TECHNISCHE UNIVERSITÄT DRESDEN

**School of Science** Department of Physics

# A Vertical Organic Transistor with Areal Current Densities in the kA/cm² Regime

Axel Fischer

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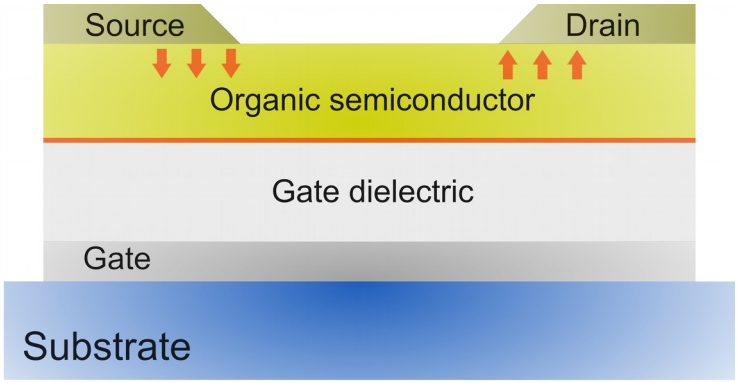
DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

NGC 2017, Tomsk

# Motivation



- What makes a good transistor?



# Motivation



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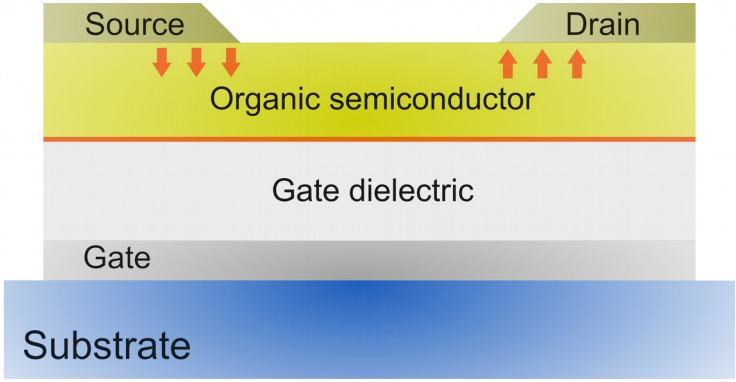
**A lot of current on a small area!**

→ high transconductance
→ small capacitance
→ high packing density



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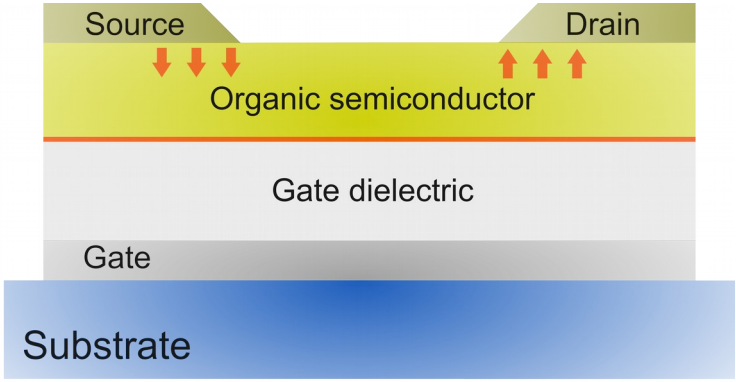



| Author | Approach/Material | $f_T$ | $j_{areal}$ | Voltage |
|---|---|---|---|---|
| Kitamura *et al.* | C60 FET | 28 MHz | ~ 10 A/cm$^2$ | 25 |
| Uno *et al.* | Step-edge OFET | 20 MHz | ~ 10 A/cm$^2$ | 15 |
| Münzenrieder *et al.* | IGZO FET | 135 MHz | ~ 500 A/cm$^2$ | 2 |
| | Si MOSFET | > 100 GHz | > 1 MA/cm$^2$ | 1 |

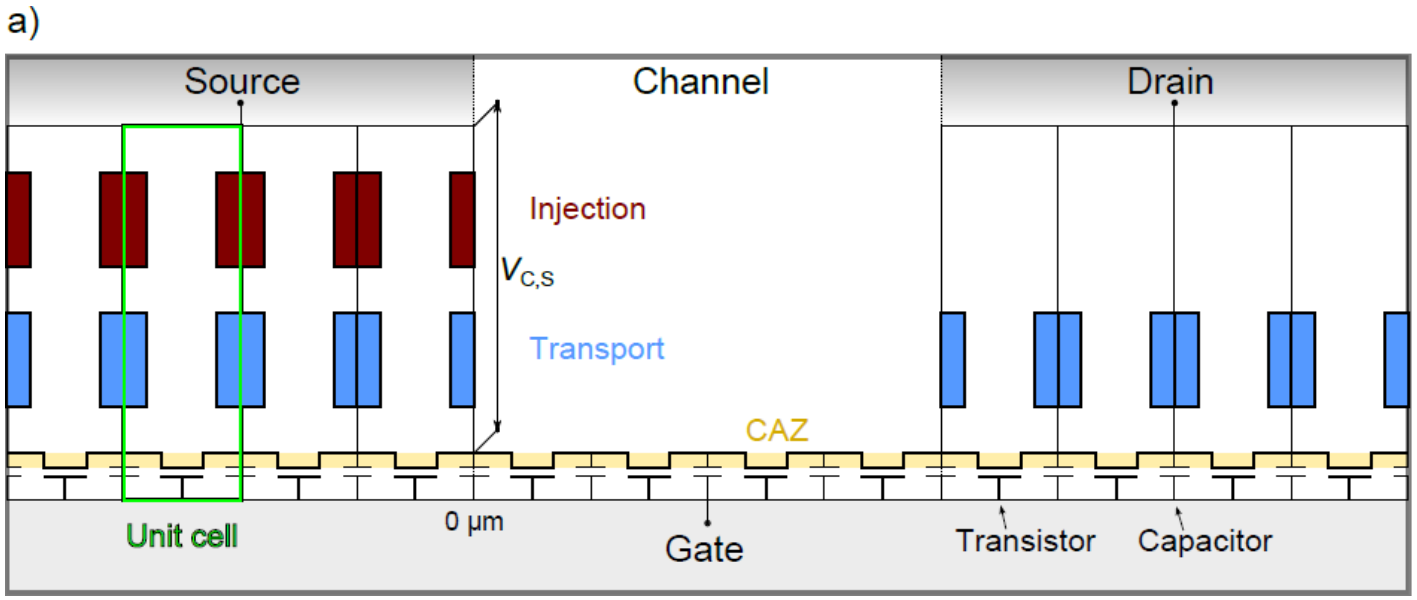
Kitamura & Arakawa, Jpn. J. Appl. Phys., **2011**, 50
Uno *et al.*, Org. Electron., **2015**, 20
Münzenrieder *et al.*, IEEE Trans. Electron Dev., **2013**, 60

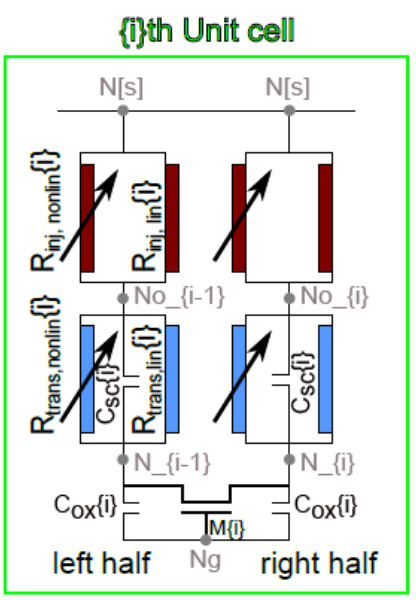
# Outline

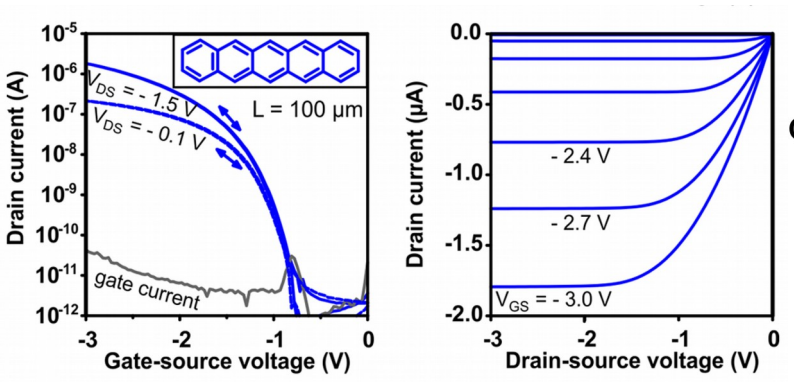


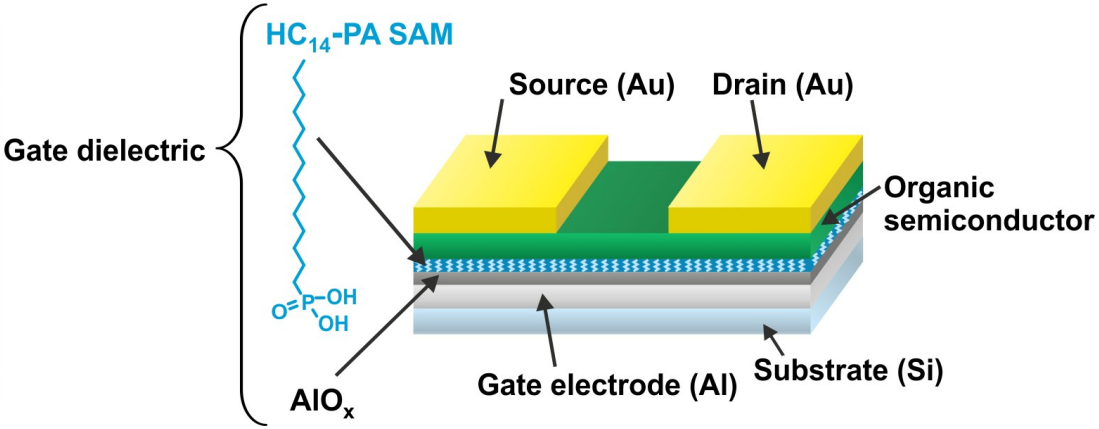
1. Contact resistance in thin-film transistors
2. The organic permable base transistor
3. Device structuring to reach higher performance
4. Understanding the device operation
5. Going to the limits
6. Electrothermal feedback

# OFET model



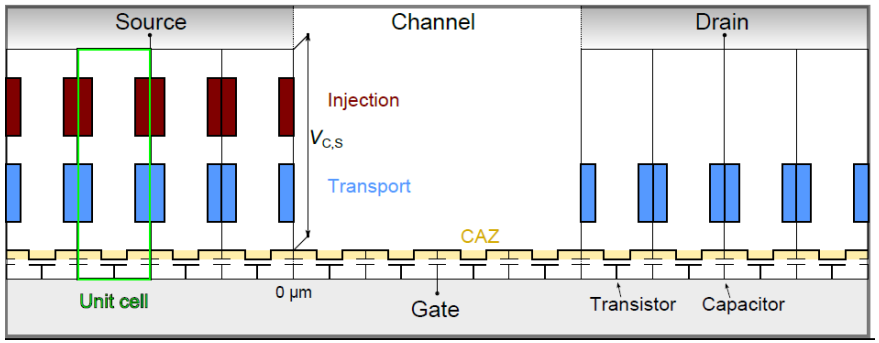



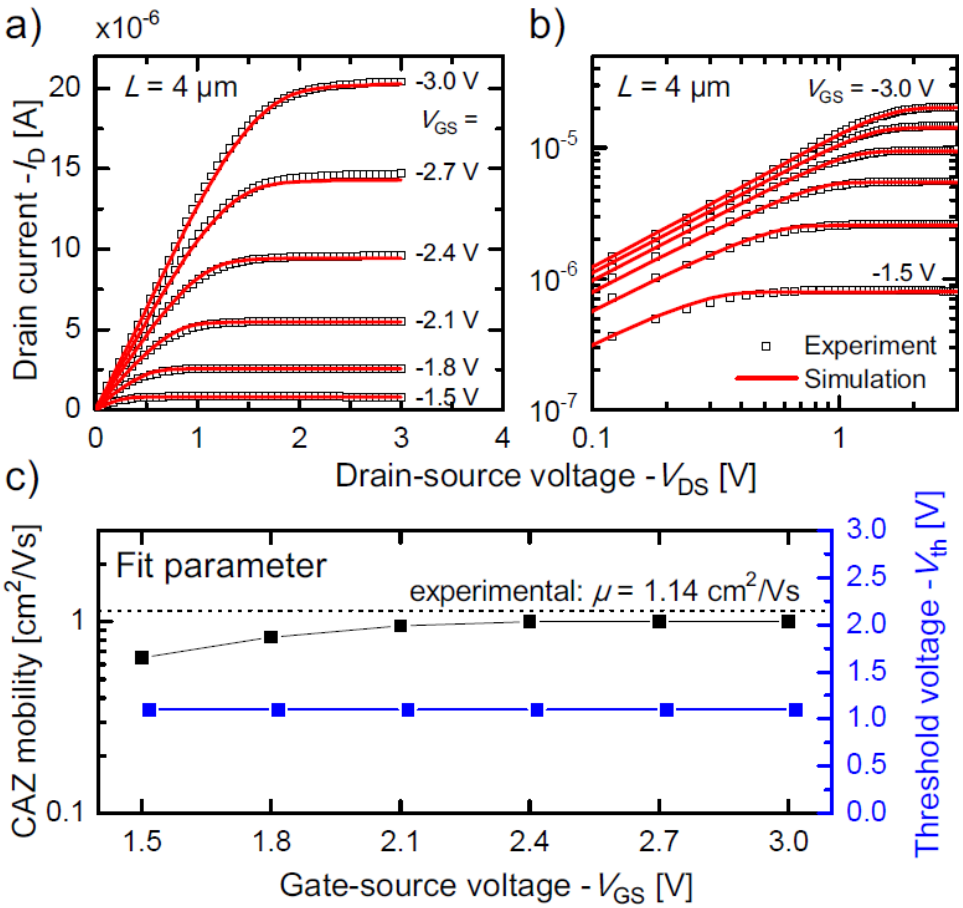




Kraft et al., Chem. Mater. **2015**, 27

# OFET model





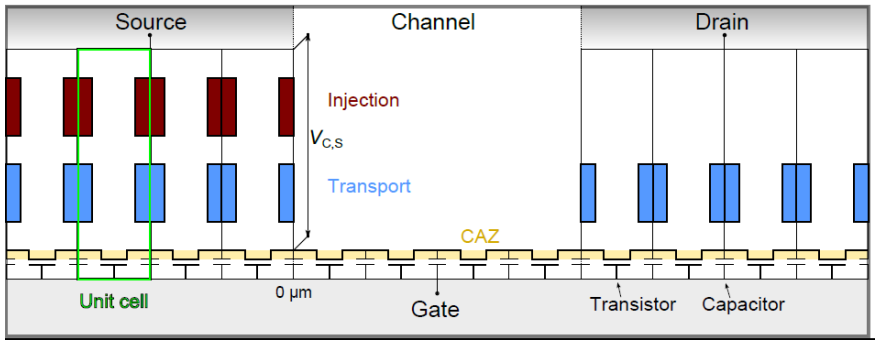



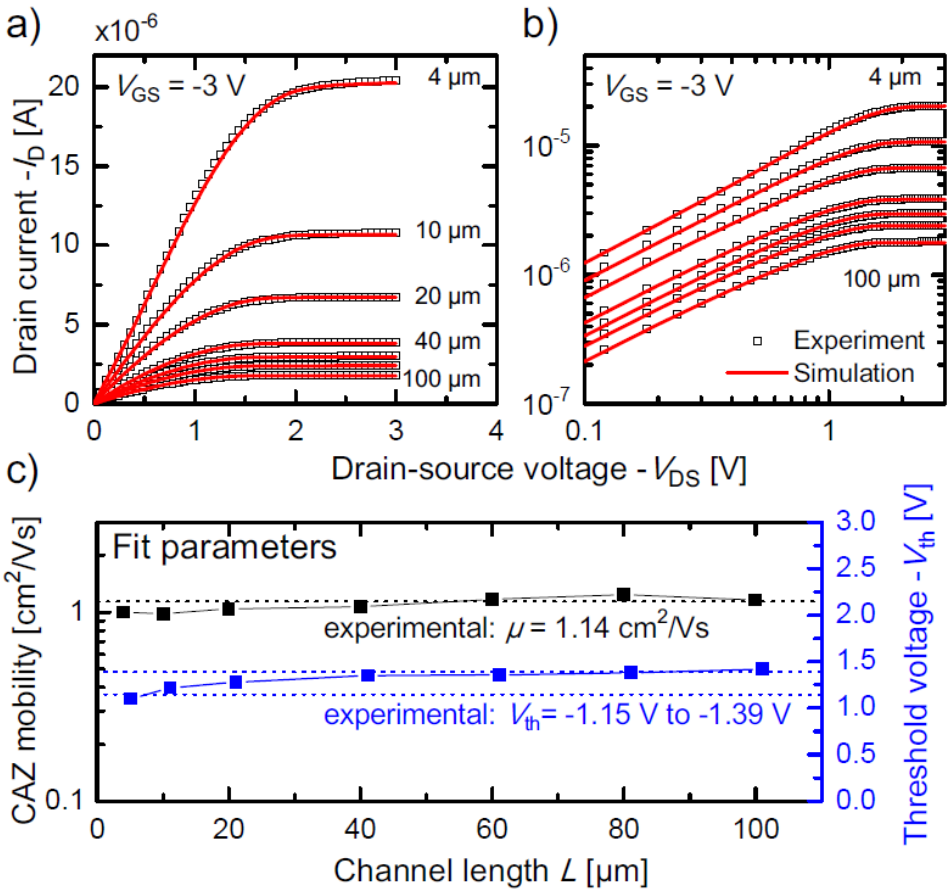

- Variation: Gate-source voltage
- Covering the full data range
- Threshold voltage constant
- Increase of mobility

