Graphene field-effect transistors

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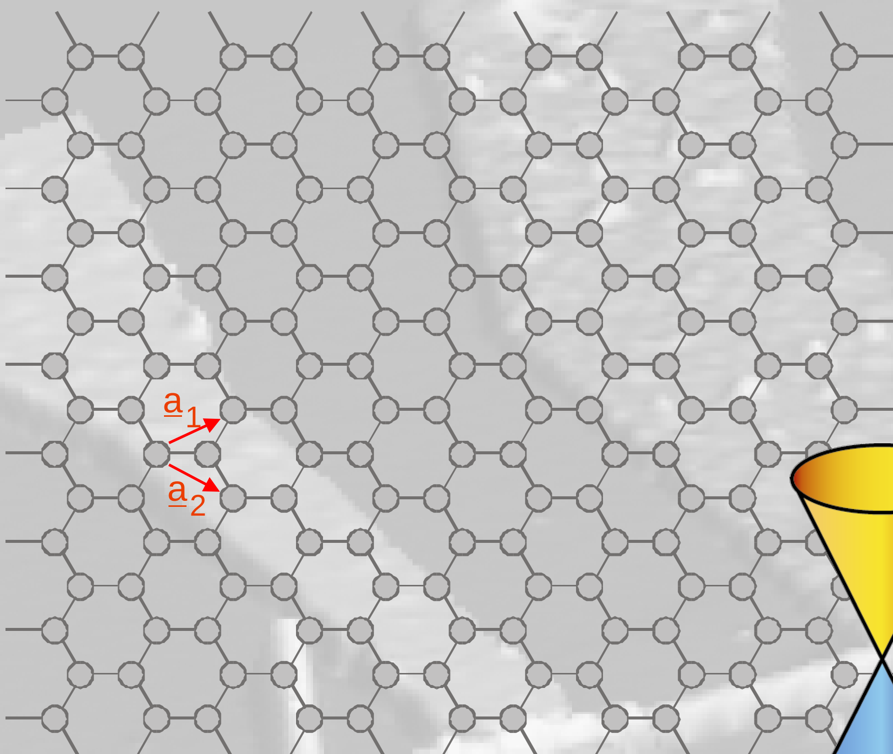
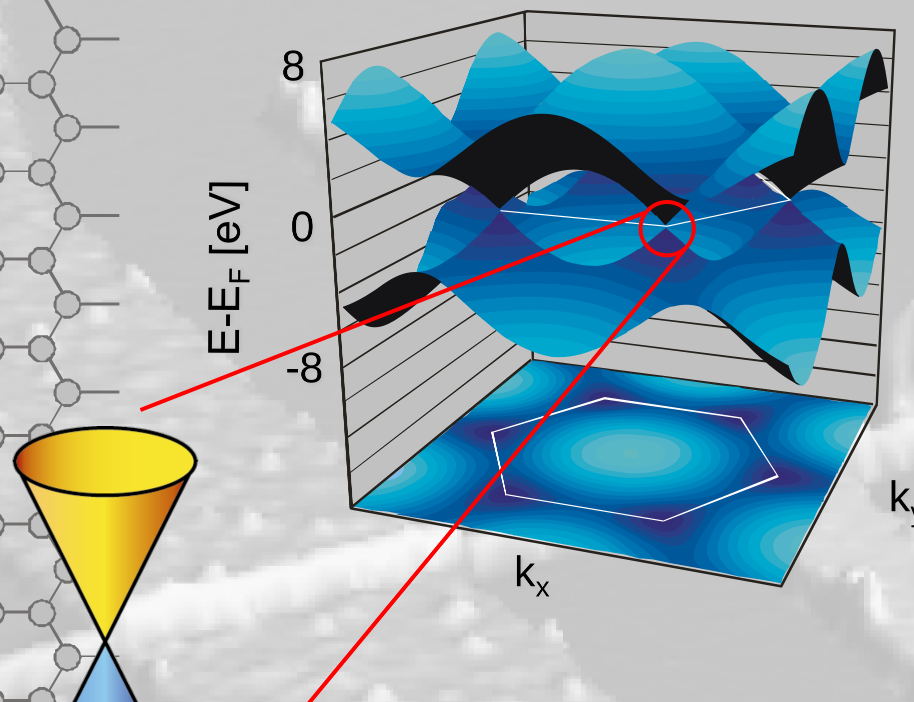
West Lafayette, IN 47907

Purdue Summer School 2009, July 22

The materials impact

One layer of graphite (graphene)- different from graphite

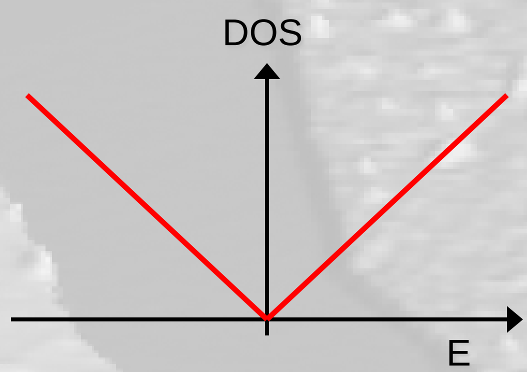




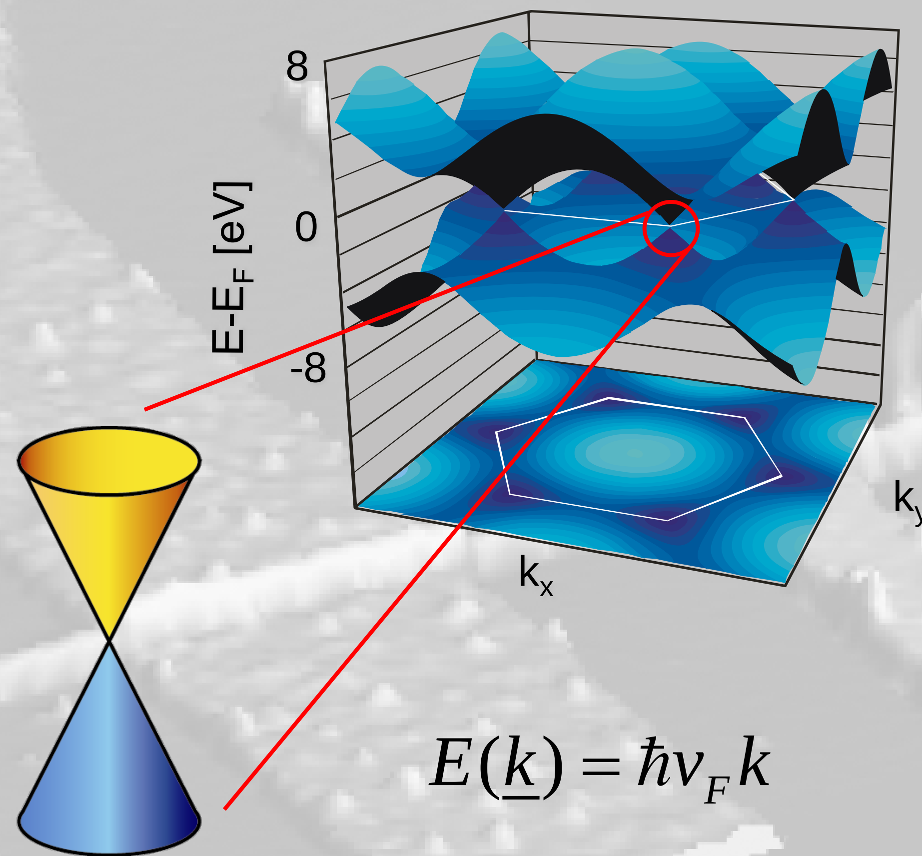
$$E(\underline{k}) = \hbar v_F k$$

The materials impact

Graphene is a gapless semiconductor



$$D_{2D-lin}(E) = \frac{2}{\hbar^2 v_F^2 \pi} \cdot E$$



$$E(\underline{k}) = \hbar v_F k$$

The materials impact

Material	Bulk Mobility	Bandgap	Effective Mass
	cm^2/Vs	eV	m^*/m_o
GaN	2,000[4]	3.47[5]	0.2[5]
Si	1,400[1,3]	1.12[1,2]	0.19[1,2]
Ge	3,900[1,3]	0.661[1,2,3]	0.082[1,2]
GaAs	8,500[1,3]	1.424[1,2,3]	0.067[1,2,3]
InGaAs	12,000[6]	0.74[7]	0.041[8]
InAs	40,000[1]	0.354[1,3]	0.023[1,3]
InSb	70,000[1,3]	0.17[1,3]	0.014[1,3]

1 – *Handbook Series on Semiconductor Parameters*, Levinshtein et al., 1996.
2 – *Advanced Semiconductor Fundamentals*, Pierret, 2003.
3 – *Compound Semiconductor Bulk Materials and Characterizations*, Oda, 2007.
4 – *Private communication*, T. Sands, 2009.
5 – *Properties of Advanced Semiconductor Materials*, Bougrov et al., 2001.
6 – J.D. Oliver et al., *J. Cryst. Growth*, **54**, 64 (1981).
7 – K.-H. Goetz et al., *J Appl. Phys.*, **54**, 4543 (1983).
8 – *GaInAsP alloy semiconductors*, John Wiley & Sons 1982.

The materials impact

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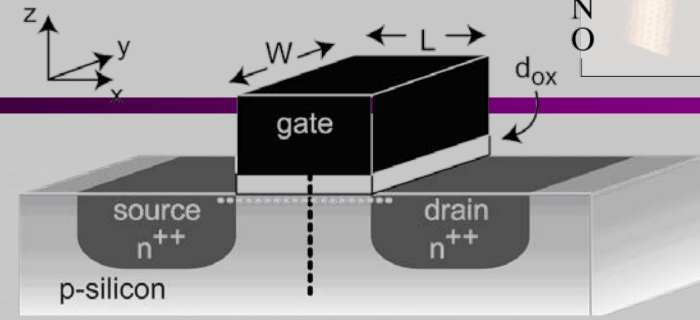
InSb	70,000[1,3]	0.17[1,3]	0.014[1,3]

graphene	100,000[9]	0	0

9 – *cond-mat 0805.1830v1 2008.*

The materials impact



$$I_d \propto \frac{1}{L^2} \cdot \mu \cdot C_{tot}$$

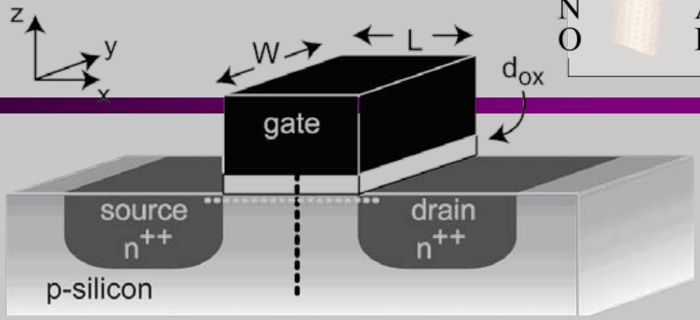
$$\tau_{delay} = \frac{C_{tot} V_{dd}}{I_d} \propto \frac{L^2}{\mu} \propto \frac{L^2 m^*}{\tau_{scatt}}$$

Direct tunneling probability from source to drain (WKB) is constant if:

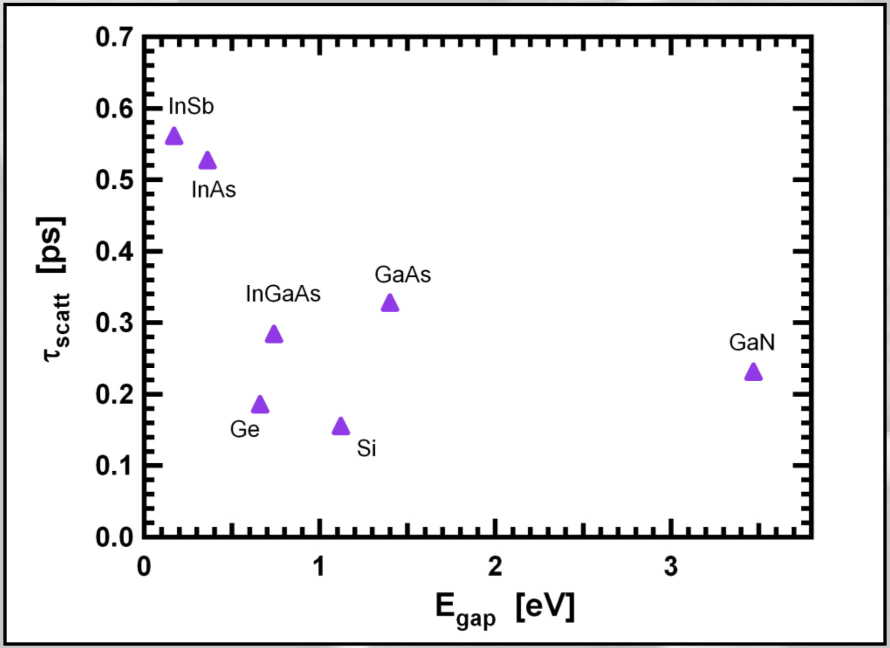
$$L \cdot \sqrt{m^*} \cdot \sqrt{E_g} = const$$

