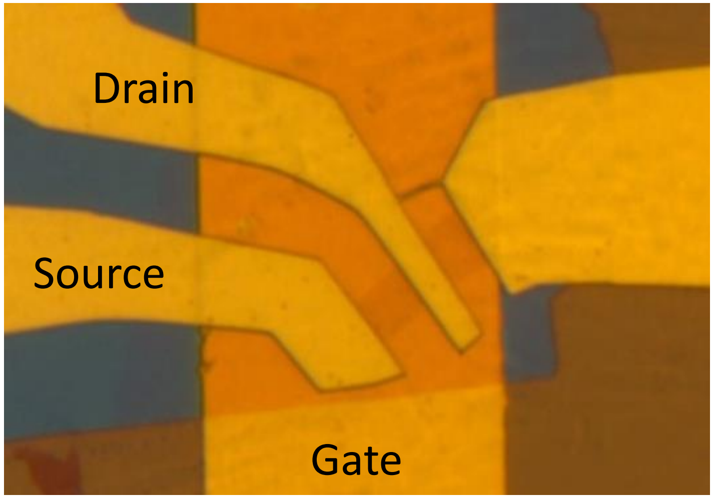
laboratoire pierre aigrain
électronique et photonique quantiques

Hyperbolic cooling of graphene Zener-Klein transistors



Wei Yang

W. Yang, S. Berthou, X. Lu[2], Q. Wilmart, A. Denis, M. Rosticher, T. Taniguchi[3], K. Watanabe[3], G. Fève, J.M. Berroir, G. Zhang[2], C. Voisin, E. Baudin, Bernard Placais

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2) Beijing National Laboratory for Condensed Matter Physics and Institute of Physics, China,
3) Advanced Materials Laboratory, National Institute for Materials Science, Tsukuba, Japan

G/BN Zener-Klein Transistor (GoBN-ZKT)

OUTLINE

- What is a G/hBN Zener-Klein transistor?
- Scattering: Current saturation in high mobility bilayer Graphene on BN
- Relaxation and Cooling : Emission of Hyperbolic Phonon Polaritons

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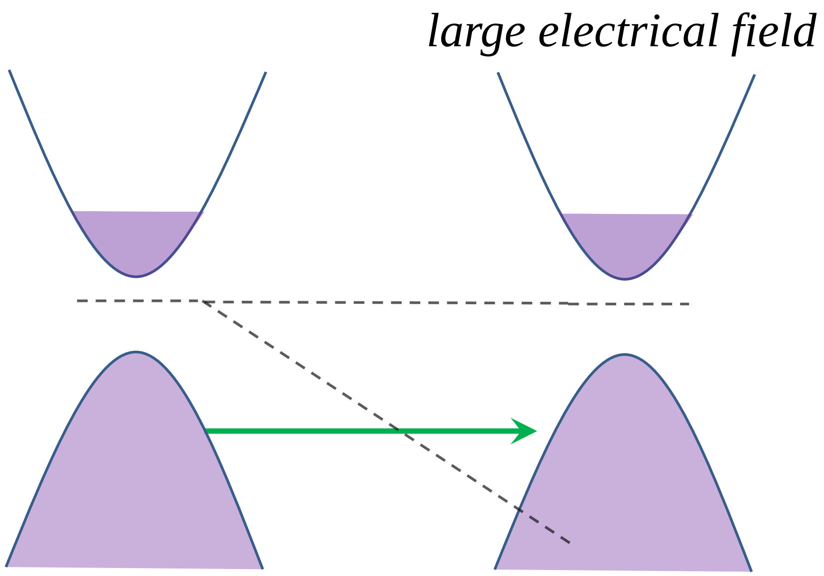
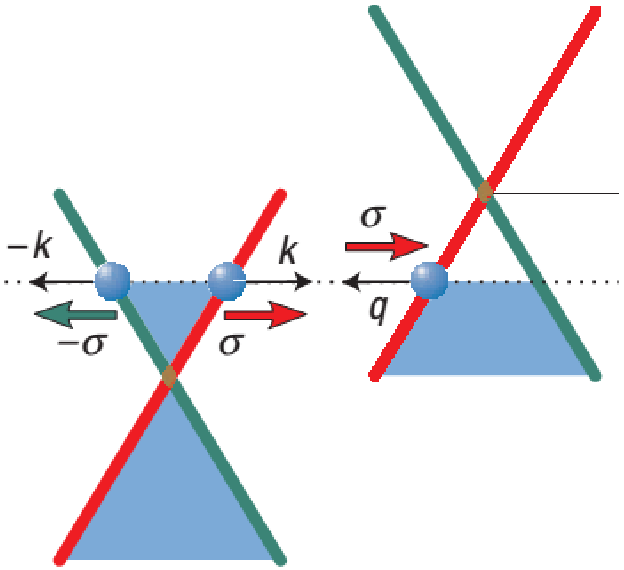
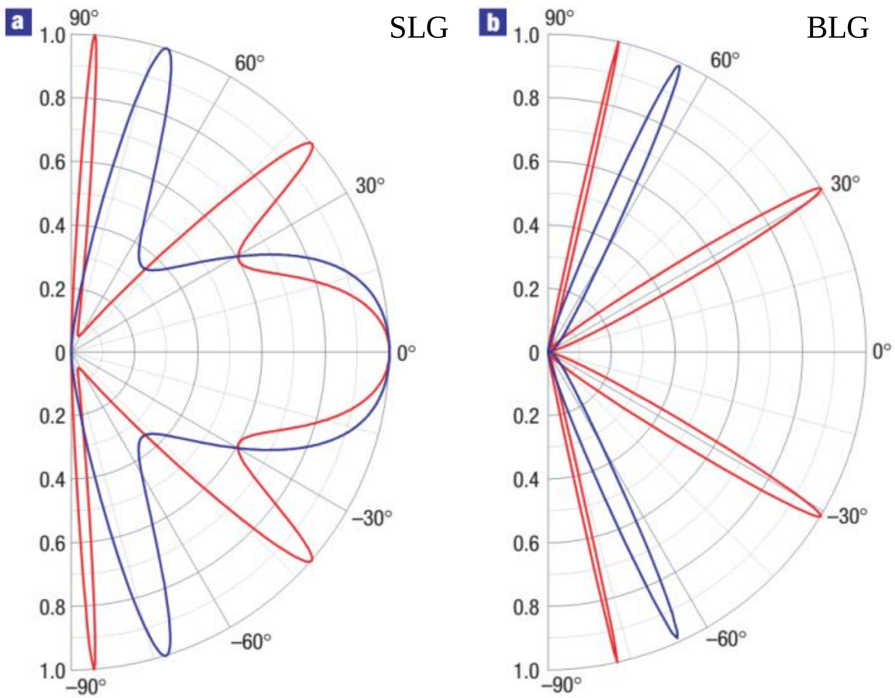
Zener Tunneling at a high electrical field



Klein tunneling





Katsnelson, Novoselov, Geim, Nat. Phys.2, 620 (2006)