Fischer et al., Phys. Rev. Applied **2017,** 8

# OFET model





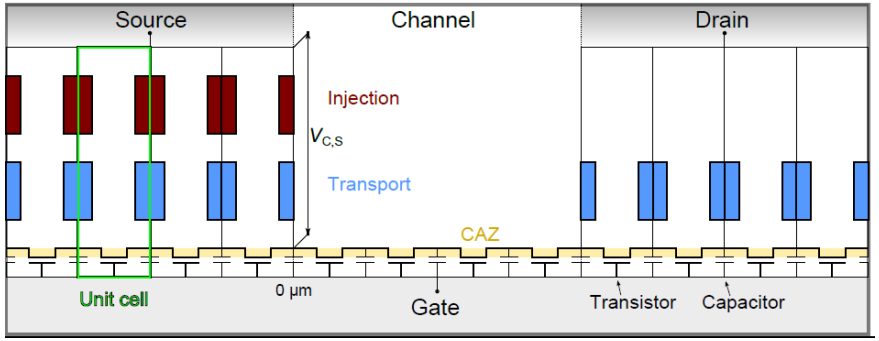



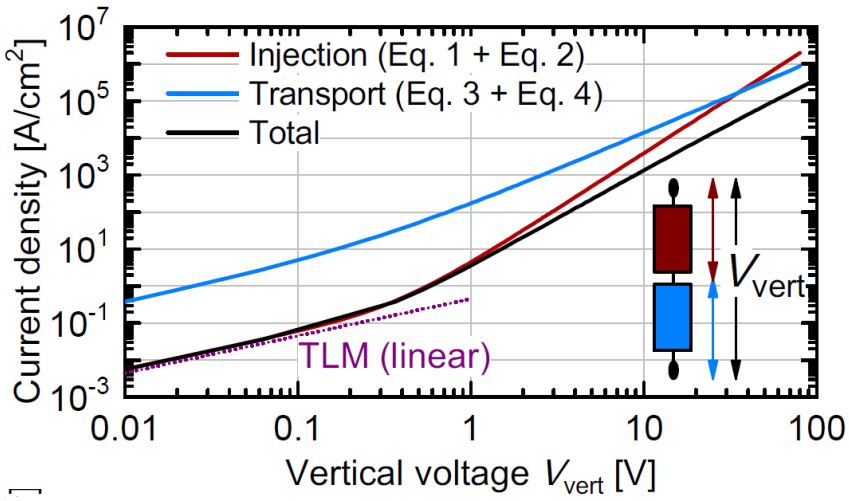

- Variation: Channel length
- Covering the full data range
- Intrinsic mobility constant
- Threshold voltage roll-off

Fischer et al., Phys. Rev. Applied **2017,** 8

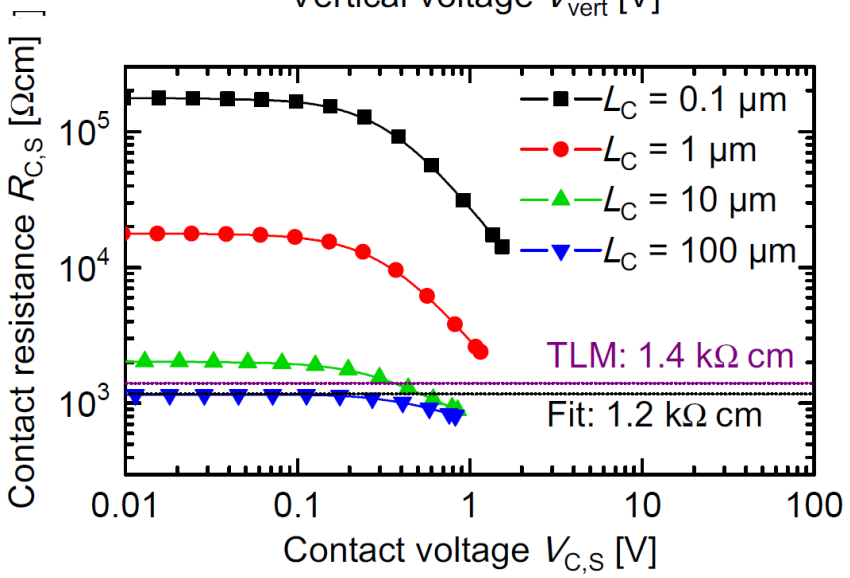
# OFET model






- Nonlinear parts essential!
- Model scales with the geometry




Fischer et al., Phys. Rev. Applied **2017,** 8

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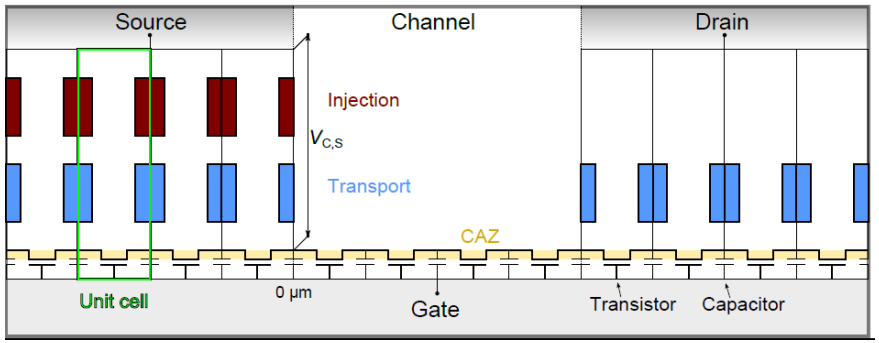


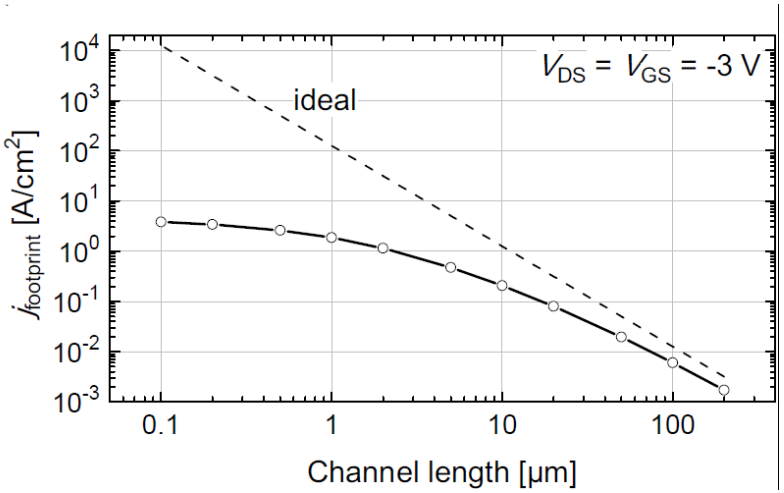


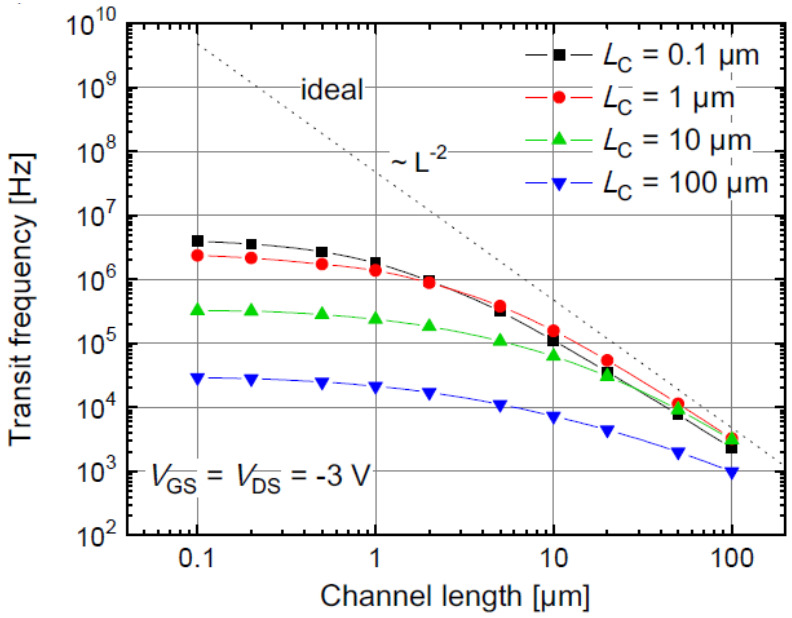


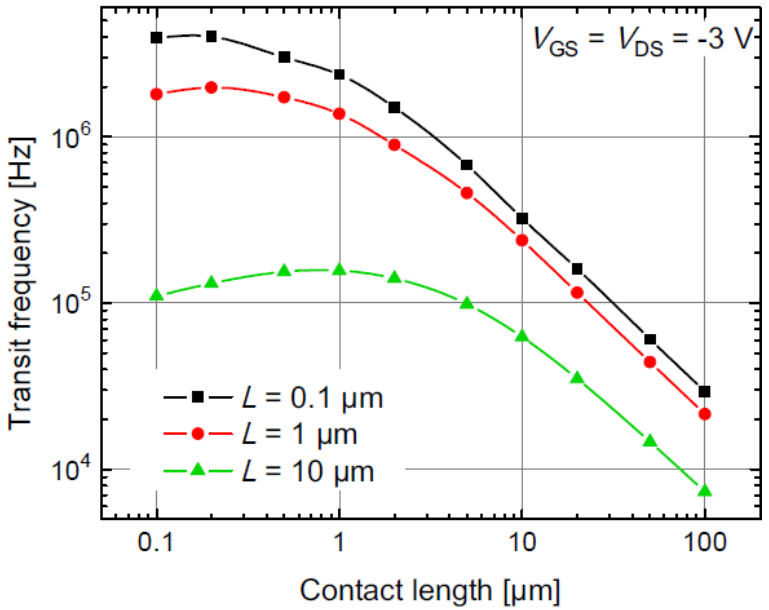


Fischer et al., Phys. Rev. Applied **2017,** 8

# Outline



1. Contact resistance in thin-film transistors
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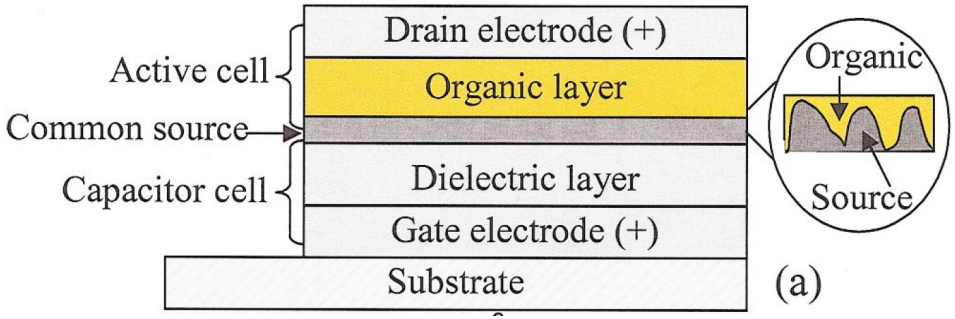
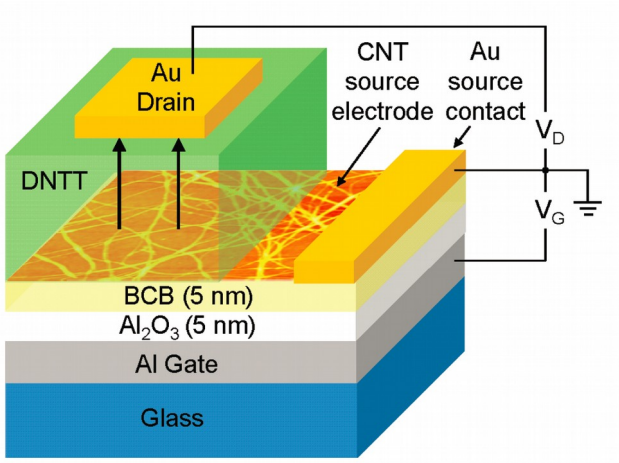
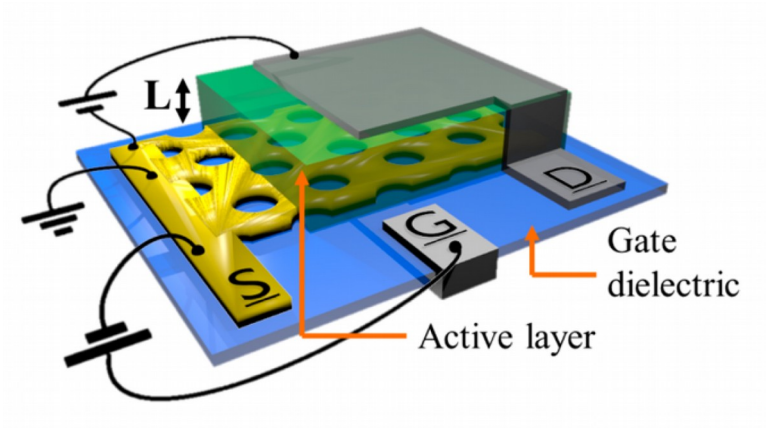
# Organic Schottky Barrier Transistor (OSBT)



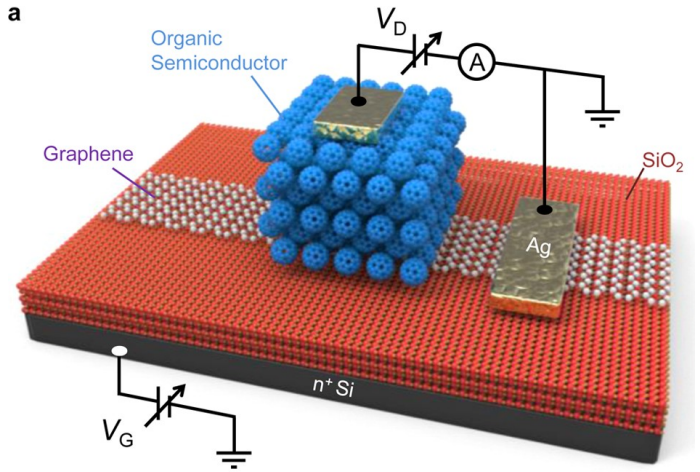

Ma & Yang, Appl. Phys. Lett., **2004**, 85




McCarthy *et al.*, Nano Lett., **2010**, 10



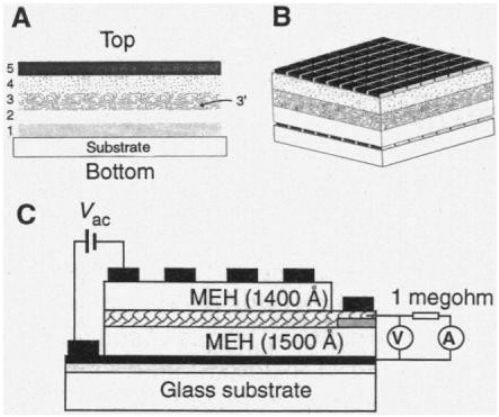

Ben-Sasson & Tessler, Nano Lett., **2012**, 12
Greenman et al., Appl. Phys. Lett., **2013**, 103



