Electrostatic Doping in Carbon-based Nanoelectronics Devices

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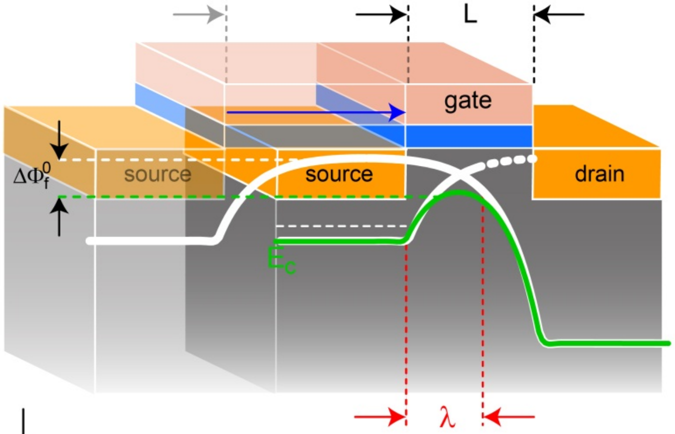
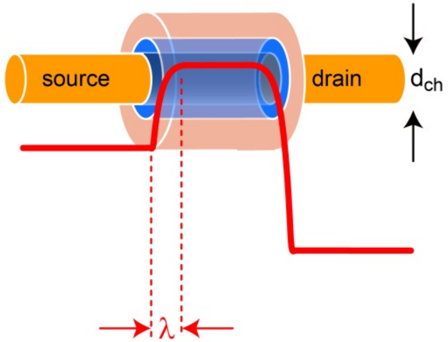
Introduction

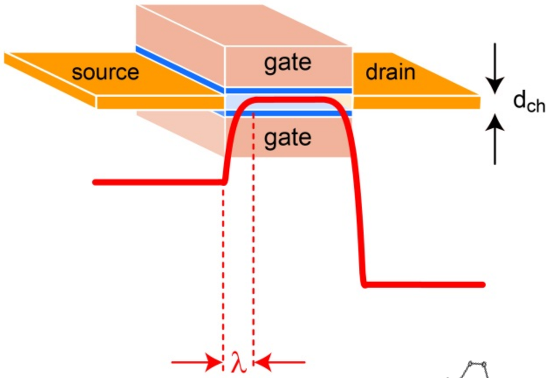


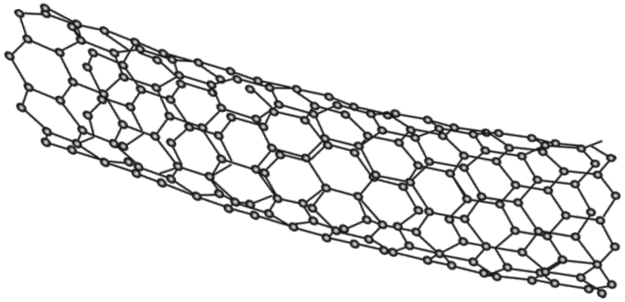
$$\lambda = \sqrt{\frac{\varepsilon_{\mathrm{nw}} d_{\mathrm{nw}}^2}{8\varepsilon_{\mathrm{ox}}} \ln\left(1+\frac{2d_{\mathrm{ox}}}{d_{\mathrm{nw}}}\right)}$$

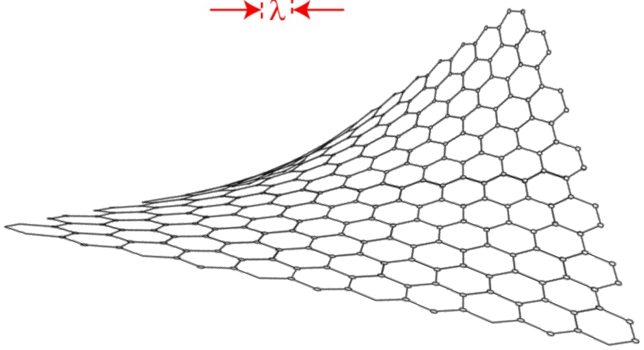


carbon-based materials hold promise to realize ultimate FETs due to optimum scalability and electronic transport properties

$$\lambda_{\mathrm{ch}} = \sqrt{\frac{\varepsilon_{\mathrm{ch}}}{\varepsilon_{\mathrm{ox}}} d_{\mathrm{ox}} d_{\mathrm{ch}}}$$







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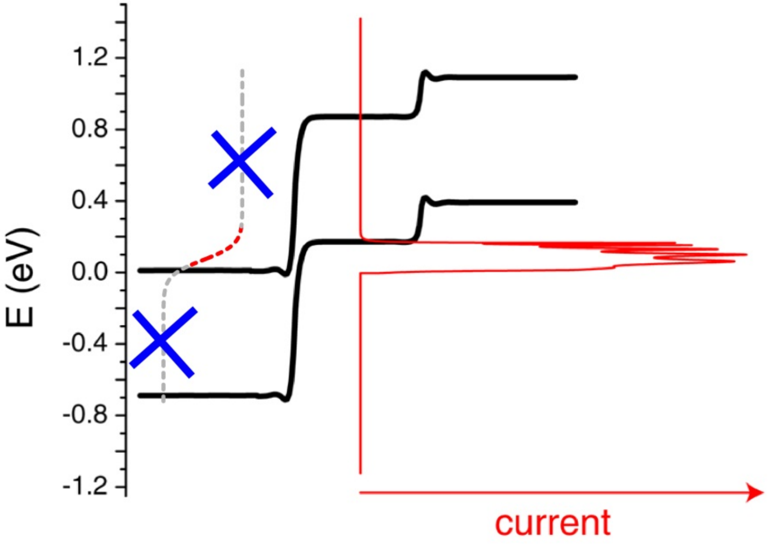
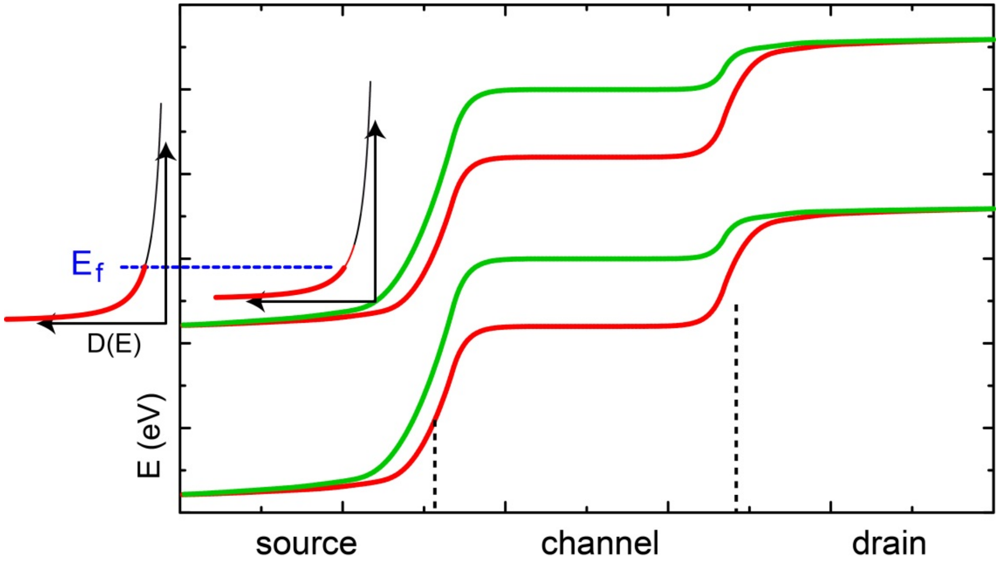
Introduction – Issues with Doping





- **need excellent gate control of channel *<u>and</u>* screening of gate impact on source contact**

- **low density of states such as in carbon nanotubes (1D) or graphene detrimental for screening**

