Contact Doping for Vertical Organic Field-Effect Transistors

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Doping is a powerful tool to overcome contact limitations in short-channel organic field-effect transistors (OFETs) and has been successfully used in the past to improve the charge carrier injection in OFETs. The present study applies this familiar concept to the architecture of vertical organic field-effect transistors (VOFETs), which are often severely limited by injection due to their very short channel lengths. The present study shows that the performance of p-type VOFETs with pentacene as an active material can be significantly enhanced by the addition of the common p-dopant C_{60}F_{36} as a thin injection layer underneath the VOFET source electrode, resulting in an increase of On-state current and On/Off ratio by one order of magnitude. The present study further investigates mixed injection layers of pentacene and the p-dopant and finds that the improvement is less pronounced than for the pure dopant layers and depends on the concentration of dopant molecules in the injection layer. Through application of the transfer length method to equivalent OFET geometries, the present study is finally able to link the observed improvement to a decrease in transfer length and can thus conclude that this length is a crucial parameter onto which further improvement efforts have to be concentrated to realize true short-channel VOFETs.

1. Introduction

The concept of contact doping, adopted from silicon technology, has been successfully employed in organic field-effect transistors (OFETs) by inserting a thin injection layer between the metal contact and the organic semiconductor, which may be only a few nanometers thick and consists of a metal oxide, self-assembled monolayer (SAM), or organic compound. Insertion of a slightly thicker layer of the active semiconductor material, doped with a suitable p- or n-dopant, has also been reported as contact doping.

Both approaches are known to decrease contact resistance in bottom- as well as top-contact OFETs through various mechanisms and are particularly important tools for counteracting the prominent contact effects often encountered in short-channel OFETs. Such contact effects can also be observed in vertical organic field-effect transistors (VOFETs), as these devices typically have channel lengths on the order of a few micrometers or less, depending on the specific geometry. This contact limitation, while clearly observed in several VOFET devices so far, has not yet been addressed by specific contact engineering, as the basic proof of principle was often the aim of the respective publication. It stands to reason, however, that the concepts for contact doping established in lateral OFETs can directly be transferred to the VOFET architecture, especially in those cases where the device structure in the vicinity of the source contact resembles that of a lateral OFET. Furthermore, the device architecture and fabrication process of certain VOFET geometries allow for selective doping of the individual contacts without the need for additional structuring steps. Consequently, it is possible to separately investigate the effects of contact doping at the source and drain electrodes.

In this contribution, we demonstrate a p-type VOFET with pentacene as the active material, source and drain contacts made of gold, and injection layers of either pure p-dopant or mixed layers of pentacene and p-dopant. As dopant molecule, the fluorinated organic compound C_{60}F_{36} is used, as it has demonstrated good doping properties for pentacene and is more stable in the VOFET fabrication process than the more common dopant F_{2}TCNQ. The effect on contact resistance of each of these layers is further investigated by the transfer length method (TLM).

2. Results and Discussion

The effects of contact doping are investigated primarily in the previously published short-channel VOFET with pentacene as semiconductor and Au source and drain contacts (see Figure 1a...
for a device schematic), while TLM analysis is performed on OFETs with the same material system and layer arrangement (see Figure 1b). This separate analysis is done in order to ensure that the TLM yields the correct results, as it is unclear whether this analysis can be employed in a VOFET geometry, the exact functional principles of this geometry not being very well understood at present. It is assumed, however, that the charge carrier injection mechanism in the OFET and VOFET are identical, so that the results of the TLM analysis in OFETs also describe the effects of contact doping in the VOFET accurately.

Presumably, the injection barrier for holes from Au into pentacene should be negligible because of the energy level alignment between the Au work function (≈5 eV) and the pentacene HOMO (≈5.1 eV). Basic metallization effects or impurities at the electrode–semiconductor interface, brought into the system, e.g., during the photolithography process (see the Experimental Section), can already lead to the formation of a noticeable injection barrier, which manifests as a nonlinear behavior of the output characteristics of the VOFET at small drain voltages \( V_D \). Indeed, Watkins et al. reported a hole injection barrier from Au top contacts into pentacene as large as 1 eV, despite the seemingly well-matching energy levels of the pure materials.

