Monitoring deflection, strain and doping in suspended graphene using Raman spectroscopy

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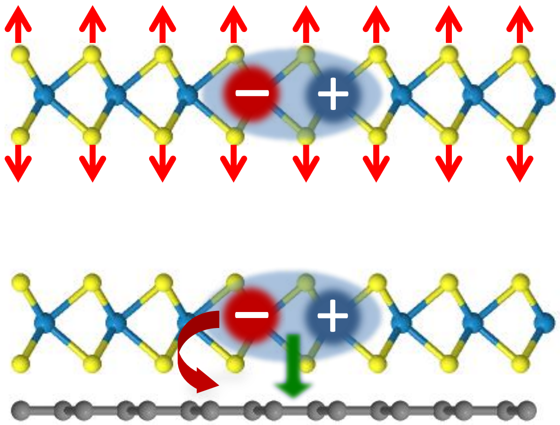
Work done with: Dominik Metten, Guillaume Froehlicher, Xin Zhang, H. Majjad
Collaborators at Univ. Lyon: Kevin Makles, Pierre Verlot

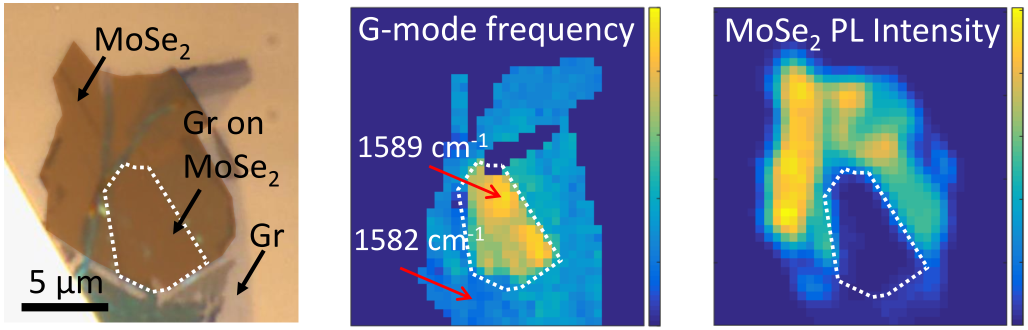
Funding: ANR NIE USIAS University of Strasbourg Institute for Advanced Study IUF

2D Materials at IPCMS

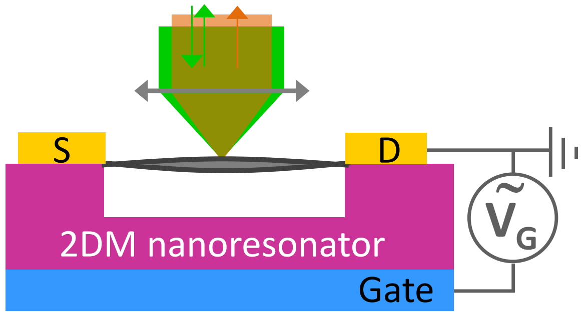
- Optical spectroscopy
- Phonons, excitons and their coupling(s)
- Energy and charge transfer
- Blisters, nanoresonators

…also spintronics, single electron devices,…

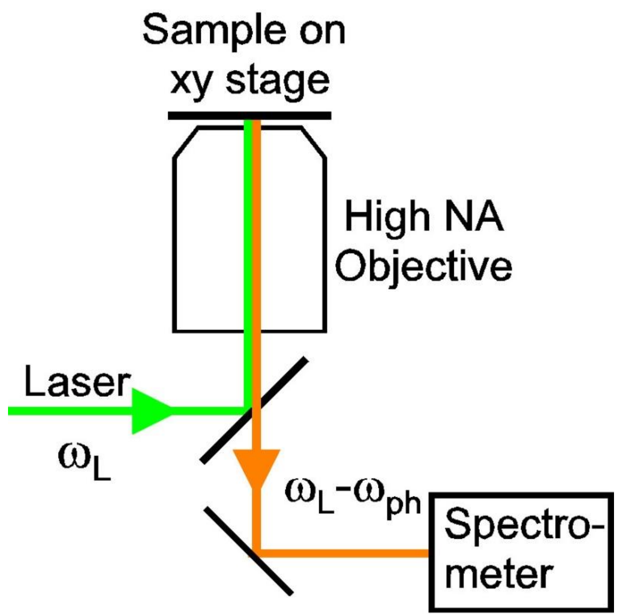




Froehlicher *et al.*, arxiv 1703.05396



Raman spectroscopy of graphene

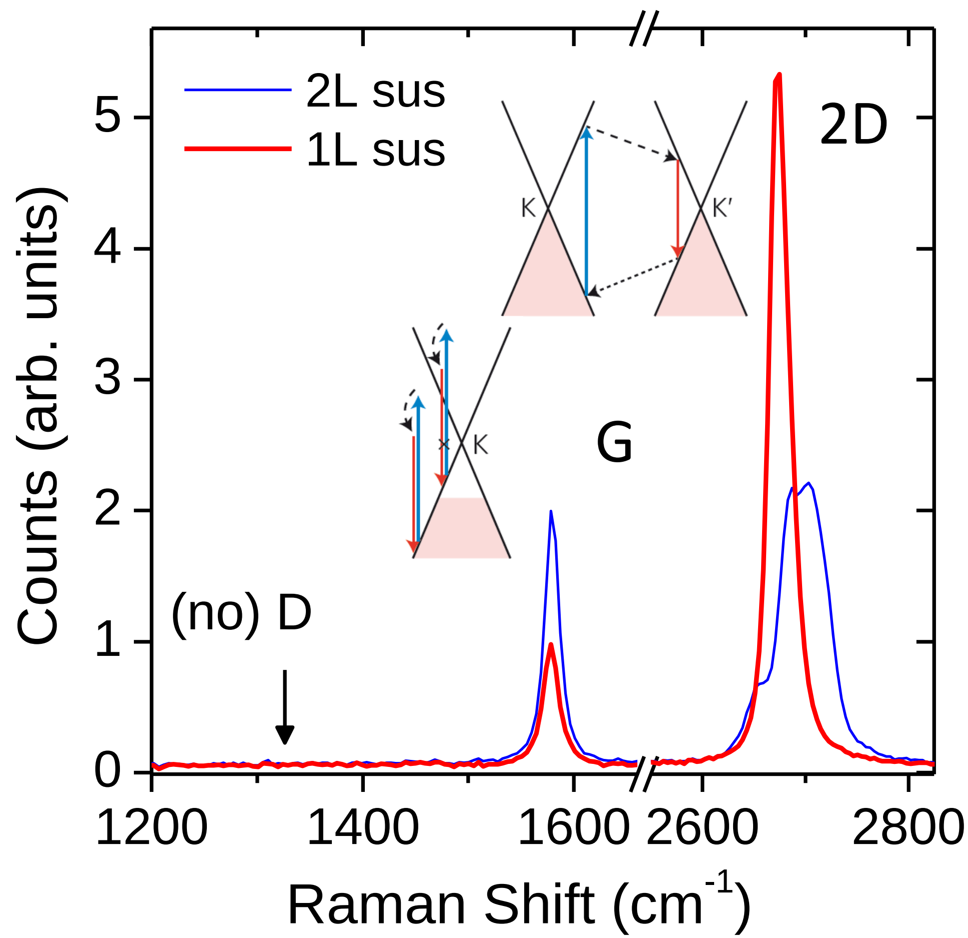


Highly sensitive probe of:

