

Maxwell-Wagner limit of copper contacts on DNTT transistors

Michal Micjan, Tomáš Vincze, Martin Weis¹

The contact resistance of dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT) thin-film transistors with copper source/drain electrodes was extracted by the transmission-line method between 200 and 400 K on two gate-dielectric treatments (OTS and HMDS). Resolved interval by interval and at constant gate overdrive, the activation energy of the contact resistance vanishes below 260 K and above 300 K, and all of the activation is concentrated in the crossover between these two plateaus, which yields an injection barrier of 0.63 eV. The contact is therefore limited by a succession of mechanisms rather than by one: tunnelling at low temperature, where the available fields lie one to two orders of magnitude below the Fowler-Nordheim scale so that the barrier remains trapezoidal; thermionic emission through the crossover; and, once injection ceases to limit, a temperature-independent floor of 3-6 k Ω ·cm, voltage independent once current crowding is removed, consistent with the Maxwell-Wagner space-charge limit for a DNTT conductivity of about 10⁻⁷ S/cm. The conventional plot of activation energy against the square root of field is linear and would alone indicate Schottky barrier lowering, but it fails the thermal-scaling test that barrier lowering equally imposes; current crowding, which accounts for the high-temperature field exponent, cannot generate the crossover. Both surface treatments give the same physics and imply the same conductivity to within a factor of two, indicating a floor set by the dielectric relaxation of the DNTT itself rather than by the metal-organic energetics.

Keywords: contact resistance, organic semiconductors, organic transistors

1 Introduction

Organic thin-film transistors (OTFTs) are a building block of flexible, large-area and low-cost electronics, and among the vacuum-processable small-molecule semiconductors dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT) has become a benchmark p-type material, combining a hole mobility of order 1 cm²/V s with a large ionization potential ($\approx$ 5.4 eV) that confers excellent ambient stability [1, 2]. Precisely because channel mobilities have improved, contact resistance R_C rather than channel transport has become the dominant performance bottleneck, particularly in short-channel devices where the channel resistance is small [3-5]. Width-normalized contact resistances below 100 Ω cm remain rare, and a quantitative, predictive understanding of what sets the achievable R_C is still lacking [4].

Conventionally, R_C is attributed to a charge-injection barrier arising from the mismatch between the electrode work function and the semiconductor transport level, overcome by field-assisted mechanisms such as Schottky barrier lowering, tunnelling, or Poole-Frenkel emission [5, 6]. The standard experimental probes are the transmission-line method (TLM) and gated four-probe measurements, which yield R_C as a function of gate voltage and temperature. The activation energy of R_C and, in particular its field dependence are then used

to infer the injection mechanism [7-10]. A $\sqrt{E}$ dependence of the activation energy is routinely read as the signature of Schottky barrier lowering.

Recently, an alternative and energetically barrier-independent mechanism has been proposed. Because organic semiconductors are relaxation-type dielectrics, the large mismatch between the dielectric relaxation times of the metal and the organic drives a Maxwell-Wagner (space-charge) accumulation at the interface, setting a fundamental contact-resistance floor $R_{MW} = \tau_2 \frac{\delta}{(\epsilon_0 \epsilon_r W L_C)}$ that is independent of the injection barrier and of applied field [11]. Within this dual-mechanism framework the two regimes are distinguished by the voltage dependence of the activation energy: voltage-dependent ($\propto \sqrt{E}$) for injection-limited (Schottky) contacts, and voltage-independent for space-charge-limited ones. Metals of intermediate work function such as Cu are predicted to display a crossover between the two regimes [11]. This picture builds on earlier analyses of injection and contact behaviour in the same material systems [10, 12].

Here we test this framework on Cu-contacted DNTT OFETs prepared with two gate-dielectric surface treatments (OTS and HMDS). We extract $R_C(V_G, T)$ by the transmission-line method over 200 to 400 K, apply an objective data-quality filter, remove the threshold-

voltage confound with a contact-free $V_{th}(T)$, and subject the $\sqrt{E}$ signature to a thermal-scaling test. We find that no single mechanism describes the whole range. The activation energy of R_C vanishes below 260 K and above 300 K and is concentrated entirely in the crossover between these plateaus, which yields an injection barrier of 0.63 eV; below the crossover injection proceeds by tunnelling, and above it, once injection ceases to limit, R_C settles on a floor quantitatively consistent with the Maxwell-Wagner limit for a DNTT conductivity $\sigma \approx 10^{-7}$ S/cm [13]. The behaviour is reproduced on both surface treatments, and the floor is set by the DNTT rather than by the metal-organic energetics or the dielectric treatment.

2 Devices and measurements

2.1 Device fabrication

DNTT thin-film transistors were fabricated in a bottom-gate top-contact configuration on heavily doped silicon wafers, which served as the common gate electrode, with a thermally grown 100 nm SiO_2 layer as the gate insulator (areal capacitance $C_i = 33.6$ nF/cm²). Prior to processing, the substrates were cleaned in successive ultrasonic baths of a 20 wt% aqueous monoethanolamine solution, isopropyl alcohol and acetone (15 min each), and were subsequently exposed to oxygen plasma in order to remove residual organics and to modify the surface wettability.

The cleaned substrates were then subjected to one of two surface treatments of the gate dielectric: immersion for 1 h in a 1 mM solution of octadecyltrichlorosilane (OTS, > 99%) in toluene, or exposure to hexamethyldisilazane (HMDS) vapours for 24 h. Both were followed by annealing at 125 °C for 10 min. The two treatments leave the injection energetics unchanged and differ only in the resulting dielectric-surface chemistry and the microstructure of the overlying organic film, which makes them a useful pair for isolating morphology-related effects on the contact.