To stabilize the interface and form a reproducible low-injection barrier, two different contact doping approaches are tested: a 2 nm thick layer of pure \( \text{C}_{60}\text{F}_{36} \) underneath the VOFET source electrode and a 10 nm thick layer of pentacene, doped with 1 mol% of \( \text{C}_{60}\text{F}_{36} \) in the same position. For completeness, a VOFET with 2 nm \( \text{C}_{60}\text{F}_{36} \) inserted between the top layer of pentacene and the Au drain electrode is also measured. The resultant transfer and output characteristics (\( I_D \) vs \( V_G \) and $V_D$ vs $V_G$) are shown in Figure 2.

![Figure 1. a) Device schematic for contact-doped VOFETs and b) TLM OFETs, with contact doping layers indicated in red, and c) the doping mechanism of \( \text{C}_{60}\text{F}_{36} \) in pentacene.](image)

![Figure 2. Comparison of transfer characteristics at a) \( V_D = -10 \) V and b) output characteristics at \( V_G = -10 \) V of VOFETs with contact doping of 2 nm \( \text{C}_{60}\text{F}_{36} \) underneath the source (red), 10 nm P5: \( \text{C}_{60}\text{F}_{36} \) underneath the source (green, doping concentration 1 mol%) and 2 nm \( \text{C}_{60}\text{F}_{36} \) underneath the drain (blue) respectively. A VOFET without contact doping is shown for reference (black). Extracted values are given in the upper section of Table 1.](image)
I_D vs V_D are shown in Figure 2 and extracted parameters for each device are summarized in the upper section of Table 1.

It is immediately evident from this data that applying a thin layer of pure dopant as contact doping substantially improves VOFET performance. This will be analyzed in more detail in the next section. Application of the same thin dopant layer to the drain electrode, on the other hand, primarily results in an increased subthreshold swing S, while having little effect on On-state current or On/Off ratio. In standard OFET geometries, S is given as

$$ S = \frac{\partial \ln V_G}{\partial \ln I_D} = \frac{k_B T}{e} \ln(10) \left( 1 + \frac{e N_i}{C_{dil}} \right) $$

where N_i is the density of traps at the gate dielectric interface and C_{dil} is the capacitance of this dielectric.[26] In the present case, the additional shallow traps are expected near the extraction contact due to ionized dopant molecules, rather than at the dielectric interface. Nevertheless, it seems reasonable to take the subthreshold swing as a general measure for trap density. The slight increase in On/Off ratio and threshold voltage (see Table 1) may then be explained by a lower leakage current due to charge carrier trapping near the drain. Evidently, the transconductance \( g_m \) is not improved upon doping the drain contact, as extraction of holes from pentacene into gold is very good already in the undoped system. Doping of the drain region thus need not concern us further.

When regarding the two versions of contact doping applied to the source electrode, one finds that they have very different effects on the VOFET performance. A more detailed discussion of each of the concepts thus appears necessary in order to understand this observation.

### 2.1. Contact Doping by a Thin Injection Layer

Application of a thin layer of pure p-dopant between the source electrode and the semiconductor significantly improves VOFET performance as indicated by Figure 2. This effect is not simply due to a shift in threshold voltage (see Table 1), but results from an actual reduction of contact resistance, as indicated by the fact that also the transconductance \( g_m \) increases by one order of magnitude. A similar effect has also been observed when exchanging the C_{60}F_{36} for the common p-dopant F_6-TCNNQ (improvement by a factor of 2, see Figure S7 in the Supporting Information) and has previously been reported for short-channel OFETs.[1] The reasons for this significant improvement can be investigated in more detail by performing a TLM analysis (see the Supporting Information for details) on bottom gate, top contact OFETs. By using the same set of materials, substrate, geometry, and fabrication process as for the VOFET devices (see the Experimental Section and Figure 1b), it is possible to transfer the results of such a TLM analysis directly back into the VOFET geometry, as the injection behavior in the OFET and VOFET devices must be identical. The extracted width-normalized contact resistance and transfer length are displayed in Figure 3. A significant drop in contact resistance is observed upon doping and the V_G dependence of the contact resistance, typical for OFETs, is considerably weakened. The drop in contact resistance is further accompanied by an equally large reduction in the transfer length, with the latter becoming independent of V_G.

