Driving Electrons Hard … Nanoscale Devices Under Strong Nonequilibrium

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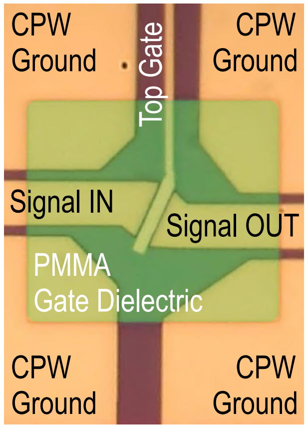

Collaborators:

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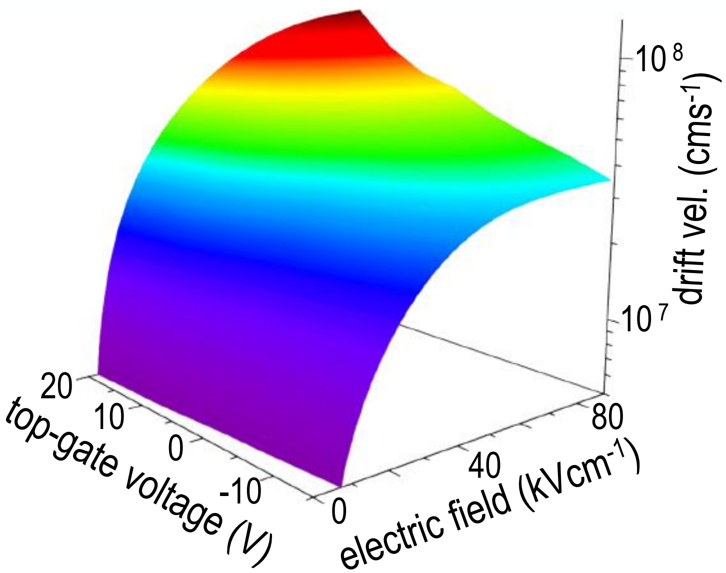
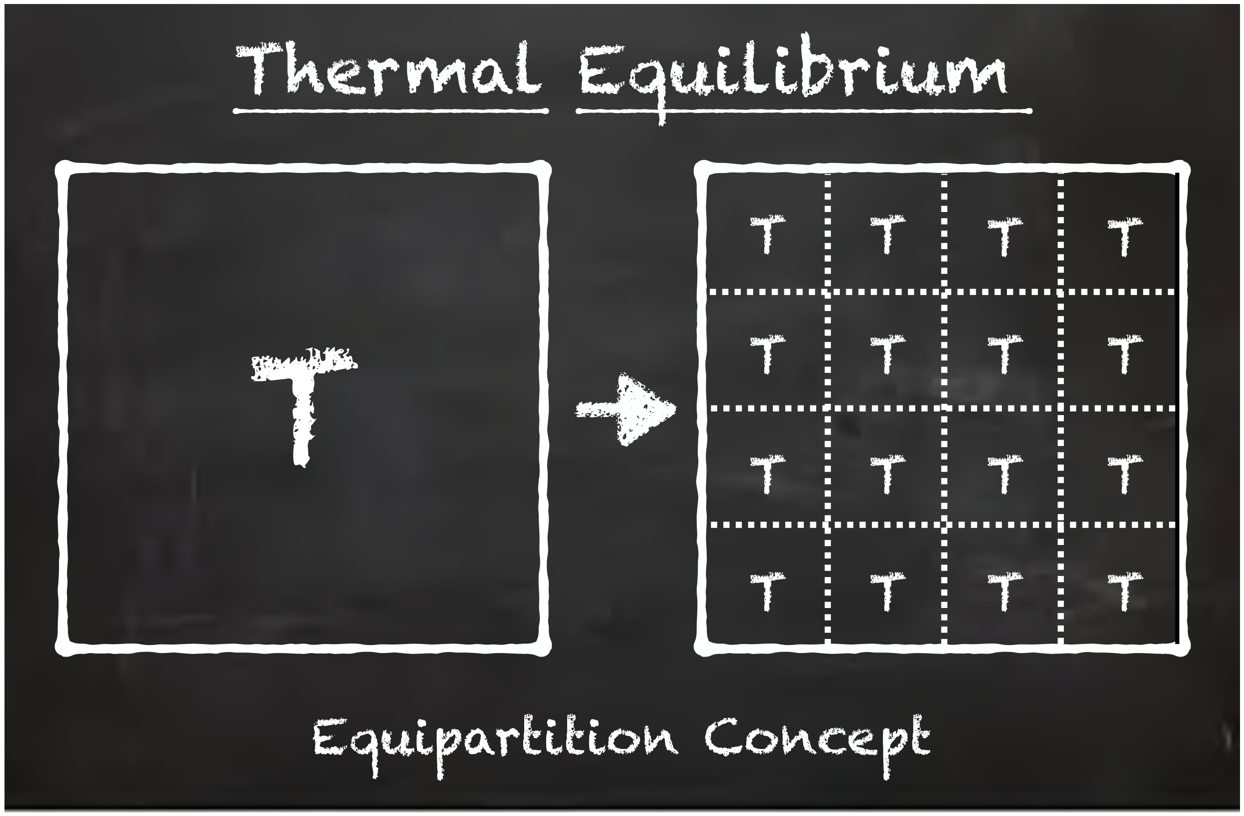


Outline

- Motivation
- Energy transfer in condensed-matter systems
- How high can you go?
- When negative is positive
- Conclusions

Motivation: Electronic Systems out of Equilibrium

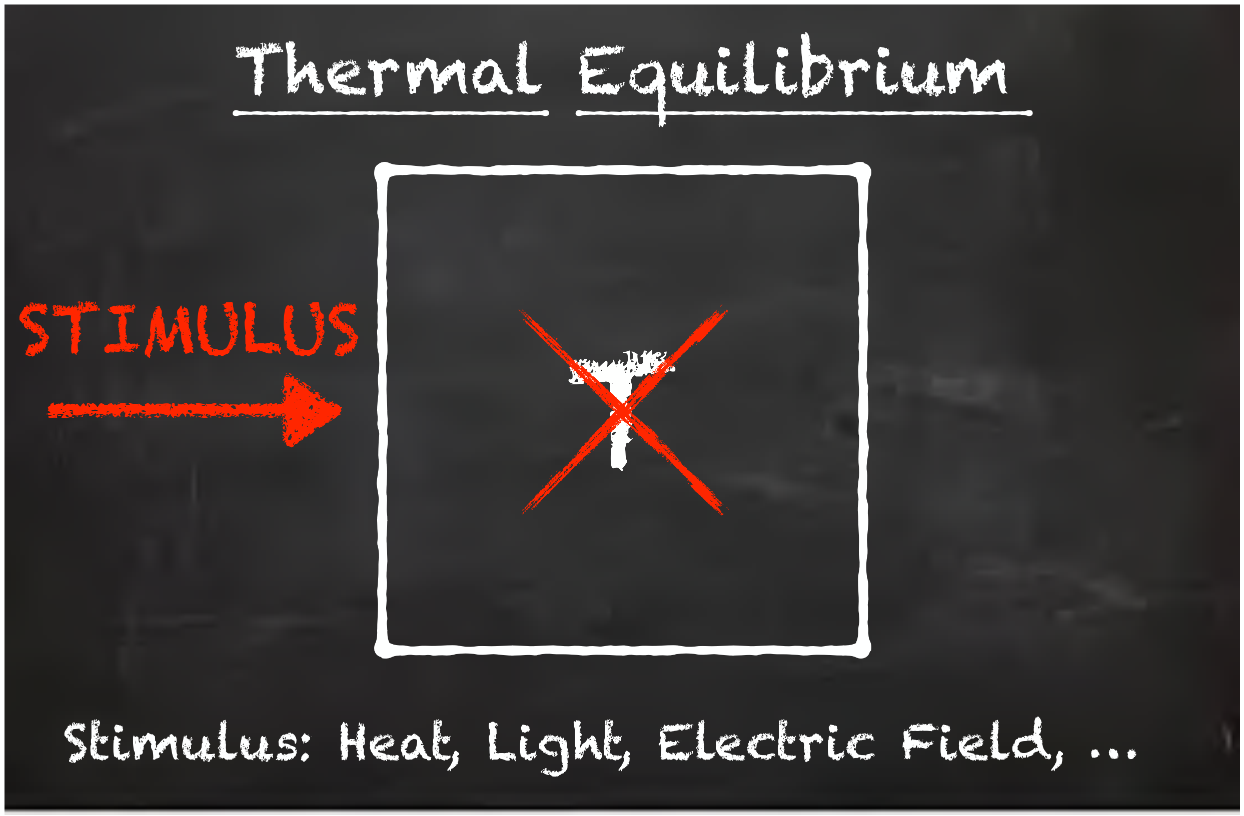
Important concept from classical thermodynamics is **thermal equilibrium**



An <u>isolated</u> system left for sufficient time will reach a final equilibrium with a spatially uniform temperature