The DNTT (99%) active layer was grown on the OTS- or HMDS-modified surface by physical vapour deposition (Spectros 100, Kurt J. Lesker, Hastings, UK) at a pressure below 5×10^{-6} Pa through shadow masks, at a rate of 3 nm/s monitored by a quartz-crystal microbalance, giving a semiconductor thickness of 50 nm. Copper source/drain electrodes (80 nm, 99.99%) were then deposited through a shadow mask without breaking the vacuum, so that the Cu/DNTT interface was never exposed to ambient. The channel width was $W=2.5$ mm and the channel length was varied from $L=40$ –200 μm , providing the length series required for the transmission-line analysis.

2.2 Electrical characterisation

All output and transfer characteristics of the fabricated OFET devices were measured under vacuum using a DL800 cryostat system (BIO-RAD Micromediation, UK) over the temperature range 200–400 K in steps of 20 K. Electrical measurements were performed using a B1500A semiconductor parameter analyser (Keysight, USA); the current resolution of the setup is ≈ 0.1 nA, which is relevant when assessing the reliability of low-current data.

At each temperature, transfer characteristics were recorded in two regimes. The saturation regime $V_{DS} = -30$ V was used to extract the threshold voltage and the field-effect mobility from the linear portion of $\sqrt{|I_D|}$ versus V_{GS} . The linear regime was used for the transmission-line analysis, which was performed at a drain-source voltage of $V_{DS} = -1$ V to ensure a uniform charge distribution in the channel region; this keeps $|V_{DS}| \ll |V_{GS} - V_{th}|$ throughout the accumulation window, so that the measured total resistance $R = \frac{V_{DS}}{I_D}$ can be decomposed into a channel term proportional to L and a length-independent contact term. For each surface treatment, devices spanning the full channel-length series were measured over the complete temperature range, yielding R_C as a function of both gate voltage and temperature.

3 Analysis methodology

3.1 Transmission-line extraction

In the linear regime the total measured resistance of a device separates into a channel contribution proportional to the channel length and a length-independent contact contribution,

$$R_{\text{tot}}(V_{GS}, T) = \frac{V_{DS}}{I_D} = 2R_C(V_{GS}, T) + \frac{L}{WC_i\mu_{\text{lin}}|V_{GS} - V_{th}|},$$

where $2R_C$ lumps the source and drain contacts. At each gate voltage and temperature, R_{tot} was therefore fitted linearly against L across the available channel-length series. The intercept yields the contact term and the slope the channel sheet resistance,

$$R_{\text{tot}}|_{L \rightarrow 0} = 2R_C, \quad \frac{\partial R_{\text{tot}}}{\partial L} = \frac{R_{\text{sheet}}}{W} = \frac{1}{WC_i\mu_{\text{lin}}|V_{GS} - V_{th}|}.$$

This equation gives, in addition, the contact-resistance-free (intrinsic) linear mobility directly from the slope, i.e., free of any contact contribution, and the transfer length

$$L_T = \frac{2R_C}{2 \partial R_{\text{tot}} / \partial L},$$

which measures the effective length over which carriers are exchanged between the electrode and the channel and which we identify with the effective contact length L_c entering the Maxwell-Wagner expression below. Contact resistances are reported width-normalised as $R_C W$.

3.2 Data-quality filter

Individual devices and individual temperature runs can fail for reasons unrelated to the physics under study (fabrication defects, contact degradation, an unstable run). Because such failures corrupt the TLM fit and propagate into every downstream quantity, they were removed by an objective criterion rather than by inspection. For every temperature, the coefficient of determination R^2 of the R_{tot} -versus- L fit was evaluated over the strong-accumulation window and its median taken; temperatures with median $R^2 < 0.9$ were treated as measurement errors and excluded in full. Channel lengths whose devices were anomalous were likewise excluded from the length series. The filter is applied identically to both surface treatments, so that the difference in the number of surviving temperatures is itself a result rather than a choice.

3.3 Contact-free threshold voltage

The threshold voltage enters the analysis twice: through TLM relation and, more importantly, through the gate overdrive at which R_C is compared across temperature. Extracting V_{th} from the linear regime is unreliable here precisely because the linear regime is contact-distorted, which is what we are trying to measure. We therefore obtain an intrinsic, contact-free threshold voltage from the TLM slope itself. From slope equation, the intrinsic sheet conductance

$$G_{\text{sh}}(V_{GS}) = \left[W \frac{\partial R_{\text{tot}}}{\partial L} \right]^{-1} = C_i \mu_{\text{lin}} |V_{GS} - V_{\text{th}}|$$

is linear in V_{GS} and contains no contact term; its extrapolation to $G_{\text{sh}} = 0$ defines V_{th} at each temperature. The resulting $V_{\text{th}}(T)$ was rigidly shifted so as to coincide at 300 K with the threshold voltage obtained independently from the saturation regime, which anchors the absolute overdrive scale to a contact-insensitive reference while preserving the measured temperature dependence.

3.4 Activation energy at constant overdrive

Assuming a thermally activated contact, $R_C \propto \exp(E_a/k_B T)$, the activation energy follows from

$$E_a = k_B \frac{\partial \ln R_C}{\partial (1/T)}.$$

Evaluating activation energy equation at a fixed gate voltage is misleading whenever V_{th} itself depends on temperature, because the accumulated charge density then differs from one temperature to the next. We therefore re-express R_C at a fixed gate overdrive,

$$V_{\text{ov}} = V_{GS} - V_{\text{th}}(T),$$

by interpolating $\ln R_C(V_{GS})$ at each temperature onto a common V_{ov} grid, and apply activation energy equation at constant V_{ov} . The accessible V_{ov} range is limited by the most negative V_{th} in the series. The linearity of the Arrhenius plot is not assumed but tested: activation energies were additionally extracted separately within restricted temperature intervals, which reveals whether a single E_a describes the whole range.