Due to the size of the dopant molecule, the addition of nominally 2 nm of C_{60}F_{36} (as measured by quartz crystal microbalance (QCM)) does not result in a closed dopant layer, but rather in small islands of C_{60}F_{36} accumulating on the surface of the pentacene film (see the Supporting Information and, for comparison, the supporting information of ref. [1]). It is to be expected that the size of C_{60}F_{36} also largely prevents dopant diffusion into the underlying pentacene. Therefore, the resistivity of the bulk semiconductor between the source and the conductive channel should remain unchanged upon doping, so that the reduction in contact resistance must stem from an enhancement at the source contact. Indeed, the

| Table 1. Extracted transistor parameters for devices displayed in Figures 2 and 4. |
|-----------------|--------|---------|-----------------|
|                | V_th [V] | g_m [µS] | S [V dec⁻¹] | On/Off ratio |
| Figure 2       |         |         |               |              |
| Reference       | -1.14 | 4.12 | 0.52 | 4.7 \times 10⁴ |
| 2 nm C_{60}F_{36} (S) | -0.29 | 40.60 | 0.86 | 1.5 \times 10⁴ |
| 10 nm P5:C_{60}F_{36} (S) | -2.44 | 2.90 | 0.65 | 5.5 \times 10⁴ |
| 2 nm C_{60}F_{36} (D) | -1.81 | 3.96 | 0.89 | 7.6 \times 10⁴ |
| Figure 4       |         |         |               |              |
| Reference       | -1.37 | 6.22 | 0.34 | 4.5 \times 10⁴ |
| 1 mol%          | -0.70 | 2.14 | 0.26 | 4.1 \times 10⁴ |
| 4 mol%          | -1.88 | 20.88 | 0.39 | 4.9 \times 10⁴ |
| 6 mol%          | -1.42 | 21.74 | 0.43 | 6.7 \times 10⁴ |

Figure 3. Width-normalized contact resistance and transfer length versus gate voltage, as extracted from the TLM analysis, for a contact-doped pentacene OFET with 2 nm C_{60}F_{36} underneath the contacts (red) and a reference device (black).
increased subthreshold swing of the doped device (see Figure 2 and Table 1) suggests that a large number of dopants have been ionized, i.e., free charge carriers have been made available near the source–semiconductor interface. While it is at present not entirely known whether this doping process occurs via a direct charge transfer, as illustrated in Figure 1c, or by a matrix–dopant hybridization,[23] the obtained TLM and VOFET data suggests that a large number of free charge carriers are provided at the source–semiconductor interface upon doping, resulting in a narrowing of the depletion region at the source contact and thus an effective narrowing of the Schottky barrier, so that injection from the source via tunneling is enhanced.

A further beneficial effect may be provided by the inherent roughness of the polycrystalline pentacene films: Some dopant clusters will naturally accumulate also on top of the thinner parts of the underlying pentacene film, a contact-doped region with narrower injection barrier may thus be located very near the gate dielectric interface. If several such regions are located close to the edge of the source contact, a large part of the transistor current may be injected from precisely these regions, which reduces the typical current crowding phenomenon somewhat and may thus explain the significant reduction in transfer length observed for contact doping by such pure dopant layers.

2.2. Contact Doping by a Mixed Layer

Figure 2 suggests that doping the injection contact with a mixed layer of pentacene and C_{60}F_{36} is not at all beneficial for the VOFET geometry, but rather decreases the On-state current. This is not merely an effect of the threshold voltage shift, as indicated by the fact that also the transconductance is slightly lowered compared to the reference device. To examine the effect of a mixed layer doping approach further, a second set of VOFETs with varying concentrations of p-dopant in the 10 nm pentacene layer is fabricated. The results of this second experiment are shown in Figure 4 and the lower section of Table 1. Here, the sample with an injection layer consisting of pentacene with 1 mol% of C_{60}F_{36} in fact has a lower threshold voltage than the reference sample (see Table 1), yet the transconductance is still noticeably lowered for this device.