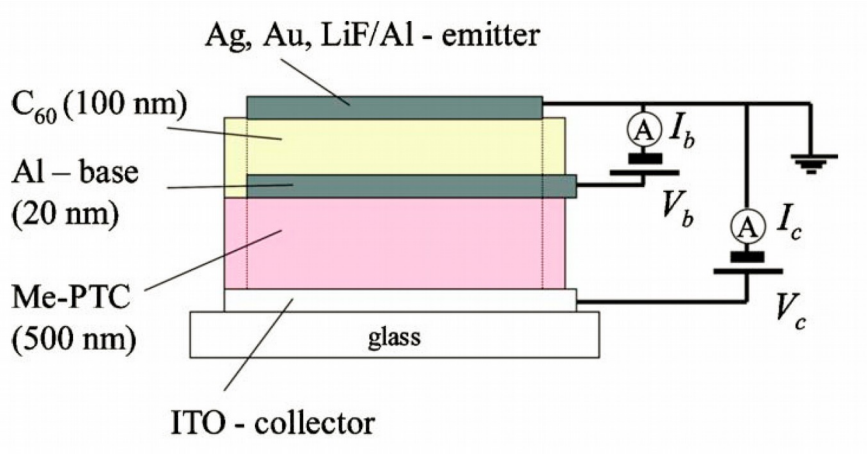

Shih *et al.*, Nano Lett., **2015**, 15
Ojeda-Aristizabal *et al.*, Phys. Rev. B, **2013**, 88

Lüssem, .., Fischer, .., J. Phys. Condens. Matter, **2015**, 27

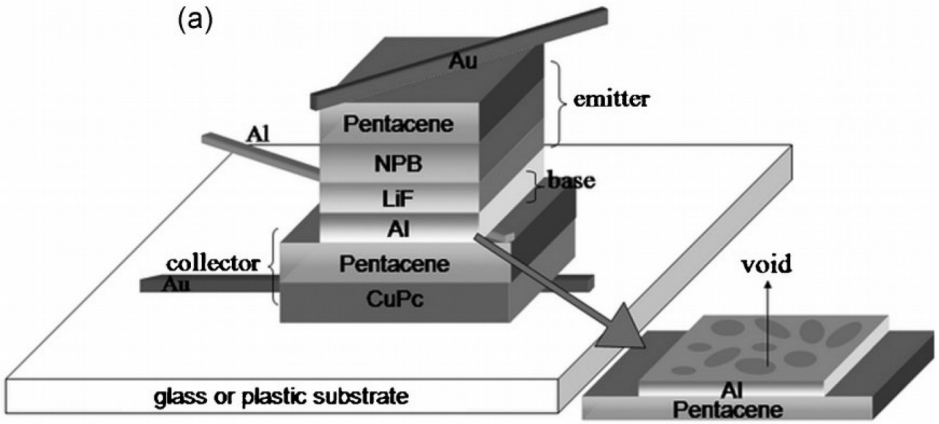
# Organic Permeable Base Transistor (OPBT)



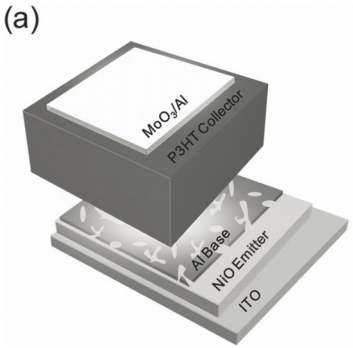

Yang & Heeger, Nature, **1994**, 372
Heeger *et al*., Science, **1995**, 270

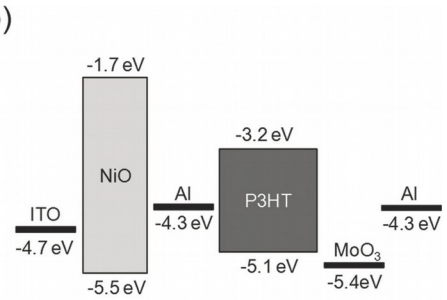



Fujimoto *et al*., Appl. Phys. Lett. **2005**, 87
Nakayama *et al.*, Appl. Phys. Lett., **2006**, 88




Cheng *et al*., Appl. Phys. Lett., **2007**, 90
Cheng *et al.*, Adv. Mater., **2009**, 21



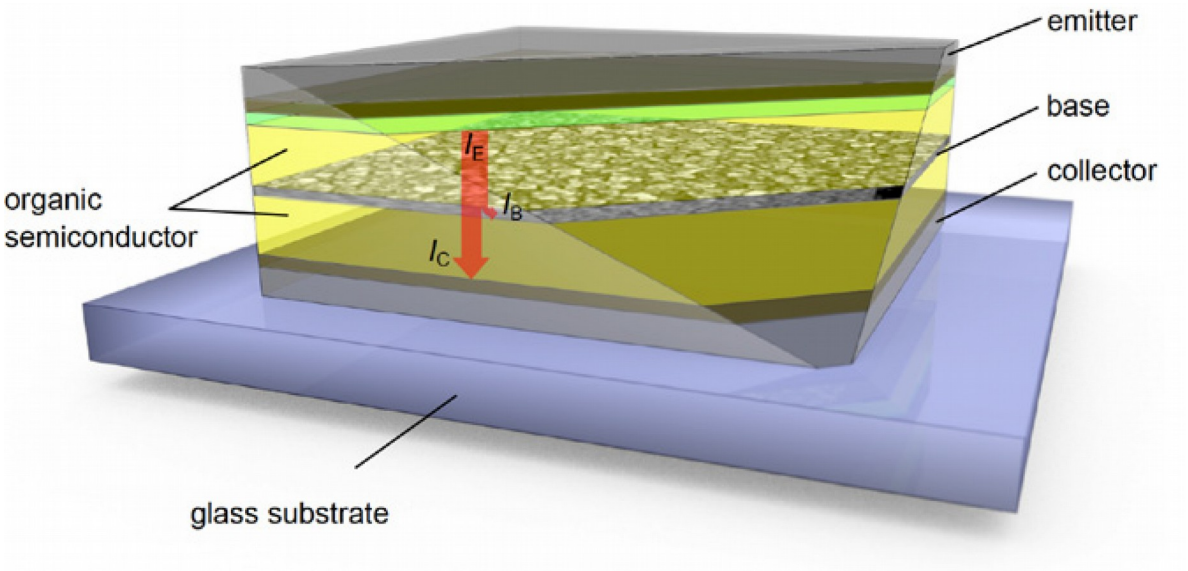




Yu *et al.*, Adv. Funct. Mater., **2014**, 24
Kim *et al.*, Small, **2014**, 10

Lüssem, .., Fischer, .., J. Phys. Condens. Matter, **2015**, 27

# Advantages of OPBT



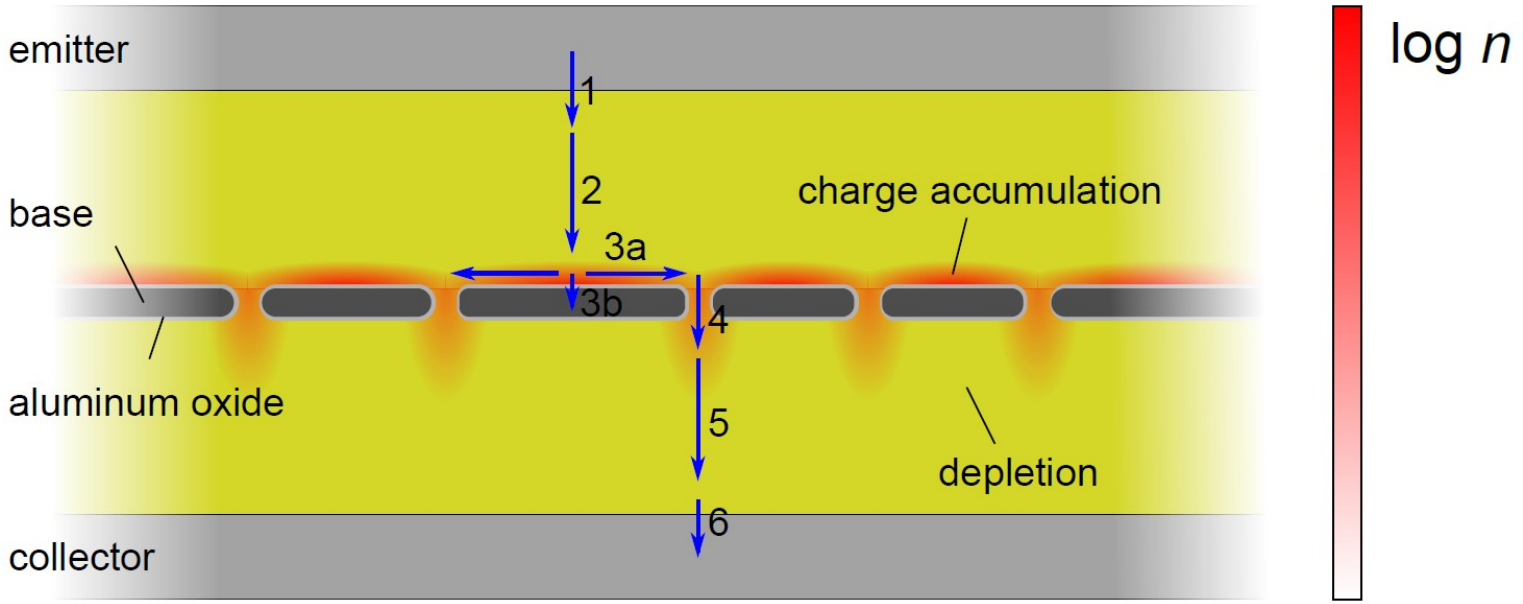



- Compatible with OLED fabrication ( → thermal evaporation & shadow masks)
- Sandwich layer stack ( → combine two devices)
- Low resolution, low cost structuring
- Integration of doped or functional layers ( → contact resistance, etc.)

Lüssem, .., Fischer, .., J. Phys. Condens. Matter, **2015**, 27

# Operation mechanism



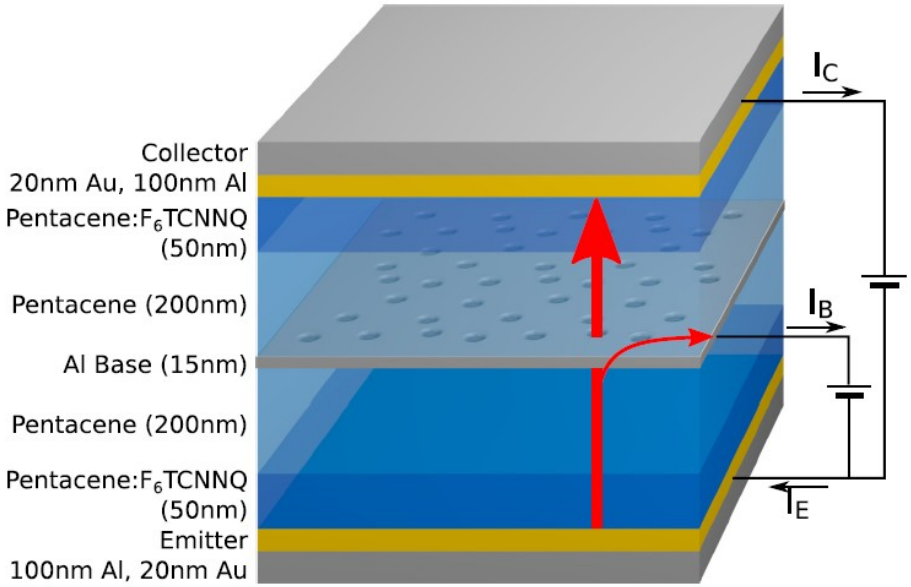


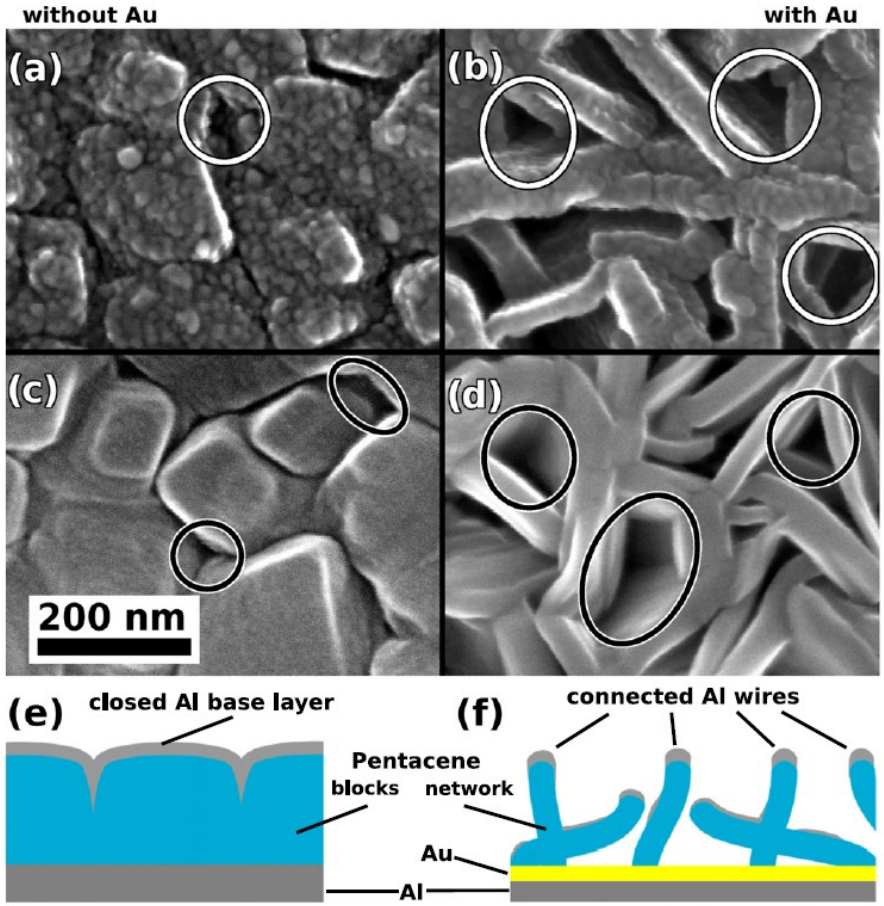

- Transmission based on nano-size openings
- Native oxide passivates the base electrode

Fischer, PhD thesis: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-180780

# Morphology






- p-type OPBT realized with pentacene

Kaschura, Fischer, .., Appl. Phys. Lett., **2015**, 107

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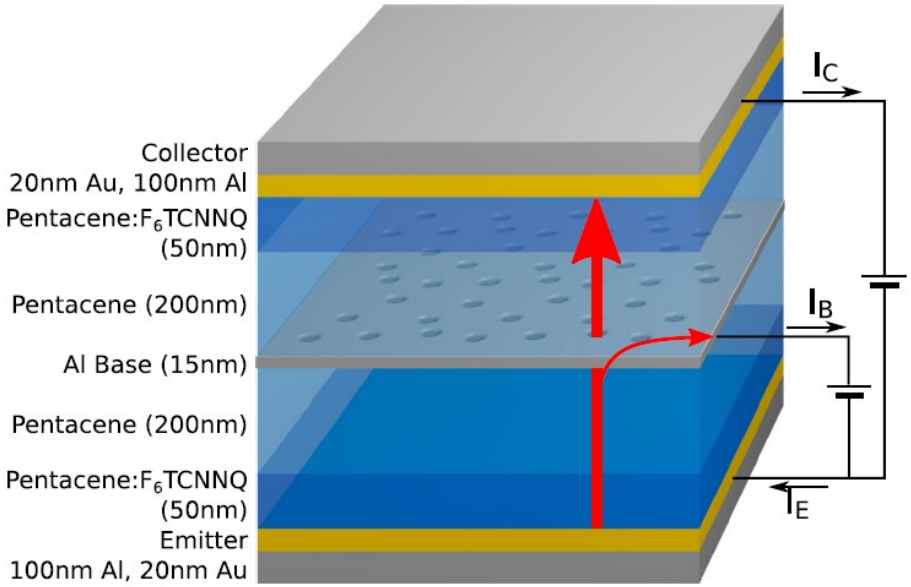


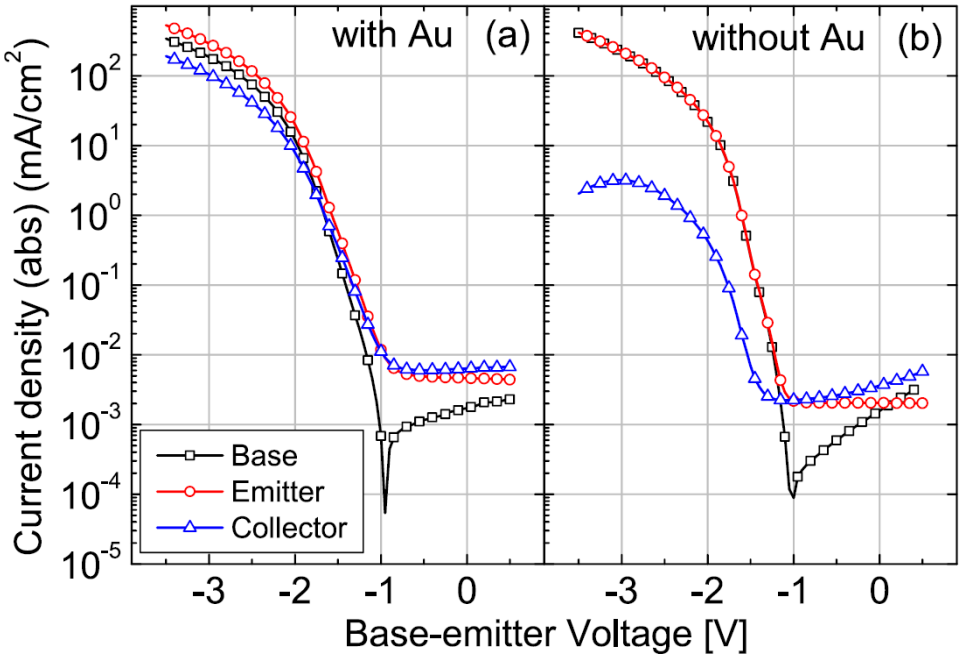


Transfer characteristic („Base sweep")

