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All-optical nanoscale temperature sensing on microelectronics using diamond quantum emitters

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School of Electrical and Data Engineering
University of Technology Sydney

21st Recontres du Vietnam

Where we are: UTS Tech Lab (Botany NSW)

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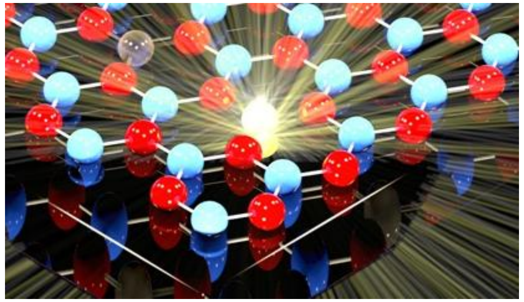
https://www.tttranlab.com/

Quantum defect in hBN



Quantum defect in diamond

Our group

Current PhD students

Mr. Shakhawath Hossain

Mr. Nhat Minh Nguyen

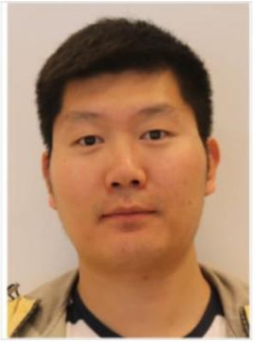
Mr. Trung Vuong

Alumni

Dr. Thi Ngoc Anh MAI

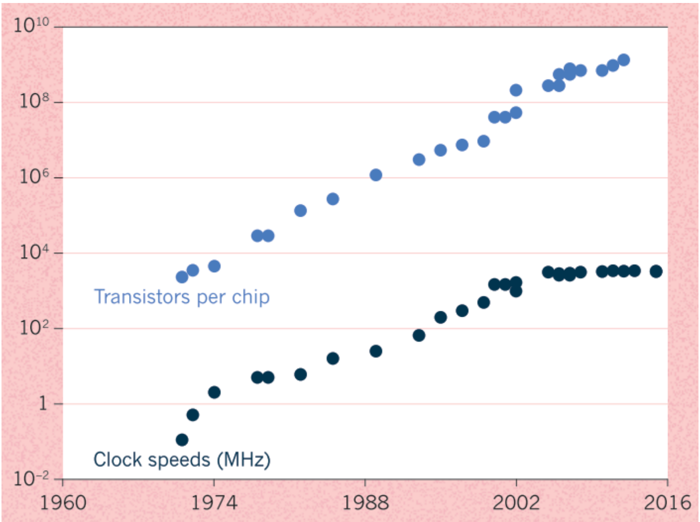
Postdoc UTS

Dr. Yongliang Chen

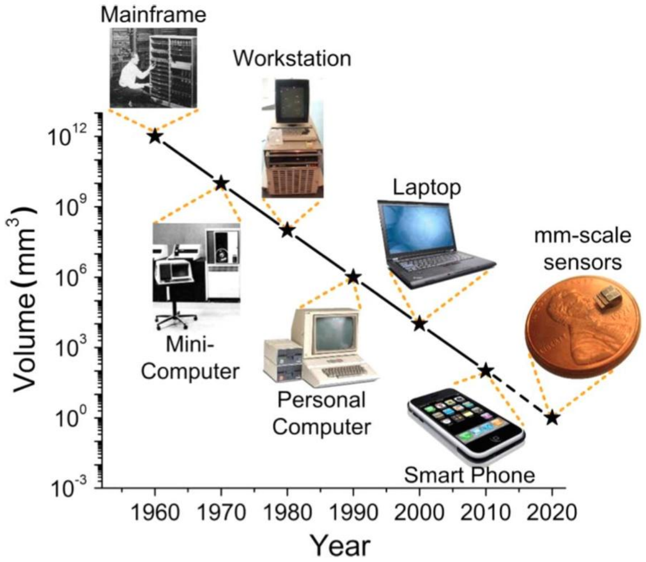


Postdoc U HK

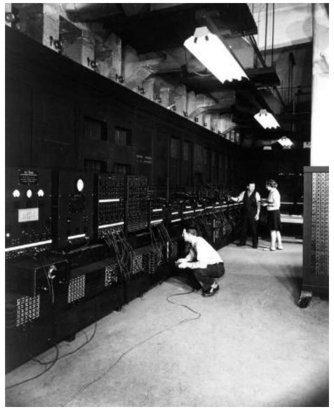
Moore's law



Waldrop, M. M., *Nature News* ***2016, 530, 144.***



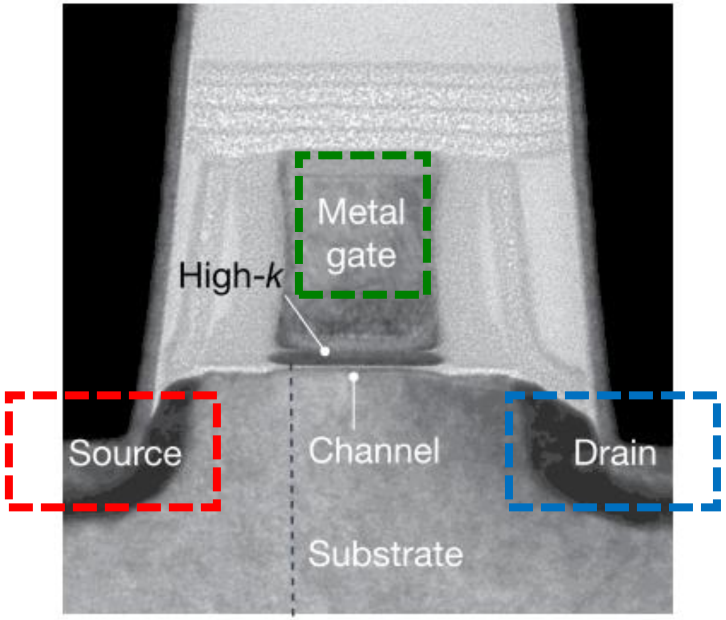
computerhistory.org



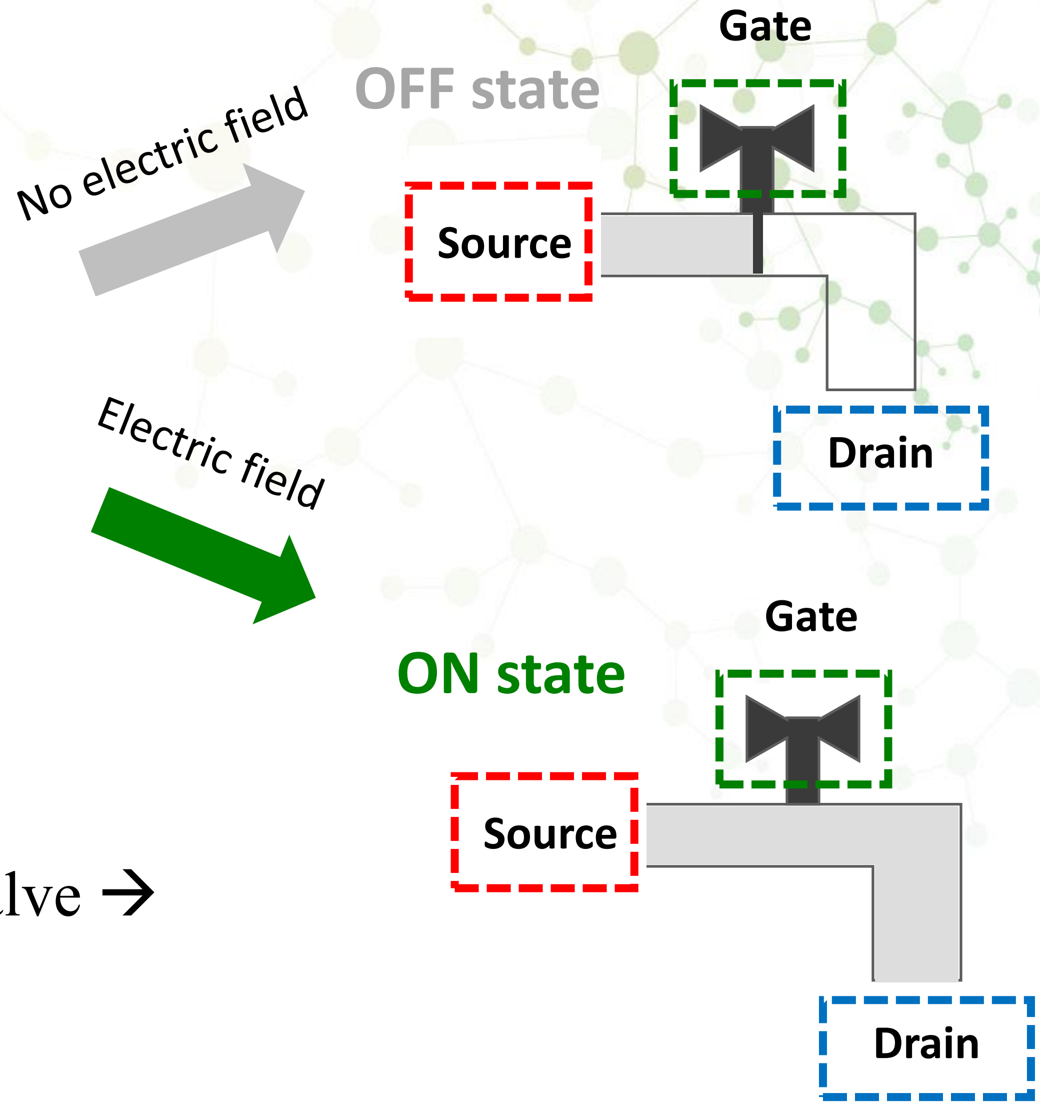
ENIAC the first computer in 1945

- Transistor number doubled every ~2 years
- Electronic devices significantly reduced in sizes