Motivation: Electronic Systems out of Equilibrium

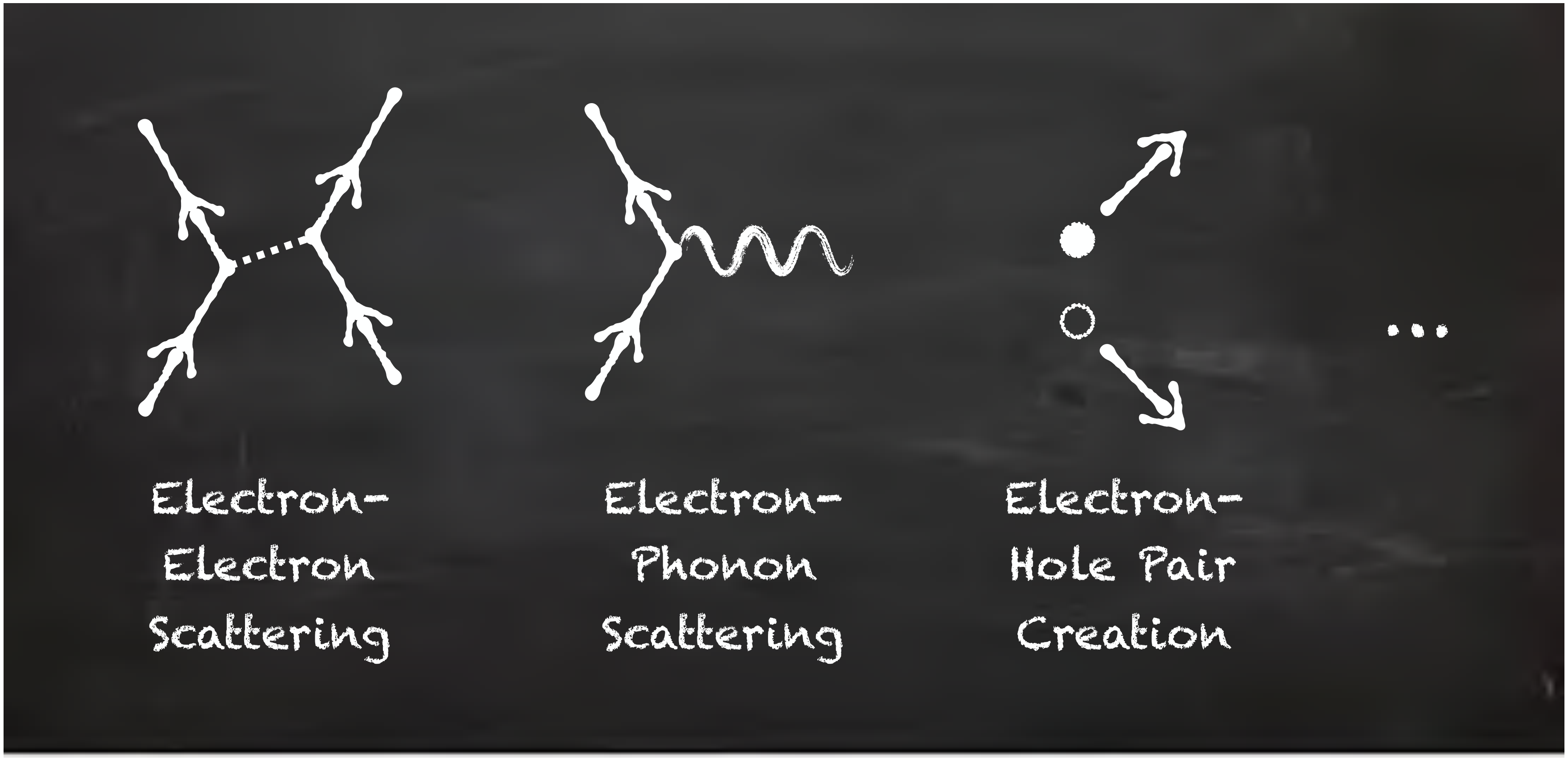
Some of the most difficult problems in physics concern the treatment of systems that are driven **out** of equilibrium by some suitable **stimulus**



System no longer defined by a unique temperature … thermal equilibrium is broken

Motivation: Electronic Systems out of Equilibrium

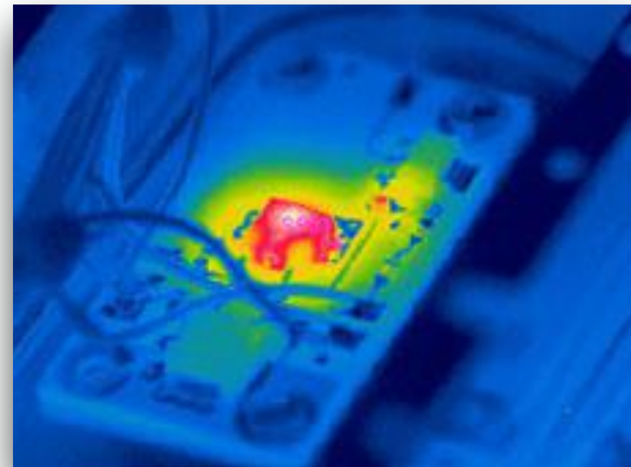
The stimulus causes **transport** in the system that can be influenced by a number of different carrier processes

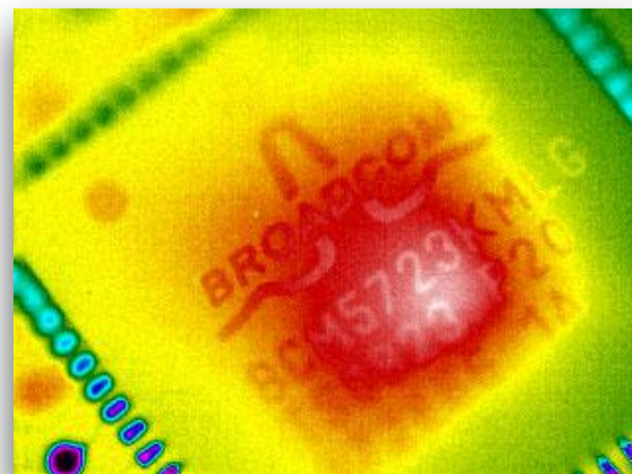


Description of transport in this many-body environment can be extremely challenging

Motivation: Electronic Systems out of Equilibrium

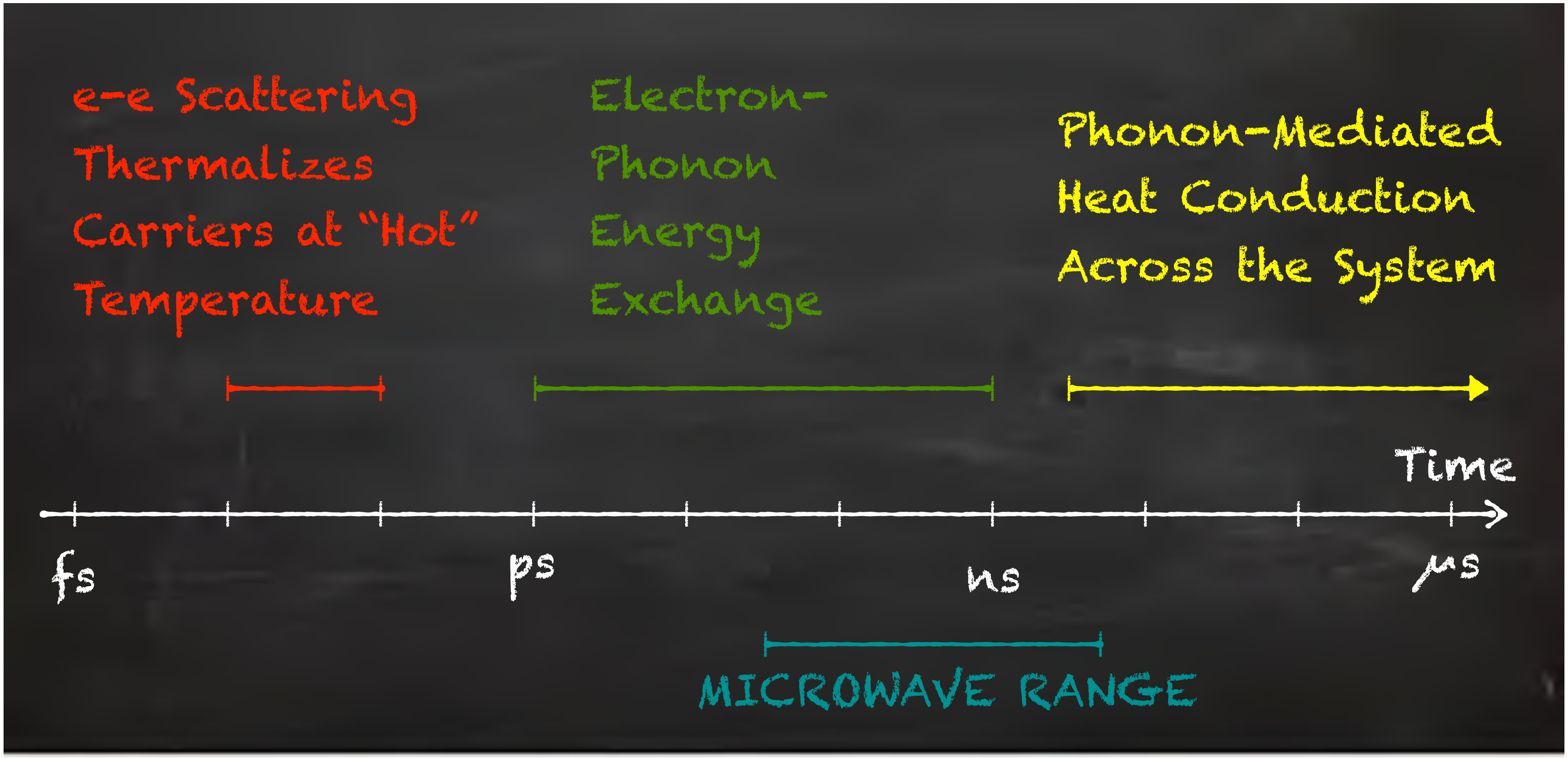
We are interested in the manifestations of this problem that arise in the discussion of transport in **nanoscale** semiconductor devices





