Closed-Form Charge-Based Current Model of Organic TFT Including Non-Linear Injection Effects

Alexander Kloes[1], Franziska Hain[1,2],
Michael Graef[1,2], Benjamin Iniguez[2]

[1]Technische Hochschule Mittelhessen, Germany
[2]Universitat Rovira i Virgili, Spain

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Outline

- Organic TFT: Basics and modeling issues
- Charge-based current model:
  - Link to physical parameters
  - Link to electrical parameters
  - Improvements related to 2nd order effects
  - Results
- Non-linear injection effects
  - Modeling approach
  - Results
- Conclusions

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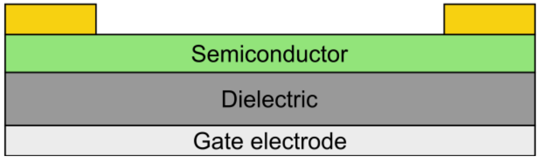
Organic TFT: Basics and Modeling Issues

Organic semiconductors:

- Polymers, small molecules
- Flexible materials allow for flexible substrates
- Low temperature processes (ambient)
- Functional inks
- Additive deposition by conventional printing processes



Structure of organic TFT

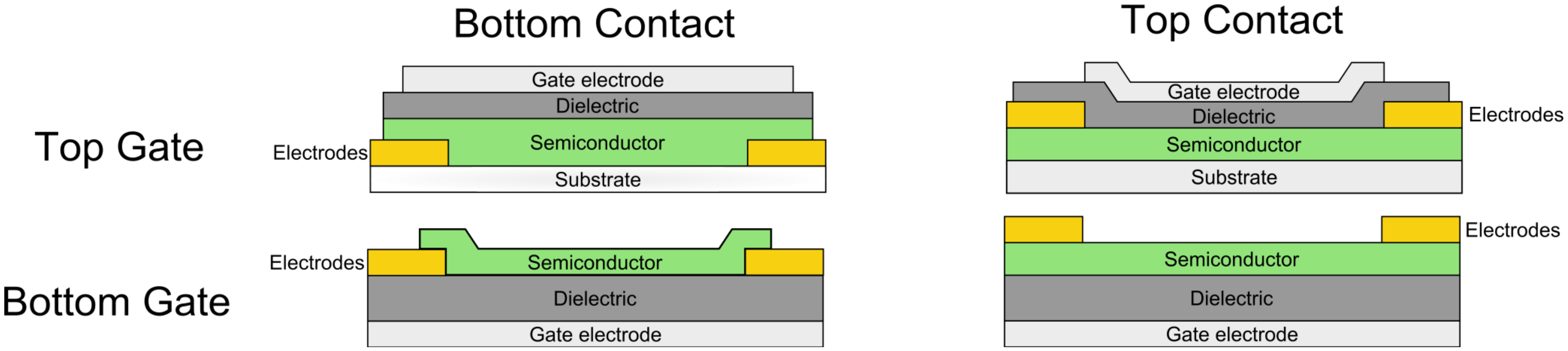
Organic TFT: Basics and Modeling Issues

Charge transport by localizes states:

- Simplified model:
  LUMO: lowest unoccupied molecular orbital (conduction band)
  HOMO: highest occupied molecular orbital (valence band)
- „Variable range hopping“ theory (VRH)
- Low mobility: 0.01 … 2 cm^2/Vs

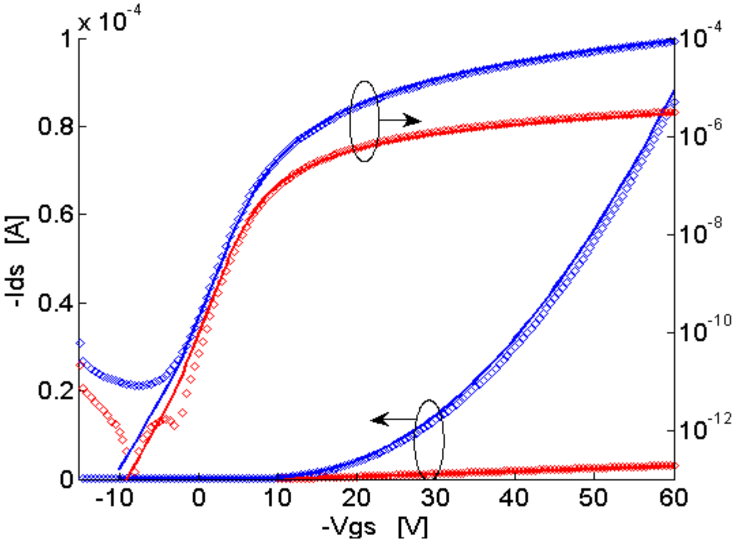
Organic TFT: principle of operation

- Gate potential accumulates charges at interface to dielectric
- Transport **strongly (!!!)** depends on:
  - morphology
  - injection barrier at source
  - traps at interface to dielectric
  - deep and shallow traps in semiconductor



Organic TFT: Basics and Modeling Issues

Classical modeling of channel current in 2 pieces:



- Above V_T:

$$I_{ds} = \mu C'_{ox} \frac{W}{L}\left(V_{gs} - V_T - \frac{V_{ds}}{2}\right)V_{ds}$$

- Below V_T:

$$I_{\mathrm{sub}} = I_0 \exp\left[-\frac{\ln 10}{S}\left(V_{\mathrm{GS}} - V_{\mathrm{T}}^{\mathrm{eff}}\right)\right]$$

- Transition by means of artificial smoothing functions
- Threshold voltage V_T and Slope S are fitting parameters without relation to physical parameters
- However, V_T and S
  - are electrical device parameters
  - performance measures of a device
  - can easily be extracted from measurements
  - are of interest from a circuit designer’s point of view!

