KEYNOTE TALK AT UPON – Budapest 2024

Noise of Charge Density Waves in Low-Dimensional Materials

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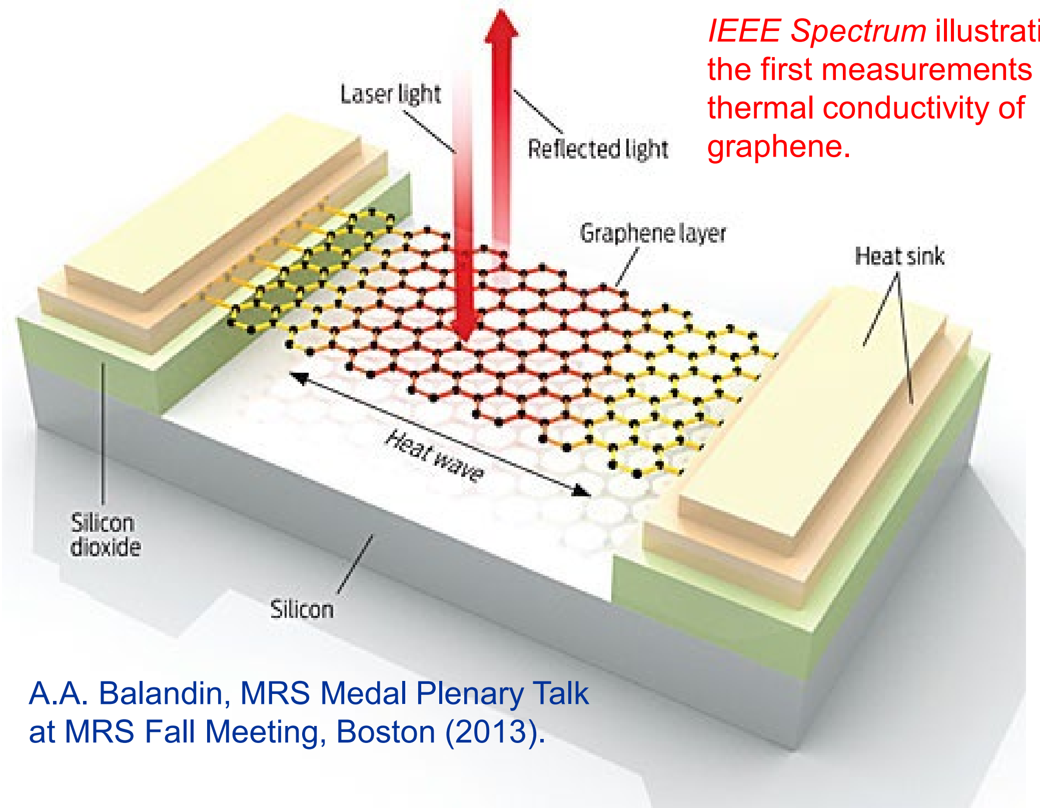
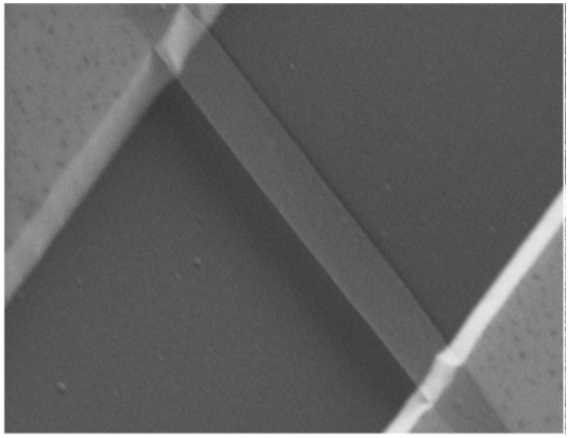
International Conference on Unsolved Problems of Noise

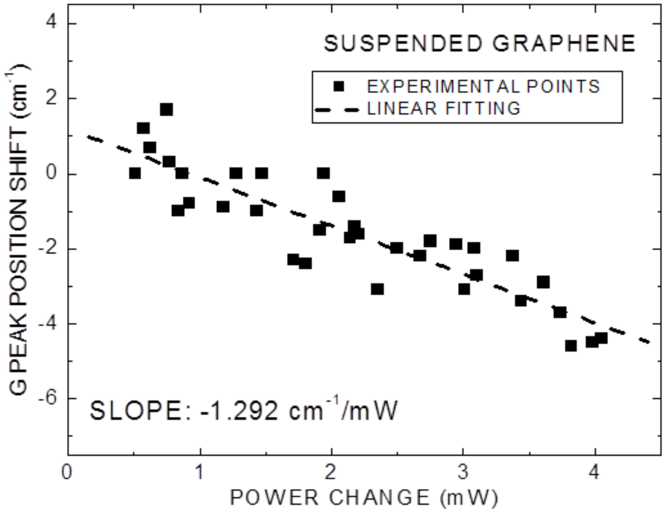
https://conf.uni-obuda.hu/upon2024/index.html

Research Area I – Heat Conduction in Graphene and Few-Layer Graphene



IEEE Spectrum illustration of the first measurements of thermal conductivity of graphene.

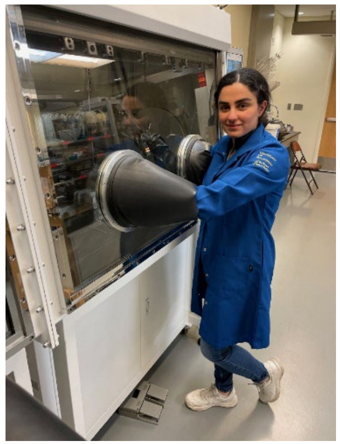


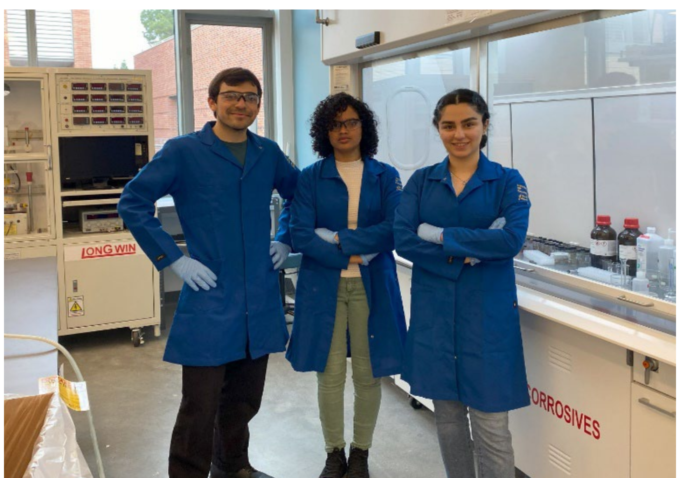


A.A. Balandin, MRS Medal Plenary Talk at MRS Fall Meeting, Boston (2013).

A. A. Balandin, "Thermal properties of graphene and nanostructured carbon materials," Nature Mater., 10, 569 (2011).

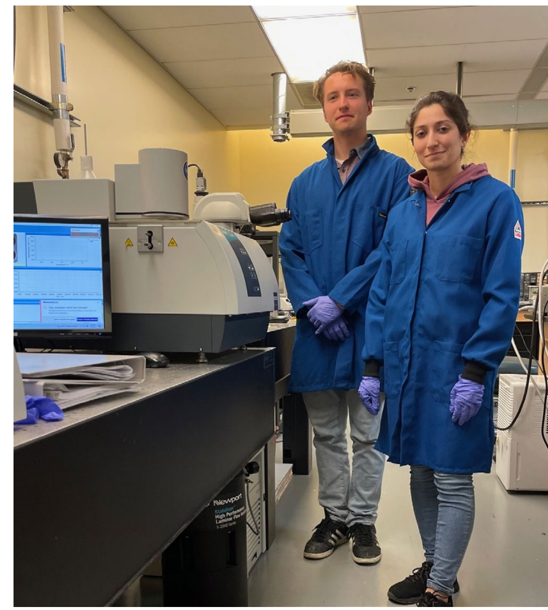
Research Area II – Quasi-1D and Quasi-2D van der Waals Materials





Technical approaches

- Take CVT material and exfoliate
- Cleanroom nanofabrication for transport measurements
- Composite preparation with 1D and 2D fillers
- Electrical, thermal and optical characterization

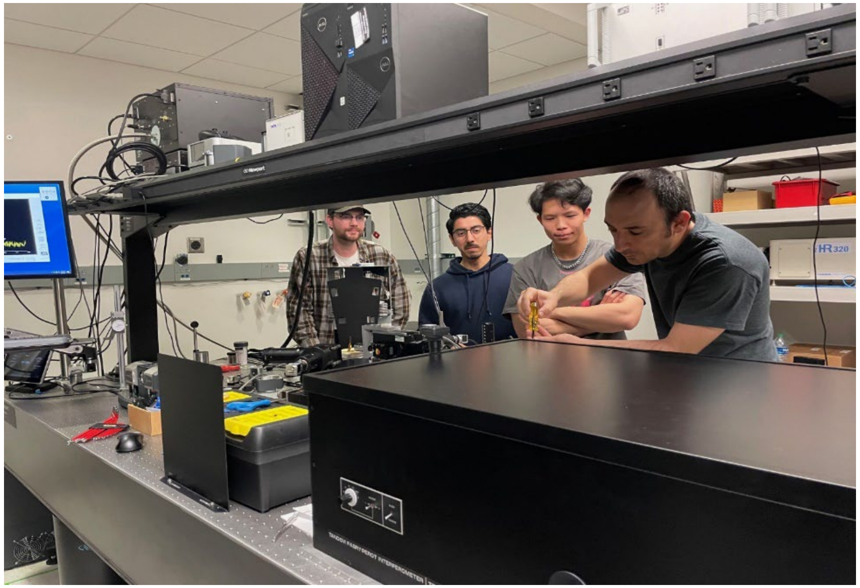


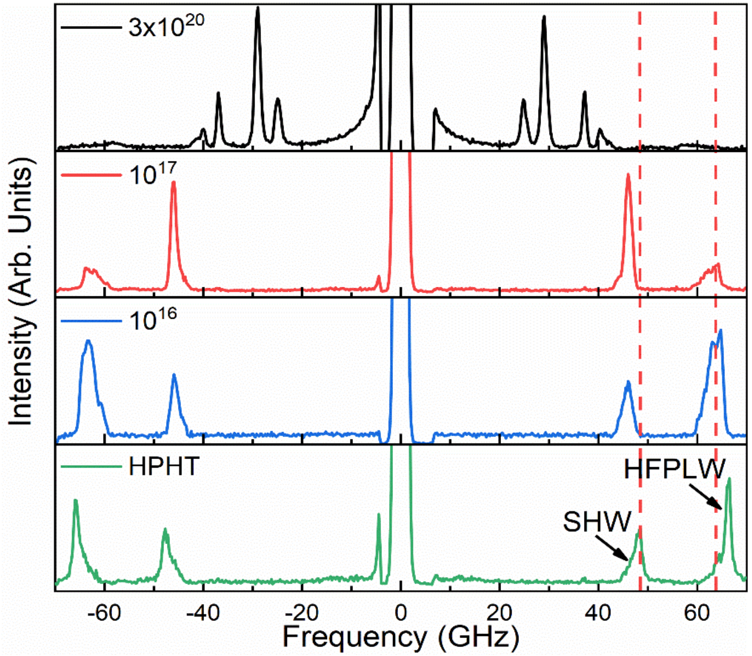
Charge-density-waves, electron and phonon transport

- A. A. Balandin, F. Kargar, T. T. Salguero, and R. Lake, “One-dimensional van der Waals quantum materials”, Mater. Today, 55, 74 (2022).
- A. A. Balandin, “Thermal properties of graphene and nanostructured carbon materials,” Nature Mat., 10, 569 (2011).

