Vertical organic transistors are an attractive alternative to realize short channel transistors, which are required for powerful electronic devices and flexible electronic circuits operating at high frequencies. Unfortunately, the vertical device architecture comes along with an increased device fabrication complexity, limiting the potential of this technology for application. A new design of vertical organic field-effect transistors (VOFETs) with superior electrical performance and simplified processing is reported. By using electrochemical oxidized aluminum oxide (AlOx) as a pseudo self-aligned charge-blocking structure in vertical organic transistors, direct leakage current between the source and drain can be effectively suppressed, enabling VOFETs with very low off-current levels despite the short channel length. The anodization technique is easy to apply and can be surprisingly used on both n-type and p-type organic semiconductor thin films with significant signs of degradation. Hence, the anodization technique enables a simplified process of high-performance p-type and n-type VOFETs, paves the road toward complementary circuits made of vertical transistors.

1. Introduction

Organic field-effect transistors (OFETs) are attracting much attention because of their enormous potential for flexible and wearable electronics.[1–3] Triggered by this strong interest, the field-effect charge carrier mobility (a main figure of merit) measured in OFETs is nowadays in excess of 10 cm² V⁻¹ s⁻¹,[4] mainly by continuous improvements in device fabrication and interface engineering[5] combined with the development of new rationally designed semiconductor materials.[5] However, these improvements in mobility did not lead to a substantial gain in important electrical device parameters such as the transition frequency, which is mainly attributed to the increasing influence of contact resistance for shorter channel lengths.[6] In fact, the fastest OFETs reported today have been fabricated from C₆₀ with a mobility of merely 2.2 cm² V⁻¹ s⁻¹.[7]

An alternative approach to improve the performance, that is, transition frequency, is given by the vertical organic transistor concept.[8] Rather than having the direction of charge carrier transport in the plane of the substrate, transport in vertical transistors is perpendicular to this. Due to the semiconductor layer thickness in the range of a few hundreds of nanometers, vertical transistors offer very short channels compared to their horizontal counterparts. In fact, with a transition frequency of 40 MHz, vertical organic transistors are today the fastest organic transistors available.[9] A fundamental drawback of these transistor structures though is an increased device fabrication complexity, often requiring processes such as lift-off[10] or shadow mask structuring,[9,11] which are difficult to scale.

Vertical OFETs (VOFETs) are a special kind of vertical organic transistors, offering convenient device integration due to the structural similarity to conventional, planar transistors (Figure 1). Furthermore, this vertical architecture has been adopted to demonstrate advanced organic electronic devices with new functionalities such as a fast nonvolatile memory,[12] vertical complementary inverter circuits,[13] or vertical organic light-emitting transistors.[14] In VOFETs, the source and drain electrode are vertically stacked and are separated by a charge-blocking structure (CBS) and the organic semiconductor (Figure 1). The CBS effectively suppresses direct leakage current between source and drain, which is not controllable via the gate electrode. However, the exact geometric arrangement and the fabrication method of the CBS are most important for the device function and process integrability. In particular, the lateral overlap length, Lᵥ, of the CBS over the source electrode governs whether the charge carrier transport mainly occurs in the vertical or lateral direction. In this regard, several materials (e.g., SiO₂,[10,14] LiF,[15] SiOₓ,[13] ZnS[16]) and methods to fabricate and pattern CBSs have been proposed in previous reports: sputtering of oxides combined with a lift-off step[10] or shadow mask patterning,[14] or a so-called double-step photolithography.
where the first step is used to define the source electrode and the second to pattern the CBSs.\textsuperscript{[17]} However, all these methods suffer at least from the following two problems: either they are not applicable in mass production lines (e.g., due to the low yield of lift-off processes, the delicate alignment of shadow mask with a sub-micrometer accuracy), or they cause a substantial and irreproducible $L_{OV}$ of the CBS over the source electrodes (e.g., several micrometers in case of shadow mask patterning\textsuperscript{[11]}). In the latter case, charge carrier transport in these devices would mainly be limited by the lateral current flow, and hence, the advantage of the vertical arrangement is sacrificed.\textsuperscript{[12,17]} Furthermore, techniques such as sputtering or UV exposure during photolithography often lead to substantial damage to the underlying organic semiconductor material.