→ Number of Layers

→ Doping level, Disorder, Strain

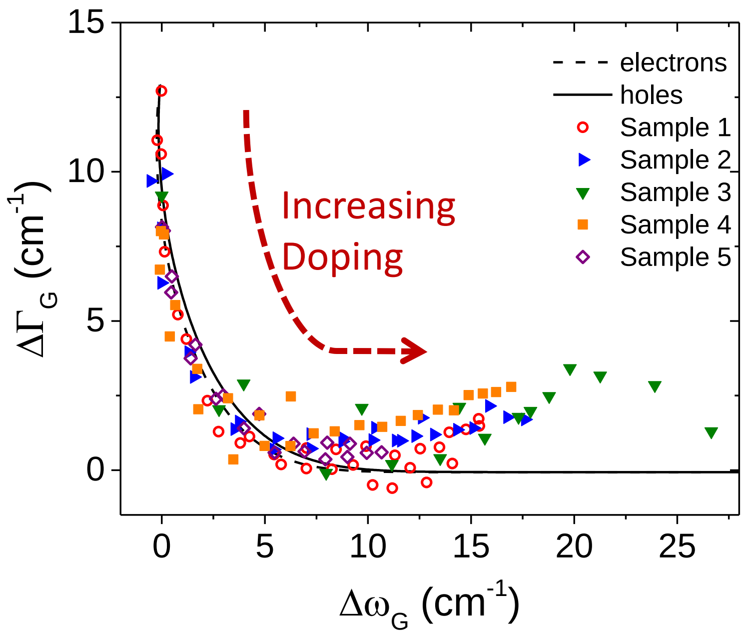
→ Temperature

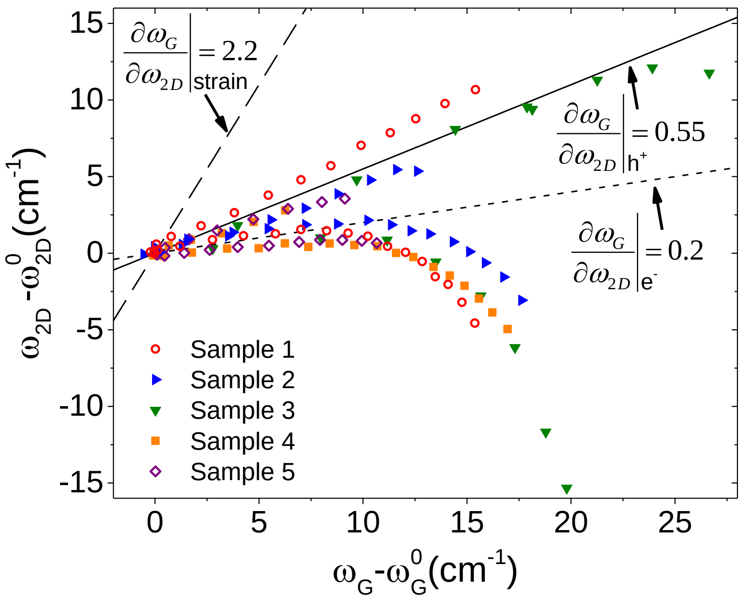


Reviews: A.C Ferrari & D.M. Basko, Nature Nano (2013)
L.M. Malard *et al.* Rep. Prog. Phys (2009)

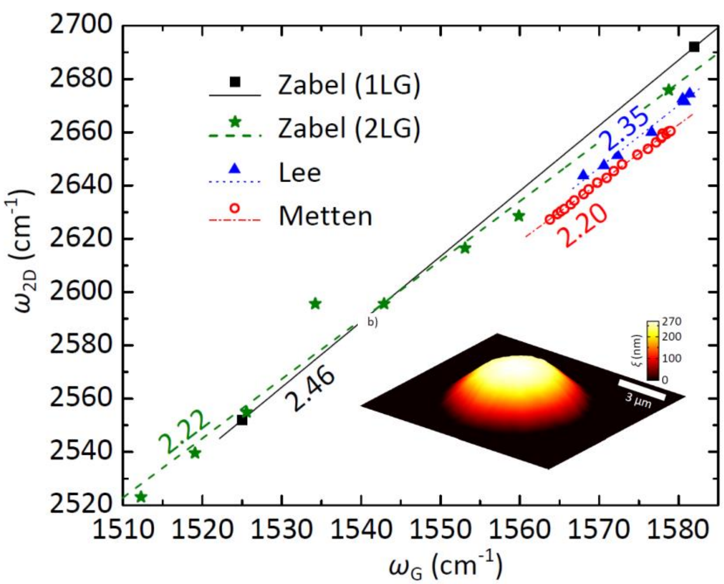
Separating doping and strain

Doping





Biaxial Strain



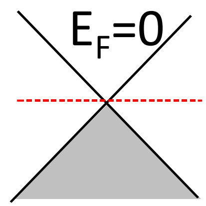
Well-defined and useful correlations between Raman parameters

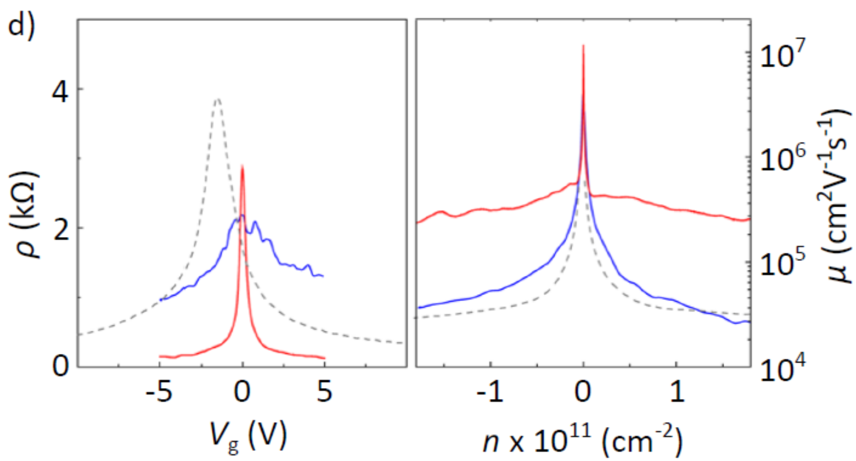
Data : Froehlicher & Berciaud, PRB 2015
Metten *et al.*, PRApplied 2014
Also : Zabel *et al.*, Nano Lett 2012
Lee *et al.*, Nano Lett 2012
See also : A. Das *et al.*, Nat Nano 2008
Lee *et al.*, Nat Comm 2012

Suspended graphene: a model system

Electronic and optical properties

- clean, unscreened system
- No residual doping
- Ultrahigh carrier mobility

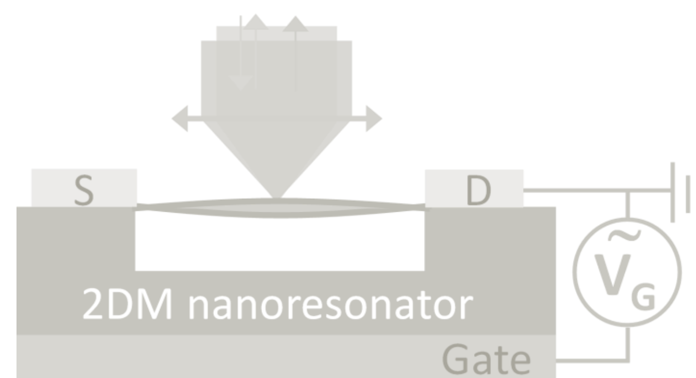




K. Bolotin, Solid State Commun 2008 (transport)
S. Berciaud *et al.* Nano Letters **9**, 346 (2009) (Raman)
S. Berciaud *et al.* Nano Letters **13**, 3517 (2013) (Raman)

Mechanical properties

- Low mass (~ 7.5 10^{-7} kg/m^2)
- High Young's modulus (~ 1TPa)
- Intrinsic strength (43 N/m)
- Negligible bending rigidity
- Ultrastrong adhesion (0.45 J/m^2)
- Impermeability



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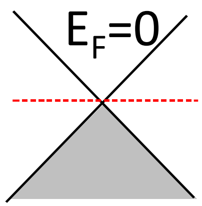