→ **electrostatic doping**

J. Knoch and J. Appenzeller, phys. stat solidi a, **205**, 679 (2008).

J. Knoch, S. Mantl and J. Appenzeller, Solid-State Electron., **51**, 572 (2007).

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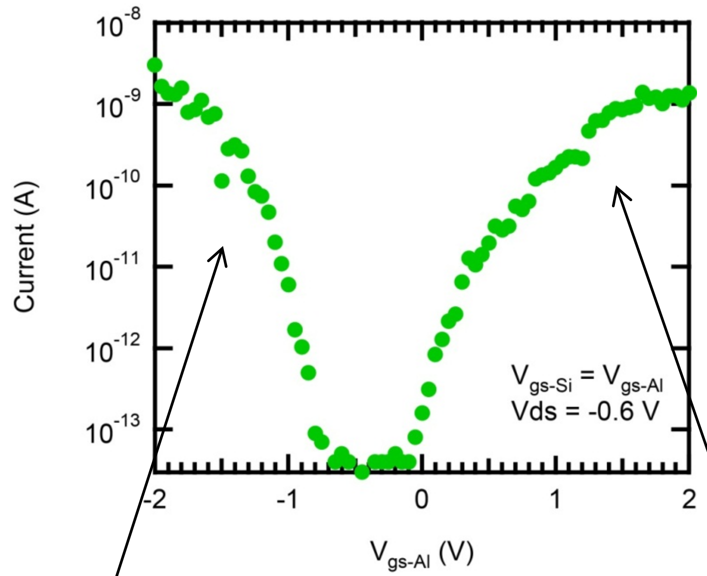
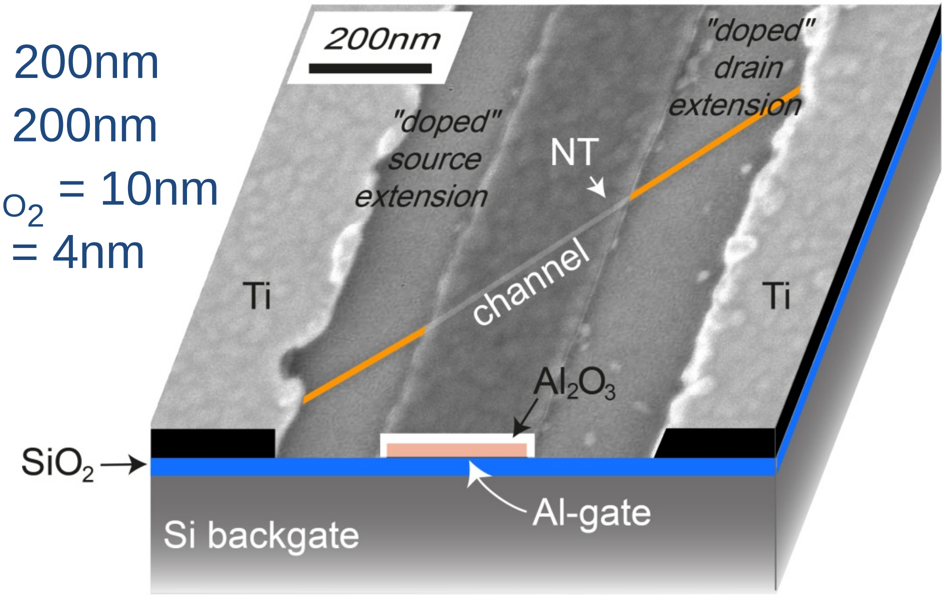
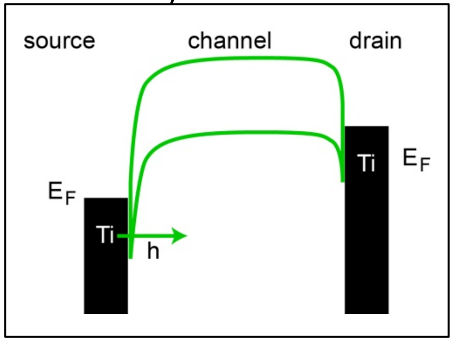
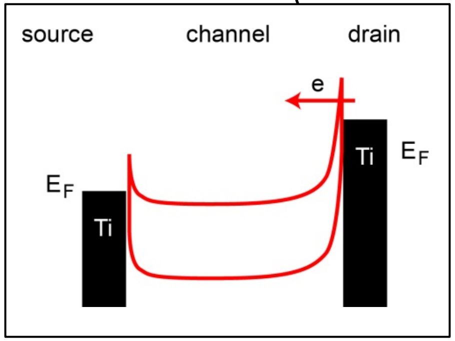
Tunable Polarity in CNFETs



- $L_{bg} \approx$ 200nm
- $L_{ch} \approx$ 200nm
- $d_{ox\text{-}SiO_2}$ = 10nm
- $d_{ox\text{-}Al}$ = 4nm



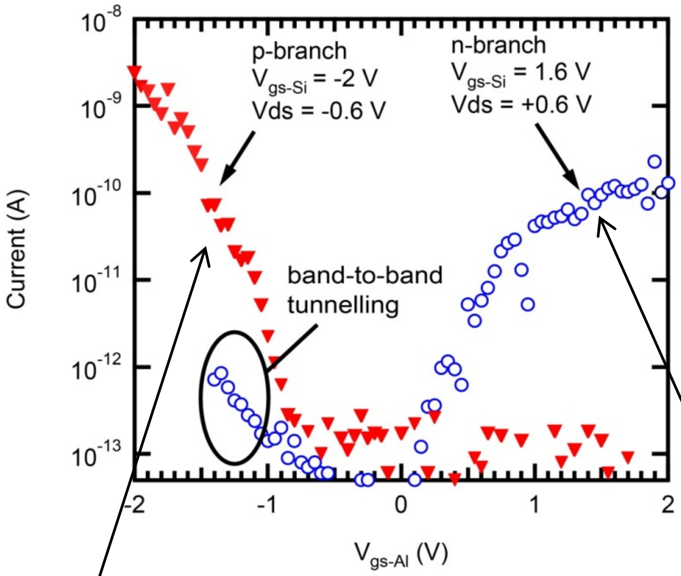




- **ambipolar behavior if both gates biased in the same direction**
- **electron and hole injection through Schottky-barrier at Ti-nanotube interface**

Y.-M. Lin, J. Appenzeller, J. Knoch and Ph. Avouris, IEEE Trans. Nanotechnol., **4**, 481 (2005).