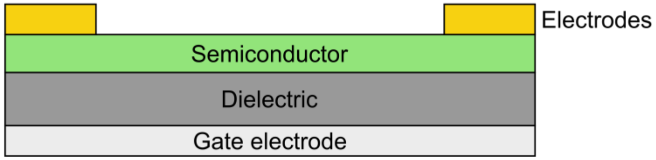
Organic TFT: Basics and Modeling Issues

Charge-based current expression for free carriers:

$$I_{ds} = \mu W \left(\frac{kT}{q} \cdot \underbrace{\frac{Q'_{ms} - Q'_{md}}{L}}_{\text{diffusion part}} + \overbrace{\frac{{Q'_{ms}}^{2} - {Q'_{md}}^{2}}{2LC'_{ox}}}^{\text{drift part}} \right)$$

- $Q'_{ms/d}$: charge density at source/drain end of channel
- Continuous definition of $Q'_{ms/d}$ from below to above V_T is necessary

For organic TFT:



- Charge transport by quasi-mobile charge
- Effect of hopping transport can be included in mobility μ

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Current Model: Physical Parameters

Calculation of quasi mobile charges:

- Separation into charges in shallow and deep traps
- Only shallow traps contribute to the device current
- Charges in shallow traps (quasi mobile charge):

$$Q'_m \approx q d_m \, N_{st} \, \exp\left(\frac{q(\phi_c - V) - E_G/2}{kT}\right)$$

N_{st}: equivalent shallow trap density

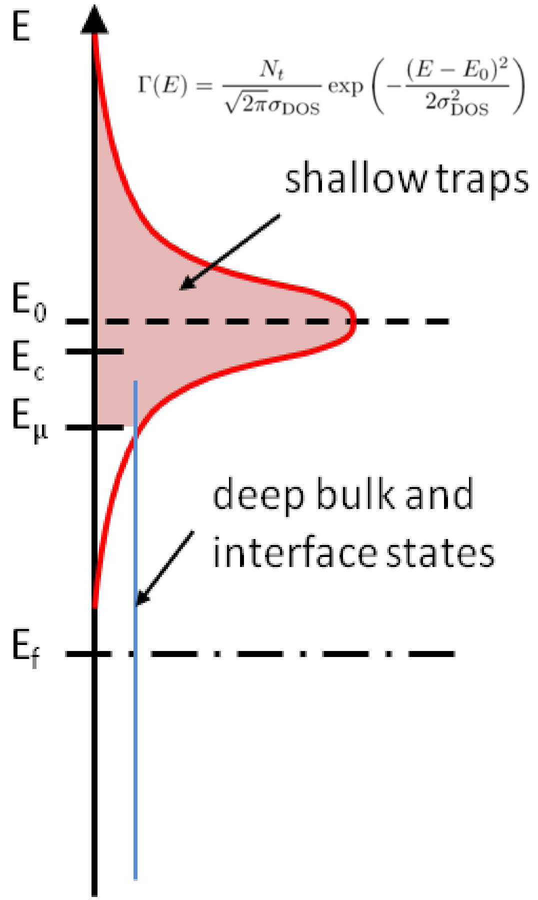
d_m: channel thickness

ϕ_c: channel potential, V: voltage drop along channel

- Charges in deep traps and interface states:

$$Q'_t = q(N'_t \phi_c + N'_{t0})$$

  - no contribution to the device current
  - influence on the electrostatics of the device



[1] F. Hain, C. Lammers, F. Horst, F. Hosenfeld, B. Iniguez, A. Kloes: Continuous charge-based current model for organic TFT derived from Gaussian DOS. Proceedings ICOE 2015, Erlangen, 2015

Current Model: Physical Parameters

- Closed form solution for the charge density at source and drain end:

$$Q'_{ms/d} = \frac{\alpha kT}{q} C'_{ox}\, LambertW\left\{ \frac{Q'_{m0}}{C'_{ox}\alpha kT/q} \exp\left(\frac{V_g - V_{s/d} - V_{fb} - E_g/2q - qN'_{t,\max}/C'_{ox}}{\alpha kT/q} \right) \right\}$$

where $Q'_{m0} = qd_m N_{st}$ and $N'_{t,max}$: max. density of filled deep traps states

- *α:* Sth slope degradation vs. ideal slope (60 mV/dec at 300 K)