Energy Transfer in Condensed Matter Systems

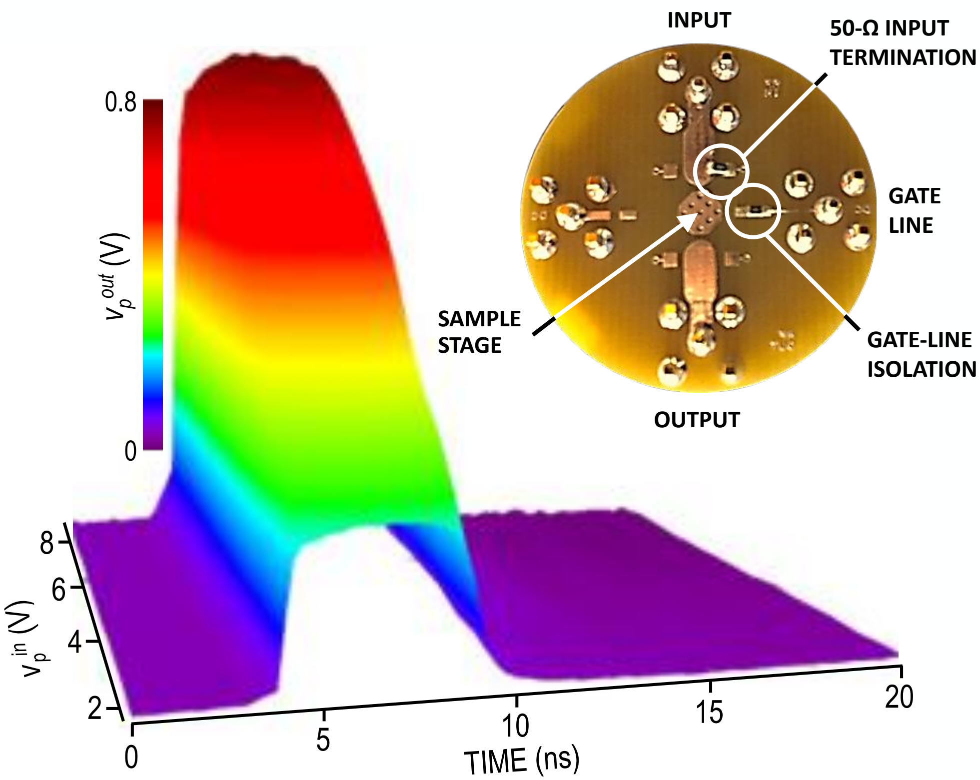
When a stimulus is applied to such devices the energy of their carriers is **redistributed** over a **number** of characteristic time scales

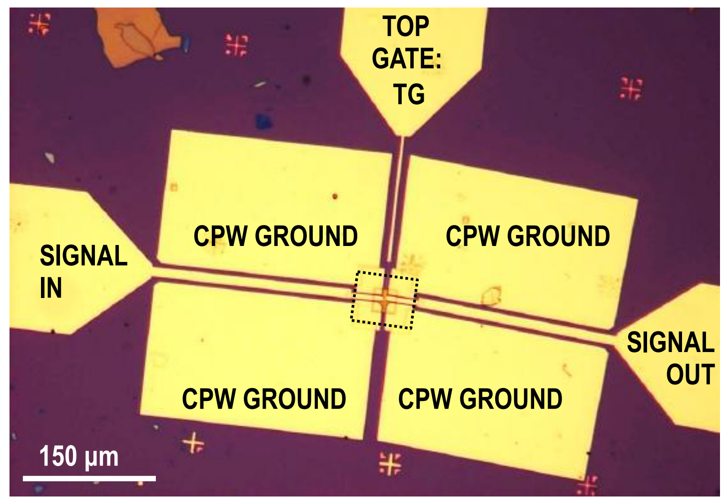


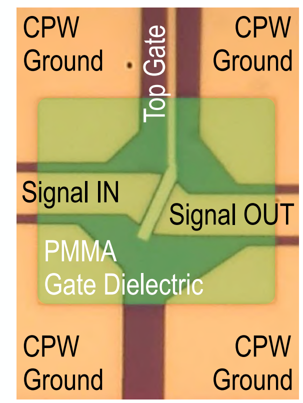
The slower processes indicated here can be accessed in real time via microwave-domain pulsing approaches

Energy Transfer in Condensed Matter Systems

Electron-phonon energy exchange can be probed by using **rapid pulsing** to investigate details of transport under **strongly-nonequilibrium** conditions





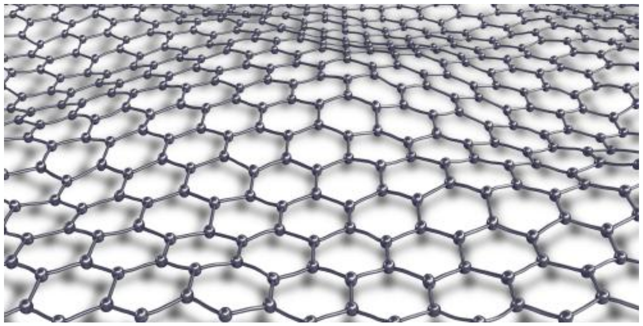


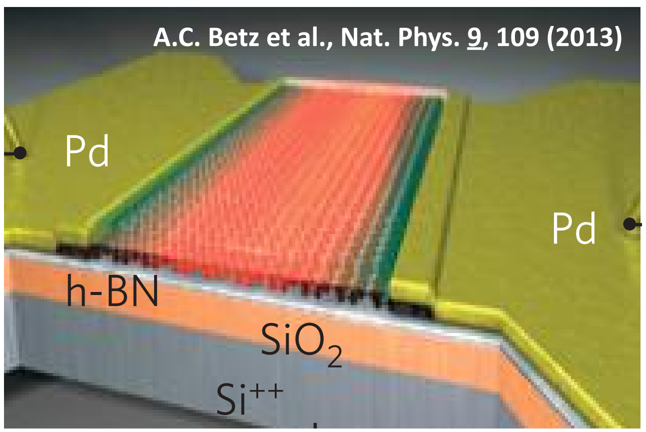
H. Ramamoorthy et al.
Nano Letters 16, 399 (2016)

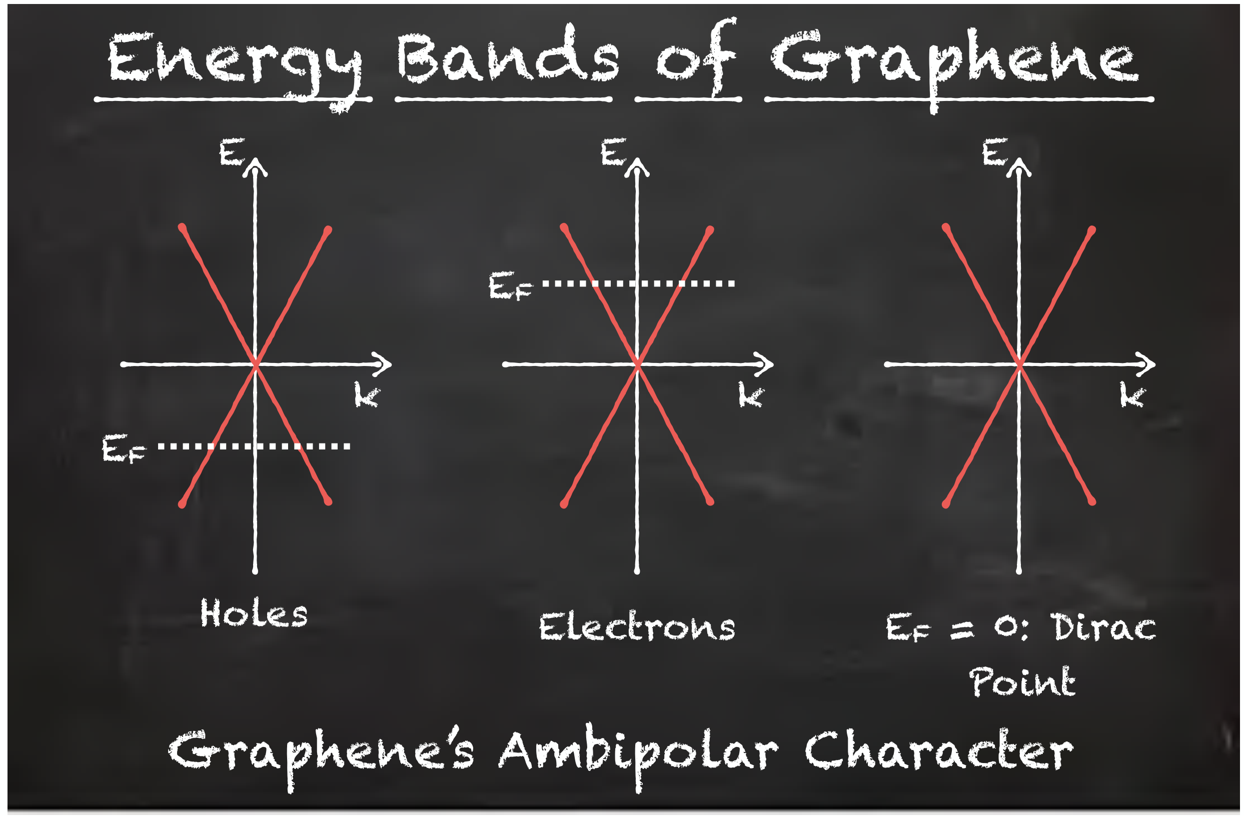
Careful application of microwave-matching techniques allows sub-100-ps time resolution in these studies

How High Can You Go?