3.5 Discriminating Schottky from space-charge behaviour

For an injection-limited contact, the barrier is lowered by the local electric field F according to $E_a = E_{\text{inj}} - \beta \sqrt{F}$ with $\beta = \sqrt{q^3/4\pi\epsilon}$, so that

$$\ln R_C = \text{const} + \frac{E_{\text{inj}}}{k_B T} - \frac{\beta}{k_B T} \sqrt{F}.$$

In the bottom-gate top-contact geometry the carriers are drawn from the source electrode towards the gate across a distance of the order of 150 nm (gate dielectric plus organic layer), whereas the source-drain separation is 40–200 μm . The vertical field therefore dominates and, at a given gate voltage, is common to all channel lengths, so that $F \propto V_{\text{ov}}$ and $\sqrt{F} \propto \sqrt{V_{\text{ov}}}$ up to a geometric constant. Because only the functional form is tested, this multiplicative constant does not affect the diagnostics below.

The Schottky equation is usually tested by plotting E_a against $\sqrt{F}$ and checking for linearity. That test is weak: a $\sqrt{\cdot}$ function is a slowly varying, featureless curve, and any smoothly decreasing $E_a(V_{\text{ov}})$ will fit it acceptably. A far more stringent test is available because Schottky equation fixes not only the field dependence but also its temperature scaling. Differentiating at constant temperature,

$$\frac{\partial \ln R_C}{\partial \sqrt{V_{ov}}} = -\frac{\beta'}{k_B T},$$

$$\text{hence} \quad T \cdot \frac{\partial \ln R_C}{\partial \sqrt{V_{ov}}} = -\frac{\beta'}{k_B} = \text{const},$$

independent of temperature. Genuine Schottky (or Poole-Frenkel) barrier lowering therefore requires the product of the $\sqrt{V_{ov}}$ slope and the temperature to be constant across the measured temperature range; any material variation of this product falsifies field-assisted thermionic emission, irrespective of how well the $E_a - \sqrt{V_{ov}}$ plot itself may look. We use this relation as the primary discriminator.

Conversely, for a space-charge-dominated Maxwell-Wagner contact the activation energy is predicted to be voltage independent, $E_{a,low} = E_{inj} - E_{hop}$, reflecting material properties rather than applied field [11].

3.6 Maxwell-Wagner floor

The Maxwell-Wagner contribution to the contact resistance,

$$R_{MW} = \frac{\tau_2 \delta}{\epsilon_0 \epsilon_r W L_c},$$

follows from the dielectric relaxation-time mismatch between the metal and the organic [11], where δ is the interfacial screening length and $\tau_2 = \frac{\epsilon_0 \epsilon_r}{\sigma}$ the relaxation time of the organic. Inserting τ_2 , the permittivity cancels and the width-normalised floor depends only on the screening length, the conductivity and the contact length,

$$R_{MW} W = \frac{\delta}{\sigma L_c}.$$

We evaluate this equation using $L_c = L_T$ from our own TLM analysis, $\delta \approx 10$ nm, and a literature DNTT conductivity, and compare it with the measured floor. Since $R_{MW} W \propto \frac{1}{\sigma}$, the comparison is an order-of-magnitude consistency check. The same procedure reproduces the reported pentacene/Au benchmark [11], which we use to validate the evaluation.

4 Results

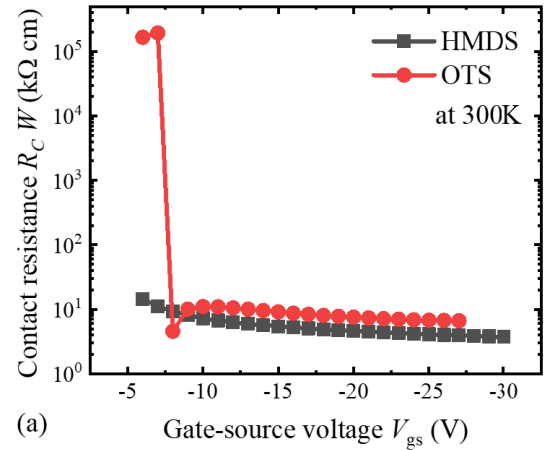
4.1 Device characteristics and data quality

In saturation at 300 K the devices behave as well-formed p-channel transistors. The HMDS-treated series is highly uniform across the length series, with a median saturation mobility of $0.65 \text{ cm}^2/\text{V s}$ (range 0.61 to $0.67 \text{ cm}^2/\text{V s}$) and a median threshold voltage of -3.9 V (range -3.7 to -4.2 V). The OTS-treated series

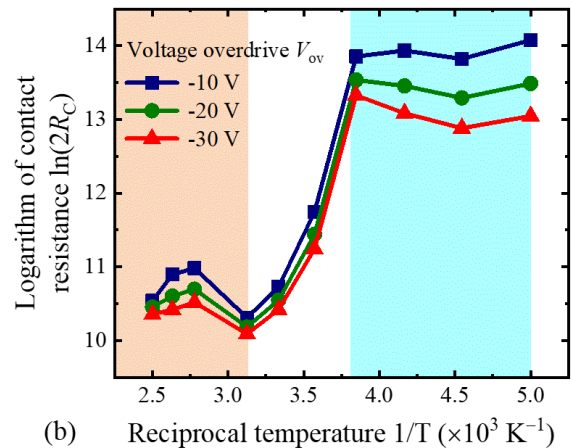
reaches a comparable median mobility of $0.63 \text{ cm}^2/\text{V s}$ and a threshold voltage of -8.2 V but is markedly less uniform.

