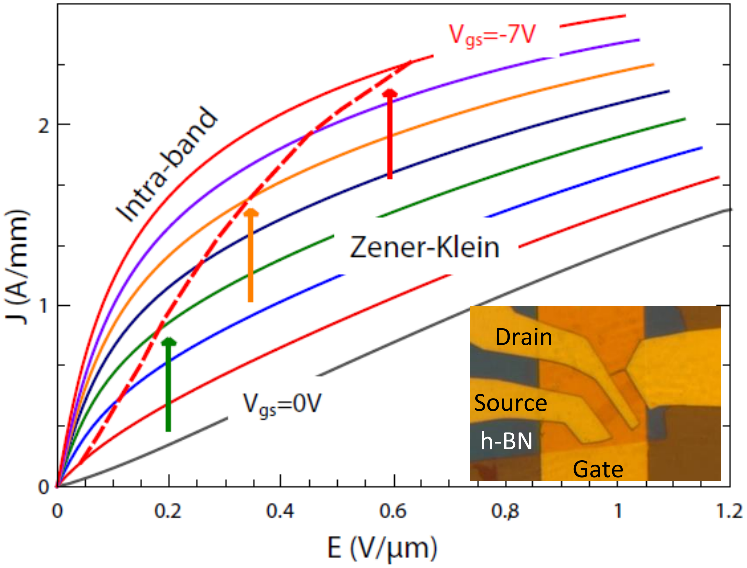
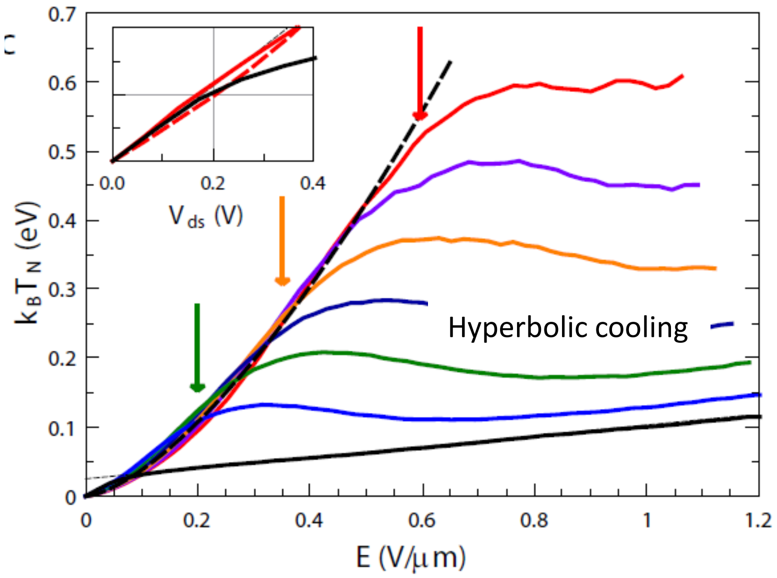
Hyperbolic cooling of graphene Zener-Klein transistors

Transport ***PLUS*** *Noise thermometry*





W. Yang, S. Berthou, X. Lu, Q. Wilmart, A. Denis, M. Rosticher, T. Taniguchi, K. Watanabe, G. Fève, J.M. Berroir, G. Zhang, C. Voisin, E. Baudin, and B. Plaçais

Noise thermometry brings new information

on scattering and relaxation of graphene carriers.

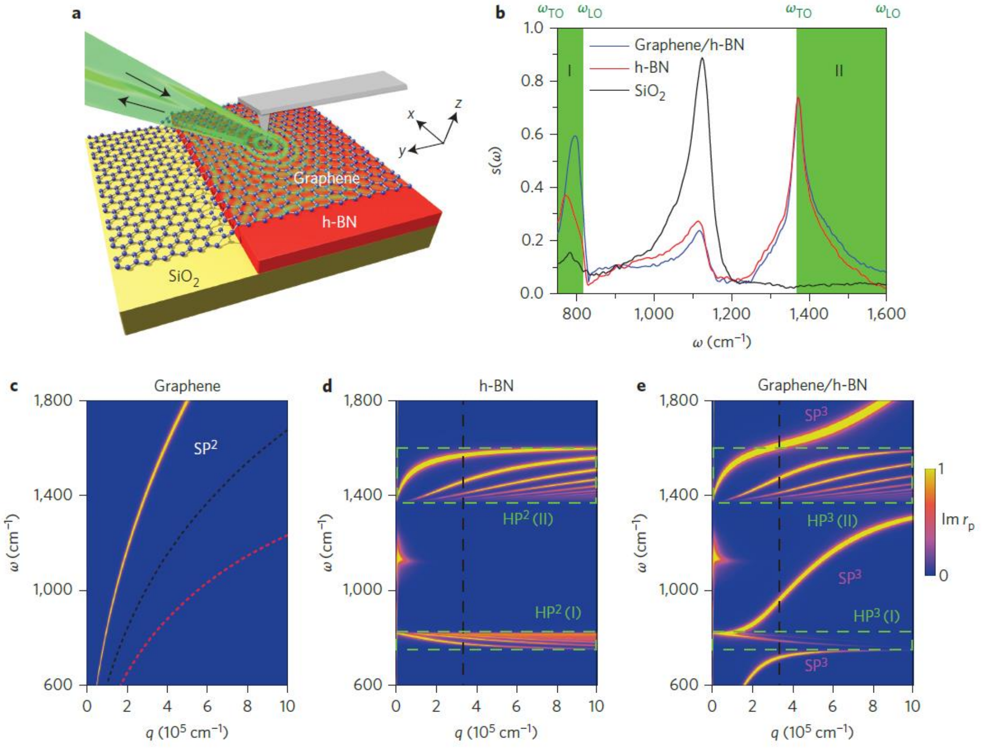
Current saturation regime is investigated here

Introduction

Hyberbolic Phonon Polaritons of uniaxial hBN

Graphene on hexagonal boron nitride as a tunable hyperbolic metamaterial

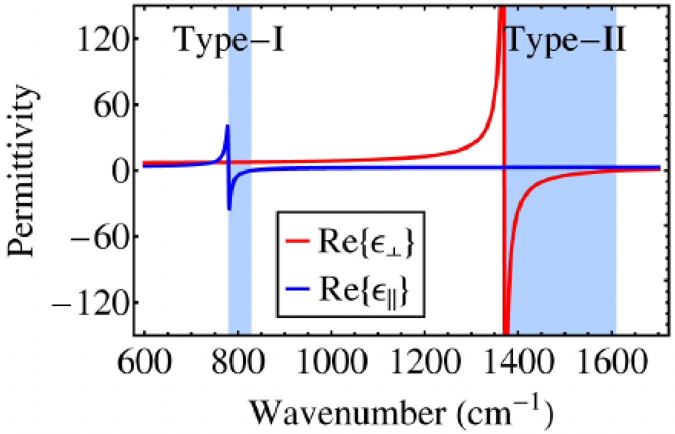
S. Dai[1], Q. Ma[2], M. K. Liu[1,3], T. Andersen[2], Z. Fei[1], M. D. Goldflam[1], M. Wagner[1], K. Watanabe[4], T. Taniguchi[4], M. Thiemens[5], F. Keilmann[6], G. C. A. M. Janssen[7], S-E. Zhu[7], P. Jarillo-Herrero[2], M. M. Fogler[1] and D. N. Basov[1]*



Dai et al. Nat. Nano. 2015

Caldwell et al. Nat Comm. 2014 ; Brar et al., Nano Letters 2014 ; .....

Propagating HPPs

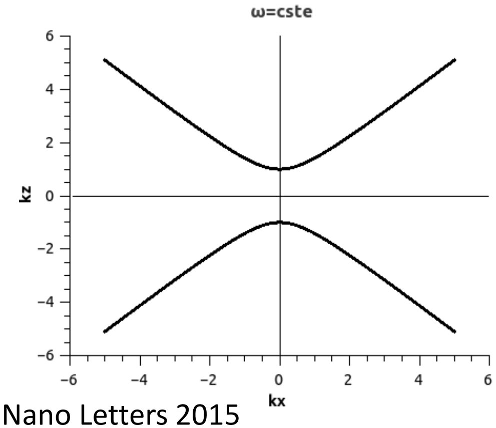


$$\epsilon_m = \epsilon_{\infty,m} + \epsilon_{\infty,m} \times \frac{(\omega_{LO,m})^2 - (\omega_{TO,m})^2}{(\omega_{TO,m})^2 - \omega^2 - i\omega\Gamma_m}$$

$$\frac{kx^2}{\epsilon_\perp} + \frac{kz^2}{\epsilon_{||}} = \frac{\omega^2}{c^2}$$

$$(\epsilon_\perp < 0, \epsilon_{||} > 0)$$

$$e^{i(k_x x - \Omega t)} \times e^{i(k_z z)}$$



Kumar et al., Nano Letters 2015

HPPs and hot graphene ?

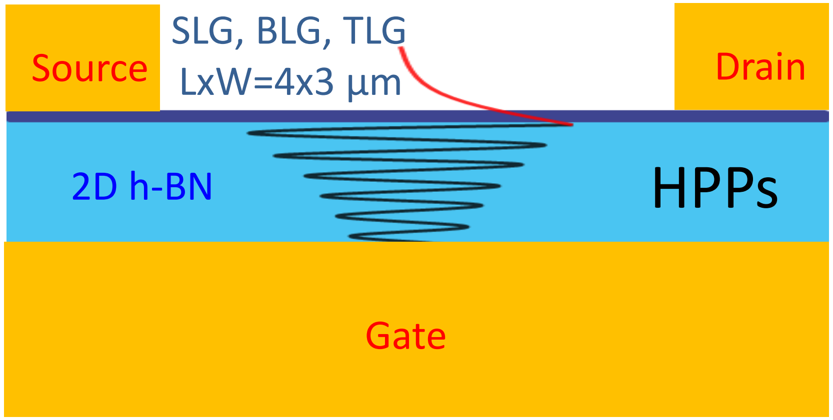
Near field coupling of graphene hot electrons with substrate phonons