Recently **graphene** has emerged as a material whose superlative electrical properties make it attractive for many electronic-device applications



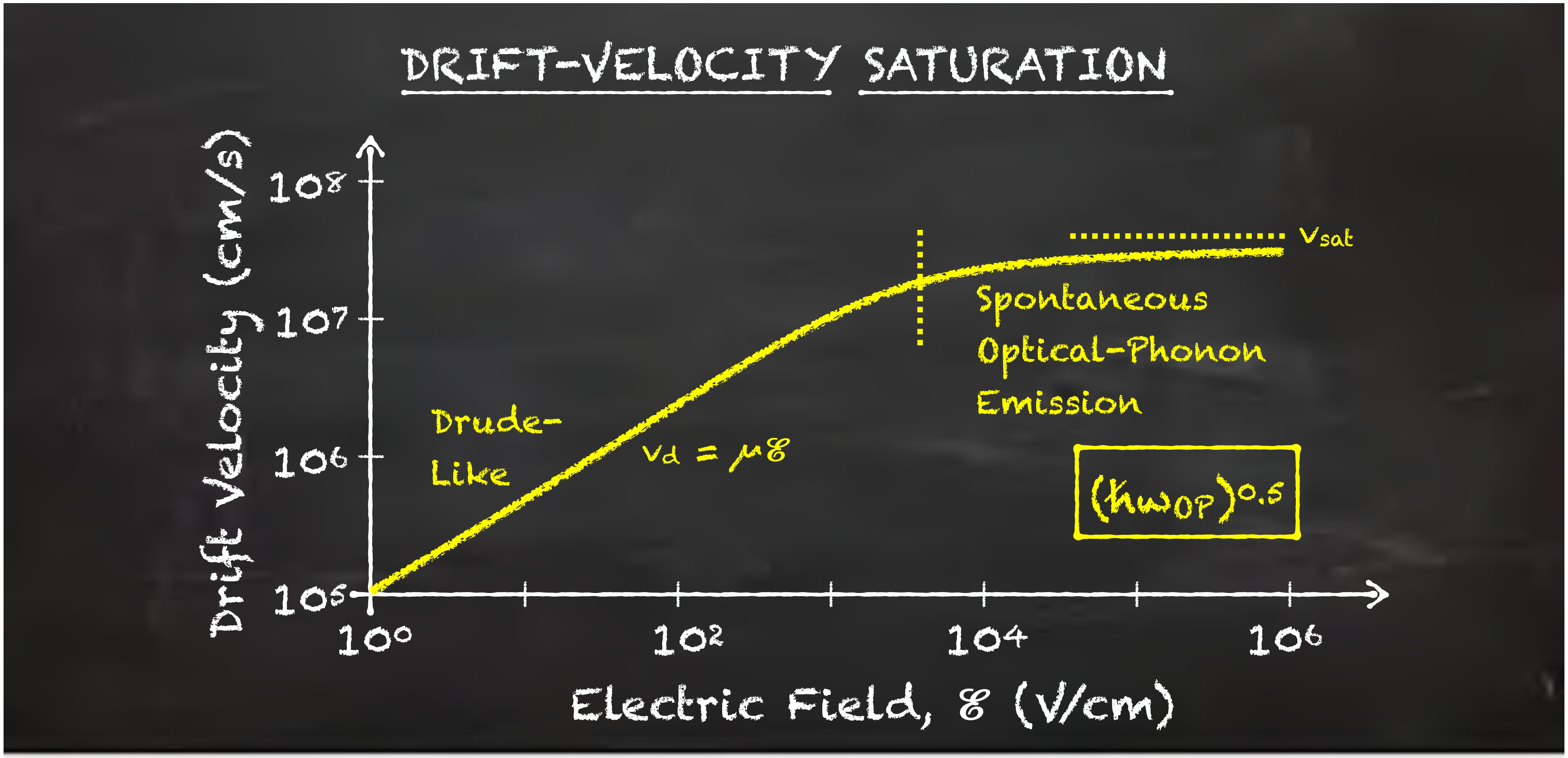




A critical question concerns the maximum (saturated) drift velocity to which graphene's carriers can be accelerated

How High Can You Go?

The drift velocity in semiconductors does not increase indefinitely but rather **saturates** at high electric fields due to **optical-phonon** emission

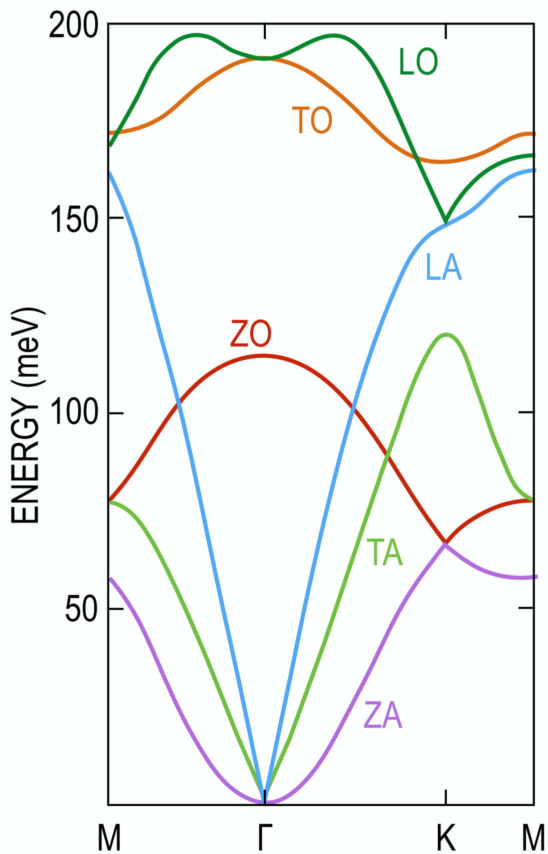


The saturation limits the ultimate current-carrying capacity of the semiconductor

The UNIVERSITY of OKLAHOMA

How High Can You Go?

The large optical-phonon energies of graphene promise **high** saturation velocities - **better** than traditional semiconductors



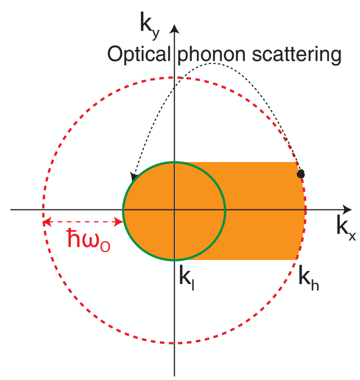
M.V. Fischetti et al.
J. Phys.: Cond. Matt. 25, 473202 (2013)

LETTERS

Current saturation in zero-bandgap, top-gated graphene field-effect transistors

INANC MERIC[1], MELINDA Y. HAN[2], ANDREA F. YOUNG[3], BARBAROS OZYILMAZ[3†], PHILIP KIM[3] AND KENNETH L. SHEPARD[1*]

Published online: 21 September 2008; doi:10.1038/nnano.2008.268



T. Fang et al., Phys. Rev. B 84, 125450 (2011)

$$v_{sat} = v_F \frac{\hbar\omega_{OP}}{E_F} \propto \frac{\hbar\omega_{OP}}{\sqrt{n}}$$

$\hbar\omega_{OP}$ = 160 - 200 meV ⇒

$v_{sat} > 5 \times 10^7$ cms^{-1} (n, p = 10^{12} cm^{-2})

c.f. $v_{sat} = 10^7$ cms^{-1} for Si

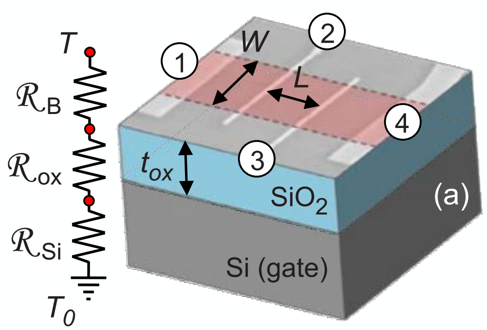
How High Can You Go?

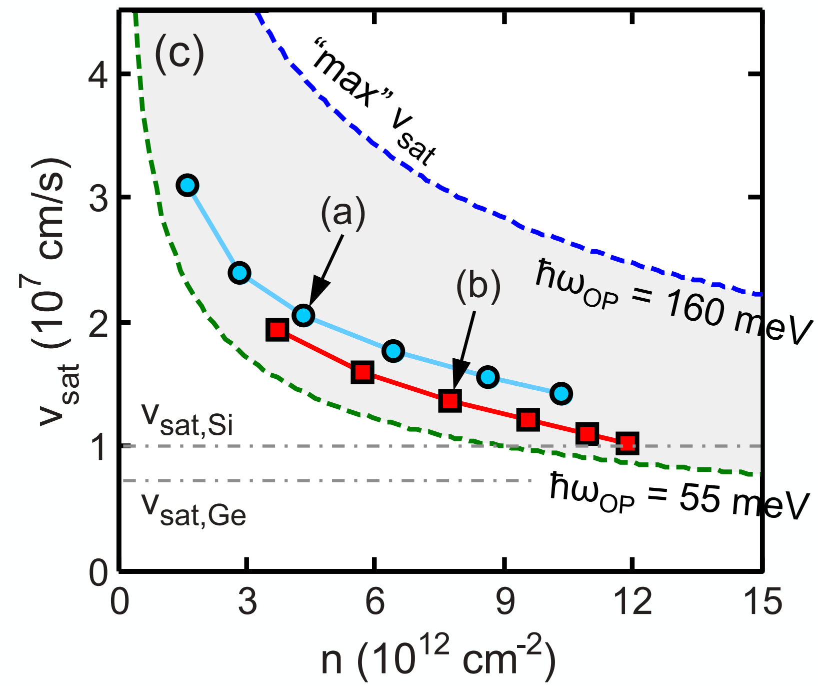
However … experiments show that velocity saturation typically occurs at significantly **lower** values than expected for intrinsic graphene