Here, we demonstrate VOFETs with a self-aligned configuration of the source electrode and our CBS fabricated by an electrochemical oxidation (so-called anodization) step on top of the organic semiconductor material. By the anodization process, the uppermost part of the source electrode is transformed into a dense and homogeneous insulating layer of AlO$_x$, which, regardless of the 3D geometry over the side-edge and plateau of the source electrode, ensures a perfectly conformal coverage. Moreover, the thickness of the CBS is well-controlled by the voltage during the anodization process. Depending on the edge profile of the source electrode, also the anodization technique causes an undesired lateral overlap of CBS, even sub-micrometer scaled, over the source electrode. However, in contrast to other techniques, anodization has the advantage that the overlap is precisely adjustable and readily optimized; therefore, we are able to demonstrate high-performance p-type as well as n-type VOFETs.

2. Results and Discussion

Figure 1 shows the structure of a vertical organic field-effect with electrochemically oxidized aluminum oxide (AlO$_x$) layers. These AlO$_x$ layers are separately used at the bottom (as a gate dielectric material) and as a CBS on the source electrode to block parasitic current paths. Additionally, the anodized AlO$_x$ at the bottom acts as a high-quality insulator ensuring a high dielectric capacitance\textsuperscript{[18–22]} of the gate insulator, and hence low driving voltage and high charge carrier density. Here, we employ a gate electrode of aluminum (50 nm) on a glass substrate, which is electrochemically oxidized (i.e., anodized) to create a gate dielectric layer of AlO$_x$ with a thickness of 8.5 nm.

Figure 2a shows a schematic diagram of the apparatus used for the anodization. A: electrolyte container, B: counter electrode (cathode), C: aluminum electrode (anode), D: potentiostat (Keithley source meter unit), E: computer to operate the potentiostat. b) Anodizing current between anode and cathode. c) Schematic image for AlO$_x$ growth on the Al surface during anodization. d) Specific capacitance of MIM (Al-AlO$_x$-Al) device (square) and anodized thickness (circle) depending on anodizing potential.
and the electrolyte for a fixed anodizing voltage (Figure 2c). For various conditions (anodizing potentials between 4 and 20 V), the capacitance of the anodized AlO\(_x\) layer is determined using metal-insulator-metal (MIM) devices of Al (50 nm)/AlO\(_x\)/Al (50 nm) with a top electrode subsequently evaporated onto the anodized layer. The specific capacitance of the MIM devices and the calculated thickness of anodized AlO\(_x\) (assuming a dielectric constant of 7) are plotted as functions of the anodizing potential (Figure 2d). As expected, the capacitance of the MIM devices (Al/AlO\(_x\)/Al) is inversely proportional to anodizing potential. Moreover, since the capacitance of the dielectric layer is inversely proportional to its thickness in this plate capacitor configuration, the thickness of AlO\(_x\) layer is precisely proportional to the anodizing potential providing precise experimental control.

When we use relatively low anodizing potential (4 V), the anodized AlO\(_x\) layer is very thin (9.3 nm). Due to the high dielectric constant of the oxide, the corresponding specific capacitance value of 800 nF cm\(^{-2}\) of this dense electrochemically grown layer is ideal for the use in field-effect transistors structures. In order to evaluate the enhancement of charge transport with the anodized AlO\(_x\) as a gate dielectric layer, conventional lateral OFETs with C\(_60\) as semiconductor material are fabricated. To further improve the interface between the organic semiconductor material and the metal oxide, we employ different interface modifying molecules, which help to passivate the anodized AlO\(_x\) surface and hence reduce the number of possible defect-states.