Graphene on 3D oxide

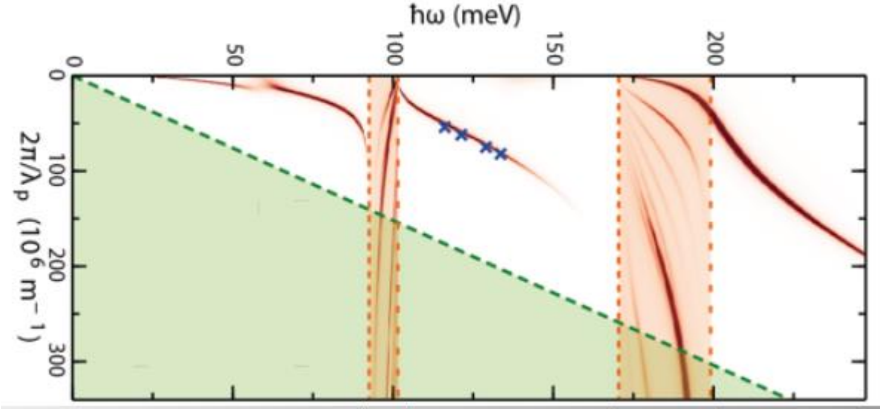
heat diffusion to the gate

Graphene current fluctuations emit HPP radiations deep into hBN bulk

Graphene on 2D h-BN

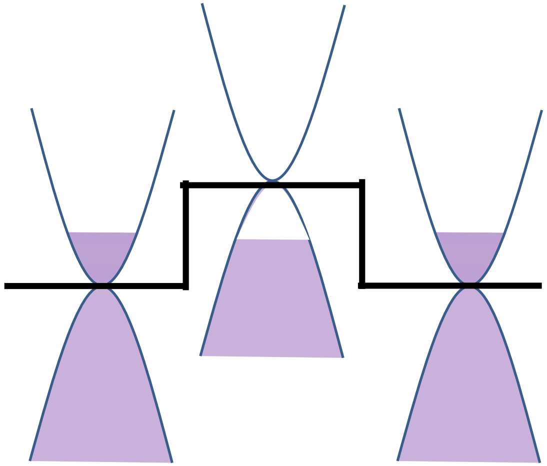


heat propagation to the gate

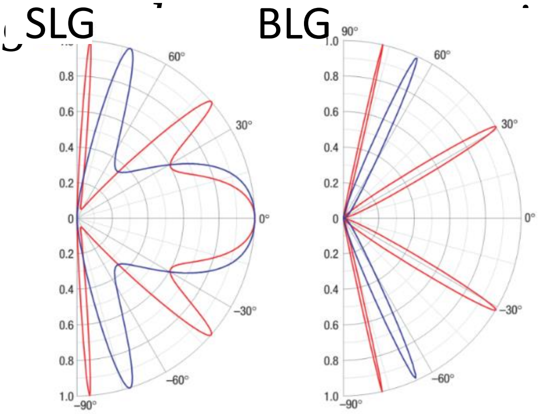


Klien and Zener Tunneling

Klein Tunneling across n-p-n barriers

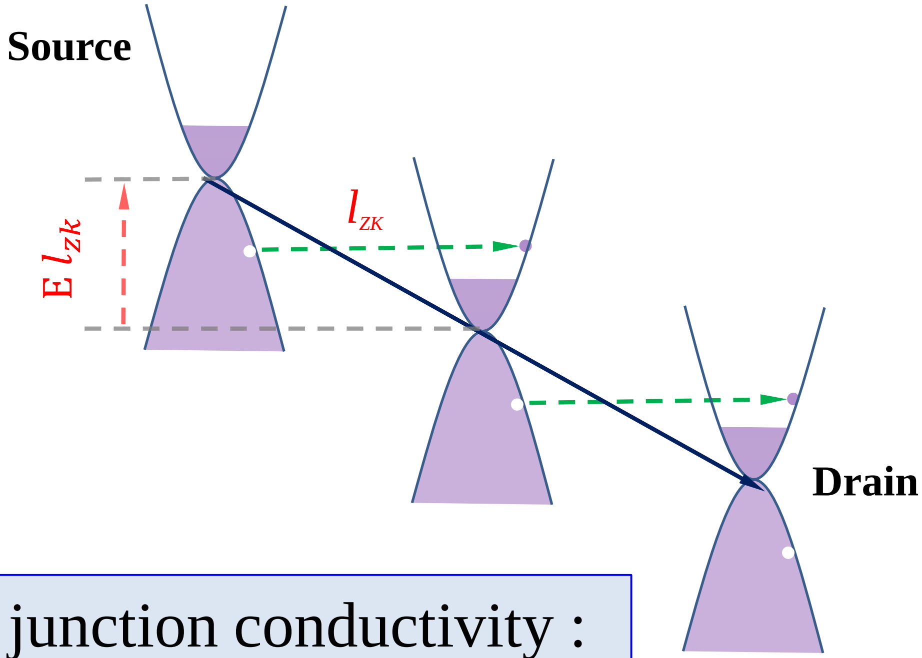


An *sion*



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

Electric field induced Zener tunneling zero bandgap semiconducitor

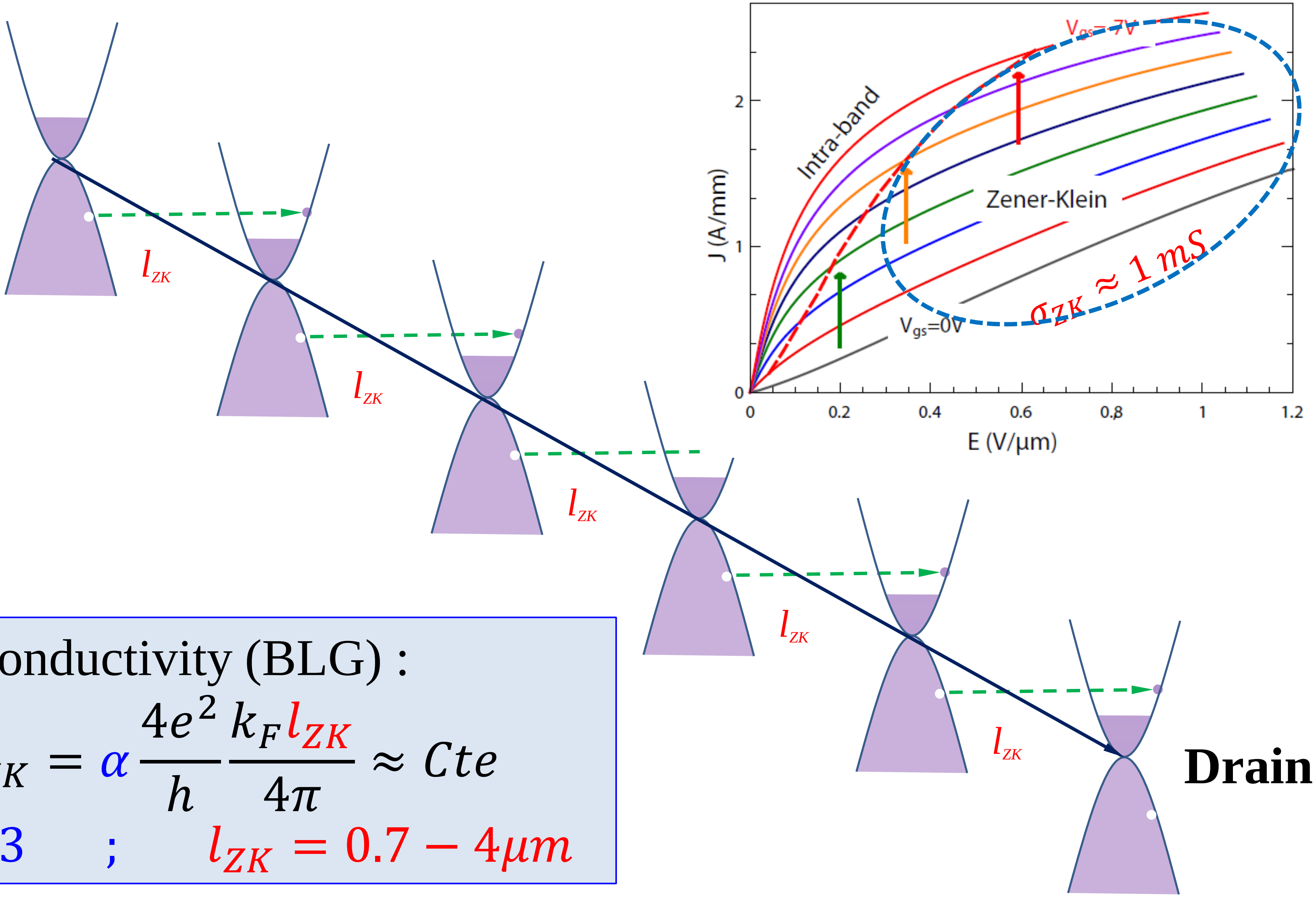


BLG junction conductivity :

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

Kane et al., J. Phys. : Condens. Matter 27 (2015)

Zener-Klein Tunneling (ZKT)

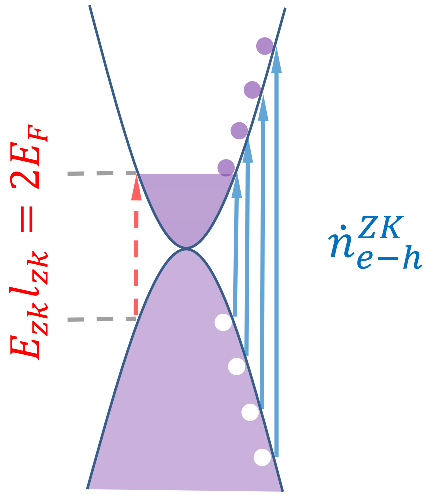


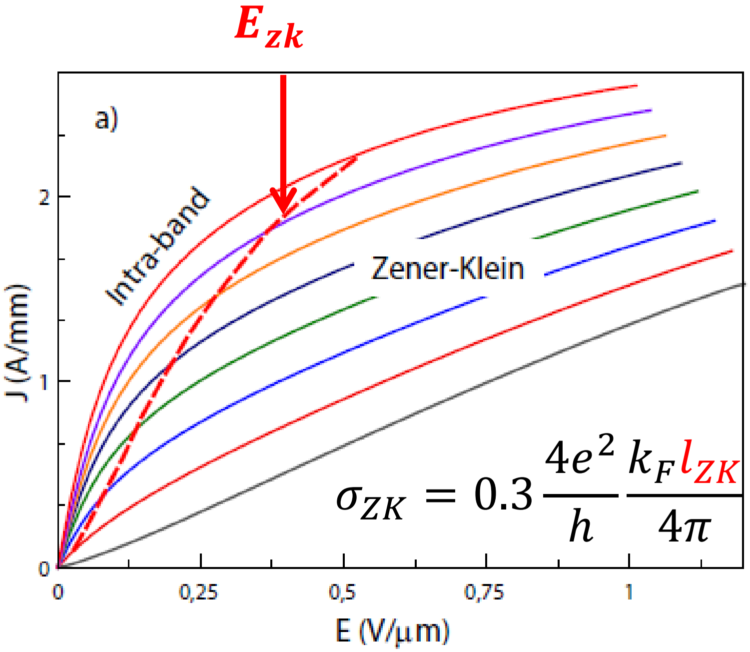
ZKT conductivity (BLG) :