Field-effect transistors: an electricity "water tap"



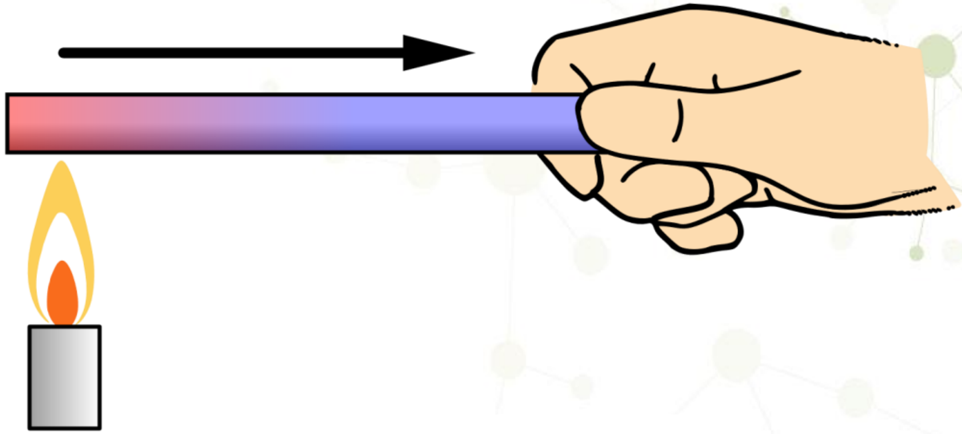
45-nm node planar n-MOSFET



- Applying electric field → open the valve → water flows

Cao, W.; Nature 2023, 620 (7974), 501-515.

Heat conduction at macroscopic scale

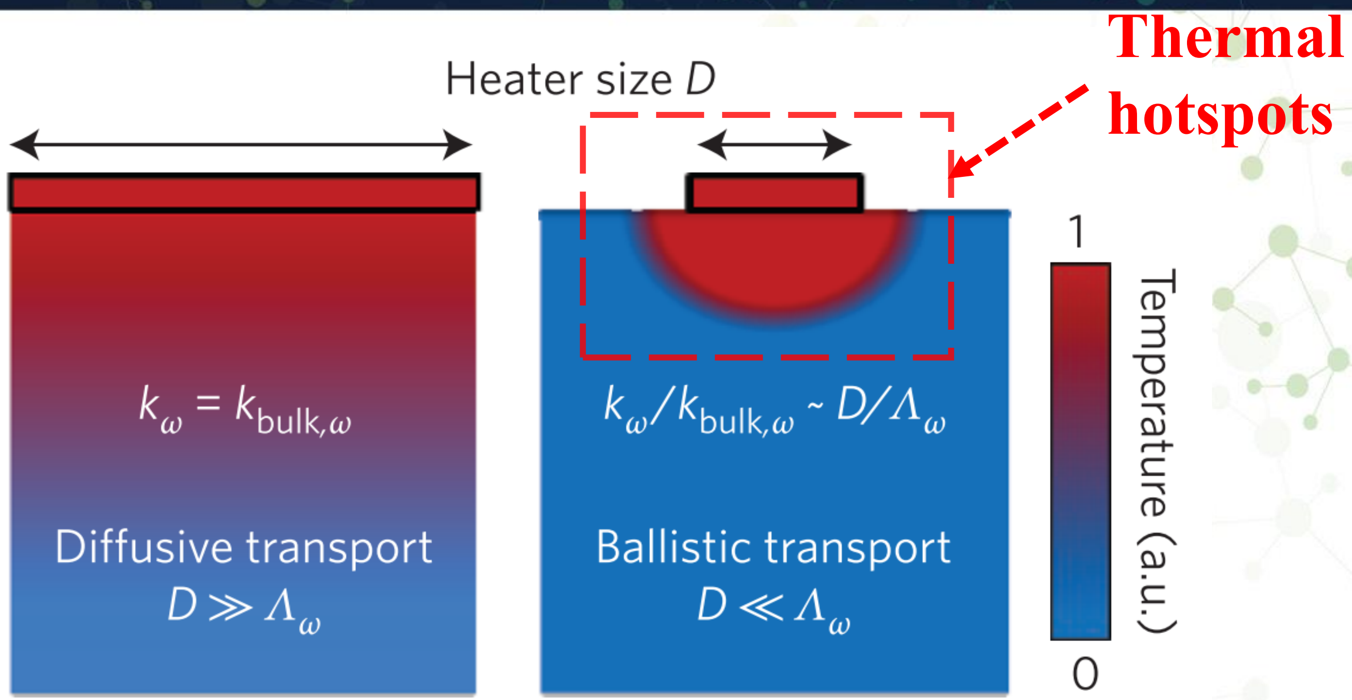


$$\mathbf{q} = -k\nabla T$$

- Fourier’s law: rate of heat flow per unit area proportional to the negative temperature gradient – **diffusive regime**

- $\mathbf{q}$ is the local heat flux density, W/m^2,
- k is the material's conductivity, W/(m·K),
- ∇T is the temperature gradient, K/m.

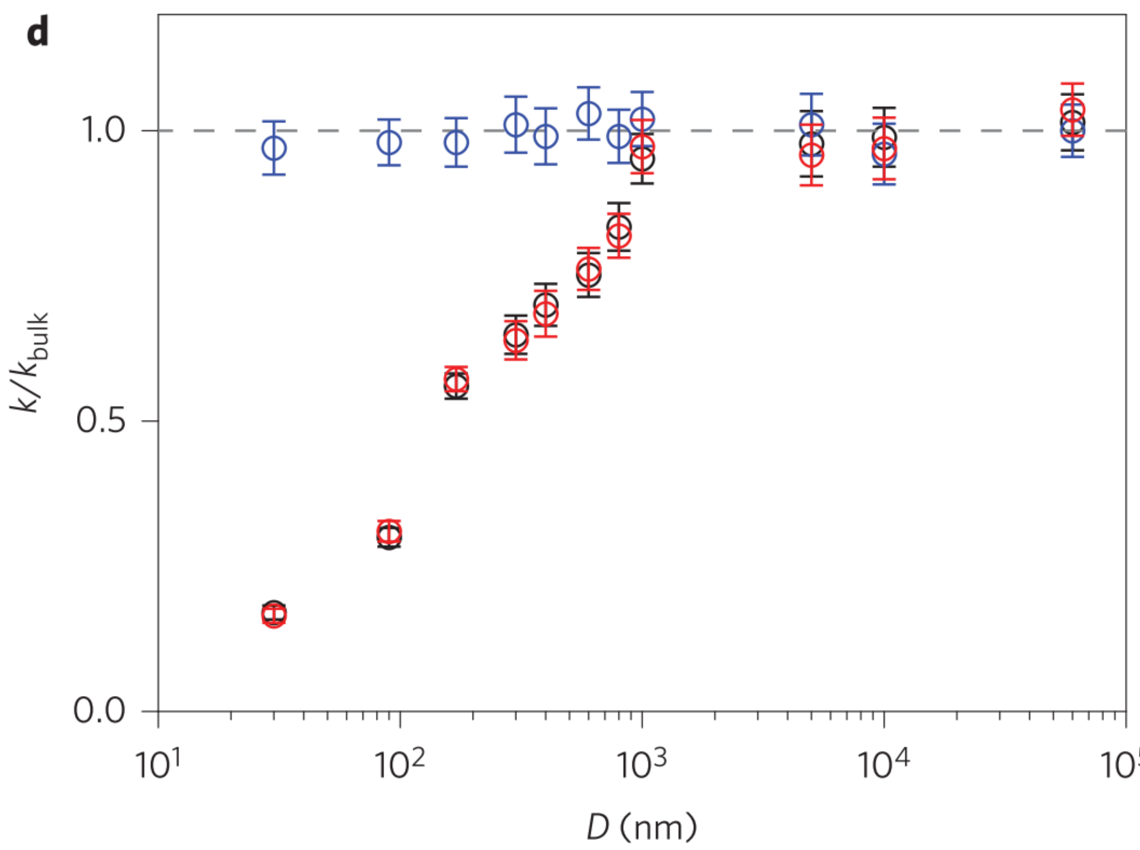
Heat conduction at nanoscale



- When heater size smaller than the phonon mean free path (MFP), the average distance phonon travelling before a collision, **ballistic transport** takes over
- These phonons having no chance to pass on their momenta to the neighboring "hot" phonons and disappearing within their short "lifetime" → ***Fourier's law breaks down! Thermal hot spots formed!***

Hu, Y.; Nat. Nanotechnol. 2015, 10 (8), 701-706.