Tunable Polarity in CNFETs



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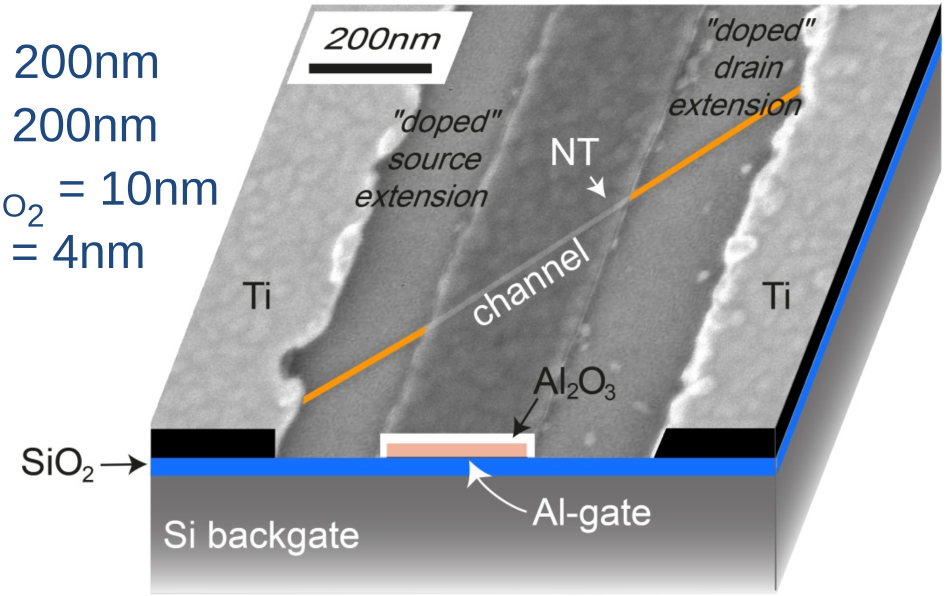
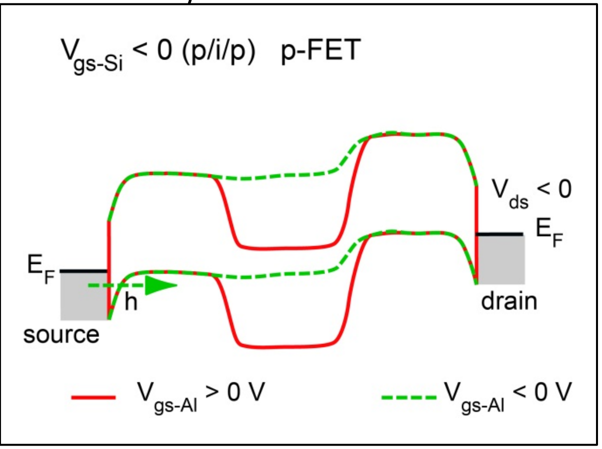
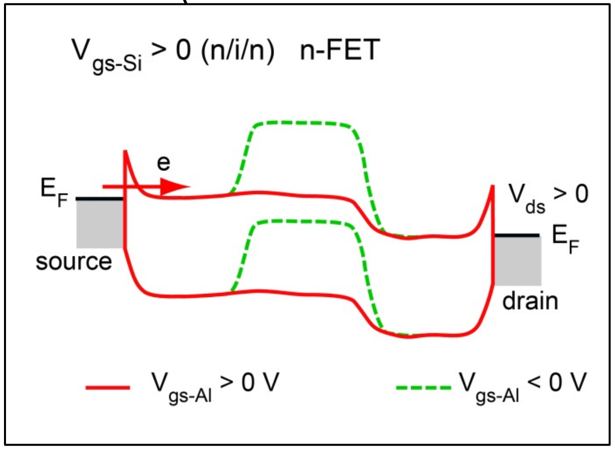


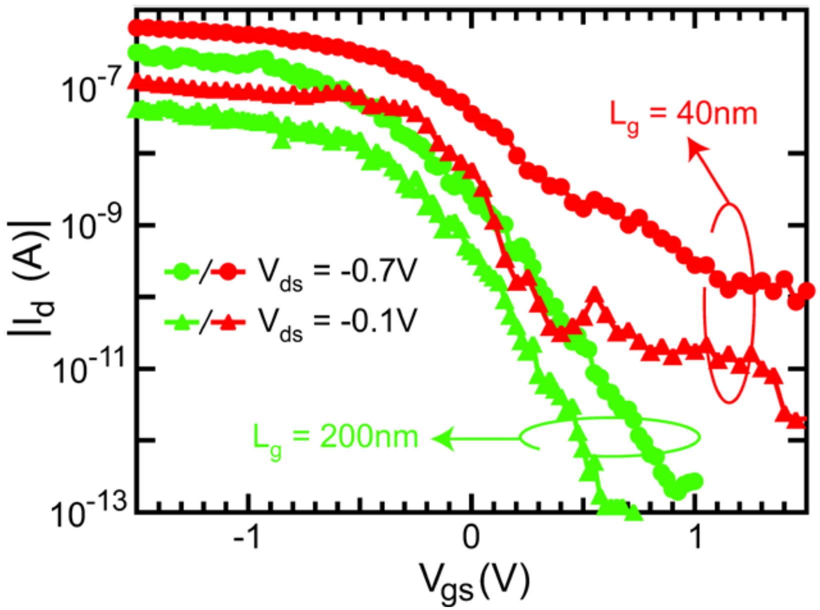




- **unipolar device behavior if both gates are biased with opposite polarity**
- **n- and p-type CNFETs possible due to excellent gate control**

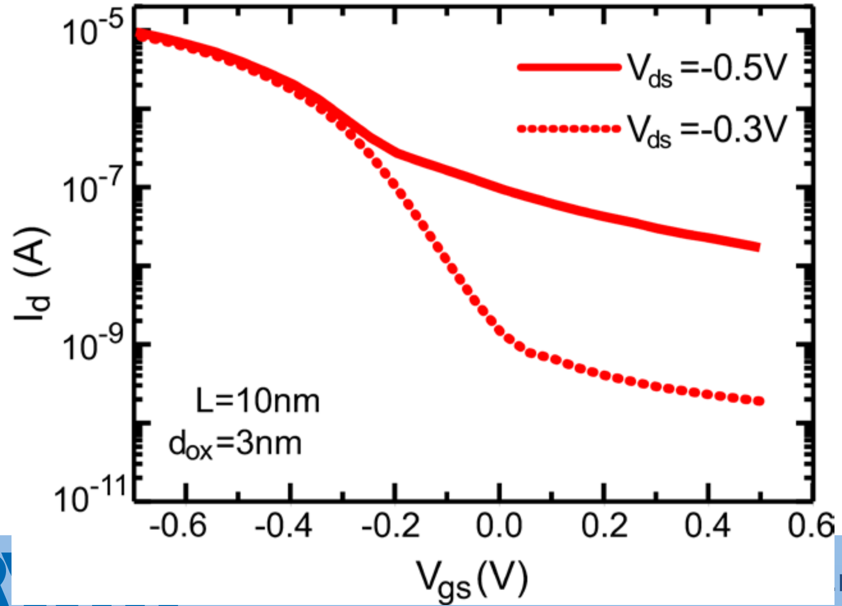
Y.-M. Lin, J. Appenzeller, J. Knoch and Ph. Avouris, IEEE Trans. Nanotechnol., **4**, 481 (2005).