4.2 Channel and contact behave differently with temperature

The two quantities delivered by the same TLM fit evolve in qualitatively different ways. The contact-resistance-free linear mobility obtained from the slope increases monotonically and smoothly with temperature – at $V_{ov} = 15 \text{ V}$ from 0.19 to $0.83 \text{ cm}^2/\text{V s}$ (HMDS) and from 0.46 to $1.45 \text{ cm}^2/\text{V s}$ (OTS) between 200 and 400 K – as expected for thermally activated hopping transport in the channel. Over the same range the channel sheet resistance varies by only about a factor of four, again smoothly and monotonically. By contrast, the contact resistance is strongly non-monotonic (Fig. 1). All of the non-trivial temperature structure therefore resides in the contact, which both isolates the contact as the object of study and rules out a change in the channel material as its cause.



(a)



(b)

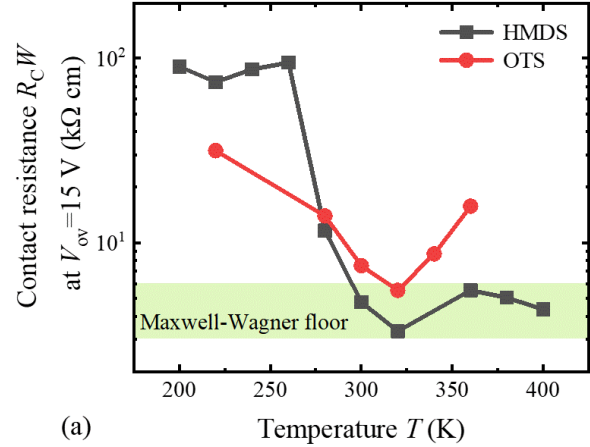
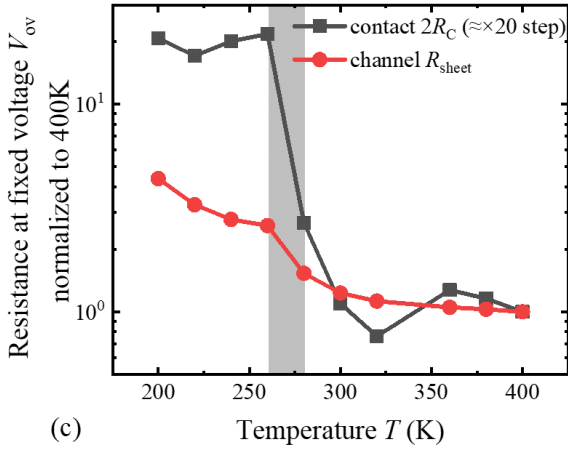


Fig. 1. (a) Width-normalised contact resistance versus V_{GS} at 300 K for HMDS and OTS. (b) Arrhenius plot of $2R_C$ at fixed overdrive (HMDS), showing the plateau-step-plateau crossover near 270 K (low-/high- T plateaus shaded). (c) At fixed overdrive the contact $2R_C$ steps $\approx 20\times$ across 270 K while the channel R_{sheet} varies smoothly, showing the crossover is contact-specific.

4.3 The apparent activation energy is dominated by the threshold shift and by a crossover

Two artifacts must be removed before the activation energy of R_C can be interpreted. First, the intrinsic threshold voltage is strongly temperature dependent: for HMDS it moves from -9.2 V at 200 K to -1.2 V at 400 K, see Fig. 2(b), a shift of more than 8 V. At a fixed gate voltage the devices are therefore compared at substantially different accumulated charge densities, and much of the apparent field dependence of E_a is simply this shift. Re-expressing R_C at constant overdrive collapses the E_a span from ≈ 0.14 eV (constant V_{GS}) to ≈ 0.035 eV: E_a falls only from 0.156 to 0.121 eV for HMDS and from 0.081 to 0.051 eV for OTS as V_{ov} grows from 8 to 20 V.

Second, and more fundamentally, the Arrhenius plots are not straight lines. They consist of two nearly flat plateaus joined by a step near 270 K [Fig. 1(b)], and the single-line fits are correspondingly poor ($R^2 \approx 0.75$ to 0.80 for HMDS and only 0.43 to 0.54 for OTS). Resolving the activation energy interval by interval makes the structure explicit (Tab. 1): E_a is zero to within the scatter throughout both plateaus and rises to ≈ 0.66 eV across the step. The activation energies quoted above are therefore not activation energies of any single process; they measure the height of the crossover step divided by the temperature span. Within either regime the contact resistance is, to within the experimental scatter, temperature independent, while the transition between them is strongly activated.

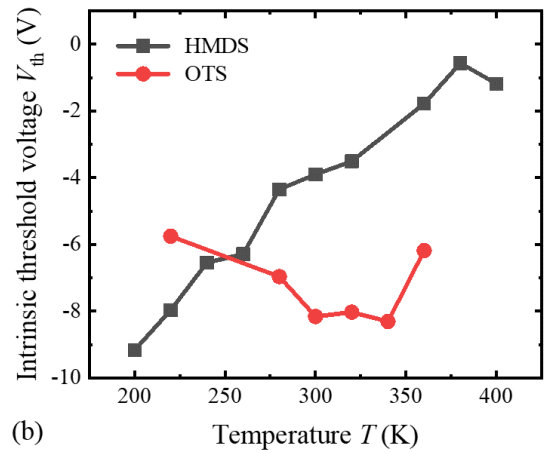


Fig. 2. HMDS versus OTS: (a) $R_C W$ versus T at fixed overdrive, with the Maxwell-Wagner floor shaded; (b) contact-free threshold voltage versus T .

Table 1. Activation energy of R_C resolved interval by interval (HMDS, $V_{ov} = 15$ V). It vanishes throughout both plateaus and rises sharply across the crossover.