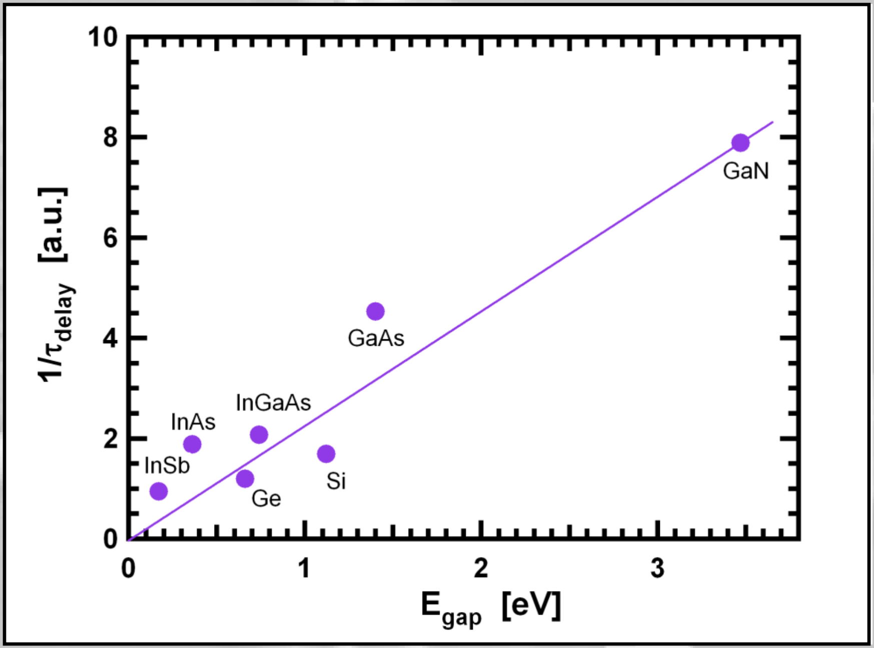
$$\tau_{delay} \propto \frac{1}{m^* \cdot E_g} \cdot \frac{m^*}{\tau_{scatt}} = \frac{1}{E_g \cdot \tau_{scatt}}$$

The materials impact



$$\tau_{delay} \propto \frac{1}{E_g \cdot \tau_{scatt}}$$





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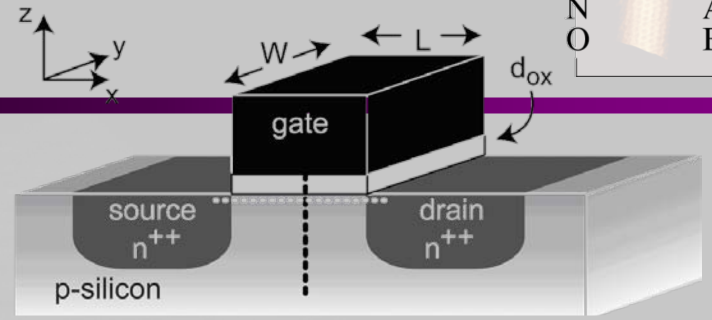

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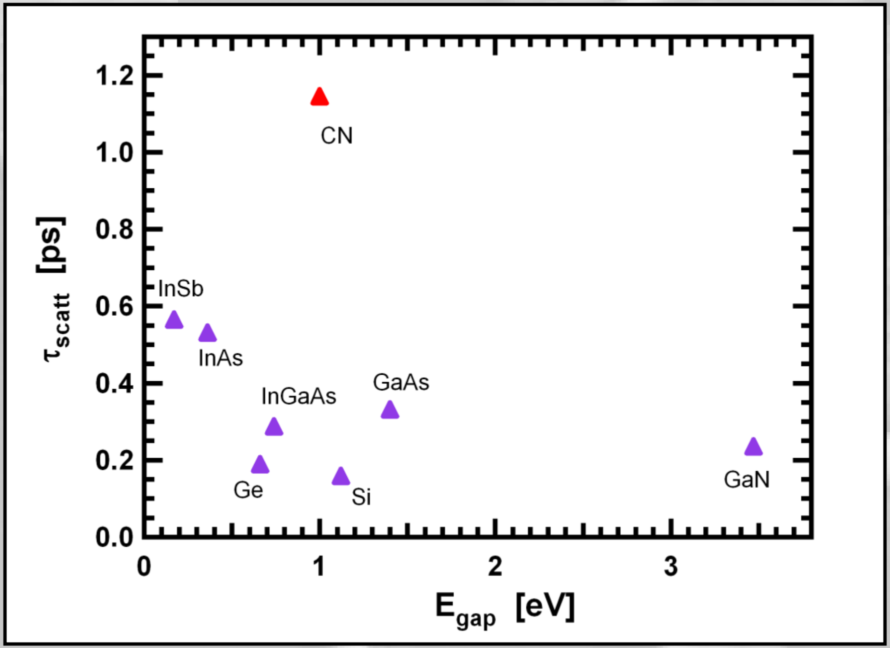
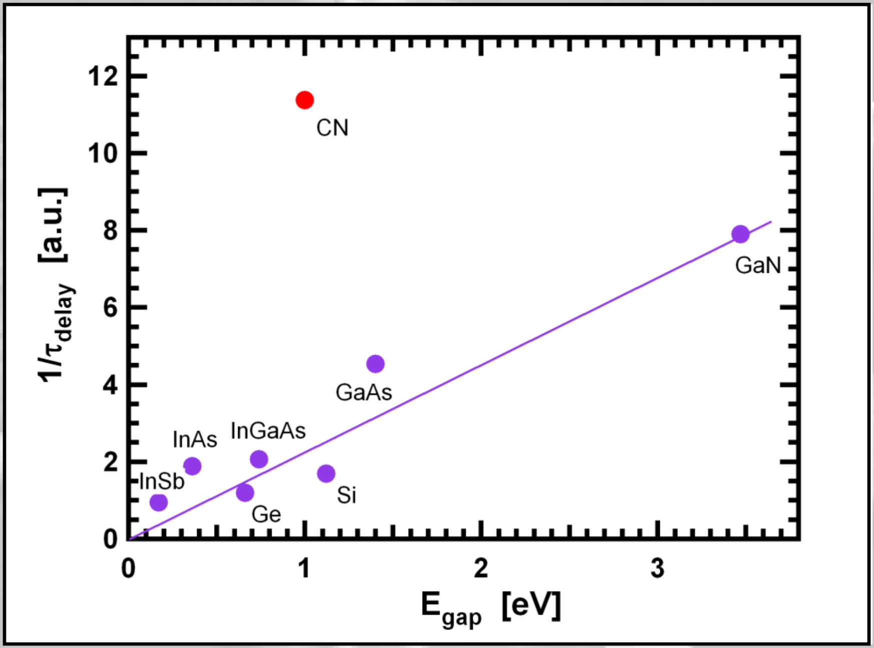
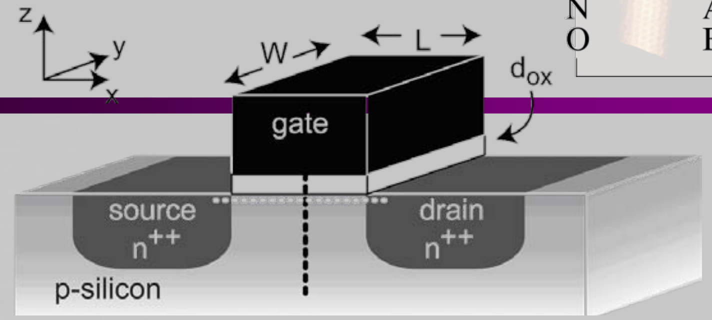




Advantages of 1D / 2D

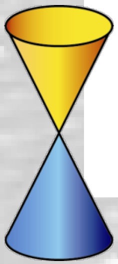


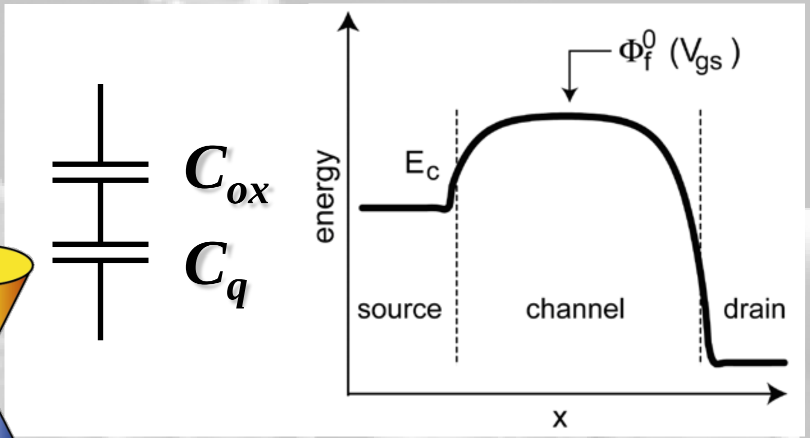
The quantum capacitance impact:

$$C_{tot} = e\frac{\partial Q_{tot}}{\partial \Phi_g} = \frac{C_{ox}C_q}{C_{ox}+C_q}$$

$$C_q = e\frac{\partial Q_{tot}}{\partial \Phi_f^0}$$

$$C_{q-2D} \approx e^2 LW \cdot DOS$$





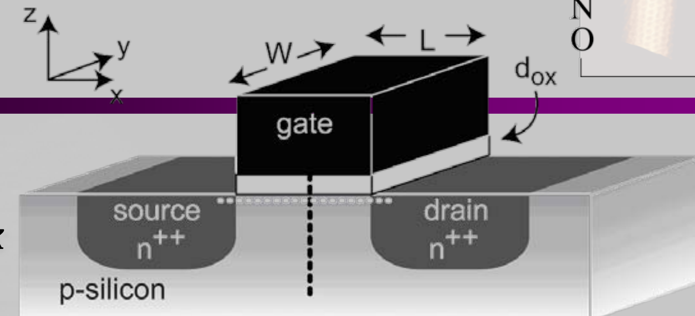
$$\delta\Phi_f^0 = \frac{C_{ox}}{C_{ox}+C_q}\cdot\delta\Phi_g \quad \left\{ \boxed{\begin{array}{lll} C_{ox} << C_q & : & \delta\Phi_f^0 \to 0 \\ C_q << C_{ox} & : & \delta\Phi_f^0 \approx \delta\Phi_g \end{array}} \right.$$

Advantages of the quantum capacitance limit

… but there is more …

C_{ox}

C_q



$$C_{tot} = e\frac{\partial Q_{tot}}{\partial \Phi_g} = \frac{C_{ox}C_q}{C_{ox}+C_q}$$

$$C_{ox} \sim \frac{L}{t_{ox}}$$

<u>classical limit</u>

$$C_{tot} \approx C_{ox}$$

$$\tau = \frac{C_{tot}V_{dd}}{I_d} \sim \boxed{L^2}$$

$$P \cdot \tau = C_{tot}V^2 \sim \boxed{\frac{L}{t_{ox}}}$$

diffusive: $I_d \sim \frac{C_{tot}}{L^2}$

$$C_q \sim L$$

<u>quantum capacitance limit</u>

$$C_{tot} \approx C_q$$

$$\tau = \frac{C_{tot}V_{dd}}{I_d} \sim \boxed{L^2}$$

$$P \cdot \tau = C_{tot}V^2 \sim \boxed{L}$$

Graphene field-effect transistors

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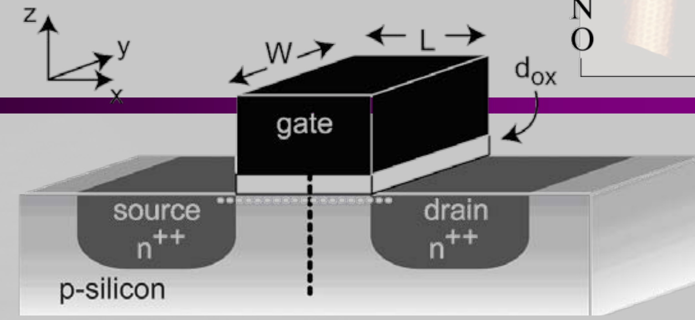
Advantages of 1D / 2D



"Nano" allows for improved electrostatics …

… improved electrostatics allows to reduce the device length

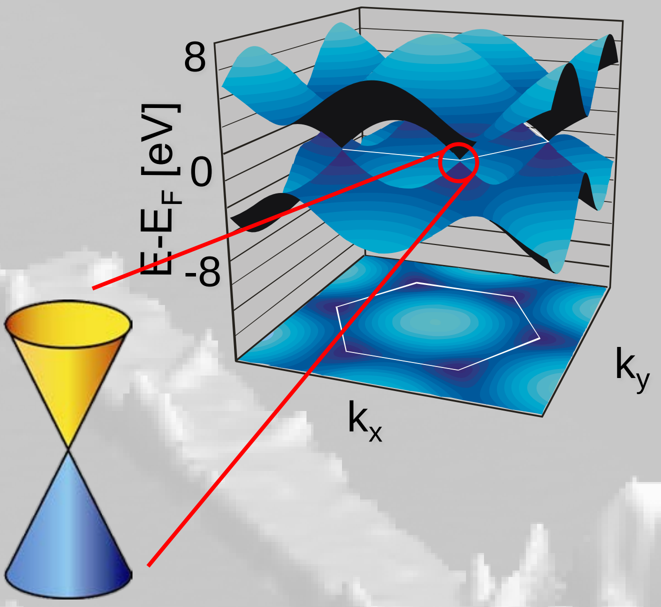
$$\lambda = \sqrt{t_{ox} t_{body} \frac{\varepsilon_{body}}{\varepsilon_{ox}}}$$

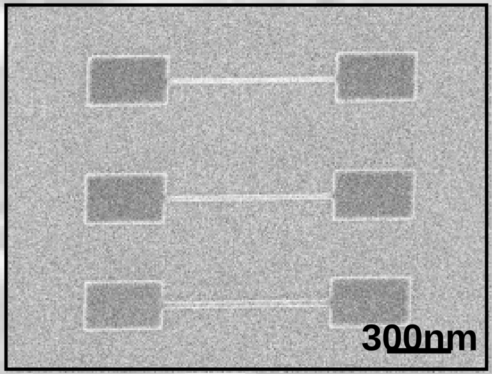
Graphene and graphene nanoribbons are ultra-thin body devices with a $t_{body} \approx 0.5$nm

