han, B. C. Schroeder, H. Bronstein, M. Heeney, I. McCulloch, and T. D. Anthopoulos, "Recent Progress in High-Mobility Organic Transistors: A Reality Check," *Adv. Mater.*, pp. 1801079, Jul 18, 2018, doi:10.1002/adma.201801079.
- [2] C. Liu, G. Li, R. Di Pietro, J. Huang, Y.-Y. Noh, X. Liu, and T. Minari, "Device Physics of Contact Issues for the Overestimation and Underestimation of Carrier Mobility in Field-Effect Transistors," *Phys. Rev. Appl.*, vol. 8, no. 3, 2017, doi:10.1103/PhysRevApplied.8.034020.
- [3] W. Shockley, "A Unipolar "Field-Effect" Transistor," *Proceedings of the IRE*, vol. 40, no. 11, pp. 1365-1376, 1952, doi:10.1109/JRPROC.1952.273964.
- [4] Y. Xu, H. Sun, A. Liu, H.-H. Zhu, W. Li, Y.-F. Lin, and Y.-Y. Noh, "Doping: A Key Enabler for Organic Transistors," *Adv. Mater.*, vol. 0, no. 0, pp. 1801830, doi:10.1002/adma.201801830.
- [5] H. Klauk, "Organic thin-film transistors," *Chem. Soc. Rev.*, vol. 39, no. 7, pp. 2643-66, Jul, 2010, doi:10.1039/b909902f.
- [6] C. Reese, and Z. Bao, "Overestimation of the field-effect mobility via transconductance measurements and the origin of the output/transfer characteristic discrepancy in organic field-effect transistors," *J. Appl. Phys.*, vol. 105, no. 2, pp. 024506, 2009, doi:10.1063/1.3029587.
- [7] Y. Hu, G. Li, and Z. Chen, "The Importance of Contact Resistance in High-Mobility Organic Field-Effect Transistors Studied by Scanning Kelvin Probe Microscopy," *IEEE Electron Device Lett.*, vol. 39, no. 2, pp. 276-279, 2018, doi:10.1109/LED.2017.2781301.

- [8] G. Ghibaudo, "New method for the extraction of MOSFET parameters," *Electronics Letters*, vol. 24, no. 9, pp. 543, 1988, doi:10.1049/el:19880369.
- [9] Y. Xu, H. Sun, A. Liu, H. Zhu, B. Li, T. Minari, F. Balestra, G. Ghibaudo, and Y.-Y. Noh, "Essential Effects on the Mobility Extraction Reliability for Organic Transistors," *Adv. Funct. Mater.*, pp. 1803907, 2018, doi:10.1002/adfm.201803907.
- [10] I. McCulloch, A. Salleo, and M. Chabinyc, "Avoid the kinks when measuring mobility," *Science*, vol. 352, no. 6293, pp. 1521-1522, 2016, doi:10.1126/science.aaf9062.
- [11] Y. Xu, T. Minari, K. Tsukagoshi, J. A. Chroboczek, and G. Ghibaudo, "Direct evaluation of low-field mobility and access resistance in pentacene field-effect transistors," *J. Appl. Phys.*, vol. 107, no. 11, pp. 114507, 2010, doi:10.1063/1.3432716.
- [12] W. Zhang, J. Smith, S. E. Watkins, R. Gysel, M. McGehee, A. Salleo, J. Kirkpatrick, S. Ashraf, T. Anthopoulos, M. Heeney, and I. McCulloch, "Indacenodithiophene Semiconducting Polymers for High-Performance, Air-Stable Transistors," *J. Am. Chem. Soc.*, vol. 132, no. 33, pp. 11437-11439, 2010/08/25, 2010, doi:10.1021/ja1049324.
- [13] D. Venkateshvaran, M. Nikolka, A. Sadhanala, V. Lemaire, M. Zelazny, M. Kepa, M. Hurhangee, A. J. Kronemeijer, V. Pecunia, I. Nasrallah, I. Romanov, K. Broch, I. McCulloch, D. Emin, Y. Olivier, J. Cornil, D. Beljonne, and H. Sirringhaus, "Approaching disorder-free transport in high-mobility conjugated polymers," *Nature*, vol. 515, no. 7527, pp. 384-8, Nov 20, 2014, doi:10.1038/nature13854.
- [14] J. Lee, J. W. Chung, D. H. Kim, B. L. Lee, J. I. Park, S. Lee, R. Hausermann, B. Batlogg, S. S. Lee, I. Choi, I. W. Kim, and M. S. Kang, "Thin Films of Highly Planar Semiconductor Polymers Exhibiting Band-like Transport at Room Temperature," *J. Am. Chem. Soc.*, vol. 137, no. 25, pp. 7990-3, Jul 1, 2015, doi:10.1021/jacs.5b04253.
- [15] S. Sze, "Physics of semiconductor devices Wiley Eastern," *New York*, 1981,
- [16] Y. Xu, H. Sun, W. Li, Y. F. Lin, F. Balestra, G. Ghibaudo, and Y. Y. Noh, "Exploring the Charge Transport in Conjugated Polymers," *Adv. Mater.*, vol. 29, no. 41, Nov, 2017, doi:10.1002/adma.201702729.
- [17] T. Sakanoue, and H. Sirringhaus, "Band-like temperature dependence of mobility in a solution-processed organic semiconductor," *Nat. Mater.*, vol. 9, pp. 736, 08/22/online, 2010, doi:10.1038/nmat2825
- [18] E. G. Bittle, J. I. Basham, T. N. Jackson, O. D. Jurchescu, and D. J. Gundlach, "Mobility overestimation due to gated contacts in organic field-effect transistors," *Nat. Commun.*, vol. 7, pp. 10908, Mar 10, 2016, doi:10.1038/ncomms10908.
- [19] T. Uemura, C. Rolin, T. H. Ke, P. Fesenko, J. Genoe, P. Heremans, and J. Takeya, "On the Extraction of Charge Carrier Mobility in High-Mobility Organic Transistors," *Adv. Mater.*, vol. 28, no. 1, pp. 151-5, Jan 6, 2016, doi:10.1002/adma.201503133.
- [20] Y. Xu, H. Sun, E. Y. Shin, Y. F. Lin, W. Li, and Y. Y. Noh, "Planar-Processed Polymer Transistors," *Adv. Mater.*, vol. 28, no. 38, pp. 8531-8537, Oct, 2016,
- [21] Y. Hu, G. Li, W. Peng, and Z. Chen, "Comparing the Gate Dependence of Contact Resistance and Channel Resistance in Organic Field-Effect Transistors for Understanding the Mobility Overestimation Issue," *IEEE Electron Device Lett.*, vol. 39, no. 3, pp. 421-423, 2018, doi:10.1109/LED.2018.2798288.
- [22] C. Liu, Y. Xu, and Y.-Y. Noh, "Contact engineering in organic field-effect transistors," *Materials Today*, vol. 18, no. 2, pp. 79-96, 2015/03/01/2015, doi:https://doi.org/10.1016/j.mattod.2014.08.037.
- [23] J. Z. Wang, Z. H. Zheng, and H. Sirringhaus, "Suppression of short-channel effects in organic thin-film transistors," *Appl. Phys. Lett.*, vol. 89, no. 8, pp. 083513, 2006, doi:10.1063/1.2234724.