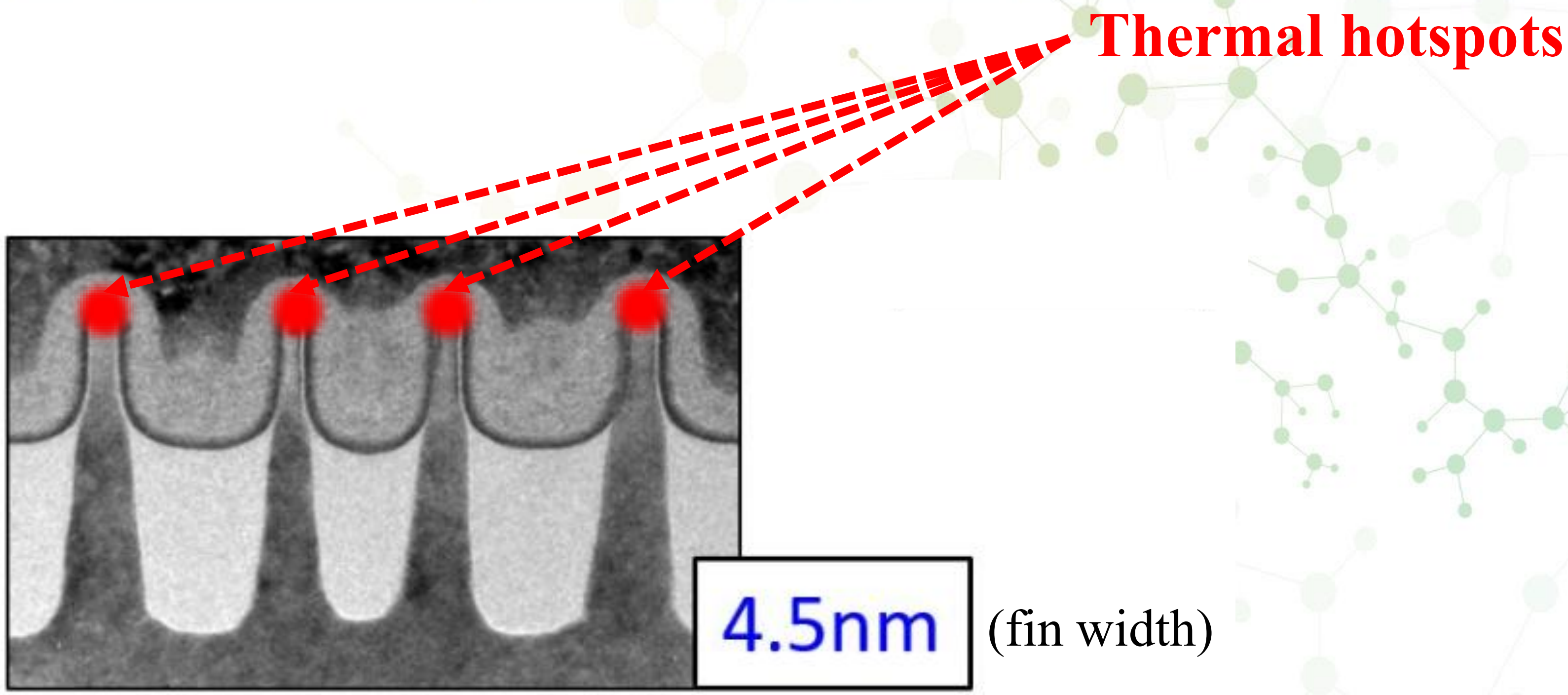
Heat conduction at nanoscale



- When heater size smaller than 1um, the thermal conductivities drops significantly due to the ballistic transport effect

Hu, Y.; Nat. Nanotechnol. 2015, 10 (8), 701-706.

Thermal hot spots formed in MOSFET



- As the transistor's dimensions shrinks, ***thermal hot spots will form at the conducting channel*** due to ballistic thermal transport

- ***How can we see these hot spots?***

Bhoir, M. S. *EEE Journal of the Electron Devices Society* **2019**, *7*, 1217-1224.

Current techniques: strengths & weaknesses

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IR thermography

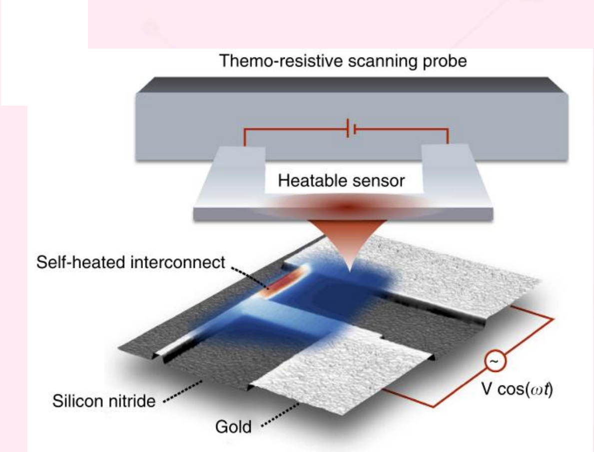
fluke.com

Planck's black body radiation

\+ inexpensive, non-contact, mature technology

\- emissivity data required, low spatial resolution.

Scanning thermal microscope



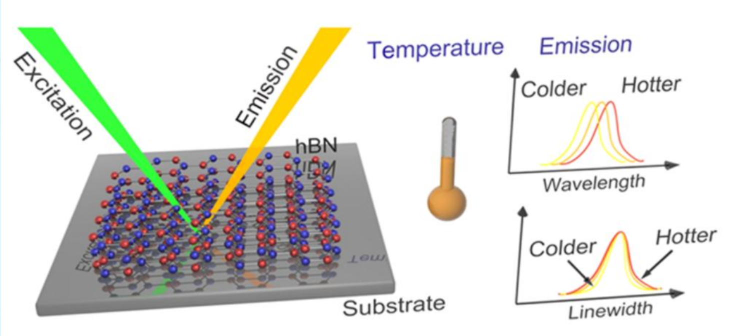
Menges, F.; Nat. Commun. 2016, 7, 10874.

Resistance changes based on sharp, scanning tip

\+ very high spatial resolution

\- complicated heat transfer, expensive, cumbersome

Fluorescence / Optical thermometry



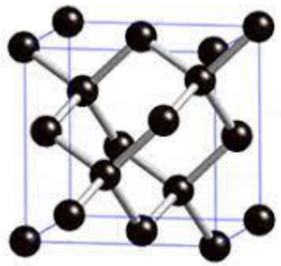
Chen, Y. ACS Appl. Mater. Interfaces 2020, 12, 25464

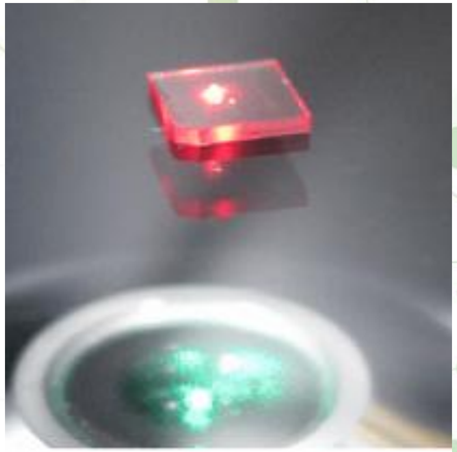
Temperature-dependent fluorescence changes

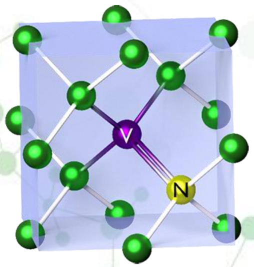
\+ high spatial resolution, non-contact, inexpensive, portable

\- low temporal resolution, difficult to do thermal mapping

Color centers in diamond





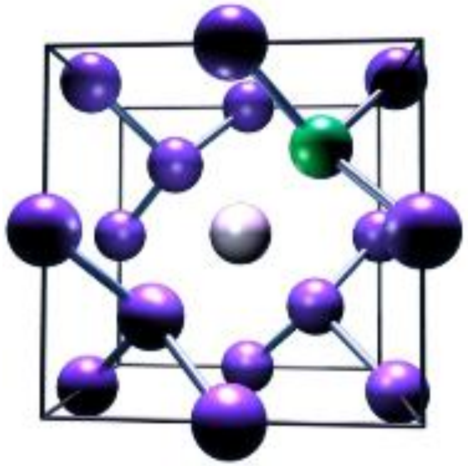


- Pure diamond has no color due to its large bandgap
- Diamond is among the most inert and durable → ideal for high temperature sensing

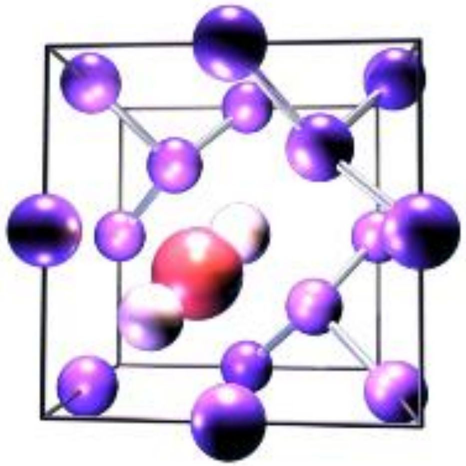
- When doped with impurities, diamond has a color due to defect complexes known as "color centers" or "quantum emitters"