Research Area III – Inelastic Light Scattering Spectroscopy

Brillouin – Mandelstam inelastic light scattering (BMS) spectroscopy: NSF MRI Facility in CNSI



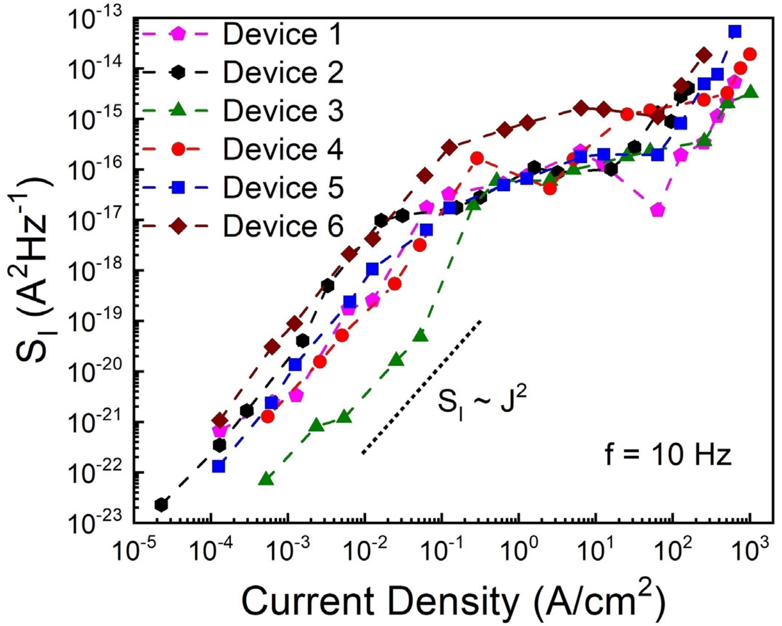


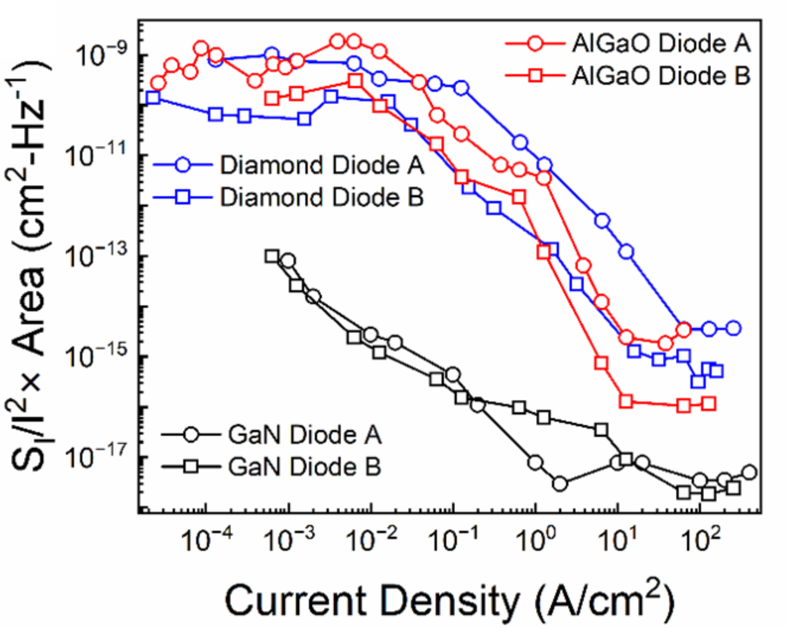
https://cnsi.ucla.edu/bms-facility/

- F. Kargar and A. A. Balandin, "Advances in Brillouin–Mandelstam light-scattering spectroscopy", Nature Photonics, 33, 720 (2021).
- E. Guzman et al., "Effects of boron doping on the bulk and surface acoustic phonons in single-crystal diamond", ACS Appl. Mater. Interfaces, 14, 37, 42223 (2022).

Research Area IV: "Conventional" Low-Frequency Noise Studies

Noise spectroscopy for reliability assessment in UWBG devices





S. Ghosh, … A.A. Balandin, "Low-frequency noise in *β*-$(Al_xGa_{1-x})_2O_3$ Schottky barrier diodes", Appl. Phys. Lett., 122, 212109 (2023).

S. Ghosh, … A. A. Balandin, "Excess noise in high-current diamond diodes", Appl. Phys. Lett., 120, 062103 (2022).

Research Area V: Charge-Density Waves and Electronic Noise

Department of Energy contract Physical Mechanisms and Electric-Bias Control of Phase Transitions in Quasi-2D Charge-Density-Wave Quantum Materials

- → Introduction
  - → Basics of charge-density waves
- → Quasi-2D charge-density-wave devices
  - → The use of NC-CDW – IC-CDW transition
  - → Room temperature operation
  - → Radiation hardness and noise
- → The search for the "narrow band noise" in 2D
- → Mechanism of switching: field *vs*. local heating
- → Noise for Monitoring Depinning of CDWs
- → Field-effect in quasi-2D CDW materials
- → Gating of CDW in quasi-1D nanowires
- → Noise of sliding CDWs in quasi-1D nanowires
- → Conclusions and UPON

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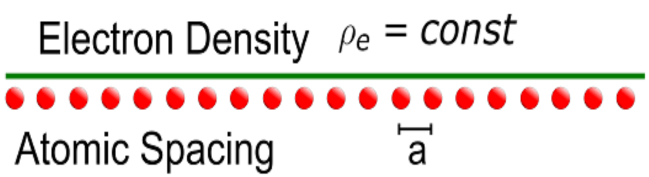
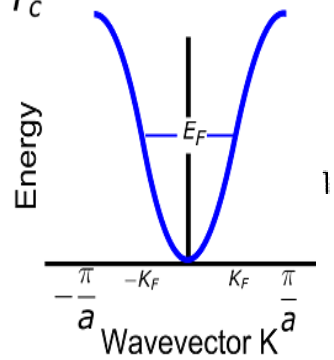
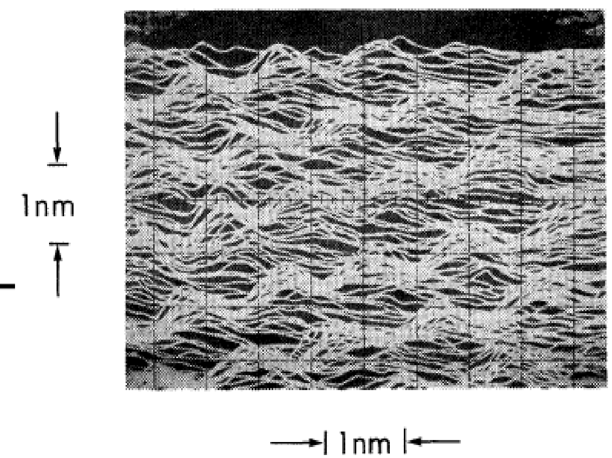
Recalling the Basics of Charge Density Waves in Metals with Quasi-1D Structure

Normal state $T > T_c$

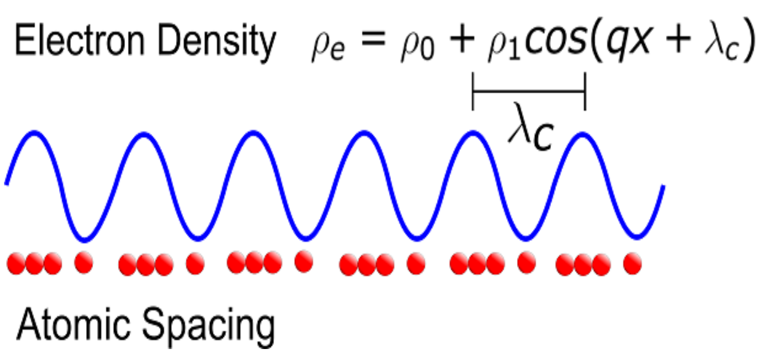


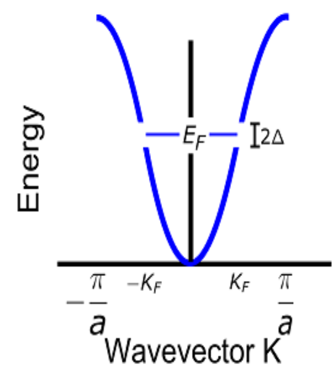




R.V. Coleman, *Phys. Rev. Lett.*, **55**, 394 (1985).

Peierls state $T < T_c$

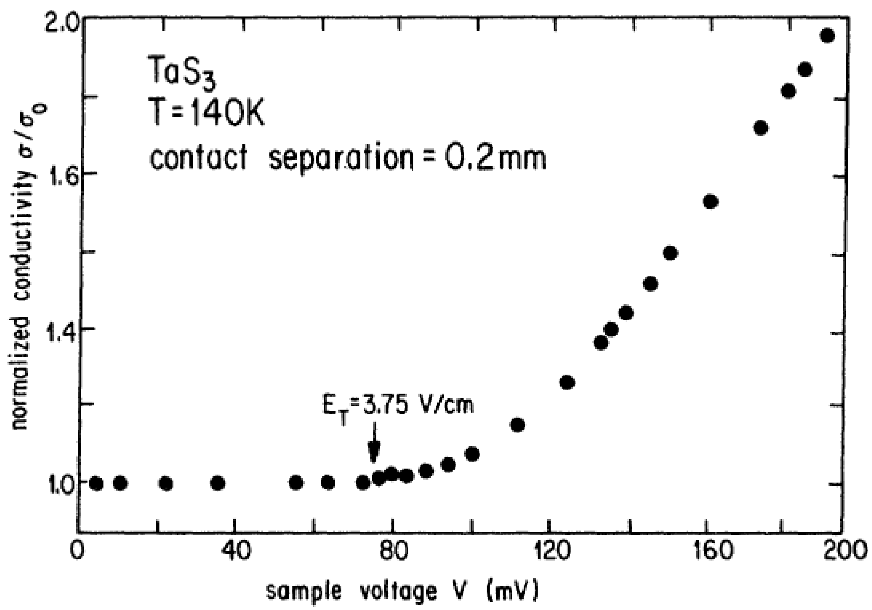




Macroscopic quantum phenomena: coherence length >1 μm

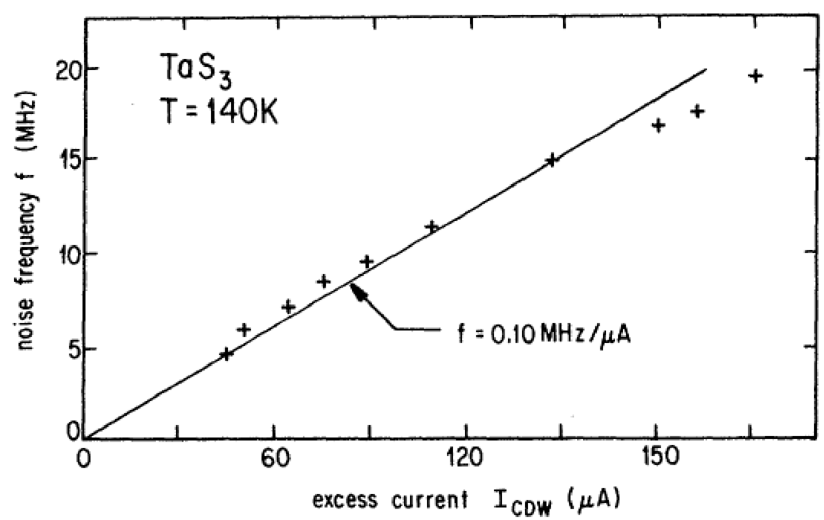
Depinning and Sliding of CDWs in Bulk Quasi-1D CDW Materials – Current Oscillations