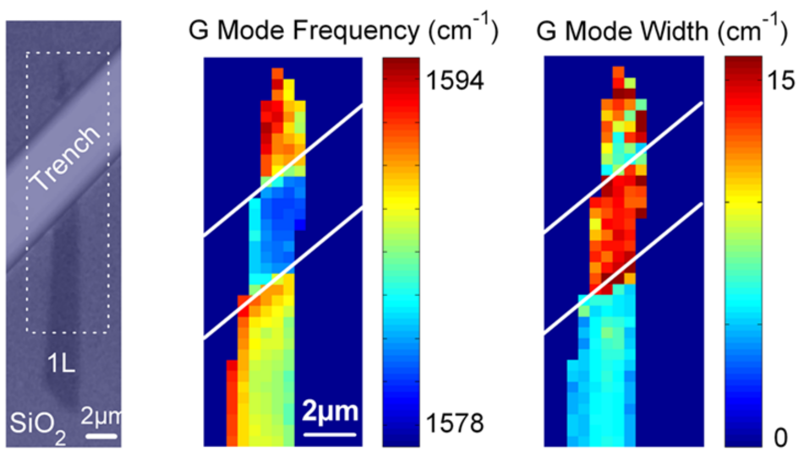

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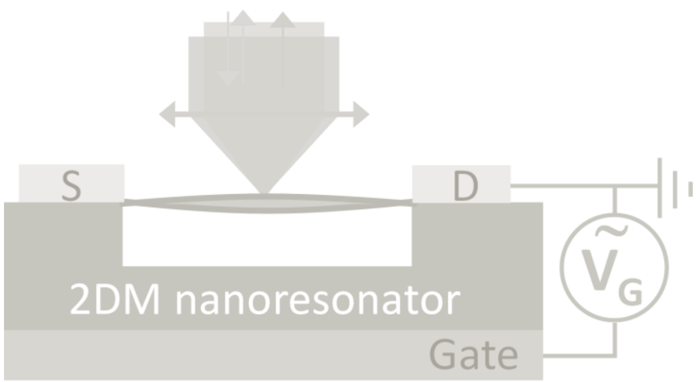

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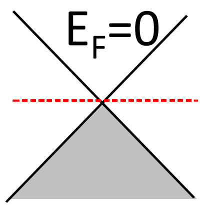
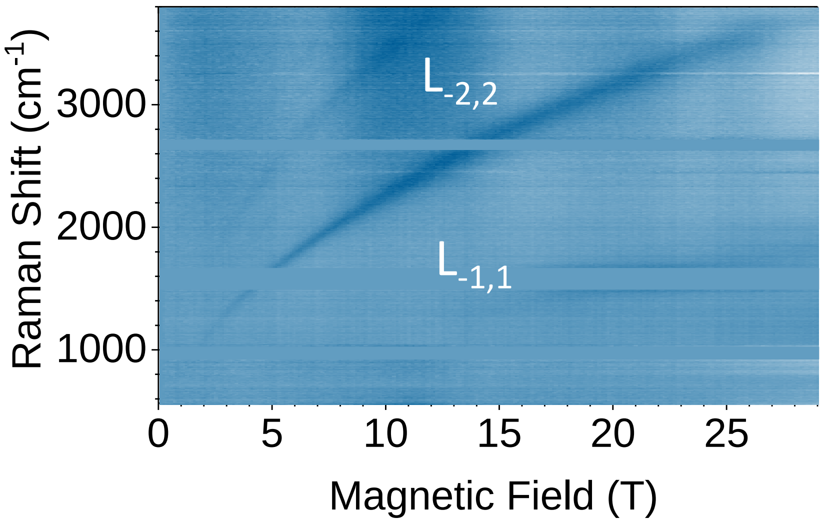
- **LL spectroscopy**
- **Many-body effects**





Berciaud, Potemski, Faugeras, Nano Lett. **14**, 4538 (2014)
Faugeras, Berciaud, Basko, Potemski *et al.*, PRL **114**, 126804 (2015)

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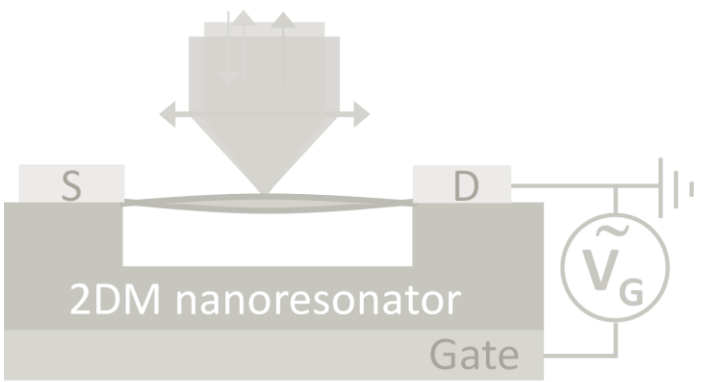

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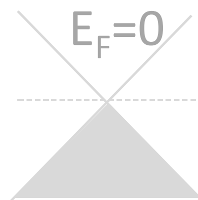

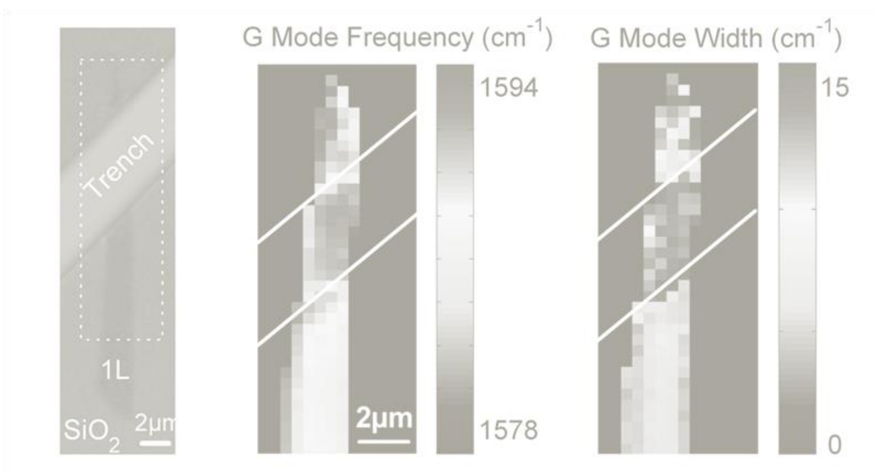

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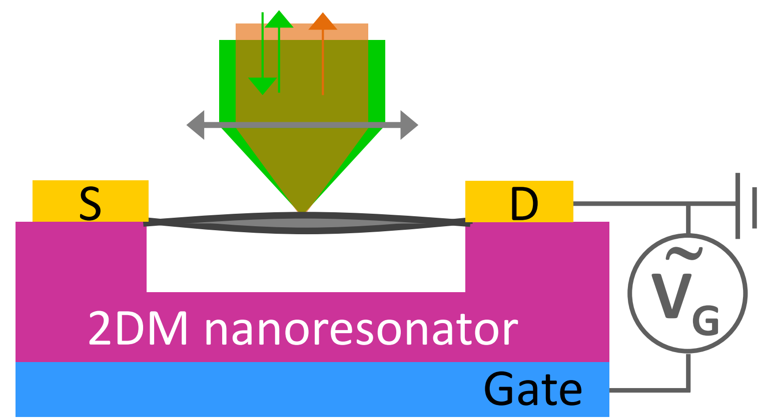

Bunch *et al.*, Science 2007, Nano Lett 2008,
Koenig *et al.*, Nat. Nano 2011

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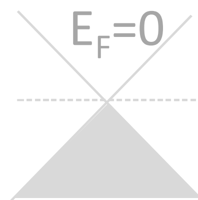