$$\sigma_{ZK} = \alpha \frac{4e^2}{h} \frac{k_F l_{ZK}}{4\pi} \approx Cte$$

$\alpha \sim 0.3$; $l_{ZK} = 0.7 - 4\mu m$

Threshold field for ZKT



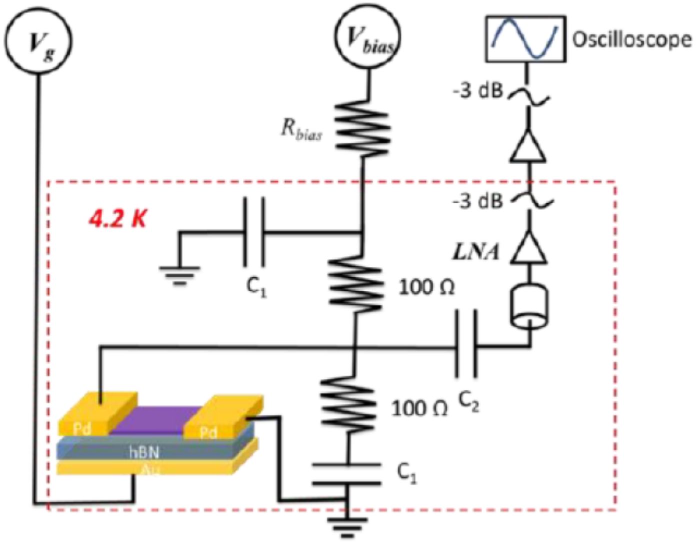


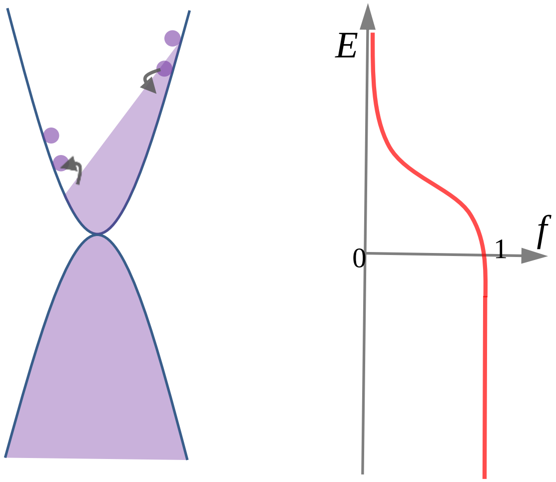
$$\sigma_{ZK} = 0.3\,\frac{4e^2}{h}\,\frac{k_F l_{ZK}}{4\pi}$$

Pauli blocking of ZKT $\quad E > E_{zk} = {}^{2E_F}\!/_{e l_{zk}} \sim {k_F}^3$

e-h creation by ZKT $\quad \dot{n}^{ZK}_{e-h} = \frac{e\,k_F}{\pi^2\,\hbar}\,(E - E_{ZK})$

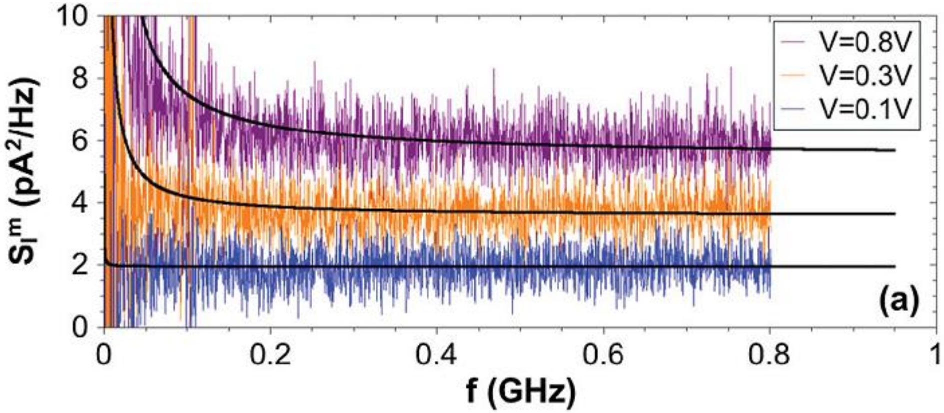
Noise thermometry at high bias





Graphene 2017, opto-electronics

High frequency to overcome 1/f noise



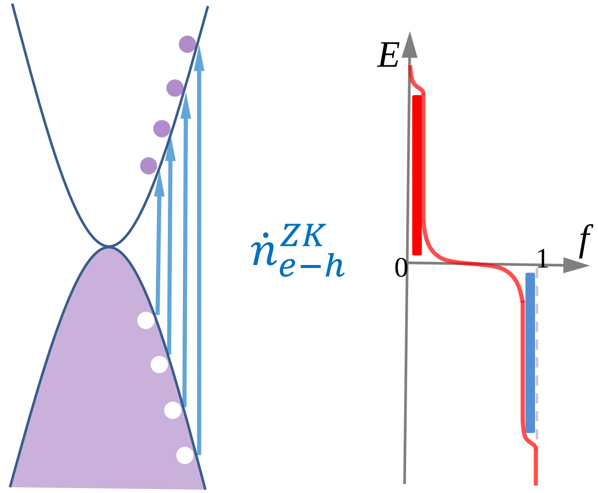
Betz et al. / Phys. Rev. Lett. 109 (2012) 056805
Betz et al. / Nat. Phys. 9 (2013) 109
Brunel et al. / J. Phys. : Condens. Matter 27 (2015) 164208
Laitinen et al. / Phys. Rev. B. 91 (2015) 121414(R)

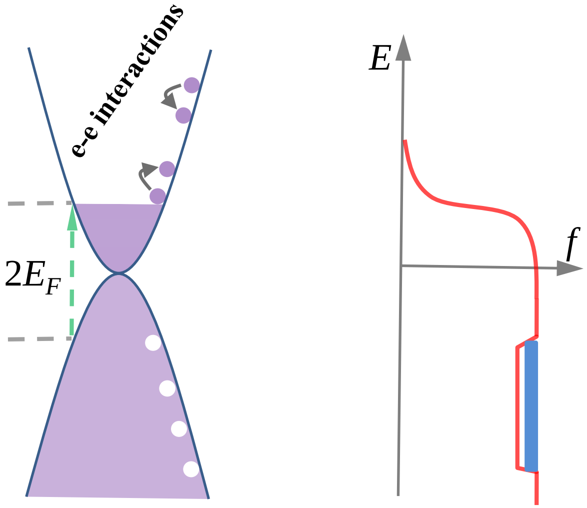
Thermal current noise $S_I = 4\,G\,k_B T_N$

Fast e-e thermalisation (20 fs)

$$k_B T_N = \int_{-\infty}^{\infty} f(1-f)dE = k_B T_e$$

Noise thermometry in the ZKT regime





Out-of-equilibrium e-h population

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

$$n_e = \int_0^{\infty} DOS \times f\,dE\,;$$

$$n_h = \int_0^{\infty} DOS \times (1-f)dE$$

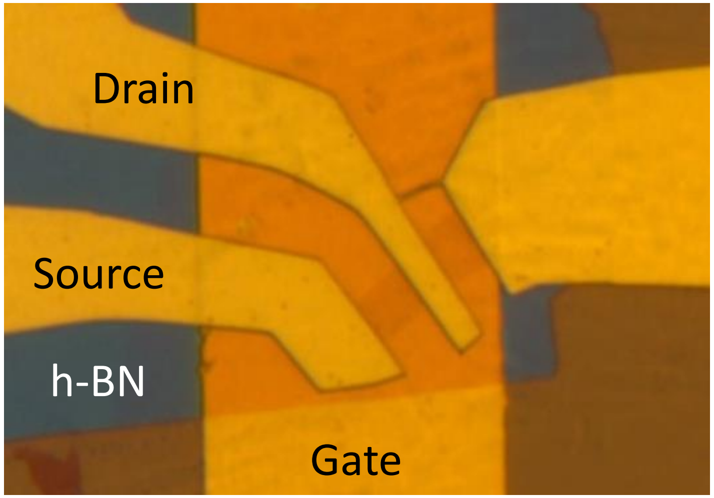
Hot electrons + holes

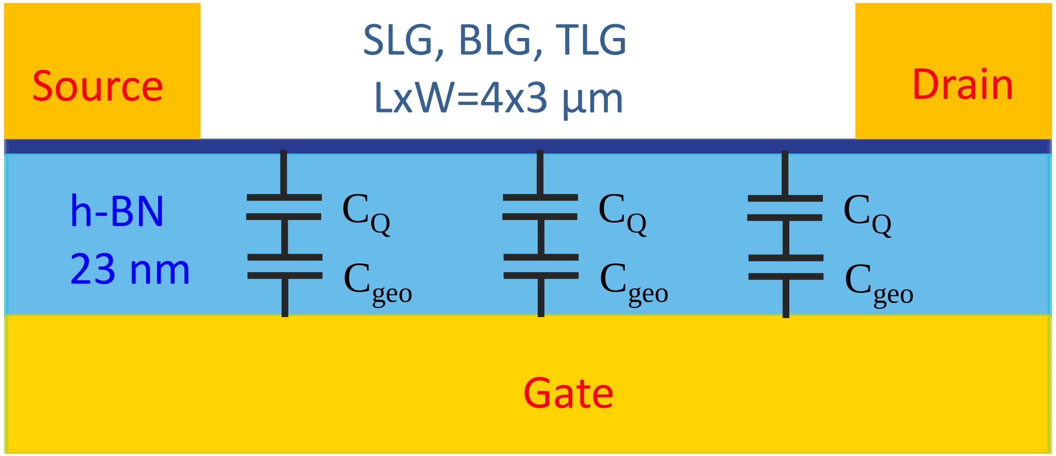
$$\int_{-\infty}^{\infty} f(1-f)dE$$

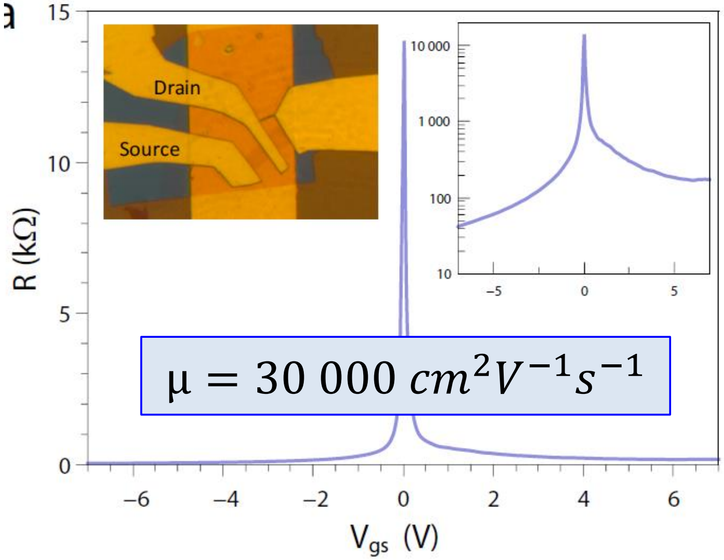
$$k_B T_N \approx k_B T_e + \frac{n_h}{DOS}$$