Point-defects in diamond

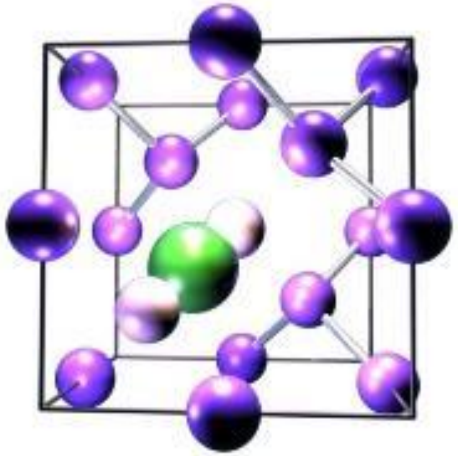
NV center



SiV center



GeV center



- There are tens of defect complexes in diamond
- Each having their own energy levels and hence their unique optical properties

Our approaches to optical thermometry

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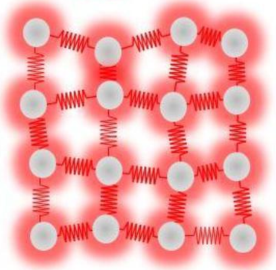
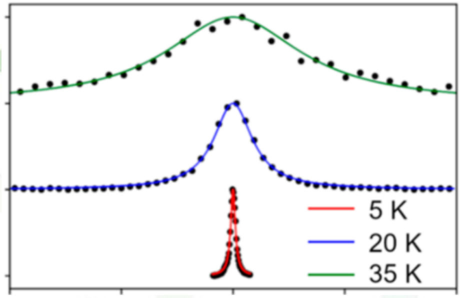
1. Anti-Stokes/Stokes ratio: stealing phonon energy

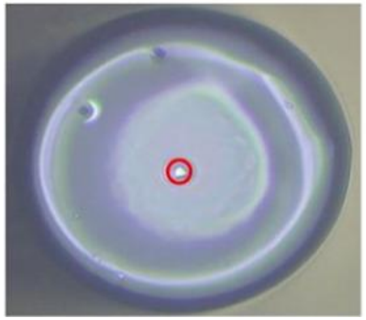


2. Linewidth-temperature dependent: phonon dephasing

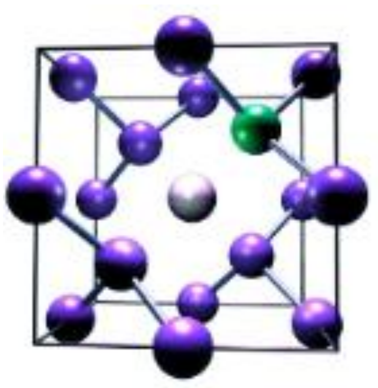


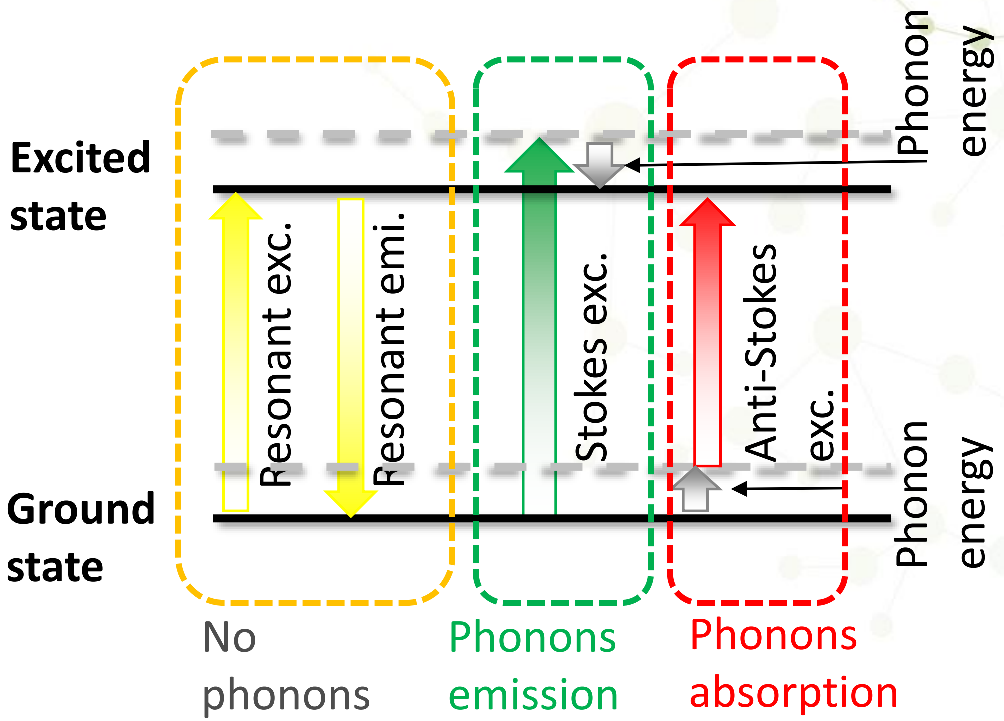
Temperature-dependent observables

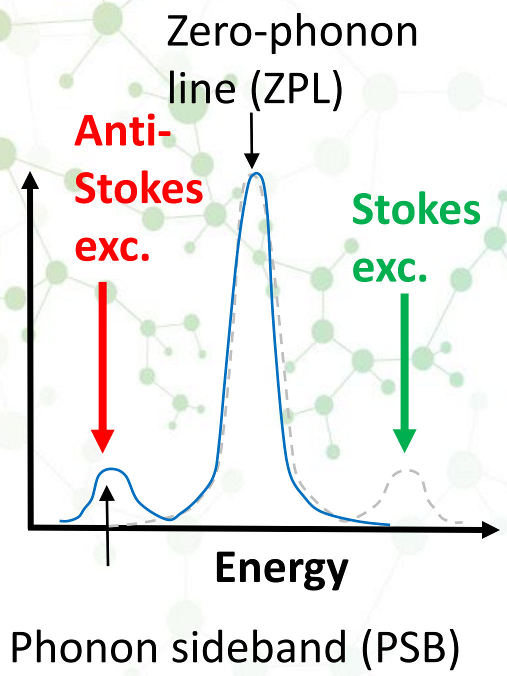
3. Fiber-based PL-to-scattered-laser ratio



1. Anti-Stokes/Stokes ratio: stealing phonon energy







- Excitation energy can be below or above optical transition

T. T. Tran, C. Bradac, et. al. ***Science Advances* 5** (5), eaav9180 (2019).

1. Anti-Stokes/Stokes ratio: stealing phonon energy

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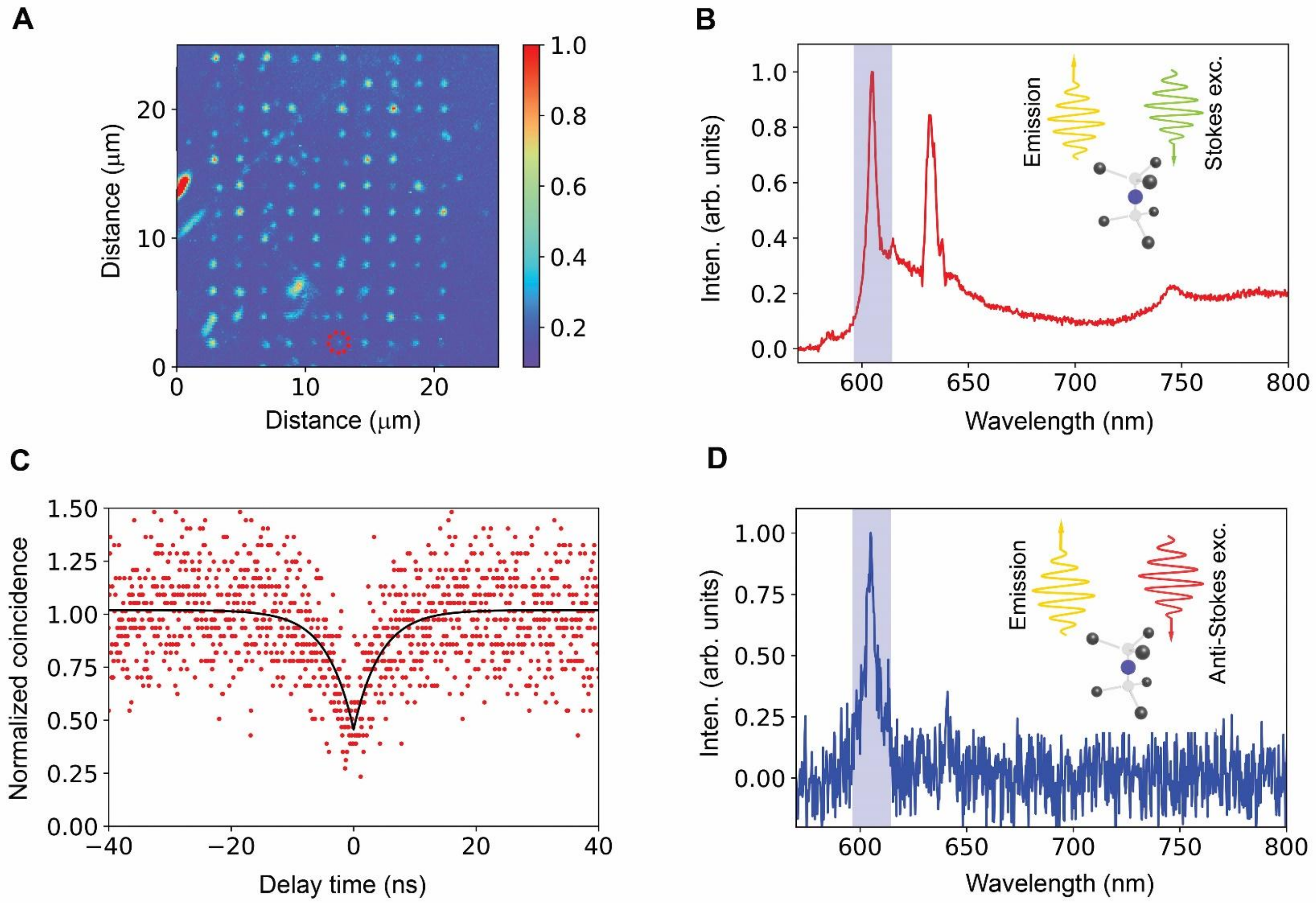