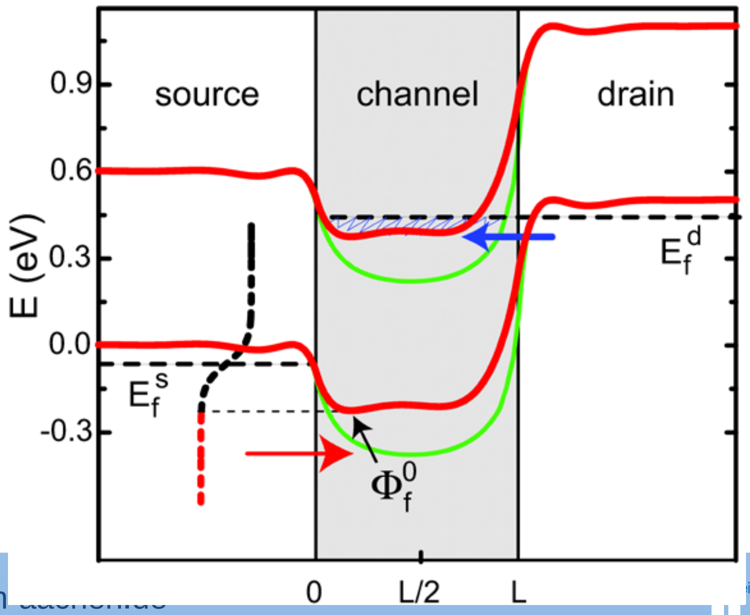
Conventional CNFETs



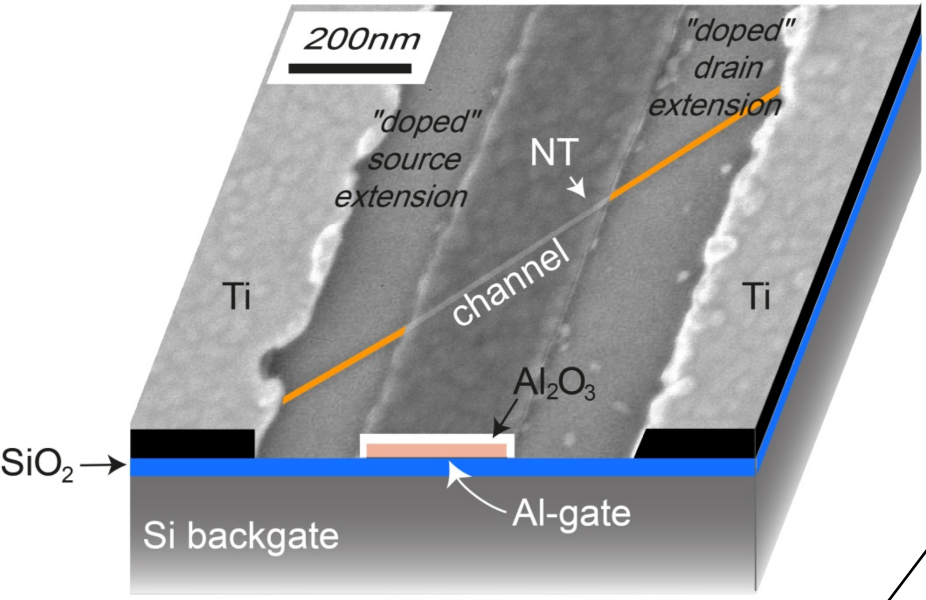
- device should be scalable to L < 20nm without SCE
- increasing off-state leakage for short conventional CNFETs

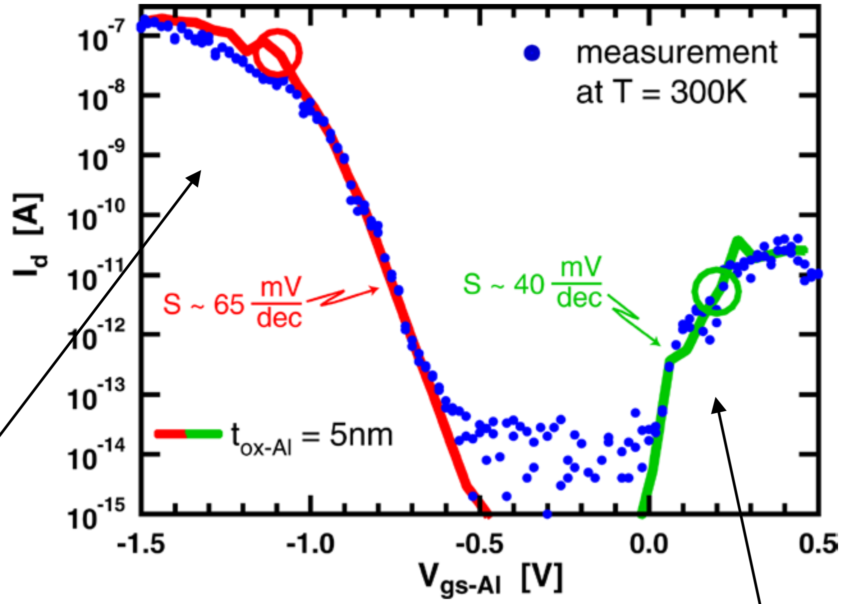
J. Knoch, S.Mantl and J. Appenzeller, Solid-State Electron., **49**, 73 (2005)



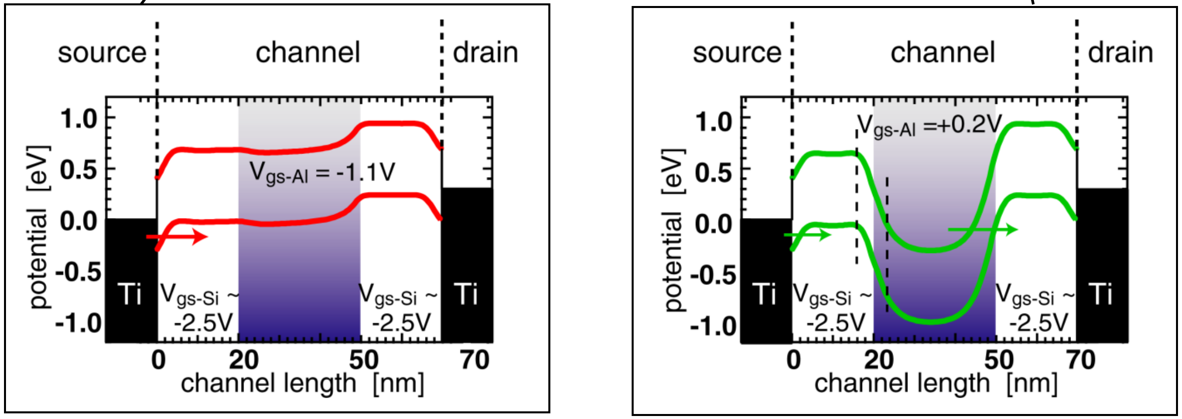


Tunnel-FET based on CNTs





$d_{\mathrm{NT}} \approx 1.4\mathrm{nm}$ $\quad d_{\mathrm{ox}} = 4\mathrm{nm}$



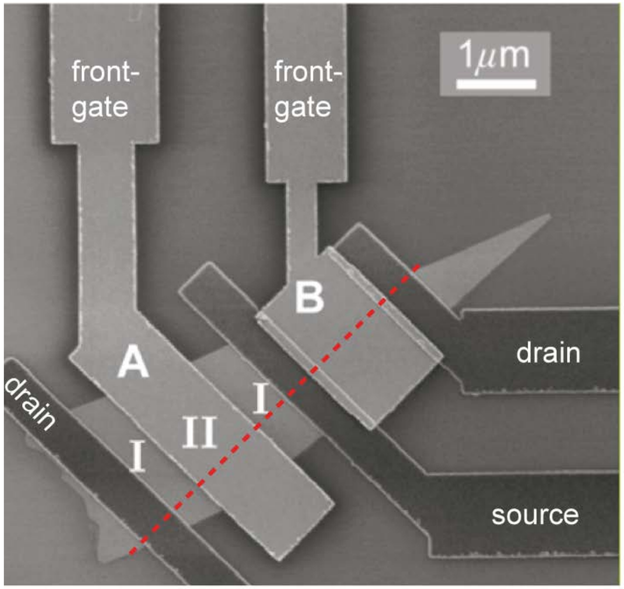
→ $S = 40\mathrm{mV/dec}$

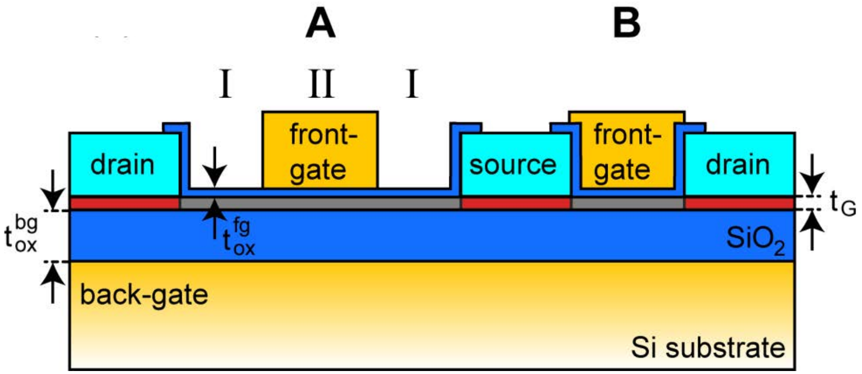
J. Appenzeller, Y.-M. Lin, J. Knoch, Z. Chen and Ph. Avouris, IEEE Trans. Electron Dev., **52**, 2568 (2005).