Experiment

High mobility BLG sample







$$\mu = 30\,000\ cm^2V^{-1}s^{-1}$$

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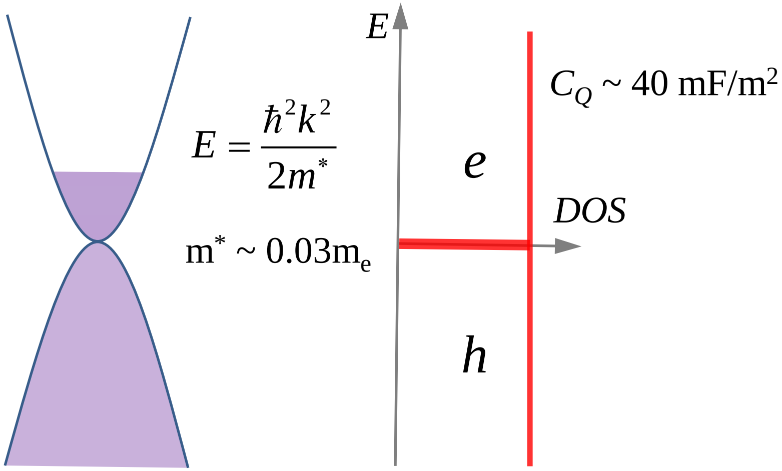
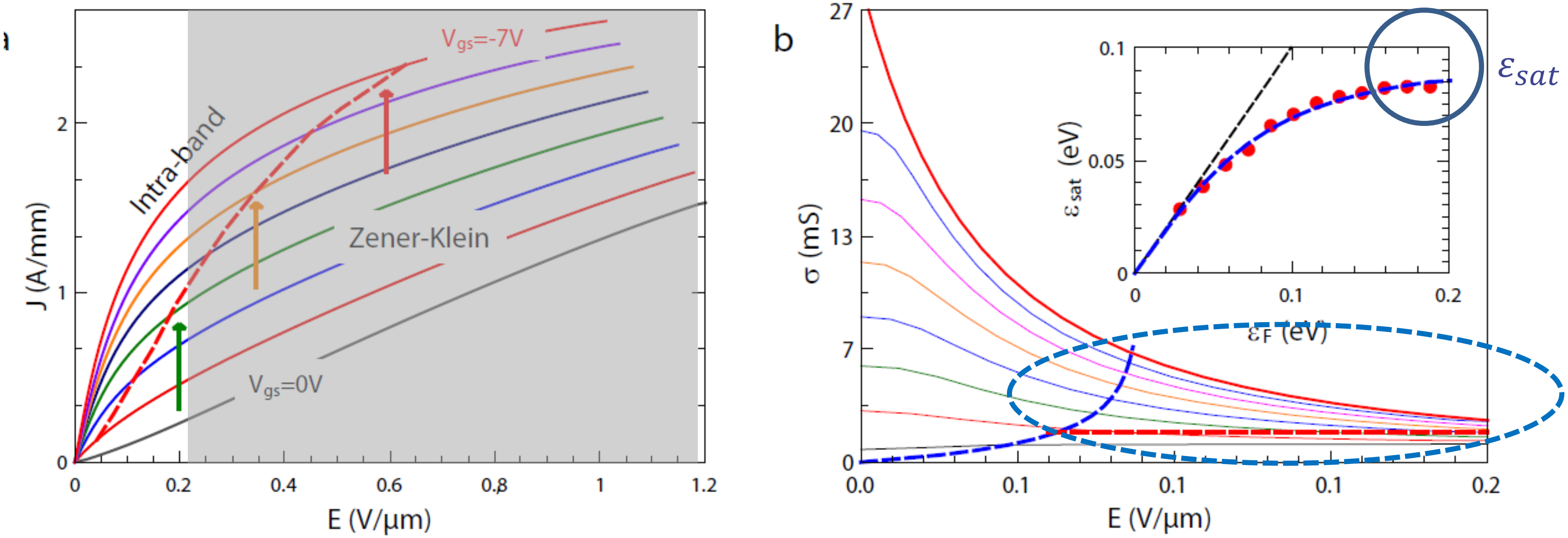


$$E = \frac{\hbar^2 k^2}{2m^*}$$

$m^* \sim 0.03 m_e$

$C_Q \sim 40$ mF/m^2

Intraband current saturation



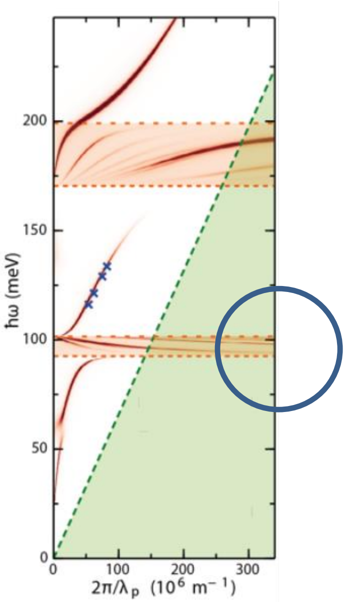
$\varepsilon_{sat} \approx 100\ meV$

$$\sigma = \frac{ne\mu}{(1+E/E_{sat})^2} \quad ; \quad v_{sat} = \mu E_{sat} \leq 3\ 10^5 m/s$$

Importantly : $E_{sat} \ll E_{ZK}$

$$J_{sat} = nev_{sat} \quad ; \quad \varepsilon_{sat} = \frac{\pi}{2}\hbar k_F v_{sat}$$

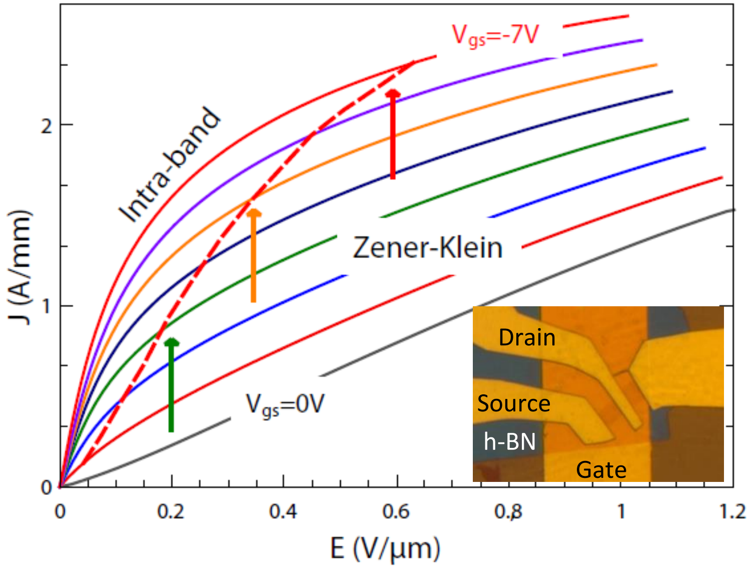
Velocity saturation by type-I hBN phonons



$\varepsilon_{HPP} \approx 100\ meV$

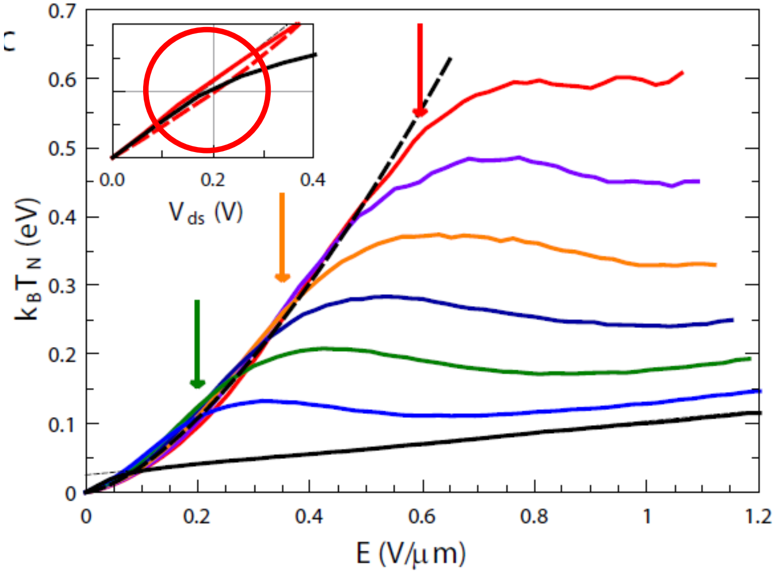
Noise temperature features

Zener-Klein Transport



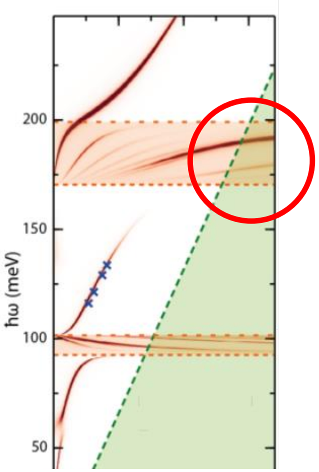
Noise thermometry

$\varepsilon_{ON} \approx 200\ meV$



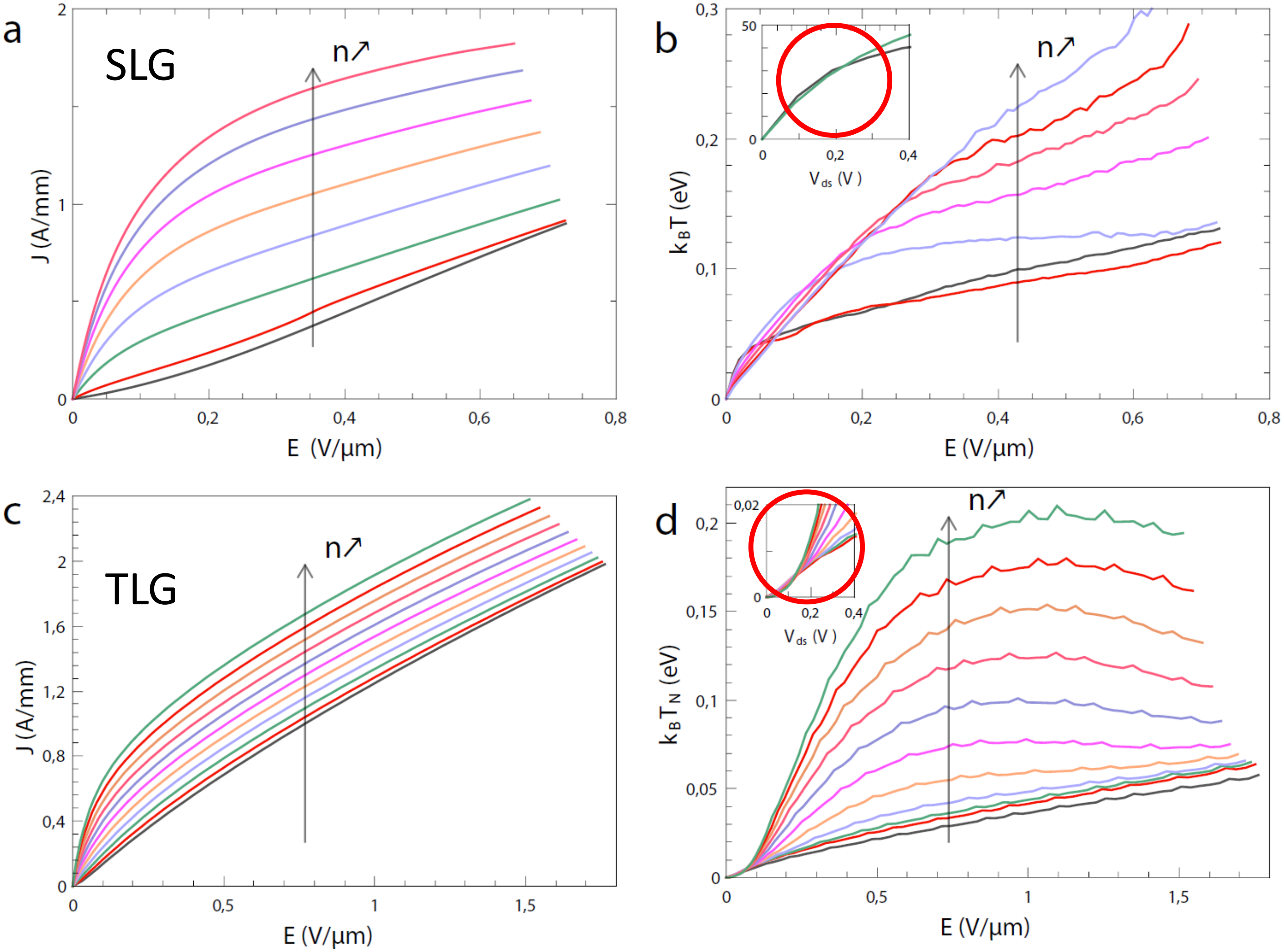
Transport is featureless. Main noise features are :