In Figure 3, transfer curves of OFETs with 8.5 nm thick anodized AlO\(_x\), as gate dielectric material treated with various self-assembled monolayers (SAM) such as octadecyltrichlorosilane, hexamethyldisilazane, or 12-cyclohexyldodecyl-phosphonic acid (CDPA) are shown. Most remarkably, the electron mobility reaches a value of 1.2 cm\(^2\) V\(^{-1}\) s\(^{-1}\) in the CDPA-treated C\(_60\) OFET structures (channel length L = 100 \(\mu\)m), and the threshold voltage \(V_{TH}\) is as low as 1.4 V (Table S1, Supporting Information). This notable high mobility can be attributed to a SAM of CDPA on the ultrathin AlO\(_x\) surface. CDPA has a phosphonic acid (PA) anchoring group with a cyclohexyl terminal group attached to a long alkyl chain. The PA anchoring group provides better stability to moisture, less tendency to homocondense between PAs, easy to react with metal oxide substrate regardless the content of surface hydroxyl groups, and more resistance of phosphonate in monolayer to hydrolysis than siloxane. Moreover, the cyclohexyl terminal group improves the interface properties between CDPA and organic semiconductor to enhance wettability and crystallinity of semiconductor. Therefore, CDPA effectively passivates the surface hydroxyl groups of high capacitance AlO\(_x\) dielectric layer and improves the carrier transfer of C\(_60\). As the results, CDPA-modified AlO\(_x\) dielectric layer enables a high performing OFETs with a high field-effect mobility and low operation voltage. For later comparison with the VOFET performance, we highlight that these horizontal OFETs with CDPA-modified AlO\(_x\) dielectrics can carry a channel-width-normalized on-state current of \(3 \times 10^{-8}\) A \(\mu\)m\(^{-1}\) at \(V_{DS} = 4\) V, \(V_{GS} = 4\) V.

Since the electrochemically oxidized AlO\(_x\) layers show excellent dielectric properties in the MIM and OFET devices, the anodized AlO\(_x\) is applied in the VOFET for the gate insulator as well as for the CBS. The fabrication and anodization steps are shown in schematic images (Figure S1, Supporting Information). First, an Al layer is deposited on glass as a gate electrode then anodized to form the AlO\(_x\) gate dielectric layer as also done for OFETs (Figure S1a, Supporting Information). After treating the gate dielectric layer with CDPA, a first organic semiconductor layer composed of C\(_60\) and the source electrode are sequentially deposited by thermal evaporation through a shadow mask on top of the anodized AlO\(_x\) gate dielectric layer (Figure S1b, Supporting Information). The source electrode consists of a thin layer of gold (10 nm) contacting with the C\(_60\) and Al on top. The Au-C\(_60\) contact allows for efficient charge carrier injection and remains unaffected during the anodization of Al due to the noble character of gold. Then the exposed surface of the Al source electrode is anodized to form an AlO\(_x\) CBS that fully covers the source electrode with 3D geometry over the side-edge and plateau (Figure S1c, Supporting Information). Subsequently a second organic semiconductor layer (also composed of C\(_60\)) and a drain electrode (Au) are deposited (Figure S1d, Supporting Information).

As discussed above, the lateral overlap length, \(L_{OV}\), is an important parameter that governs the performance of VOFETs. Ideally, \(L_{OV}\) should be as small as possible to make use of the short vertical channel length. However, a certain overlap is also required in order to exclude an undesired direct contact between source and drain. Therefore, the overlap length in VOFETs is mainly determined by the length of anodized AlO\(_x\), CBS (Figure 1). To estimate \(L_{OV}\) in VOFETs, 50 nm thick patterned Al films on glass substrates are electrochemically oxidized as a function of anodizing potentials (0–40 V), and the side edge is observed by an optical microscope (Figure 4). The aluminum (bright region due to reflecting light) at the edge of the Al film (Figure 4a) is partially transformed to AlO\(_x\) (dark region due to being transparent) after anodization (Figure 4b–d). Area of AlO\(_x\) and \(L_{OV}\) at the side edge of the patterned Al film increase as a function of anodizing potential from 4 to 40 V. More especially, \(L_{OV}\) is linearly increased with the anodizing potential (Figure 4e).

The geometry of patterned Al film is further measured by a surface profilometer, cross-sectional SEM, and cross-sectional TEM (Figure 5). In a surface profilometer data (Figure 5a), the

![Figure 3. Transfer curves of C\(_60\) n-type lateral OFETs with various SAM materials on anodized AlO\(_x\) gate dielectric layer by anodizing potential 4 V.](image-url)
thickness of Al gradually drops from the flat layer (region D) toward the border of the patterned Al film (region C) due to a pattern enlargement effect at a penumbra region of evaporation. After anodization, the Al layer in region B, which is thinner than the anodized ALO\textsubscript{x} thickness \( t_h \) (e.g., 9.3 nm at anodizing potential 4 V) at the outermost penumbra region of the film, is completely transformed into ALO\textsubscript{x} without a remaining Al underlayer. Here, the lateral length of the completely anodized ALO\textsubscript{x} in region B is defined as the overlap length \( L_{OV} \) which can be determined by \( t_h \), the native oxide thickness \( t_N \), and the inclination \( \theta \) at side edge of the Al layer as described in Equation (1)

\[
L_{OV} = \frac{t_h - t_N}{\sin \theta}
\]