APPLIED PHYSICS LETTERS **97**, 082112 (2010)

Mobility and saturation velocity in graphene on SiO_2

Vincent E. Dorgan,[1] Myung-Ho Bae,[1] and Eric Pop[1,2,a)]
[1]*Dept. of Electrical and Computer Engineering, Micro and Nanotechnology Laboratory, University of Illinois, Urbana-Champaign, Illinois 61801, USA*
[2]*Beckman Institute, University of Illinois, Urbana-Champaign, Illinois 61801, USA*





See Also:
I. Meric et al., Nat. Nanotechnol. 3, 654 (2008)
A.M. DaSilva et al., Phys. Rev. Lett. 104, 236601 (2010)
I. Meric et al., Nano Lett. 11, 1093 (2011)

Attributed to velocity cutoff provided by lower-energy ($\hbar\omega_{OP}$ = 55 meV) surface optical phonons of SiO_2

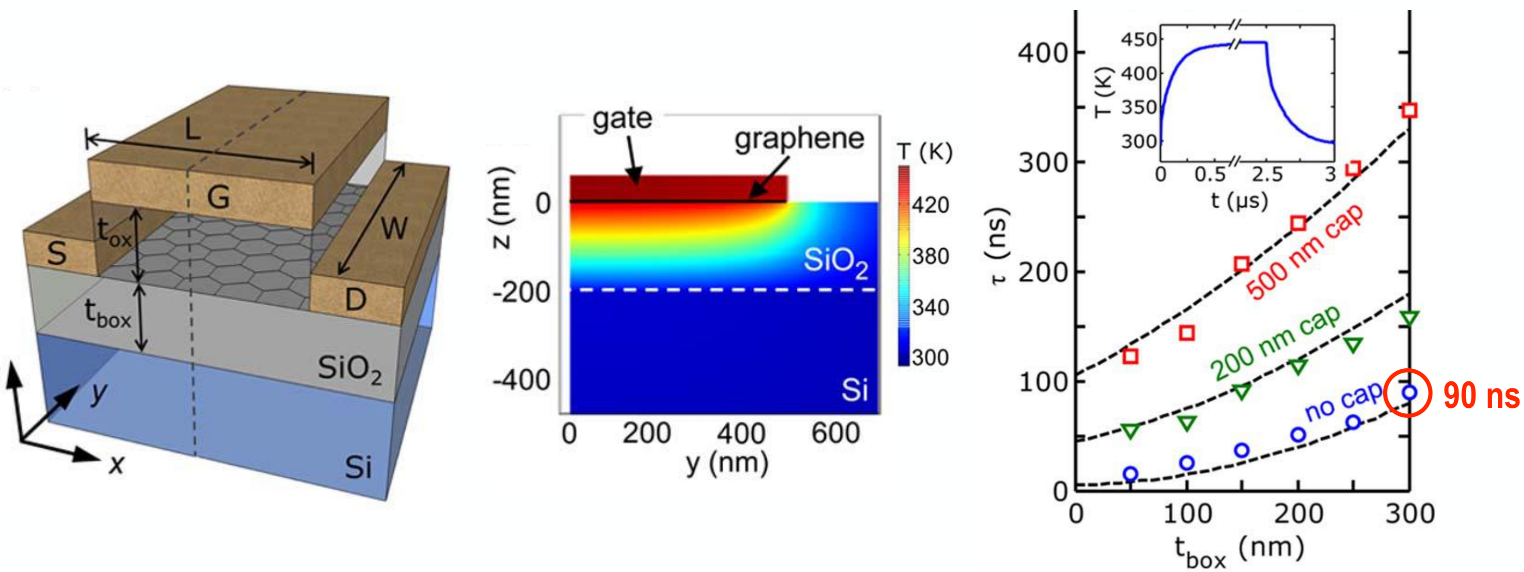
How High Can You Go?

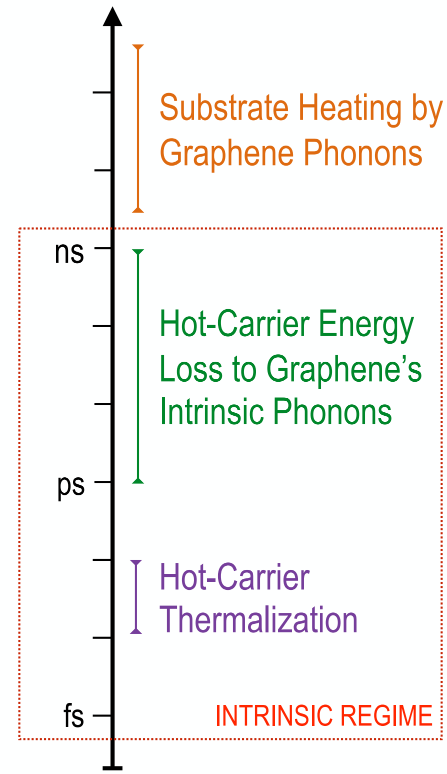
Detailed thermal simulations show heating of the SiO_2 - responsible for activating its optical phonons - is inherently **slow** (**nano**second scale)

166 IEEE ELECTRON DEVICE LETTERS, VOL. 34, NO. 2, FEBRUARY 2013

Role of Joule Heating on Current Saturation and Transient Behavior of Graphene Transistors

Sharnali Islam, Zuanyi Li, Vincent E. Dorgan, Myung-Ho Bae, and Eric Pop, *Senior Member, IEEE*

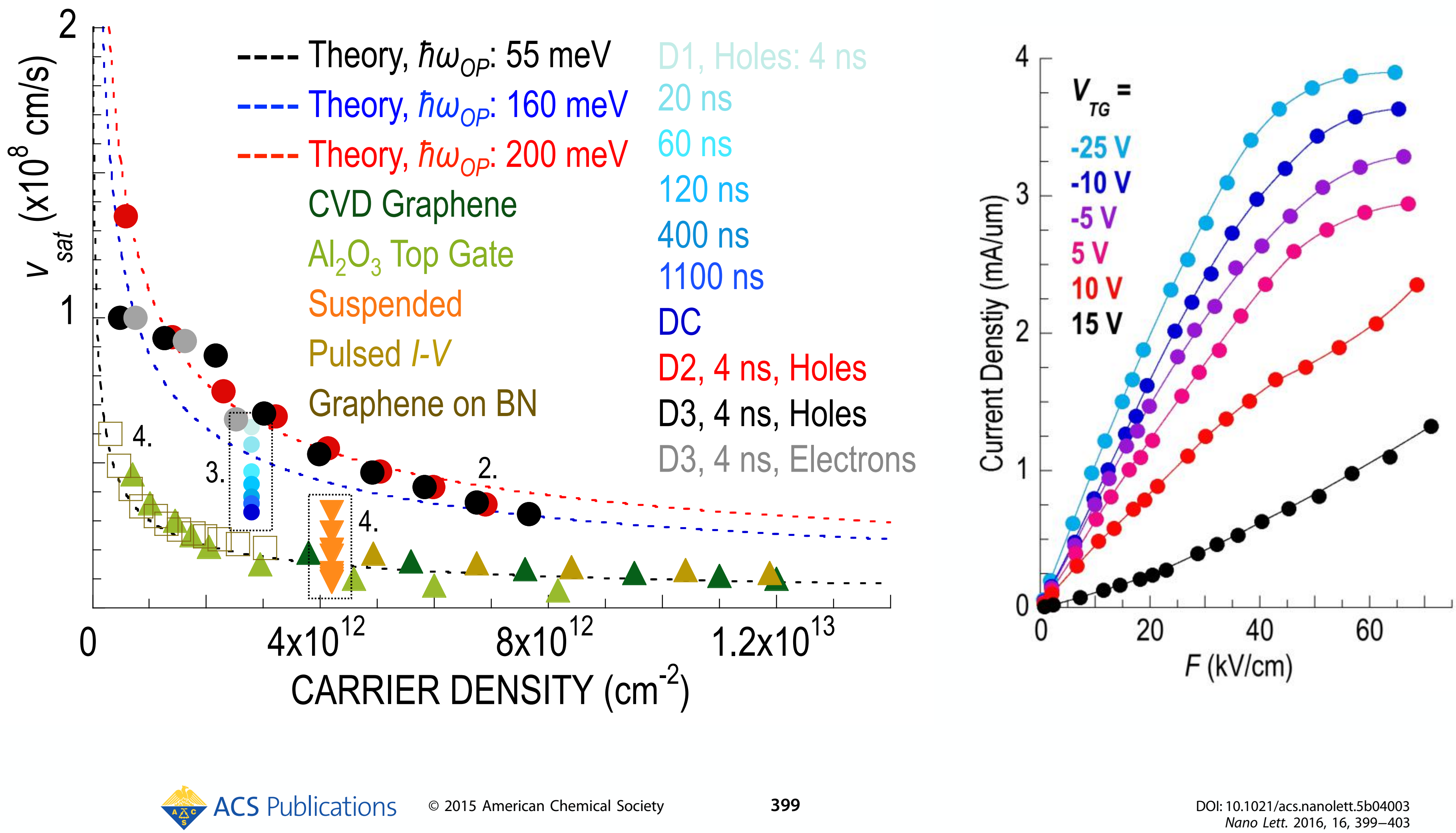




A strategy of rapid pulsing should allow the intrinsic dynamics of graphene's hot carriers to be revealed