Once again, a TLM analysis of the equivalent OFETs yields an explanation for this phenomenon. As is visible from

![Figure 4](image)

**Figure 4.** Comparison of transfer characteristics at a) \(V_D = -6\) V and b) output characteristics at \(V_G = -6\) V between a reference VOFET (black) and VOFETs with a contact doping layer of 10 nm P5:C_{60}F_{36} at doping ratios of 1 mol% (green), 4 mol% (red), and 6 mol% (blue). Extracted values are displayed in the lower section of Table 1.

![Figure 5](image)

**Figure 5.** Width-normalized contact resistance and transfer length versus gate voltage, as extracted from the TLM analysis, for contact-doped pentacene OFETs with 10 nm P5:C_{60}F_{36} underneath the contacts at doping concentrations of 1 mol% (green), 4 mol% (red), and 6 mol% (blue). A reference device without contact doping is shown as well (black).
Figure 5, the injection layer with 10 nm pentacene, doped by 1 mol% of C₆₀F₃₆, in fact increases contact resistance and transfer length rather than reducing it. Only increasing the doping concentration to 4 mol% or higher results in a noticeable improvement in contact resistance and thus OFET and VOFET performance.

The effects of increasing doping concentration in a pentacene film can be investigated in a simple OFET geometry, as previously done for F₆-TCNNQ.²⁷ Performing conductivity and mobility measurements in such an OFET geometry reveals a clear trade-off between the conductivity of a pentacene film doped by C₆₀F₃₆ and the resultant hole mobility, which is caused by a change in pentacene morphology due to the dopant addition (see Figure 6) and a simultaneous increase of trap filling and free charge carriers in the semiconductor due to the p-doping effect.

Consequently, a mixed layer of low doping concentration, inserted as injection layer between the VOFET source contact and the semiconductor, provides a certain amount of trap filling and perhaps even free charge carriers. This may result in injection barrier narrowing, as discussed previously. At the same time, however, the mixed layer contributes an additional component to the bulk semiconductor resistance between the source and the conductive channel. This contribution is naturally larger for mixed layers with low doping concentrations and may therefore outbalance the reduction in contact resistance due to barrier narrowing, as is the case for the 1 mol% layer investigated here. Increasing the doping concentration to 4 or 6 mol% evidently results in a net positive effect, as the conductivity of these layers is higher (see Figure 6), thus the contribution to the bulk resistance is decreased, while the increased doping concentration results in a larger number of free charge carriers (see the subthreshold swing for these samples in Table 1) and thus the expected barrier narrowing.

Comparing the characteristics of VOFETs employing different kinds of contact doping, it seems evident that from a material usage point, application of a thin injection layer of pure dopant is the more efficient choice, as this also provides the best On/Off ratio of all the devices presented here. The drawback of an increased subthreshold swing in this case may perhaps be overlooked for many applications as the significant reduction in threshold voltage still affords low driving voltages and thus makes these contact-doped VOFETs particularly interesting for applications with low-power consumption.

3. Discussion of VOFET Operation

In the light of the results presented here, it seems necessary to briefly revisit the operational principles of the presented VOFET geometry. Firstly, the successful application of injection layers to the VOFET geometry proves conclusively that charge carriers are indeed injected from the bottom surface of the source contact, just as in a conventional top contact OFET. The good On/Off ratios achieved through this mechanism further suggest that injection through the vertical edge of the source is suppressed, since it would otherwise constitute a considerable Off-state current (as observed, e.g., by Stutzmann et al. and Parashkov et al.¹⁷,¹⁸). Examining the source–drain overlap region by scanning electron microscopy (SEM), one finds that the insulating layer of SiO₂, which is placed on top of the source electrode, does in fact have a considerable overlap into the vertical channel and thus prevents injection from the edge of the source electrode. From the SEM image displayed in Figure 7a, it is possible to estimate this overlap as \( L_{\text{inst}} = 3.2 \, \mu \text{m} \). A charge carrier emitted from the source electrode into the underlying semiconductor must consequently move this distance \( L_{\text{inst}} \) in the lower semiconductor layer before it is able to enter the vertical channel and be collected by the drain electrode. This, however, is only true for charge carriers emitted directly at the edge of the source contact. The majority of carriers, however, will be injected from within an area \( A = WL_{\text{inst}} \) of the source electrode’s bottom surface, where \( W \) is the width of the source contact and \( L_{\text{inst}} \) is the transfer length as before. The average distance traveled by any charge carrier inside the VOFET is thus gate-voltage-dependent and may be used as an effective channel length for the VOFET, given as

\[
L_{\text{eff}}(V_C) = L_{\text{ch}} + L_{1/2}(V_C) + L_{\text{inst}}
\]