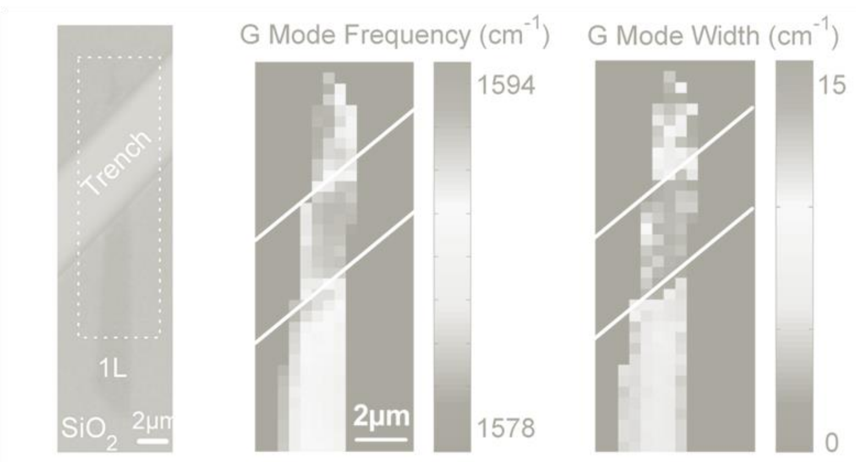

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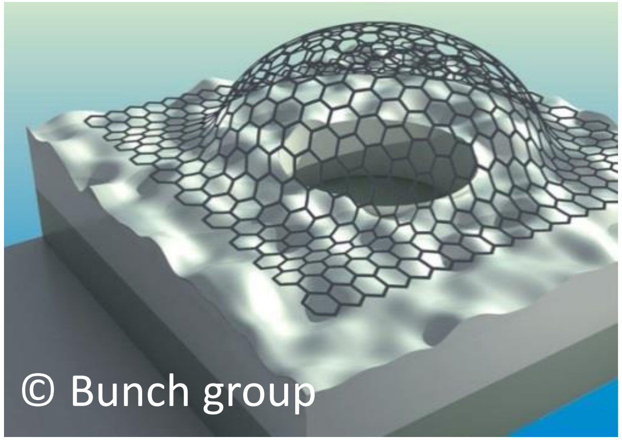

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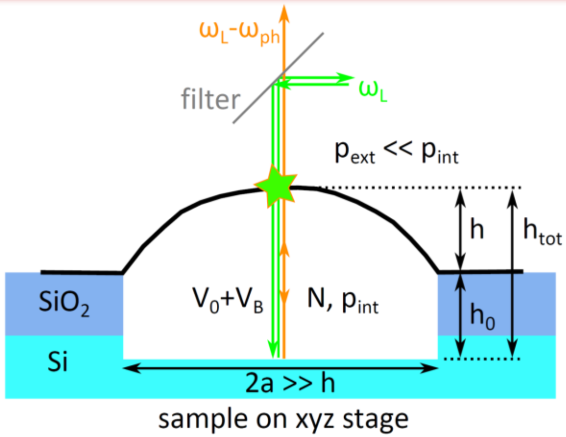
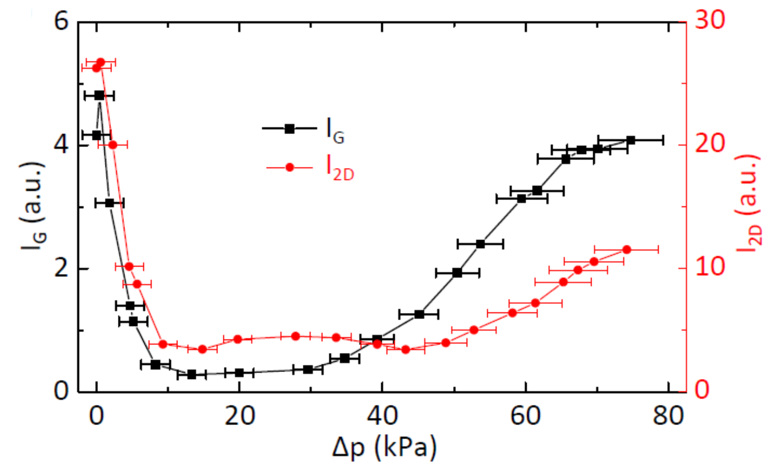
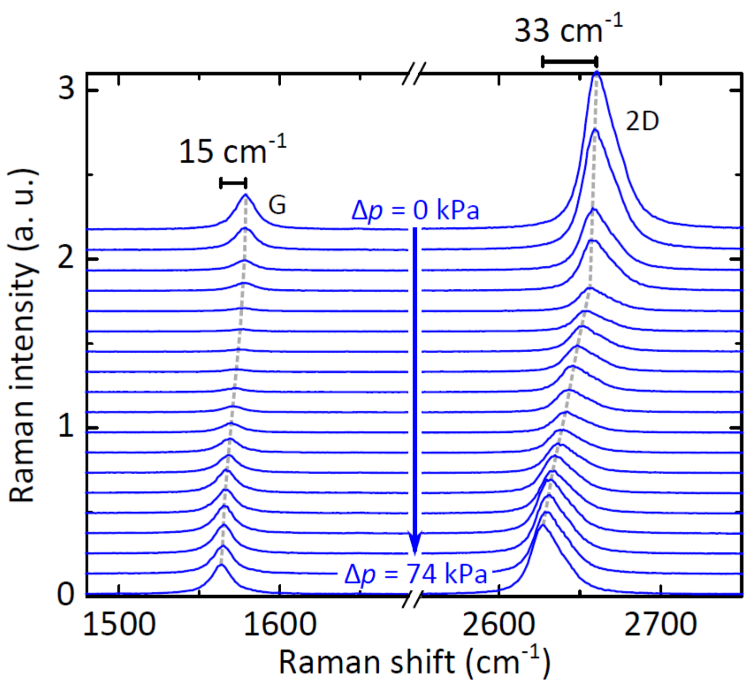
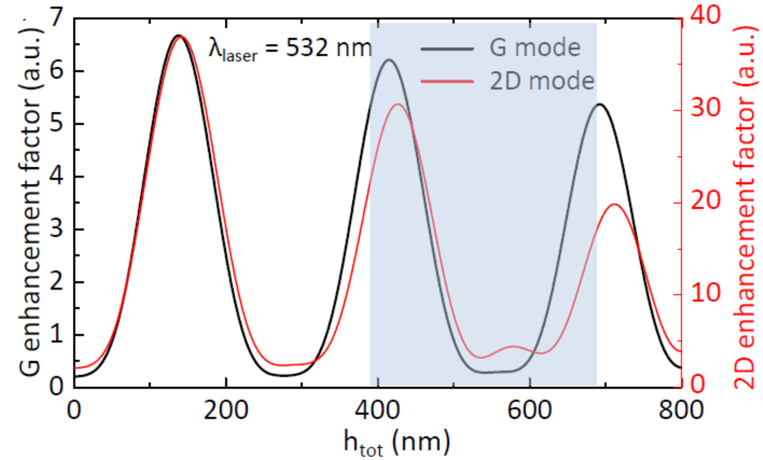
All-optical blister test of freestanding graphene (1)

- *The Raman intensity depends sensitively on the blister height*

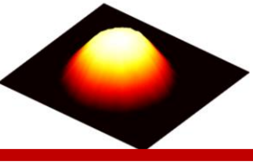








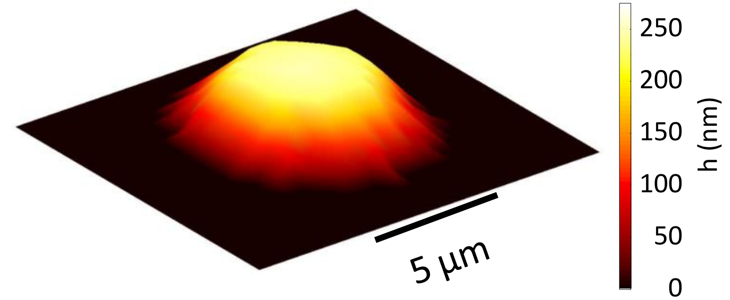
Metten et al. PRApplied 2014, PSSb 2015, D. Yoon *et al.* PRB 2009