Here, \( \theta \) is measured around 0.014°–0.15° by a surface profilometer, \( t_N \) is \( \approx 2 \text{ nm} \).[18] These small angles originate from the distance between shadow mask and substrate in the range of 100 \( \mu \text{m} \), which can hardly be avoided. The \( L_{OV} \) of the ALO\textsubscript{x} CBS measured by a cross-sectional SEM at the side edge is \( \approx 2.5 \mu \text{m} \) (Figure 5b) and comparable with the calculated \( L_{OV} \) (2.8 \( \mu \text{m} \)) for an anodization voltage of 4 V. Therefore, we can conclude that \( L_{OV} \) is systematically controlled by the conditions of the anodization process.

The formation of the ALO\textsubscript{x} in VOFETs is investigated in the cross-sectional images taken by TEM at the region A–D (Figure 5c), and the energy-dispersive X-ray analysis (EDX) cross-sectional images at region A and D (Figure 5d,e). In the cross-sectional TEM images, the thickness of the Al/ALO\textsubscript{x} layer (marked with an arrow) is gradually increased from region B to D at the interface between \( C_{60} \) (white) and the drain electrode (black) due to the penumbra during deposition. In addition, the EDX analysis reveals oxide formation (red-colored) in the VOFETs. ALO\textsubscript{x} can be clearly observed as CBS on the Al source electrode and ALO\textsubscript{x} gate dielectric layer on the bottom Al gate electrode, respectively. Furthermore, a very thin layer of ALO\textsubscript{x} is also observed at the contact between \( C_{60} \) and the Al source electrode. For this reason, the VOFETs discussed in the following were built using a double-electrode composed of Au (in contact with \( C_{60} \)) and Al.

The electrical performance of VOFETs with the electrochemically oxidized ALO\textsubscript{x} CBSs is shown in Figure 6. Figure 6a summarizes the transfer curves (drain current normalized by the width of the drain electrode) for n-type VOFETs built with different CBSs (different anodization voltages and sputtered SiO\textsubscript{2}). For better comparability, the gate dielectric layers for all devices are anodized at a potential 4 V. Table S2, Supporting Information, summarizes the geometry and performance parameters of VOFETs with CBSs. For the VOFET with the SiO\textsubscript{2} CBS (110 nm-thick SiO\textsubscript{2} layer patterned by the photolithography and SiO\textsubscript{2} sputtering on the source electrode in the previous research[18]), the drain current and on/off ratio are lower than for the anodized ALO\textsubscript{x} CBS devices. Furthermore, comparing the devices with CBSs anodized at different potentials (2 or 4 V, corresponding to an \( L_{OV} \) of 0.6 and 2.5 \( \mu \text{m} \), respectively), the threshold voltage of the VOFETs decreases with smaller anodized potential. As a result of short \( L_{OV} \) of VOFET, operation speed is noticeably increased in VOFETs. The maximum operation speed of transistor is characterized by transition frequency \( f_T \). OFETs with the modified gate dielectric layer composed of CDPA and ultrathin ALO\textsubscript{x} show the highest \( f_T \) of \( 5.7 \times 10^3 \) compared with the device with other SAM materials (Table S1, Supporting Information). However, the operation speed is noticeably increased in our VOFETs with anodized CBS in spite of identical semiconductor and dielectric layers in OFETs. \( f_T \) of VOFET is increased by two order of magnitude \( (2.7 \times 10^5) \) due to the shortened \( L_{OV} \) of anodized CBS.