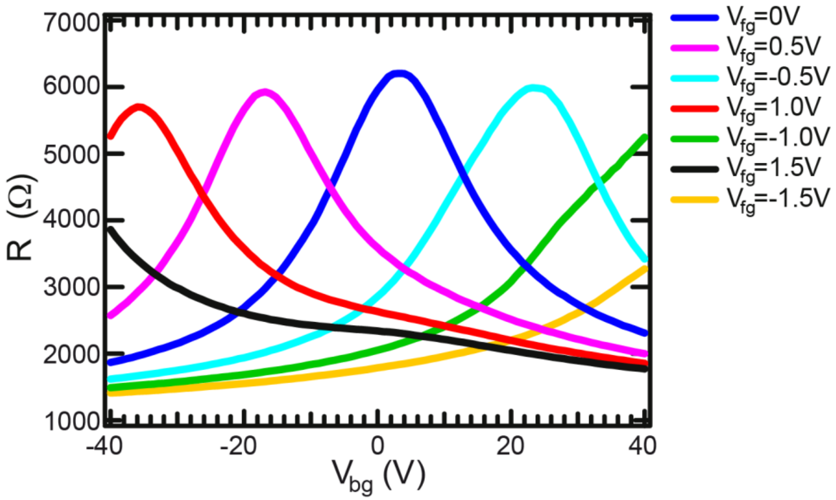
Electrostatic Doping in Graphene

L=1mm
W=1mm
$t_{ox,bg}$ =300nm
$t_{ox,fg}$ =10nm

Pd contacts







- **back-gate characteristics of device „B“ show double peak-structure**
- **second peak much less pronounced than main peak**

J. Knoch, Z. Chen and J. Appenzeller, IEEE Trans. Nanotechnol., **11**, 513 (2012).

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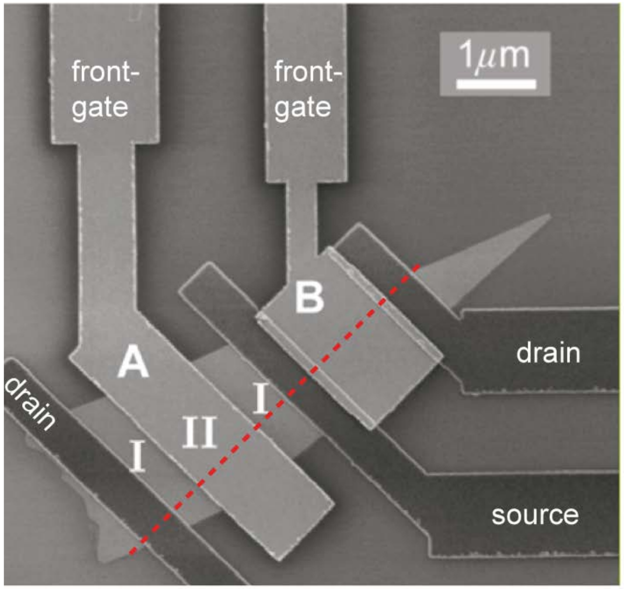
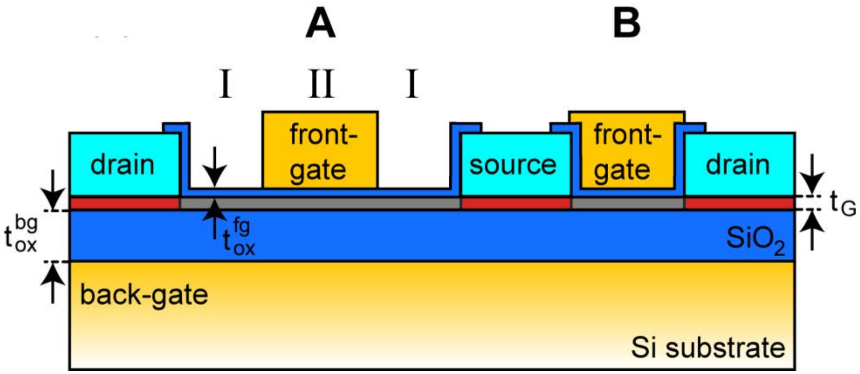
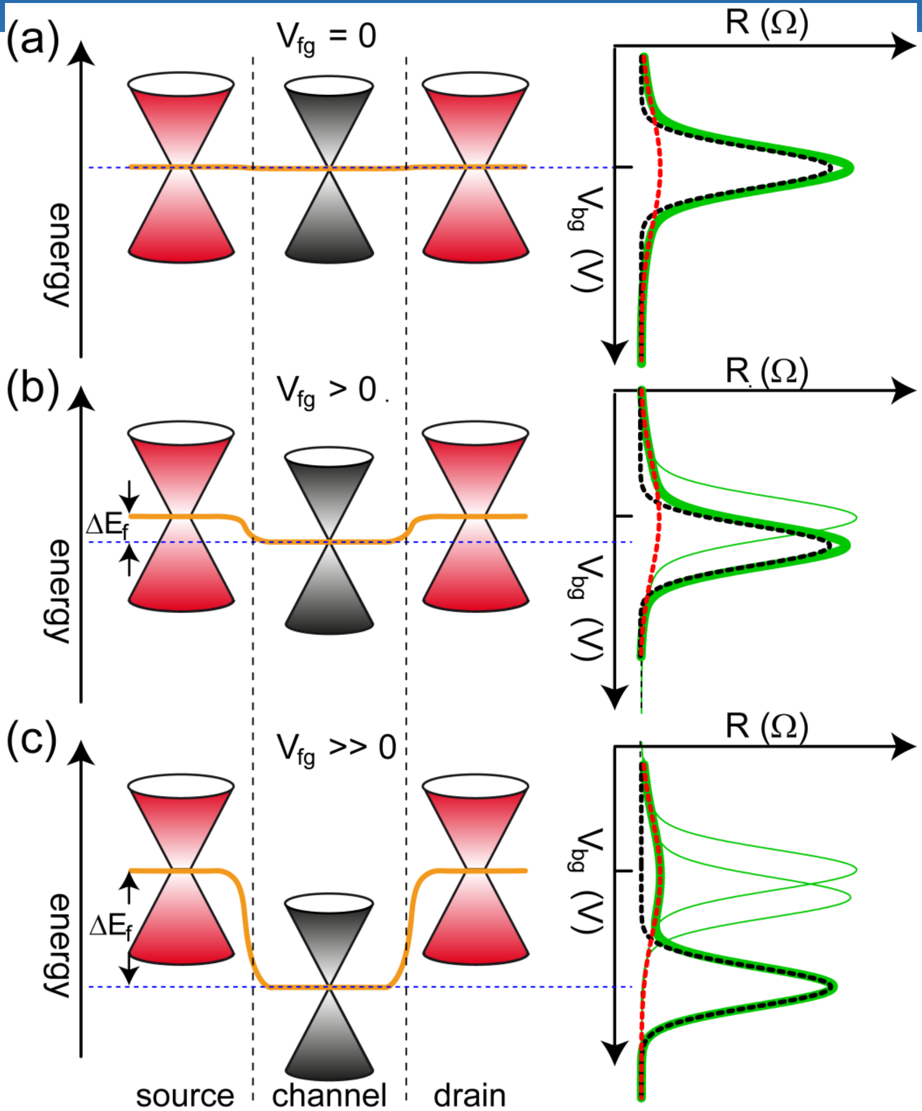