- Charge based current equation of quasi-free carriers:

$$I_{ds} = \mu_{FET} W \left[\frac{kT}{q} \cdot \frac{Q'_{ms} - Q'_{md}}{L} + \frac{Q'^{\,2}_{ms} - Q'^{\,2}_{md}}{2LC'_{ox}} \right]$$

- **Result: current equation with a close link to physical parameters**

Current Model: Electrical Parameters

Objective: Introduce V_T in expression for $Q'_{ms/d}$

- Keep one-piece expression from below to above V_T
- If $V_{ds} = 0$ the quasi mobile charge above V_{T0} is given by:

$$Q'_m = C'_{ox}(V_{gs} - V_{T0})$$

- Equating to Q'_{ms} (for $V_{gs} >> V_{T0}$) results in an expression for the threshold voltage:

$$V_{T0} = V_{fb} + E_G/2q + qN'_{t,max}/C'_{ox} - \alpha\frac{kT}{q}\;C'_{ox}\;\ln\left(\frac{Q'_{m0}}{C'_{ox}\alpha kT/q}\right)$$

- Sth slope is given by:

$$S = \alpha\frac{kT}{q}\ln(10) = \left(1 + \frac{q^2 N'_t}{C'_{ox}}\right)\frac{kT}{q}\ln(10)$$

Current Model: Electrical Parameters

- Incorporating expression for V_{T0} in quasi mobile charge:

$$Q'_{ms/d} = \alpha \frac{kT}{q} \, C'_{ox} \, \mathrm{LambertW}\left\{\exp\left(\frac{V_{gs/d} - V_{T0}}{\alpha kT/q}\right)\right\}$$

which still results in a continuous current equation from below to above threshold:

$$I_{ds} = \mu_{FET} W \left[\frac{kT}{q} \cdot \frac{Q'_{ms} - Q'_{md}}{L} + \frac{{Q'_{ms}}^2 - {Q'_{md}}^2}{2LC'_{ox}} \right]$$

Current Model: Electrical Parameters

Additional effects which are defined by a V_T-based description can be included by using continuous $Q'_{ms/d}$:

- Introducing power-law field-effect mobility model [2]:

$$\mu = \kappa \left(V_{gs} - V_{T0}\right)^{\beta} = \kappa \left(\frac{Q'_{ms}}{C'_{ox}}\right)^{\beta}$$

- Including first-order approximation for a contact resistance [3]:

$$\mu_{eff} = \frac{\mu}{1 + \mu C'_{ox} \frac{W}{L} R_c (V_{gs} - V_{T0})} = \frac{\mu}{1 + \mu \frac{W}{L} R_c Q'_{ms}}$$

- Output conductance included by an improved expression from [4]:

$$I_{ds,sat} = \ldots \cdot (1 + \lambda (V_{ds} - V_{dsat}))$$

[2] G. Horowitz et al., Temperature and gate voltage dependence of hole mobility in polycrystalline oligothiophene thin film transistors, Journal of Applied Physics 87, 4456 (2000)

[3] A. Benor, D. Knipp: Contact effects in organic thin film transistors with printed electrodes, Organic Electronics 9 (2008)

[4] C. H. Kim et al.: A compact model for organic field-effect transistors with improved output asymptotic behaviors, IEEE Trans. Electron Devices, vol. 60, no. 3,pp.1136-1141, 2013

Current Model: Electrical Parameters

- Final current model:

$$I_{ds} = \mu_{eff} W \left[\frac{kT}{q} \cdot \frac{Q'_{ms} - Q'_{md}}{L} + \frac{Q'^2_{ms} - Q'^2_{md}}{2LC'_{ox}} \right] \cdot (1 + \lambda(V_{ds} - V_{dsx}))$$

$$Q'_{ms/d} = \alpha \frac{kT}{q} C'_{ox} \ \mathrm{LambertW} \left\{ \exp\left(\frac{V_{gs/d} - V_{T0}}{\alpha kT/q} \right) \right\}$$

$$\mu_{eff} = \frac{\kappa \left(\frac{Q'_{ms}}{C'_{ox}} \right)^{\beta}}{1 + \kappa \left(\frac{Q'_{ms}}{C'_{ox}} \right)^{\beta} \frac{W}{L} R_c Q'_{ms}}$$