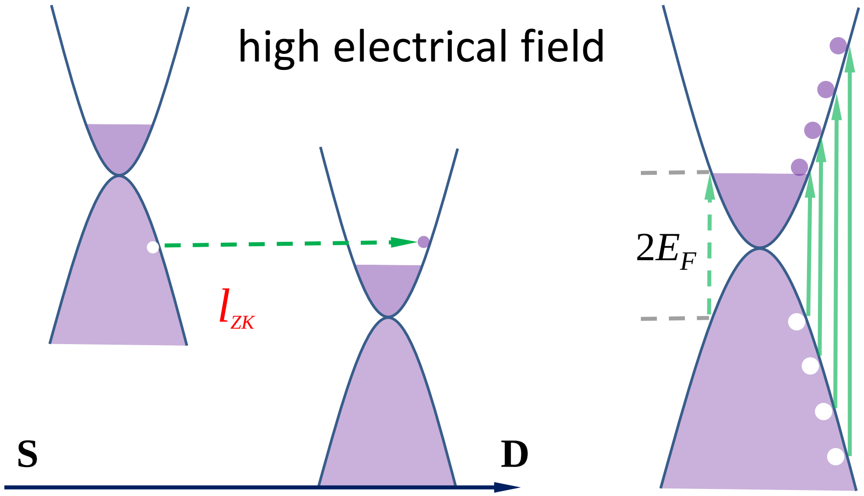
Sharp Klein p-n junction

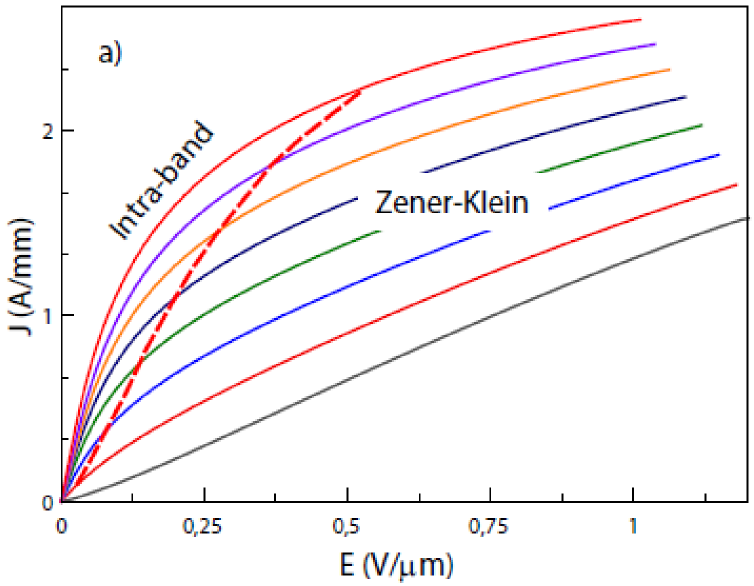
$$\sigma_{pn} = \frac{4e^2}{h} \times \frac{k_F l_{pn}}{4\pi}$$

$$\dot{n}^{pn}_{e-h} = \frac{e\, k_F}{\pi^2\, \hbar}\, E_{pn}$$

Smooth Klein p-n junction

$$\sigma_{pn} = \alpha \frac{4e^2}{h} \times \frac{k_F l_{pn}}{4\pi}\ ; \quad (\alpha \sim 0.2)$$





Zener-Klein Tunneling, Pauli blocking:

$$\sigma_{ZK} = \alpha \frac{4e^2}{h} \frac{k_F l_{ZK}}{4\pi} = Const. \quad ; \quad \dot{n}_{e-h}^{ZK} = \frac{e\, k_F}{\pi^2\, \hbar} (E - E_{ZK})$$

$$E_{zk} = {}^{2E_F}\!/_{e l_{zk}}$$ (dashed line)

GoBN ZKT is a graphene/hBN transistor operating at a high electrical field where interband Zener-Klein tunneling dominating the transport

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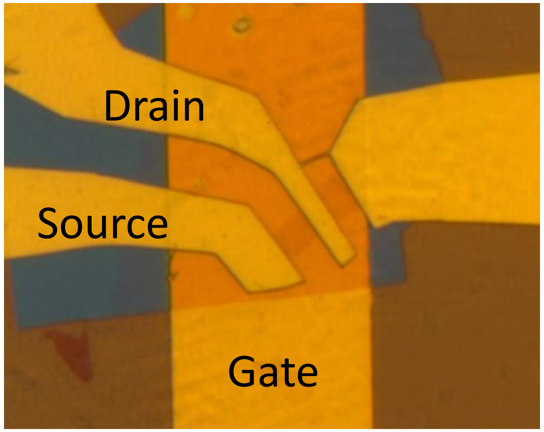
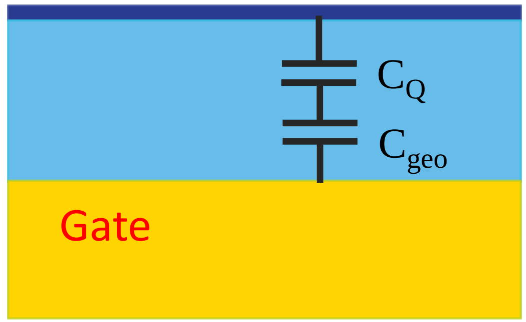
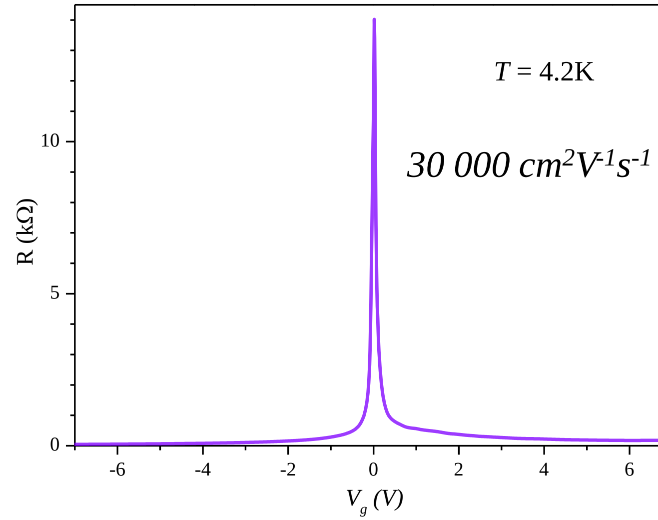
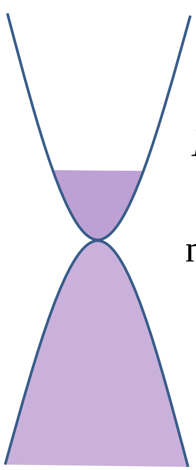
Characteristic of the GoBN ZKT device