The IC-CDW has translational invariance with respect to the lattice so that there is no energy barrier to translation. In practice, there are defects that pin the IC-CDW to the lattice so that a finite electric field, E_T, is required to de-pin the IC-CDW and cause it to slide.



G. Gruner, *et al*., Phys. Rev. B, 23, 6813 (1981).

Narrow Band Noise (NBN)

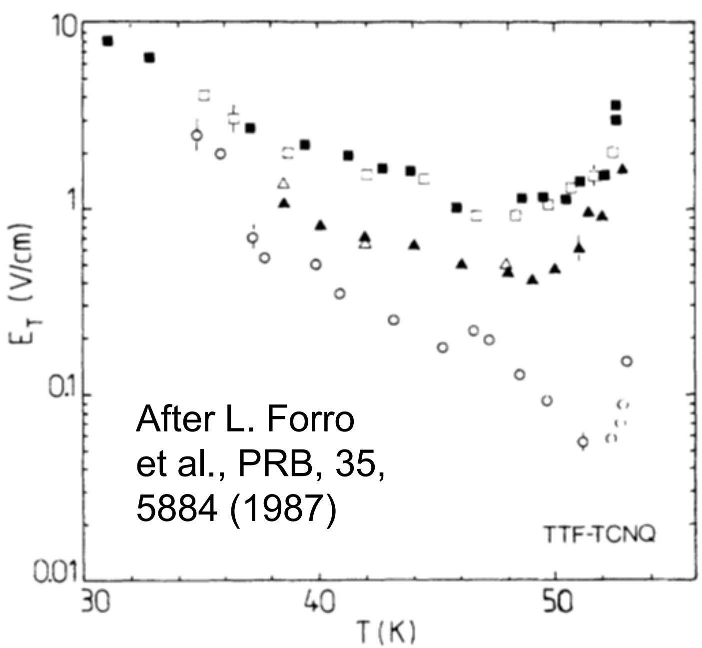


Non-linear electrical conductivity and oscillations for large fields.

Temperature Dependence of CDW Depinning Field in Quasi-1D Materials

Is NBN still UPON (Unsolved Problems of Noise)?

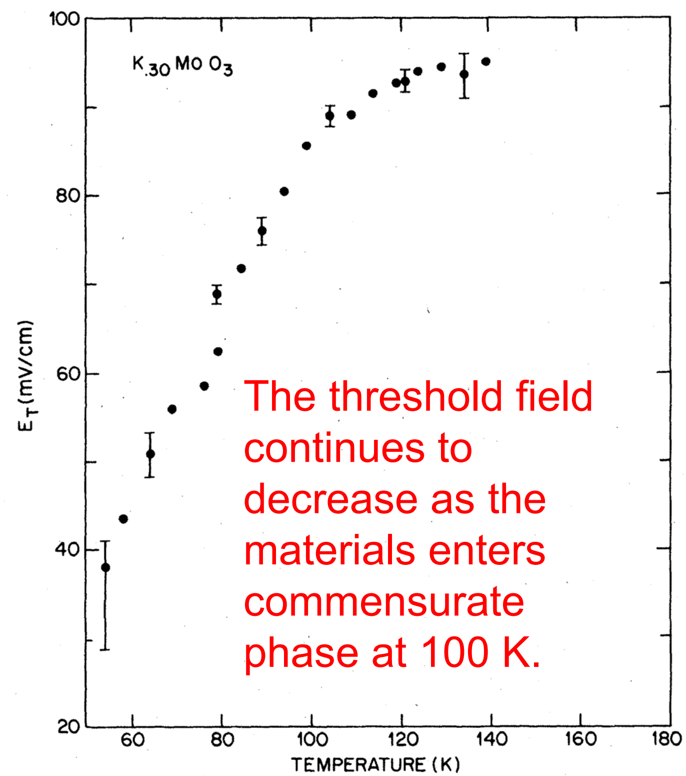
"Conventional" Theory for 1D CDWs



After L. Forro et al., PRB, 35, 5884 (1987)

- → For many quasi-1D, E_T increases at low temperature with an exponential dependence ~exp(−T/T_0)
- → Energetically prohibitive to move CDW in the commensurate phase

"Exceptions" to Conventional Theory



The threshold field continues to decrease as the materials enters commensurate phase at 100 K.

R.M. Fleming, *et al.*, PRB, 31, 899 (1985)

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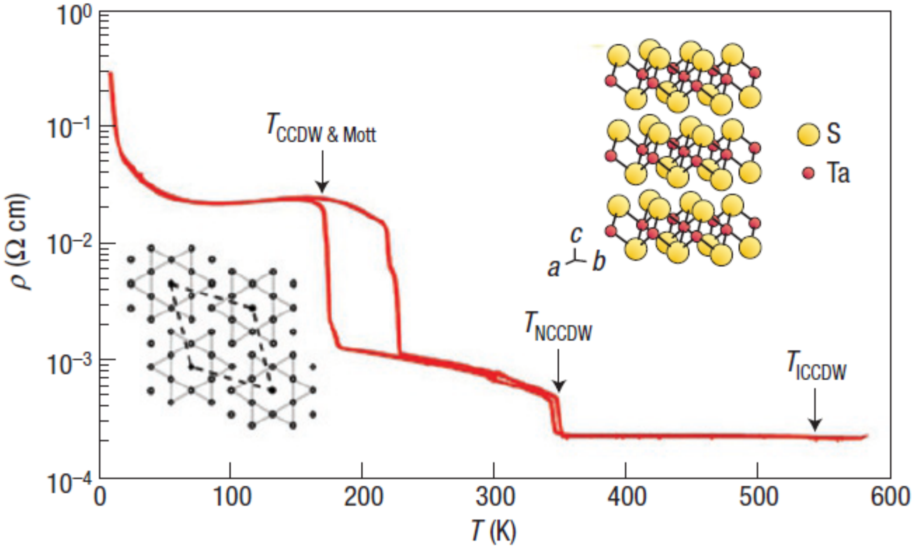
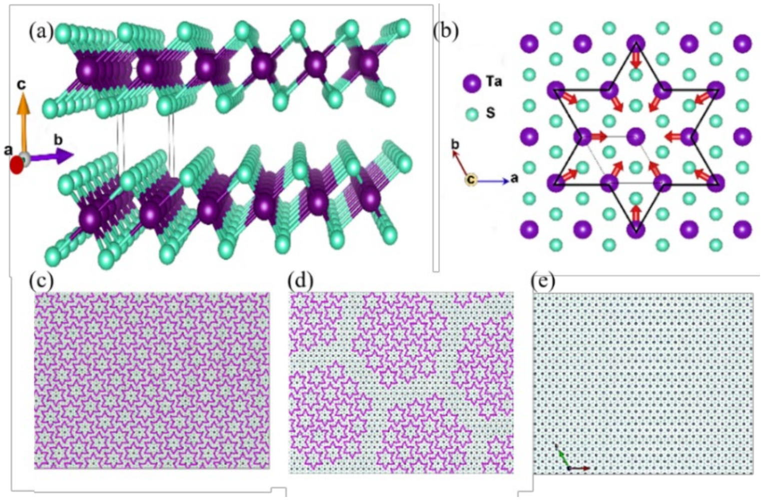
Renewal of Interest to CDW Materials: Quasi-2D 1T-TaS_2