$$\alpha = \frac{S}{\frac{kT}{q} \ln(10)}$$

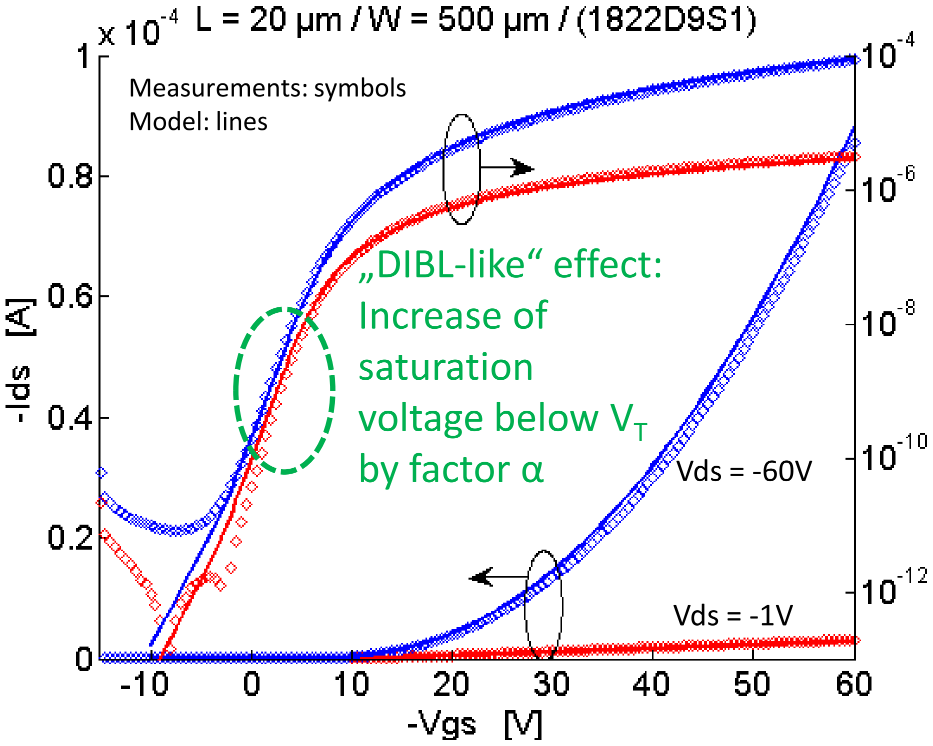
$$V_{dsx} = \frac{1}{C'_{ox}} (Q'_{ms} - Q'_{md})$$

- Parameters: V_{T0}, κ, β, S, λ, C'_{ox}, W, L, R_c

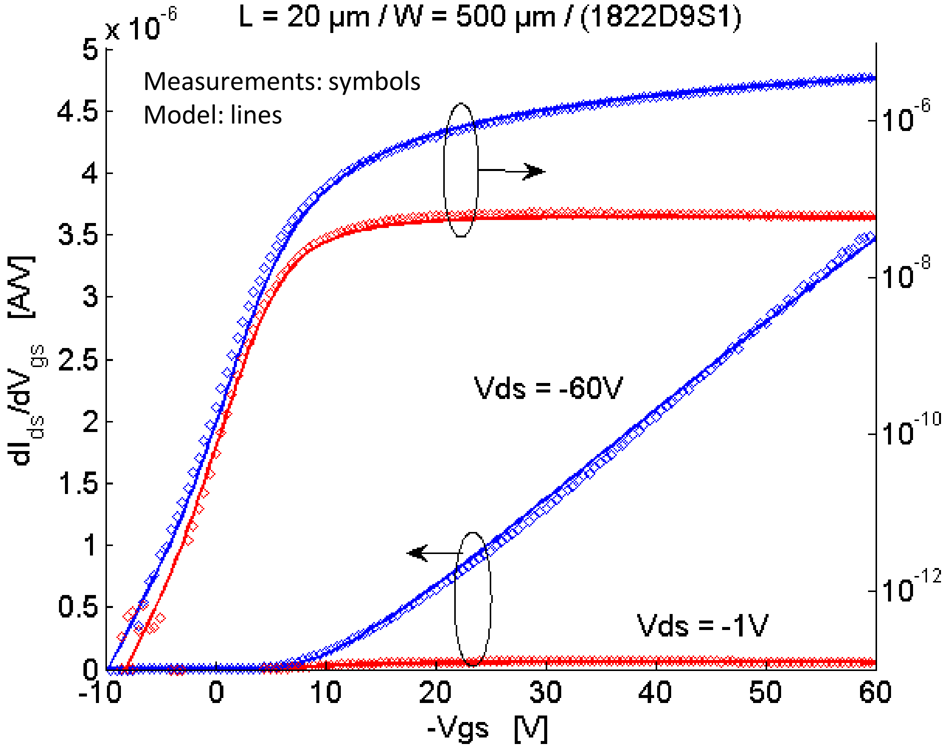
Current Model: Results

Measurements on TFT (small molecule pOSC)