BL-Graphene



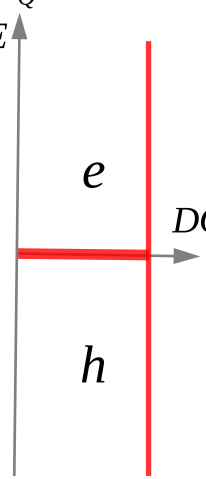


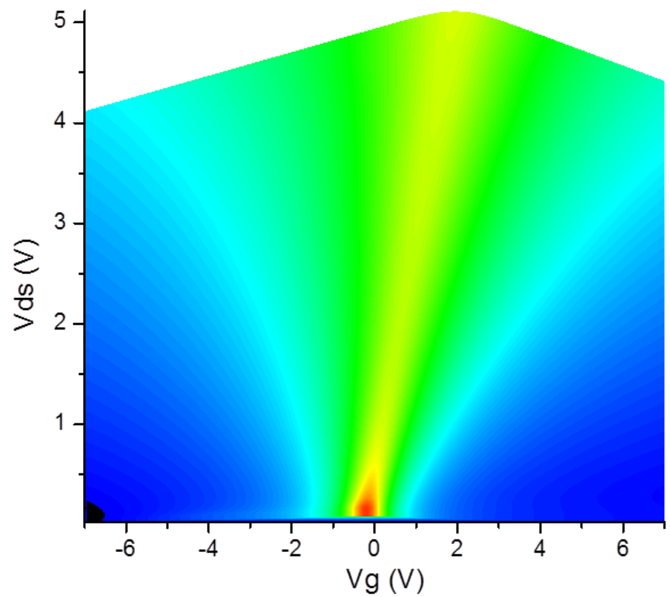


$$E = \frac{\hbar^2 k^2}{2m^*}$$

$m^* \sim 0.03 m_e$

$C_Q \sim 40$ mF/m²

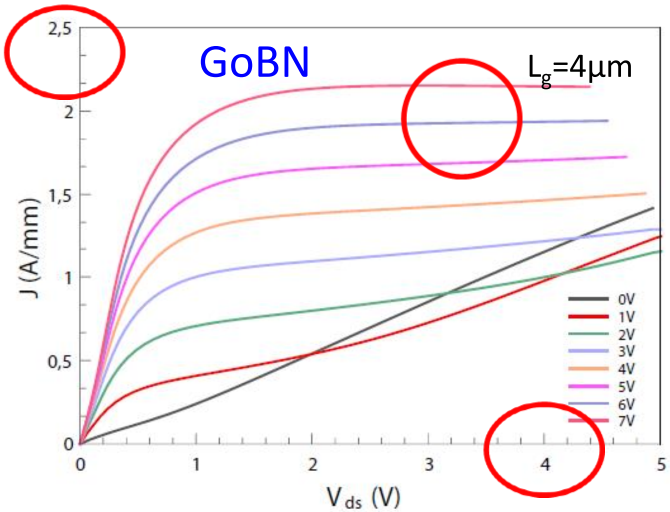




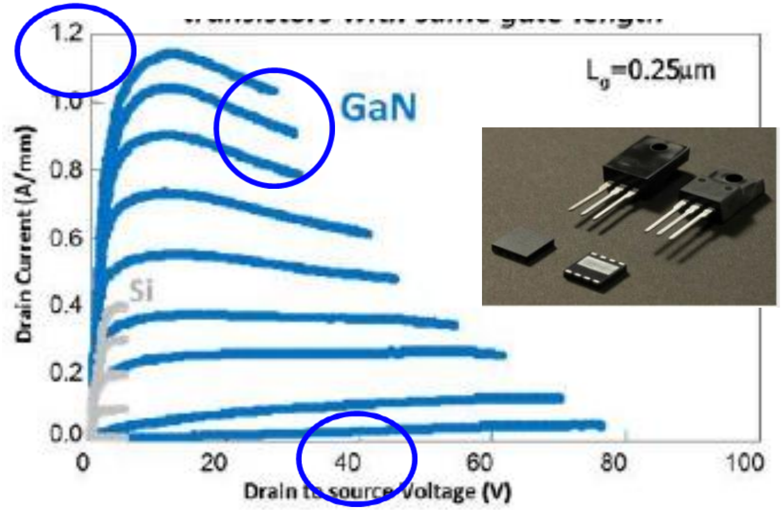
Bias is gating

Comparison with GaN or Si transistors

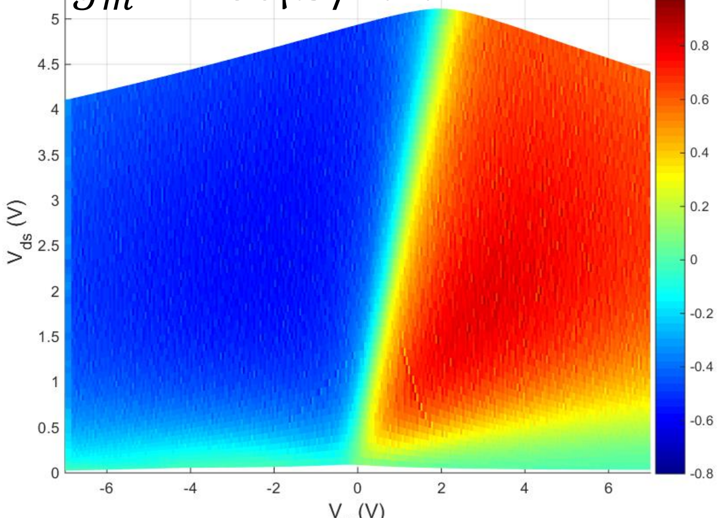
GoBN Zener-Klein transistor



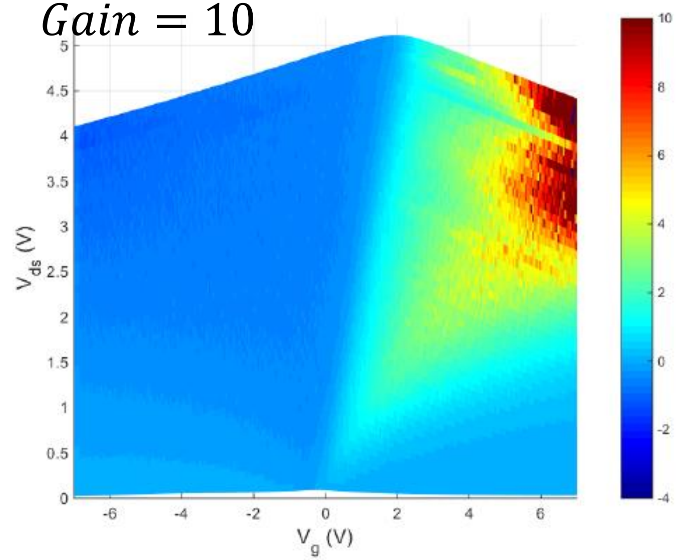
Panasonic : X-GaN Power transistor



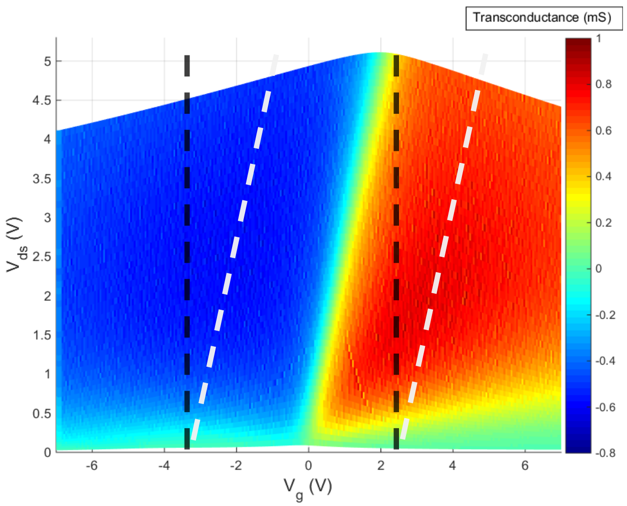
$g_m = 250\mu S/mm$



$Gain = 10$

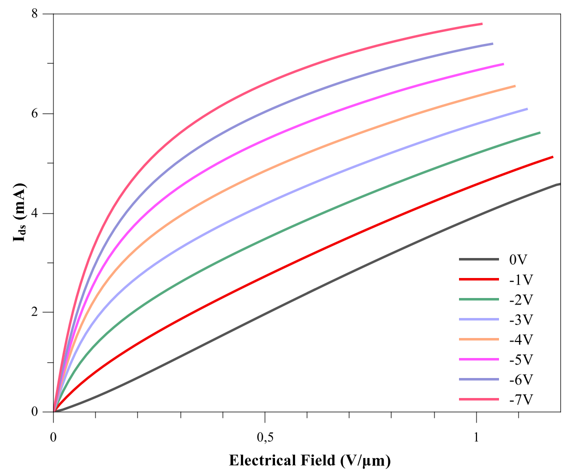


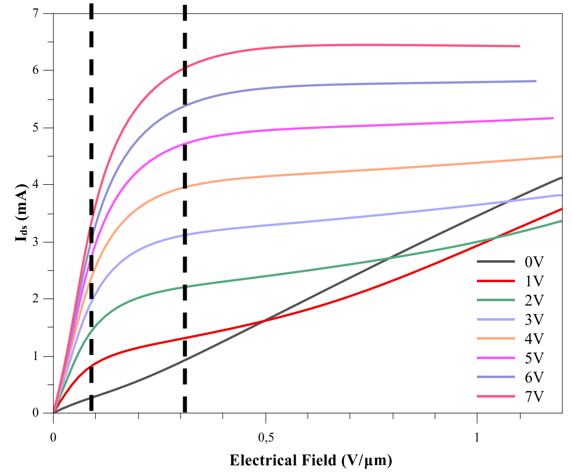
I-V characteristics



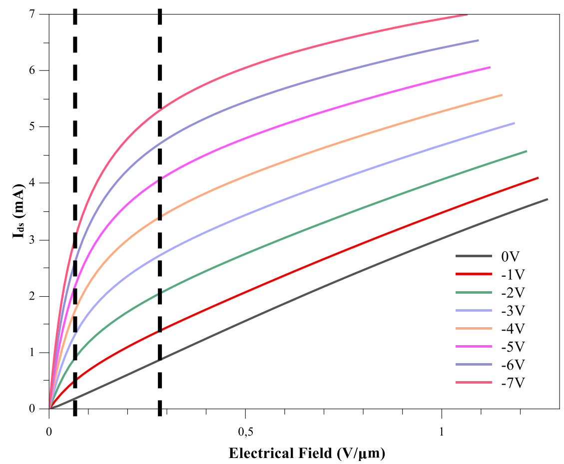
$$J = ne\mu\mathcal{E}/(1+\mu\mathcal{E}/v_{sat}) + \sigma_{ZK}\mathcal{E}$$