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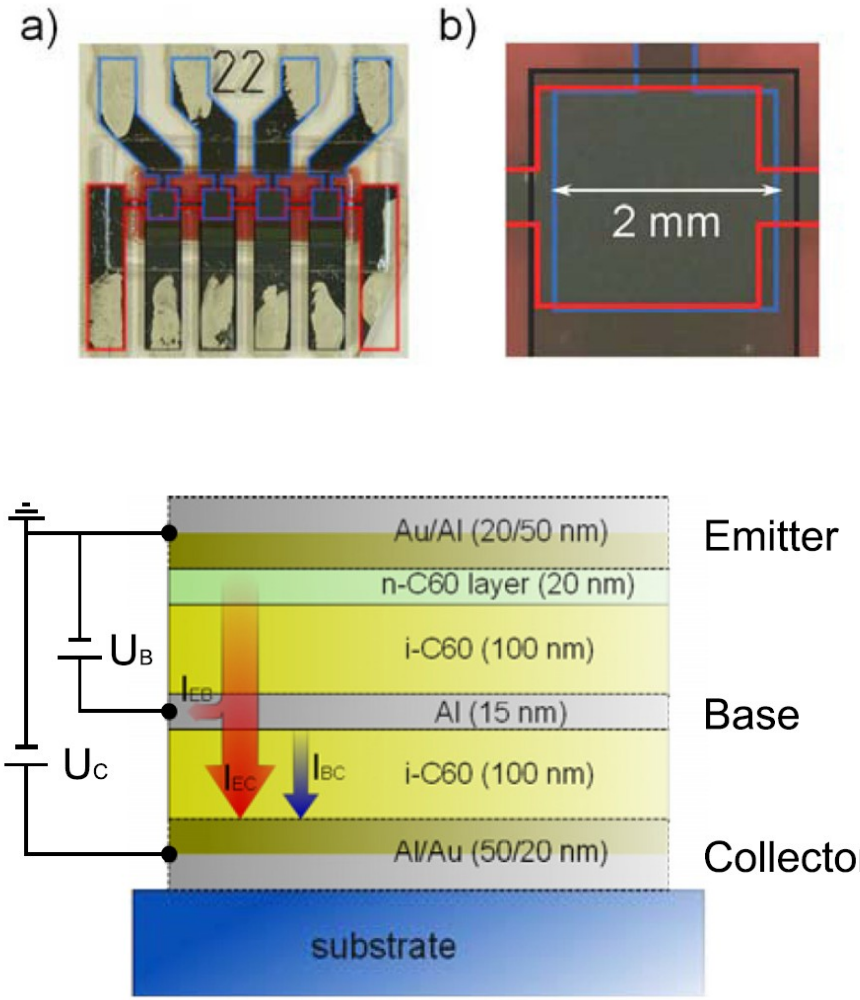
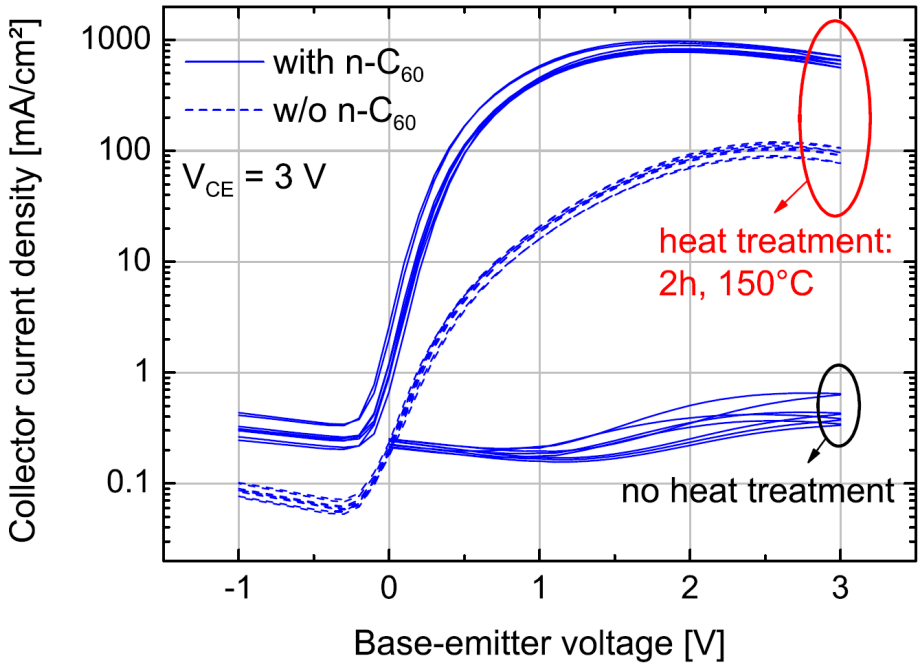
Kaschura, Fischer, .., Appl. Phys. Lett., **2015**, 107

# First C60 OPBT






Transfer characteristic („Base sweep“)

Fischer, *et al.*, Appl. Phys. Lett., **2012**, 101
Fischer, *et al.*, J. Appl. Phys., **2012**, 111

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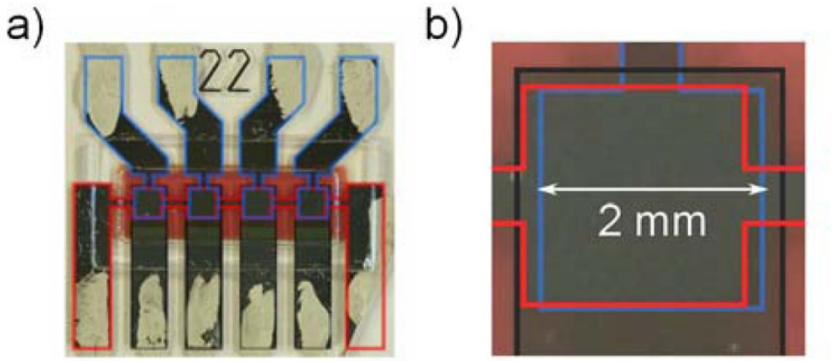
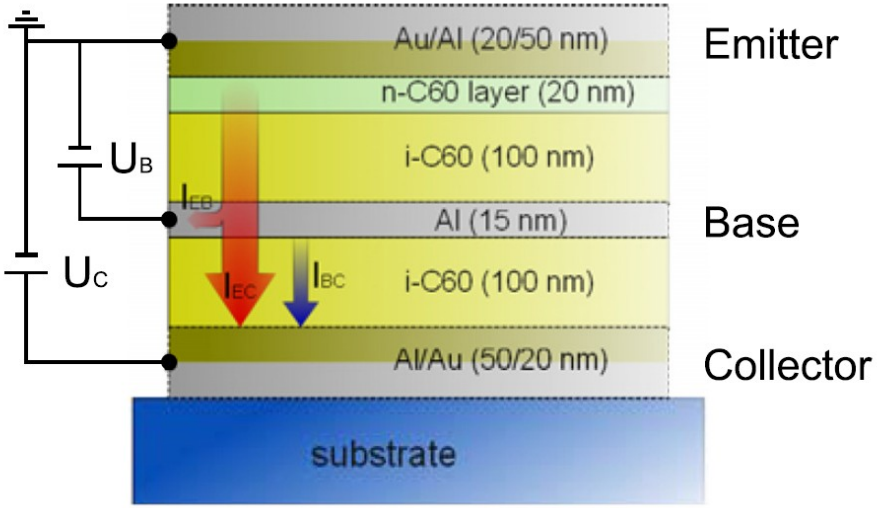
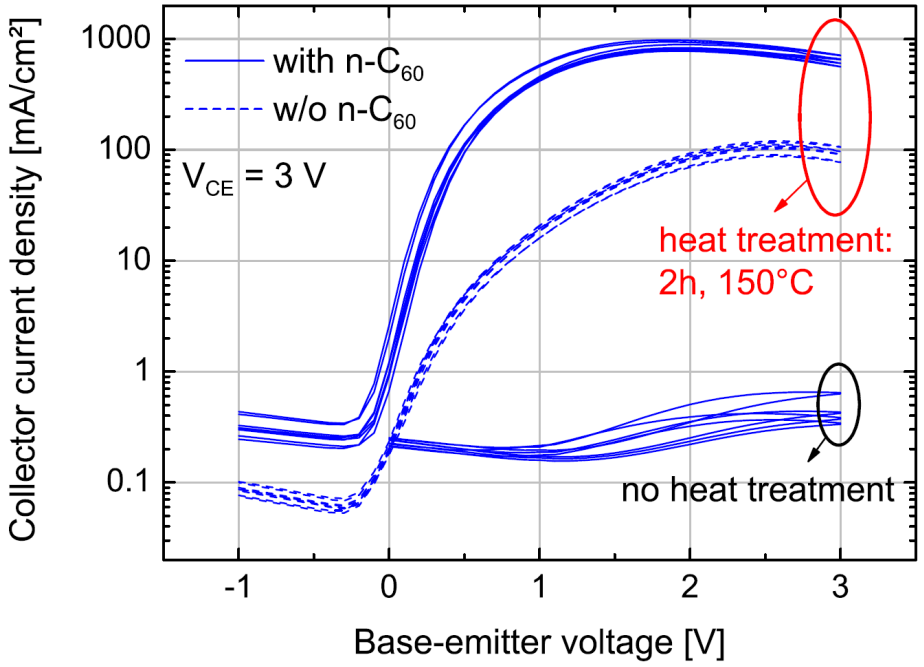



On-state resistance: 75 Ω → electrodes

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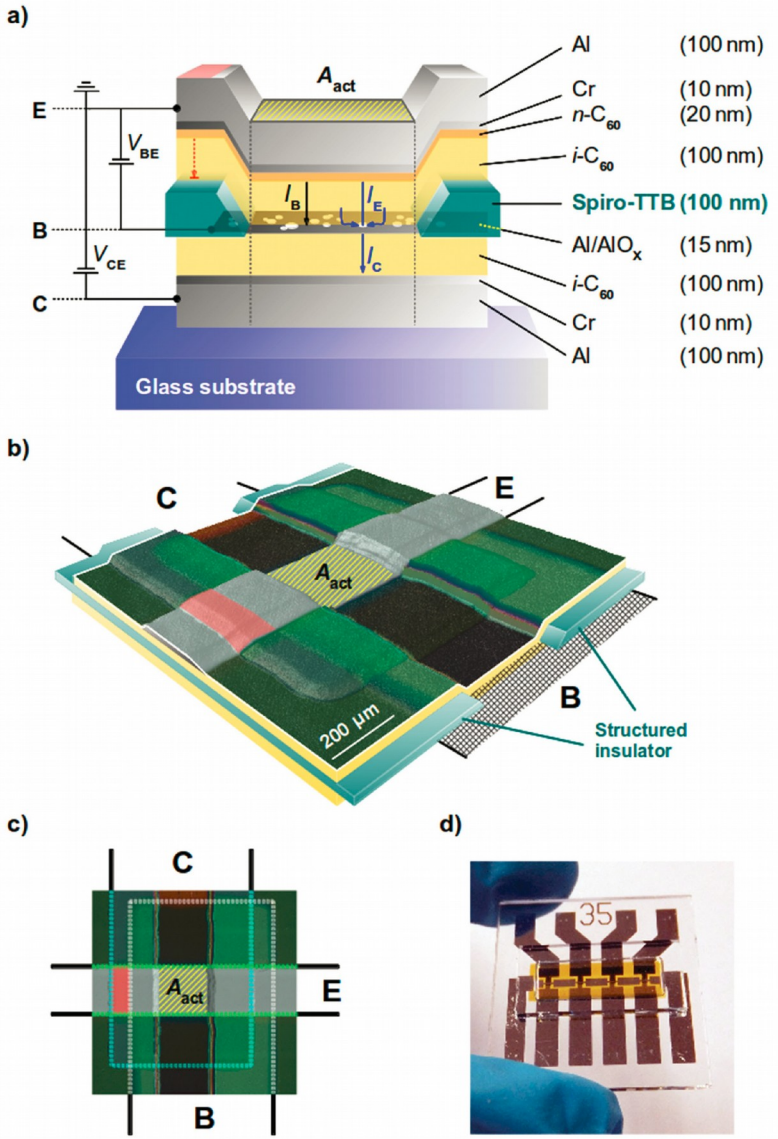
# Structured OPBTs






Klinger, Fischer,.. , Adv. Mater., **2015**, 27

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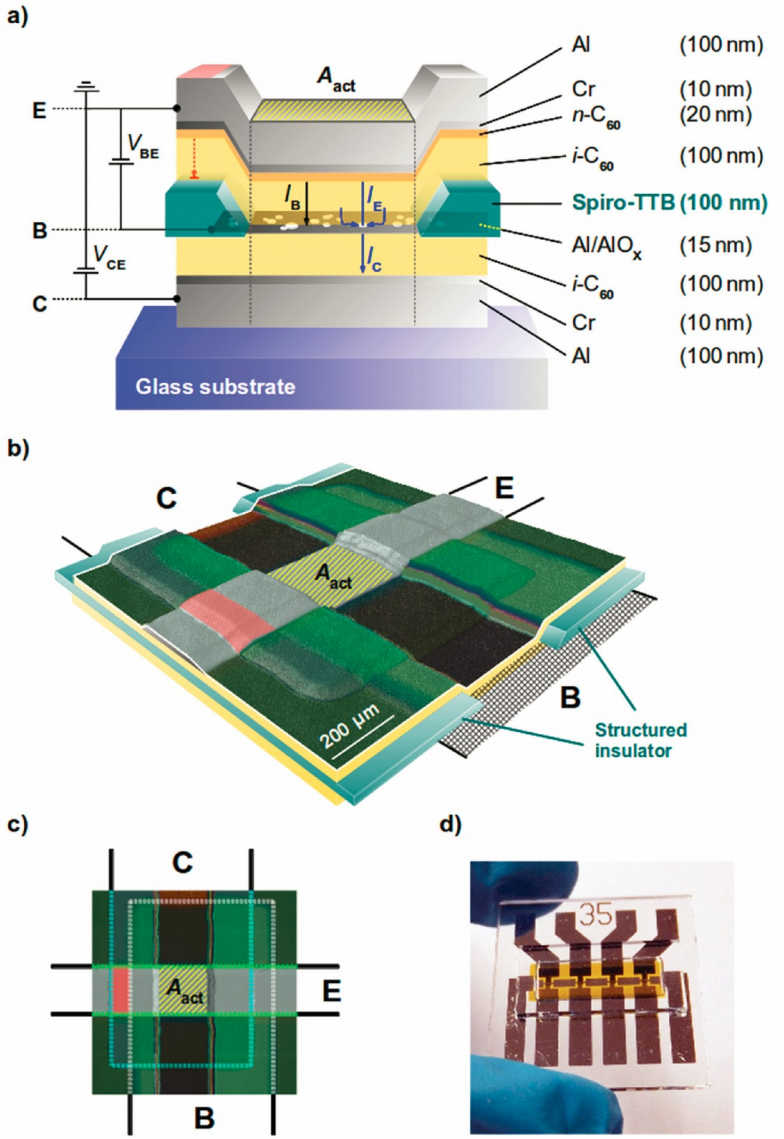
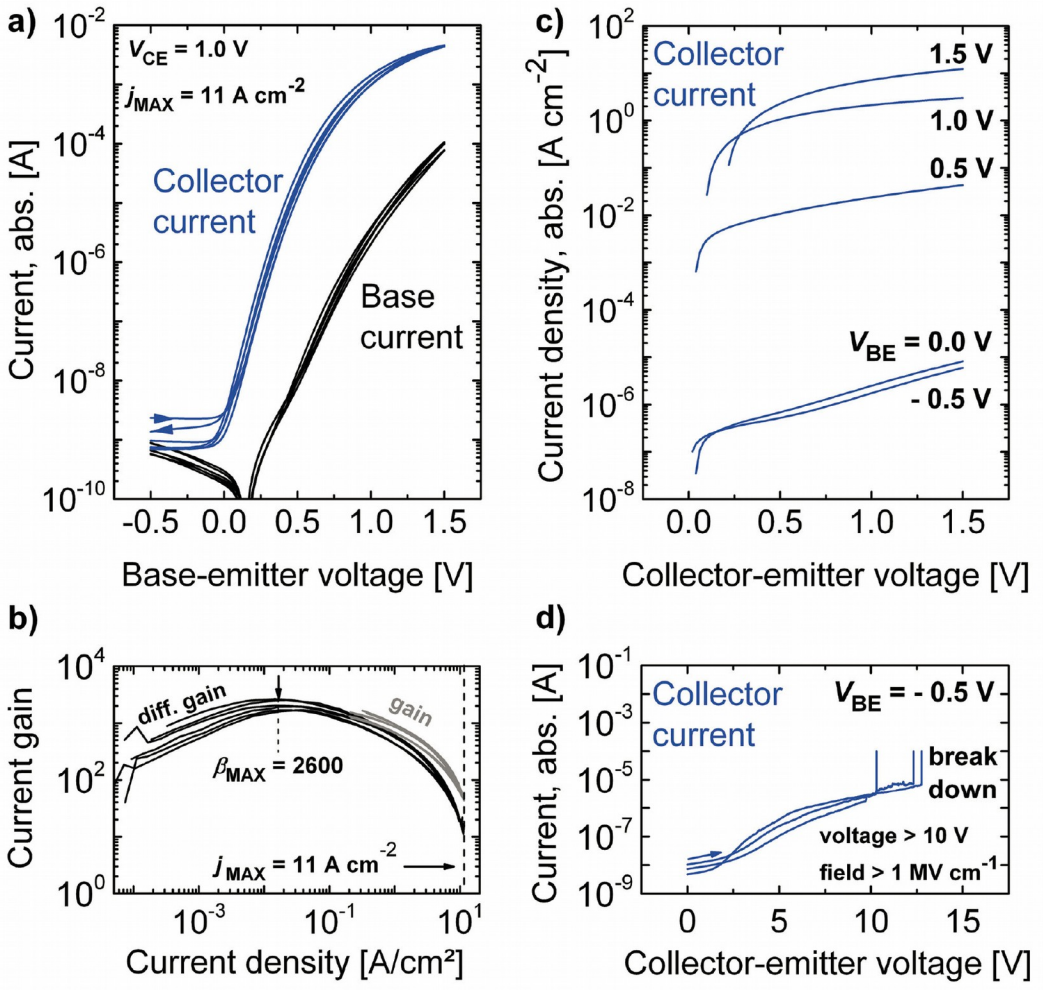