1) Superlinear $T_N(E) \Leftrightarrow$ current saturation
2) Temperature plateaus in ZKT regime
3) Thershold at ZKT onset (arrows)
4) Linear $T_N(E)$ at neutrality (ZKT e-h creation)
5) Voltage threshold ⇔ activation energy 200 meV



$\varepsilon_{HPP2} \approx 200\ meV$

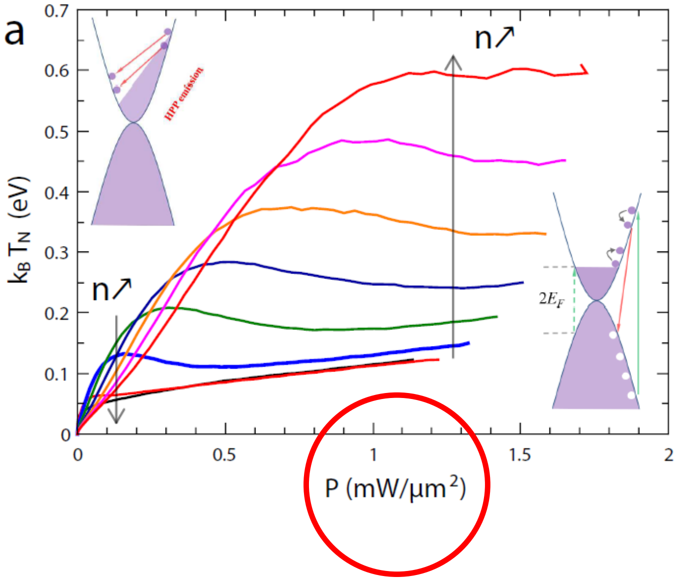
Same features in SLG/TLG



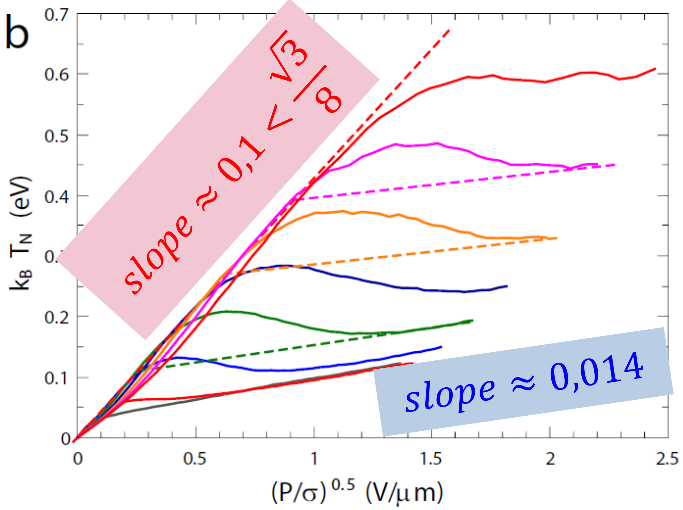
Conventional cooling mechanism ?

electron conduction to the leads

Raw noise thermometry



Wiedemann-Frantz analysis



$slope \approx 0{,}1 < \sqrt{3}/8$

$slope \approx 0{,}014$

e-e interactions (thermalisation) → $\tau_{ee} \sim 20\ fs$

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

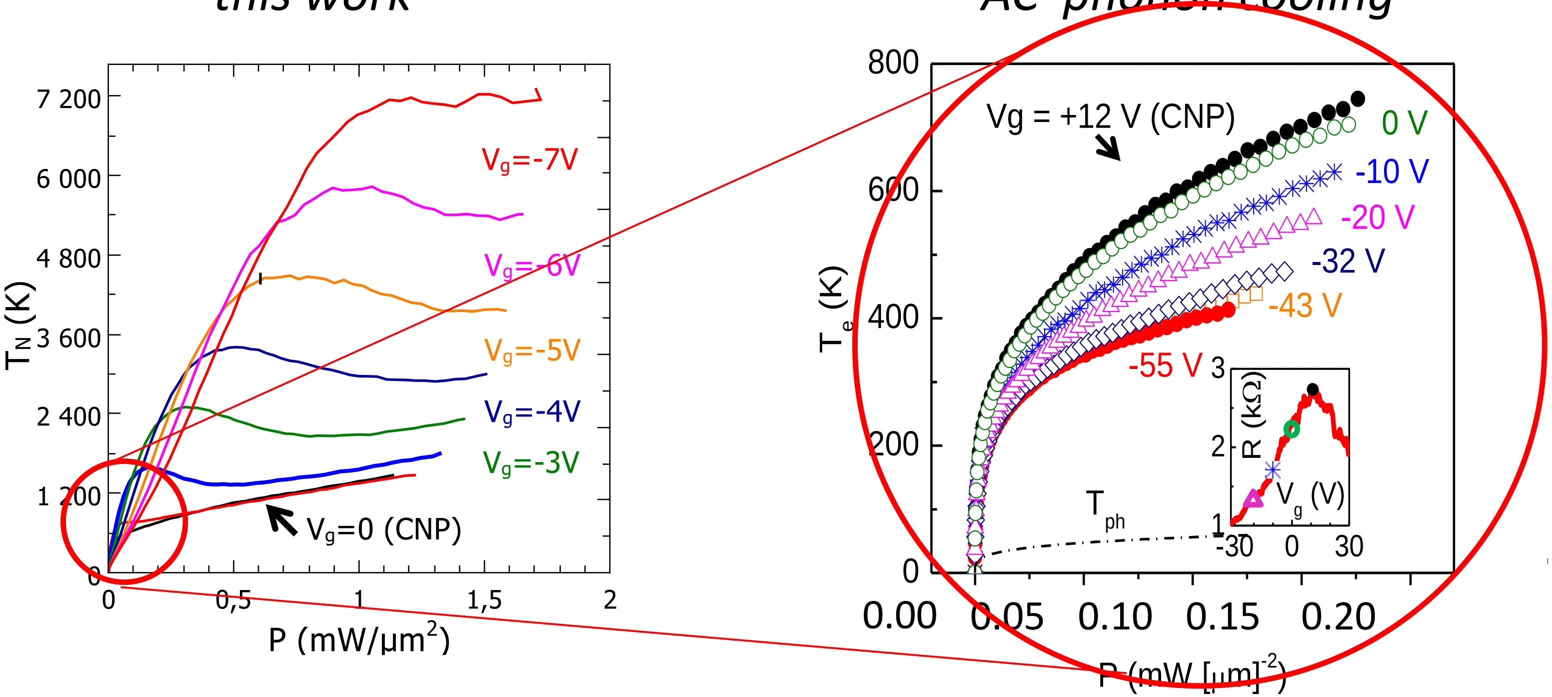
~~electron conduction~~

arXiv:1702.02829v1 (2017

AC phonon cooling ?

this work

AC phonon cooling



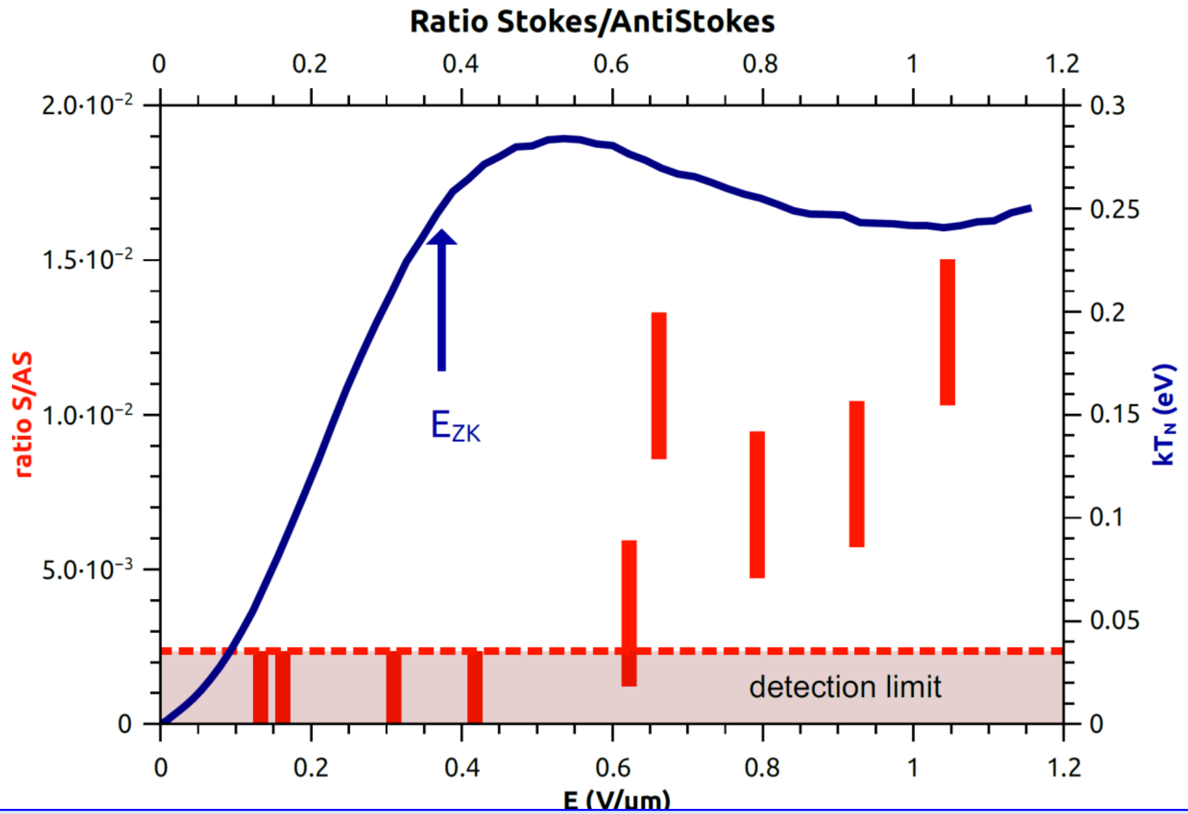
Yang et al. / arXiv:1702.02829v1 (2017)

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

Neutral graphene cools better than doped graphene at high bias !