Interval (K)	E_a (eV)
200 – 220	+0.04
220 – 240	–0.04
240 – 260	–0.02
260 – 280	+0.66
280 – 300	+0.32
300 – 320	+0.15
360 – 380	+0.06

The transition window is thus the only part of the data from which a genuine injection barrier can be read. Fitting $R_C(T)$ over 260–300 K yields E_a decreasing from 0.545 to 0.493 eV as V_{ov} grows from 8 to 20 V; extrapolation to zero field along $E_a = E_{inj} - \beta\sqrt{F}$ gives

$$E_{inj} \approx 0.63 \text{ eV} \quad (R^2 = 0.98),$$

with a fitted β within a factor of two of the theoretical value for $\varepsilon_r = 3$. The scale of the step is consistent with this barrier: a process activated by ≈ 0.6 eV changes by a factor of ≈ 37 between 260 and 300 K, against the factor of ≈ 20 observed.

4.4 No single Schottky description holds across the range

Plotted in the conventional way, the data look like a textbook confirmation of Schottky barrier lowering: E_a versus $\sqrt{V_{ov}}$ is linear with $R^2 \approx 0.950$ – 0.999 for both treatments [Fig. 3(a)]. The thermal-scaling test of discriminator relation, however, fails decisively. The product $T \cdot \frac{\partial \ln R_C}{\partial \sqrt{V_{ov}}}$, which barrier lowering requires to be constant, instead varies by a factor of three across the measured range for both treatments (coefficient of variation $\approx 43\%$ for HMDS and $\approx 40\%$ for OTS) [Fig. 3(b)].

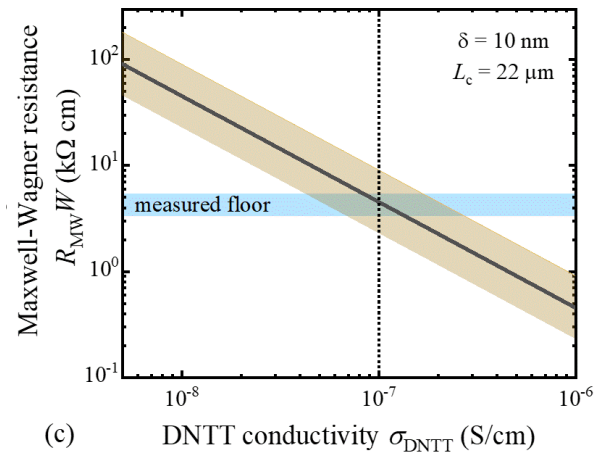
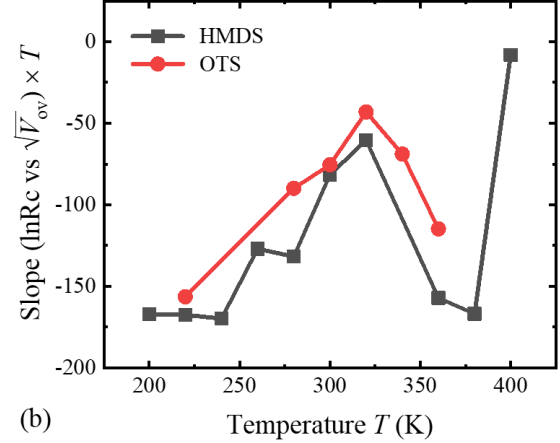
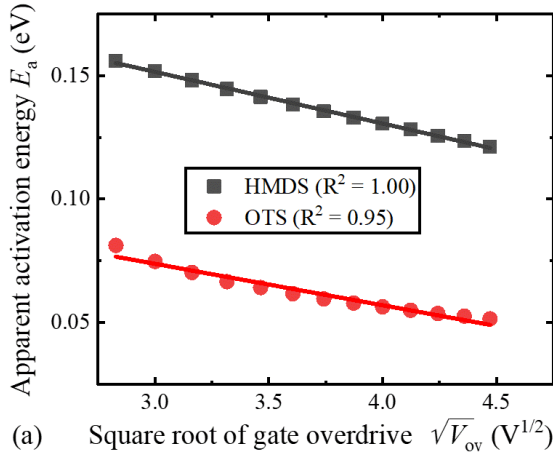


Fig. 3. (a) Apparent activation energy versus $\sqrt{V_{ov}}$ (the “Schottky plot”) appears linear. (b) The Schottky discriminator slope $(\ln R_C \text{ vs } \sqrt{V_{ov}}) \times T$ is not constant for either treatment, so no single barrier-lowering description holds across the range. (c) Maxwell-Wagner floor $R_{MW}W$ versus σ ; the measured floor band matches $\sigma \approx 10^{-7}$ S/cm.

Field-assisted thermionic emission therefore cannot describe the whole temperature range, and neither can Poole-Frenkel emission, which shares the same $\frac{\beta}{k_B T}$ scaling. This is not in itself surprising once the plateau structure of the previous section is recognised: both plateaus have $E_a \approx 0$ and cannot be thermionic at all, so a mechanism that presupposes emission over a barrier can at best apply to the narrow transition window, and the linearity of Fig. 3(a) is an average over three different regimes rather than evidence for one.

4.5 The crossover is contact-specific and not an artifact

Three independent checks establish that the 270 K step is a genuine property of the contact. First, it is not a current-floor artifact: at $V_{GS} = -30$ V the drain currents lie between 1.8 and 25 μ A across the whole temperature range, some four orders of magnitude above the 0.1 nA resolution of the setup. Second, it is specific to the contact: at fixed overdrive $R_C W$ falls from 94.6 k Ω cm at 260 K to 4.8 k Ω cm at 300 K, a step of ≈ 20 , while the channel sheet resistance extracted from the same fits passes through the same temperature interval smoothly and with a total variation of only ≈ 4 over the entire range [Fig. 1(c)]. A change in the DNTT film, or a systematic measurement error, would move both. Third, the step follows physical temperature rather than measurement order: the 300 K run was recorded first, before the low- and high-temperature series, yet it belongs unambiguously to the low-resistance high-temperature group, which excludes a monotonic drift or degradation during the measurement sequence.