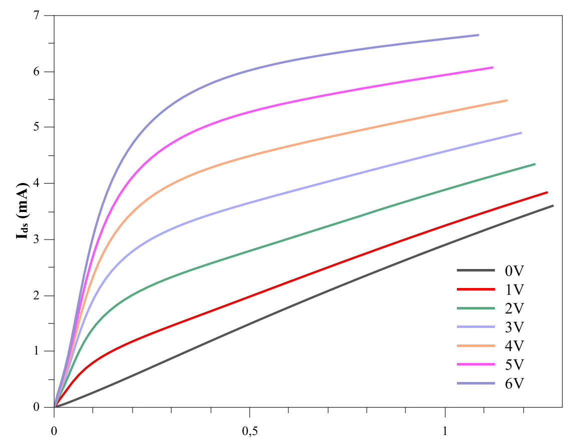
Constant gate





Constant carrier density



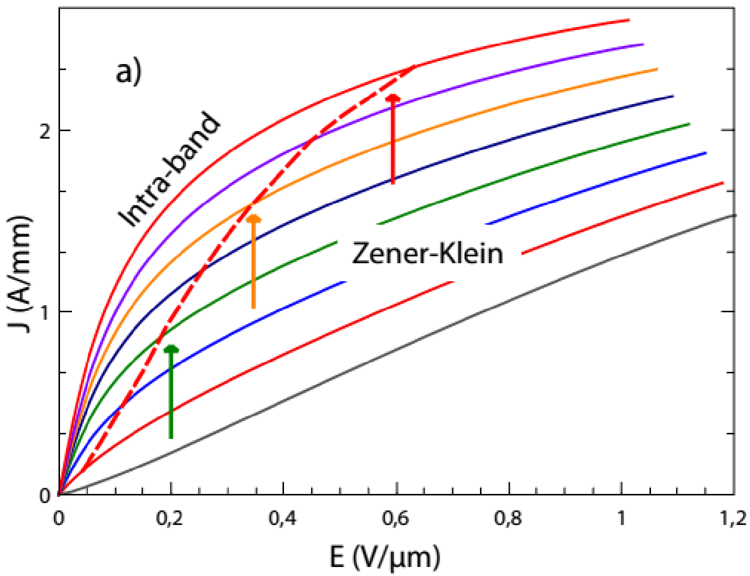


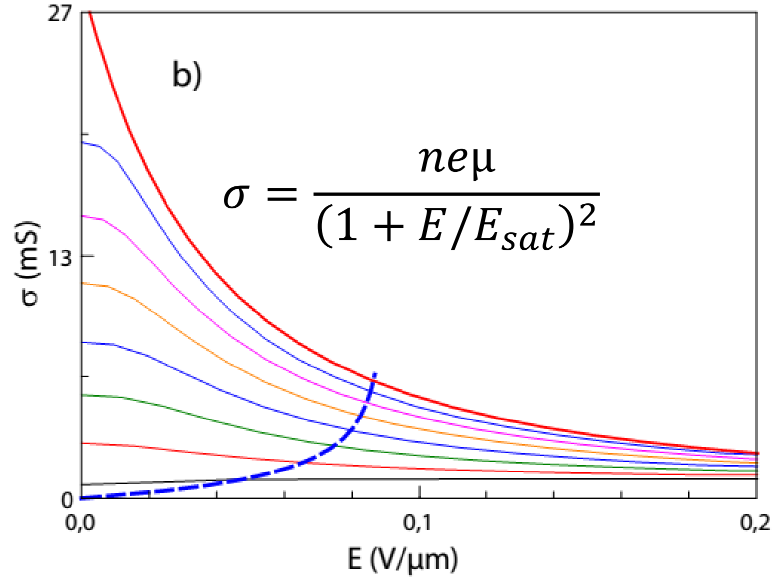
Impurity scattering

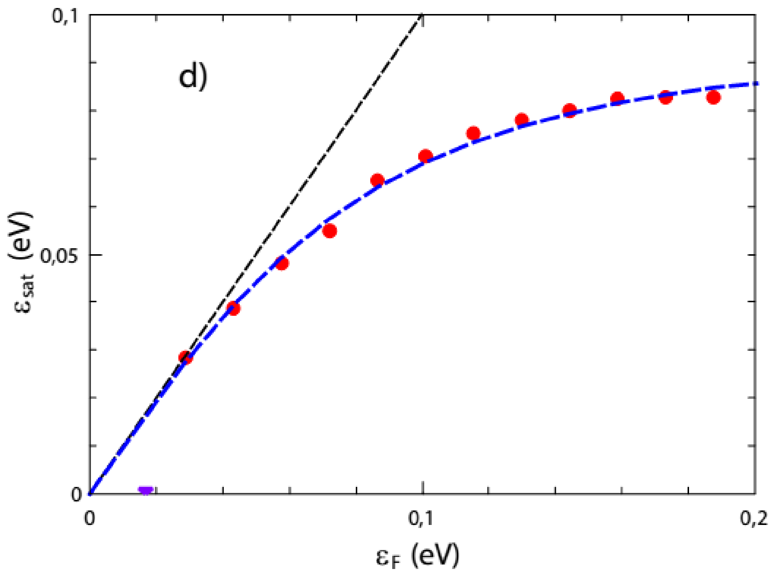
Optical phonon scattering

Zener-Klein tunneling

Focus on current saturation at low field







Saturation energy ε_{sat}

E_F at a low doping

100meV at a high doping

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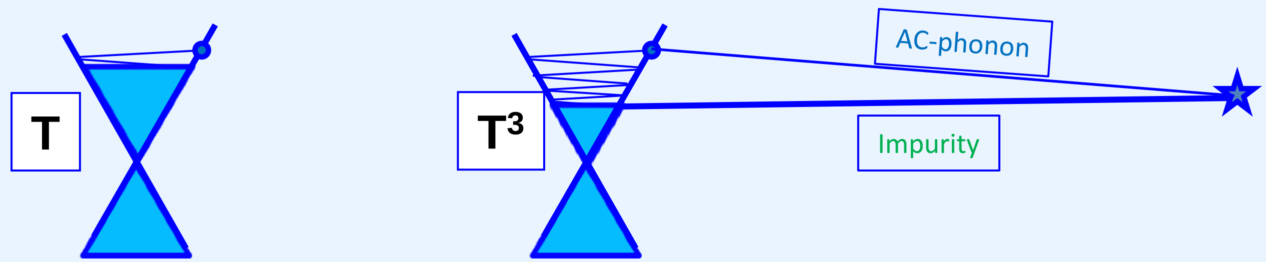
Relaxation in Graphene

1. e-e interactions → electron multiplication and thermalisation

   ($\tau \sim 20\ fs$) + heat conduction : $\mathrm{div}(-\kappa \nabla T) = -E.J$, $\kappa = \left(\frac{\pi^2 k_B^3}{3e^2}\right) \sigma\, T$

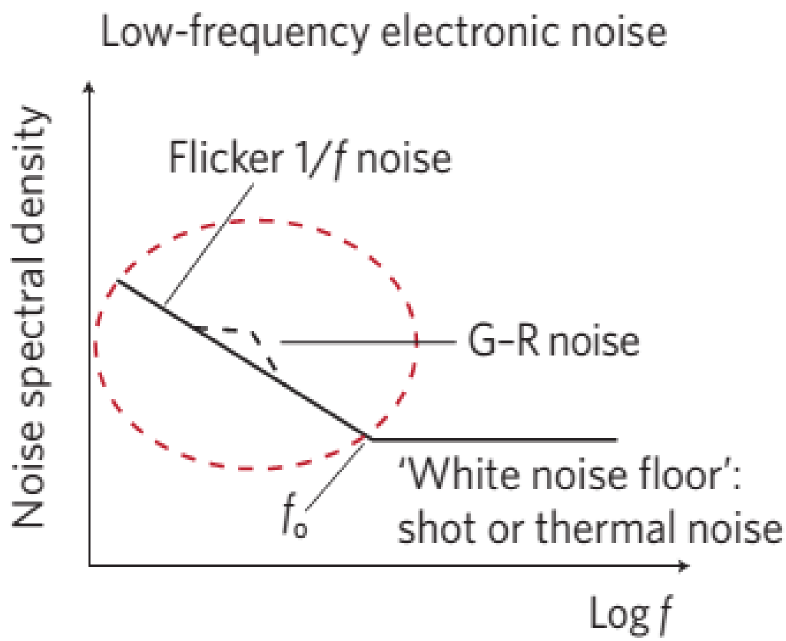
2. e-AC-imp supercollisions → prominent in diffusive G but suppressed in G/BN
3. e-OP interaction → deformation potential coupling ($\tau \geq 2\ ps$)
4. e-HPP interaction → fast ($\tau \approx 200\ fs$)!!