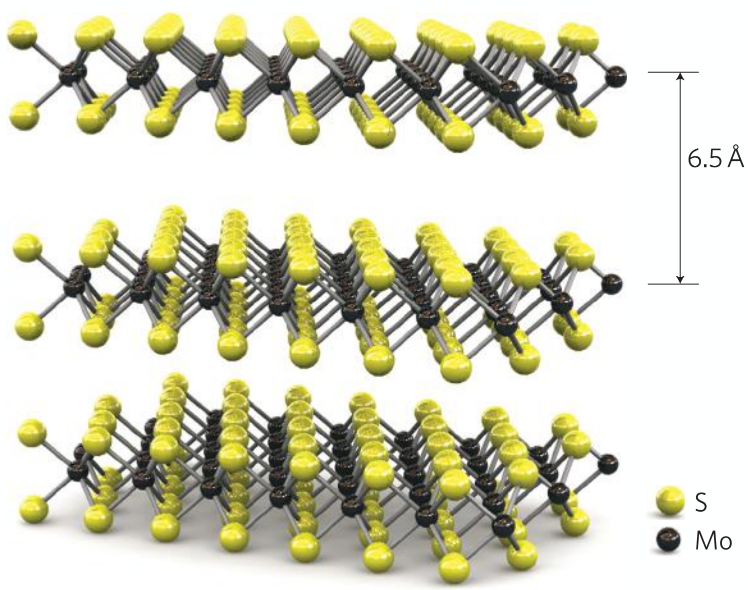
How High Can You Go?

By reducing the pulse duration to the nanosecond range we observe the **true** velocity-saturation characteristics of graphene

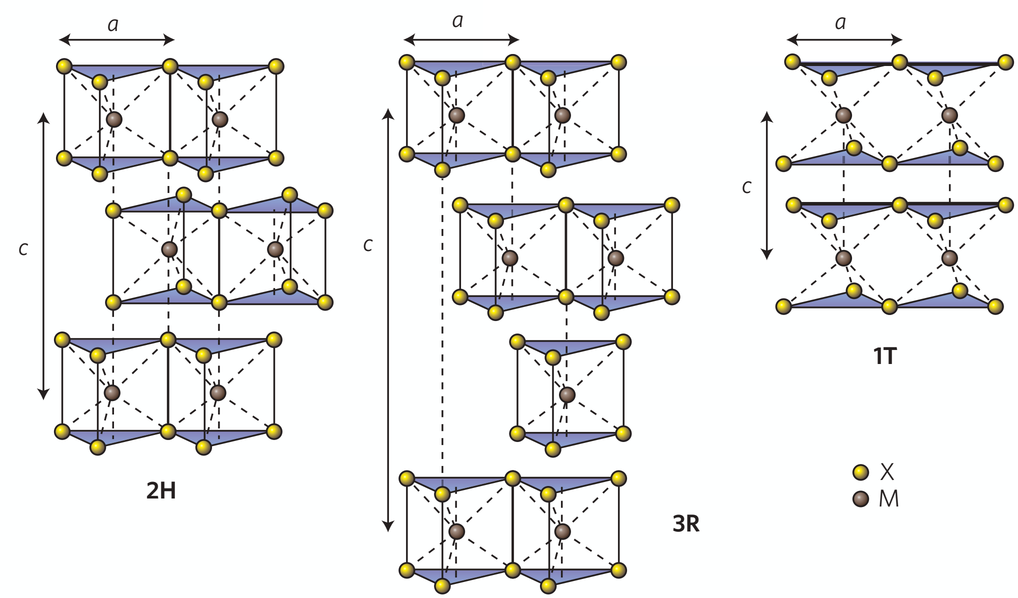


When Negative is Positive

Atomically-thin **transition-metal dichalcogenides** (TMDs) are another class of materials that are of interest for use as possible channel replacements



Q. H. Wang et al.
J. Phys.: Cond. Matt. 25, 473202 (2013)

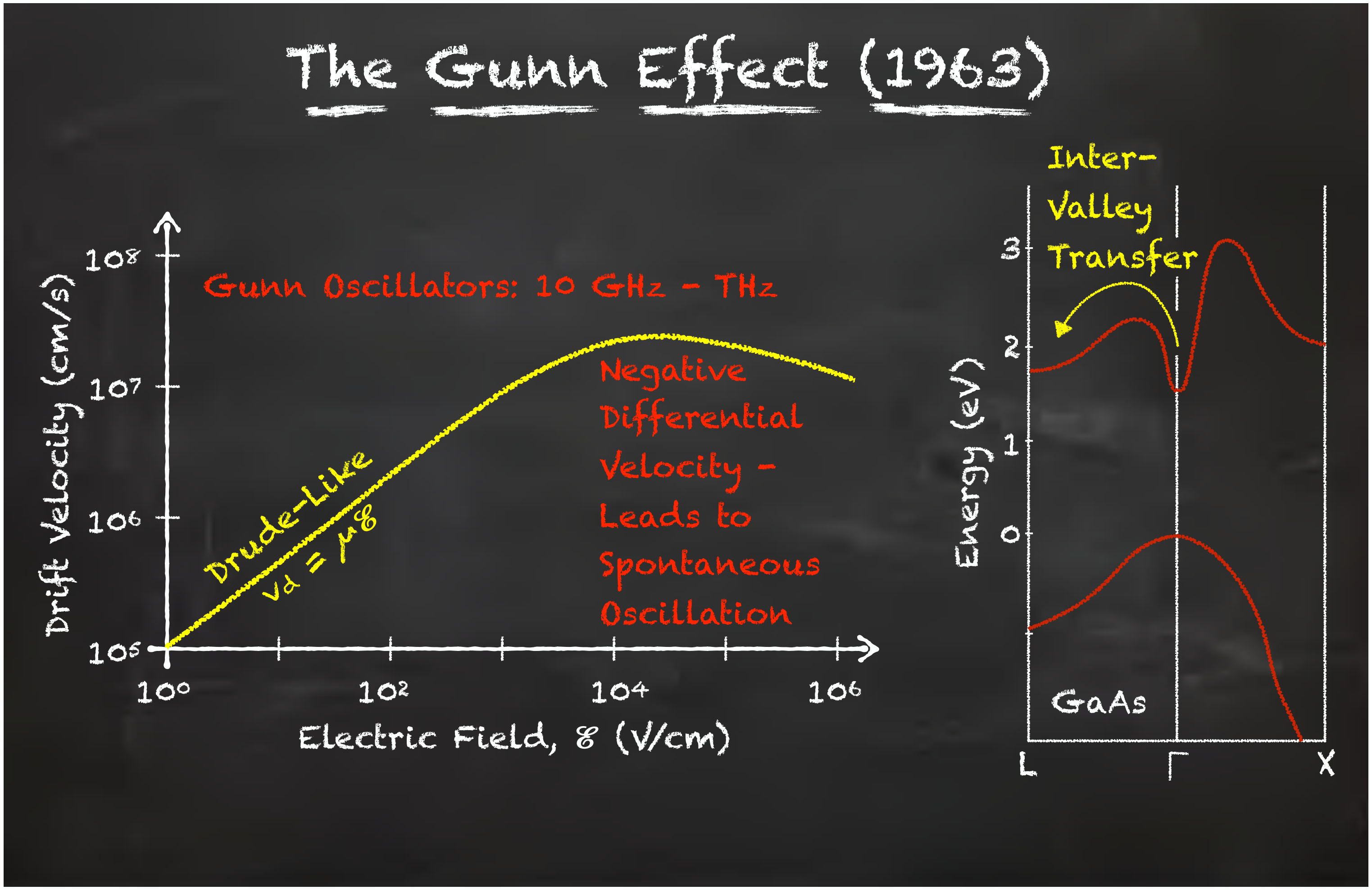


M: Transition-metal element from **Groups IV** (Ti, Zr, Hf, …), **V** (V, Nb or Ta) & **VI** (Mo, **W**, …)

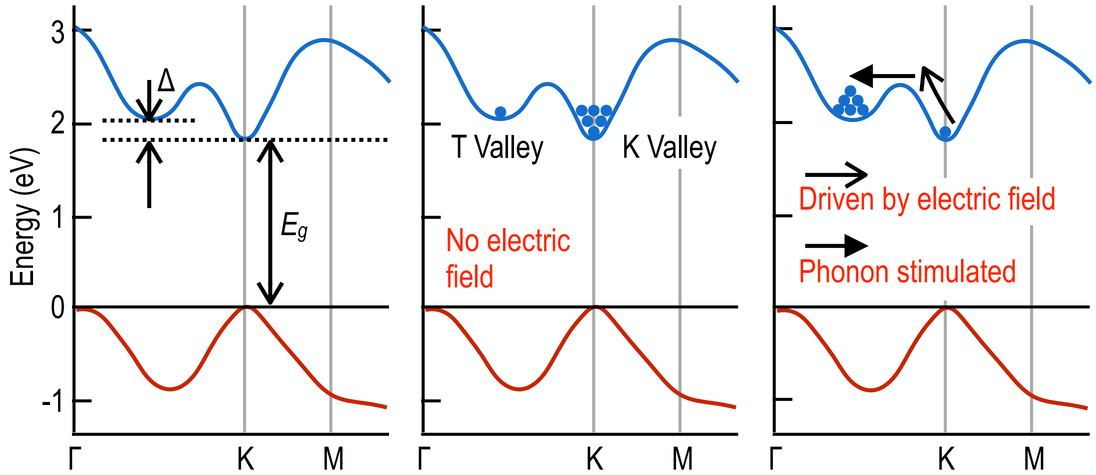
X: Chalcogen from **Group VI** (**S**, Se or Te)