The two plateaus also differ in how strongly the field acts on them. Describing the gate dependence empirically as $R_C \propto V_{ov}^n$ – a power law that fits every temperature with $R^2 \geq 0.996$, better than any of the exponential forms – the exponent evolves from $n = -1.41$ at 200 K through -1.29 and -1.19 to -0.82 at 260 K, and then from -0.46 at 300 K to -0.32 at 320 K. The low-temperature contact is thus markedly more field-sensitive than the high-temperature one, and the two plateaus, although both temperature independent, are not the same state of the contact.

4.6 The high-field floor matches the Maxwell-Wagner limit

Above the crossover, $R_C W$ settles at 3.3 k Ω cm (HMDS, at 320 K) and 5.5 k Ω cm (OTS, at 320 K) [Fig. 2(a)], and becomes temperature independent and only weakly field dependent ($n \approx -0.4$, see Sec. 5.4). The transfer lengths are $L_T \approx 22$ μ m (HMDS) and ≈ 50 μ m (OTS). Evaluating the Maxwell-Wagner floor using these transfer lengths, $\delta \approx 10$ nm and a DNTT conductivity $\sigma \approx 10^{-7}$ S/cm [13], gives $R_{MW} W \approx 4$ to 5 k Ω cm [Fig. 3(c)], in agreement with the measured values. The same evaluation reproduces the reported pentacene/Au benchmark (37.6 k Ω cm against the published 38 k Ω cm [11]), which validates the procedure.

Read in the opposite direction, the measured floors correspond to $\sigma \approx 1.2 \times 10^{-7}$ S/cm (HMDS) and $\approx 0.7 \times 10^{-7}$ S/cm (OTS). The quantities extracted for both treatments are collected in Tab. 2.

Table 2. Key extracted quantities.

Quantity	HMDS	OTS
Anchored $V_{th}^{(300\text{ K})}$ (V)	-3.9	-8.16
E_a at const. overdrive ($V_{ov} = 8 \rightarrow 20$ V) (eV)	0.156 $\rightarrow 0.121$	0.081 $\rightarrow 0.051$
Schottky discriminator CV: coefficient of variation	not const. CV $\approx 43\%$	not const. CV $\approx 40\%$
Contact crossover	≈ 270 K, $\times 20$	not resolvable
Transfer length L_c (median)	≈ 22 μ m	≈ 50 μ m
Measured floor $R_C W$ (k Ω cm)	≈ 3.3	≈ 5.5
Implied σ (S/cm)	$\approx 1.2 \times 10^{-7}$	$\approx 0.7 \times 10^{-7}$

5 Discussion

5.1 A sequence of bottlenecks rather than a single mechanism

The temperature dependence assembled above is not that of one process with one activation energy, but of a succession of bottlenecks, each dominating where the others are cheaper. Below 260 K the contact resistance is high, flat in temperature, and strongly field-sensitive ($n \approx -1.3$). Between 260 and 300 K an activated process with $E_{inj} \approx 0.63$ eV switches on and drops R_C by a factor of twenty. Above 300 K the contact resistance flattens again, at 3-6 k Ω cm, and becomes only weakly field-dependent ($n \approx -0.4$).

The natural reading follows the decomposition $R_C = R_{inj} + R_{MW}$ [11]. At low temperature thermionic emission over a 0.63 eV barrier is frozen out – at 200 K, $\exp(-E_{inj}/k_B T) \approx 10^{-16}$ – so injection proceeds by tunnelling, and $R_{inj} \gg R_{MW}$. Warming through 270 K switches thermionic emission on, which is why the transition and only the transition carries a large activation energy. Once injection ceases to limit, R_{inj} falls below the Maxwell-Wagner term and $R_C \rightarrow R_{MW}$: the space-charge floor becomes the high-temperature constant. Each plateau is flat for a different reason, which is why a single Arrhenius fit describes neither.

The barrier itself deserves a comment. The value 0.63 eV is measured, not inferred from level alignment. Taking the DNTT ionisation potential as 5.4 eV [2] and the polycrystalline Cu work function as 4.65 eV [11] would give 0.75 eV. Such vacuum-level arithmetic should not be pressed: an interfacial dipole is almost always present at metal-organic contacts and is rarely

negligible, so deviations of this size between the ideal and the measured barrier are expected, and the experimental value is the one to rely on. Even at zero field the ideal estimate is indicative only.

5.2 Why tunnelling, but not Fowler-Nordheim

Field emission of the Fowler-Nordheim type can be excluded on the fields alone. With $J \propto F^2 \exp(-B_{FN}/F)$ and $B_{FN} = \frac{4\sqrt{2m^*}E_{inj}^{3/2}}{(3q\hbar)}$, the barrier gives $B_{FN} = 2.4$ to 4.8×10^9 V/m for $m^* = 0.5$ to $2 m_e$, whereas the vertical field in these devices reaches only 1.3×10^8 V/m. The ratio $\frac{B_{FN}}{F} \approx 18$ to 90 makes the Fowler-Nordheim contribution vanishingly small, and the equivalent statement in real space is that the potential drop across an interfacial barrier of width $w \approx 1$ - 3 nm is only $qFw \approx 0.05$ - 0.4 eV, well below E_{inj} . The barrier therefore remains trapezoidal rather than being cut to a triangle, which is the defining condition for direct rather than Fowler-Nordheim tunnelling; the onset of the latter would require fields two to five times higher than those accessible here. This is precisely why the Fowler-Nordheim form fits the low-temperature data less well than a simple power law.