All-optical blister test of freestanding graphene (2)

Reconstructed blister

height profile at Δp=74 kPa

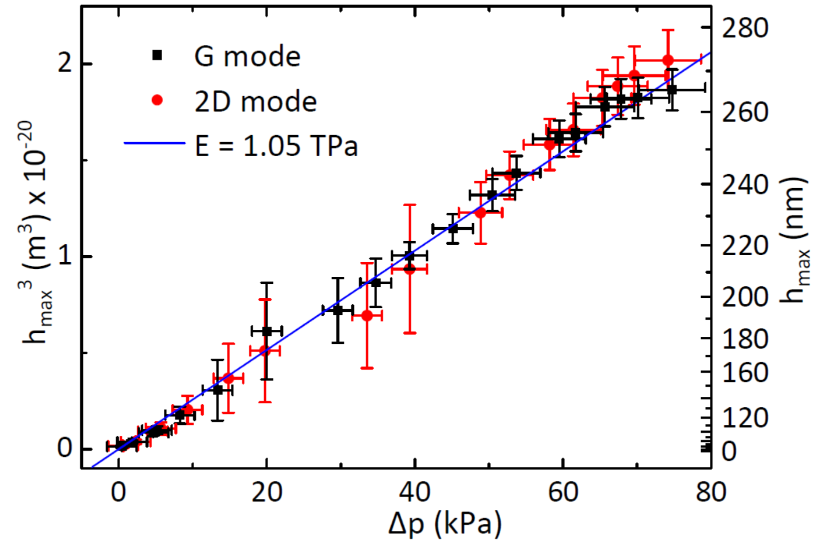


Pressure dependent study

$$\Delta p = \frac{K(\nu)\, Et}{a^4} h^3$$

$$K(\nu = 0.16) \approx 3.1$$

$$E \approx 1.0 \pm 0.1\,\mathrm{TPa}$$

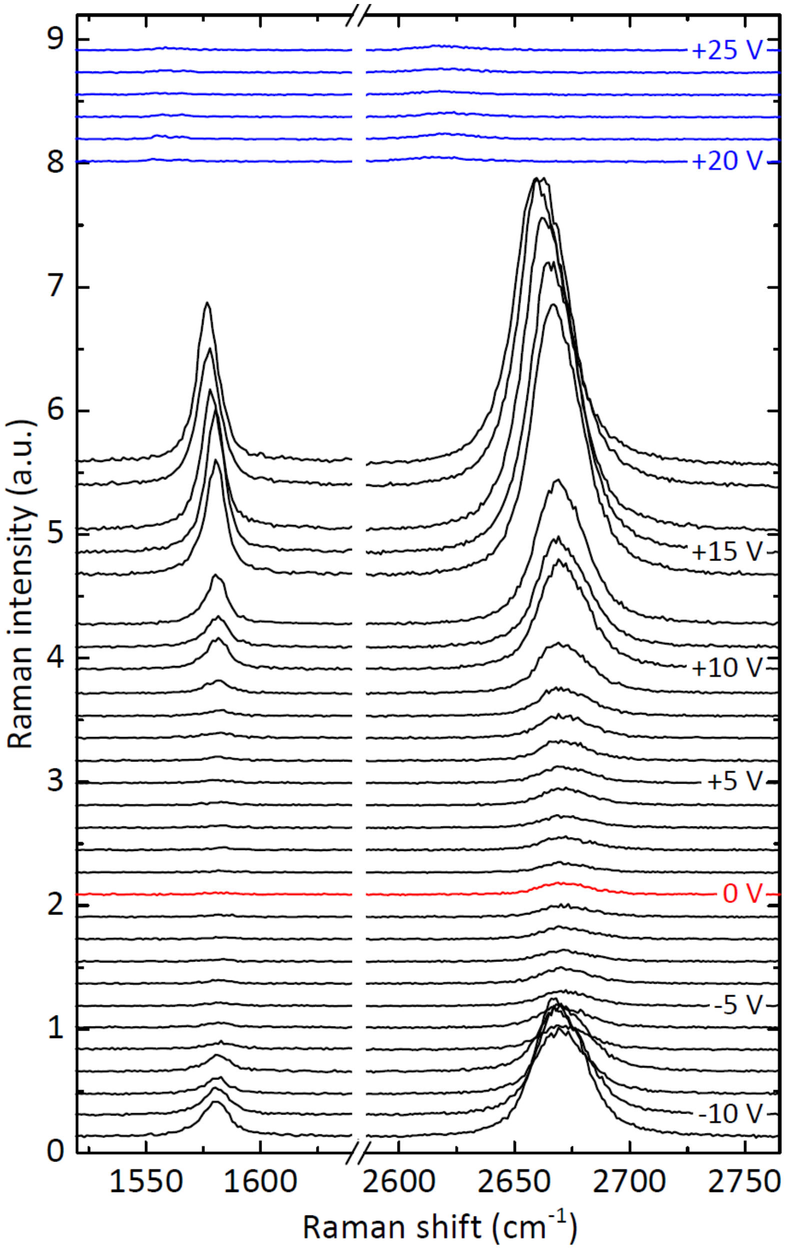


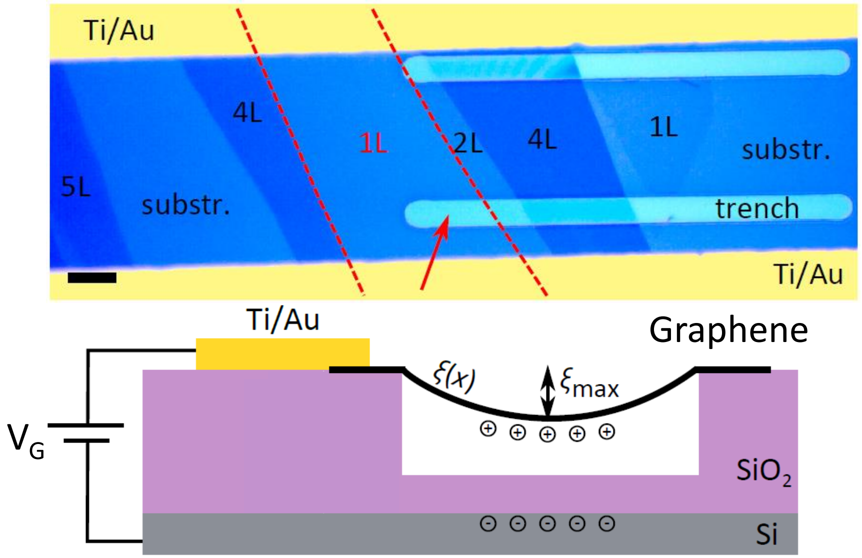
- Measurement of the Grüneisen parameters (phonon shift rate under known strain)
- Young modulus in excellent agreement with nano-indentation measurements
  - ➢ Generalization to other 2D-systems
  - ➢ Sensitive graphene-based pressure sensors (ΔI_{Raman}>100% for Δp≈2 kPa)