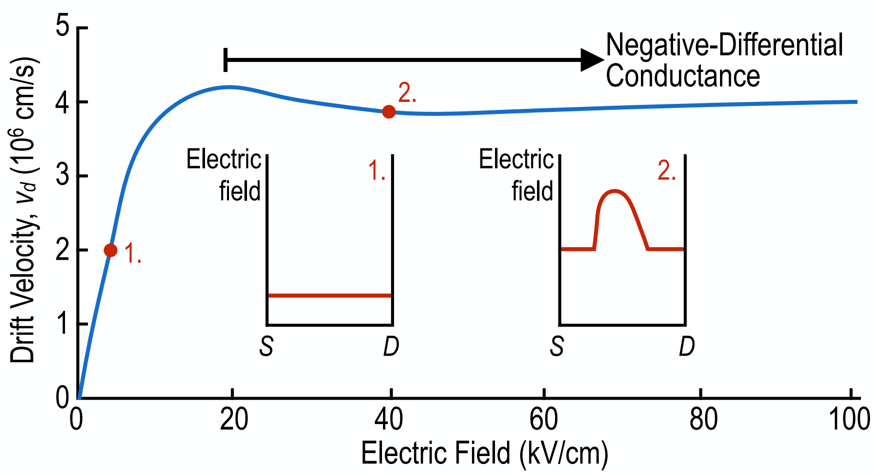
When Negative is Positive

TMDs exhibit **multi-valley** bandstructures that are reminiscent of those utilized in so-called **transferred-electron** devices



When Negative is Positive





1. Bandgap of WS_2:
   $E_g \lesssim$ **2 eV**
2. K-T valley separation:
   Δ ≲ 0.1 meV
3. Electron mass in T valley:
   $m_T^* = 0.75m_o$
4. Electron mass in K valley
   $m_K^* = 0.32m_o$

Can TMDs exhibit negative differential conductance (NDC) like that exhibited by some conventional semiconductors?

When Negative is Positive

SCIENTIFIC REPORTS | 7: 11256 | DOI:10.1038/s41598-017-11647-6

www.nature.com/scientificreports

SCIENTIFIC REPORTS

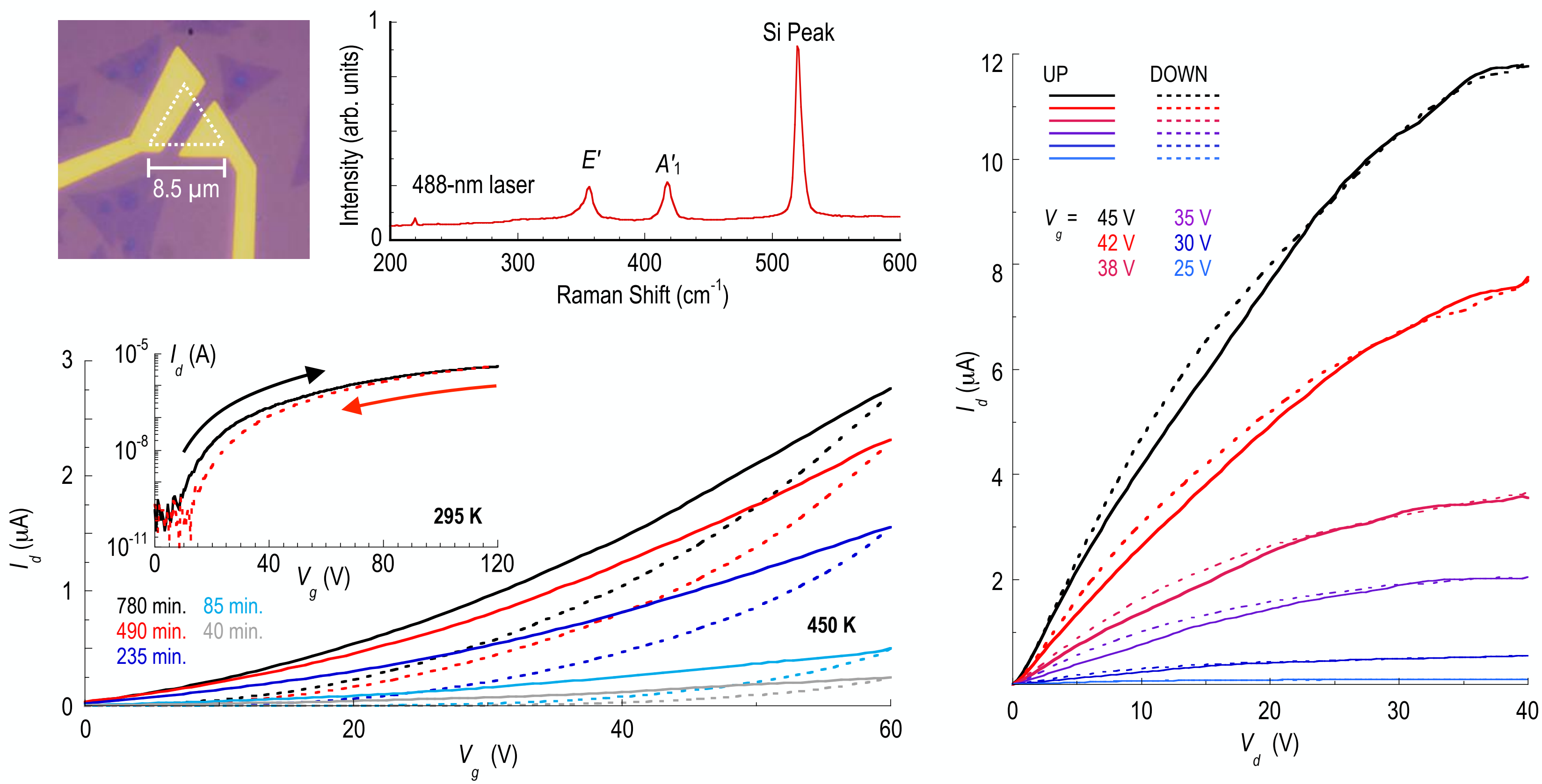
Received: 11 May 2017

Accepted: 29 August 2017

Published online: 12 September 2017

Negative Differential Conductance & Hot-Carrier Avalanching in Monolayer WS2 FETs

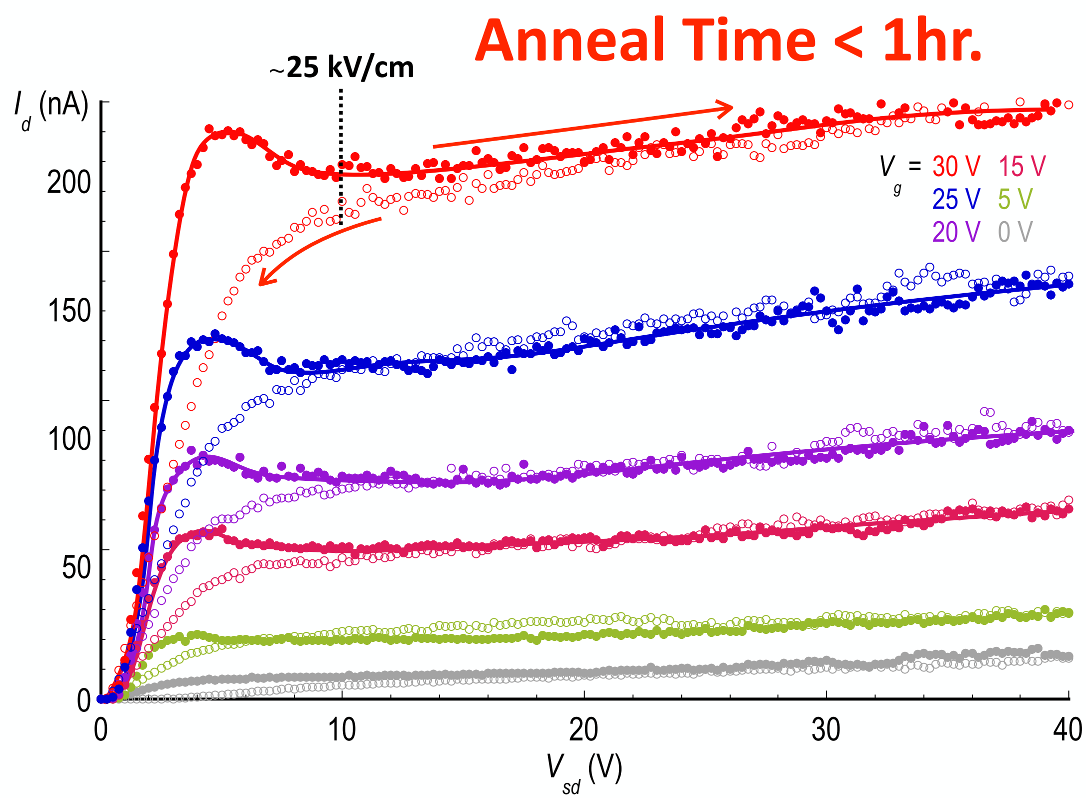
G. He[1], J. Nathawat[1], C.-P. Kwan[2], H. Ramamoorthy[1], R. Somphonsane[3], M. Zhao[4], K. Ghosh[1], U. Singisetti[1], N. Perea-López[5], C. Zhou[6], A. L. Elías[5], M. Terrones[5,6,7], Y. Gong[8], X. Zhang[8], R. Vajtai[8], P. M. Ajayan[8], D. K. Ferry[9] & J. P. Bird[1]