Transfer characteristics and transconductance



„DIBL-like“ effect: Increase of saturation voltage below V_T by factor α

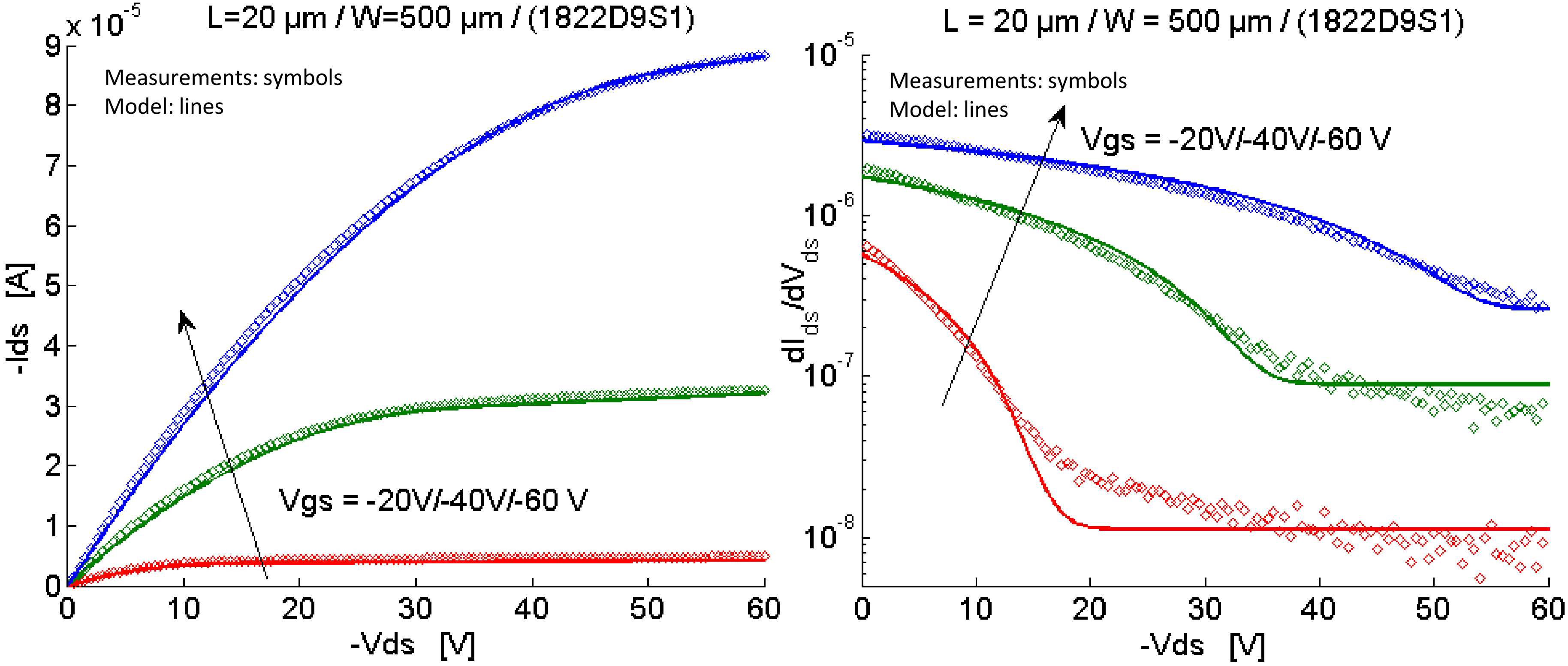


(Measurements provided by CEA-Liten Grenoble)

Current Model: Results

Model vs. measurements on OTFT (small molecule pOSC)

Output characteristics and output conductance



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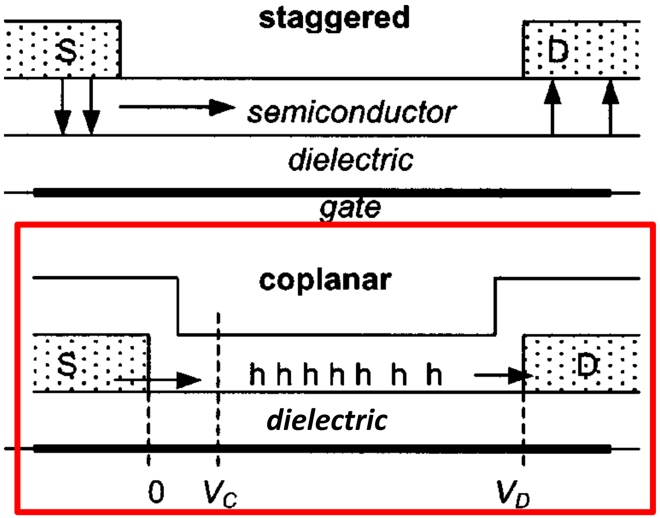
Non-Linear Injection Effects

Modeling issues:

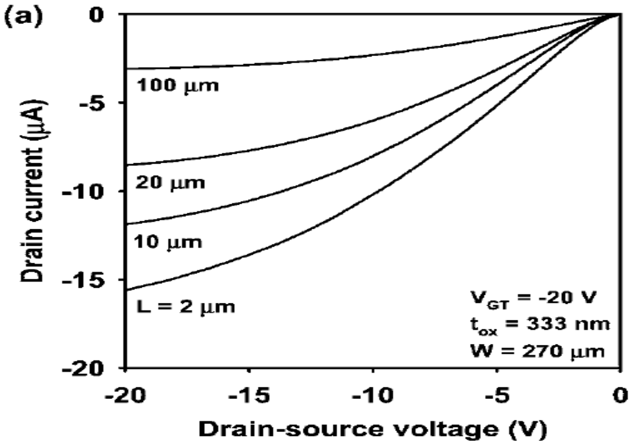
- S/D contacts form Schottky barriers (SB) to channel
- Getting more important for shorter channels (increasing influence of parasitics)