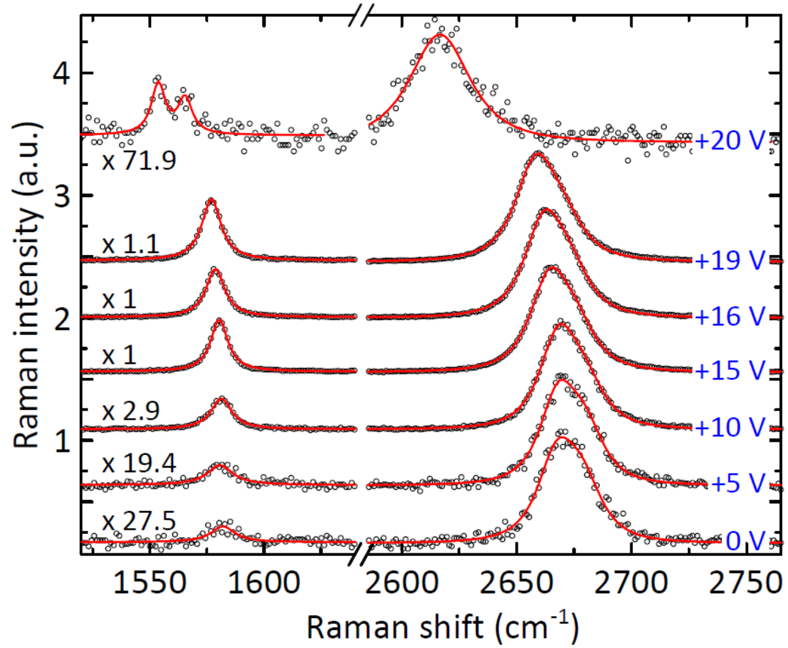
Theory: Hencky (1915)

D. Metten *et al.* Phy. Rev. Applied **2**, 054008 (2014)

Suspended graphene under electrostatic pressure







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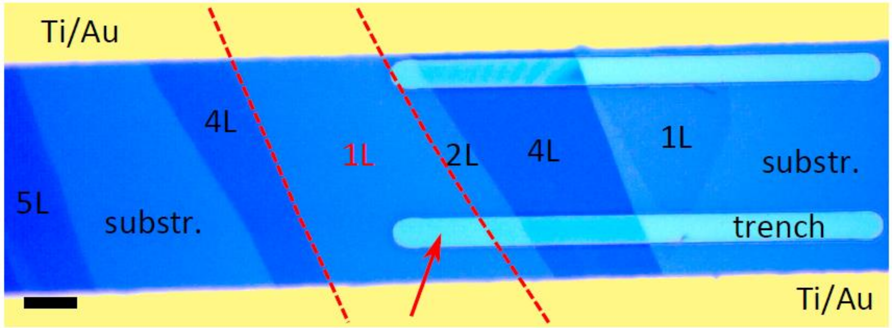
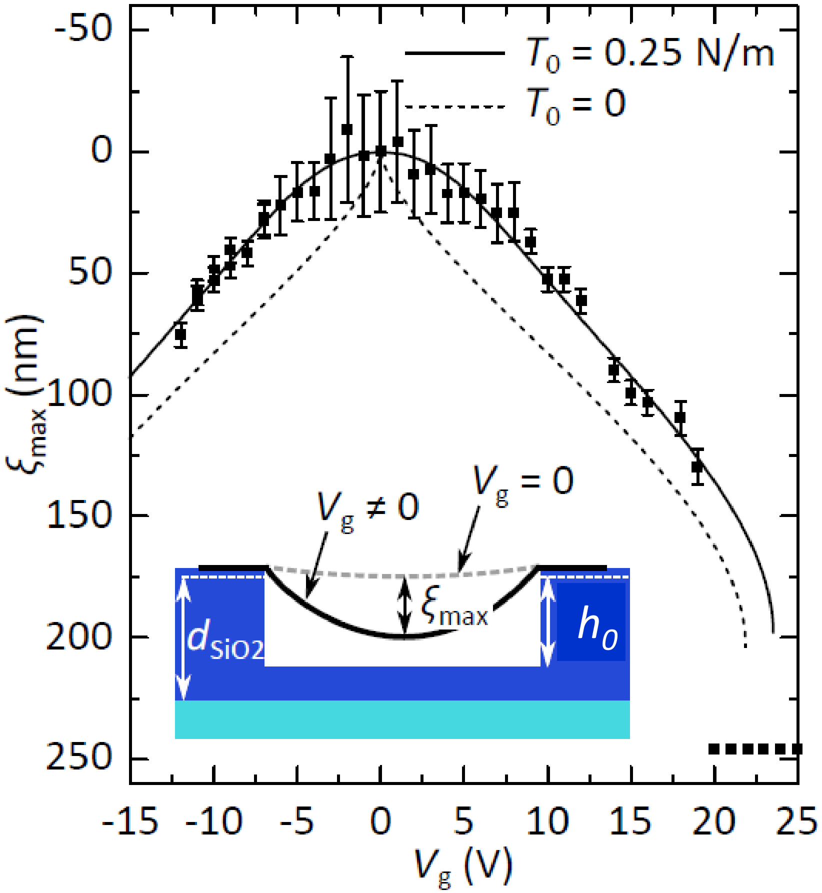


$$P_{\mathrm{el}} = \frac{8T_0}{L^2}\,\xi_{\mathrm{max}} + \frac{64Et}{3(1-\nu^2)L^4}\,\xi_{\mathrm{max}}^3$$

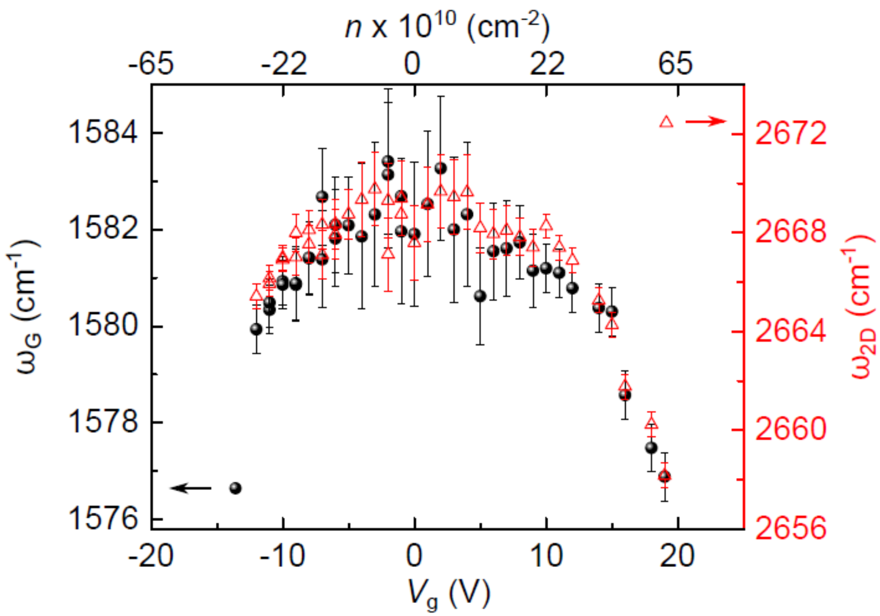
T_0: built-in tension, L: trench width
Et: 2D Young's modulus, ν : poisson ratio

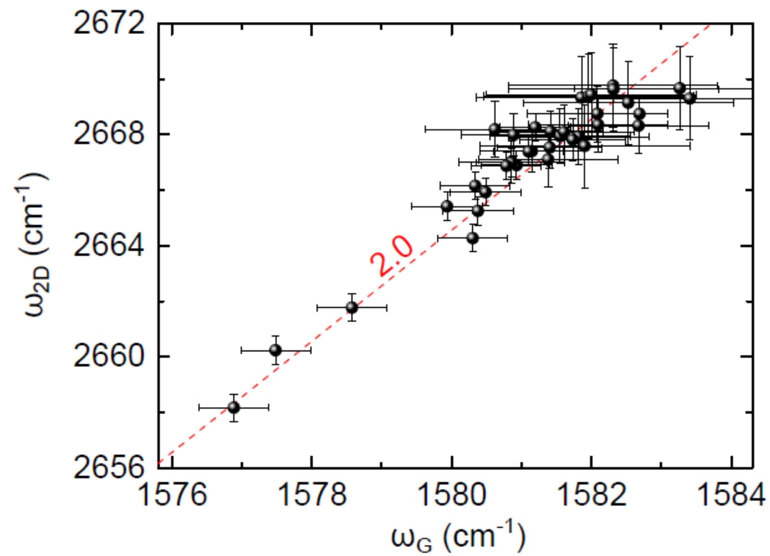


Gate-induced (static) deflection in suspended graphene
→ in situ height calibration in nanoresonators
→ Interplay between strain and doping