Output curves of VOFETs with ALO\textsubscript{x} CBS anodized at 2 V and the gate dielectrics at 4 V are shown in Figure 6b. The output curves do not possess a linear regime. Additionally, they show only a poor saturation of drain current for larger drain-source voltage. Nevertheless, according to the transfer characteristics, the VOFET operates as a transistor, and a clear on- and off-state can be obtained by varying the gate-source voltage. According to previous publications, the non-ideal behavior of the output curves for VOFETs and overall device performance decrease are from the presence of contact resistance.[10,16] In general, when the channel resistance is smaller than the contact resistance, the contact resistance will determine the device performance. However, our best VOFETs (anodizing voltage of 2 V for the CBS and 4 V for the gate dielectrics) provide a normalized...
current density of up to $\approx 2 \times 10^{-7} \ \text{A} \ \mu\text{m}^{-1}$ at $V_{GS} = V_{DS} = 4 \ \text{V}$, hence they clearly outperform the reference OFET. It is because the inert interfacial layer (10 nm thick Au layer) is used underneath the Al source electrode to protect from the oxidation of the bottom of the source electrode film and the resulting poor contact at the interface. Thus contact resistance and charge injection at the interface in VOFET were compensated by the inert interfacial layer. In addition, although VOFETs have been exposed to ambient atmosphere and the anodization bath that potentially damage the semiconductor materials, no significant deterioration was observed. This is because the electrochemical reaction is selectively oxidizing the Al surface while nonreactive with organic semiconductor, and the residual moisture is promptly removed by heating the device in the inert nitrogen gas right after the anodization.

In order to evaluate the charge-blocking ability of the anodized CBSs, we apply the source-drain voltage on VOFETs with various CBSs and observe the source-drain leakage current and the dielectric breakdown of VOFETs. (Figure 6c). The leakage current via the SiO$_2$ CBS layer steeply increases with voltage starting at 0 V, and an irreversible breakdown is observed at 6 V, which corresponds to a breakdown field of only $545 \ \text{kV} \ \text{cm}^{-1}$. This low breakdown field is probably caused by poor side edge coverage of the Al electrode by SiO$_2$. However, the VOFETs with the electrochemically oxidized AlO$_x$ CBSs, which anodized with various potential (2, 4, 10 V) show the significantly lower source-drain leakage current and higher breakdown fields of up to $5 \ \text{MV} \ \text{cm}^{-1}$ (for 10 V anodization voltage). The drain leakage current per channel width is as low as $10^{-11} \ \text{A} \ \mu\text{m}^{-1}$, and we believe it results from the inherent off-state leakage current across the organic semiconductor material itself. As a consequence, the VOFETs with anodized AlO$_x$ CBS show the higher on/off current ratio and on-current level in the output curve compared to VOFETs with the conventional CBS such as sputtered SiO$_2$. We analyze the current breakdown electric field of various CBSs depending on semiconductor bottom layers (Figure S2, Supporting Information). Anodized AlO$_x$ CBSs are additionally formed on n-type polymer semiconductor layer (N2200) with anodizing potential of 4 and 10 V for comparison. The leakage current levels of AlO$_x$ CBSs on N2200 are at the same

---

Figure 5. a) Height profile at the edge of the Al source electrode for various anodizing potential. Region A: the surface of the bottom C$_{60}$ layer, B: the side edge of the CBS, C: the inclination face of the CBS, D: the top surface of the CBS. b) SEM image of the CBS at the edge on C$_{60}$. c) TEM cross-sectional images at the positions A–D. EDX cross-sectional images at position d) A and e) D. O, Al, and C are colored red, green, and blue, respectively.
level (lower $10^{-11}$ $\text{A} \cdot \text{m}^{-2}$) as the CBSs on $C_{60}$. This iterative current level of CBS regardless of the semiconductor film proves the reproducible electrochemical fabrication of fine-tuned CBS architecture and the corresponding reliable performance of VOFET. The breakdown electric field of VOFET with anodized AlO$_x$ CBS is significantly higher (>3 MV cm$^{-1}$) than that with 110 nm thick SiO$_2$ CBS (0.5 MV cm$^{-1}$) due to better charge blocking ability. The breakdown electric field of VOFET with anodized AlO$_x$ CBS by 10 V on N2200 is slightly lower than that on $C_{60}$ due to the relatively poor surface uniformity of the spin-cast polymer film.

Finally, to study whether this electrochemically oxidation method can also be applied to hole conducting devices, we fabricated p-type VOFETs based on pentacene with the anodized AlO$_x$ for CBS and gate dielectric which is anodized at 2 and 4 V, respectively. The transfer curve of such a device is shown in Figure 7. Also, p-type VOFETs work well even though a larger threshold voltage is observed compared to n-type devices. Overall, the performance of p-type and n-type devices is comparable in terms of on/off ratio and maximum on-current.