Advantages of 1D / 2D

Advantages of graphene and graphene nanoribbons

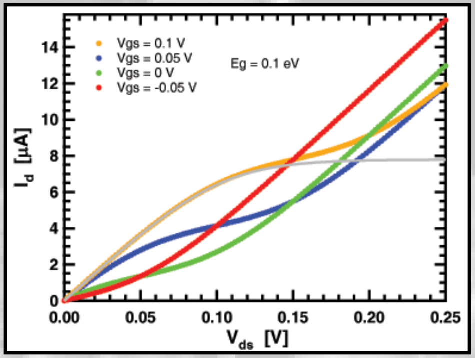
- reduced scattering
- top-down approach
- ultra-thin body
- 1:1 band movement
- improved scaling





Switching in graphene versus carbon nanotubes

The energy dependence of the density of states is the key for current modulation in G-FETs



Graphene field-effect transistors

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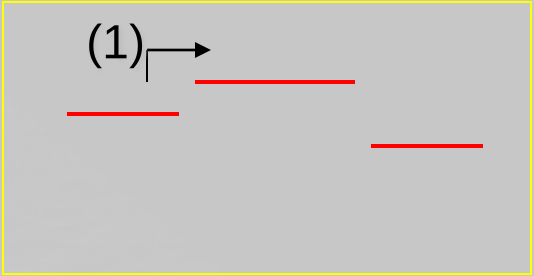
One-dimensional transport in the QCL limit

$$I_1 = e \cdot \int_{-eV_{gs}}^{\infty} dE \left(D_{1D}(E) \cdot v(E) \cdot f_s(E,T) \right)$$



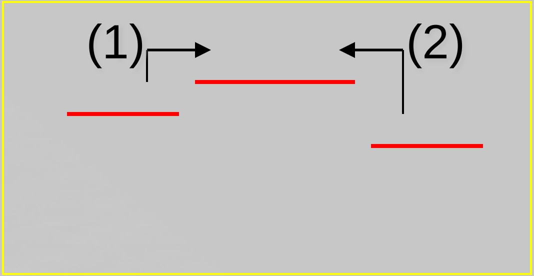
Source to drain through conduction band:

$$I_1 = \frac{2e^2}{h} V_{gs} + \frac{2ek_B T}{h} \ln\left(1 + \exp\left[-\frac{eV_{gs}}{k_B T} \right] \right)$$

Note: In our calculations, we will consider only one k_F-point.

All currents need to be multiplied by 2 for carbon nanotubes.

One-dimensional transport in the QCL limit



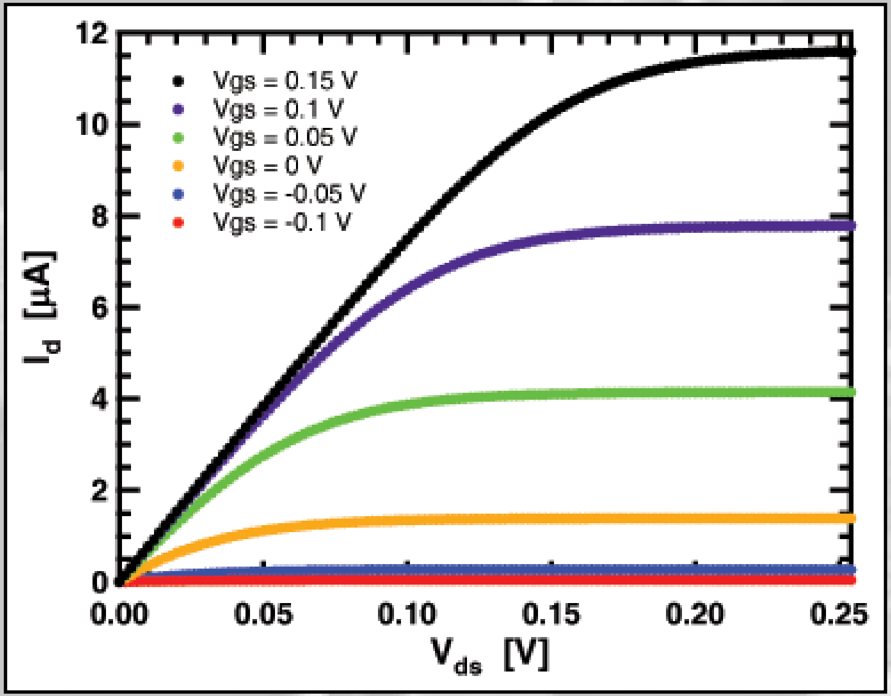
Source to drain through conduction band:

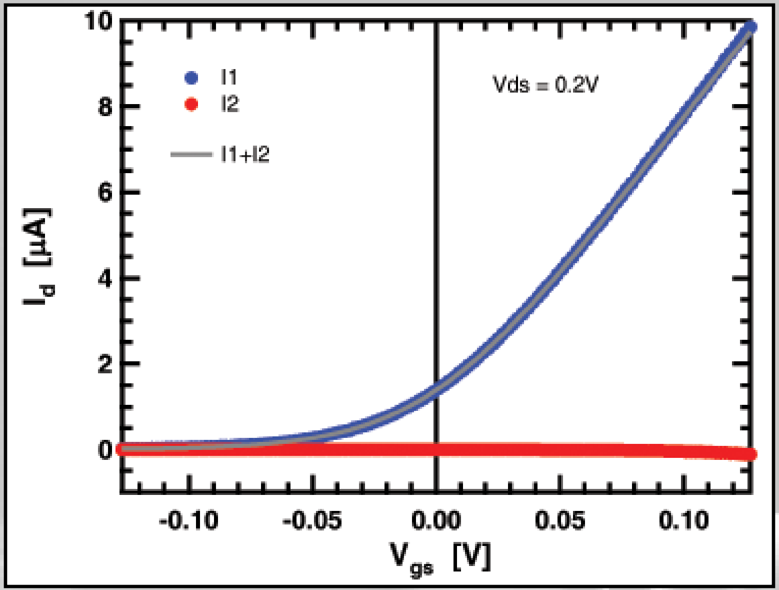
$$I_1 = \frac{2e^2}{h} V_{gs} + \frac{2ek_B T}{h} \ln\left(1 + \exp\left[-\frac{eV_{gs}}{k_B T}\right]\right)$$

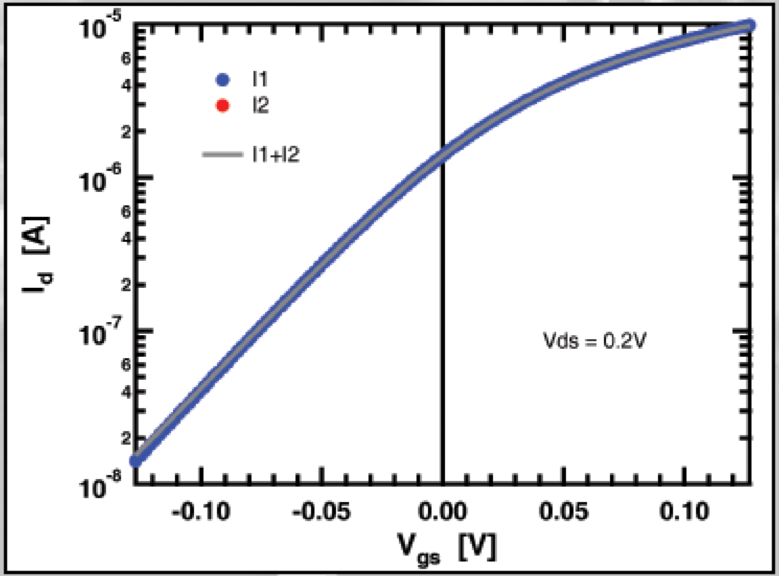
Drain to source through conduction band:

$$I_2 = \frac{2e^2}{h} V_{ds} - \frac{2e^2}{h} V_{gs} - \frac{2ek_B T}{h} \ln\left(1 + \exp\left[\frac{eV_{ds}}{k_B T} - \frac{eV_{gs}}{k_B T}\right]\right)$$

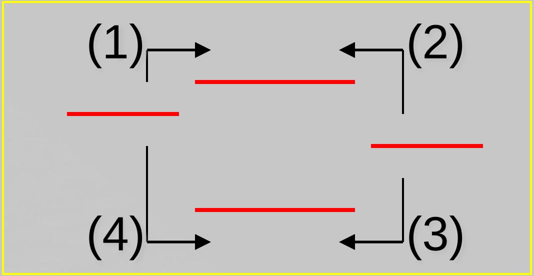
One-dimensional transport in the QCL limit







One-dimensional transport in the QCL limit



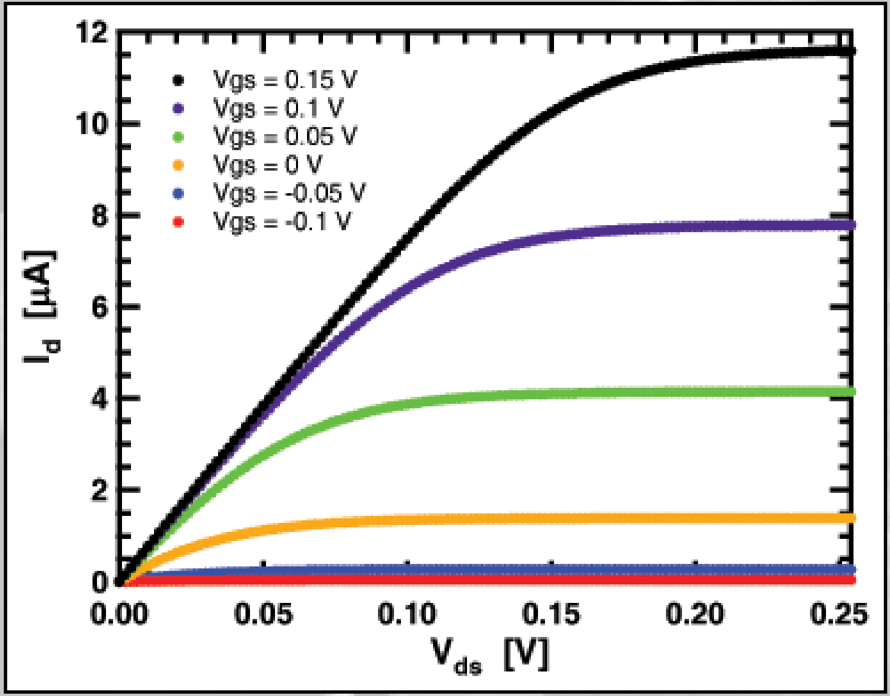
Drain to source through valence band:

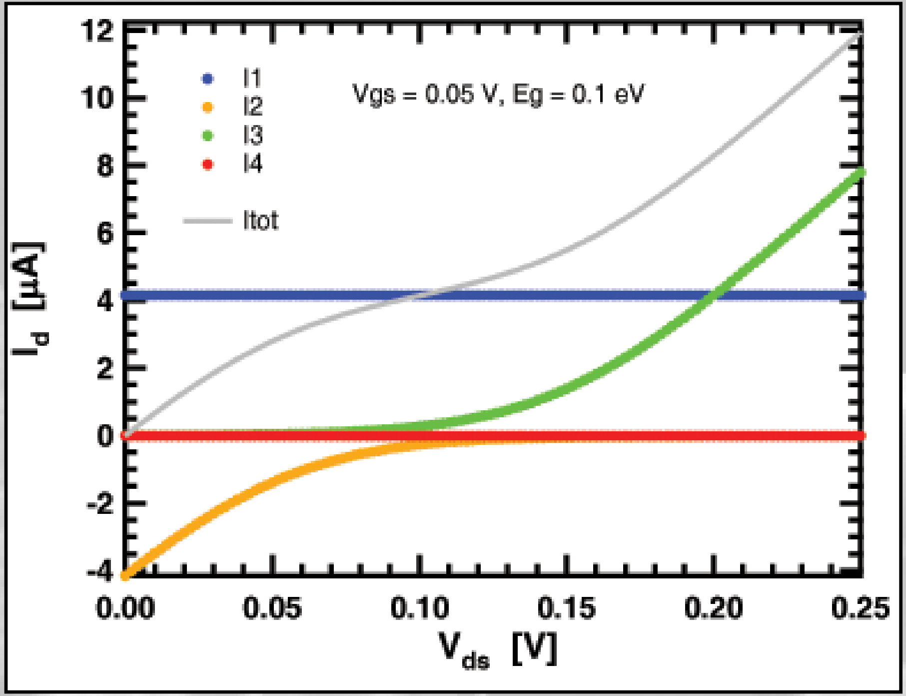
$$I_3 = \frac{2e^2}{h}V_{ds} - \frac{2e^2}{h}V_{gs} - \frac{2e}{h}E_g + \frac{2ek_BT}{h}\ln\left(1+\exp\left[\frac{eV_{gs}}{k_BT} - \frac{eV_{ds}}{k_BT} + \frac{E_g}{k_BT}\right]\right)$$

Source to drain through valence band:

$$I_4 = \frac{2e^2}{h}V_{gs} + \frac{2e}{h}E_g - \frac{2ek_BT}{h}\ln\left(1+\exp\left[\frac{eV_{gs}}{k_BT} + \frac{E_g}{k_BT}\right]\right)$$

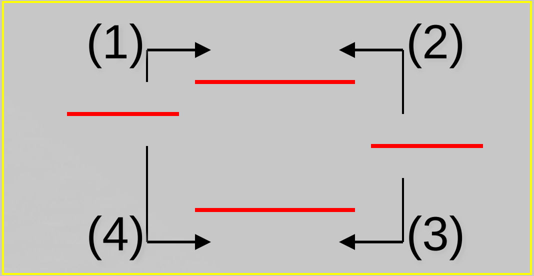
One-dimensional transport in the QCL limit