B. Sipos, et al., From Mott state to superconductivity in 1T-TaS_2, Nature Mater., 7, 960 (2008).

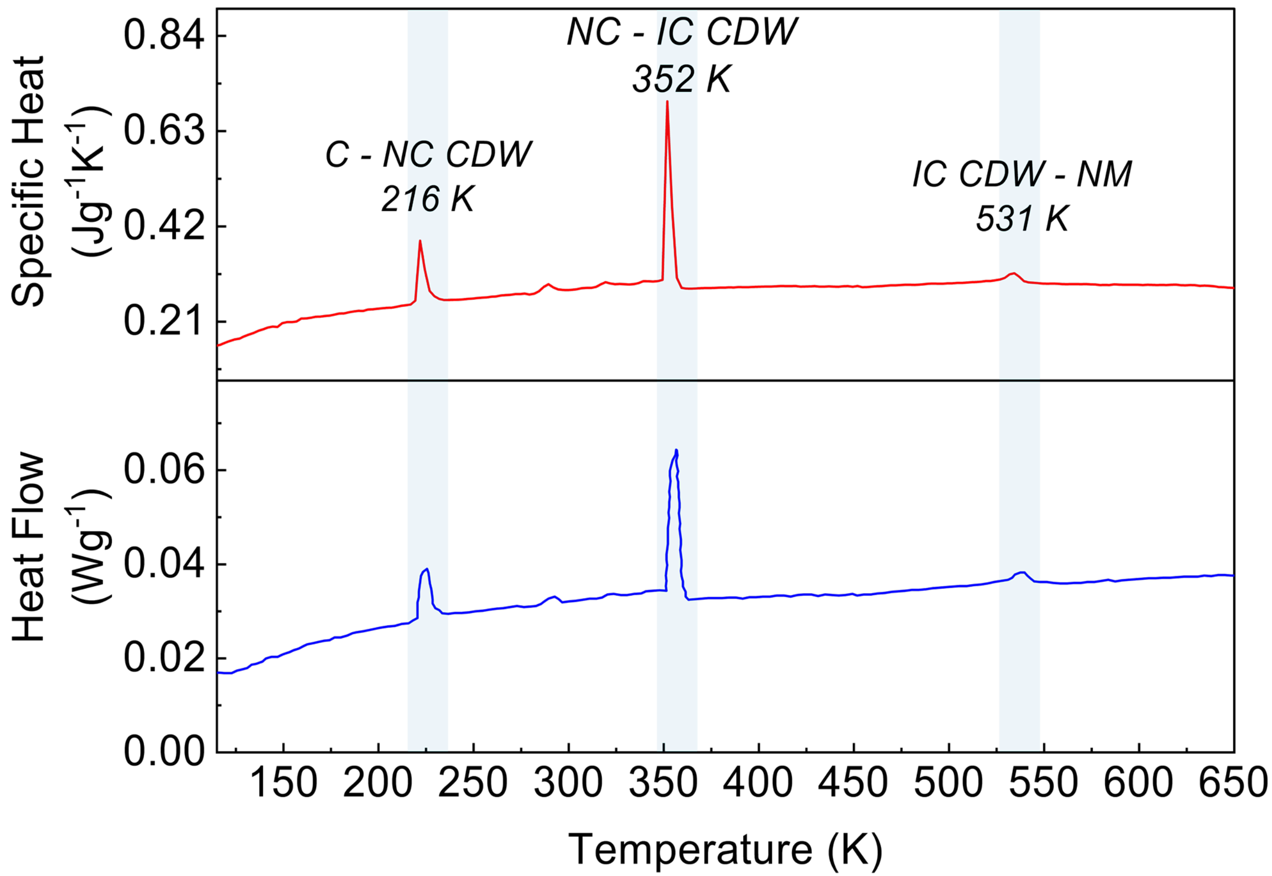


C-CDW – NC-CDW transition is at 200 K and NC-CDW – IC-CDW transition is at 350 K

G. Liu, … A. A. Balandin, A charge-density-wave oscillator based on an integrated tantalum disulfide–boron nitride–graphene device operating at room temperature, Nature Nano, 11 845 (2016).

M. Taheri, … and A. A. Balandin, Electrical gating of the charge-density-wave phases in two-dimensional h-BN/1T-TaS_2 devices, ACS Nano, 16, 11, 18968 (2022).

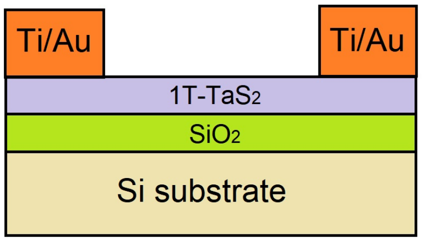
Verification of CDW Phase Transitions in Quasi-2D 1T-TaS_2



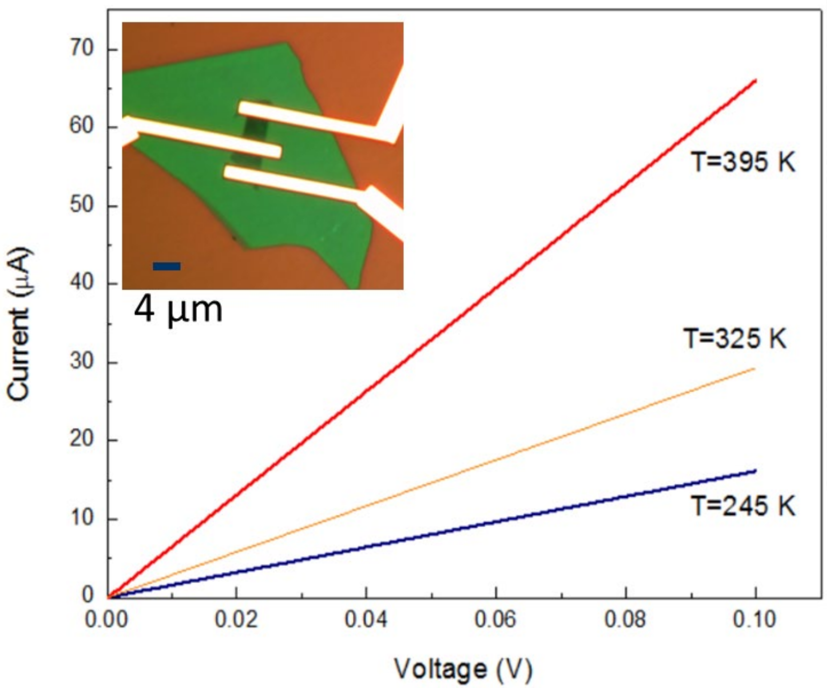
The 1T-TaS_2 Phases

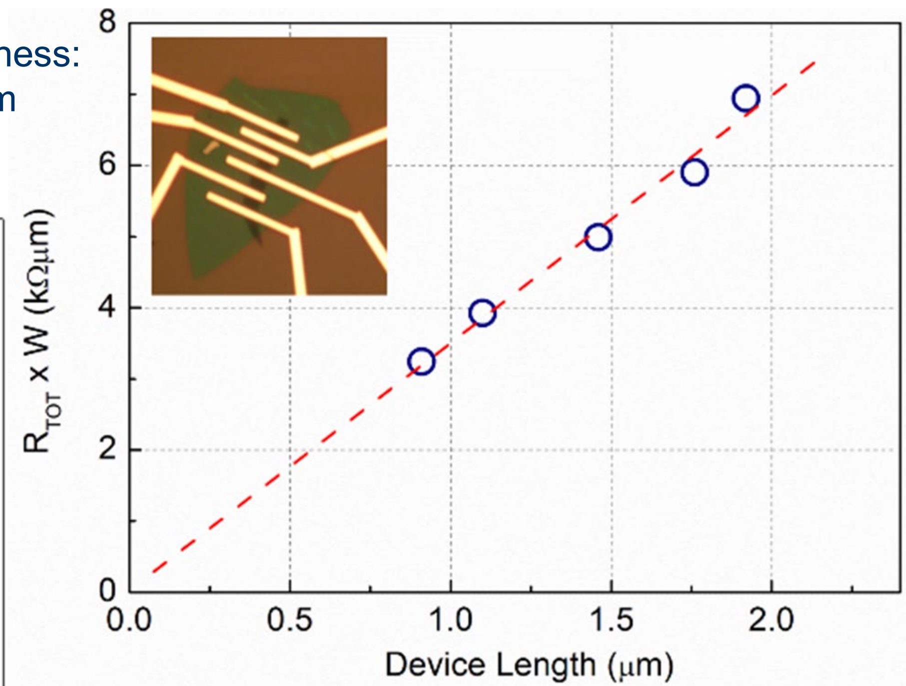
→ Metallic phase at temperatures above ~530 K
→ IC-CDW phase above ~350 K
→ NC-CDW phase above ~220 K
→ C-CDW Mott phase ~below 220 K

CDW Device Structure and Contacts



Channel thickness:
t = 6 nm - 9 nm
t = 10 -20 nm





Contacts: Pd/Au or Ti/Au (15 nm / 60 nm)

The h-BN cap provides air stable passivation for the 1T-TaS_2.

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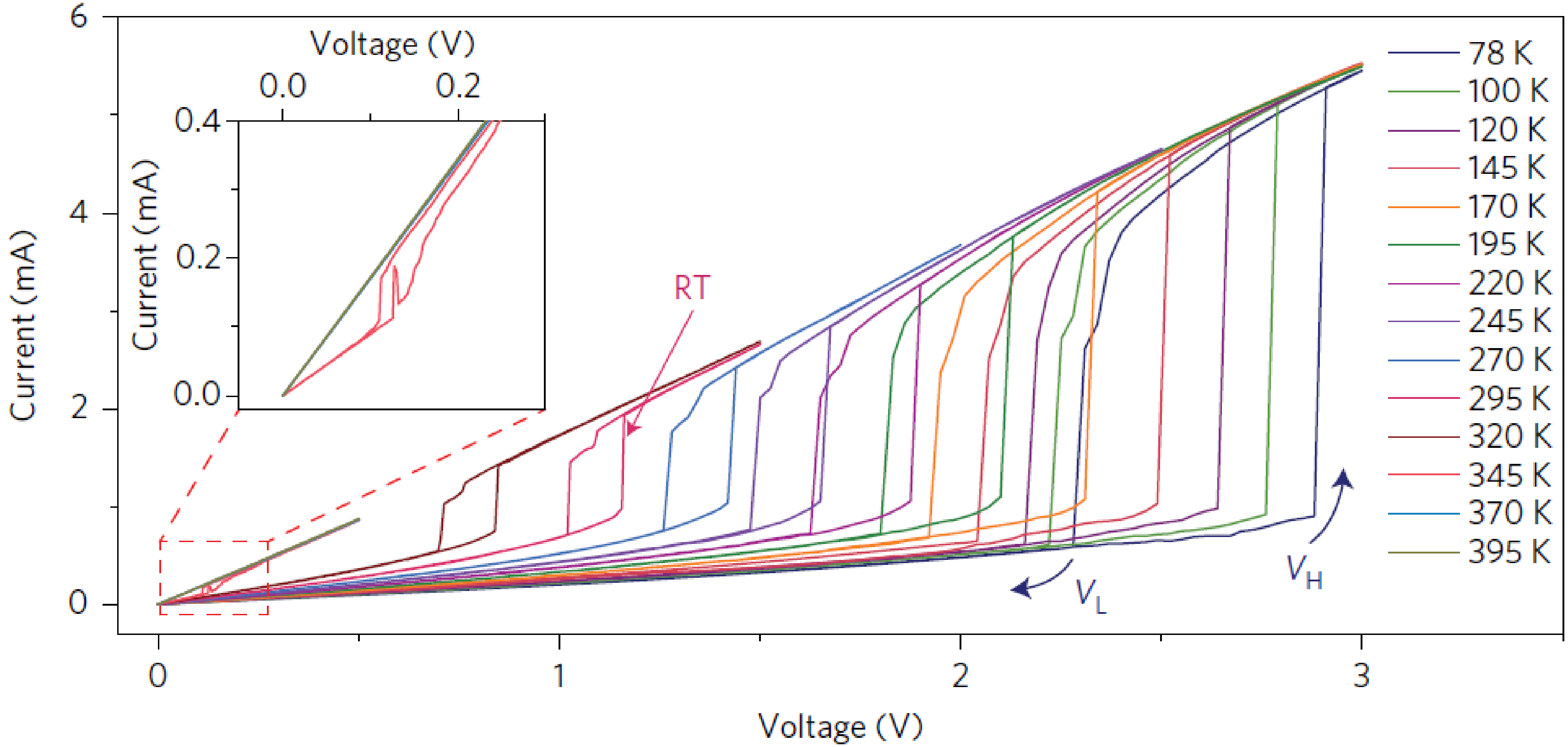
I-V Characteristics of Thin-Film 1T-TaS_2 Channel