~~AC phonons~~

OP phonon cooling ?



e-OP interaction = deformation potential ⇒ $\Gamma_{OP} \ll \Gamma_{HPP,SPP}$

OP-phonon Raman thermometry ⇒ OP cooling negligible

HPP cooling !

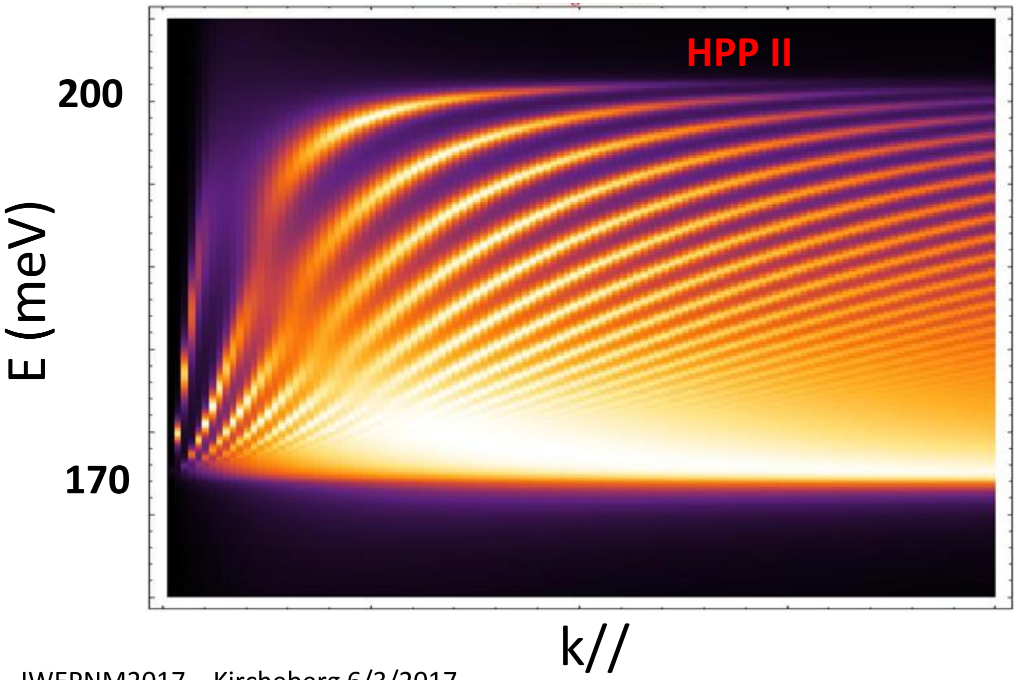
Superplanck HPP cooling of Graphene

Impedance matching

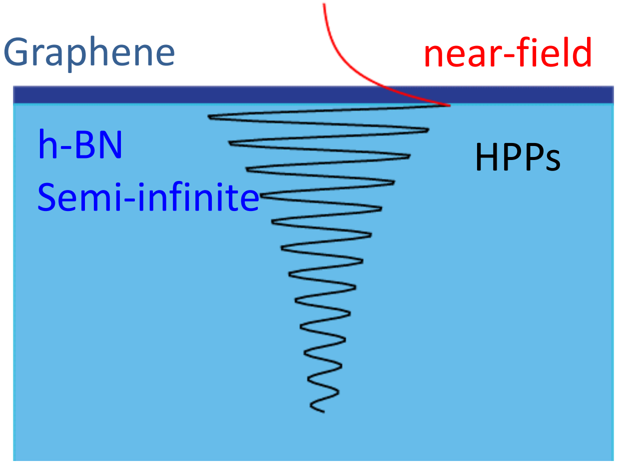
$$P = \frac{n}{4\pi^2}\frac{\hbar\omega\Delta\omega}{exp[\hbar\omega/k_B T]-1}\times M$$

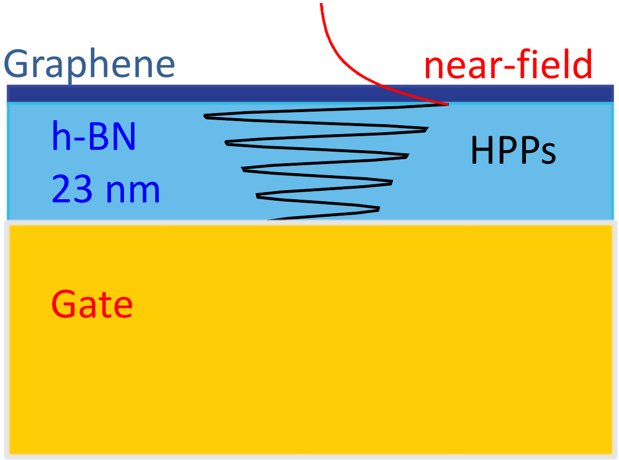
$$M = \left[\frac{4Re(Y_0)4Re(\sigma)}{|Y_0+\sigma|^2}\right]$$ (non-local emissivity)

$\sigma(q,\omega)$ (non-local graphene conductivity)