[5] R. A. Street and A. Salleo, Appl. Phys. Lett.Vol. 81, No. 15 (2002)

Focus on coplanar structures:

- Injection at source contact limits device current (reverse biased SB)
- Superlinear behaviour in output characteristics
- If $V_{ds} \approx 0$ most of V_{ds} drops across SB



[6] Gundlach et al., J. Appl. Phys. 100, 024509 (2006)

Non-Linear Injection Effects

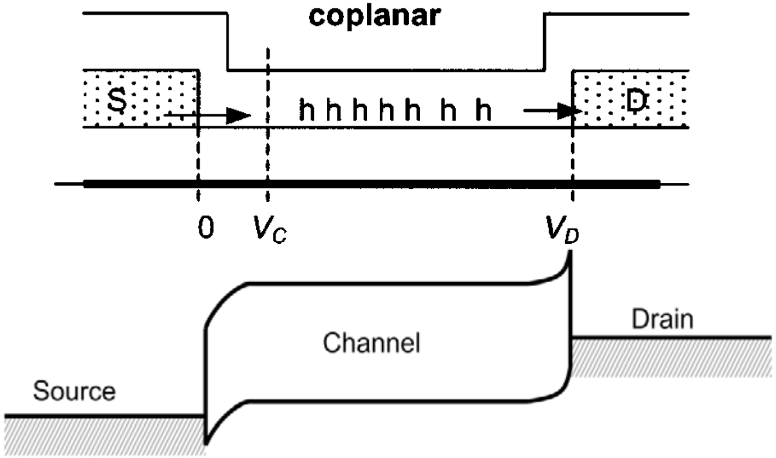
- Schottky barrier lowering, depending on contact voltage V_c and gate bias V_g
- Exponential I/V dependence of contact
- Well known model (diode-type equation):

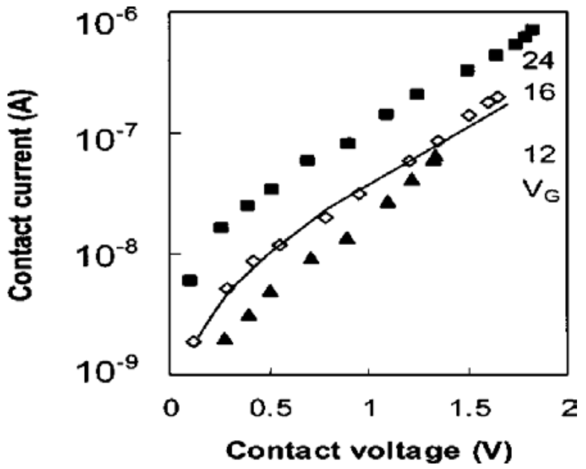
$$I_D = I_0[\exp(V_C / V_0) - 1]$$

[5] R. A. Street and A. Salleo, Appl. Phys. Lett.Vol. 81, No. 15 (2002)

Fitting parameters: V_0, I_0
(V_0 depends on gate voltage)
No explicit expression for V_c

- No dependence to gate bias in model, but in measurements
- Physical interpretation more complex…



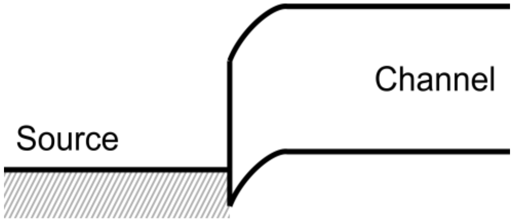


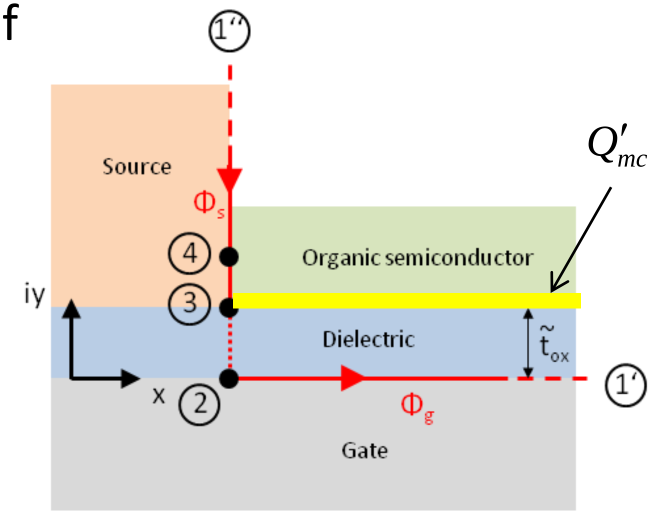
[5] R. A. Street and A. Salleo, Appl. Phys. Lett.Vol. 81, No. 15 (2002)

Non-Linear Injection Effects

Modeling Approach:

- Gate potential causes SB lowering, but will be screened by accumulated charge
- Q_{mc}: accumulated charge density at source end of intrinsic channel
- Lowering of barrier: $\Delta\phi_B = \sqrt{\frac{qE_0}{4\pi\varepsilon_c}}$
- Closed-form solution for electric field E_0 at point 4 by conformal mapping
  (average for the electric field in layer of injection)
- Fitting parameter: distance 3-4
  (in order of thickness of accumulated charge layer)