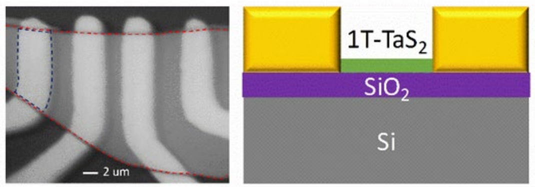


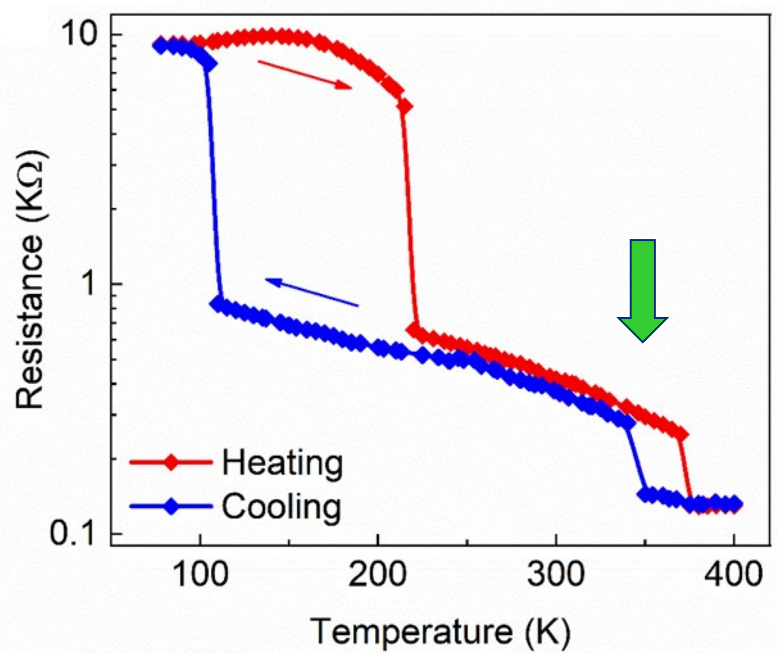
The threshold switching effect is prominent from 78 K to 320 K.. The switching is prominent up to 320 K, and becomes less pronounced as the temperature approaches the NC-CDW–IC-CDW transition at 350 K. As shown in the inset, at 345 K (red curve), the switching is still measurable.

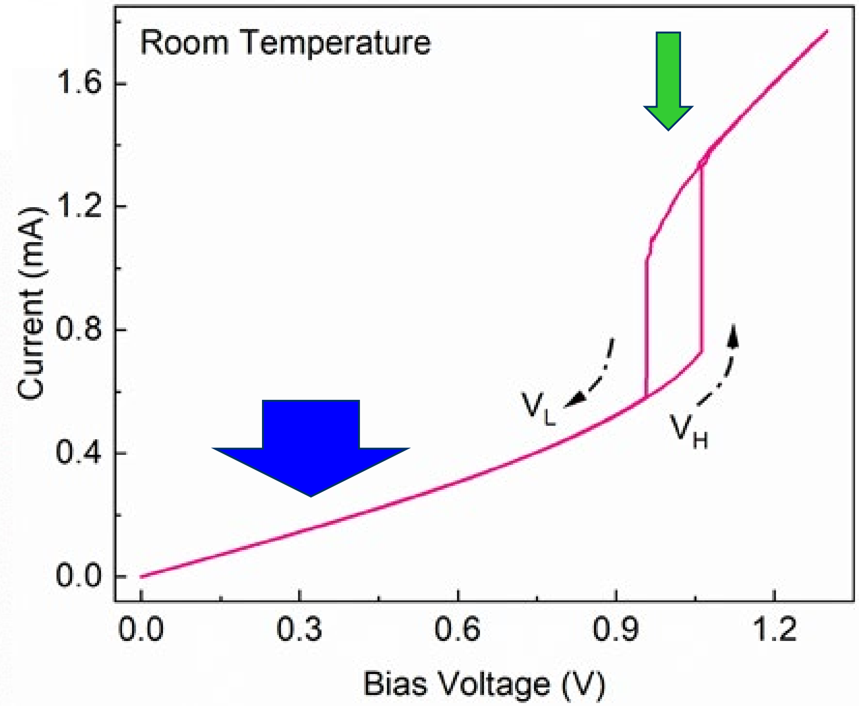
G. Liu, B. Debnath, T. T. Salguero, R. K. Lake, and A. A. Balandin, Nature Nano, 11, 845 (2016).

UCLA

The NC-CDW – IC-CDW Hysteresis Induced by Temperature or Current





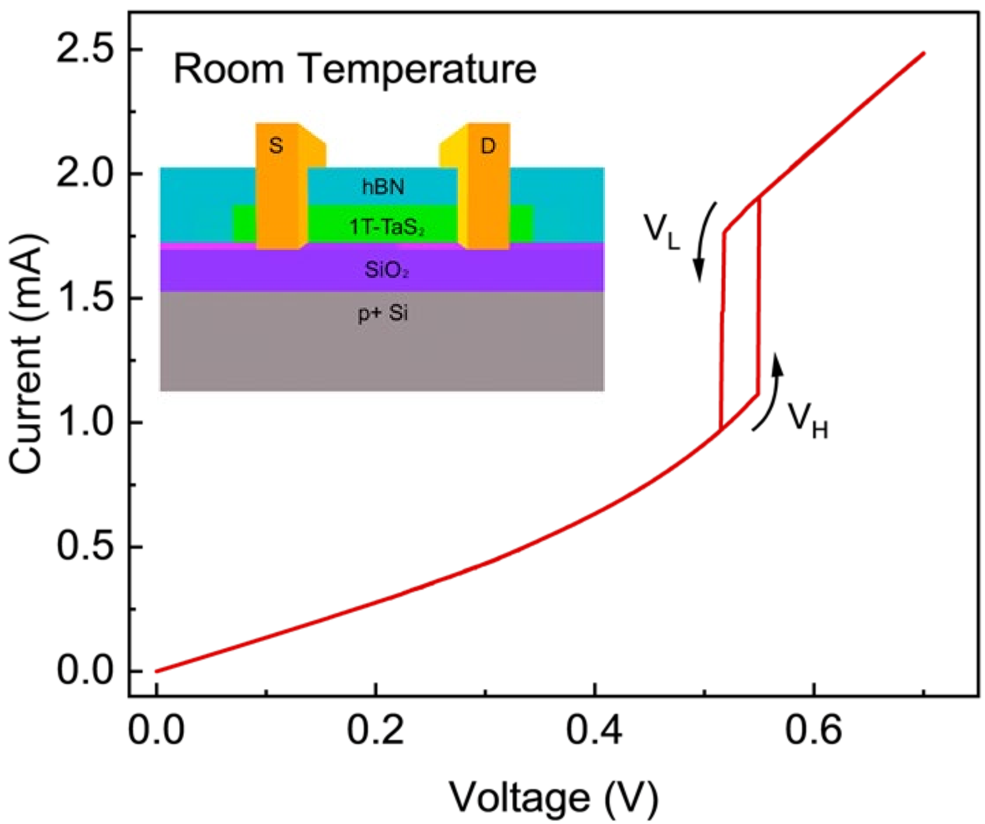


- A. K. Geremew, *et al*., ACS Nano, 13, 7231 (2019).
- M. Taheri, *et al*., ACS Nano, 16, 18968 (2022).

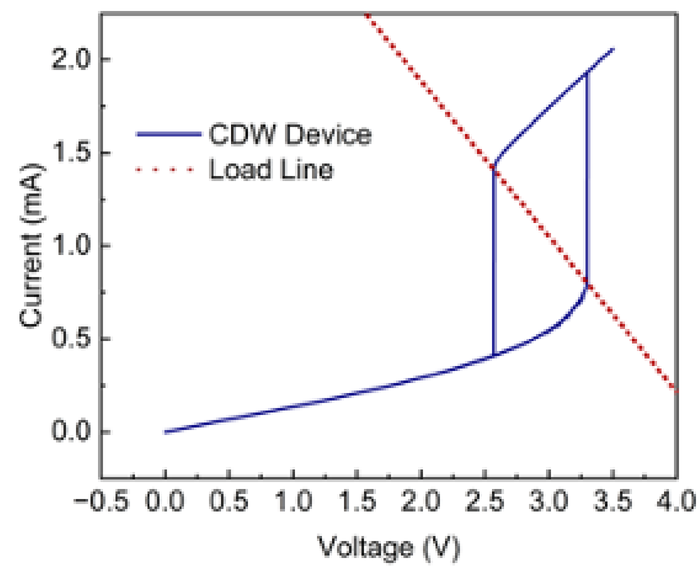
We are not using on/off resistance change for the functionality but rather the hysteresis and "depinning" of the domains.