J. Knoch, Z. Chen and J. Appenzeller, IEEE Trans. Nanotechnol., **11**, 513 (2012).



- **second peak observable**

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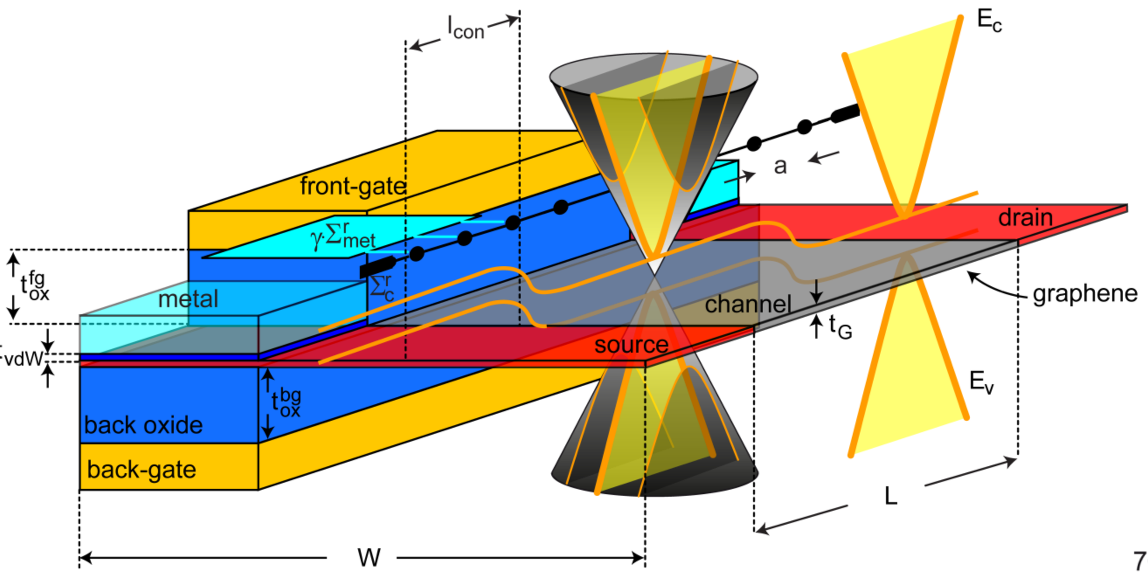
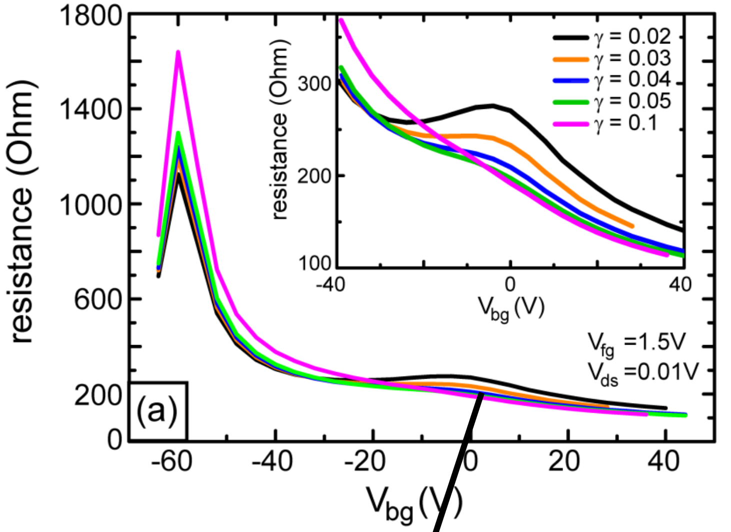
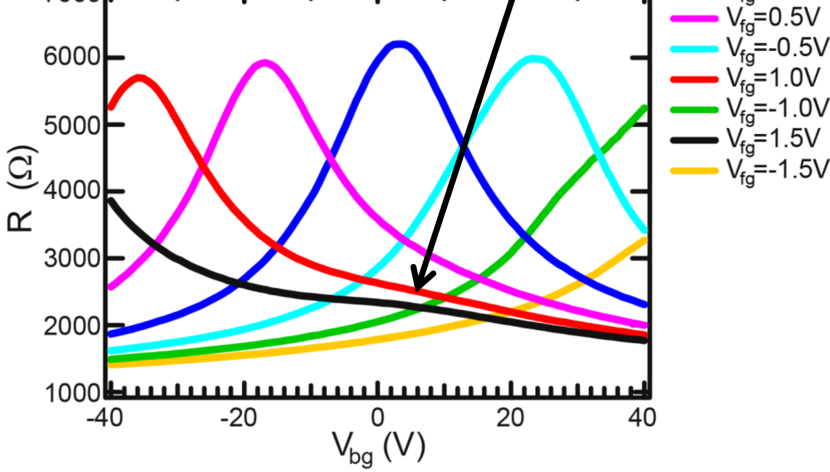
Electrostatic Doping in Graphene



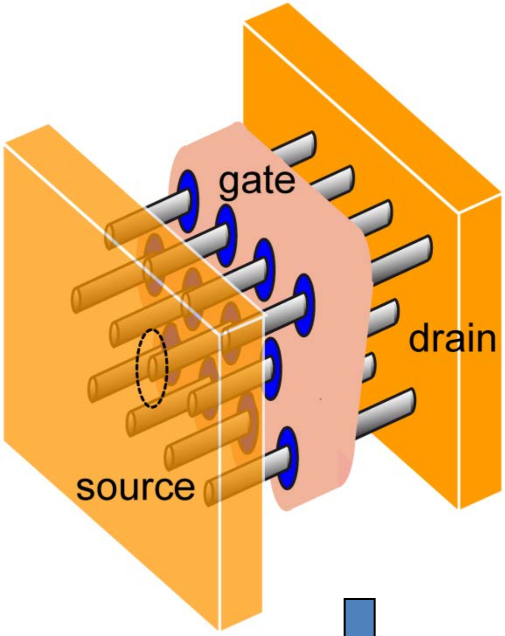




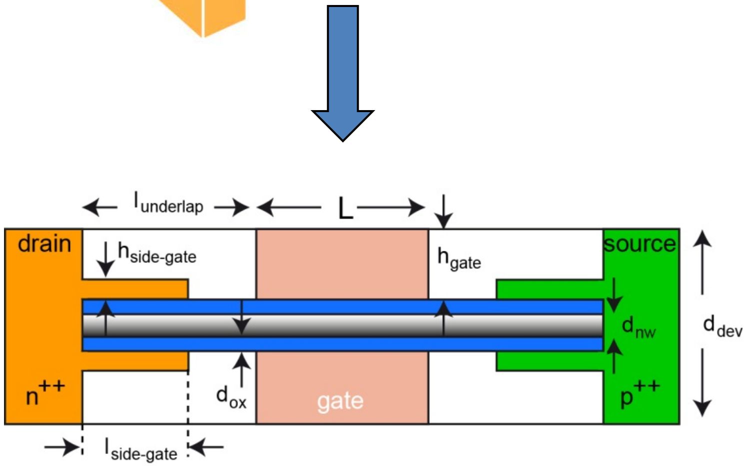
- **back-gate voltage characteristics for different coupling strengths**
- **second peak unobservable if coupling too large**

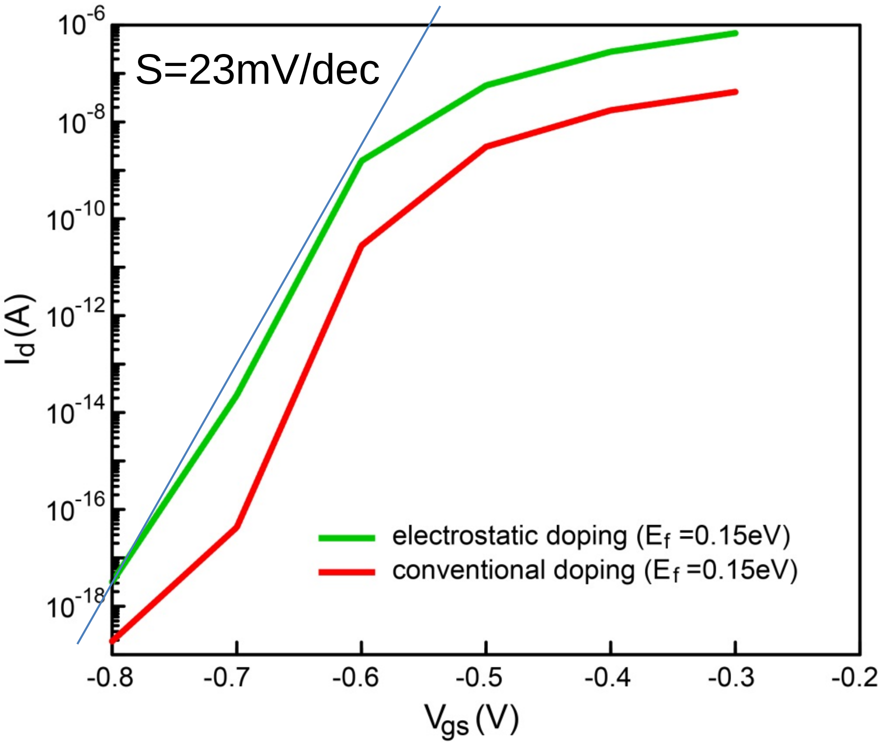
J. Knoch, Z. Chen and J. Appenzeller, IEEE Trans. Nanotechnol., **11**, 513 (2012).