Contributions from I_1 to I_4

One-dimensional transport in the QCL limit



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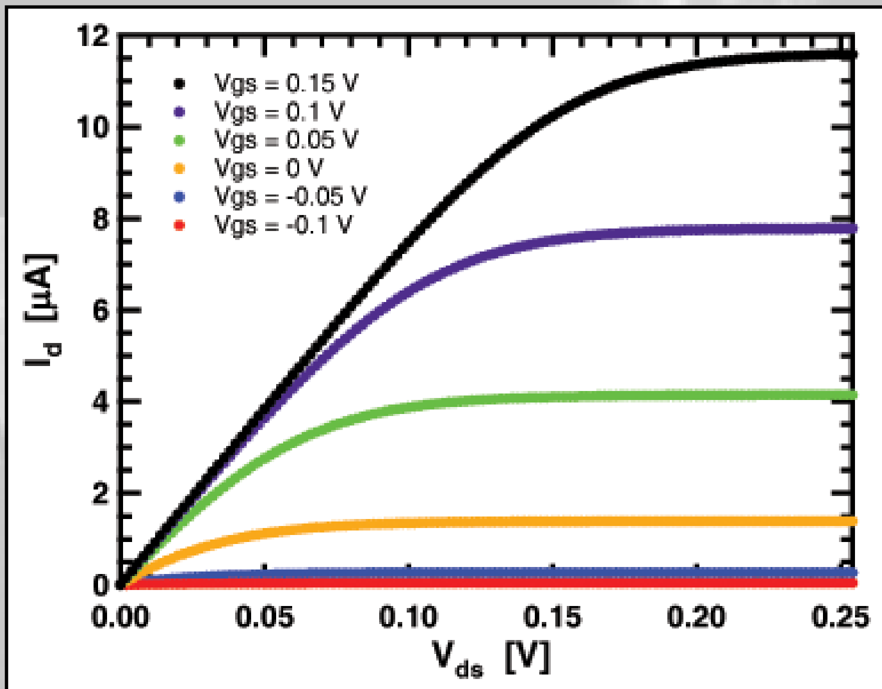
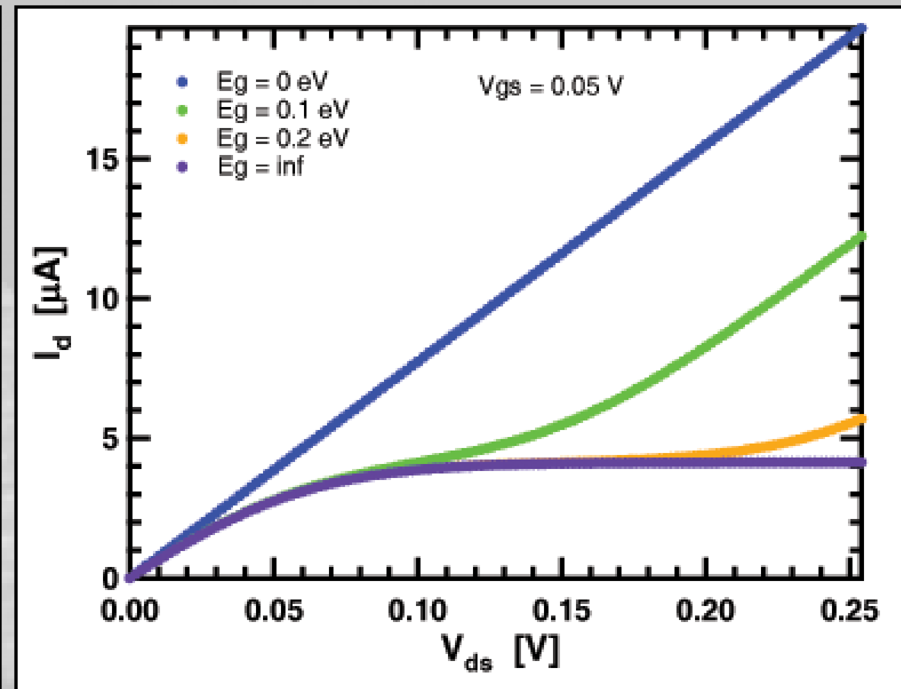
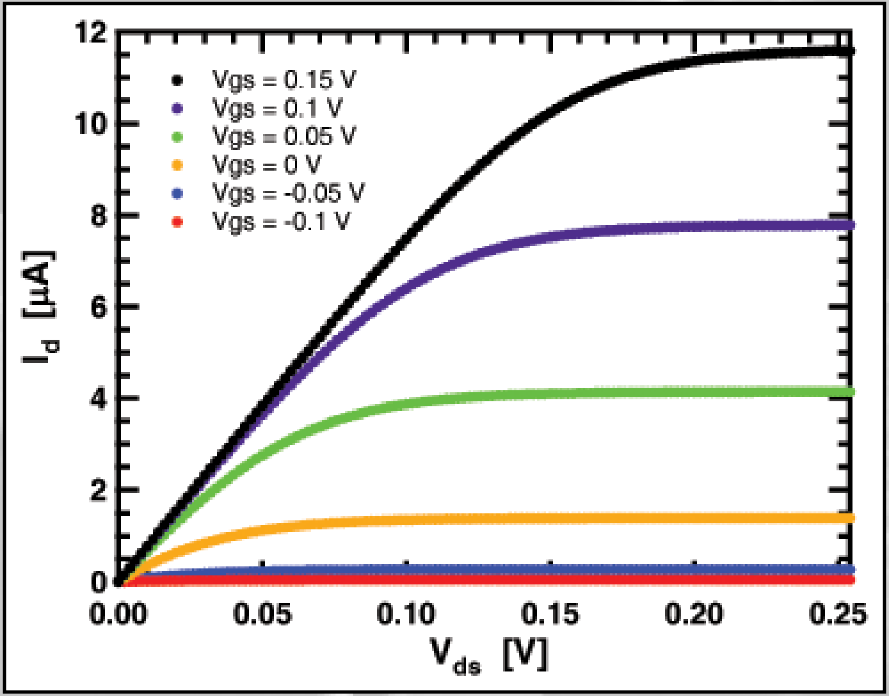
One-dimensional transport in the QCL limit

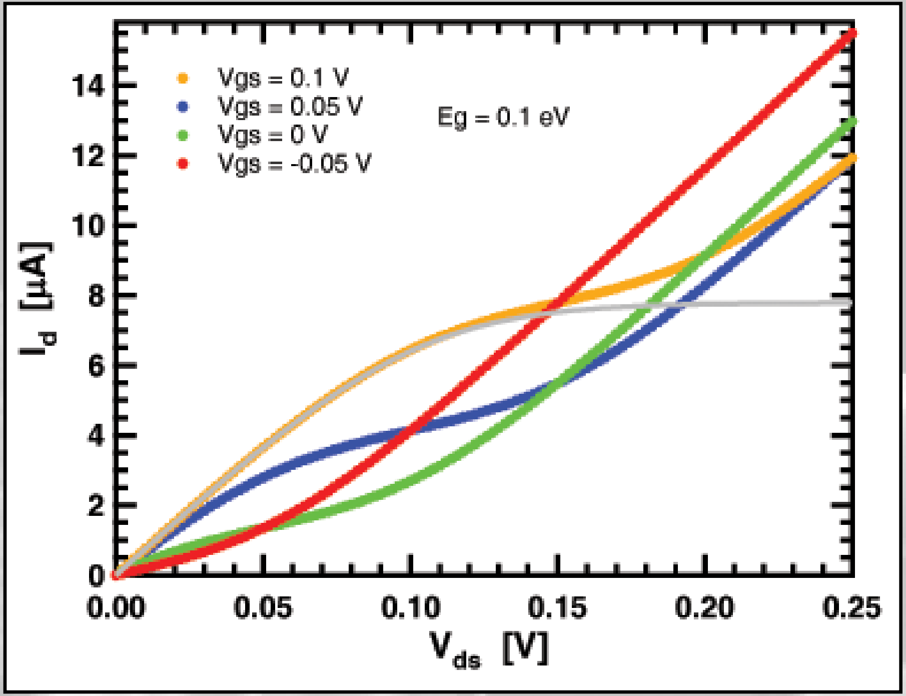




E_g-dependence of output characteristics

One-dimensional transport in the QCL limit





CNFET with E_g=0.1eV

Graphene field-effect transistors

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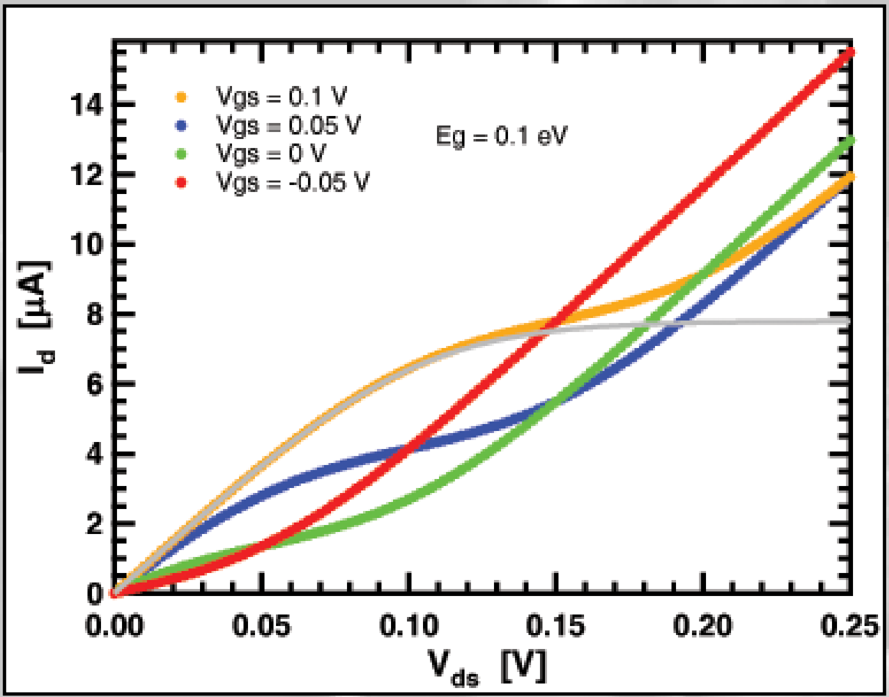
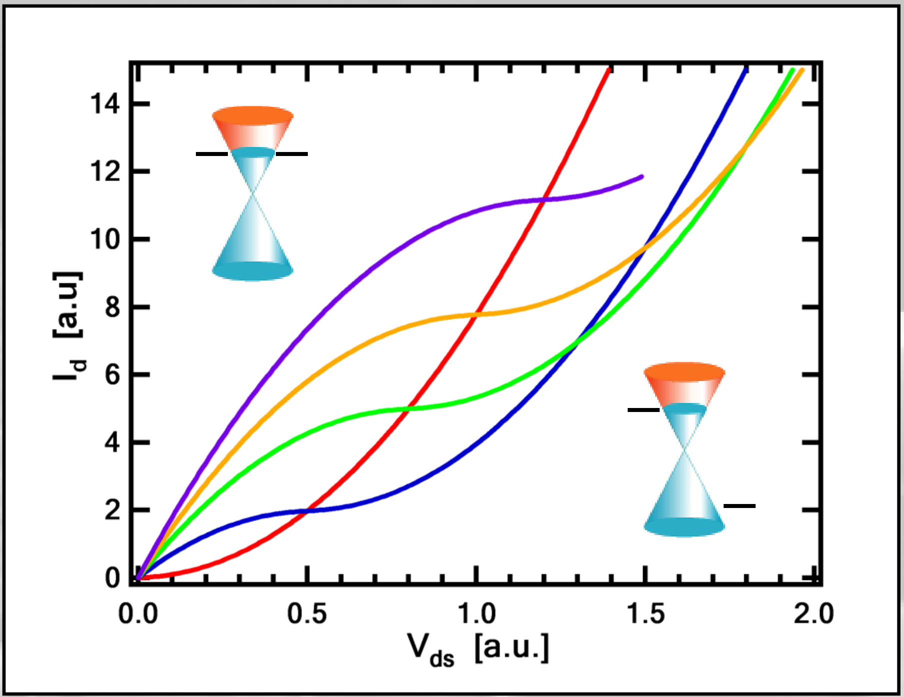
1D and 2D transport in the QCL limit