Ordinary electron-phonon collision | 3-body electron-phonon-impurity supercollisions

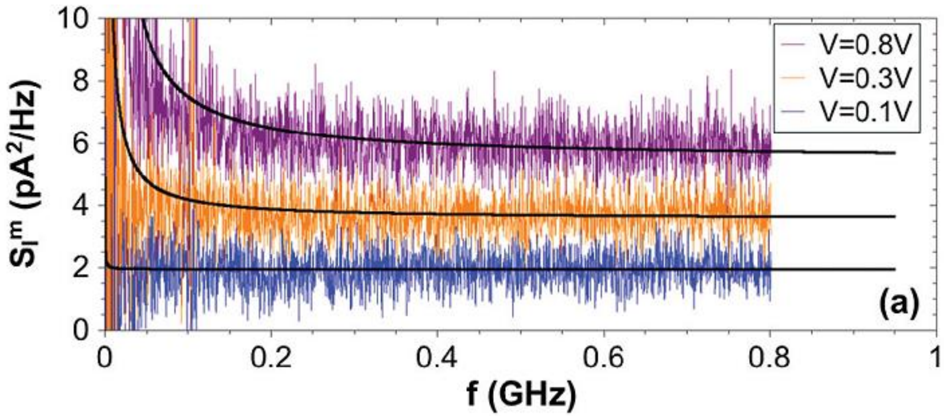


A. Betz et al. / Phys. Rev. Lett. 109 (2012) 056805; A. Betz et al. / Nat. Phys. 9 (2013) 109

Noise in graphene transistor



Alexander A. Balandin, Nat. Nano. ***8****, 549 (2013).*



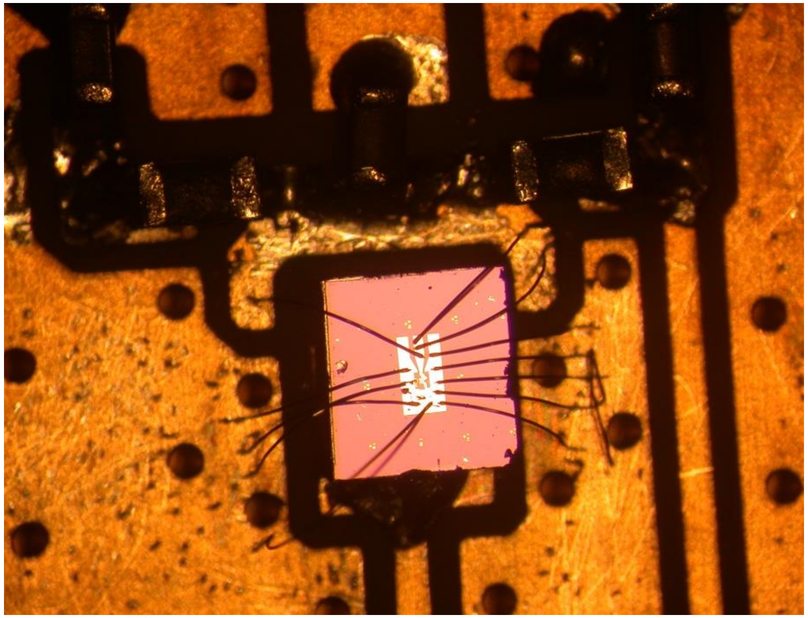
A. Betz et al. PRL.109,056805 (2012).

$$S_{total} = \alpha_H V^2/\,N f + \boxed{S_V}$$

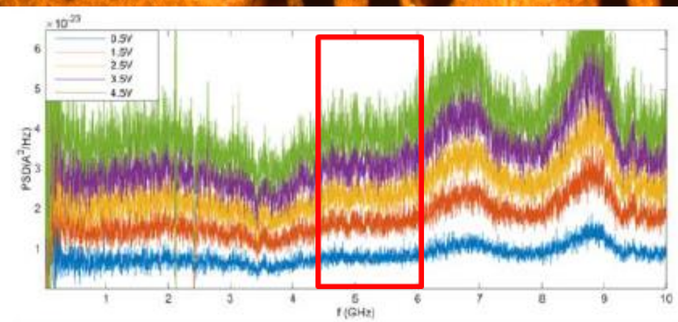
thermal noise

The bandwidth of Noise spectra in GHz range

RF noise thermometry principles



b



Bath temperature $T_0 = 4.2\ K$

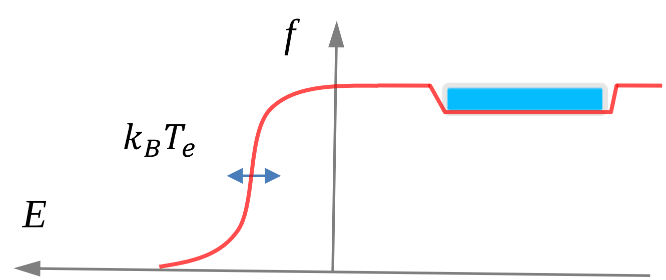
Noise temperature $k_B T_N \equiv S_I / 4G_{diff}$

Hot electrons, heat equation, Wiedemann-Frantz

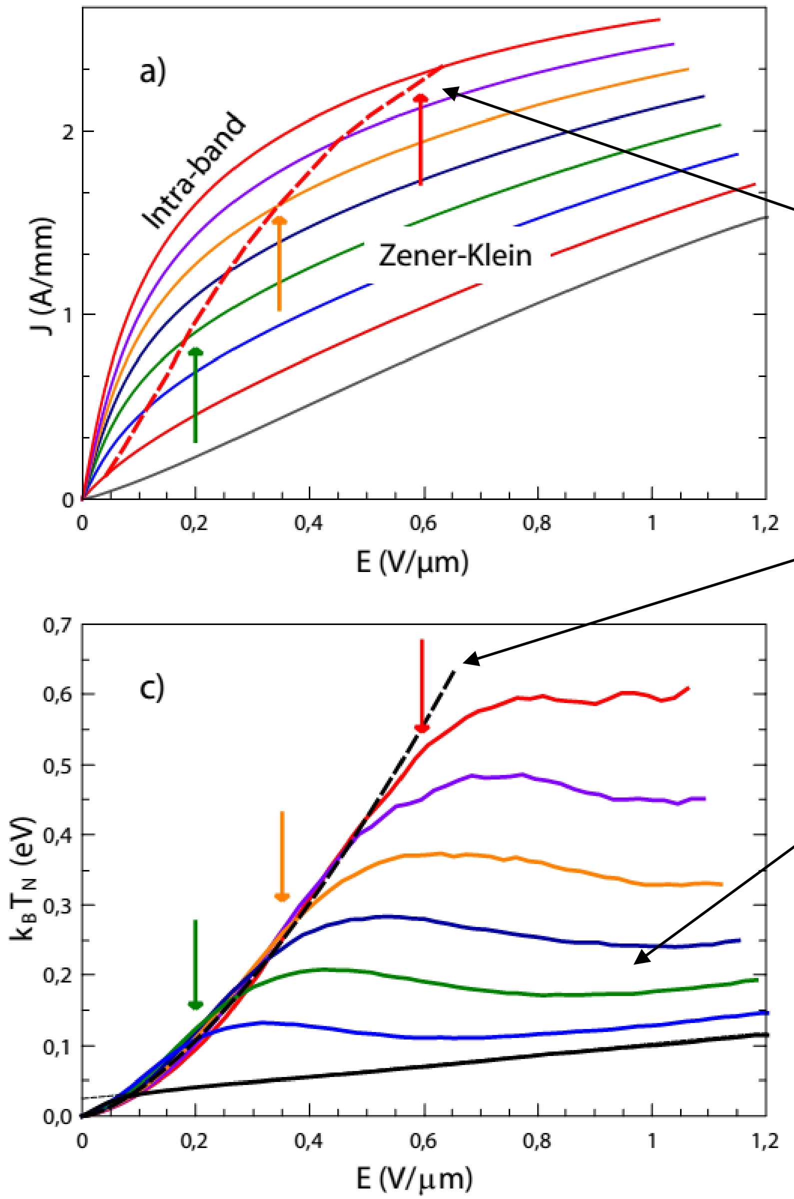
$$k_B T_N \equiv \langle k_B T_e \rangle = \frac{\sqrt{3}}{8} \times\ Length\ \times \sqrt{P/\sigma}$$