Device Concept – Instability and Feedback in 1T-TaS_2 CDW Channel

Typical Experimental Data

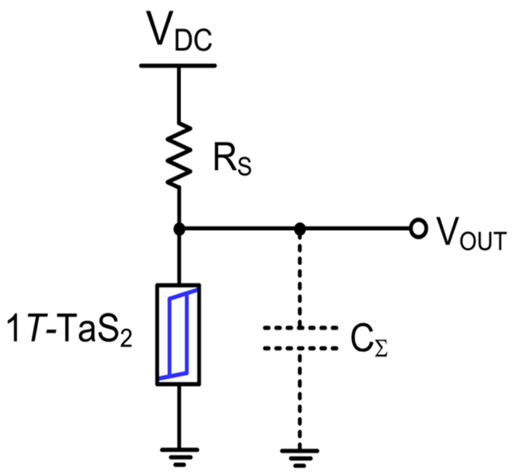


Schematic – Feedback

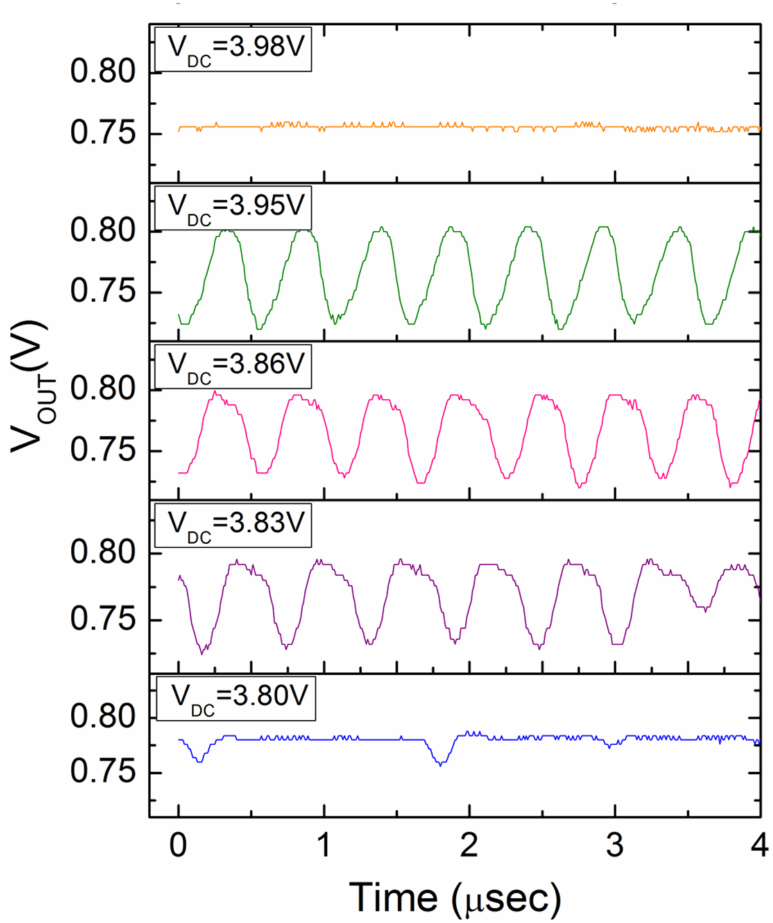


The hysteresis is due to the NC-CDW – IC-CDW phase transition

Room-Temperature CDW Voltage Controlled Oscillator



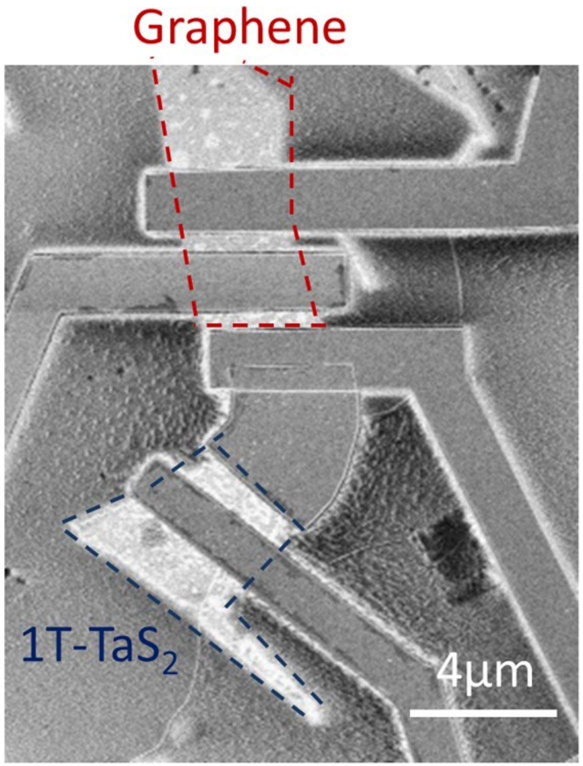
Different operation mechanism from early CDW devices – no substantial collective current due to sliding



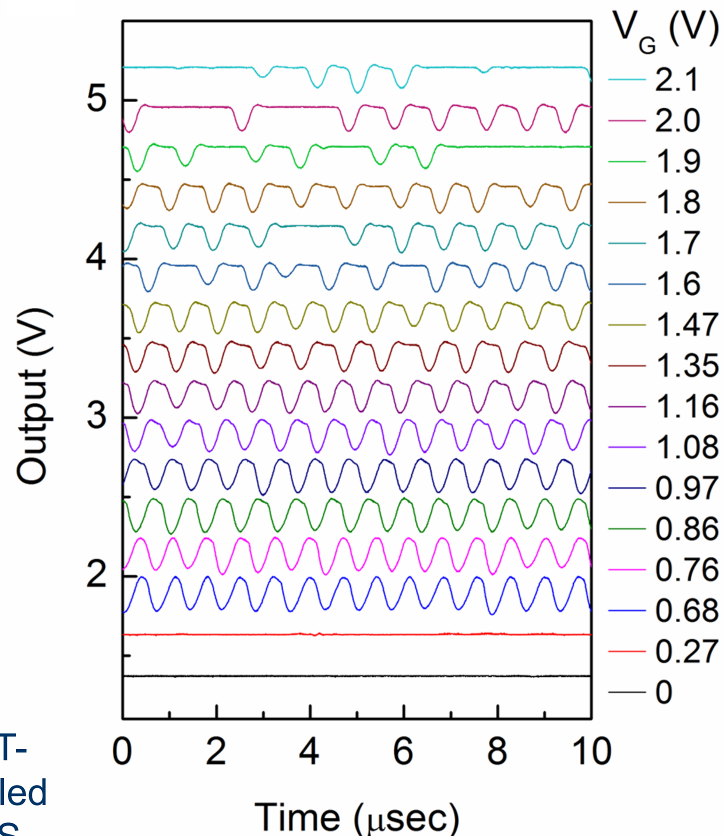
→Circuit schematic of the oscillator consists of the 1T-TaS_2 film, a series connected load resistor, and a lumped capacitance from the output node to ground. The load resistance is 1 kΩ.

→Voltage oscillations under different V_{DC}. The circuit oscillates when V_{DC} is within the range of 3.83-3.95 V. The frequency is 1.77 MHz, 1.85 MHz, and 2 MHz when V_{DC} is 3.83, 3.86 and 3.95 V, respectively.

Integrated 1T-TaS_2–h-BN–Graphene VCO – Functionality Based on Intrinsic Properties



The SEM image of the integrated 1T-TaS_2–BN–graphene voltage controlled oscillator. The graphene and the TaS_2 are highlighted by dashed lines.

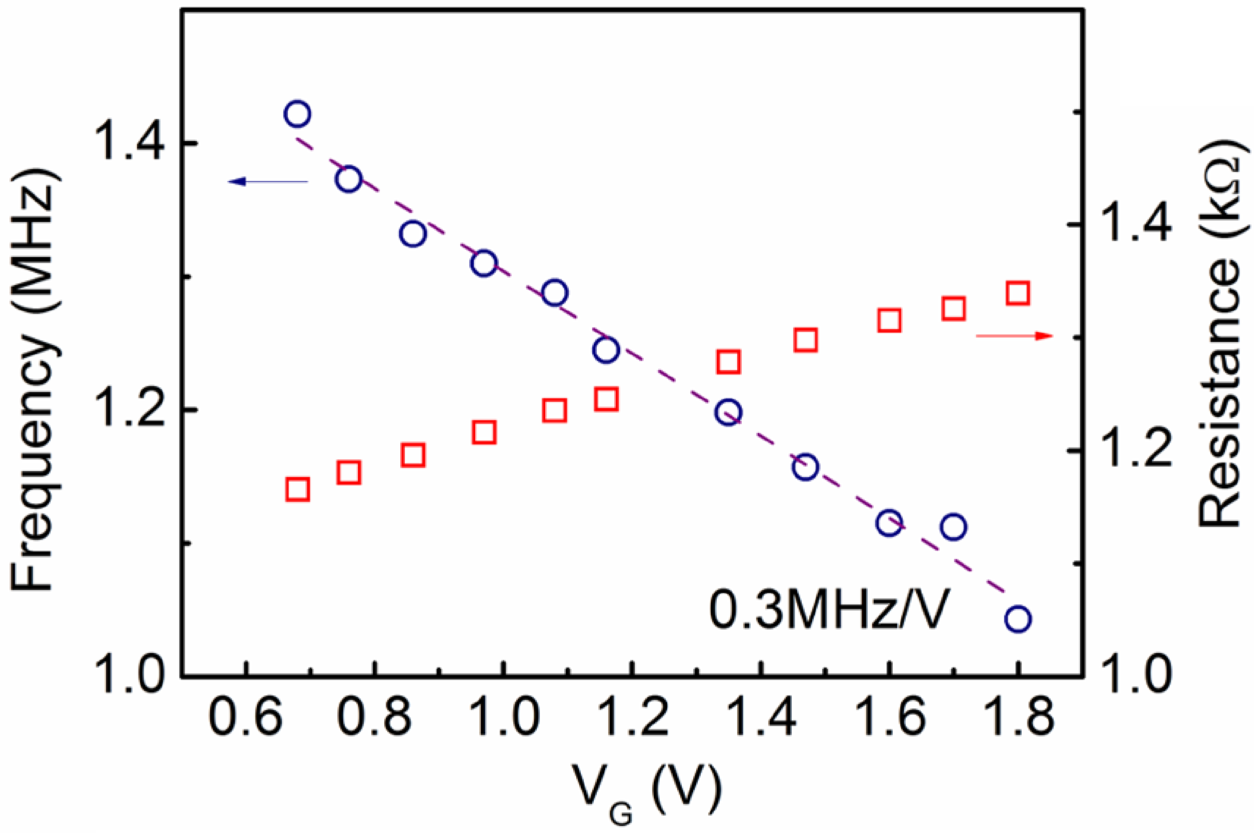


Output waveforms at different gate biases when V_{DC} is fixed at 3.65 V. The oscillation frequency is tunable with gate biases in the range of 0.68 V to 1.8 V. The different waveforms are vertically offset of 0.25 V for clarity.

G. Liu, B. Debnath, T. T. Salguero, R. K. Lake, and A. A. Balandin, Nature Nano, 11, 845 (2016).

1T-TaS_2 – h-BN – Graphene CDW VCO

Oscillation Frequency as Function of Gate Bias



Blue circles show the frequency of the oscillation under increased gate bias. The frequency can be adjusted monotonically with the tuning sensitivity of 0.3M Hz/V.

The red squares are the resistance value of the G-FET under different gate biases with fixed V_{DC}=2.4V.

