# Understanding Performance Limitations in Organic Transistors

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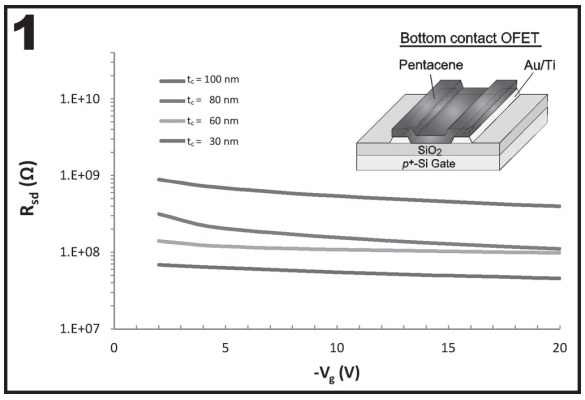


*Figure 1: Contact resistance for varying pentacene thickness in TC OFETs (inset).*

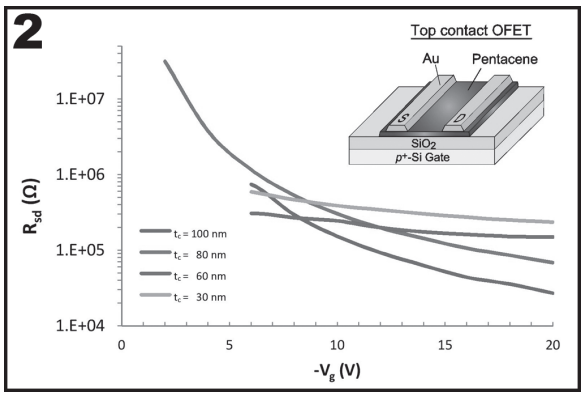


*Figure 2: Contact resistance for varying contact thicknesses in BC OFETs (inset).*

## Introduction:

Organic field-effect transistors (OFET) are critical components of many prospective organic electronic products [1], but their performance is limited by poor charge injection and weak charge transport, manifesting as high contact resistance and low mobility. The goal of this work was to understand performance limitations in pentacene-based OFETs by varying device architecture and processing to empirically demonstrate optimal design parameters.

## Experimental Methods:

Pentacene OFETs of top/bottom-contact (TC/BC) and bottom-gate (BG) configuration were fabricated (Figures 1 and 2). BC devices suffer from contact effects because molecular self-organization is disrupted, resulting in poor film morphology near the contacts. Small charge injection area (~ contact thickness) is also believed to limit performance in BC OFETs. In this study, BC devices with various contact thicknesses were fabricated to explore both issues. Compared to BC OFETs, TC OFETs perform better, demonstrating lower contact resistance and higher mobility. The OSC film is not disturbed by contact deposition and, furthermore, TC OFETs have larger charge injection area as the entire contact surface contributes to injection. However, in TC OFETs, charge carriers must cross the entire OSC film to reach the channel, causing high access resistance. Meanwhile, large numbers of traps limit charge transport. So, TC devices with different pentacene film thicknesses and diverse dielectric treatments were fabricated to understand contact resistance and trap origins.

Current-voltage (I-V) characterization and low-frequency noise (LFN) measurements were performed in ambient conditions. The contact resistance ($R_{sd}$) was evaluated by the modified transfer length method [3] with devices having different channel lengths. Intrinsic low-field mobility ($\mu_0$) was extracted via the Y-Function method [4]. Normalized power spectral density of drain current fluctuations at $f = 20$ Hz were plotted against drain current to identify noise mechanisms. The normalized noise spectra were accurately modeled by carrier number fluctuations induced by charge trapping/detrapping and, thus, a surface equivalent trap density ($N_{ST}$) was extracted.

## Results and Discussions:

The $R_{sd}$ of BC OFETs is depicted in Figure 1 as a function of gate voltage ($V_G$). Surprisingly, $R_{sd}$ increased with contact thickness, contrary to the expectation that charge injection should be enhanced by greater charge injection area. Our results indicated this enhancement was negligible and the small grain contact region played a dominant role. Thicker contacts produced a steeper edge profile, causing poorer molecular packing. Charge injection was limited by this

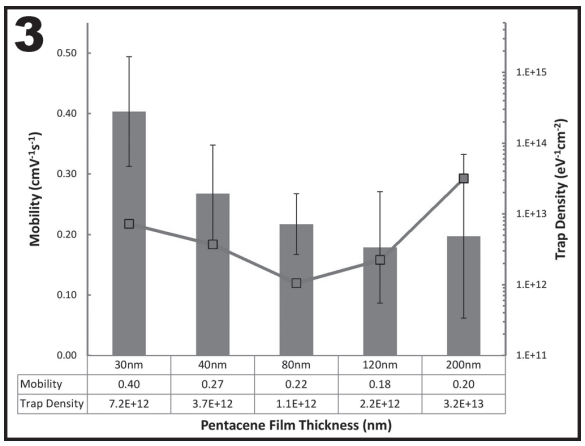


*Figure 3: Intrinsic mobility (left axis) and trap density (right axis) for several pentacene thicknesses.*