Electrostatic Doping in CNT Tunnel-FETs



nanotube bundle

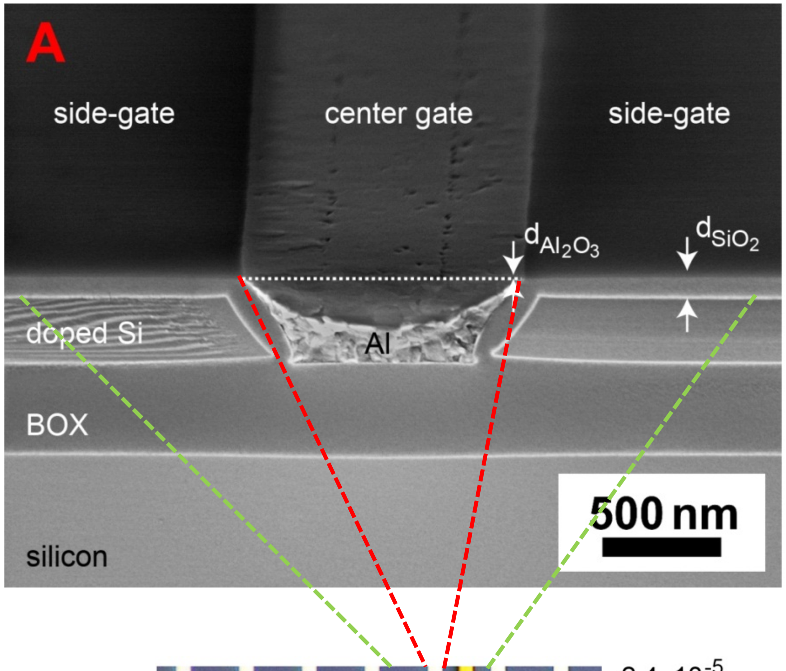


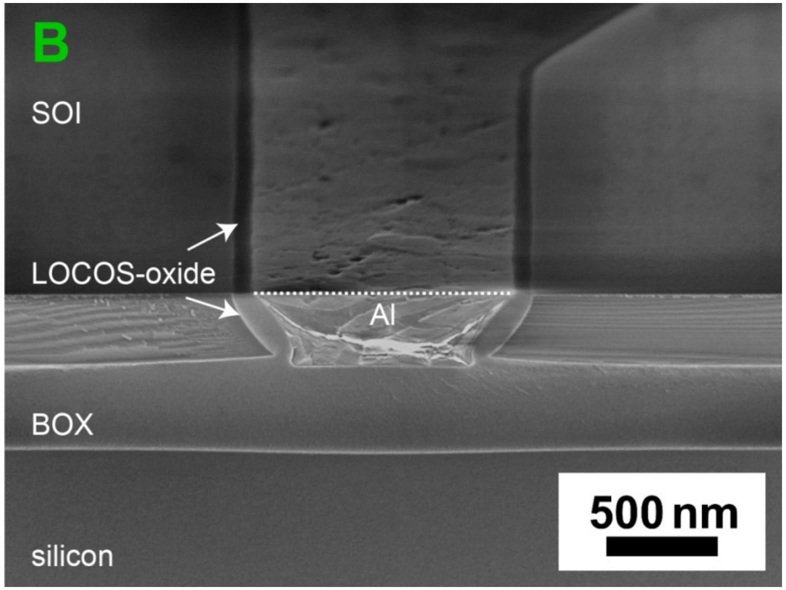


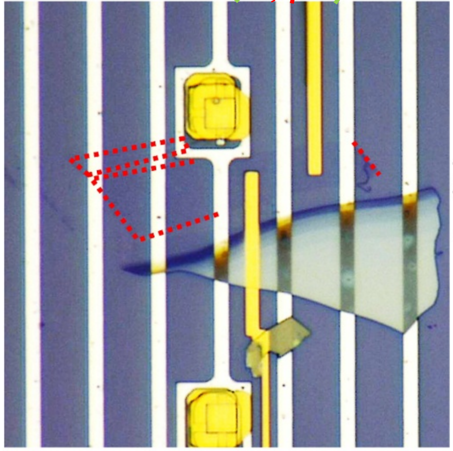
- **significantly improved on-state due to improved screening**
- **steep inverse subthreshold slope of 23mV/dec over several orders of magnitude**

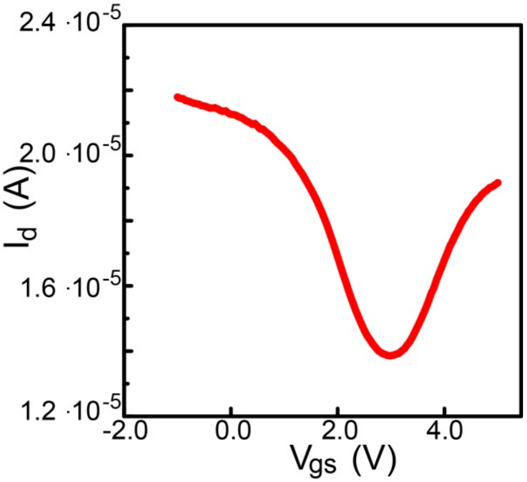
T. Grap and J. Knoch, submitted for publication