Hot Fermi sea + holes

$$k_B T_N = \int_{-\infty}^{\infty} f(1-f)dE \approx k_B T_e + \frac{\boldsymbol{n_h}}{DOS}$$



What do we learn from noise ?

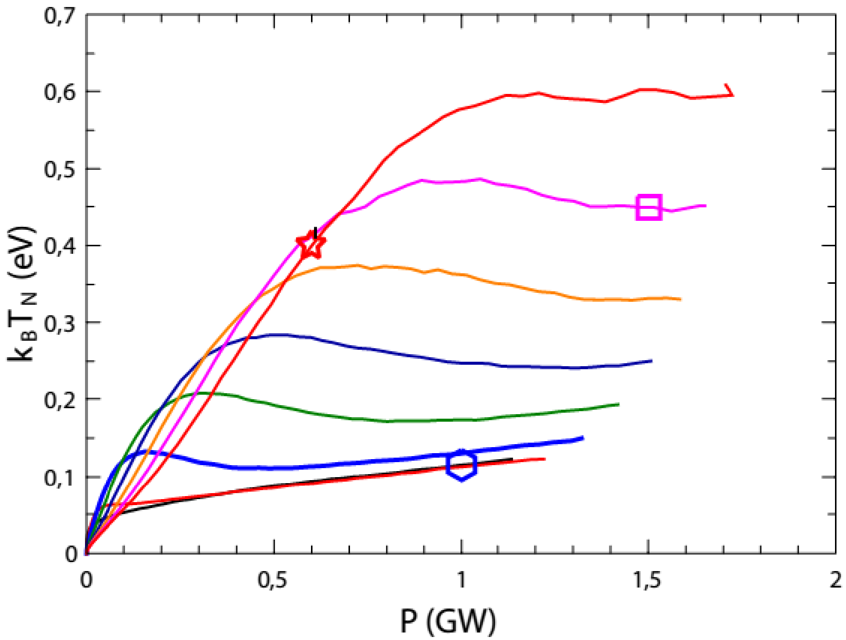


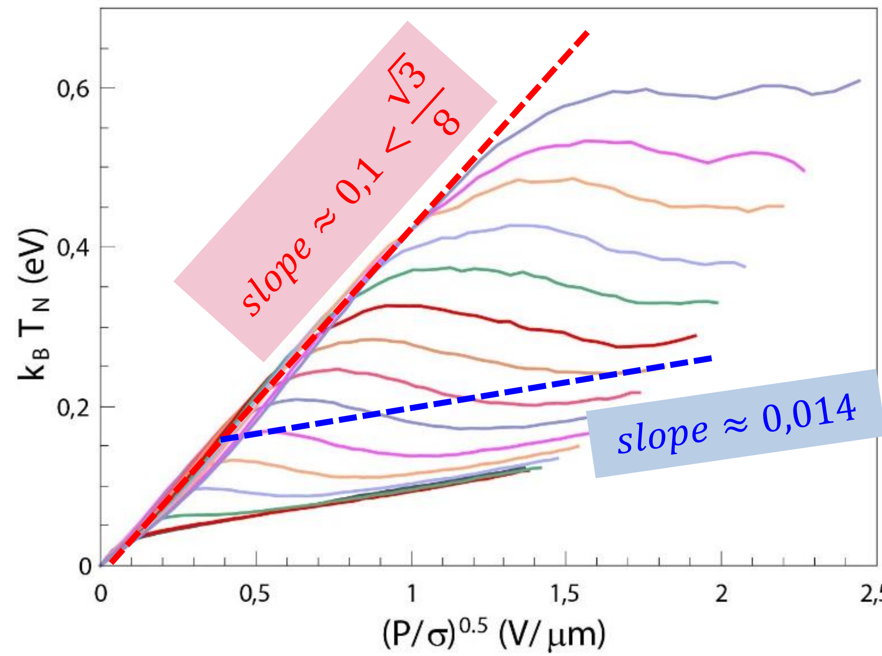
Discontinuity in $k_BT_N[E]$ at $E \approx E_{zk}$

Superlinear $k_BT_N[E]$ for $E \leq E_{zk}$

Quasi-plateaus $k_BT_N[E]$ for $E \geq E_{zk}$

Hot electron analysis of noise





« hot » electron dashed line : $k_B T_N[E \leq E_{zk}] \approx \frac{F}{2} L\sqrt{P/\sigma}$

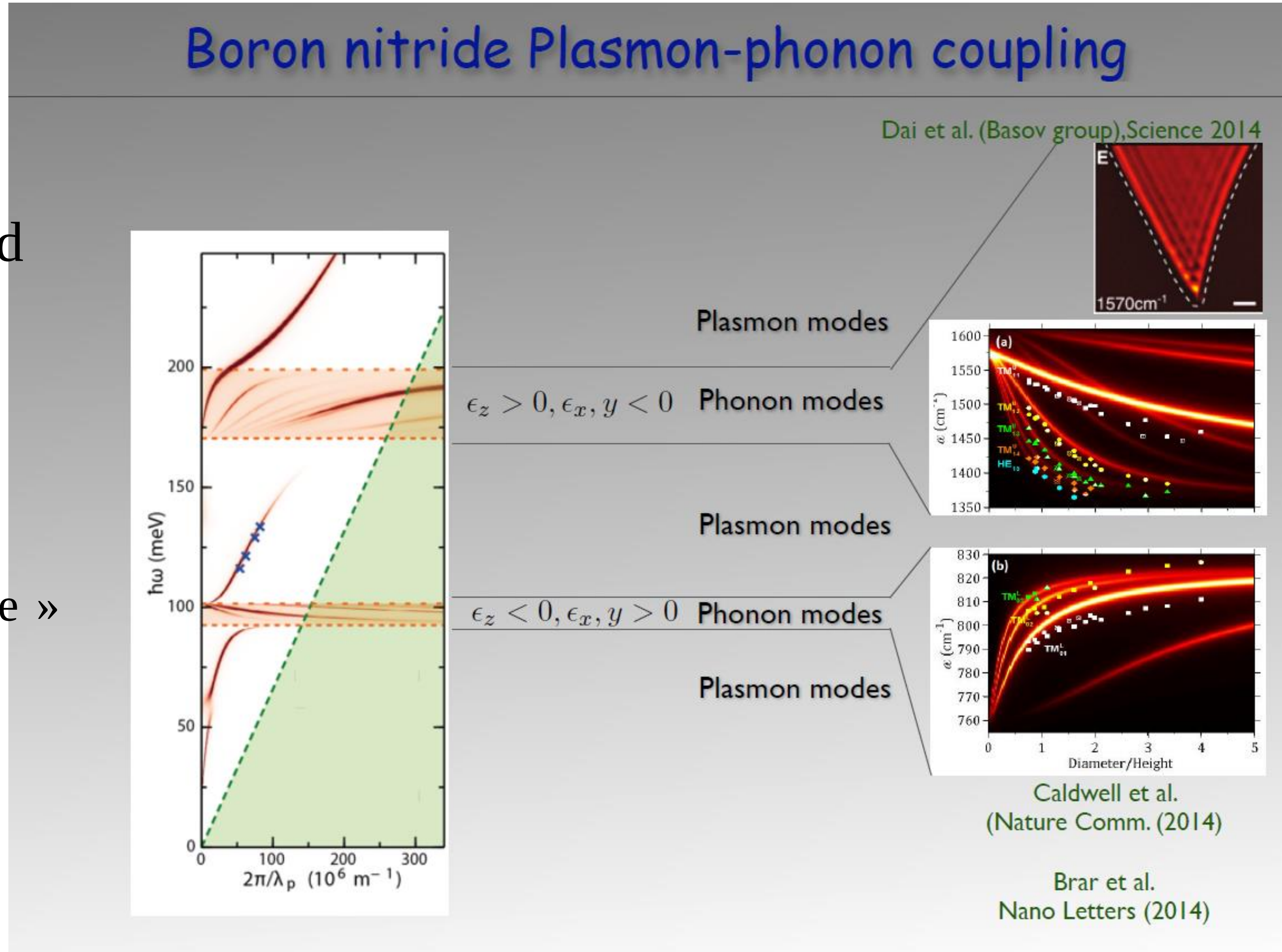
« cold » electron dashed line : $k_B T_N[E \geq E_{zk}] \approx k_B T_e[E_{zk}] + \frac{F}{14} L\sqrt{P/\sigma}$