532 nm excitation

Stokes exc.

637 nm excitation

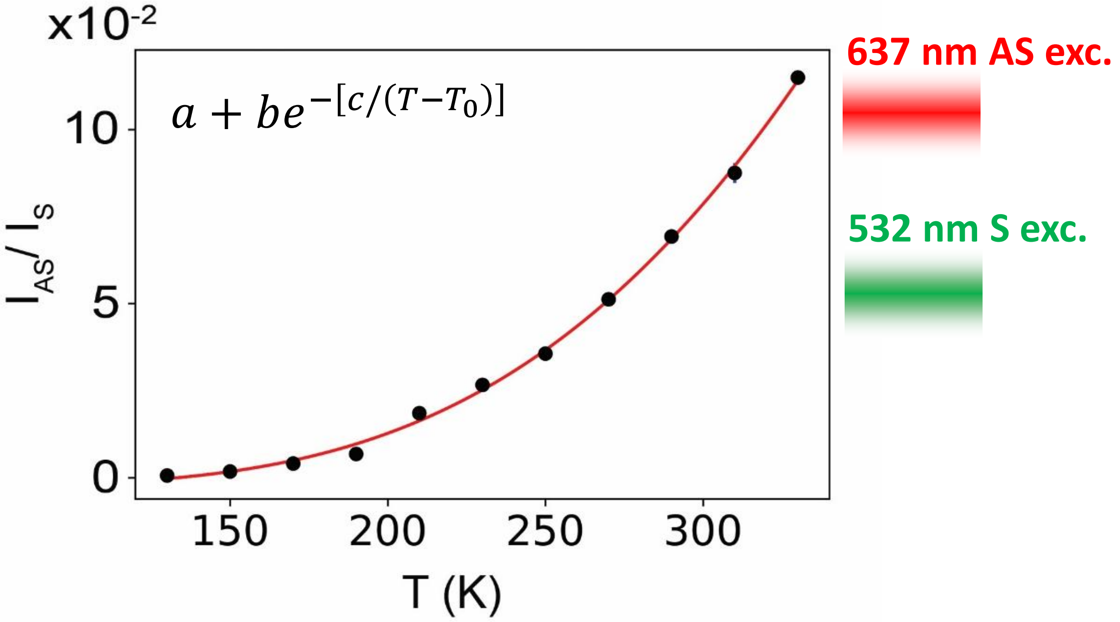
Anti-Stokes exc.

- Anti-Stokes excitation on a single GeV color center possible!

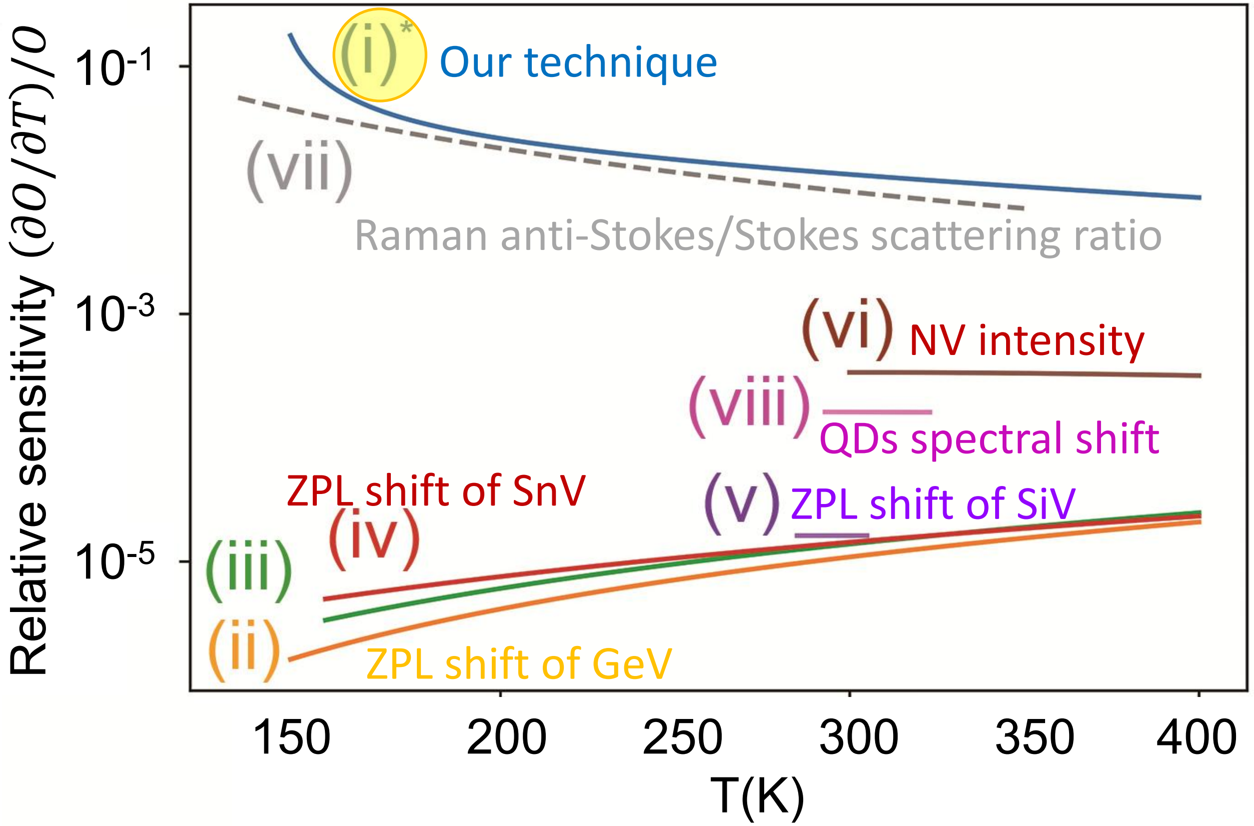
T. T. Tran, C. Bradac, et. al. ***Science Advances*** **5** (5), eaav9180 (2019).

1. Anti-Stokes/Stokes ratio: stealing phonon energy

- Arrhenius-type exponential scaling with temperature



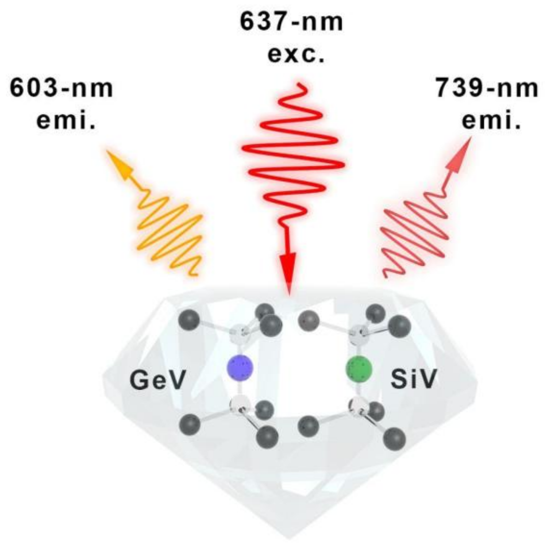
Resolution: 455 mK·Hz$^{-½}$ at 300K
2.494–0.420 K·Hz$^{-½}$ over 110–330 K