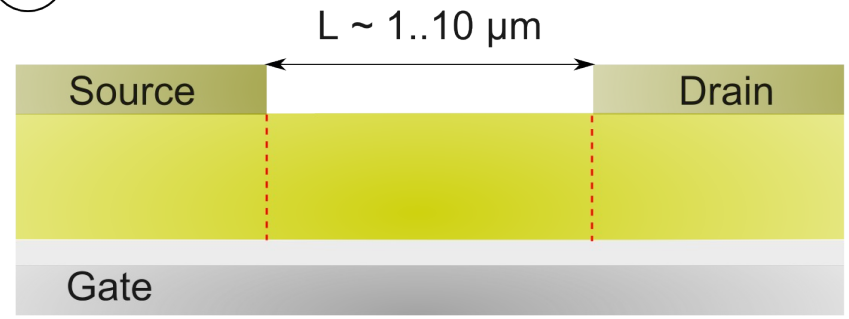

Klinger, Fischer,.. , Adv. Mater., **2015**, 27

# Outline

# From OFET to OPBT...



1.




Organic semiconductor ( ~50 nm)

Gate dielectric (3 nm)
Gate (9 nm)

# From OFET to OPBT...



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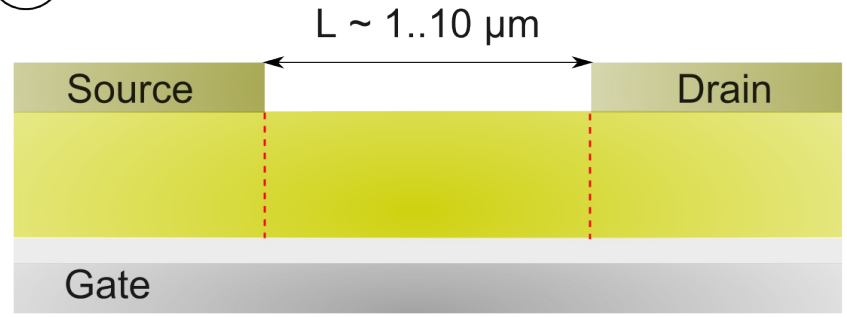


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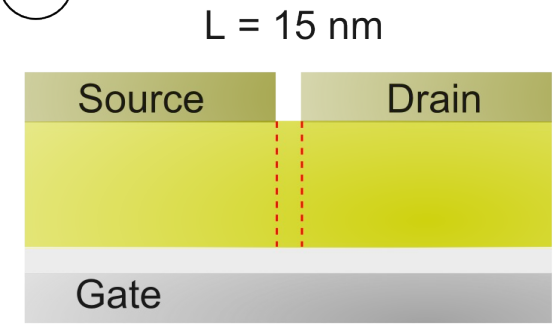

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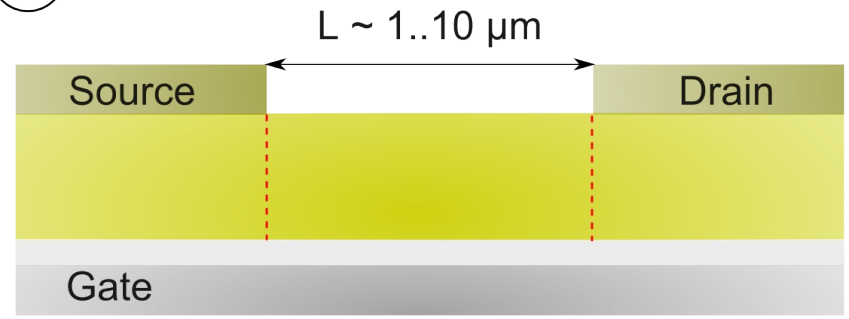


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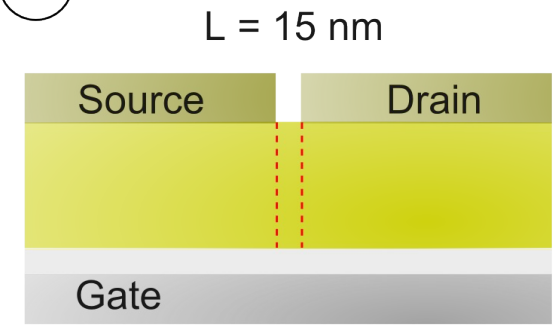


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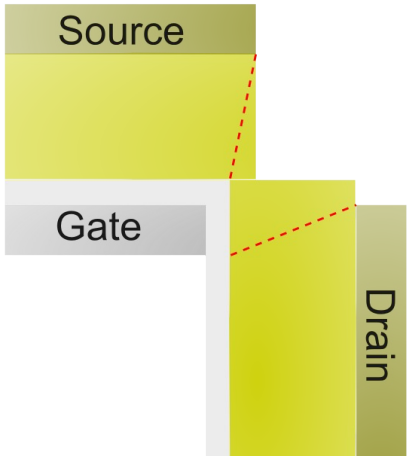

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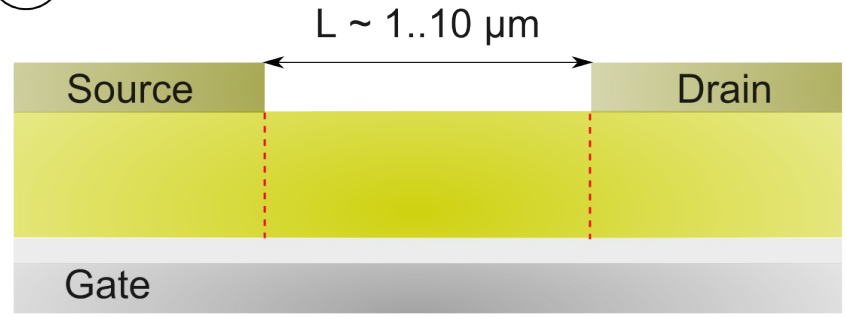


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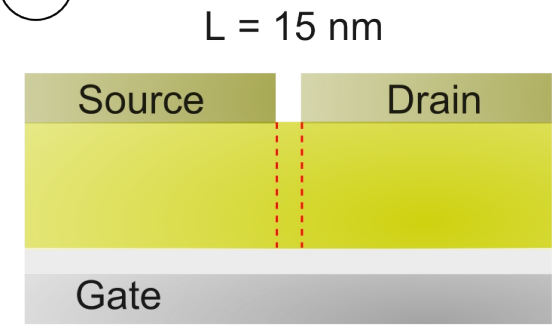


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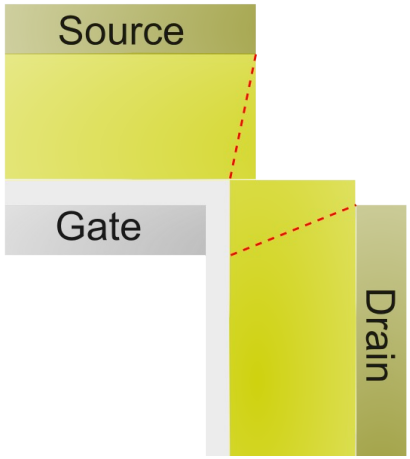
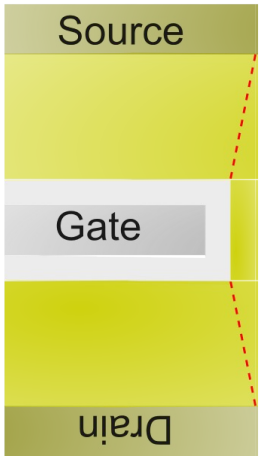


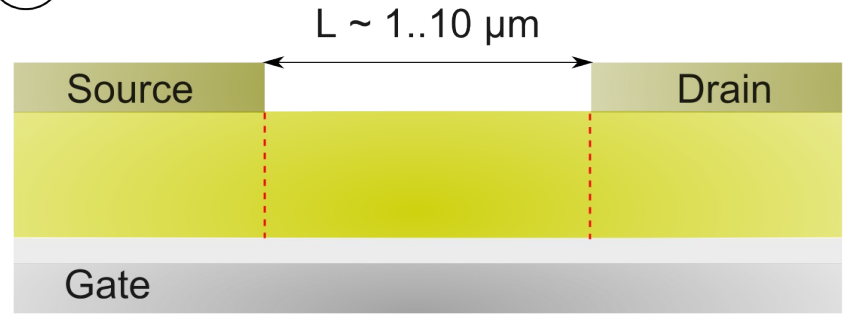

4.



# From OFET to OPBT...



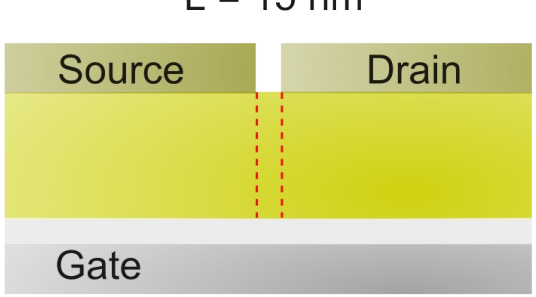
1.




Organic semiconductor ( ~50 nm)

Gate dielectric (3 nm)
Gate (9 nm)

2.

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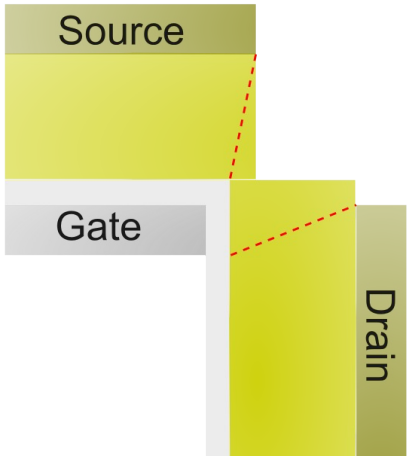
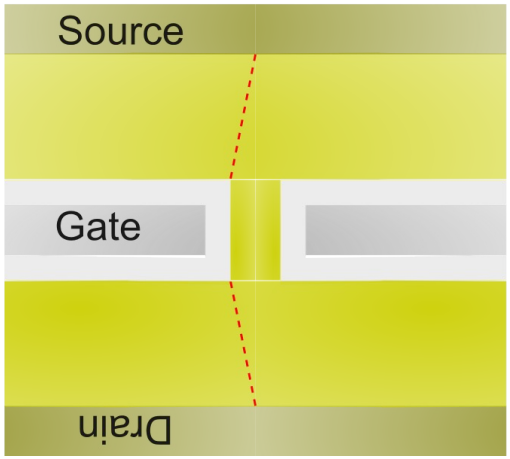



4.

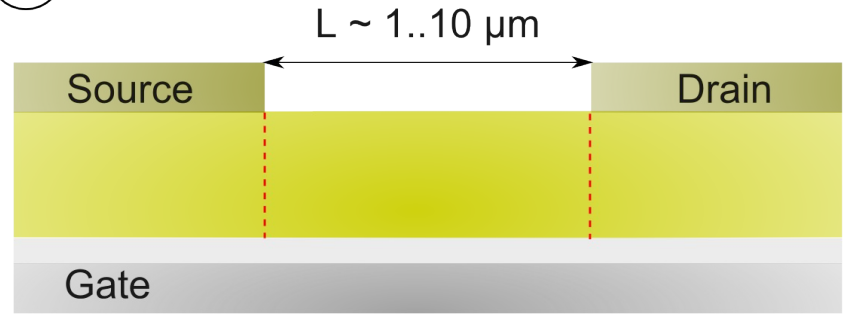
5.



# From OFET to OPBT...



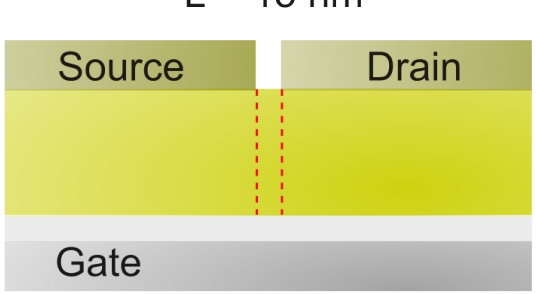
1.




Organic semiconductor ( ~50 nm)

Gate dielectric (3 nm)
Gate (9 nm)

2.

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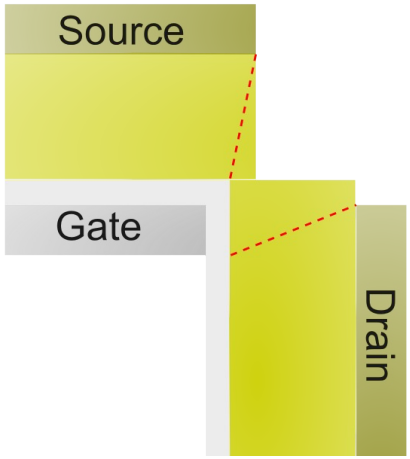
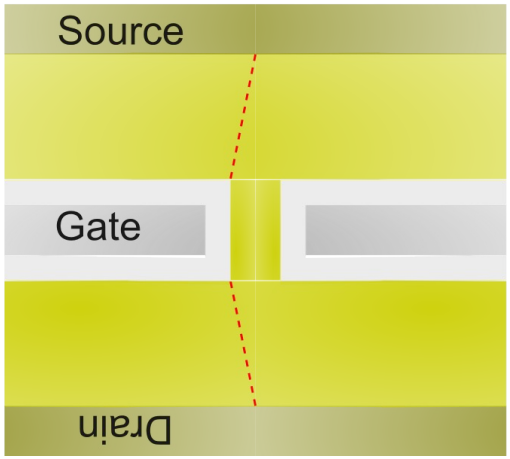



4.