D. Metten, G. Froehlicher and SB, 2D Materials **4** 014004 (2017)

Strain vs Doping (1)



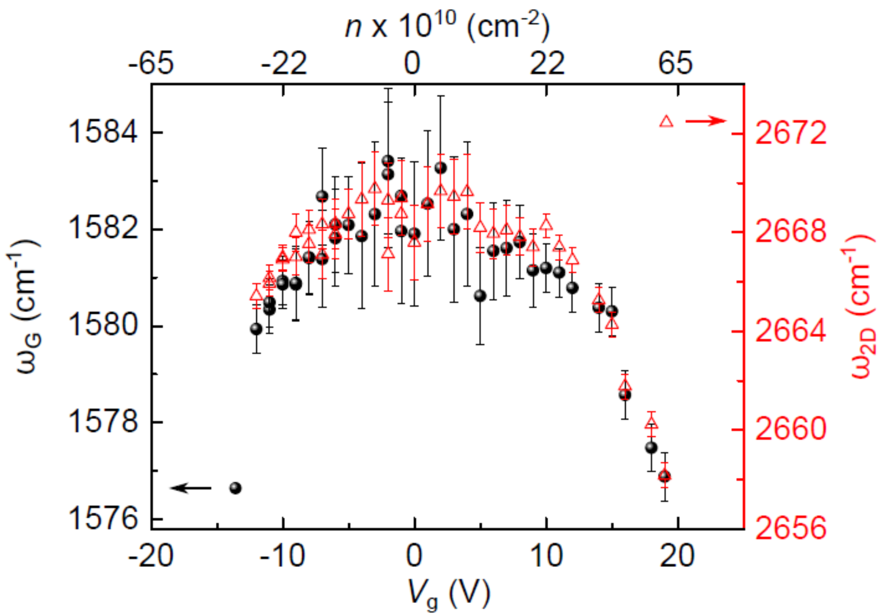


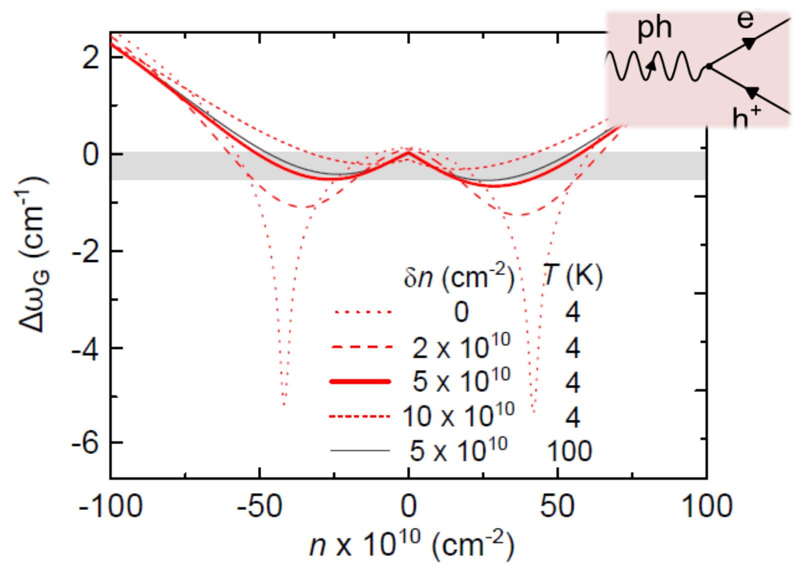
✓ Maximal estimated strain ~ 0.1 to 0.15 % *

➢ How about doping?

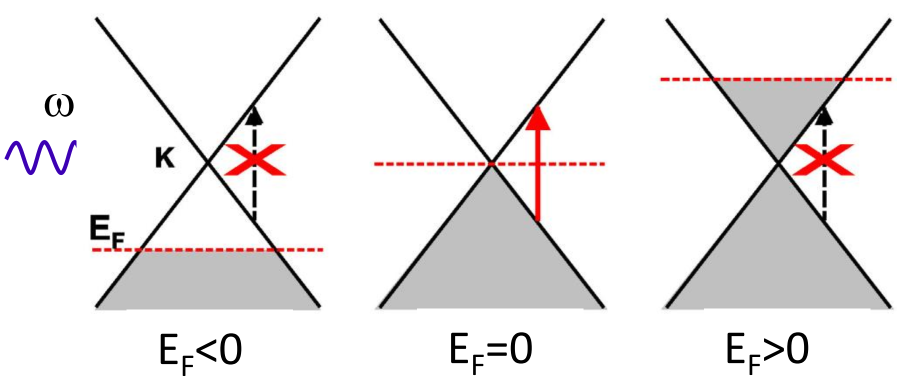
* Estimated from Mohuiddin PRB 2009, Huang PNAS 2009, Zabel NL 2012, Metten PR Applied 2014, Androuliakis Sci. Rep 2016, Polyzos Nanoscale 2015, & many more

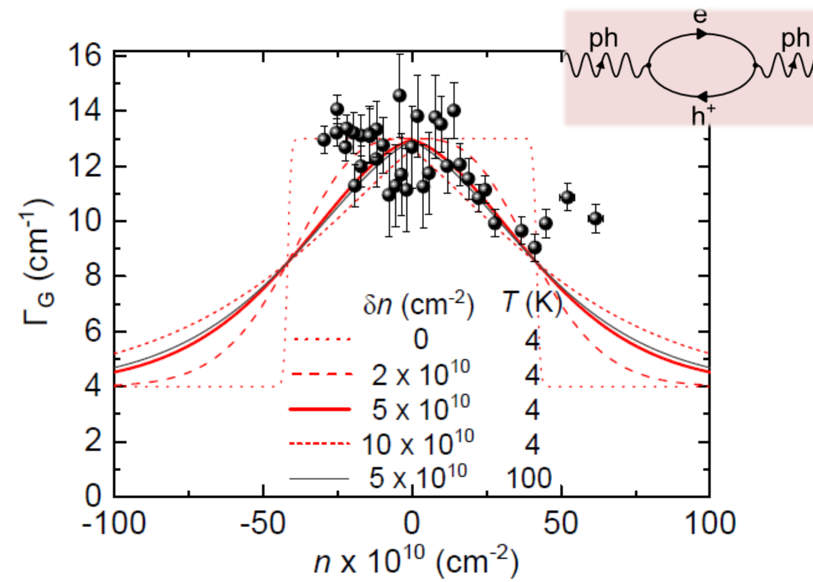
Strain vs Doping (2)





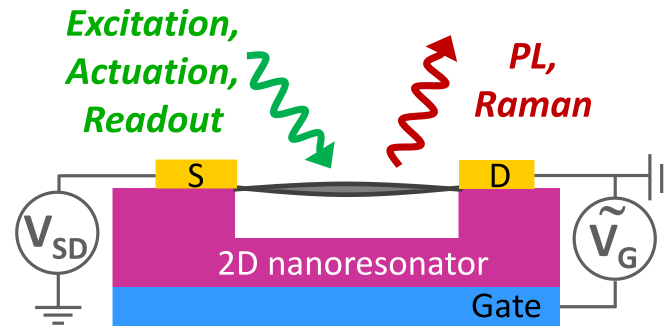
✓ G-mode narrowing due to Pauli blocking