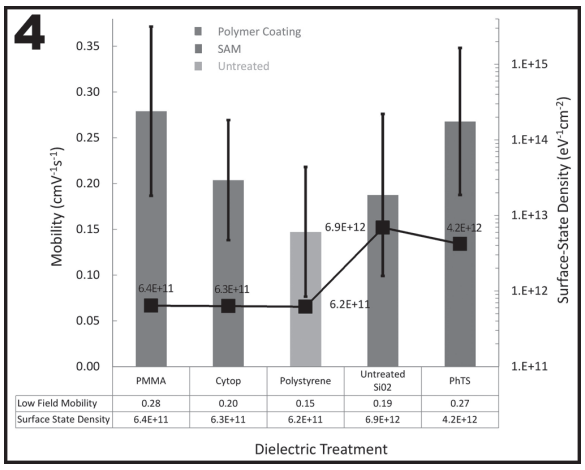


*Figure 4: Intrinsic mobility and surface-state density for several dielectric treatments.*

highly resistive zone, yielding high contact resistance and reduced mobility.

Figure 2 illustrates the $R_{sd}$ in TC OFETS with various pentacene film thicknesses ($t_{SC}$). Simulations showed that $R_{sd}$ increased drastically with $t_{SC}$ as VG dependence weakened [2]. The former was due to longer vertical transport required in thicker films, and the latter was from weaker charge concentration modulation by $V_G$.

The present results qualitatively match simulations, but the range of magnitudes spanned is much smaller. This non-ideality is likely because of contact metal (Au) diffusion into the pentacene film, which may make the actual $t_{SC}$ smaller than the nominal thickness. Future experiments will address this by alternative fabrication techniques such as contact lamination.

Besides determining charge injection, $t_{SC}$ affects charge transport in the channel. In Figure 3, mobility $\mu_0$ decreased with $t_{SC}$. To understand this, the trap density ($N_{ST}$) by LFN was plotted against $t_{SC}$ in Figure 3, showing an inverse trend to that of mobility. High $N_{ST}$ in the film might be due to poor film quality and interfacial traps. This agreed with the understanding that thicker grain boundaries will produce more deep traps. Indeed, the nearly proportional dependence of $N_{ST}$ on $t_{SC}$ implied uniformly distributed traps within the OSC bulk.

It appears mobility variation was not strictly due to charge trapping. One possible interpretation is limited charge injection in thicker films, as charge must traverse the contact region mainly by hopping. Since the contact provided insufficient charge to the channel, the apparent mobility was limited.

The OSC/dielectric interface is crucial to transport. Figure 4 illustrates the mobility and the surface state density ($N_{SS}$, deduced by sub-threshold swing) in TC devices with different treatments of the $SiO_2$ dielectric. PMMA and PhTS-SAM gave the comparably highest mobility and untreated $SiO_2$ had lower mobility, as expected. The small $N_{SS}$ for polymer treatments (Cytop, PMMA, and polystyrene) showed high interface quality, probably due to the similar material properties between pentacene and polymeric dielectric treatments. Strikingly, a high $N_{SS}$ was obtained for PhTS-SAM treatment though SAM layers typically improved mobility. Untreated $SiO_2$ showed the largest $N_{SS}$, presumably from charge trapping hydroxyl groups.

The $N_{ST}$ by LFN indicates pentacene film quality also strongly depends on dielectric, providing additional explanation for the mobility variation. The $N_{ST}$ in untreated $SiO_2$ was the largest, followed by PhTS-SAM. Approximately an order of magnitude lower $N_{ST}$ obtained in PMMA treated devices indicated a higher quality pentacene film.

## Conclusions:

Fabrication and measurement of pentacene-based OFETs with varying device architectures and processing methods enabled deeper understanding of OFET performance limitations. Choosing a proper contact thickness that preserves the film morphology is critical to optimizing charge injection in BC OFETs. For TC OFETs, a thin but a high quality OSC film is key to strong charge injection in the contact and efficient charge transport in the channel. In addition, polymeric dielectrics improved OSC film quality and reduced the interface traps. Future efforts will examine a larger parametric range of device parameters to better understand trends in trap density and contact resistance as well as define changes in the film morphology.

## Acknowledgements:

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## References:

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