3. Conclusion

In summary, a novel and easy-to-apply processing method for the fabrication of high-performance VOFETs has been presented. This method is based on potentiostatic electrochemical oxidation, so-called anodization, which is carried out directly on top of the organic semiconductor materials without significant damage and it enables the formation of high quality anodized AlO$_x$ films that are used to electrically separate source and drain electrodes and clearly defined the channel length in this vertical transistor configuration. The anodized AlO$_x$ layer covers the 3D geometry of the side edge of the source electrode perfectly and helps to suppress undesired leakage current. Furthermore, the anodization method offers the possibility to precisely adjust the lateral overlap of the source electrode and CBS, which is an essential device parameter and hence enables a facile control over the electrical device performance. Moreover, we successfully applied this method for p- as well as n-type vertical organic transistors and obtained a similar device performance in terms of on/off ratio and on-current. This demonstration of p- and n-type VOFETs with AlO$_x$ CBS, which is precisely controlled by...
anodization, might open up the possibility to build complementary circuits based on high-performance vertical organic transistors with a substantially simplified process. The anodization is used not only for industry-friendly method, but also it enables fine-tuned and reproducible VOFET designs. Therefore, we believe the anodized CBS method paves the road toward high performance VOFETs based on scalable and industry-friendly processes.

4. Experimental Section

Anodized Aluminum Oxide: To anodize aluminum films, a 0.01 M citric acid monohydrate (C₆H₈O₇⋅H₂O) electrolyte was prepared using deionization water. A total of 30 nm thick aluminum films were vacuum-deposited on a glass substrate to form the AlOₓ layer. The glass/Al substrate and aluminum foil were immersed into the electrolyte as a working electrode (anode) and a counter electrode (cathode), respectively. A constant voltage of 4 V as an anodization potential was applied to a working electrode by aKeithley 2400. The anodization potential had been applied for several minutes in room temperature until the monitored current was decreased and unchanged. The samples were subsequently rinsed with deionization water and carefully dried in a nitrogen stream.

Measurement of Capacitance and Leakage Current: The capacitance of anodized AlOₓ layer was measured from a MIM structure, which had vacuum-deposited Al layers as top and bottom electrodes. The specific capacitance (capacitance per unit area, nF cm⁻²) of AlOₓ layer was measured in a frequency range of 20 Hz to 1 MHz from a MIM structure. The leakage current was measured from the same MIM structure with a voltage of 0–10 V.

Device Fabrication and Characterization: To fabricate VOFET devices, we used two different substrates of p-type silicon wafers coated with vacuum-deposited Al film and anodized AlOₓ (glass/Al/AlOₓ). The substrates were cleaned with acetone and isopropanol in an ultrasonic bath for 10 min each, and then dried in a nitrogen stream. After oxygen plasma treatment, the device was heated up 150 °C and subsequently rinsed with deionization water and carefully dried in a nitrogen filled glove box using HP 4145B parameter analyzer. Electrical characterization was performed in a nitrogen filled glove box using HP 4145B parameter analyzer.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
K.-G.L. and E.G. contributed equally to this work. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2018R1C1B6004422) and the German Research Foundation (DFG) within the Cluster of Excellence Center for Advancing Electronics Dresden (cfaed) and the DFG project HEFOS (grant no. FI2449/1-1). E.G. acknowledges the financial support from China Scholarship Council (no. 201706890003).

Conflict of Interest
The authors declare no conflict of interest.

Keywords
aluminum oxide, anodization, charge transfer length, organic transistors, VOFET

Received: February 23, 2020
Revised: March 24, 2020
Published online: May 14, 2020