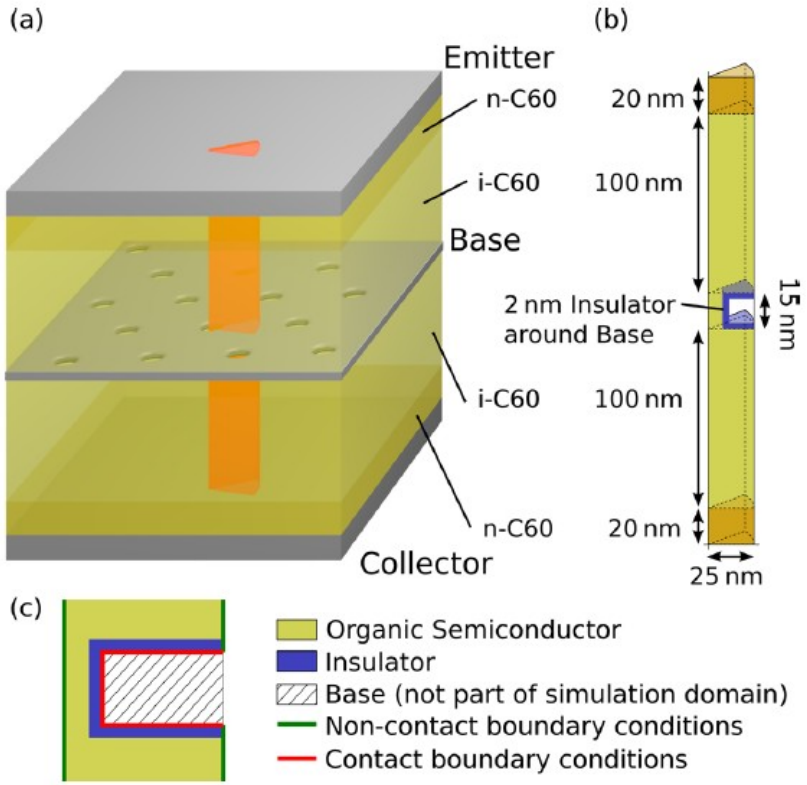
5.




Do the openings limit the charge flow?

# Simulation



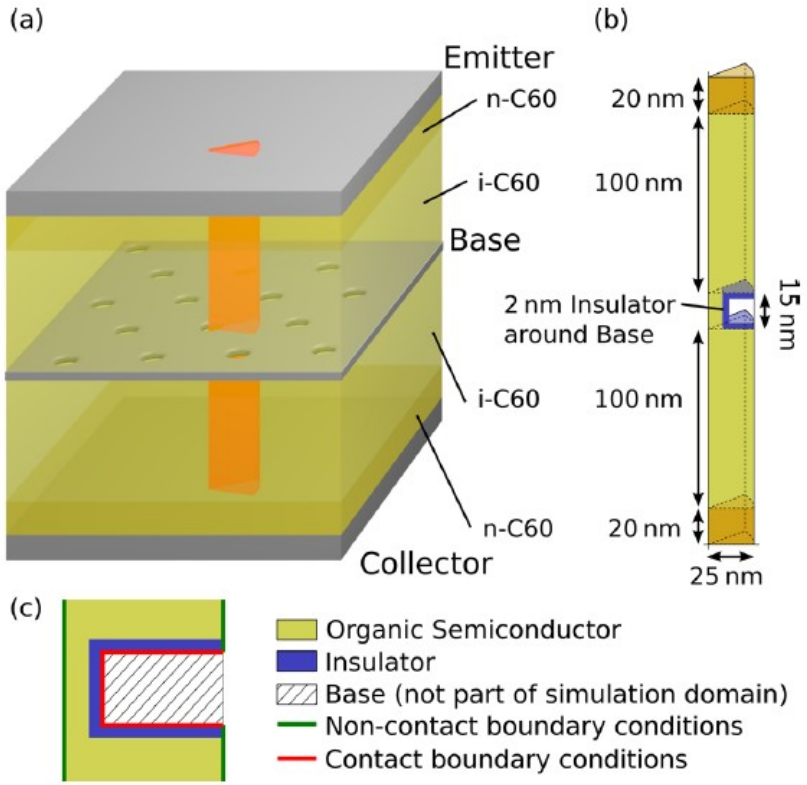


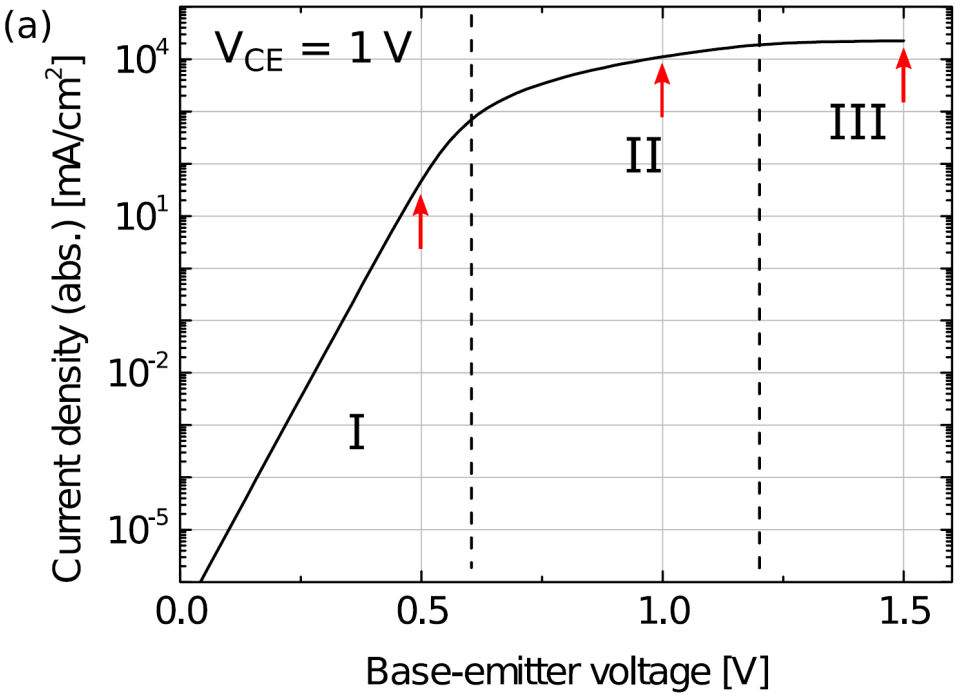

Drift-diffusion simulation done at Weierstraß institute Berlin

Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

# Simulation





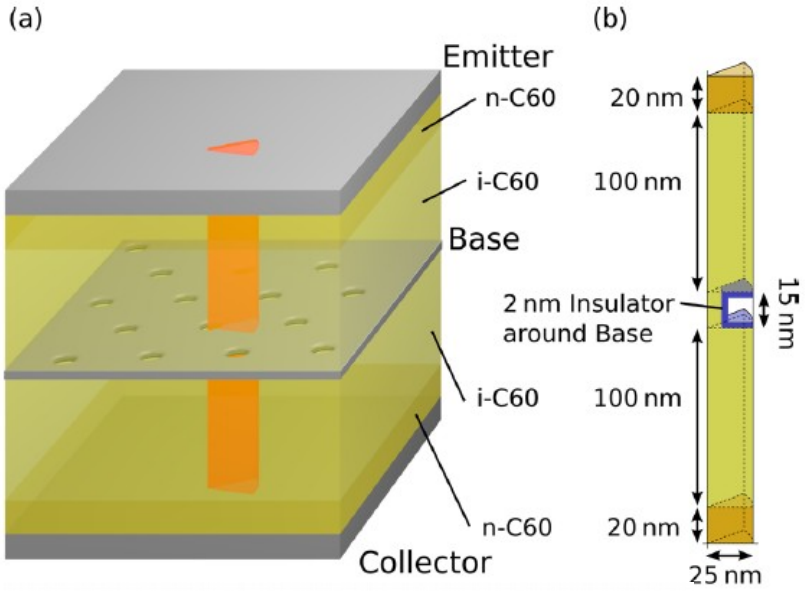



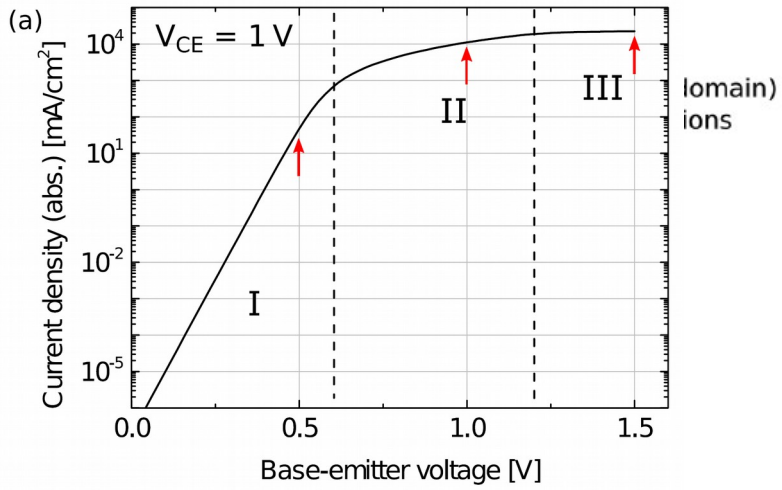

Transfer characteristic („Base sweep“)

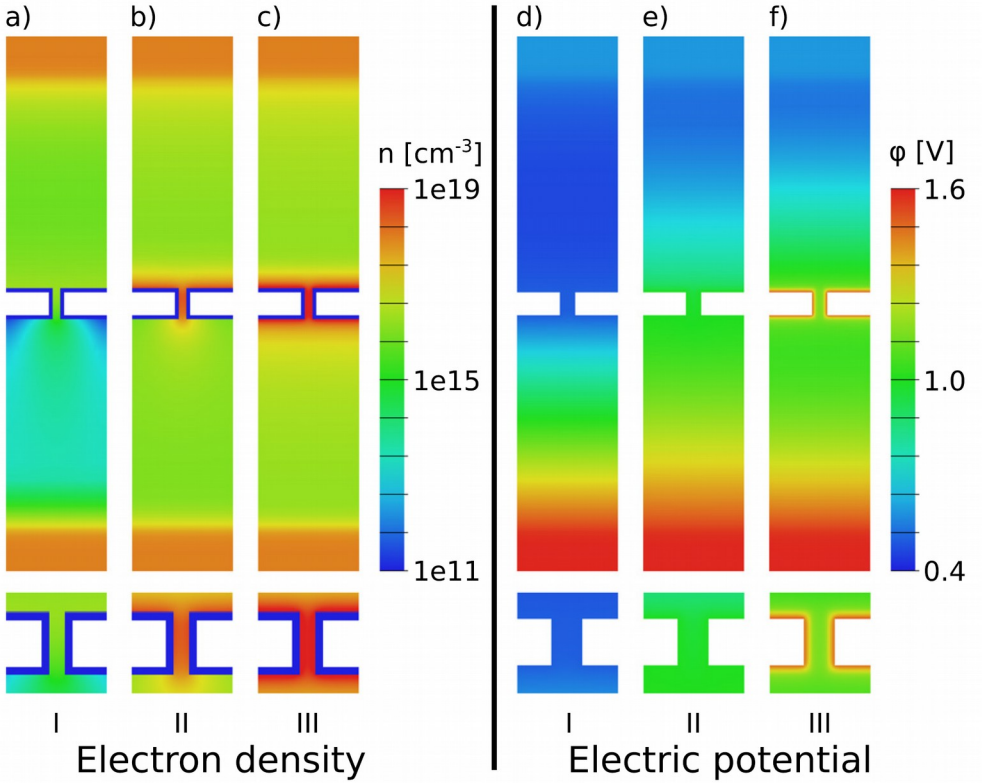
Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