Direct tunnelling, by contrast, needs a thin barrier rather than a high field, and the barrier is thin: the image-force maximum sits 0.95 to 1.5 nm from the interface at these fields, giving a transmission $\mathcal{T} \approx 10^{-3}$ to 10^{-5} – small, but far larger than the thermionic factor at 200 K. Because a trapezoidal barrier is only weakly modulated by the field, $\mathcal{T}$ gains merely a factor of 1.2 - 1.5 between $V_{ov} = 8$ and 20 V while the gate-accumulated charge gains 2.5 ; with $R_C \propto (n\mathcal{T})^{-1}$ this predicts $n \approx -1.2$ to -1.5 against the measured -1.19 to -1.41 . The low-temperature power law is therefore not an empirical curiosity: its exponent lies close to -1 because the field dependence is carried mainly by the carrier density and only weakly by the barrier, which is also why no exponential barrier-lowering form fits it better. Given the freedom in m^* and w this is a consistency check rather than a fit; the exclusion of Fowler-Nordheim, resting on one to two orders of magnitude in field, does not depend on it.

5.3 The high-temperature floor and the Maxwell-Wagner limit

Above the crossover the floor of 3 - 6 k Ω cm is reproduced by Maxwell-Wagner resistance relation, $R_{MW} \cdot W = \delta/\sigma L_C$, with $\sigma \approx 10^{-7}$ S/cm, and the comparison between the two treatments strengthens the assignment: OTS and HMDS differ in surface chemistry, in film microstructure, in threshold voltage by more than 4 V and in transfer length by more than a factor of two,

yet the conductivities implied by their floors agree to within a factor of two. A floor governed by the metal-organic energetics would not behave this way, since the metal is the same in both; nor would one governed by the dielectric treatment. A floor set by the dielectric relaxation of the DNTT itself is what the observation demands.

It is also consistent with the framework quantitatively. For an intermediate-work-function metal such as Cu, injection limitation is expected to give way to space-charge limitation above a transition field of $\approx 2 \times 10^5$ V/cm [11]; the vertical field here is 5×10^5 to 1.3×10^6 V/cm, a factor of three to seven above it. The high-temperature data are thus taken in exactly the regime where the space-charge floor, and not Schottky behaviour is expected.

5.4 Current crowding is geometry, not mechanism

In staggered devices current crowding relates the measured contact resistance to the specific contact resistivity ρ_c by $R_C W = \sqrt{\rho_c R_{sheet}}$, so one may ask how much of the behaviour above is merely this geometric dressing. Our own data settle it: the same TLM fit delivers $R_C W$ and R_{sheet} , hence $\rho_c = \frac{(R_C W)^2}{R_{sheet}}$.

Crowding cannot produce the crossover. Across it R_{sheet} changes by only a factor of 2.1 , so at constant ρ_c the model predicts a step of $\sqrt{2.1} = 1.45$ against the factor of 19.9 observed; ρ_c must itself change by ≈ 190 . The step is interfacial, not geometric. What crowding does explain is the high-temperature exponent. Since $R_{sheet} \propto \frac{1}{V_{ov}}$, a gate-independent ρ_c yields $R_C W \propto V_{ov}^{-1/2}$ irrespective of mechanism, and the exponent of ρ_c follows as $2n + 1$. Evaluating it, we find $2n + 1 \approx 0.1$ at 300 K, i.e., ρ_c is gate-independent within the scatter, so the measured $n \approx -0.5$ at high temperature is the crowding dressing of a voltage-independent interface – and voltage independence is exactly the space-charge signature the framework predicts [11]. At low temperature the same construction gives $2n + 1 = -1.4$ to -1.8 : there ρ_c is strongly gate-dependent, which crowding alone cannot generate and which the field sensitivity of tunnelling naturally does. Crowding and the interfacial mechanisms are therefore complementary, and separating them sharpens rather than blurs the assignment.

The crowding construction has its own domain of validity, and it is instructive that the data mark it out. The transfer lengths it returns at low temperature, 86 – 152 μ m, are comparable to or larger than the channel lengths themselves, violating the assumption that the electrode overlap greatly exceeds L_T ; at high temperature, $L_T = 12$ to 22 μ m and the construction is

sound. We therefore quote the barrier from R_C directly; the crowding-corrected value would be 0.89 eV, but it is obtained precisely where the correction is least trustworthy. That each description holds over a limited window is not a defect of the analysis but the same message as the physics: which process is rate-limiting, and which model is appropriate, both depend on where in temperature and field one looks.

5.5 Limitations

The Maxwell-Wagner comparison rests on a literature conductivity, and $R_{MW}W \propto \frac{1}{\sigma}$ transfers that uncertainty directly to the predicted floor. Our own devices cannot supply σ : the on-state value extracted from the channel describes the gate-accumulated layer and is five orders of magnitude too large, while the off-state current is length-independent and lies within about an order of magnitude of the 0.1 nA resolution, so that it reflects the measurement floor rather than the film. Together with the uncertainties in δ (5–20 nm) and in L_c , the agreement between measured and predicted floors is an order-of-magnitude consistency check not a fitted result. Temperature-resolved impedance spectroscopy, which would deliver τ_2 directly, is the natural next experiment. Finally, the crossover analysis rests on the HMDS series alone, since the OTS series retains no reliable data below 280 K; whether the step occurs at the same temperature for both treatments is untested.

6 Conclusion

Contact resistance in Cu-contacted DNTT thin-film transistors is governed not by one mechanism but by a succession of them, each rate-limiting over its own window of temperature and field. Resolved interval by interval, the activation energy of R_C vanishes on both sides of a crossover near 270 K and is concentrated entirely within it, yielding an injection barrier of 0.63 eV. Below the crossover thermionic emission over that barrier is frozen out and injection proceeds by direct tunnelling – the accessible fields lie one to two orders of magnitude below the Fowler-Nordheim scale, so the barrier remains trapezoidal. Above it, injection ceases to limit and the contact settles on a floor of 3 to 6 k Ω cm, temperature independent, voltage independent once current crowding is removed, and quantitatively consistent with the Maxwell-Wagner limit.