Hyperbolic Phonon Polaritons of h-BN ?

Reststrahlen band

Type-II « in-plane »
~170-200meV

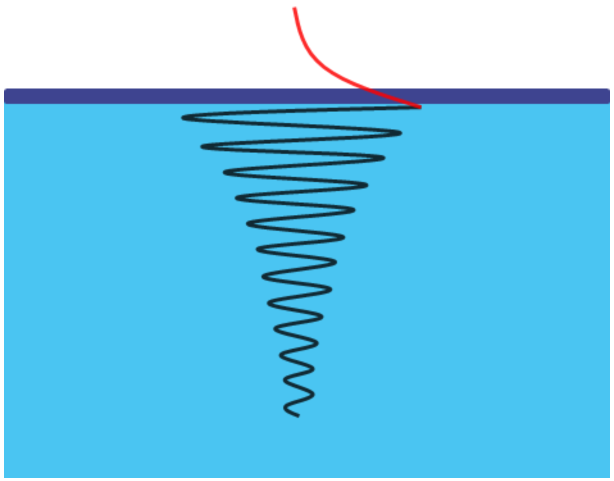
Type-I « out-of-plane »
~90-100meV



(Courtesy of F. Koppens, Kaprun School 2015)

Superplanck HPP cooling of Graphene

HPPs are propagative modes



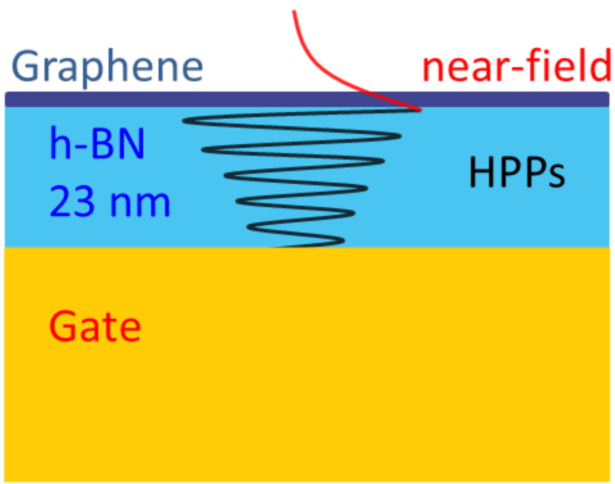
Graphene/HPP impedance matching

$$P = \frac{n}{4\pi^2} \frac{\hbar\omega\Delta\omega}{\exp[\hbar\omega/k_B T] - 1} \times M$$

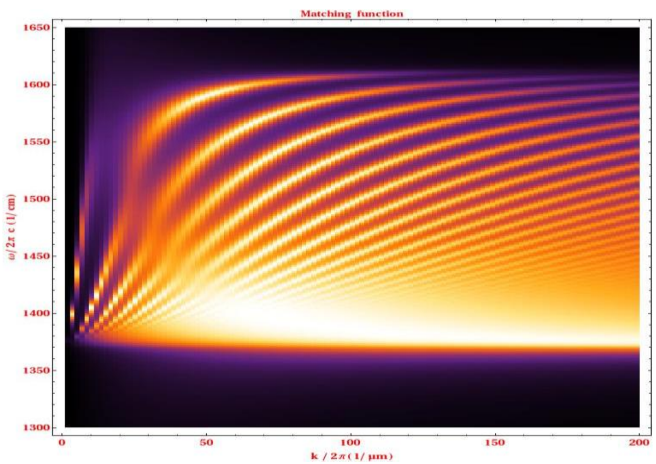
$$M = \left[\frac{4\, \Re \boldsymbol{Y_0}(\boldsymbol{\omega}, \boldsymbol{q}) \Re \boldsymbol{\sigma}(\boldsymbol{\omega}, \boldsymbol{q})}{|\boldsymbol{Y_0} + \boldsymbol{\sigma}|^2}\right]$$

Semi-infinite h-BN : $\boldsymbol{Y_0} \sim \mathbf{40}\mu \boldsymbol{S}$ (M~0.01)

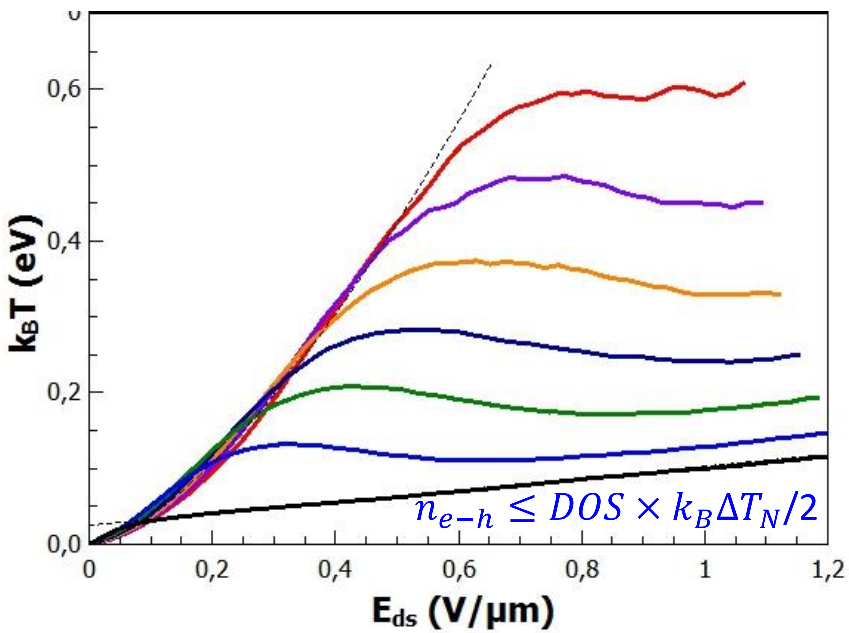
Confined HPPs : $\boldsymbol{Y_0}(\boldsymbol{\omega}, \boldsymbol{q}) \sim \boldsymbol{Q} \times \mathbf{40}\mu \boldsymbol{S}$ $(\langle M \rangle \sim 0.1)$