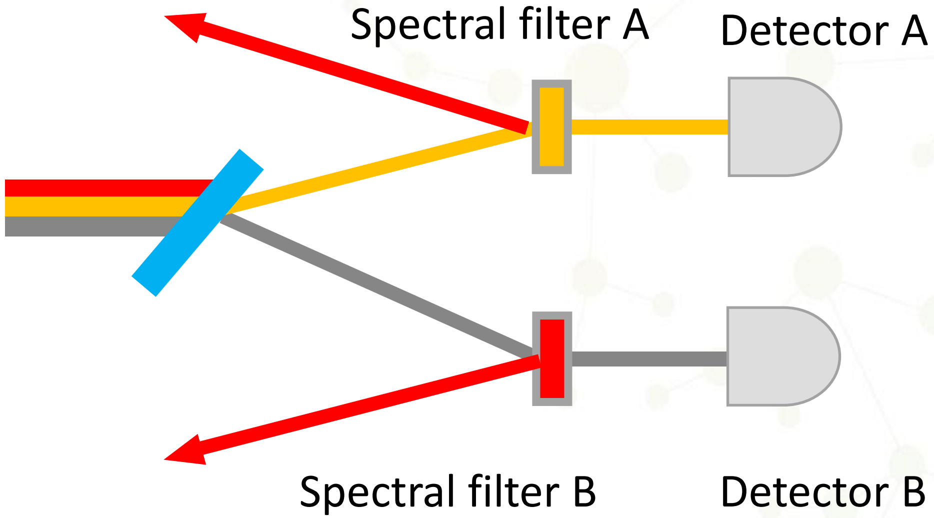


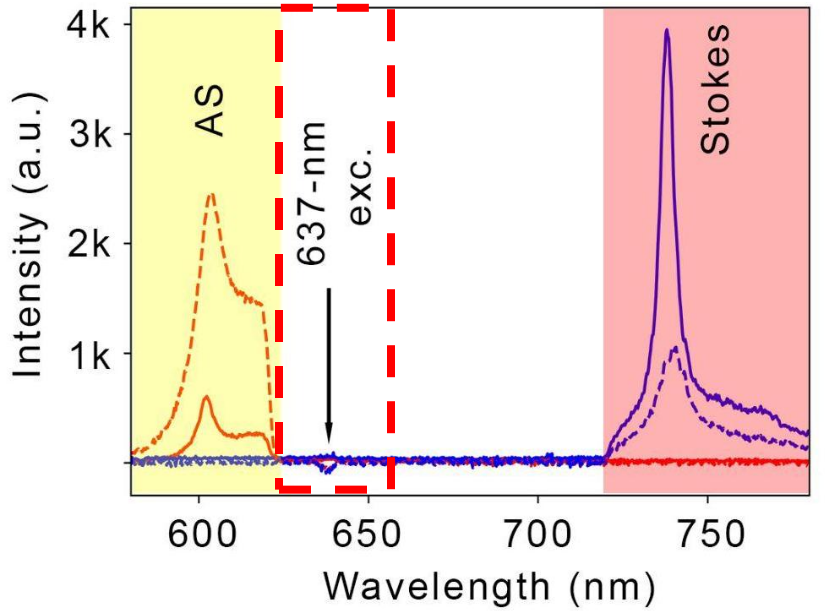
- High relative sensitivity due to exponential scaling!

T. T. Tran, C. Bradac, et. al. ***Science Advances* 5** (5), eaav9180 (2019).

1. Anti-Stokes/Stokes ratio: stealing phonon energy







- Greatly simplifying the scheme by combining co-doping GeV and SiV on the same nanodiamond and utilizing spectral filtering & photon counting

Y. Chen, ***ACS Nano***, *2023*, *2725.*

1. Anti-Stokes/Stokes ratio: stealing phonon energy

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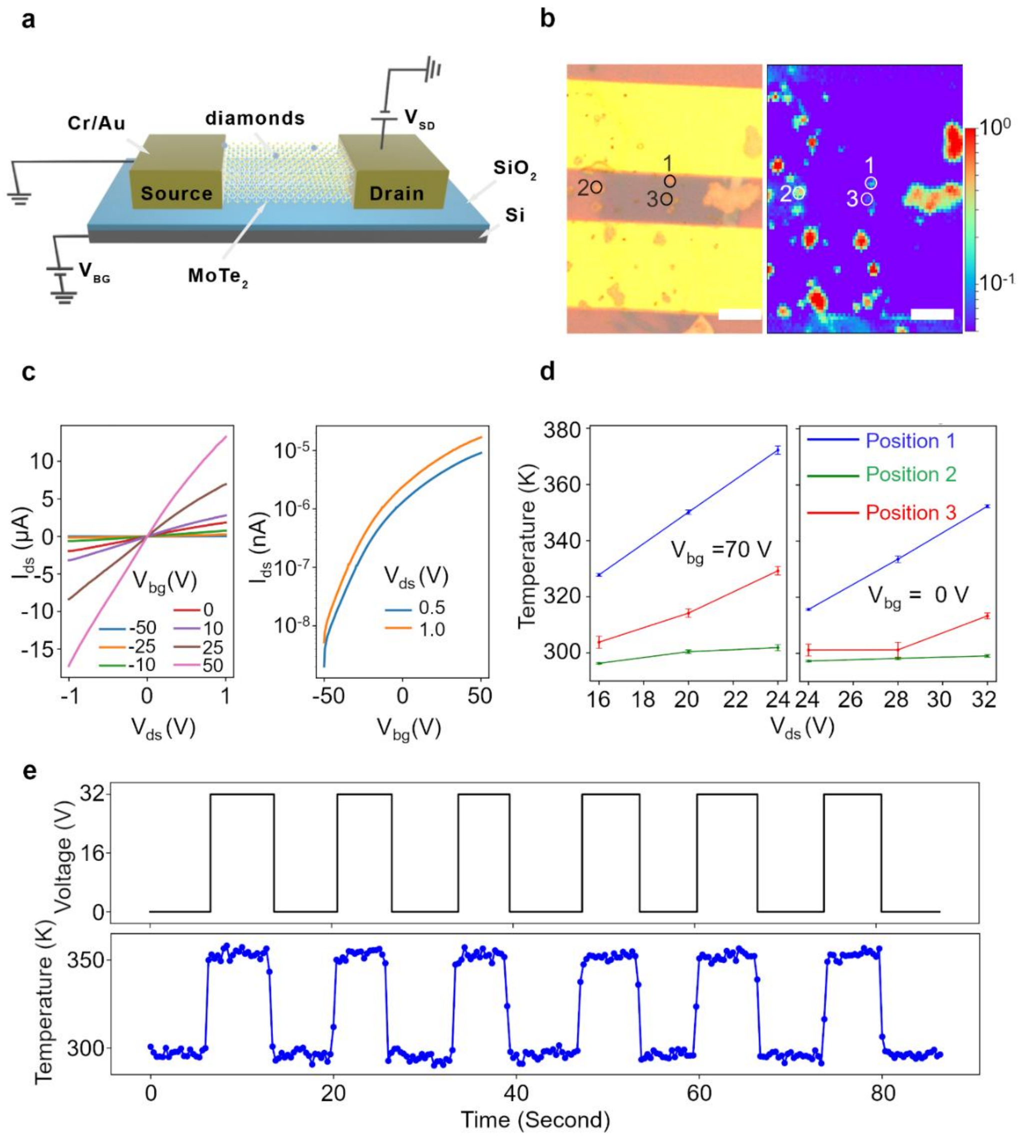
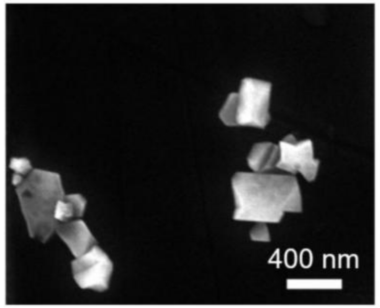
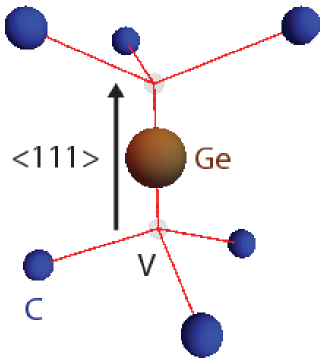


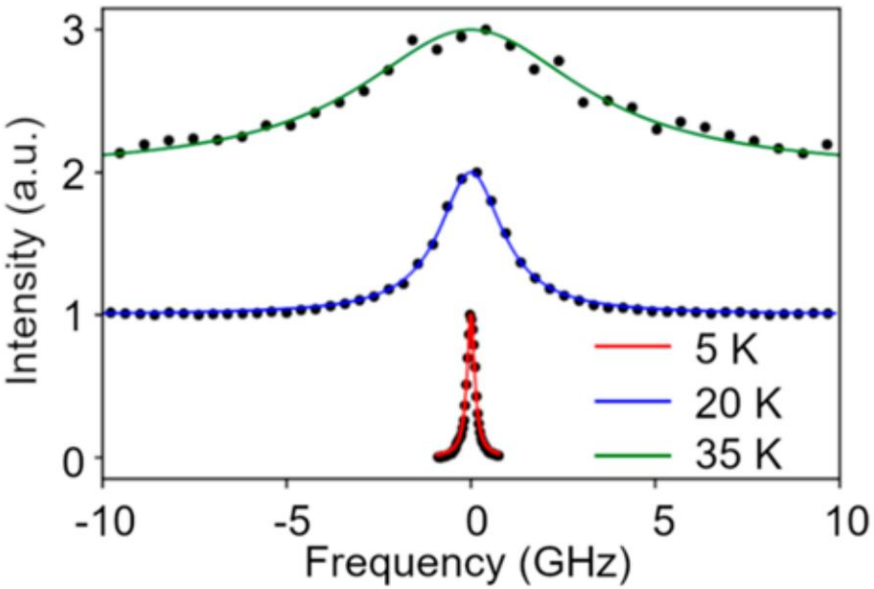
- Real-time local temperature monitoring of a $MoTe_2$ field-effect transistor using nanodiamonds.
- The ND (#1) close to the electrode showing largest temperature increase
- Temperature responding well to the changes in the input voltage