(2)

Figure 6. Tapping mode AFM images of 30 nm P5:C₆₀F₃₆ in doping concentrations of a) 0 mol%, b) 1 mol%, c) 4 mol%, and d) 6 mol% on silicon substrates coated with 30 nm Al₂O₃ and treated with HMDS. e) Conductivity and mobility as a function of doping concentration, measured in an OFET geometry of 30 nm P5:C₆₀F₃₆ and 40 nm Au on silicon substrates with 30 nm Al₂O₃ as gate dielectric, as previously done in ref. [²⁷].
The simulated curves are produced by using Equations (2) and (6) and assuming $L_{Ch} = 50$ nm and $L_{ins} = 3.2$ μm. Fit parameters for the red lines are $\mu = 0.27 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 1.66 \times 10^{-5}$ Ωm for the contact-doped device in (b) and $\mu = 0.34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 6.46 \times 10^{-3}$ Ωm for the reference device in (c). Other fits are obtained by excluding either the transfer length (blue) or both transfer length and insulator overlap (green and purple) from Equation (2). The green line is then obtained using a lower vertical mobility for pentacene, as suggested by ref. [29], while the purple line represents the transfer characteristics of a VOFET with the previously used values for $\mu$ and only considering the vertical channel length.

where $L_{Ch}$ is the length of the vertical channel, $L_T$ ($V_C$) is the gate-voltage-dependent transfer length (as extracted from TLM analysis), and $L_{ins}$ is the overlap length of the source insulator over the vertical edge of the source contact. Within the crowded current model,[28] the transfer length is given as

$$L_T(V_C) = \frac{r_C}{W_{Ch}}$$

where $r_C$ and $r_{Ch}$ are the contact and channel resistivities and $W$ is defined in the same way as before. Using

$$r_C = \frac{1}{WC_{ad}\mu(V_C - V_{th})}$$

for the channel resistivity, the gate-voltage-dependent transfer length becomes

$$L_T(V_C) = \sqrt{r_{Ch}C_{ad}\mu(V_C - V_{th})}$$

Using the effective mobility $\mu$ and the contact resistivity $r_C$ as fit parameters, one may fit this equation to the TLM data presented in the previous sections. This is done in the lower sections of Figure 7b,c (red line). It is further possible to insert this expression into Equation (2), so as to obtain an expression for the effective channel length of the VOFET which is gate-voltage-dependent.

In the devices presented here, it has been demonstrated that $L_{Ch} \ll L_T + L_{ins}$ and so charge transport in the VOFET may be dominated by the horizontal diffusion transport near the gate dielectric interface, rather than drift transport in the vertical channel. If this is the case, then it should be possible to model the characteristics of a VOFET by the standard expression derived from the gradual channel approximation,[29] so that

$$I_{D,sat} = \frac{\mu C_{ad} W}{2L_{eff}} (V_C - V_{th})^2$$

for the saturation regime. Using Equations (2) and (5) for the channel length in this expression, the transfer characteristics of the reference device and contact-doped device discussed in Section 2.1 have been fitted. A least-squares algorithm has been employed to determine the best fit parameters for $\mu$ and $r_C$ and the results of this fit are displayed in the upper sections of Figure 7b,c (red lines). It is indeed found that the use of the effective channel length describes the observed transfer characteristics of these devices rather well, provided that one assumes an effective mobility in the pentacene layers which is somewhat lower than the typically measured field-effect mobilities. The best fit parameters indeed are $\mu = 0.27 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 1.66 \times 10^{-5}$ Ωm for the contact-doped device (Figure 7b) and $\mu = 0.34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 6.46 \times 10^{-3}$ Ωm for the reference device (Figure 7c). The mobilities obtained from the fit are in good agreement with those determined from the transfer characteristics of the equivalent OFETs during TLM. Figure 7b,c further shows fit lines obtained by removing the $L_T$ term from Equation (2) (blue line) or by excluding both $L_T$ and $L_{ins}$ and using only $L_{Ch}$ as effective VOFET channel length. In the latter case, fits have been attempted both with the previously used