Two methodological points follow. First, the conventional $E_a - \sqrt{F}$ plot is linear here and would, taken alone, have produced a confident identification of Schottky barrier lowering; the thermal-scaling test that barrier lowering equally imposes rejects it. A $\sqrt{F}$ plot

without that test is not evidence. Second, that each model holds only over a limited window is not a weakness of the analysis but a restatement of its result: which process is rate-limiting, and which description applies, both depend on where in temperature and field one looks. For contact engineering the consequence is that once the Maxwell-Wagner floor is reached, energy-level alignment has no remaining leverage; the parameters that do are the screening length, the conductivity of the organic near the contact, and the effective contact length – the last of which, at the transfer lengths reported here, leaves the most headroom.

Acknowledgements

This work was supported by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project no. 09I03-03-V04-00178.

References

- [1] T. Yamamoto and K. Takimiya, “Facile synthesis of highly π -extended heteroarenes, dinaphtho[2,3-b:2',3'-f]chalcogenopheno[3,2-b]chalcogenophenes, and their application to field-effect transistors,” *J. Am. Chem. Soc.*, vol. 129, no. 8, pp. 2224–2225, 2007, doi: [10.1021/ja068429z](https://doi.org/10.1021/ja068429z).
- [2] U. Zschieschang *et al.*, “Dinaphtho[2,3-b:2',3'-f]thieno[3,2-b]thiophene (DNTT) thin-film transistors with improved performance and stability,” *Org. Electron.*, vol. 12, no. 8, pp. 1370–1375, 2011, doi: [10.1016/j.orgel.2011.04.018](https://doi.org/10.1016/j.orgel.2011.04.018).
- [3] M. Waldrip, O. D. Jurchescu, D. J. Gundlach, and E. G. Bittle, “Contact resistance in organic field-effect transistors: Conquering the barrier,” *Adv. Funct. Mater.*, vol. 30, no. 20, p. 1904576, 2020, doi: [10.1002/adfm.201904576](https://doi.org/10.1002/adfm.201904576).
- [4] J. W. Borchert, R. T. Weitz, S. Ludwigs, and H. Klauk, “A critical outlook for the pursuit of lower contact resistance in organic transistors,” *Adv. Mater.*, vol. 34, no. 2, p. 2104075, 2022, doi: [10.1002/adma.202104075](https://doi.org/10.1002/adma.202104075).
- [5] C.-H. Kim, “Contact resistance in organic transistors: Use it or remove it,” *Appl. Phys. Rev.*, vol. 7, no. 3, p. 031306, 2020, doi: [10.1063/5.0005441](https://doi.org/10.1063/5.0005441).
- [6] G. Horowitz, “Organic field-effect transistors,” *Adv. Mater.*, vol. 10, no. 5, pp. 365–377, 1998, doi: [10.1002/\(SICI\)1521-4095\(199803\)10:5<365::AID-ADMA365>3.0.CO;2-U](https://doi.org/10.1002/(SICI)1521-4095(199803)10:5<365::AID-ADMA365>3.0.CO;2-U).
- [7] P. V. Necliudov, M. S. Shur, D. J. Gundlach, and T. N. Jackson, “Contact resistance extraction in pentacene thin film transistors,” *Solid-State Electron.*, vol. 47, no. 2, pp. 259–262, 2003, doi: [10.1016/S0038-1101\(02\)00204-6](https://doi.org/10.1016/S0038-1101(02)00204-6).
- [8] P. V. Pesavento, R. J. Chesterfield, C. R. Newman, and C. D. Frisbie, “Gated four-probe measurements on pentacene thin-film transistors: Contact resistance as a function of gate voltage and temperature,” *J. Appl. Phys.*, vol. 96, no. 12, pp. 7312–7324, 2004, doi: [10.1063/1.1806533](https://doi.org/10.1063/1.1806533).
- [9] P. V. Pesavento, K. P. Puntambekar, C. D. Frisbie, J. C. McKeen, and P. P. Ruden, “Film and contact resistance in pentacene thin-film transistors: Dependence on film thickness, electrode geometry, and correlation with hole mobility,” *J. Appl. Phys.*, vol. 99, no. 9, p. 094504, 2006, doi: [10.1063/1.2197033](https://doi.org/10.1063/1.2197033).

- [10] M. Micjan, M. Novota, P. Telek, M. Donoval, and M. Weis, "Hunting down the ohmic contact of organic field-effect transistor," *Chin. Phys. B*, vol. 28, no. 11, p. 118501, 2019, doi: [10.1088/1674-1056/ab44a1](https://doi.org/10.1088/1674-1056/ab44a1).
- [11] M. Weis, "The fundamental contact limit in organic electronics defined by Maxwell-Wagner resistance," *J. Appl. Phys.*, vol. 138, no. 17, p. 175501, 2025, doi: [10.1063/5.0297813](https://doi.org/10.1063/5.0297813).
- [12] M. Hanic, T. Vincze, V. Rezo, and M. Weis, "Nature of ohmic and Schottky contacts on pentacene-based organic field-effect transistor," *Synth. Met.*, vol. 305, p. 117590, 2024, doi: [10.1016/j.synthmet.2024.117590](https://doi.org/10.1016/j.synthmet.2024.117590).
- [13] H. Becharguia *et al.*, "Effects of illumination on the electrical characteristics in organic thin-film transistors based on DNNT: Experiment and modeling," *Synth. Met.*, vol. 283, p. 116985, 2022, doi: [10.1016/j.synthmet.2021.116985](https://doi.org/10.1016/j.synthmet.2021.116985).

Received 30 May 2026