Y. Chen, ***ACS Nano***, *2023, 2725.*

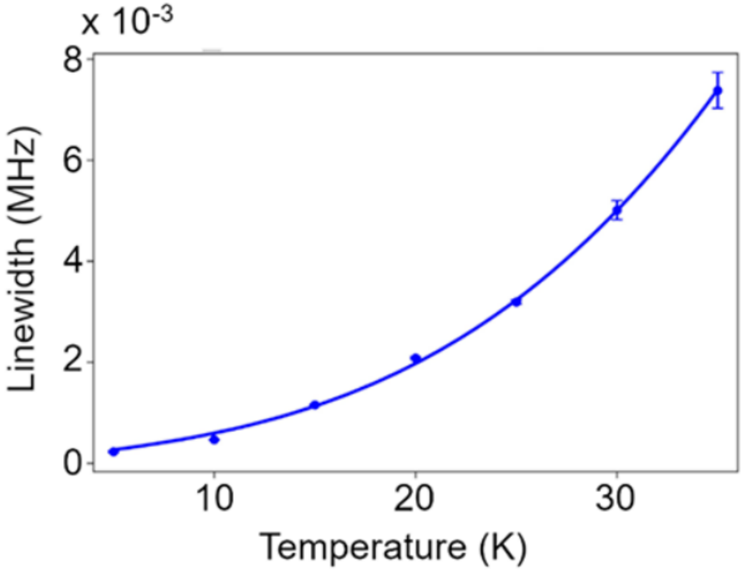
2. Linewidth-temperature dependent: phonon dephasing







- By using photoluminescence excitation (PLE) at low temperatures, we can determine and correlate linewidths with temperatures



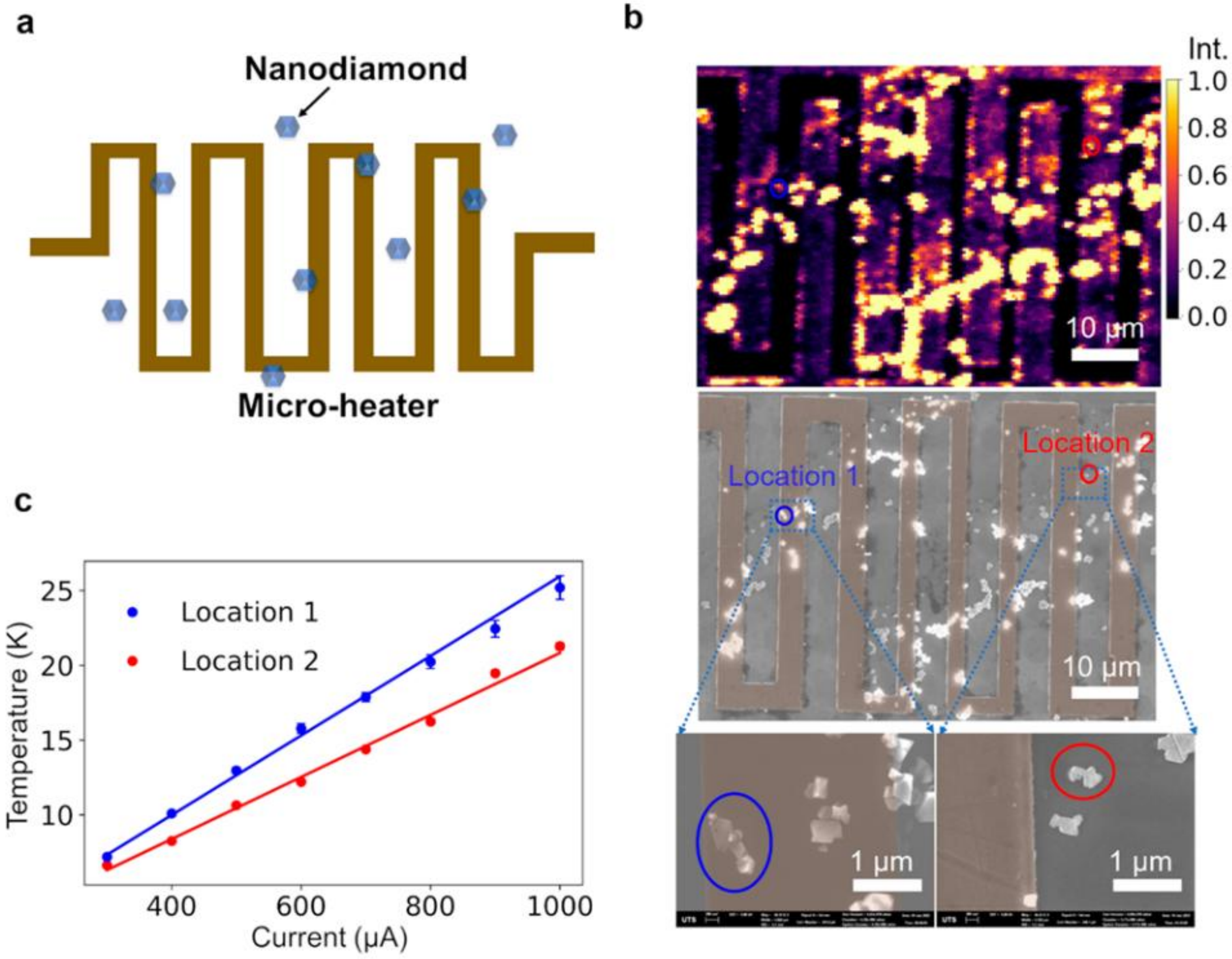
Lifetime-broadened term

electron-phonon interaction term

$$\gamma_{\text{tot}} = \gamma_{\text{lt}} + \gamma_{\text{first}} + \gamma_{\text{second}} = c + bT + aT^3$$

Y. Chen, ***ACS Photonics* 2023,** *10* (8), 2481-2487

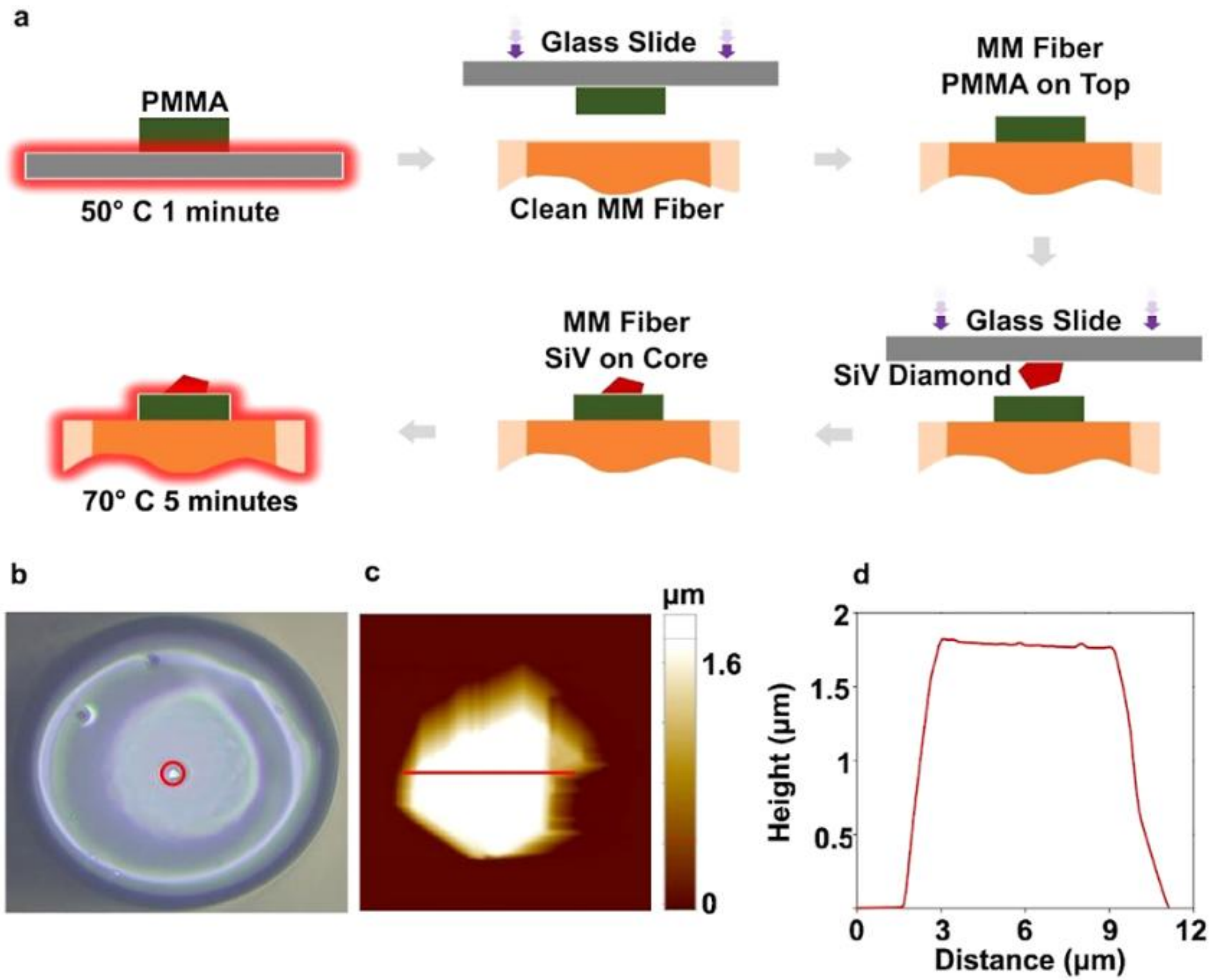
2. Linewidth-temperature dependent: phonon dephasing