Z plane

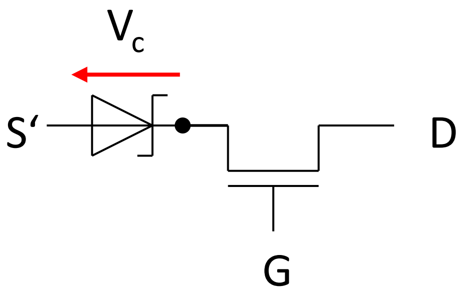
Non-Linear Injection Effects

Current calculation:

- Source injection: reverse biased Schottky diode

$$I_{sb} = J_{s0} \cdot t_{ch} \cdot \left(\exp\left(-\frac{V_c}{V_t} \right) - 1 \right)$$

$$J_{s0} = J_{s00} \cdot \exp\left(-\frac{\phi_{Bp} - \Delta\phi_B}{V_t} \right)$$



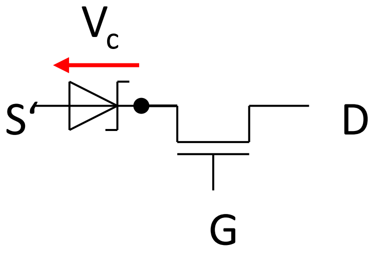
- J_{s00}, t_{ch}, ϕ_{Bp}: fitting parameters
  (materials, work function difference, morphology, thickness of injection layer…)
- **Model captures effect of gate bias on SB lowering at source injection**
- Coupled to intrinsic channel current model by numerical iteration, solving for voltage V_c

Non-Linear Injection Effects

Approach for closed-form model

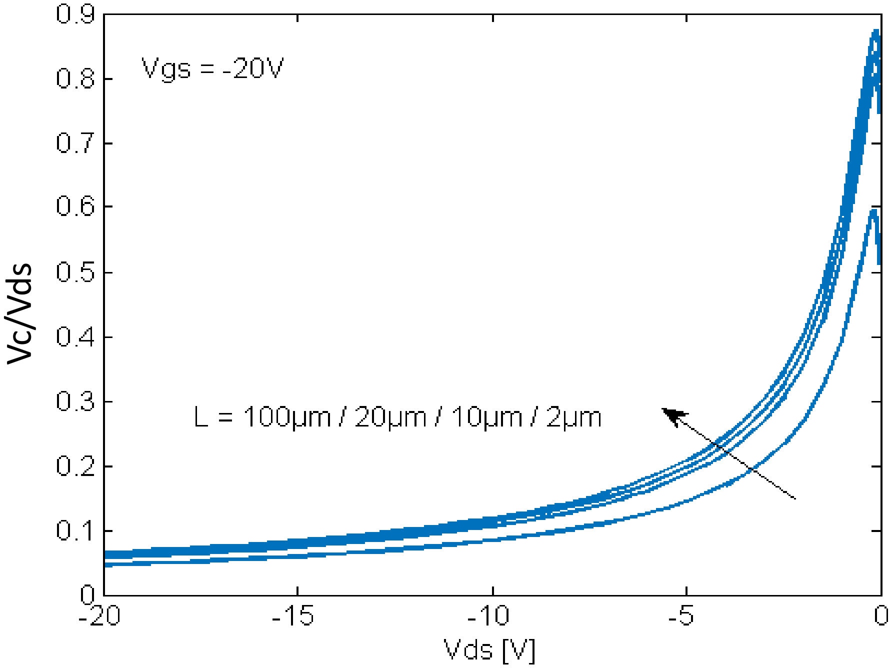
Problem:

- No explicit expression for contact voltage V_c



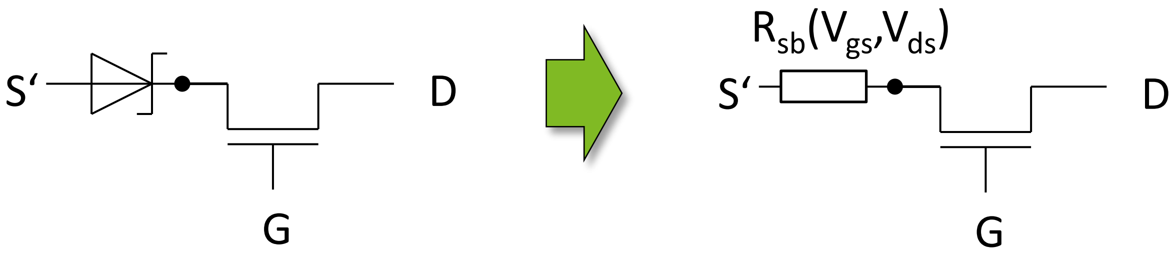
Simplifications:

- Non-linear injection effect most important for short channel devices
- In superlinear region most of V_{ds} drops across SB
- Approximate $Q'_{ms} \approx Q'_{md}$ in model equations for $\Delta\phi_B$