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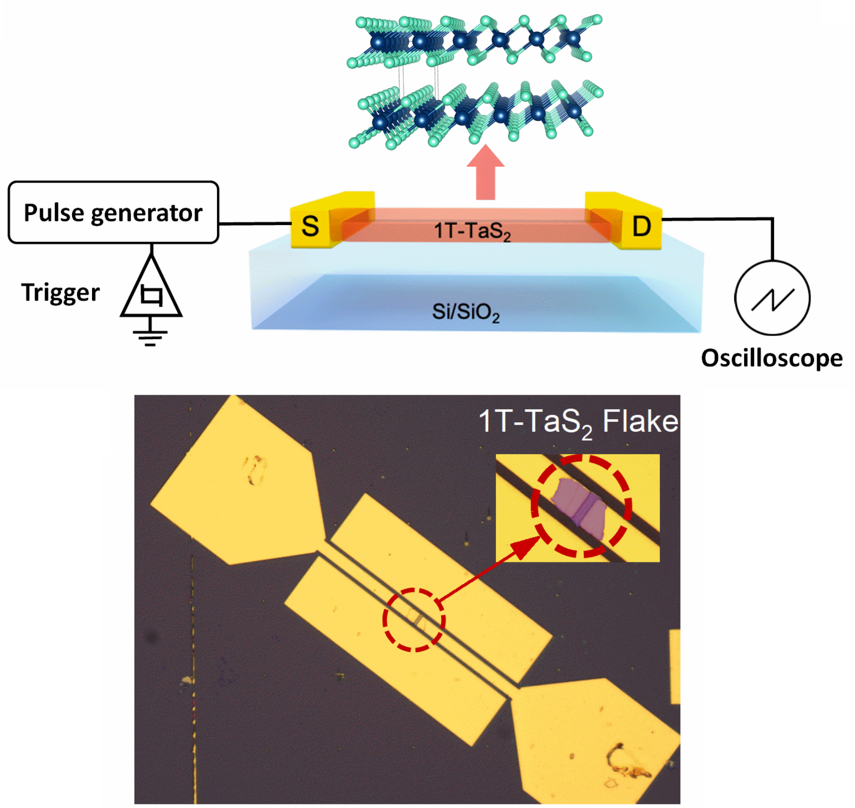
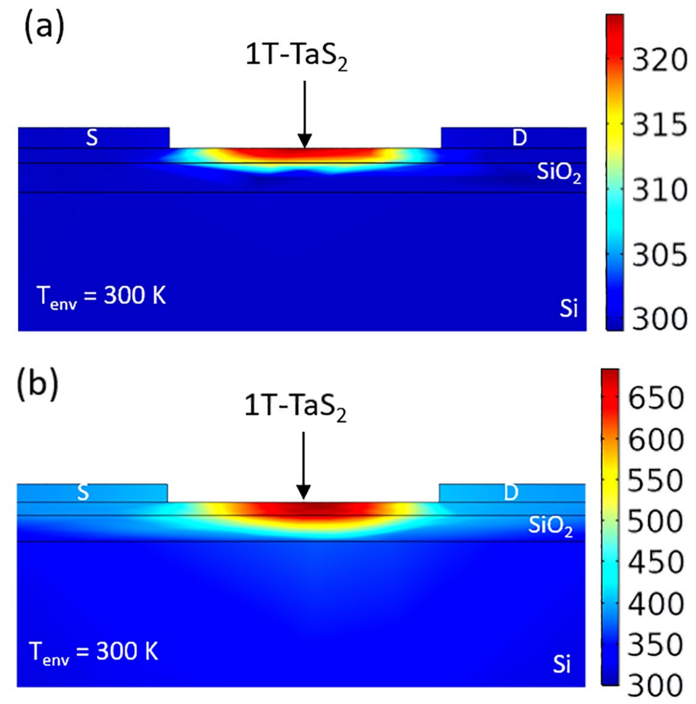
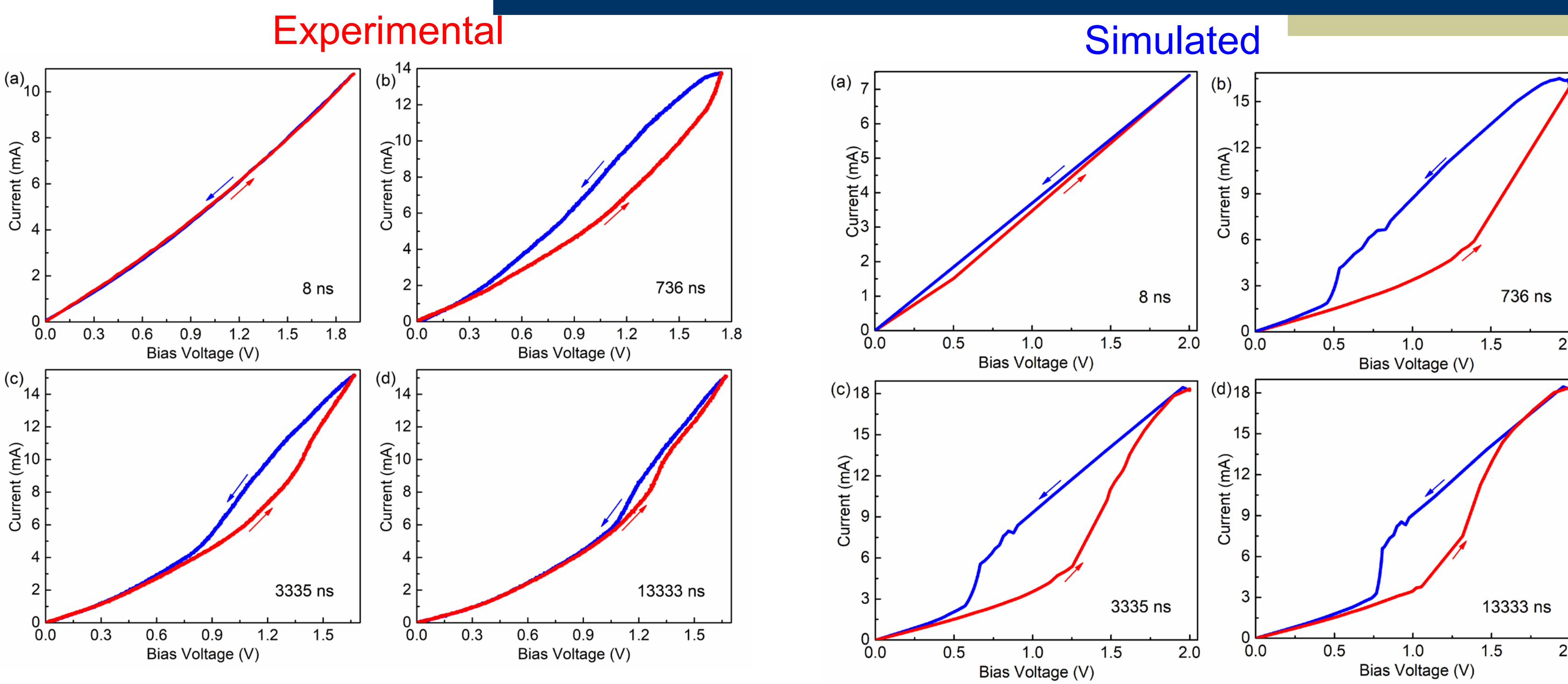
Nature of CDW Switching: Heat *vs.* Field





The SiO_2 layer acts as an efficient thermal barrier. While the heating is insufficient for 8-ns pulse duration (a) to drive the NC- to IC-CDW phase transition, by increasing the pulse duration to 13.3 μs the local temperature in the TaS_2 rises well above 350 K (b).

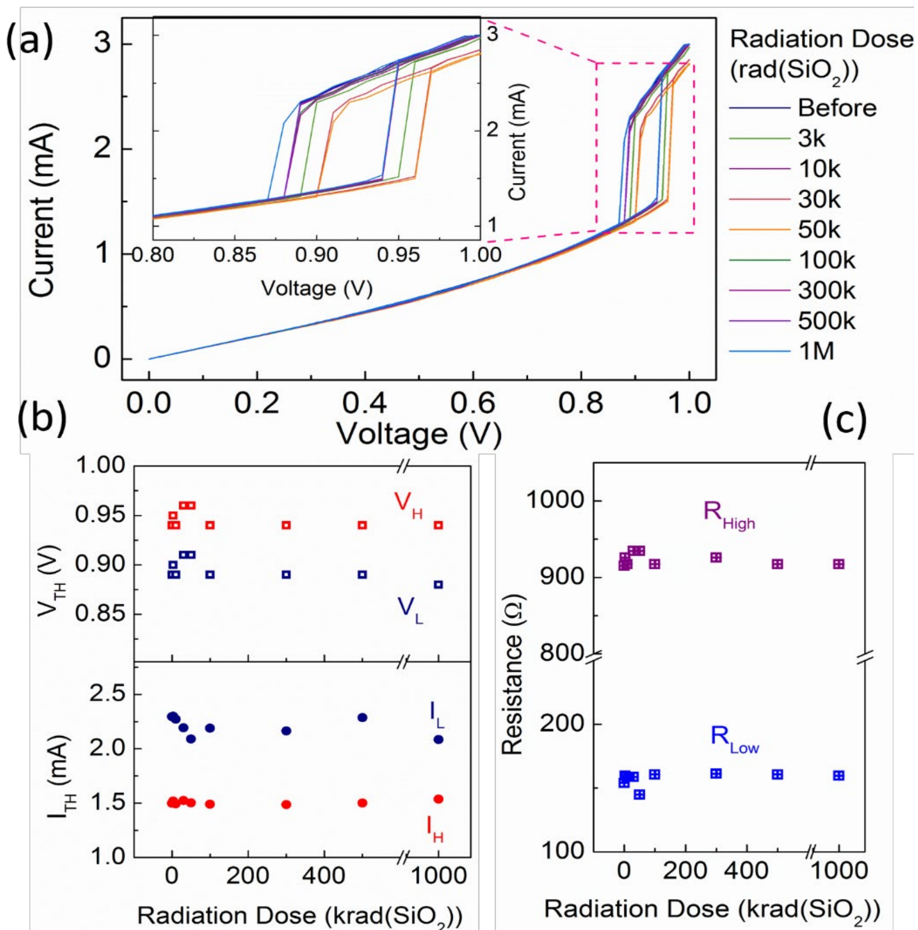
Experimental and Calculated I-V Characteristics of 1T-TaS_2/SiO_2-Si Devices



Experimental (left) and simulated (right) I-V characteristics for (a) 8 ns, (b) 736 ns, (c) 3,335 ns, and (d) 13,333 ns pulses. For the shortest duration shown (8 ns), no hysteresis window is observed. With increasing the pulse duration, the width of the hysteresis window expands and then shrinks again. This behavior is attributed to the transient heat diffusion characteristics of the 1T-TaS_2 film, during the up and down sections of the pulse, causing the film to attain different temperatures at fixed bias in the hysteresis region.

A. Mohammadzadeh, *et al*., Appl. Phys. Lett. 118, 093102 (2021).

$1T\text{-}TaS_2$ CDW Devices Under Extreme Environment - X-Ray Irradiation

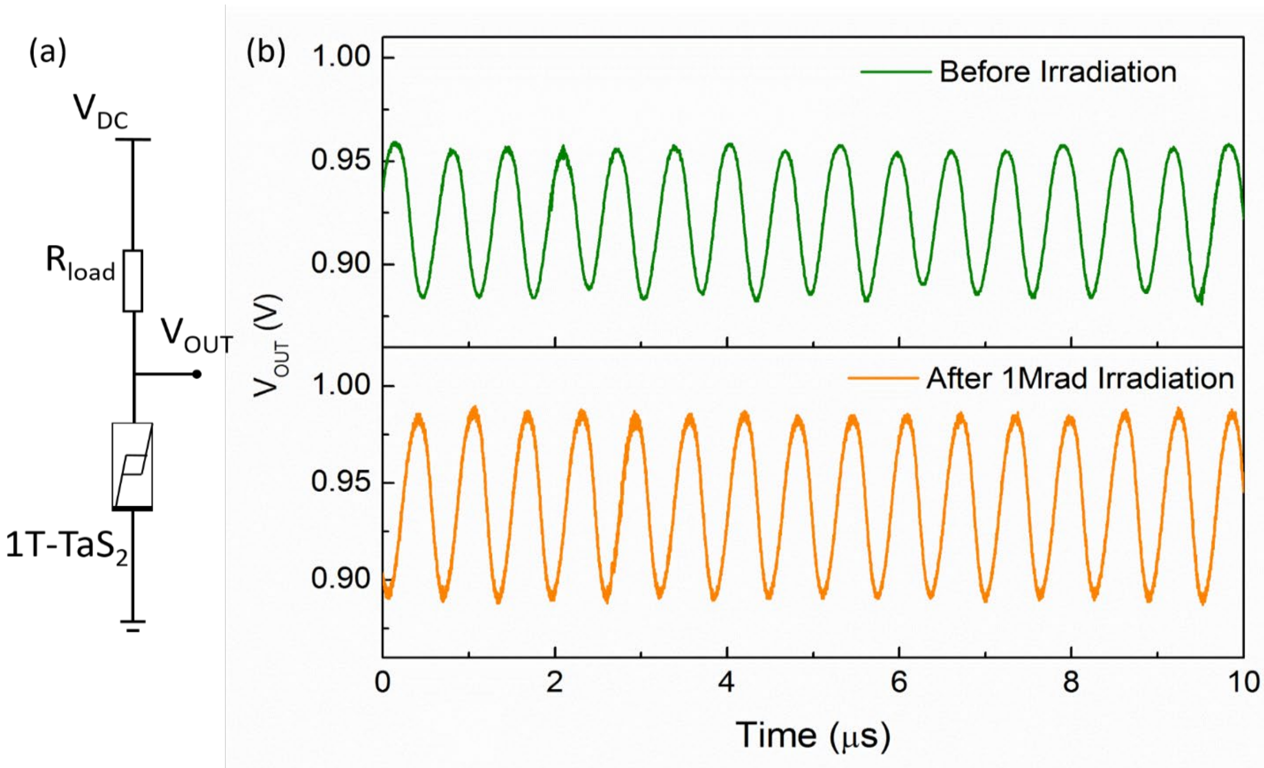


TID response of $1T\text{-}TaS_2$ devices up to 1 M rad (SiO_2). (a) I-V curves measured after each X-ray irradiation step. (b) Threshold voltages, V_H and V_L, threshold currents, I_H and I_L as function of dose. (c) Extracted resistance at the high resistance and low resistance states as a function of dose.