- By placing the nanodiamonds on different locations of a microheater, we showed the corresponding temperature responses at these spots with increasing input current

Y. Chen, ***ACS Photonics* 2023,** *10* (8), 2481-2487

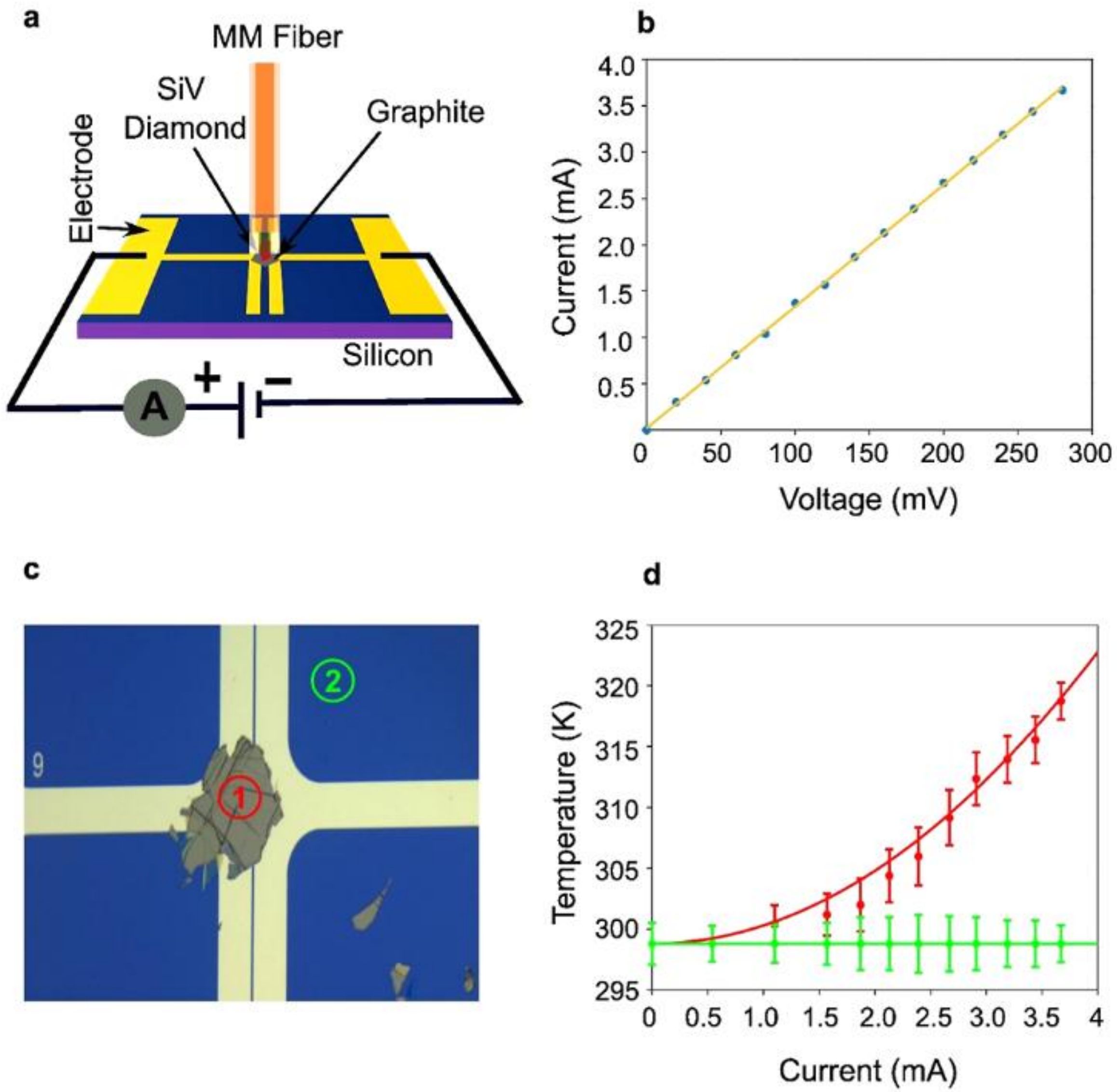
3. Fiber-based thermometry using PL-to-scattered-laser ratio

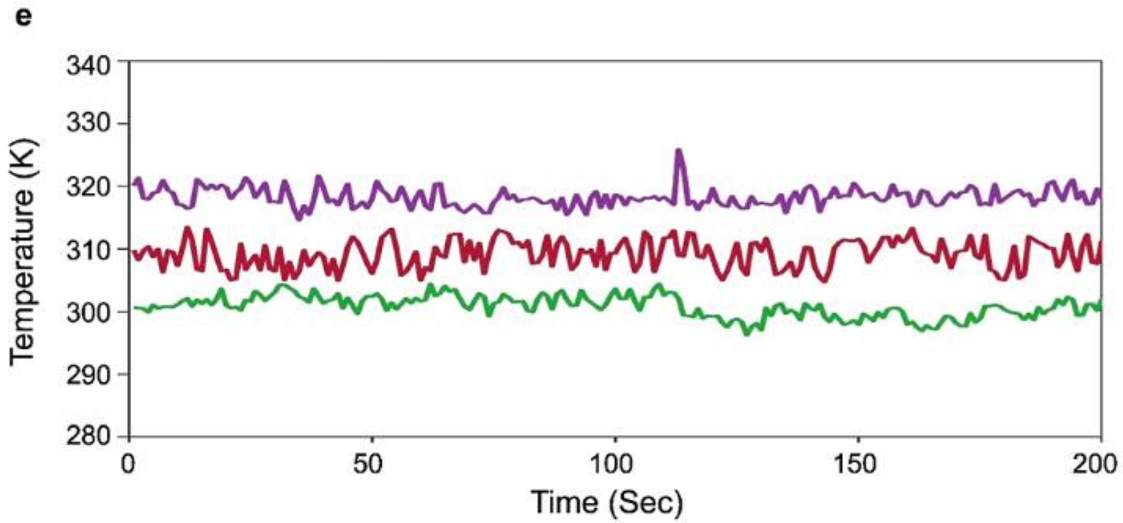


- Microdiamond was aligned transferred onto a multimode optical fiber using dry-transfer technique.

Hossain, M. S. **ACS Applied Optical Materials 2024**, 2, 97

3. Fiber-based thermometry using PL-to-scattered-laser ratio

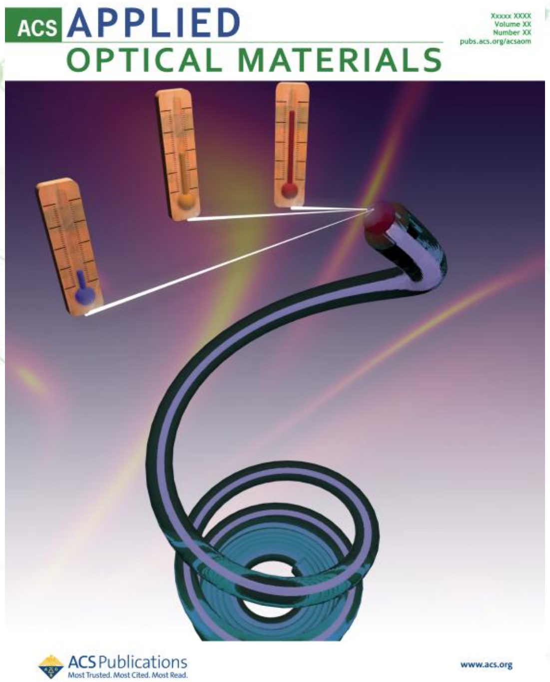




- Real-time monitoring of local temperature on a graphite-based microheater

Hossain, M. S. **ACS Applied Optical Materials 2024**, 2, 97

Thank you!



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Dr. Carlo Bradac (Trent U)
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Prof. Weibo Gao (NTU)
Dr. Evgeny Ekimov (IHPP)
Prof. Prineha Narang (Harvard U)
Prof. Milos Toth (UTS)
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https://www.tttranlab.com/

Australian Government
Australian Research Council

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