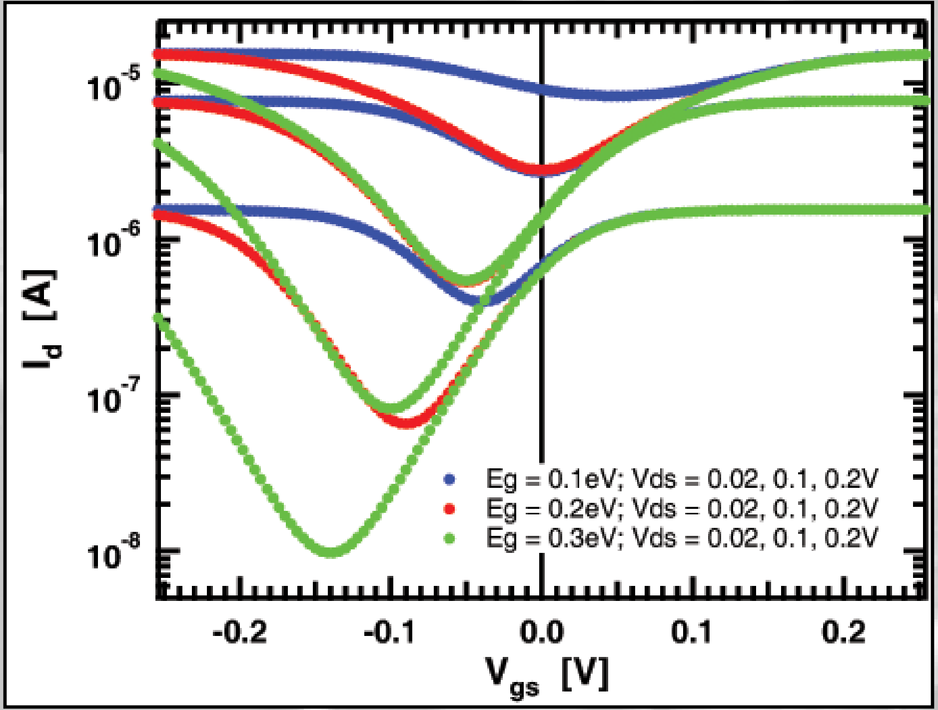
CNFET with E_g=0.1eV

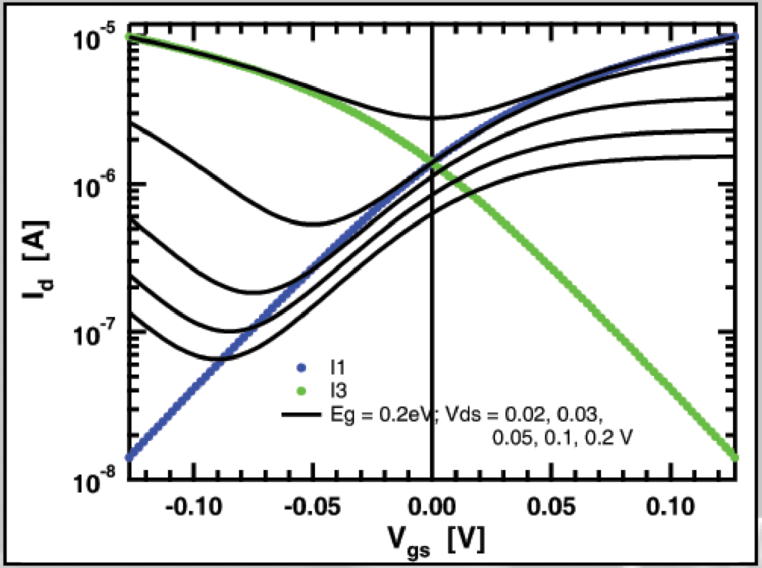


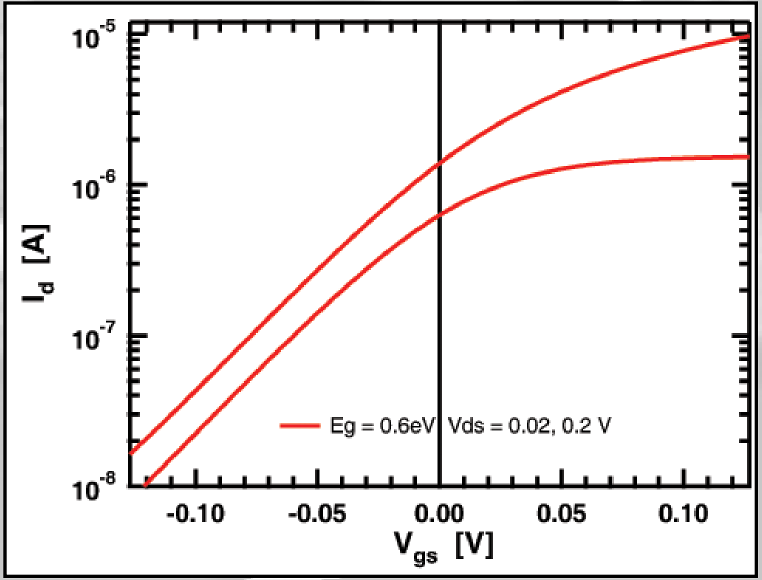
G-FET with E_g=0eV



One-dimensional transport in the QCL limit







On the operation of different FETs

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Silicon MOSFET (with gap)

$$I_d = \frac{1}{L^2} \cdot \mu \cdot C_{tot} \cdot \left(V_{gs} - V_{Th}\right) V_{ds} \longrightarrow I_d \propto Q(V_{gs})$$

Carbon nanotube FET (with gap)

$$I_d = e \cdot \int_{Vgs} dE \cdot D_{1D}(E) v(E) \cdot \left[f_s(E,T) - f_d(E,T) \right]$$

$$\longrightarrow I_d \propto \int_{Vgs} dE \cdot \left[f_s(E,T) - f_d(E,T) \right]$$

Graphene FET (without gap)

$$I_d = e \cdot L \cdot \int_{Vgs} dE \cdot D_{2D}(E) v(E) \cdot \left[f_s(E,T) - f_d(E,T) \right]$$

$$\longrightarrow I_d \propto \int_{Vgs} dE \cdot D_{2D}(E)$$

On the operation of different FETs

Silicon nanowire FET

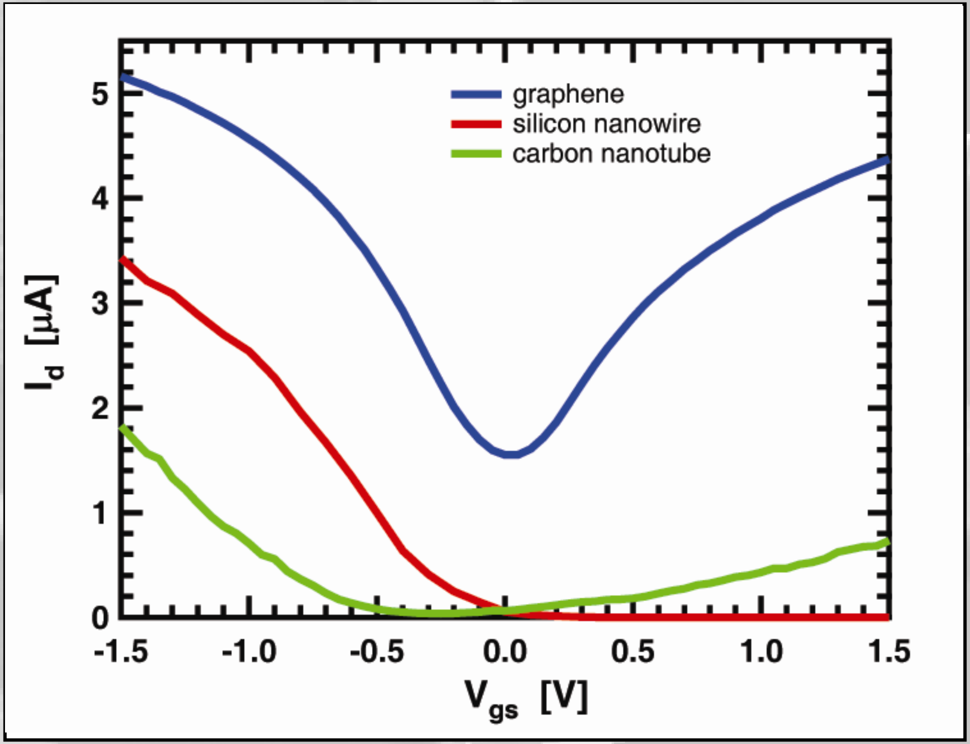
$$I_d \propto Q(V_{gs})$$

Carbon nanotube FET (with gap)

$$I_d \propto \int_{Vgs} dE \cdot \left[f_s(E,T) - f_d(E,T) \right]$$

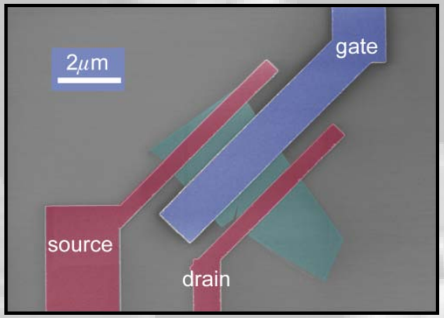
Graphene FET (without gap)

$$I_d \propto \int_{Vgs} dE \cdot D_{2D}(E)$$



The quantum capacitance

Large area graphene devices for quantum capacitance characterization



Graphene field-effect transistors

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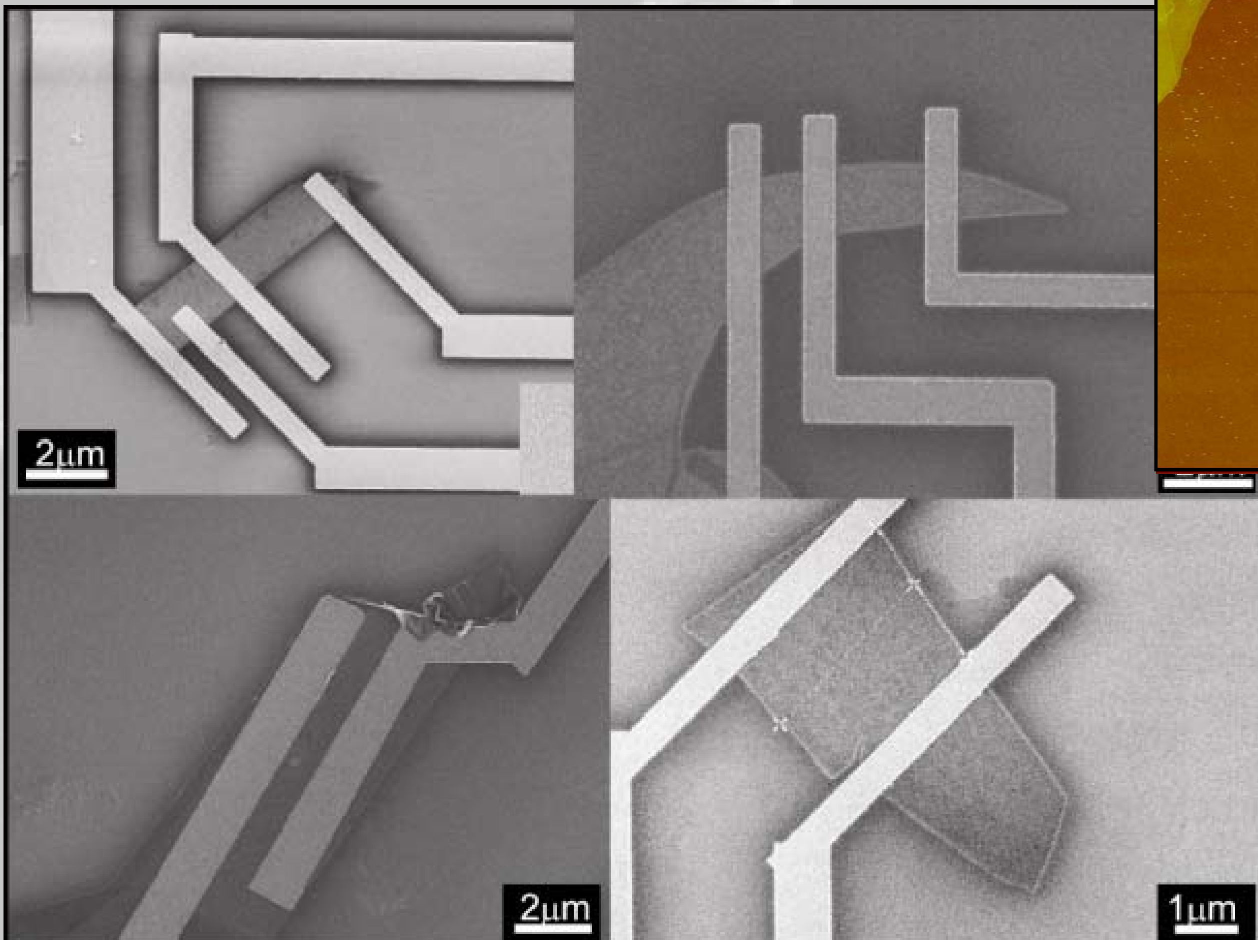
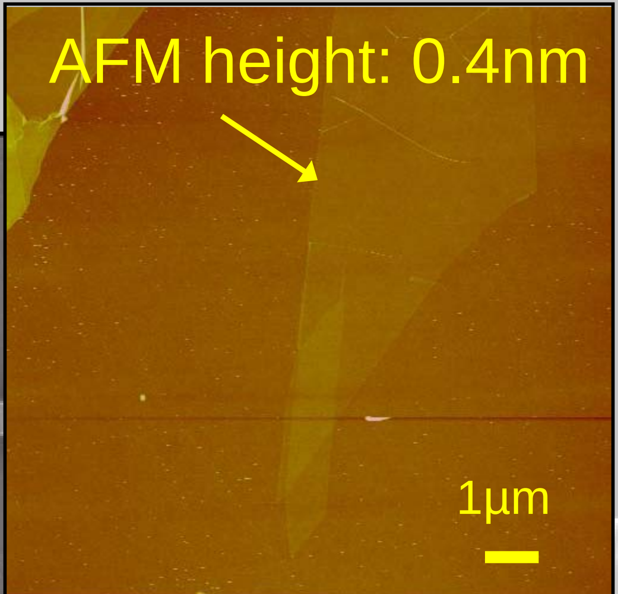
Sample fabrication