Non-Linear Injection Effects

- Calculate voltage dependent, non-linear resistance of SB:



$$R_{sb} = \frac{V_{gs} - V_{T0} + \frac{E_g}{2q} - V_{bi} - Q'_{md}/C'_{ox}}{I_{sb}}$$

I_{sb}: max. injection current at SB

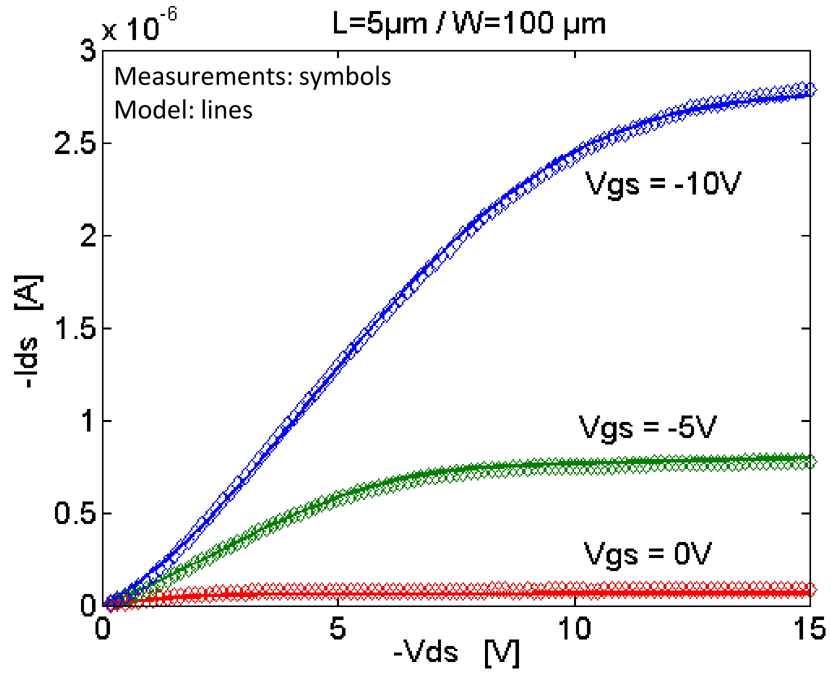
- Include SB resistance in effective mobility:

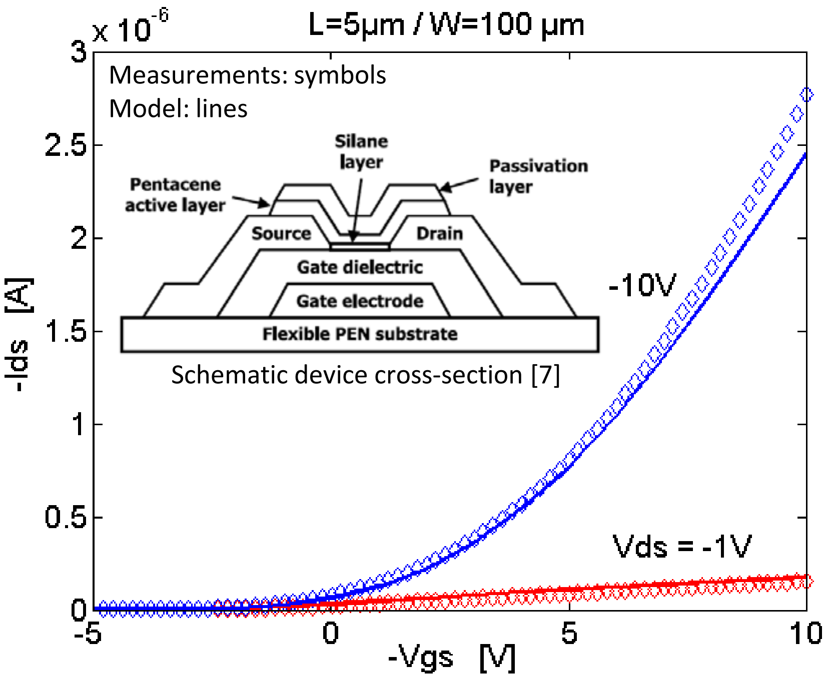
$$\mu_{eff} = \frac{\mu}{1 + \mu \frac{W}{L} (R_c + R_{sb}) Q'_{ms}}$$

Non-Linear Injection Effects

Model vs. measurements on pentacene TFT

Output and transfer characteristics





Schematic device cross-section [7]

Measurements from:

[7] Hagen Klauk et al., Contact resistance in organic thin film transistors, Solid-State Electronics 47 (2003) 297–301

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Conclusions

- Charge-based current model for organic TFT
- One-piece, current equation valid from below to above threshold
- Two compatible parameter sets:
  - Physical parameters (deep/shallow trap densities...)
  - Electrical parameters (VT, slope)
- Additional effects included:
  - Hopping transport by power-law field effect mobility model
  - Contact resistance (first-order approx.)
  - Output conductance
- Non-linear injection model for coplanar device structures:
  - Physics-based and bias dependent
  - Coupled to current equation in closed form
- Results are in good agreement with measurements

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