Electrostatic Doping



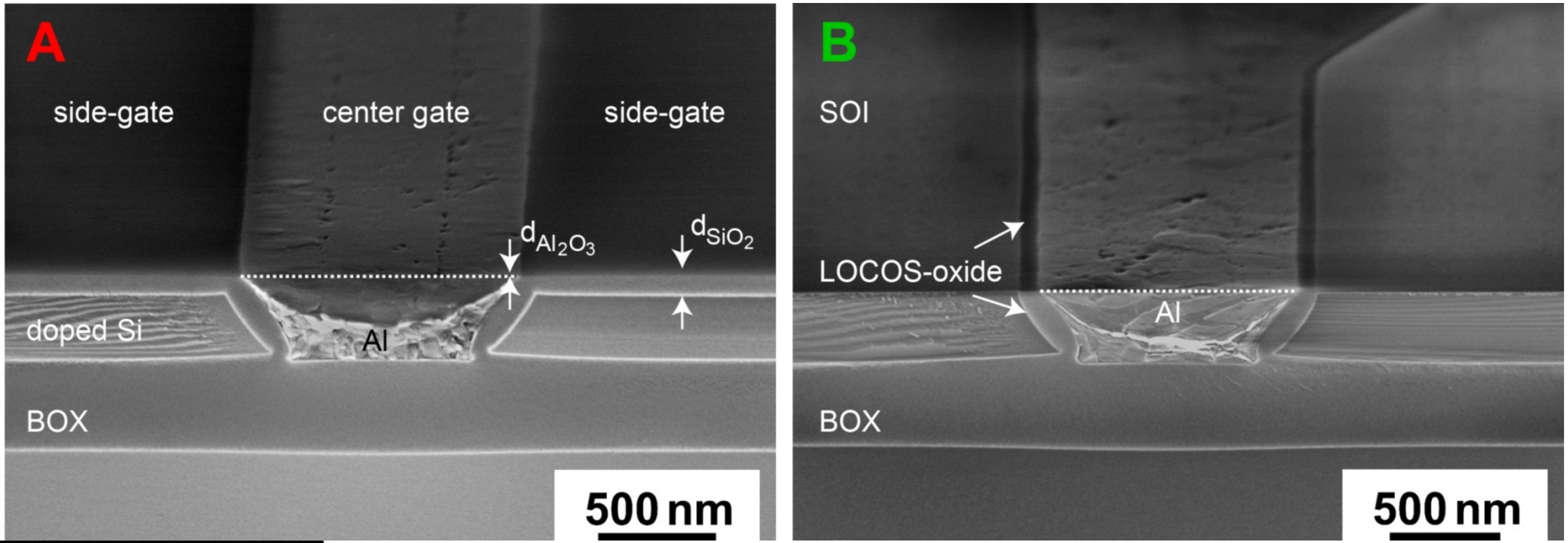


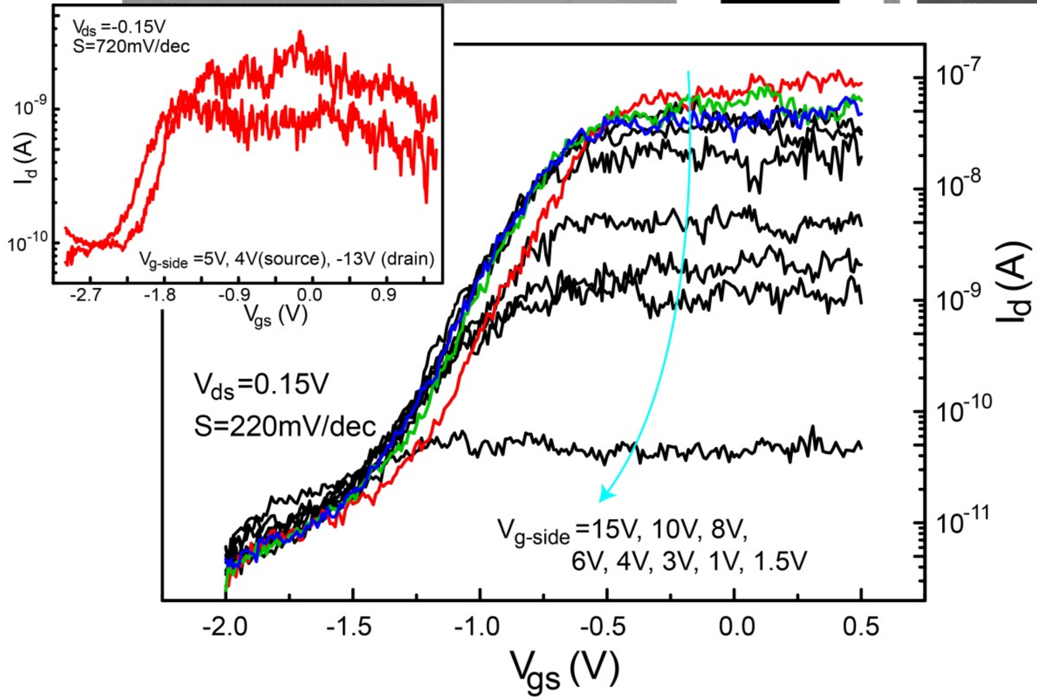


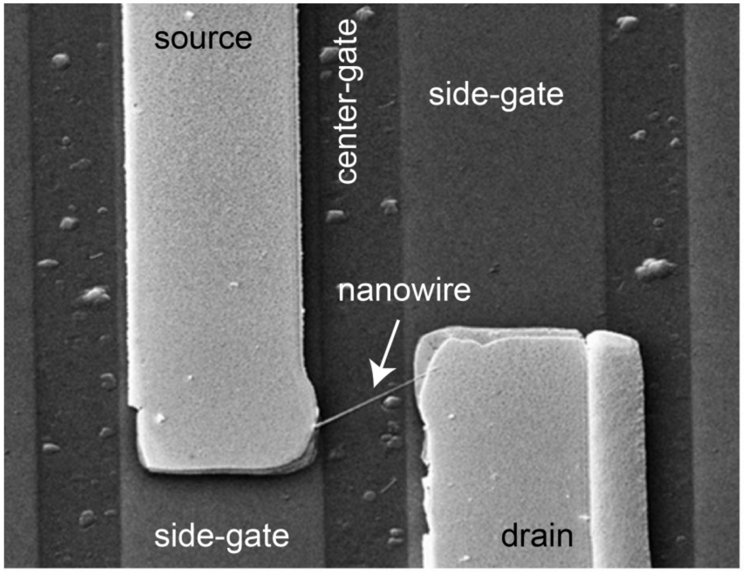


C. Kontis, M. Müller, K. Kallis and J. Knoch, Appl. Optics, **51**, 385 (2012).

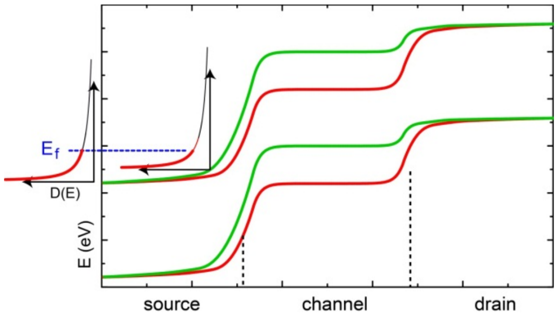
Electrostatic Doping



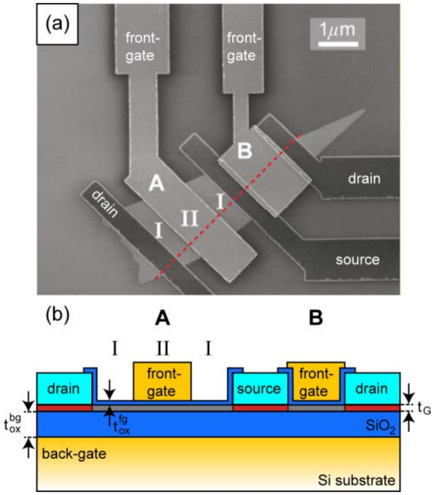




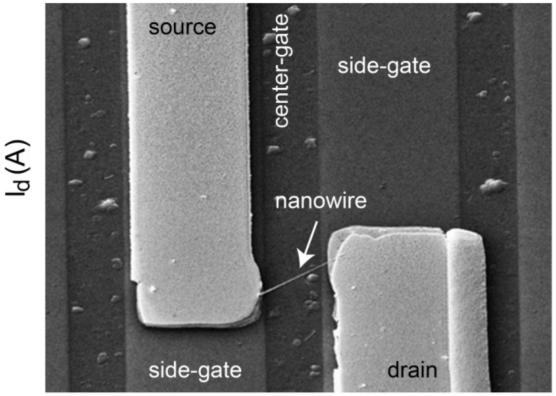
Conclusion

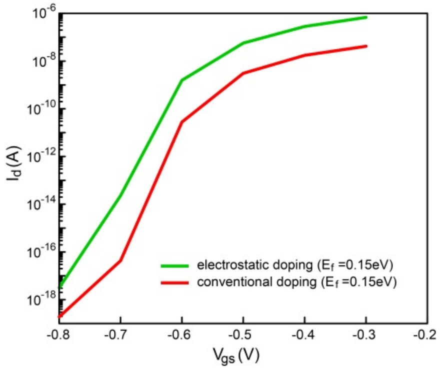


- **low density of states detrimental for novel transistor concepts such as tunnel FETs due to insufficient screening**



- **electrostatic doping avoids issues related to doping *and* adds flexibility for general investigations of carbon based nanostructures**





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- **H. Riel – IBM Zurich Research Lab**
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Graphene

STEEPER