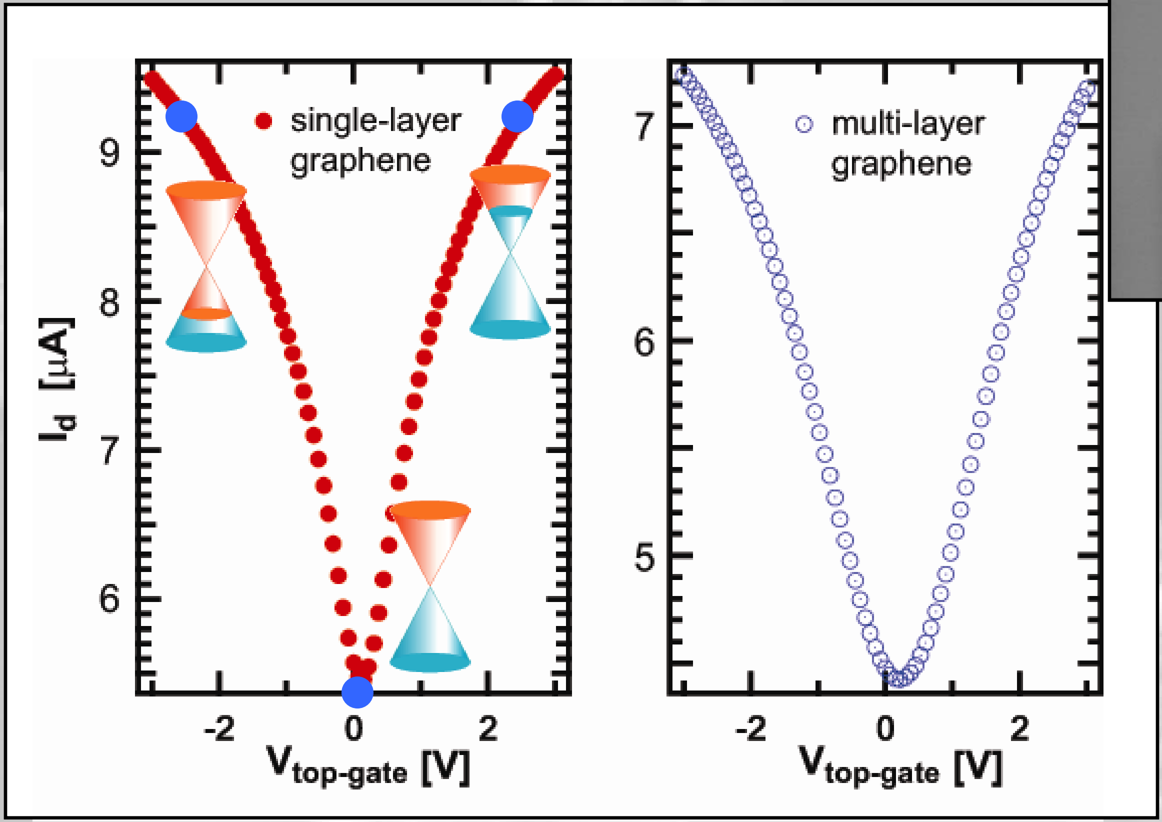
Single layer graphene through „peeling“

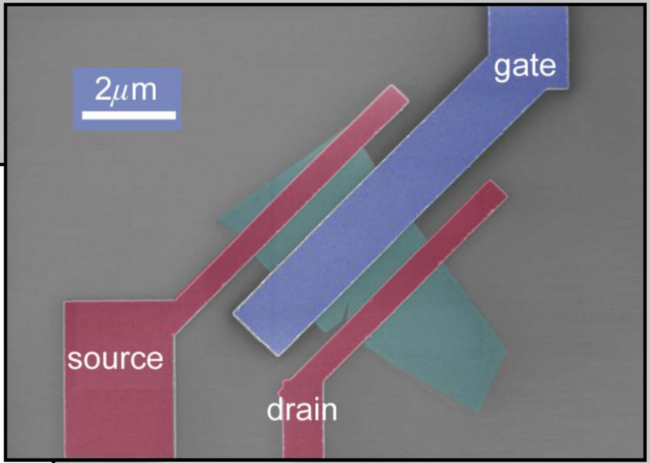




IEDM Technical Digest, 509 (2008)

Graphene capacitance measurements

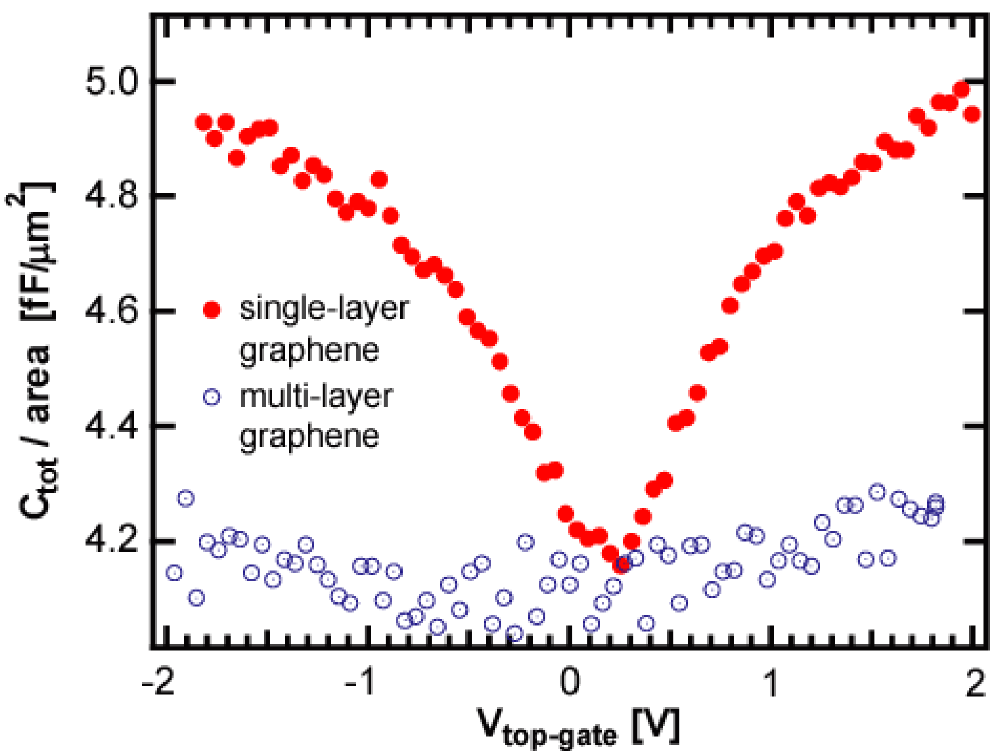


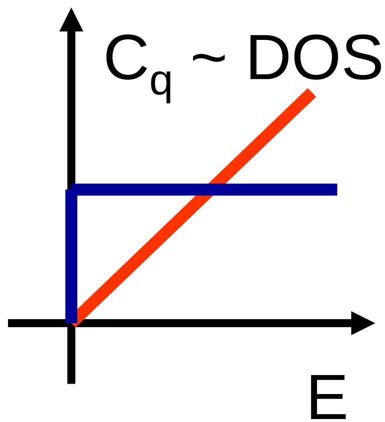


Similar I_d-V_{gs} are obtained for single and multi-layer graphene

IEDM Technical Digest, 509 (2008)

Graphene capacitance measurements





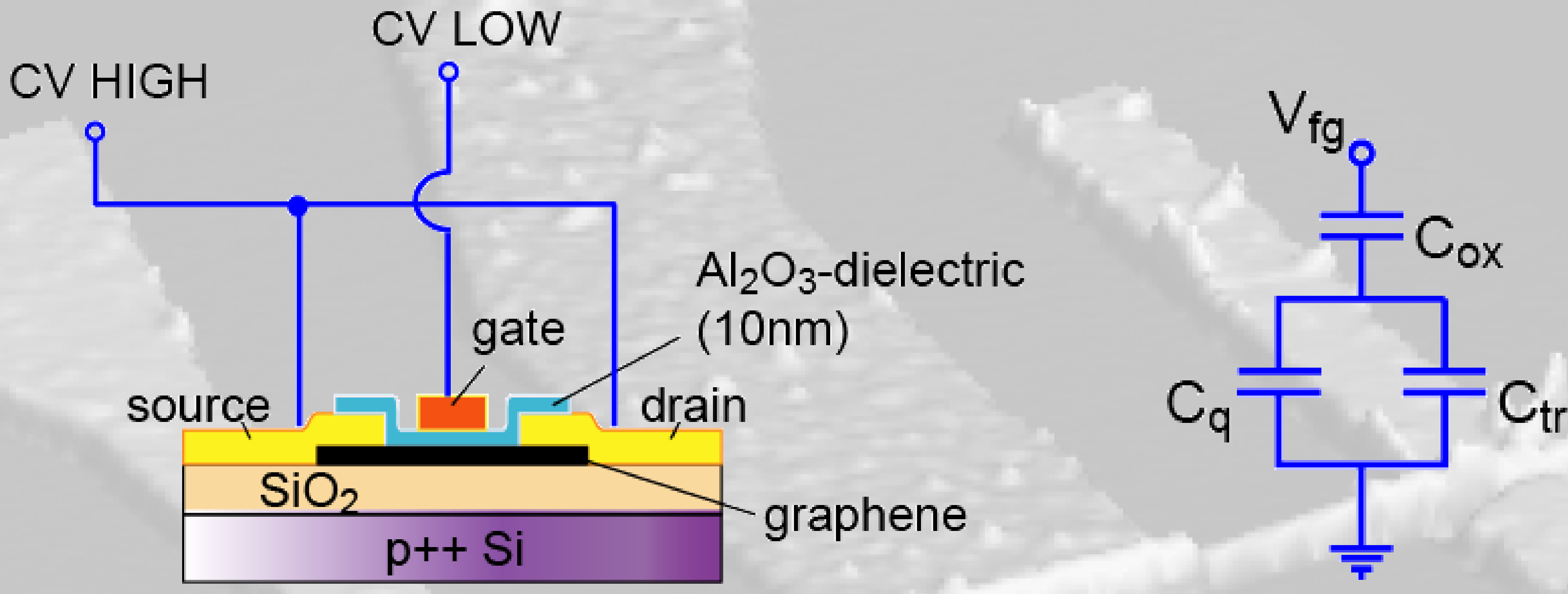
$$DOS_{graphene} = \frac{2E}{\pi \hbar^2 v_F^2}$$

$$DOS_{multi-graphene} = \frac{2m}{\pi \hbar^2}$$

However, C-V_{gs} characteristics are very different

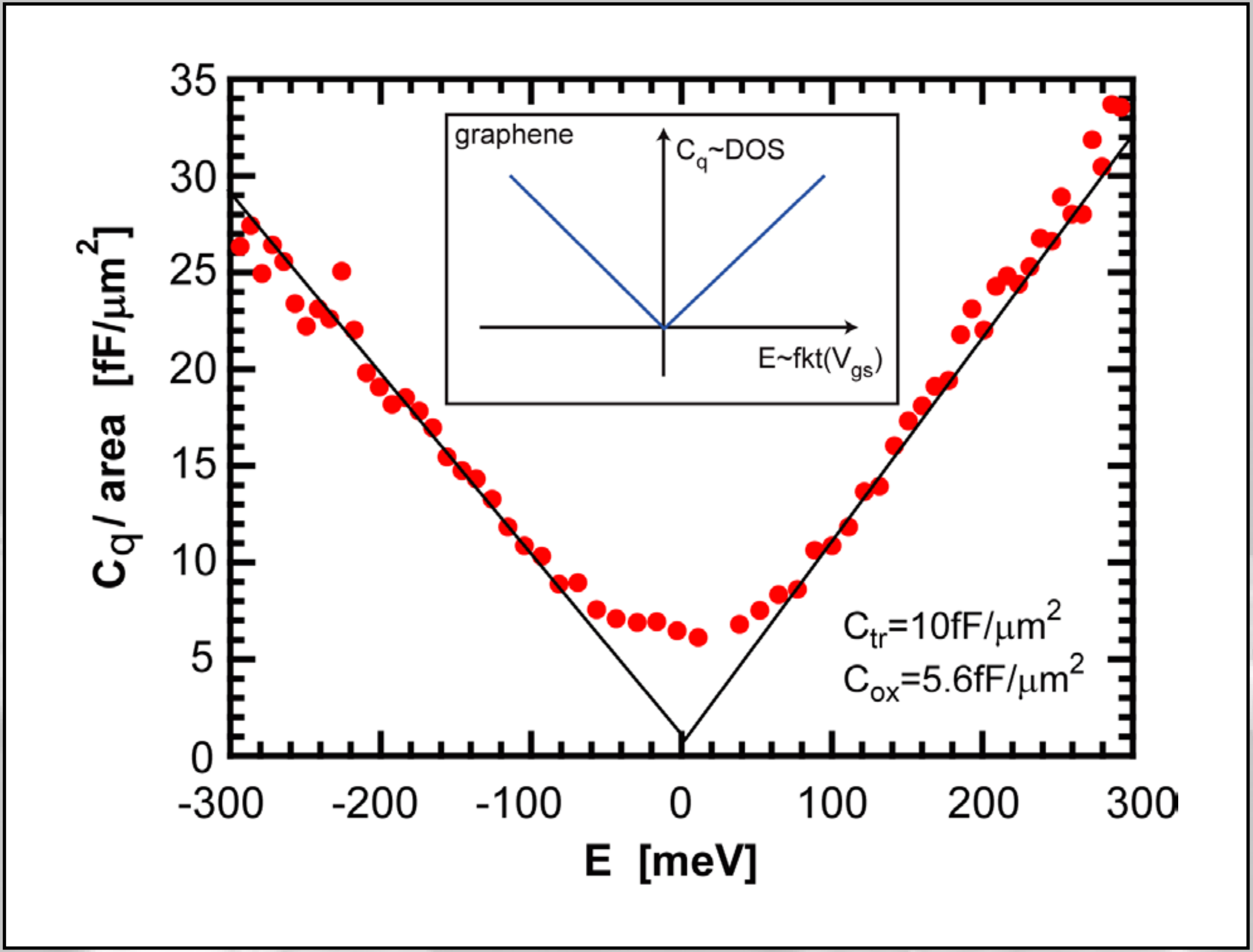
IEDM Technical Digest, 509 (2008)