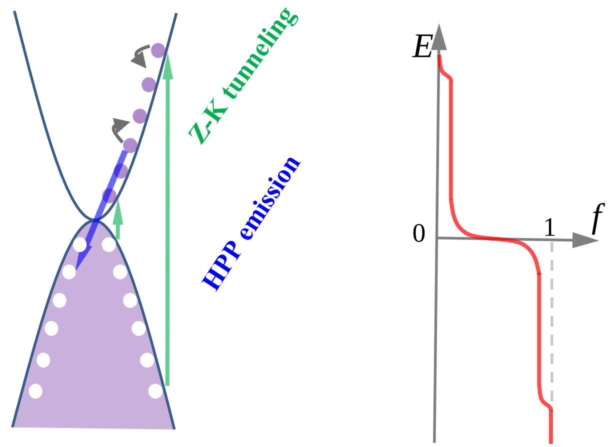
⇒



HPP relaxation time



ZK+HPP at charge neutrality

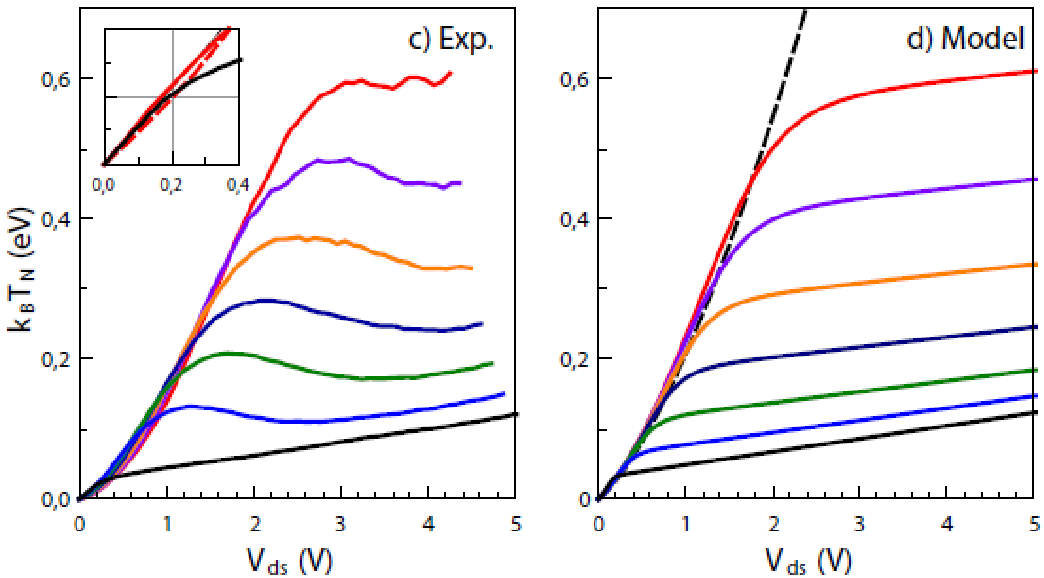


e-h pumping : $\dot{n}_{e-h}^{ZK} = \frac{e\,k_F}{\pi^2\,\hbar}(E - E_{ZK}) = \frac{n_{e-h}}{\tau_{HPP}}$ $\Rightarrow$ $\tau_{HPP} = \frac{\pi^2\,\hbar}{e\,k_F}\frac{dn_{e-h}}{dE}$

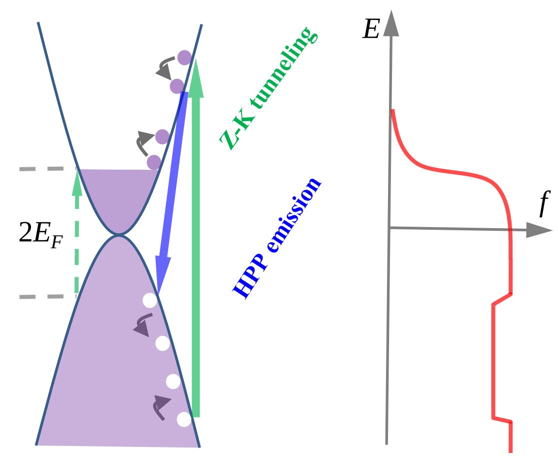
Noise temperature « Cold electron regime » $n_{e-h} \leq DOS \times k_B \Delta T_N/2$

$$\tau_{HPP} \leq \frac{\pi^2\,\hbar}{e\,k_F}\,DOS\,\frac{dk_B T_N}{dE} = 0.46\,ps \qquad (n = 1.10^{12})$$

HPP cooling in the ZK regime



HPP cooling doped regime



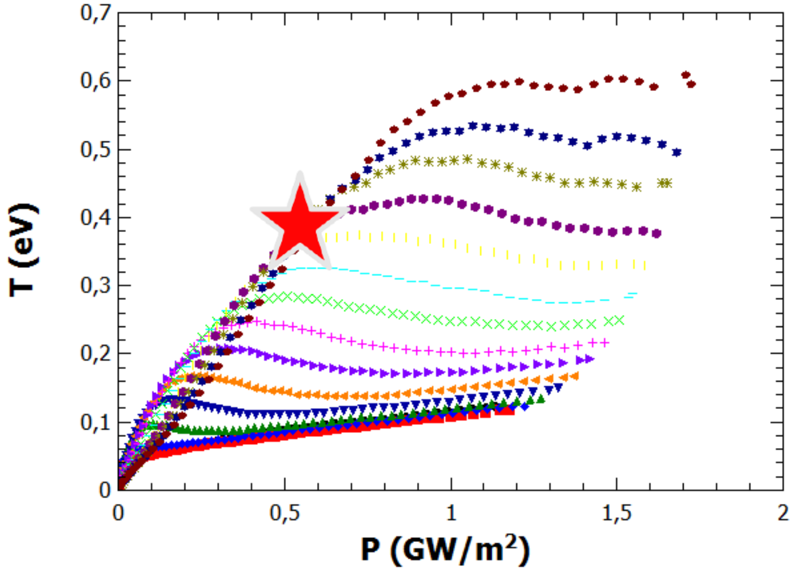
ZK current : $J_{zk} = \alpha \left(\frac{4e^2}{h}\frac{k_F l_{zk}}{4\pi}\right)(E - E_{zk})$ ZK pumping : $\dot{n}_{e-h}^{ZK} = \frac{e\,k_F}{\pi^2\,\hbar}(E - E_{ZK})$

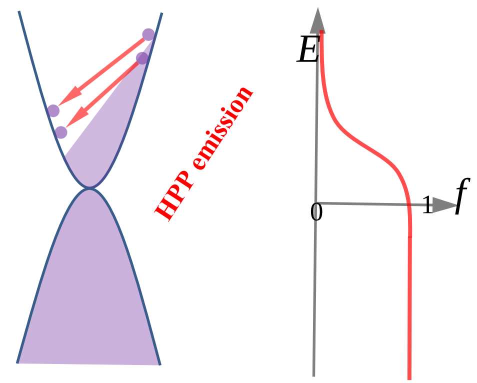
HPP cooling : $P_{HPP} = \hbar\Omega\,\dot{n}_{e-h}^{HPP} = \hbar\Omega\,\dot{n}_{e-h}^{ZK} = \hbar\Omega\frac{e\,k_F}{\pi^2\,\hbar}(E - E_{zk})$

Joule Heating : $\Delta P_{Joule} = J_{sat}(E - E_{zk}) = \boldsymbol{2\varepsilon_{sat}}\frac{e\,k_F}{\pi^2\,\hbar}(E - E_{zk})$

in GoBN, where $\hbar\Omega_{II} \approx 2\hbar\Omega_I \approx 200\ meV \Rightarrow \boldsymbol{P_{HPP} \approx P_{Joule}}$

HPP cooling of hot electrons





<u>Super-Planck HPP thermal emission</u> ($\sigma_{hot}(\omega, q)$ by Polini at al.)

$$P_J = 0.5\,\frac{GW}{m^2},\ kT = 0{,}4eV,\ \ n_e = 4\ 10^{12}$$

★ $$P_{HPP}^{th} = 2.4 \times M\ \frac{GW}{m^2} = 0{,}24\ \frac{GW}{m^2} = P_J/2 = P_{WF} \qquad by\ taking \quad M^{th} \approx 0.1$$

Conclusions

- *G/BN ZKT-Transistors are performant*
- *HPP-I is responsible for current saturation*
- *HPP-II s give rise to hyper-Plank cooling in the ZKT regime*

Thanks very much for your attention