![Figure 7](https://www.materialsviews.com/afm/journal/10.1002/adfm.201600582){:target="_blank"} a) SEM image of the source–drain overlap region of the VOFET. Measured (black squares) and simulated (lines) transfer characteristics of the b) contact-doped and c) reference devices presented in Section 2.1. The simulated curves are produced by using Equations (2) and (6) and assuming $L_{Ch} = 50$ nm and $L_{ins} = 3.2$ μm. Fit parameters for the red lines are $\mu = 0.27 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 1.66 \times 10^{-5}$ Ωm for the contact-doped device in (b) and $\mu = 0.34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 6.46 \times 10^{-3}$ Ωm for the reference device in (c). Other fits are obtained by excluding either the transfer length (blue) or both transfer length and insulator overlap (green and purple) from Equation (2). The green line is then obtained using a lower vertical mobility for pentacene, as suggested by ref. [29], while the purple line represents the transfer characteristics of a VOFET with the previously used values for $\mu$ and only considering the vertical channel length. The best fit parameters indeed are $\mu = 0.27 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 1.66 \times 10^{-5}$ Ωm for the contact-doped device (Figure 7b) and $\mu = 0.34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $r_C = 6.46 \times 10^{-3}$ Ωm for the reference device (Figure 7c). The mobilities obtained from the fit are in good agreement with those determined from the transfer characteristics of the equivalent OFETs during TLM. Figure 7b,c further shows fit lines obtained by removing the $L_T$ term from Equation (2) (blue line) or by excluding both $L_T$ and $L_{ins}$ and using only $L_{Ch}$ as effective VOFET channel length. In the latter case, fits have been attempted both with the previously used
values for $\mu$ (purple line) and with a lower mobility for transport through the vertical channel as approximated in a previous publication $^{[29]}$ (green line). From these latter fits it is immediately obvious that inclusion of both $L_T$ and $L_{\text{ins}}$ into the effective channel length is vital in order to arrive at the correct transfer characteristics. This, in turn, is conclusive proof that the vertical transport, even when considering the lowered mobility for pentacene in this direction, $^{[29]}$ cannot be the limiting factor in this VOFET geometry.

In the case of a proper fit with voltage-dependent $L_T$ and $L_{\text{ins}}$ as measured by SEM, the fitting functions for both devices show inaccuracies at lower $V_G$ due to the lack of $L_D$ data obtained in this region. Nevertheless, this simple simulation illustrates that it is indeed possible to describe the present VOFET geometry as an OFET, i.e., by the gradual channel approximation, if one takes into account the insulator overlap and transfer length as limiting parameters for the effective transistor channel length. While the VOFET structure, at first glance, differs significantly from the conventional OFET, the present condition of $L_{\text{Ch}} \ll L_T + L_{\text{ins}}$ may be used to interpret the VOFET as a short-channel OFET with $L = L_T + L_{\text{ins}}$, where transport through the vertical channel may simply be included as a larger contact resistance at the drain electrode.

Together with the experimental data presented in the previous sections, this now represents a much more complete understanding of the VOFET geometry discussed here, as well as similar geometries published previously by other groups. $^{[15,17-21,30]}$ It is evident from the data that while many groups working on such VOFET geometries claim to have reduced their devices channel length to 1 $\mu$m or less, a truly accurate description of a VOFET can only be given if the total transport path, including especially the transfer length of the source contact and (in geometries similar to the present one) the insulator overlap, is known. Devices such as those of Stutzmann et al. $^{[15]}$ and Parashkov et al. $^{[18]}$, which emit charge carriers from a vertical source edge, are free of horizontal transport contributions and consequently limited in the On-state by a space-charge current through the vertical channel, which results in the observed loss of saturation (a typical short-channel effect). Onsets of such behavior can also be observed for sufficiently doped VOFETs of the type presented here, as illustrated by the output characteristics in Figures 2b and 4b. The absence of such short-channel effects in a VOFET geometry, however, may point toward a comparatively long transport path and in such cases it certainly seems necessary to address the question of transfer length and other horizontal transport contributions to the total transport path of the device.