Graphene capacitance measurements



Including a trap capacitance contribution allows to …

Graphene capacitance measurements



… extract the quantum capacitance C_q

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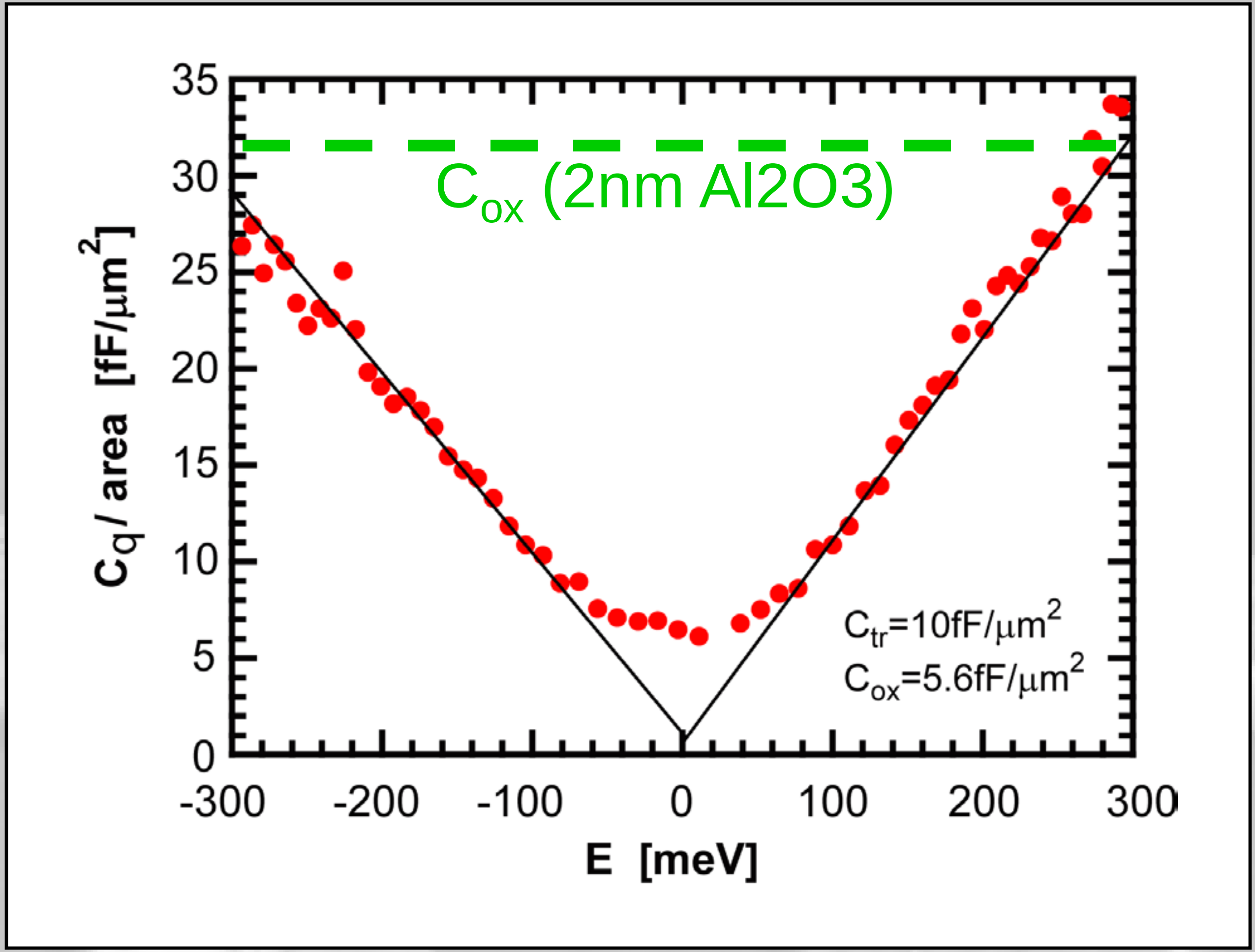
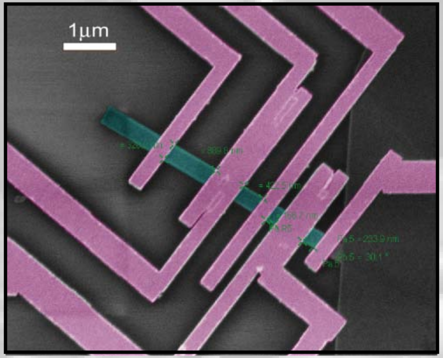
Graphene capacitance measurements



Scaled graphene devices will operate in the QCL!

Graphene mobility

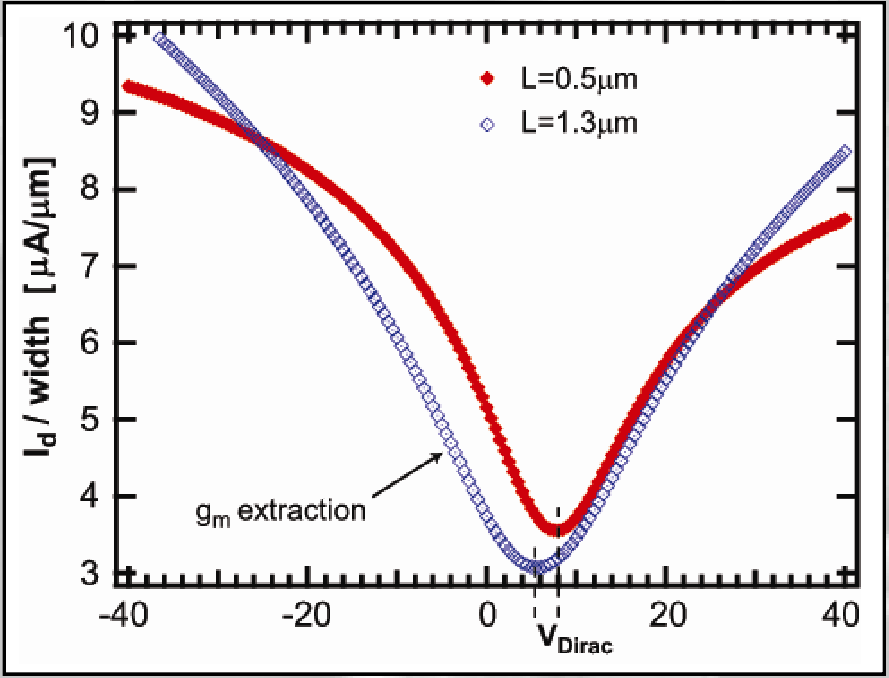
Intrinsic and extrinsic contributions in graphene devices

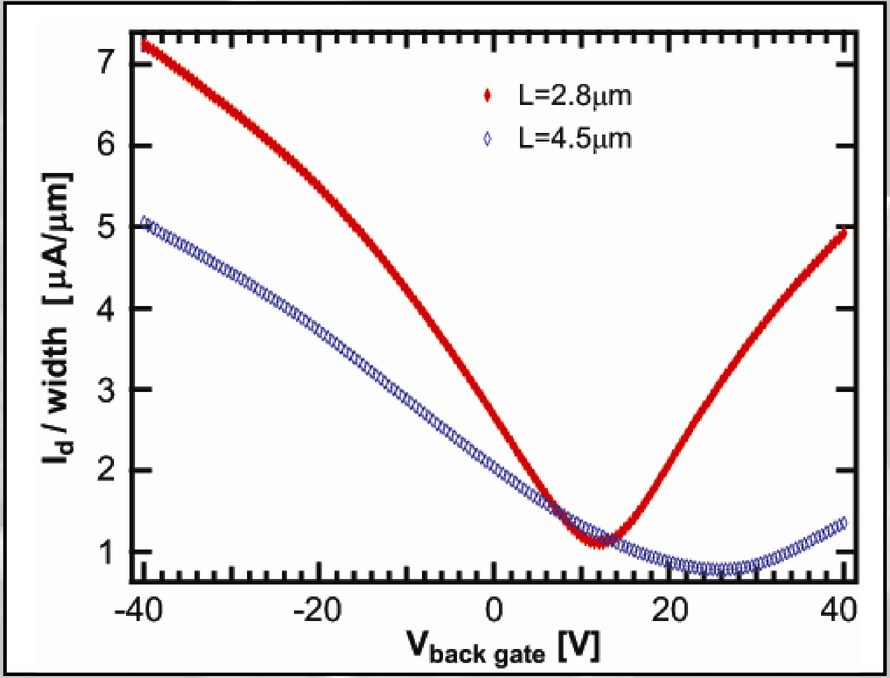


Graphene device characteristics

mobility extraction from g_m

carrier concentration in g_m- region: $n_s \sim 10^{12} cm^{-3}$

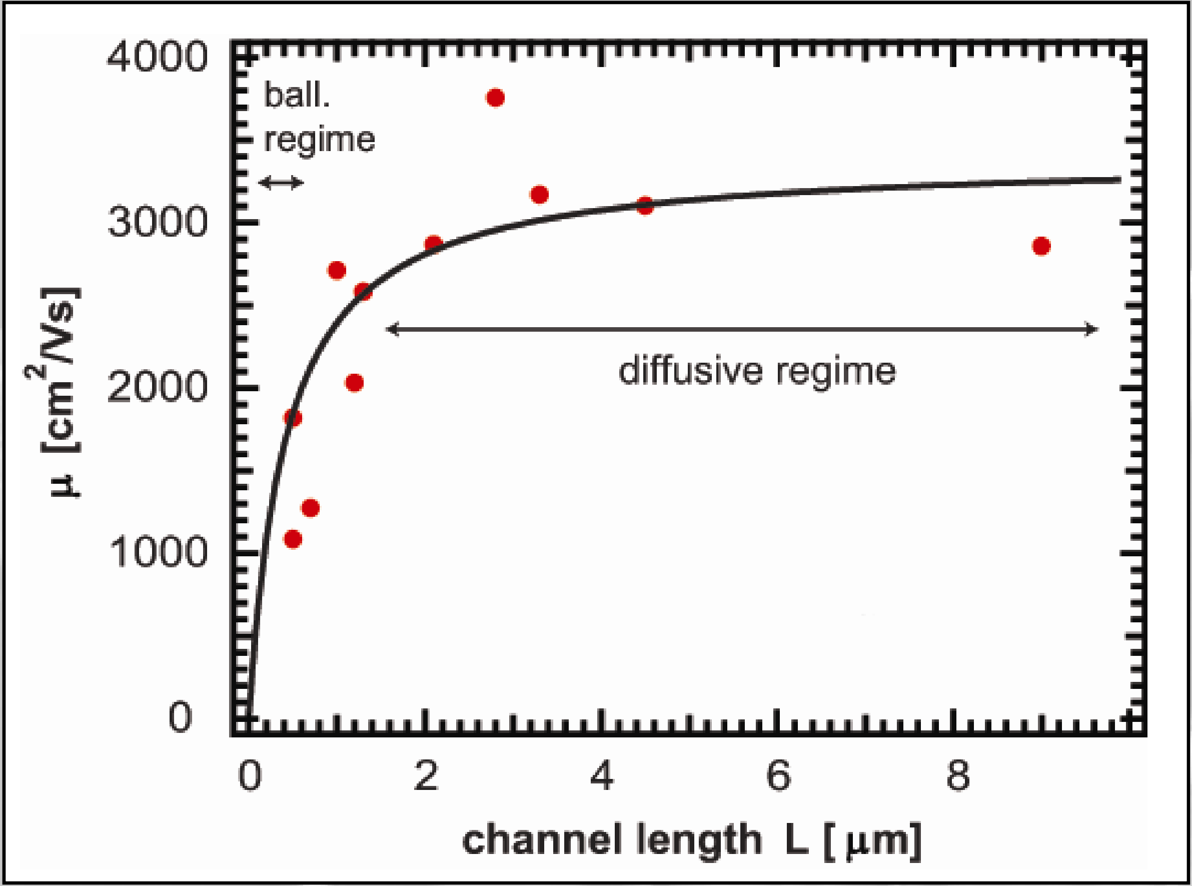




short channel characteristics

long channel characteristics

Graphene device characteristics



Mobility decrease is evidence of transition into the ballistic transport regime

$$\mu = \frac{\Delta I_{ds}}{\Delta V_{gs}} \frac{L^2}{C_{ox} V_{ds}} = \frac{g_m}{W V_{ds}} \frac{d_{ox}}{\varepsilon_0 \varepsilon_r} L$$