We study these effects in monolayer WS_2 FETs

When Negative is Positive

SCIENTIFIC REPORTS | 7: 11256 | DOI:10.1038/s41598-017-11647-6



1. NDC seen for **partially-annealed** devices with currents **<1 μA/μm**
2. NDC accompanied by **increased** noise level – as expected for **traveling domains** in the Gunn effect
3. **Hysteresis** in transistor curves also typical of the Gunn effect – reflects different **valley populations** for up and down sweeps

When Negative is Positive

We attribute these results to the influence of annealing on mechanical **strain** in the atomically-thin WS_2 layers

Ann. Phys. (Berlin) 526, No. 9–10, L7–L12 (2014) / DOI 10.1002/andp.201400098

annalen der physik

Rapid Research Letter

Many-body and spin-orbit effects on direct-indirect band gap transition of strained monolayer MoS_2 and WS_2

Luqing Wang[1], Alex Kutana[1], and Boris I. Yakobson[1,2,3,]*

Received 4 May 2014, revised 11 July 2014, accepted 14 July 2014
Published online 6 August 2014

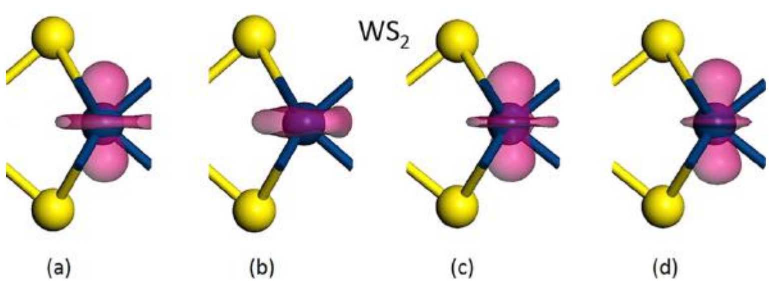
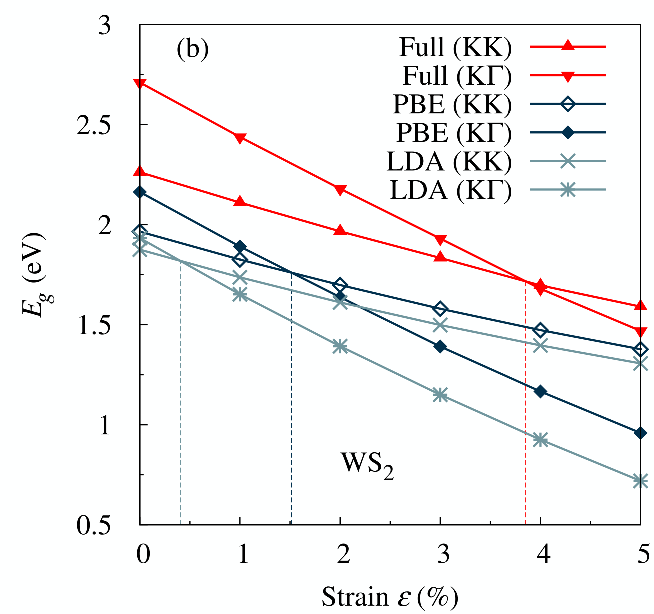


Figure 2 Partial charge densities of (a) conduction band minimum (CBM) and (b) valence band maximum (VBM) states of 2D WS_2 without strain, and (c) CBM and (d) VBM states of 2D WS_2 under 5% strain. Yellow spheres represent sulfur atoms, and dark blue spheres represent tungsten atoms. All charge density iso-surfaces are shown at the same level of charge density.

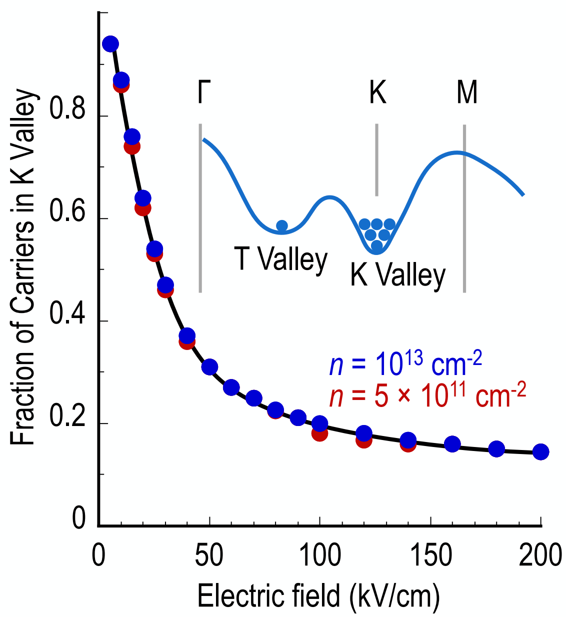


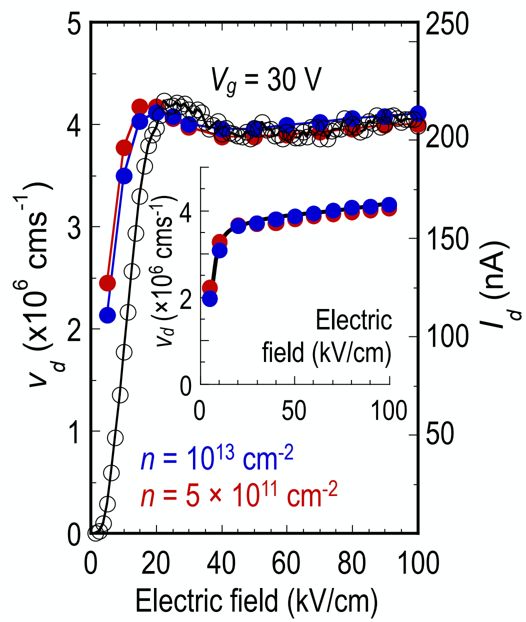
Biaxial strain raises the T valleys relative to the K valleys – changing the conditions for the onset of NDC

When Negative is Positive

In the unstrained state the energy separation of the T and K valleys in monolayer WS_2 is around **80 meV**

Carriers transfer to the T valleys at **vanishingly-small** fields and we thus obtain **no** negative differential conductance in EMC calculations



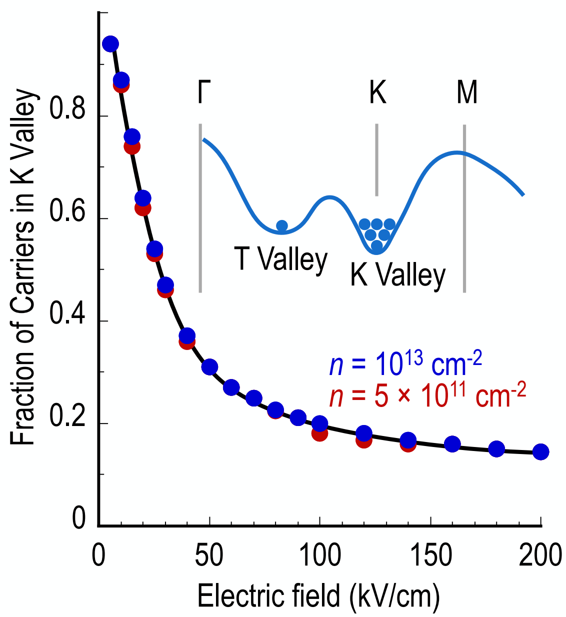


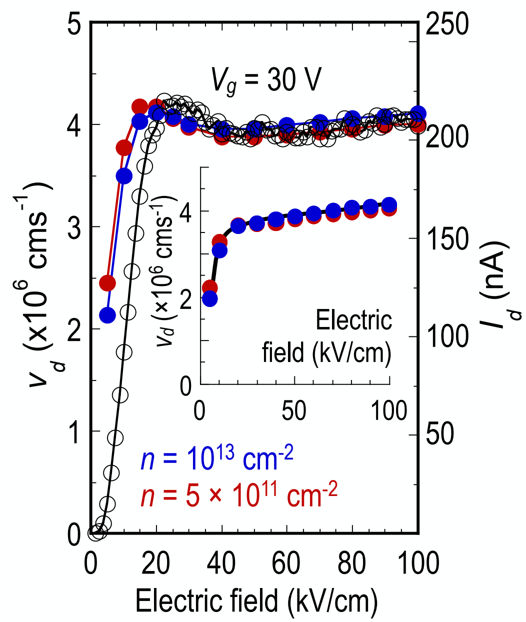
As we steadily raise the T valleys we find NDC begins for an inter-valley separation (Δ) of as little as 100 meV

When Negative is Positive

In the unstrained state the energy separation of the T and K valleys in monolayer WS_2 is around **80 meV**

Carriers transfer to the T valleys at **vanishingly-small** fields and we thus obtain **no** negative differential conductance in EMC calculations





This corresponds to a strain level of just 1%

Conclusions

- Semiconductor nanodevices are ideal systems for investigating manifestations of **nonequilibrium** physics
- Energy-transfer processes in these devices can be probed via a strategy of **nanosecond-scale** electrical pulsing
- This has allowed us to reveal the **superior** electrical properties **intrinsic** to graphene[1]

These results are important for the development of high-speed devices based on graphene

[1] H. Ramamoorthy et al., Nano Letters **16**, 399 (2016).

Conclusions

- We have investigated **hot-carrier** transport phenomena in **monolayer WS_2** transistors
- **NDC** is observed in **partially-annealed** devices[2] and shows all the features typical of the Gunn effect
- The influence of **annealing** was discussed in terms of its role in mediating **strain** and the **T-K valley separation**[2]

These results are relevant for the realization of high-frequency sources based on atomically-thin TMDs

[2] G. He et al., Scientific Reports **7** (2017) 11256; DOI: 10.1038/s41598-017-11647-6