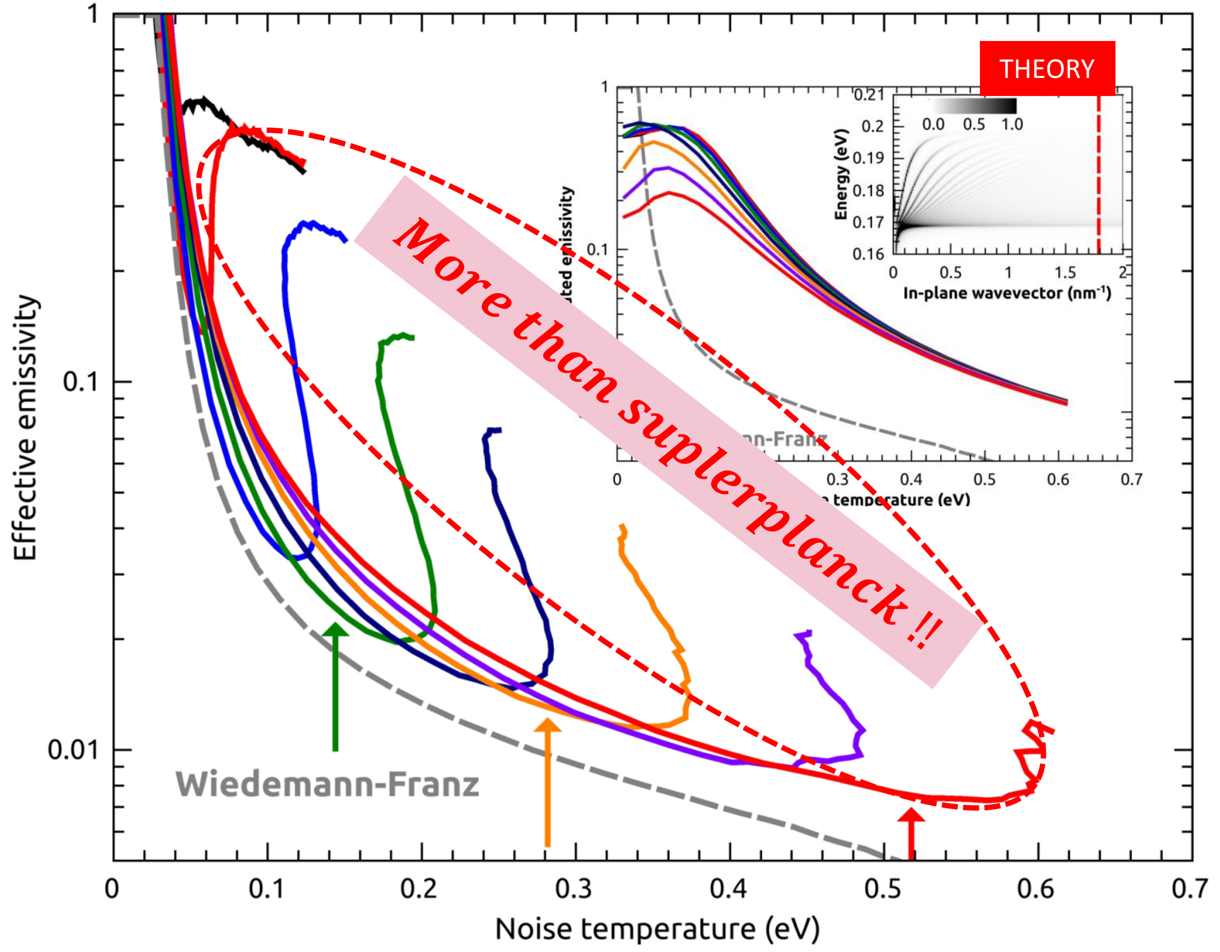
HPPs are propagative modes





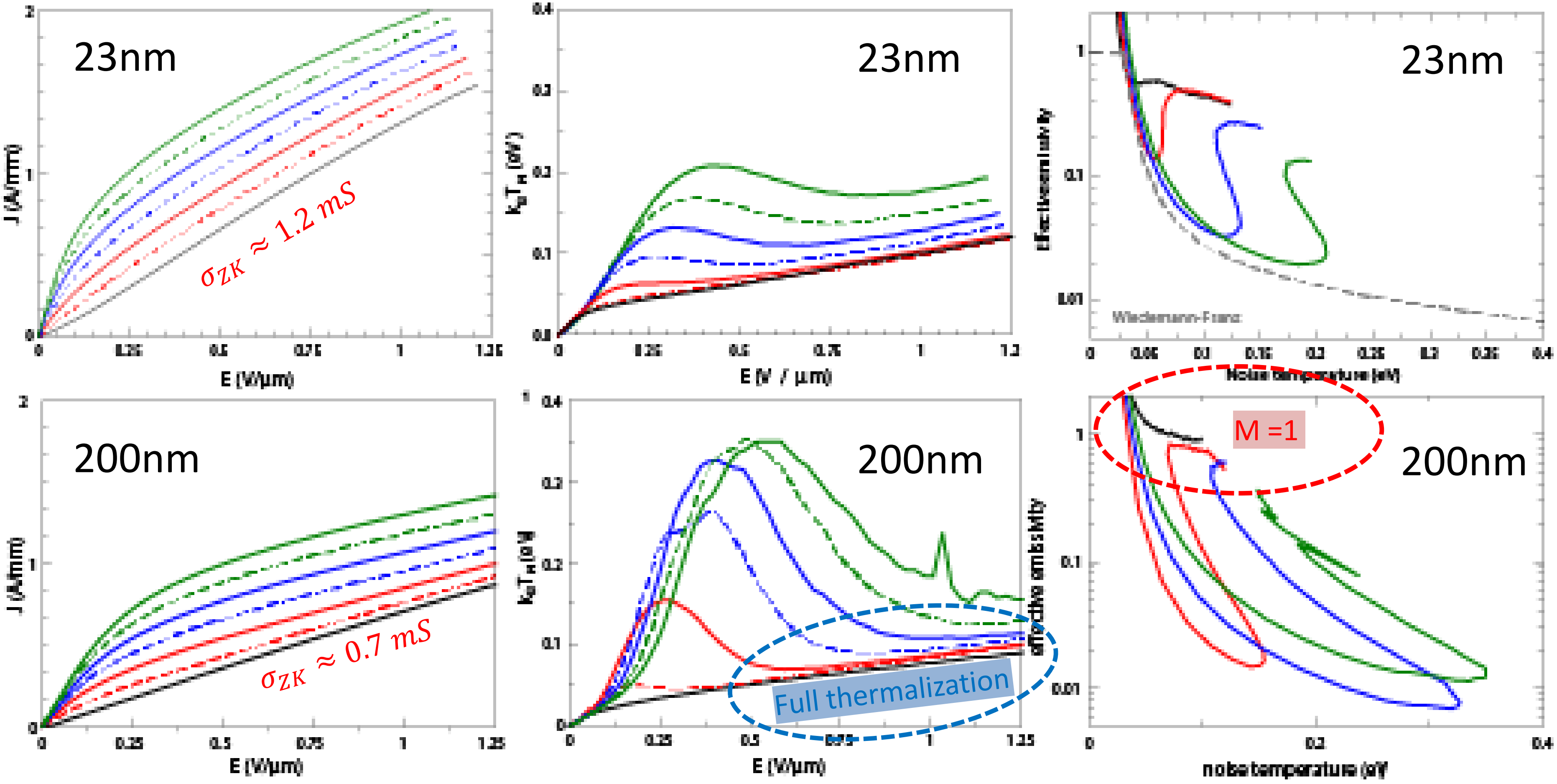
The thermal radiative cooling picture

EXPERIMENT



More than suplerplanck !!

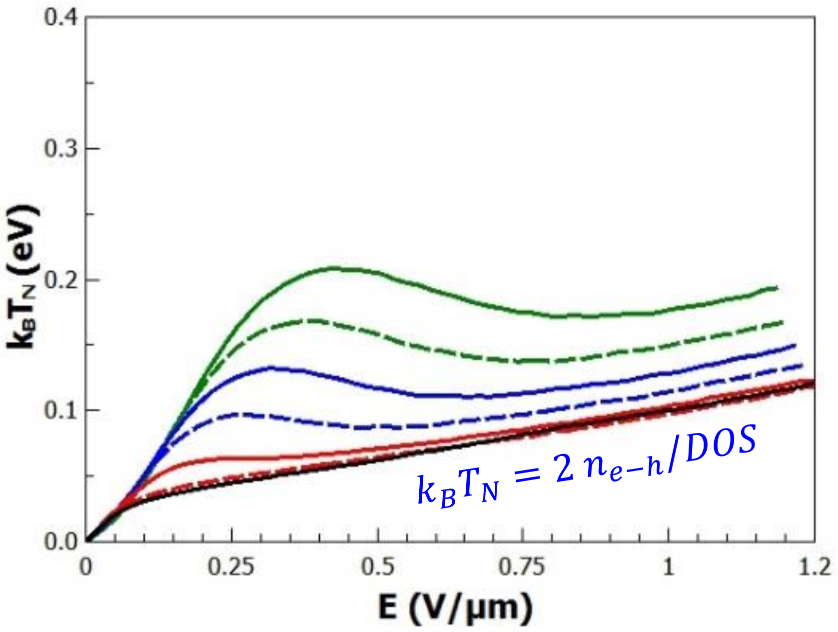
From thin to thick h-BN



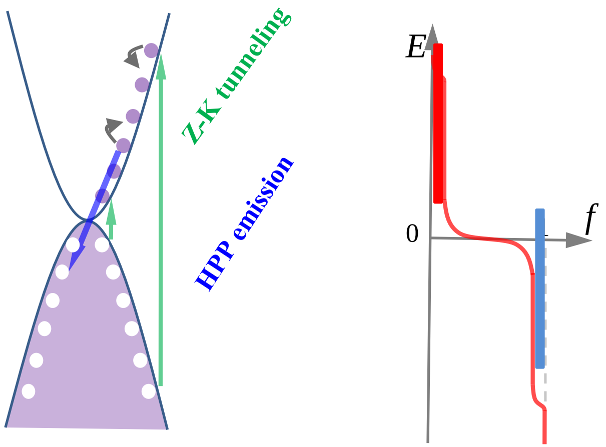
- Same J_{sat}
- Smaller σ_{ZK}

- HPP cooling $\gg$ Joule Power in ZKT regime
- Emissivity $\approx$ 1 in ZKT regime

Noise measurement of τ_{HPP}

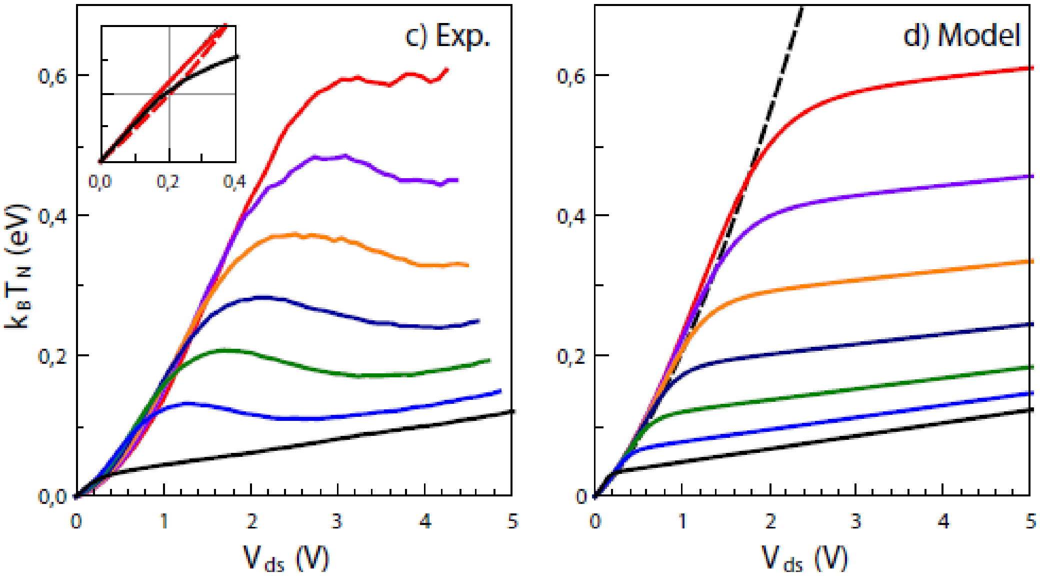


Stationary e-h pair density

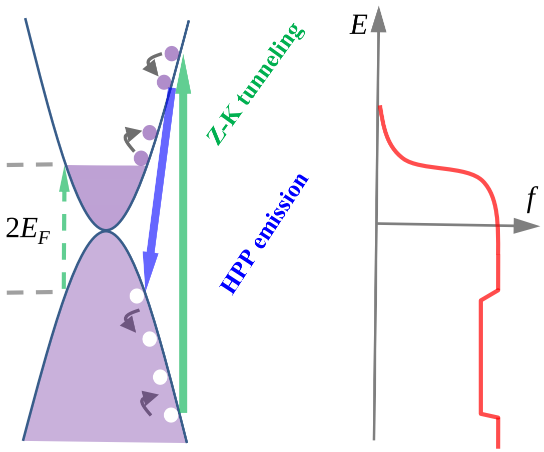


e-h pumping rate (th.)	$\dot{n}_{e-h}^{ZK} = \frac{e\,k_F}{\pi^2\,\hbar}(E - E_{ZK}) = \frac{n_{e-h}}{\tau_{HPP}}$
e-h density (exp.):	$n_{e-h} = DOS \times k_B \Delta T_N/2$
HPP cooling rate :	$\tau_{HPP} \leq 0.46\,ps \quad \left(\frac{4\pi^2}{\Delta\Omega_{HPP2}} \approx 0.8\,ps\right)$

HPP cooling balances max Joule Power



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

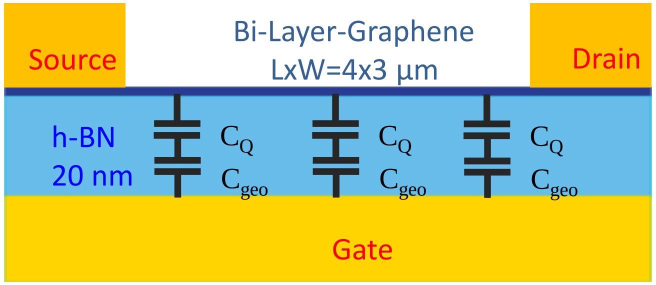
HPP cooling : $P_{HPP} = \hbar\Omega\,\dot{n}^{HPP}_{e-h} = \hbar\Omega\,\dot{n}^{ZK}_{e-h} = \hbar\Omega\frac{e\,k_F}{\pi^2\,\hbar}(E - E_{zk})$

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

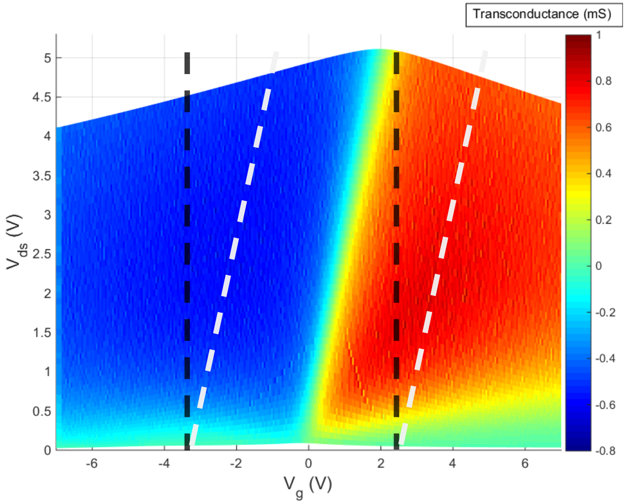
in GoBN, where $\hbar\Omega_{II} \approx 2\hbar\Omega_I \approx 200\ meV \quad \Rightarrow \boldsymbol{P_{HPP} \approx P_{Joule}}$