# Simulation





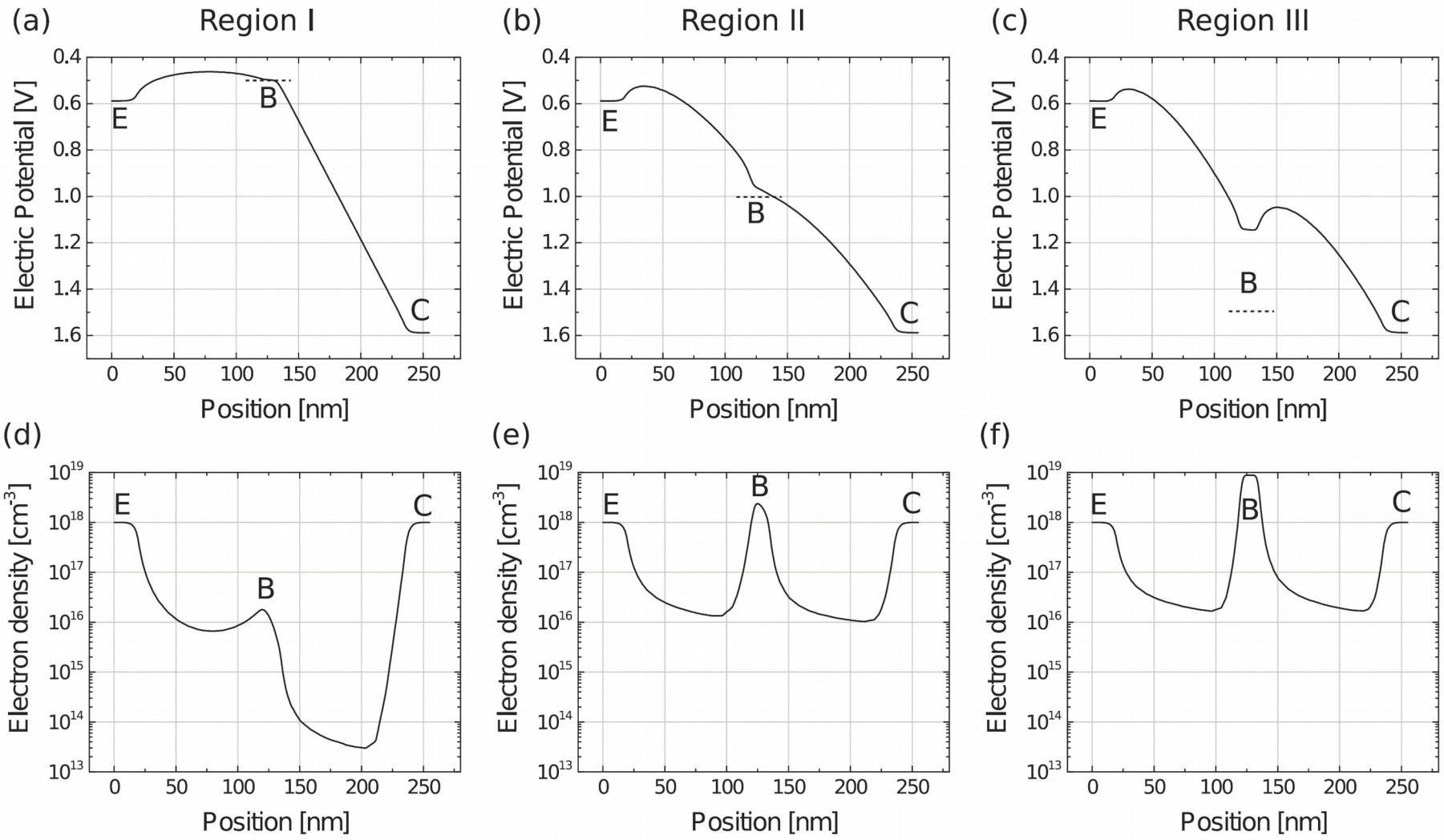




Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

# Simulation

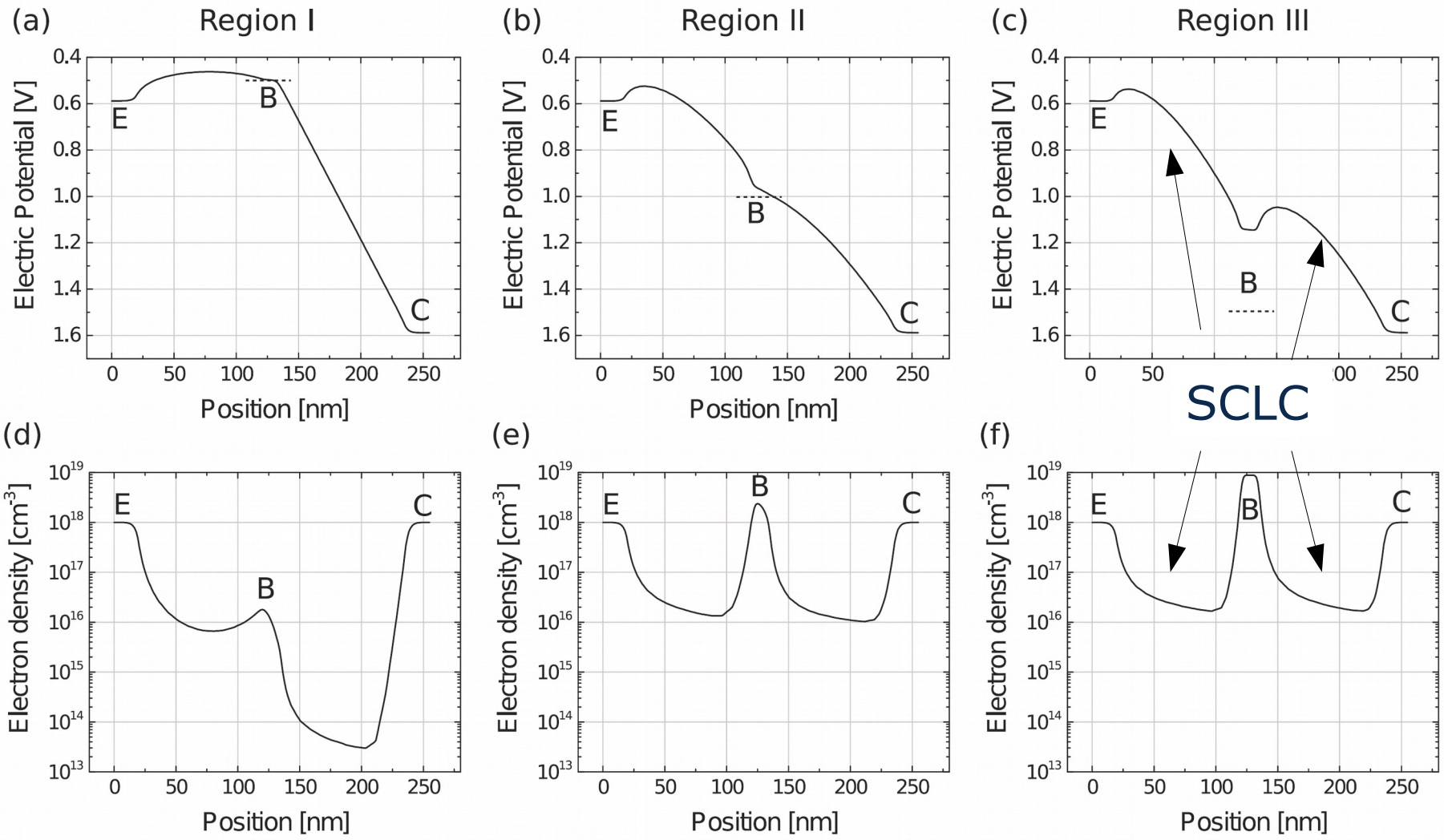





Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

# Simulation

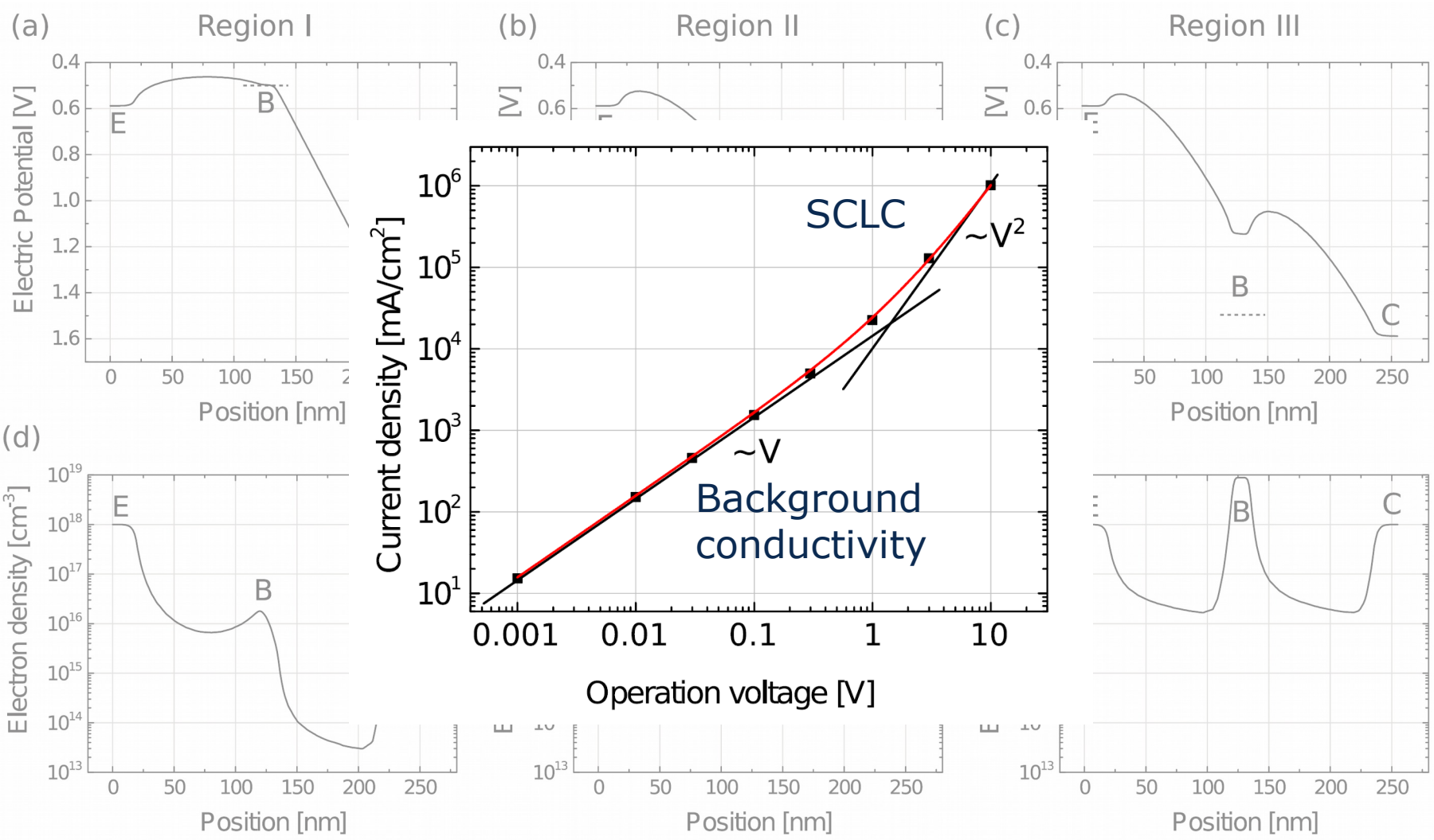





Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

# Simulation

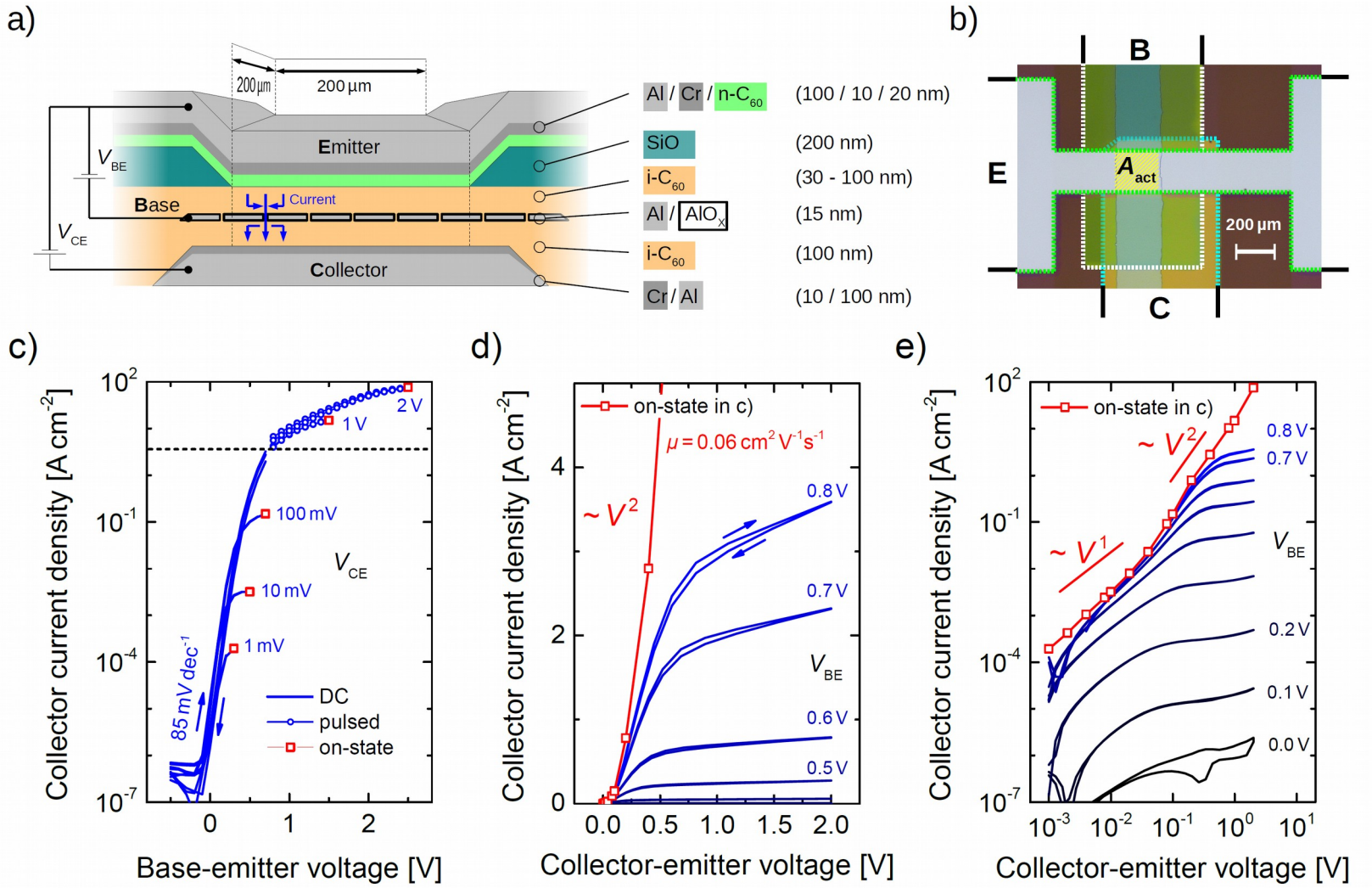





Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

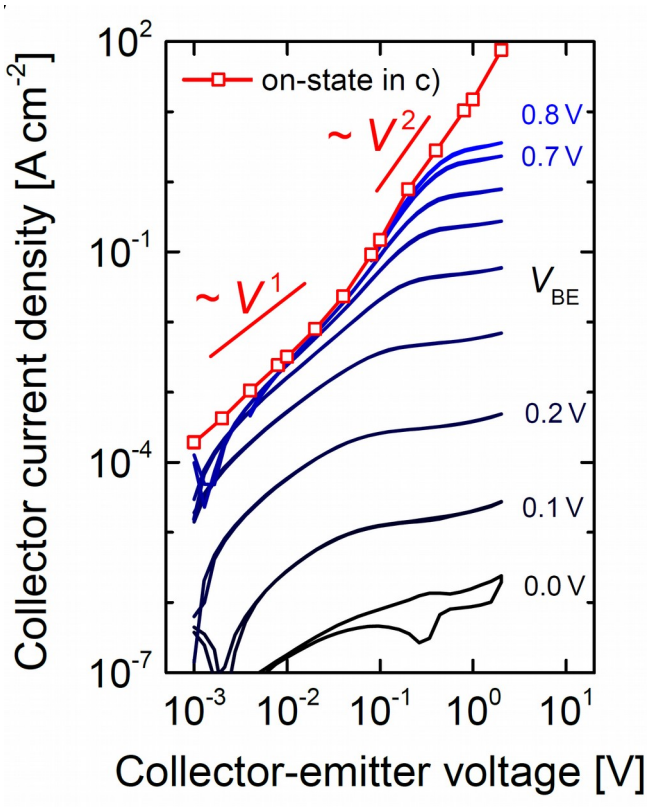
# Outline

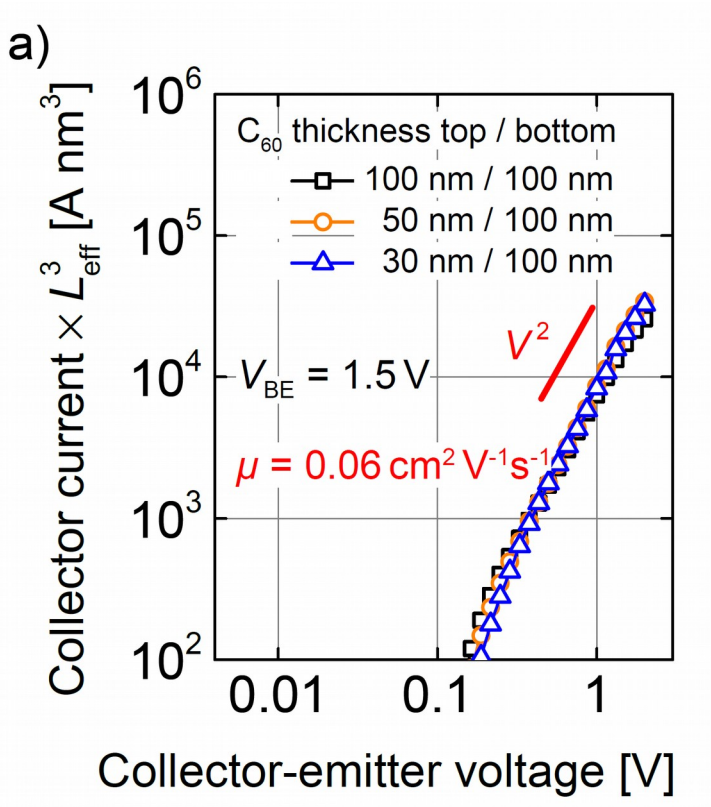
# High current density




Klinger, Fischer, .., Sci. Rep., **2017**, 7

# High current density

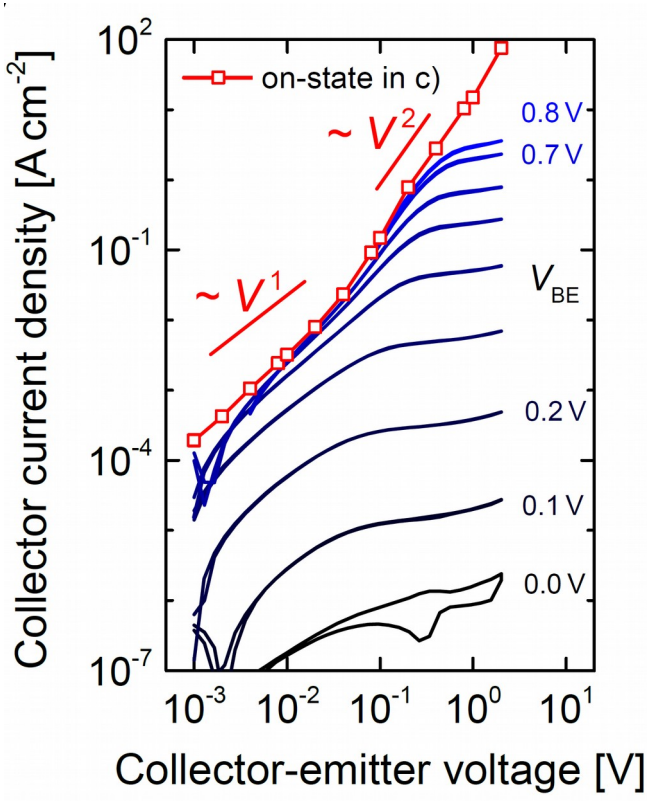


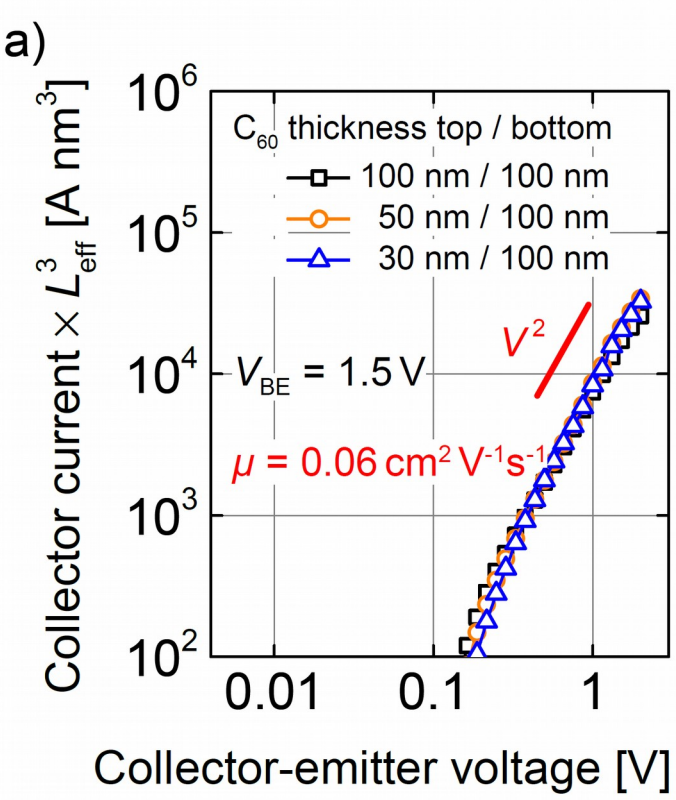



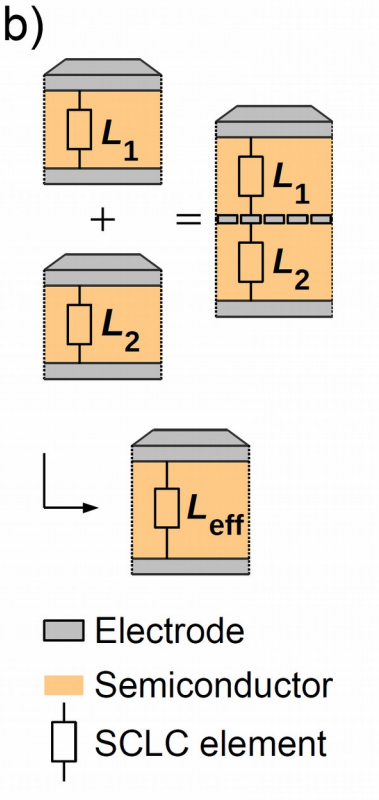

Klinger, Fischer, .., Sci. Rep., **2017**, 7

# High current density





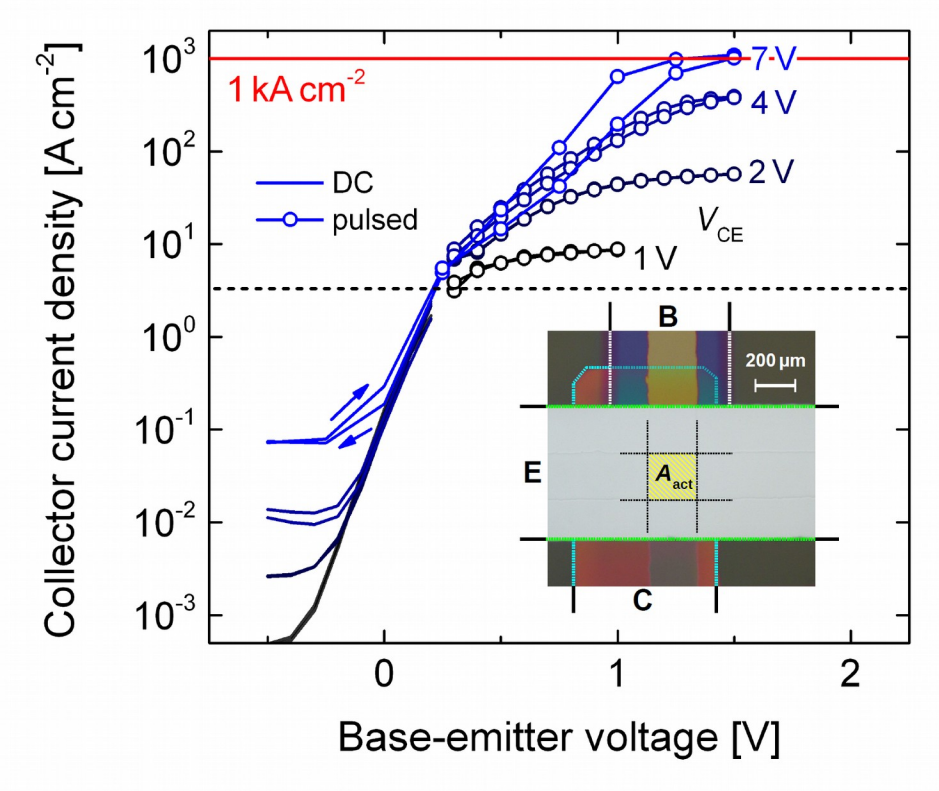

$$j = \frac{9}{8}\epsilon\epsilon_0\mu\frac{V^2}{L^3}$$

$$L_{\mathrm{eff}} = \left(\sqrt{L_1^3} + \sqrt{L_2^3}\right)^{2/3}$$

Klinger, Fischer, .., Sci. Rep., **2017**, 7

# High current density



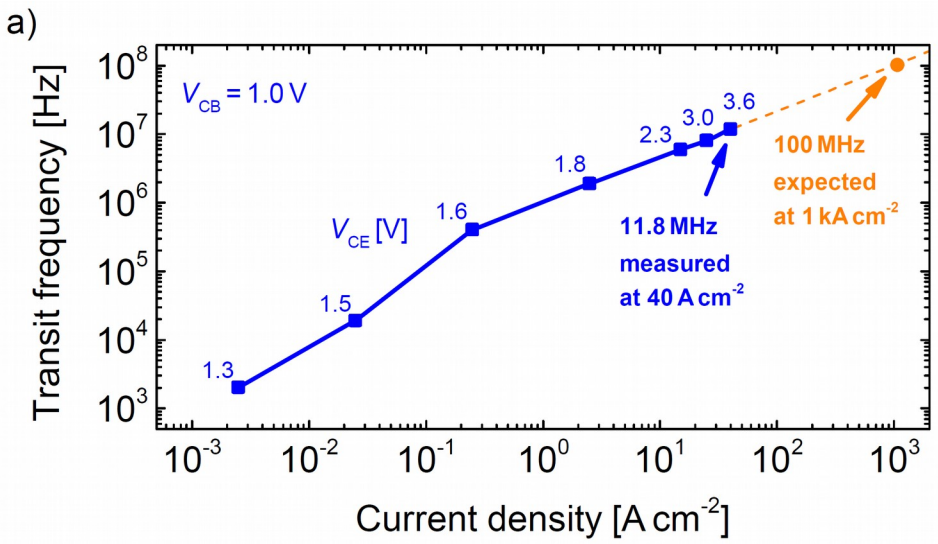


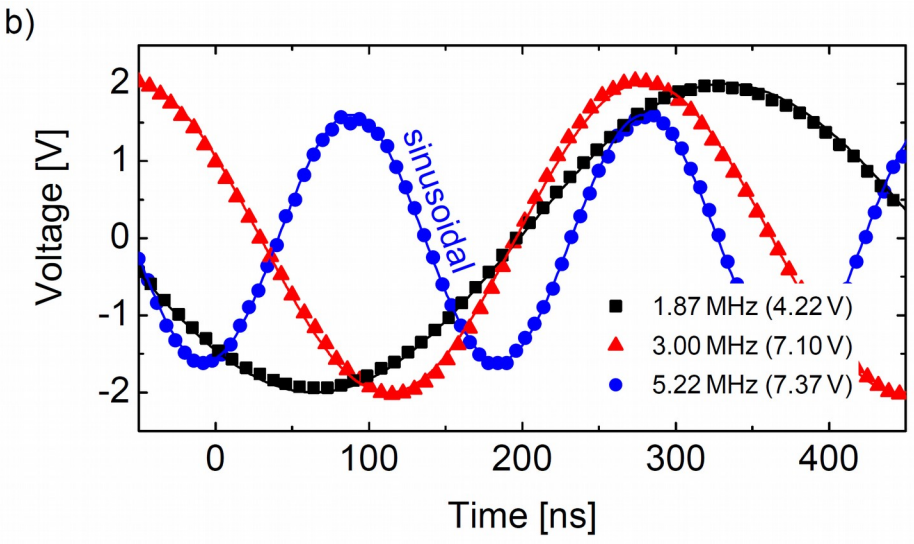

- Improved electrode design to decrease series resistance
- Intrinsic C60: 30 nm top / 50 nm bottom

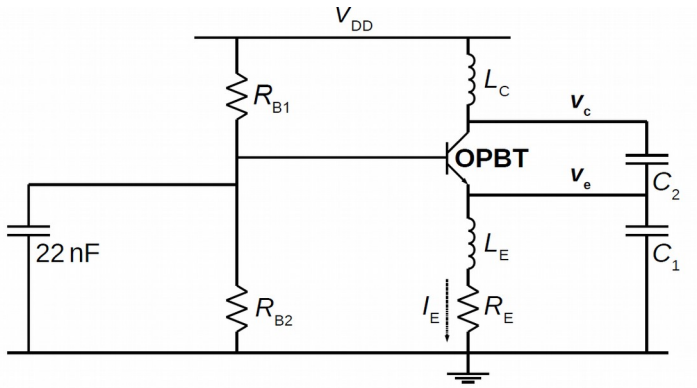
Klinger, Fischer, .., Sci. Rep., **2017**, 7

# High current density






Colpitts oscillator circuit

Measurements done at CCN, TU Dresden

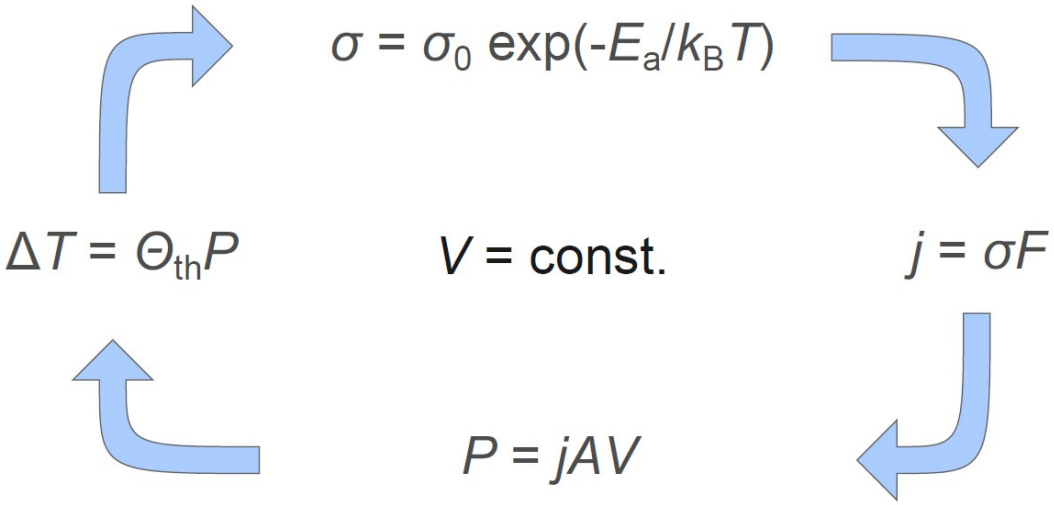
Klinger, Fischer, .., Sci. Rep., **2017**, 7

# Outline

1. Contact resistance in thin-film transistors
2. The organic permable base transistor
3. Device structuring to reach higher performance