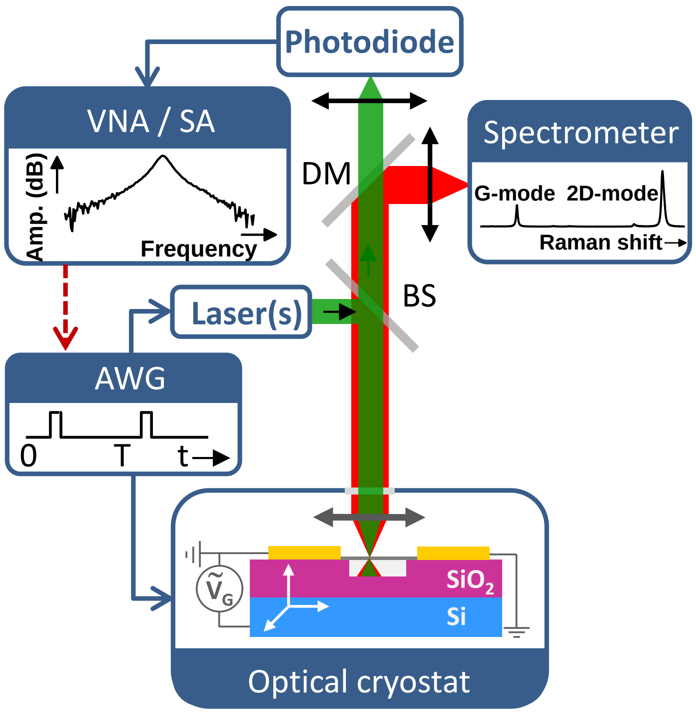


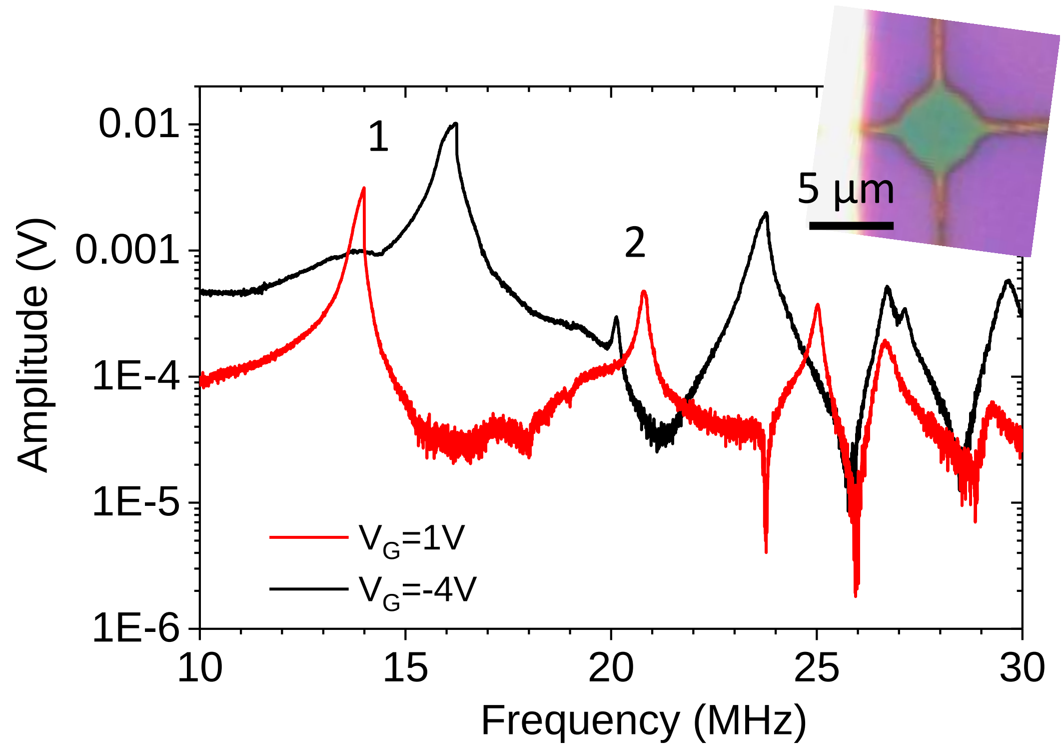


Theory : Lazzeri Mauri PRL 2006 Ando JSPS 2006
Exp : J. Yan *et al.* PRL 2008 (Bilayer Graphene)
1LG : Pisana Nat Mater 2007, Yan PRL 2007, Das Nat Nano 2008

Outlook: AC OptoElectroMechanics
Coll: Pierre Verlot – Uni. Lyon







K. Makles *et al. unpublished*

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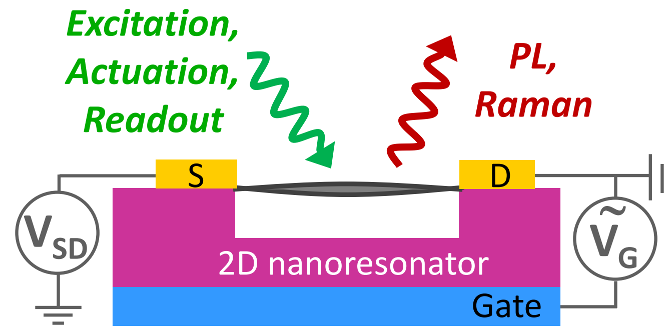

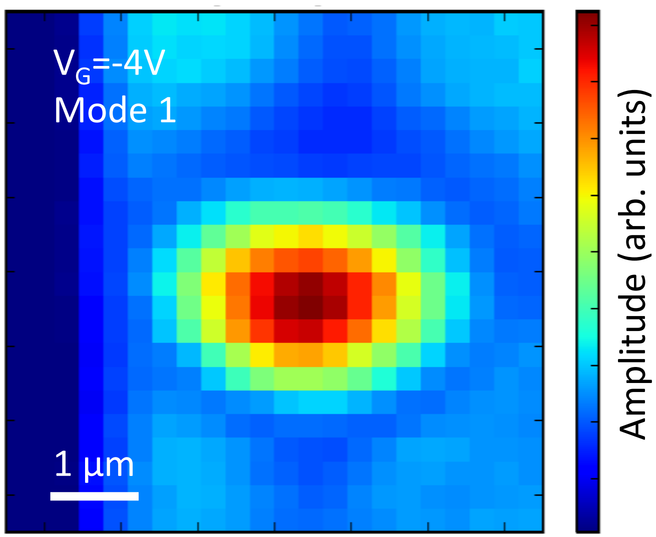

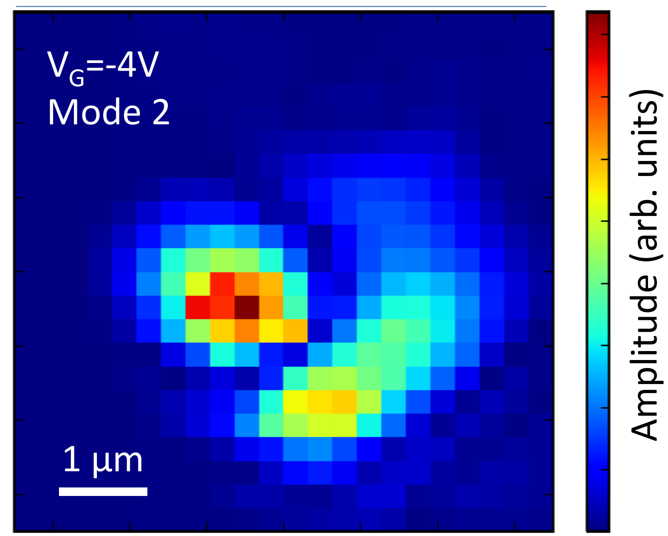

K. Makles *et al. unpublished*

- Optical spectroscopy of 2D resonators (graphene, TMD) in the dynamical regime
- Interplay between flexural modes (~10 MHz) and optical phonons (1-50 THz)
- Single photon hybrid optomechanics in 2DM

Mech. mode mapping: See also Davidovikj Nano Lett 2016, de Alba Nat Nano 2016

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Univ. Lyon 1

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- Olivia Zill
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