ZKT-FETs as power amplifiers with efficient HPP cooling

Bottom gated G-FETs



Transconductance



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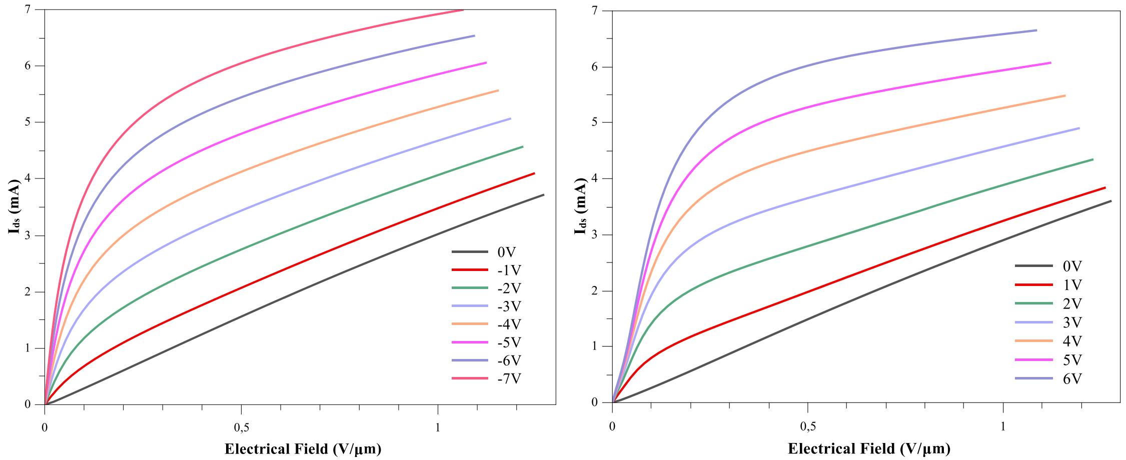
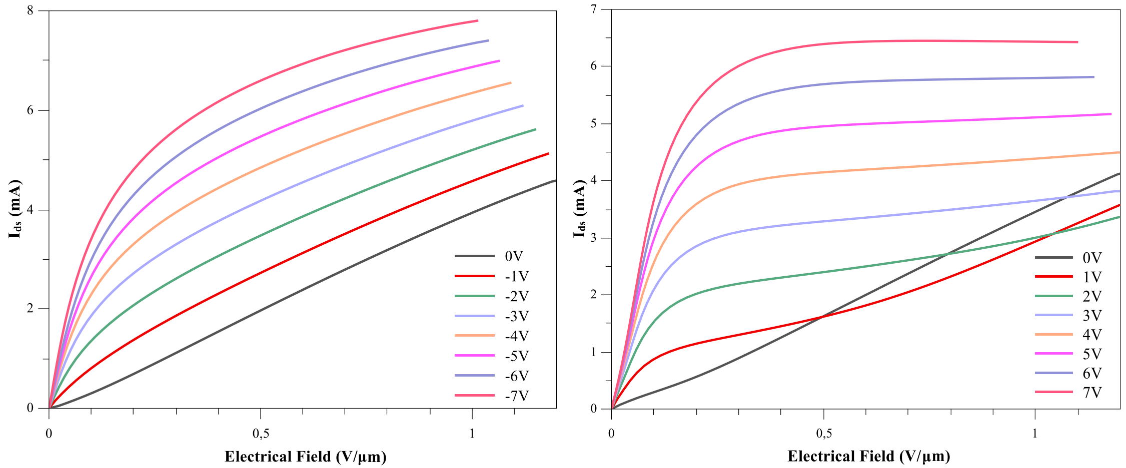
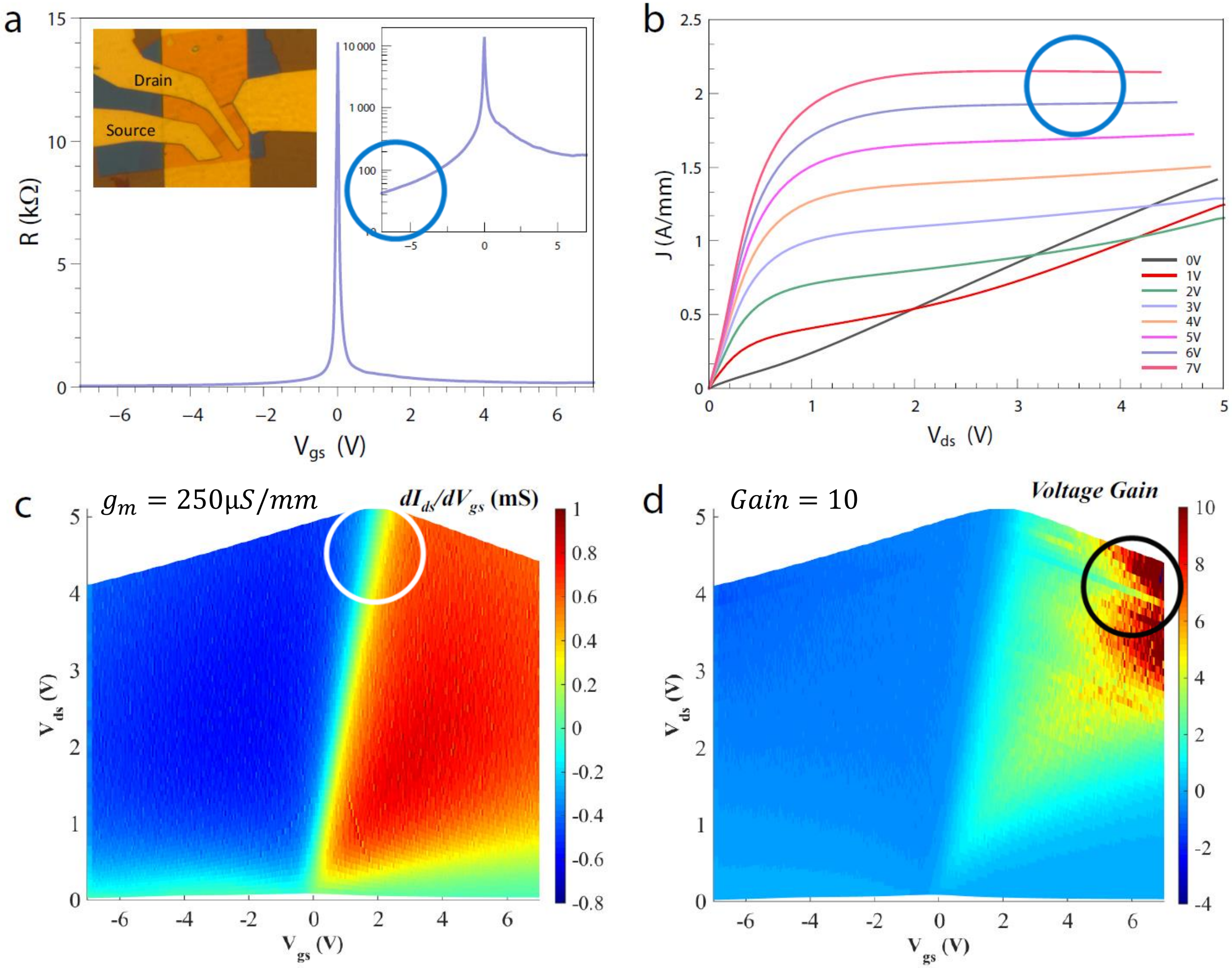
Constant carrier density



Constant gate voltage



Zener-Klein-Tunneling transistor



GoBN

- High mobility (30 000 cm^2/V/s)
- Low contact resistance
- Current saturation ++
- High-power ++
- Zener-Klein regime operation ++
- Negligible self heating effects

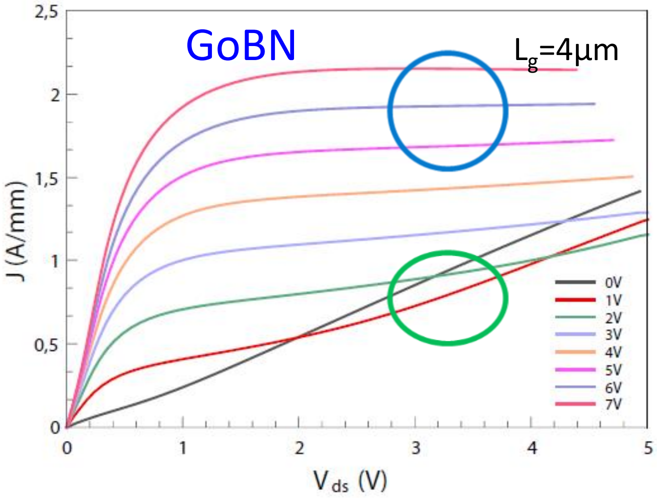
Bottom gating

- Drain gating (bottom gate effect)
- Transconductance (250 µS/mm)
- Large voltage gain (G~10)

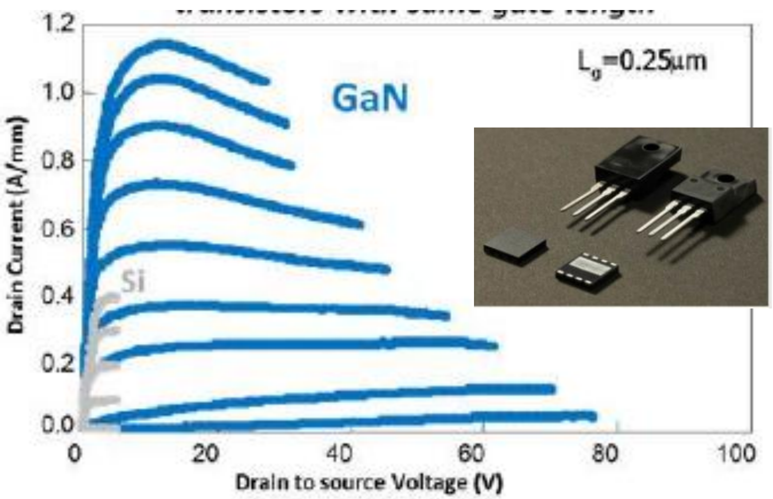
Graphene 2017, opto-electronics

ZKT-FETs as power amplifers

GoBN Zener-Klein transistor



Panasonic : X-GaN Power transistor



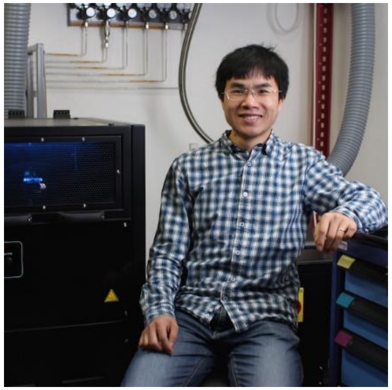
5 merits of h-BN

1. High mobility
2. Large saturation currents (power amplification ?)
3. Pinchoff replaced by Zener-Klein tunneling
4. Compensation of ZK tunneling by a bias induced doping depletion
5. No thermal degradation => cooling by hyperbolic hBN phonons !!!

Conclusions

1. *HPP cooling promotes h-BN is the ideal heat sink*
2. *Zener-Klein Tunneling optimizes HPP emission*
3. *ZKT-FETs are promising high power transistors*

Contributors



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