Graphene device characteristics

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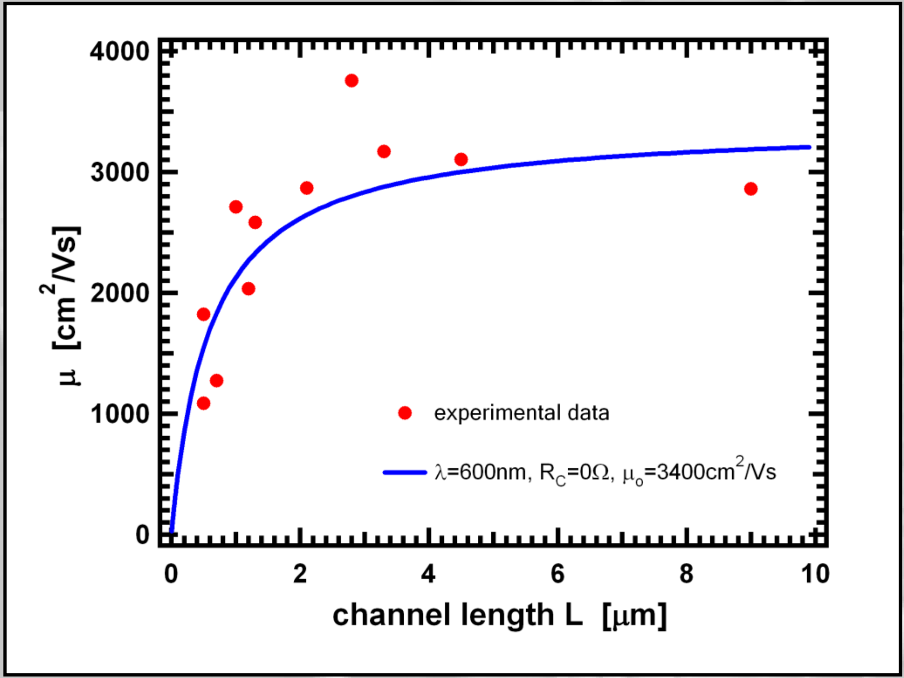
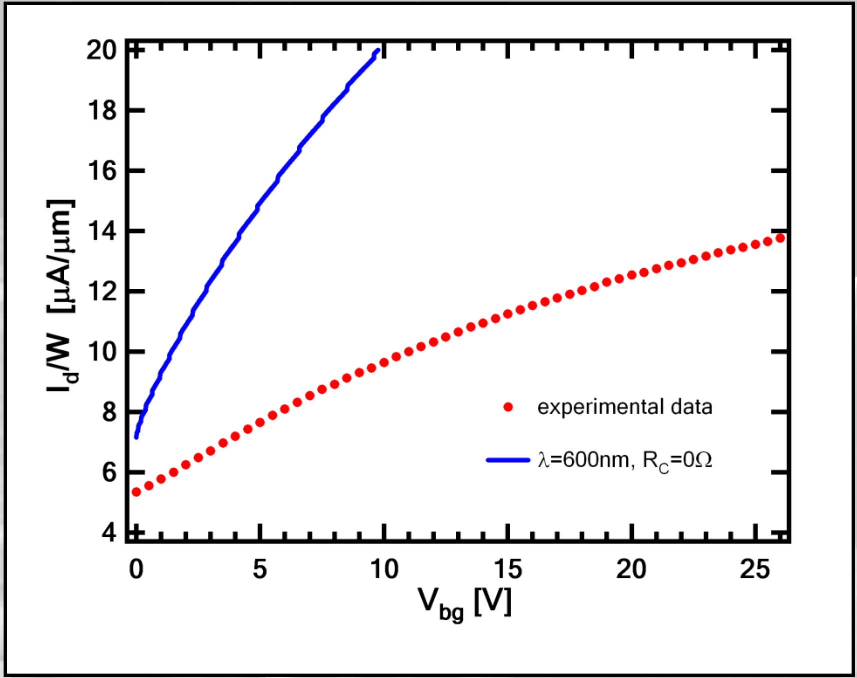
$$I = \frac{1}{L}\mu\frac{C_{ox}}{L}(V_{gs} - V_{th})V_{ds} = \frac{\lambda}{\lambda + L}\frac{C_{ox}}{L}(V_{gs} - V_{th})v_{inj}$$





$$\longrightarrow \boxed{\mu = \mu_0 \frac{L}{\lambda + L}}$$

$$I_{ball}(L \to 0) = \frac{V_{ds}}{R_{ball}} = \frac{C_{ox}}{L}(V_{gs} - V_{th})v_{inj}$$

Graphene device characteristics

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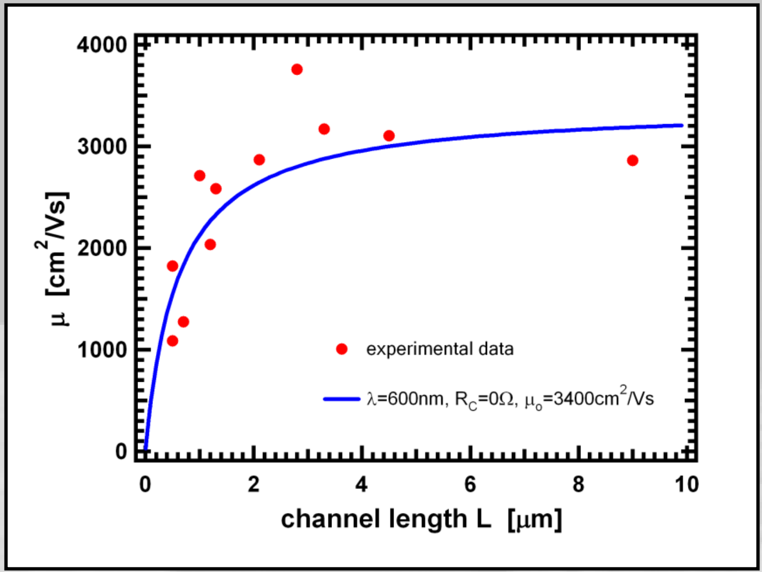
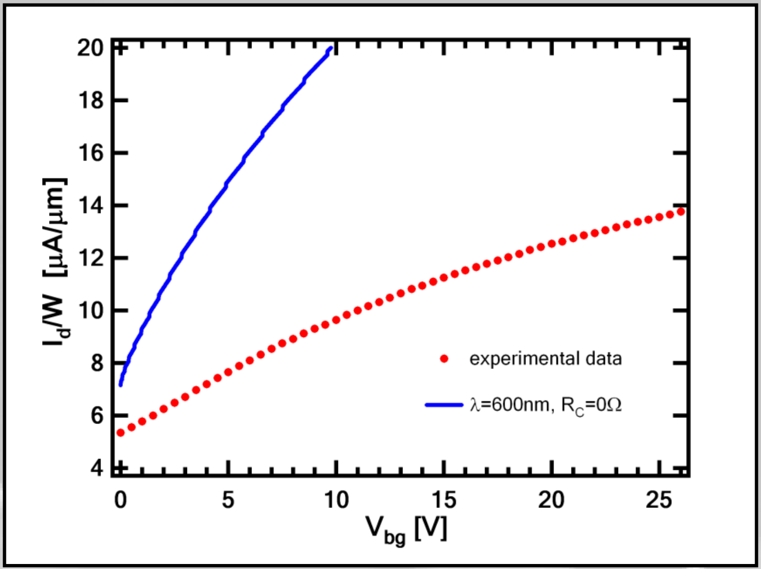
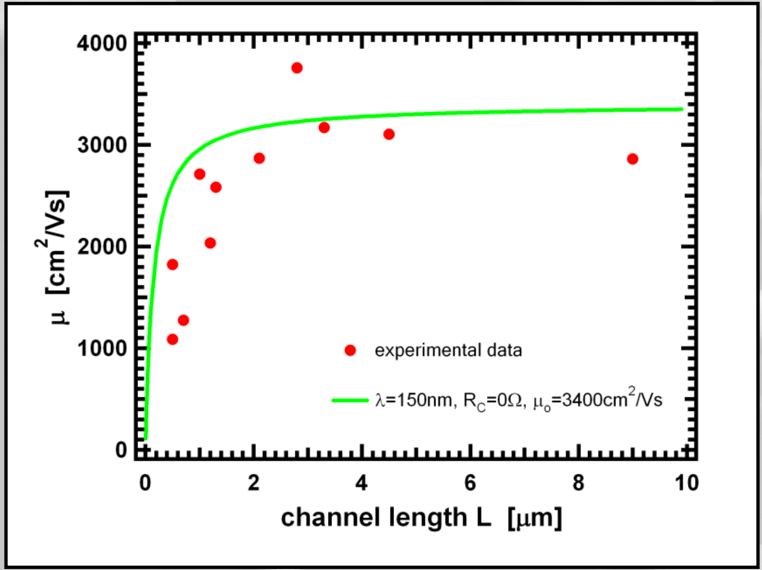
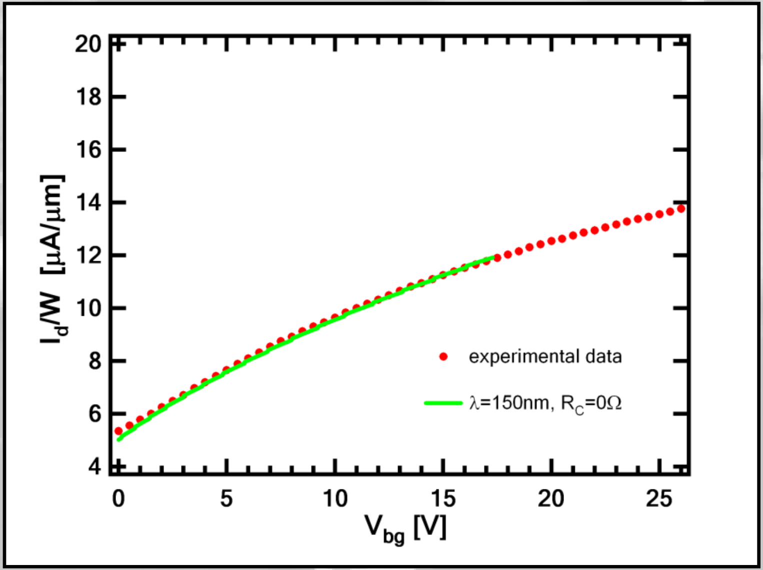




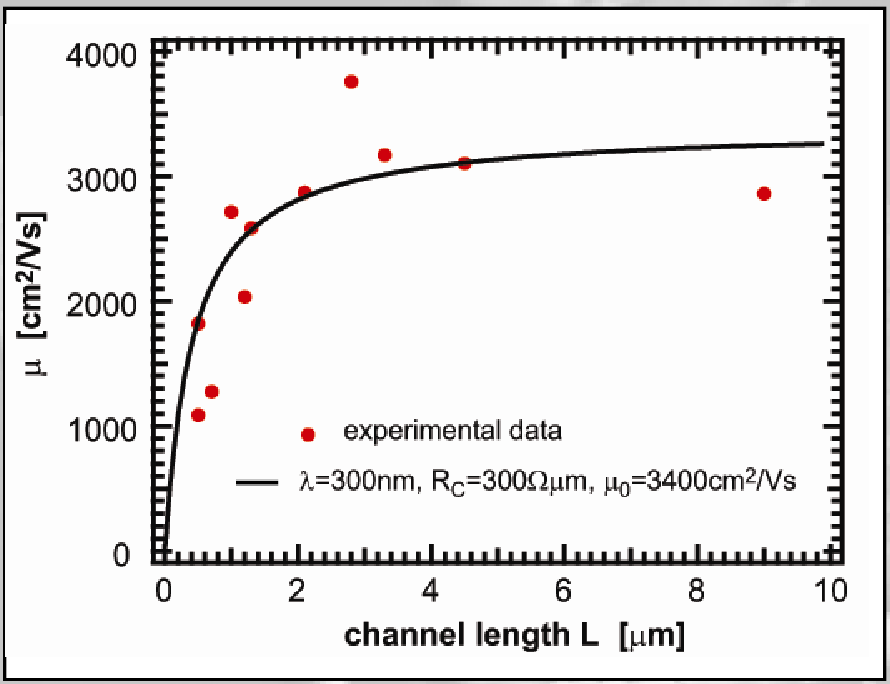


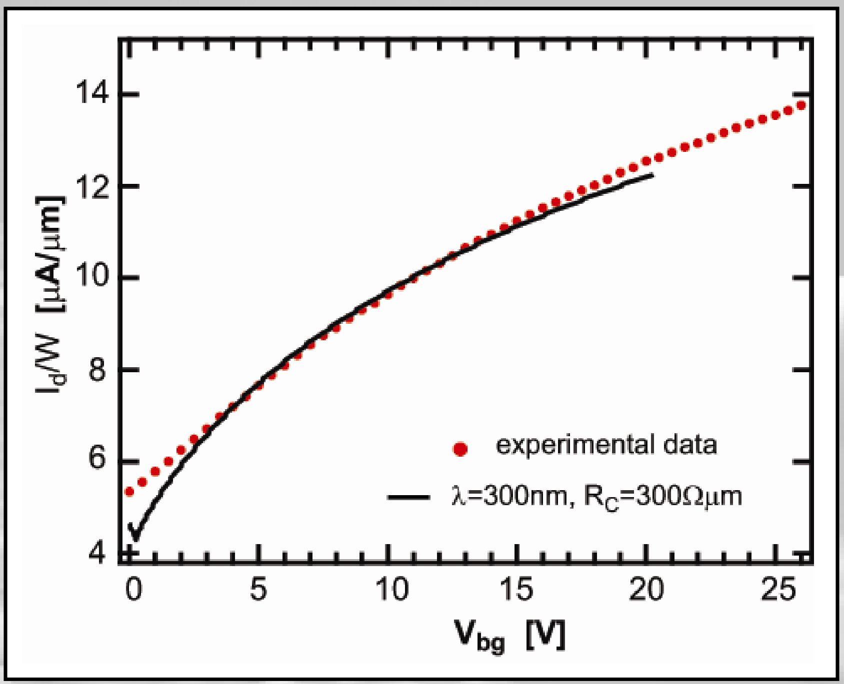


Graphene device characteristics

$$\mu = \mu_0 \frac{L}{\lambda + L} / (1 + \frac{\mu_0 a R_c}{\lambda + L})$$

$$a = \frac{\varepsilon_o \varepsilon W}{d_{ox}} (V_{gs} - V_{th})$$





$$\boxed{\lambda = 300nm \quad R_c = 300\Omega\mu m}$$

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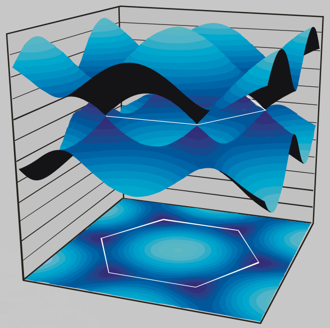
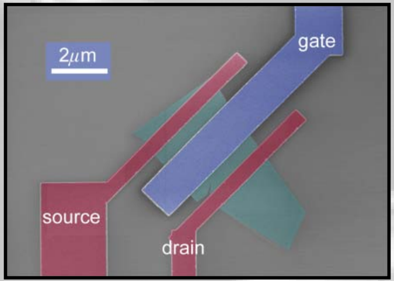
Summary

- Graphene offers a number of intrinsic materials related properties that make it particularly suited for electronic applications



- Graphene devices can operate in the quantum capacitance regime



- Contact effects need to be considered in graphene even in the absence of a bandgap