3. Conclusion

In this contribution, the effect of contact doping on the novel architecture of vertical organic field-effect transistors was investigated and two approaches to contact doping, namely the insertion of a thin injection layer and the use of a thicker, mixed layer of matrix and dopant, were presented. It was found that thin injection layers improve the VOFET performance much more than mixed layers due to the formation of very thin, highly doped interfaces which significantly reduce contact resistance and transfer length in conventional OFETs as well as VOFETs. This resulted in an On/Off ratio and transconductance which were increased by one order of magnitude, to $10^6$ and 40.6 $\mu$S, compared to an undoped reference device. It was concluded from these results that the VOFET presented in this work must be limited not by transport in the vertical channel, but by the charge carrier transport near the source electrode, as this explains the tremendous improvement in performance observed for contact-doped devices with a small transfer length. Therefore, any future efforts in the field of VOFET research, especially those aiming at high performance, ought to consider first of all not the further reduction of the vertical channel length, but the reduction of the transfer length in order to truly realize the short transport paths promised by this novel device architecture. In geometries which further rely on an overlapping source insulator, this overlap length, too, will need to be addressed. Only then will it be possible to truly outperform conventional OFETs and to utilize the great potential of the VOFET technology.

4. Experimental Section

All devices presented in this study were fabricated on p-doped silicon substrates, coated with 30nm of aluminum oxide ($\text{Al}_2\text{O}_3$, $\varepsilon = 7.8$) using PE-ALD (SenTech Instruments ALD LL). The substrates were then immersed in acetone and isopropanol and cleaned in an ultrasonic bath for 5 min each, followed by exposure to oxygen plasma for 10 min. The cleaned substrates were passivated via dipping into hexamethyldisilazane ($\text{HMDS}, \text{Merck}$) for 30 min prior to material deposition and residuals of HMDS were removed by spin rinsing with isopropanol.

To produce VOFET devices, 25 $\mu$m of pentacene (P5, Sensient, sublimated twice before use, $\rho = 1.32$ g cm$^{-3}$) were deposited via thermal deposition under high vacuum conditions with a base pressure of $\approx 10^{-5}$ mbar. The layer thickness was monitored using a QCM. A lithographic mask for source contacts was then formed using orthogonal photolithography $^{[14,31]}$ and a 2 nm thick layer of pure $\text{C}_6\text{F}_{36}$ (Ionic Liquids Technologie GmbH, used as received, $\rho = 1.97$ g cm$^{-3}$) as well as 50 nm thick Au source contacts were thermally deposited through this mask to form source contacts with contact doping. A source insulator, made of 100nm SiO$_2$, was added through the same mask via magnetron sputtering to prevent leakage between the source and drain electrodes. A lift-off was performed to remove the lithography mask and additional 25 $\mu$m pentacene and 40nm Au were thermally deposited through a second lithography mask to form the vertical channel and drain electrode of the VOFET. In the same way, VOFETs with mixed injection layers were produced. Here the injection layers were formed by coevaporation of pentacene and $\text{C}_6\text{F}_{36}$ in varying molar ratios (separate QCMs were used for the two materials). All VOFETs have the same dimensions of 50 nm vertical channel length ($L_{\text{Ch}}$) and 600 $\mu$m channel width ($W$).

In order to perform a detailed TLM analysis on the different injection layers, a series of OFETs with $W = 1000 \mu$m and $L$ of 25, 50, 100, and 200$\mu$m were fabricated for each type of injection layer. The OFETs were built on the same substrate type as the VOFETs, with 25 nm of pentacene as the active layer and 30 nm thick Au source and drain contacts, which were also patterned by orthogonal photolithography.

Electrical characteristics of all devices were measured under nitrogen atmosphere using a HP 4145B semiconductor parameter analyzer. Atomic force microscopic (AFM) images of the organic layers were obtained with an AIST-NT Combiscope1000 (scan rate = 0.1 Hz) and SEM images of the completed devices were taken with a Zeiss NOEN40 SEM/FIB8 system.
Supporting Information

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

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