[1] T. Sekitani, U. Zschieschang, H. Klauck, T. Someya, Nat. Mater. 2010, 9, 1015.
[2] H. Sirringhaus, Adv. Mater. 2014, 9, 1319.
[3] K. J. Woon, Y. Takeda, R. Shibaku, S. Tokito, K. Cho, S. Jung, Nat. Commun. 2019, 10, 54.
[4] K. Haase, C. T. da Rocha, C. Hauenstein, Y. Zheng, M. Hamsch, S. C. B. Mannsfeld, Adv. Electron. Mater. 2019, 4, 1800076.
[5] G. Schweicher, G. D’Avino, M. T. Ruggiero, D. J. Harkin, K. Broch, D. Venkateshvaran, G. Liu, A. Richard, C. Ruzié, J. Armstrong, A. R. Kennedy, K. Shankland, K. Takimiya, Y. H. Geerts, J. Zeiter, S. Fratini, H. Sirringhaus, Adv. Mater. 2019, 31, 1902407.
[6] U. Zschieschang, J. W. Borchert, M. Giorgio, M. Caironi, F. Letzkus, J. N. Burghartz, U. Waizmann, J. Weis, S. Ludwigs, H. Klauck, Adv. Funct. Mater. 2019, 1903812.
[7] M. Kitamura, Y. Arakawa, Jpn. J. Appl. Phys. 2011, 50, 01BC01.
[8] H. Kleemann, K. Krechan, A. Fischer, K. Leo, Adv. Funct. Mater. 2020, 1907113.
[9] B. K. Boroujeni, M. P. Klinger, A. Fischer, H. Kleemann, K. Leo, F. Ellinger, Sci. Rep. 2018, 8, 7643.
[10] H. Kleemann, A. A. Günther, K. Leo, B. Lussem, Small 2013, 9, 3670.
[11] A. A. Günther, M. Sawatzki, P. Formánek, D. Kasemann, K. Leo, Adv. Funct. Mater. 2016, 26, 768.
[12] X. J. She, D. Gustafsson, H. Sirringhaus, Adv. Mater. 2017, 160, 4769.
[13] M. Greenman, S. Yoffs, N. Tessler, Appl. Phys. Lett. 2016, 108, 043301.
[14] G. Lee, I. H. Lee, H. L. Park, S.-H. Lee, J. Han, C. Lee, C. M. Keum, S.-D. Lee, J. Appl. Phys. 2017, 121, 024502.
[15] X.-J. She, D. Gustafsson, H. Sirringhaus, Adv. Mater. 2017, 29, 1604769.
[16] H. Kwon, M. Kim, H. Cho, H. Moon, J. Lee, S. Yoo, Adv. Funct. Mater. 2016, 26, 6888.
[17] F. M. Sawatzki, D. H. Doan, H. Kleemann, M. Liero, A. Glitzky, T. Koprucci, K. Leo, Phys. Rev. Appl. 2018, 3, 034069.
[18] M. Kaltenbrunner, P. Stadler, R. Schwödiauer, A. W. Hassel, N. S. Sariciftci, S. Bauer, Adv. Mater. 2011, 23, 4892.
[19] D. Diesing, A. W. Hassel, M. Lohrengel, Thin Solid Films 1999, 342, 282.
[20] M. Wang, Y. Liu, H. Yang, Electrochim. Acta 2012, 62, 424.
[21] L. A. Majewski, R. Schroeder, M. Voigt, M. Grell, J. Phys. D: Appl. Phys. 2004, 37, 3367.
[22] F. Dollinger, K.-G. Lim, Y. Li, E. Guo, P. Formánek, R. Hübner, A. Fischer, H. Kleemann, K. Leo, Adv. Mater. 2019, 31, 1900917.
[23] S. Yogev, R. Matsubara, M. Nakamura, U. Zschieschang, H. Klauk, Y. Rosenwaks, Phys. Rev. Lett. 2013, 110, 036803.

[24] D. Liu, X. Xu, Y. Su, Z. He, J. Xu, Q. Miao, Angew. Chem., Int. Ed. 2013, 52, 6222.

[25] D. Liu, Z. He, Y. Su, Y. Diao, S. C. B. Mannsfeld, Z. Bao, J. Xu, Q. Miao, Adv. Mater. 2014, 26, 7190.

[26] X. Xu, Y. Yao, B. Shan, X. Gu, D. Liu, J. Liu, J. Xu, N. Zhao, W. Hu, Q. Miao, Adv. Mater. 2016, 28, 5276.

[27] H. Ma, O. Acton, D. O. Hutchins, N. Cernetic, A. K.-Y. Jen, Phys. Chem. Chem. Phys. 2012, 14, 14110.

[28] G. J. Burger, E. J. T. Smulders, J. W. Berenschot, T. S. J. Lammerink, J. H. J. Fluitman, S. Imai, Sens. Actuators, A 1996, 54, 669.