4. Understanding the device operation
5. Going to the limits
6. Electrothermal feedback

# Electrothermal Feedback

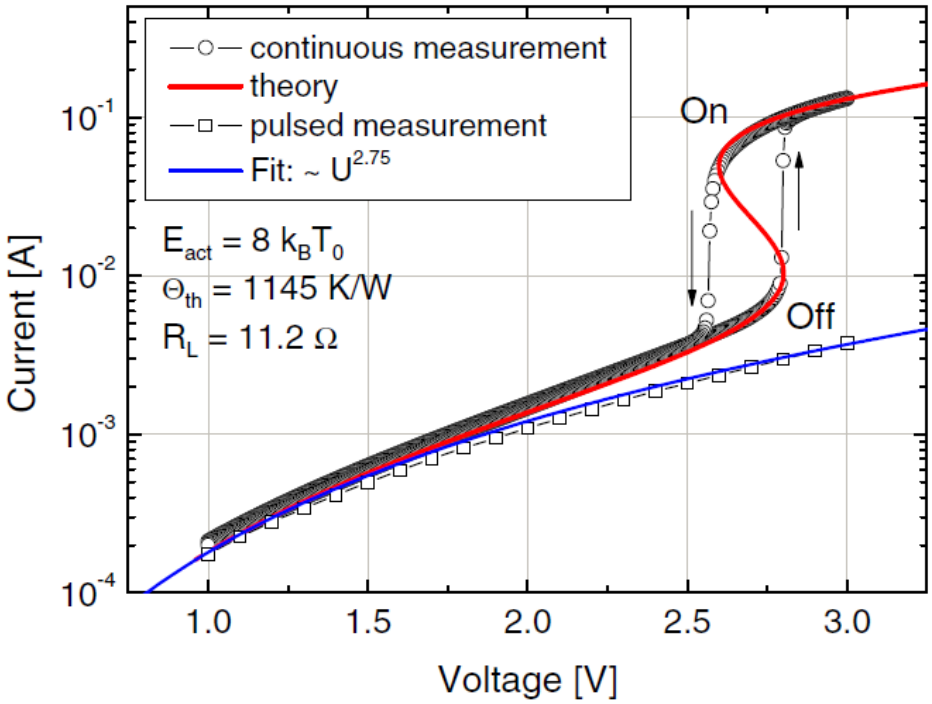


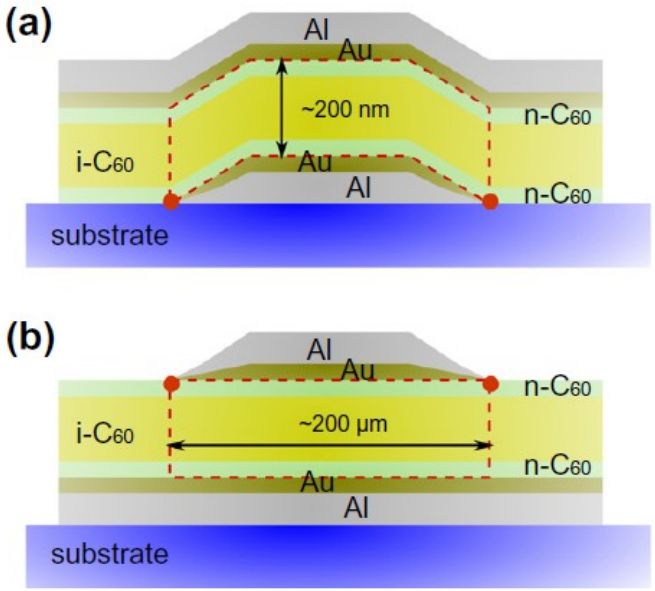


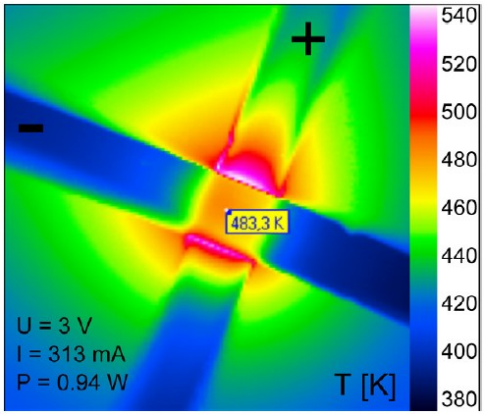

- Positive feedback loop of conductivity, current, power, and heat dissipation

Fischer *et al.*, Phys. Rev. Lett. **2013**, 110

# Electrothermal Feedback



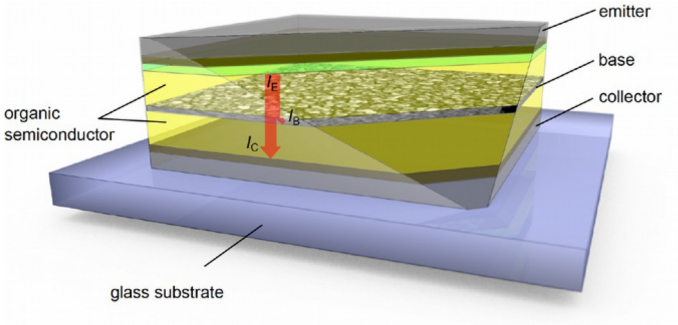



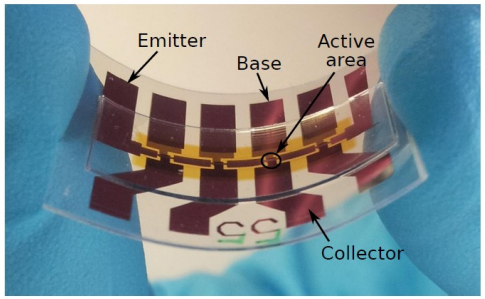

- nin C60 device = OPBT without base electrode

Fischer *et al.,* Org. Electron. **2012**, 13
Fischer *et al.,* Phys. Rev. Lett. **2013**, 110

# Conclusion

- OPBTs reach $f_T$ above 10 MHz with a material having $\mu$ = 0.06 cm²/Vs and active area of 200 µm x 200 µm at low voltages.
- OPBTs could operate close to the GHz regime if we use „faster materials", make them thinner, smaller, more structured, and incorporate thermal management.





Fischer *et al.*, Appl. Phys. Lett., **2012**, 101

Fischer *et al.*, J. Appl. Phys., **2012**, 111

Fischer *et al.,* Org. Electron. **2012**, 13

Fischer *et al.,* Phys. Rev. Lett. **2013**, 110

Kaschura, Fischer *et al.*, Appl. Phys. Lett., **2015**, 107

Klinger, Fischer, .., Adv. Mater., **2015**, 27

Lüssem, .., Fischer, .., J. Phys. Condens. Matter, **2015**, 27

Fischer, PhD thesis: http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-180780

Kaschura, Fischer, .., J. Appl. Phys., **2016**, 120

Klinger, Dollinger, Fischer et al., Science Open **2016**

Klinger, Fischer, .., Sci. Rep., **2017**, 7

Fischer et al., Phys. Rev. Applied **2017,** 8

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- *Hilke Zündorf*
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