Carrier concentration:
10^{21} cm^{-3} - 10^{22} cm^{-3}

G. Liu, E. X. Zhang, C. Liang, M. Bloodgood, T. Salguero, D. Fleetwood, A. A. Balandin, "Total-ionizing-dose effects on threshold switching in $1T\text{-}TaS_2$ charge density wave devices," IEEE Electron Device Letters, 38, 1724 (2017).

Radiation Hardness of CDW Devices – Robustness of NC-CDW – IC-CDW Transition

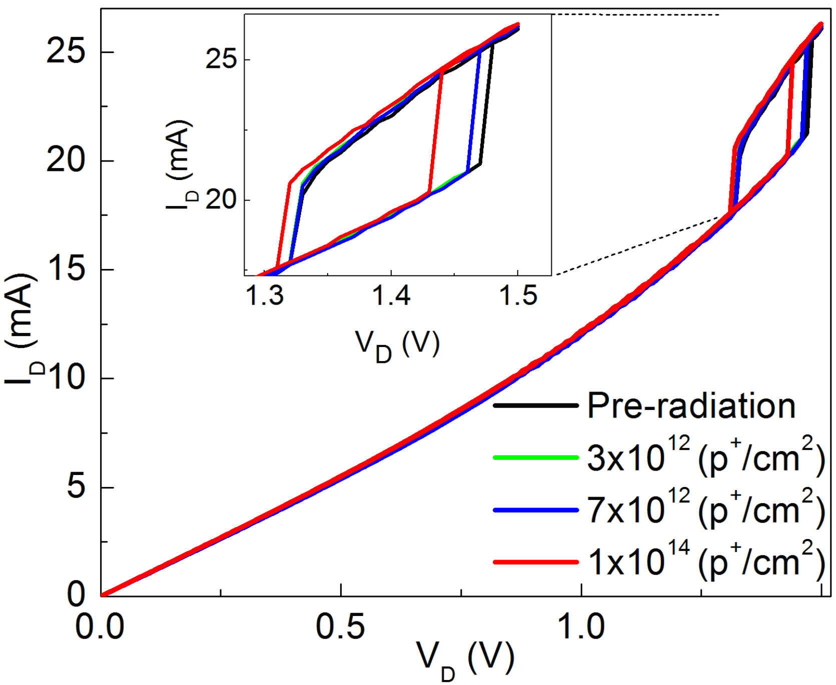


(a) Circuit schematic diagram of a self-sustaining oscillator implemented with one 1T-TaS_2 device and a load resistor.

(a) Oscillation waveform before and after 1 Mrad(SiO_2) X-ray irradiation

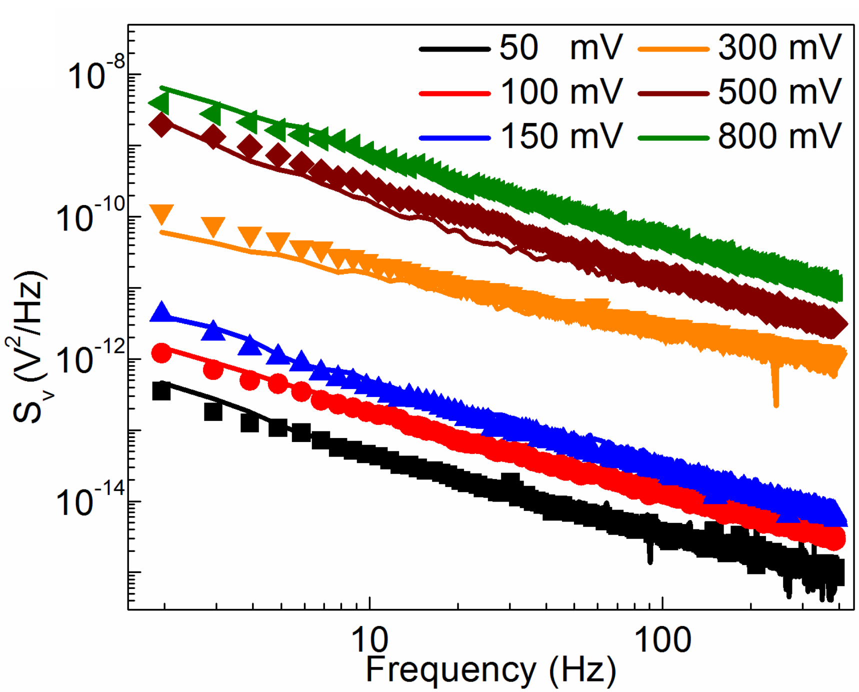
G. Liu, E. X. Zhang, C. Liang, M. Bloodgood, T. Salguero, D. Fleetwood, A. A. Balandin, Total-ionizing-dose effects on threshold switching in 1T-TaS_2 charge density wave devices, IEEE Electron Device Letters, 38, 1724 (2017).

Proton Bombardment Immune CDW Devices – Using 1/*f* Noise to Assess the Damage



The quasi-two-dimensional (2D) 1T-TaS_2 channels show a *remarkable* immunity to bombardment with the high-energy 1.8 MeV protons to, at least, the irradiation fluence of 10^{14} $H^{+}cm^{-2}$.

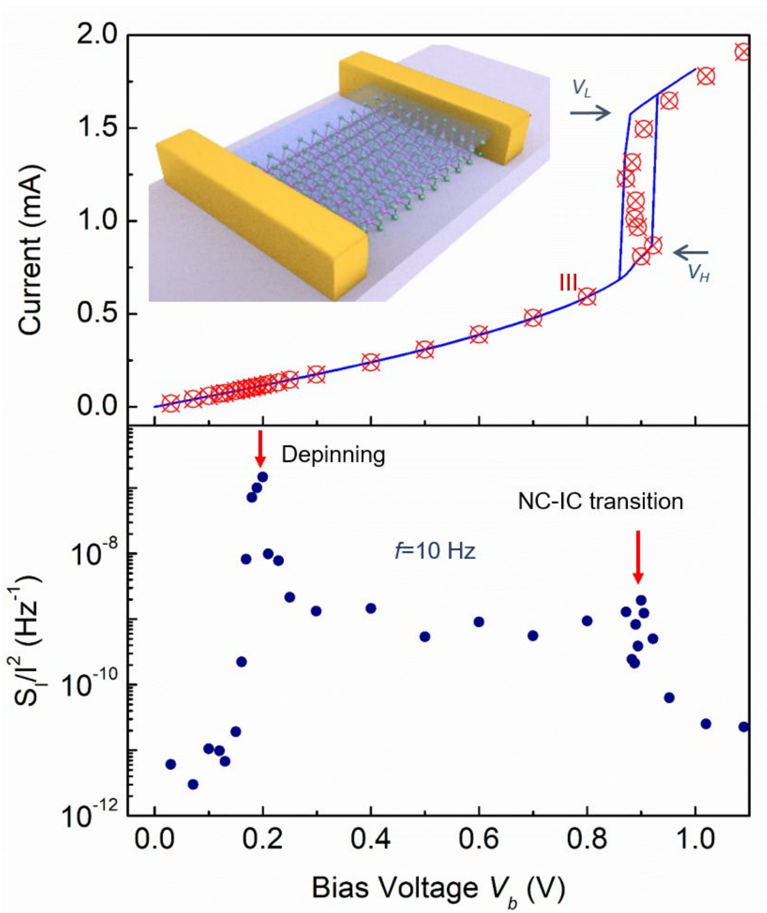
Testing at Vanderbilt Pelletron



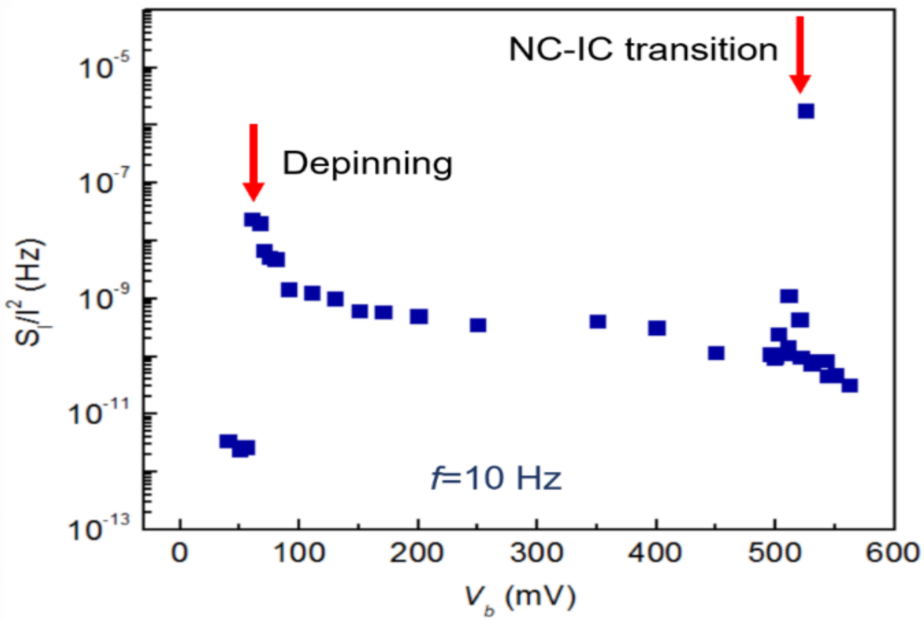
A. K. Geremew, F. Kargar, E. X. Zhang, S. E. Zhao, E. Aytan, M. A. Bloodgood, T. T. Salguero, S. Rumyantsev, A. Fedoseyev, D. M. Fleetwood and A. A. Balandin, Nanoscale, 11, 8380 (2019).

Where is the CDW Depinning in Quasi-2D Materials?

UPON: Only LFN can tell!

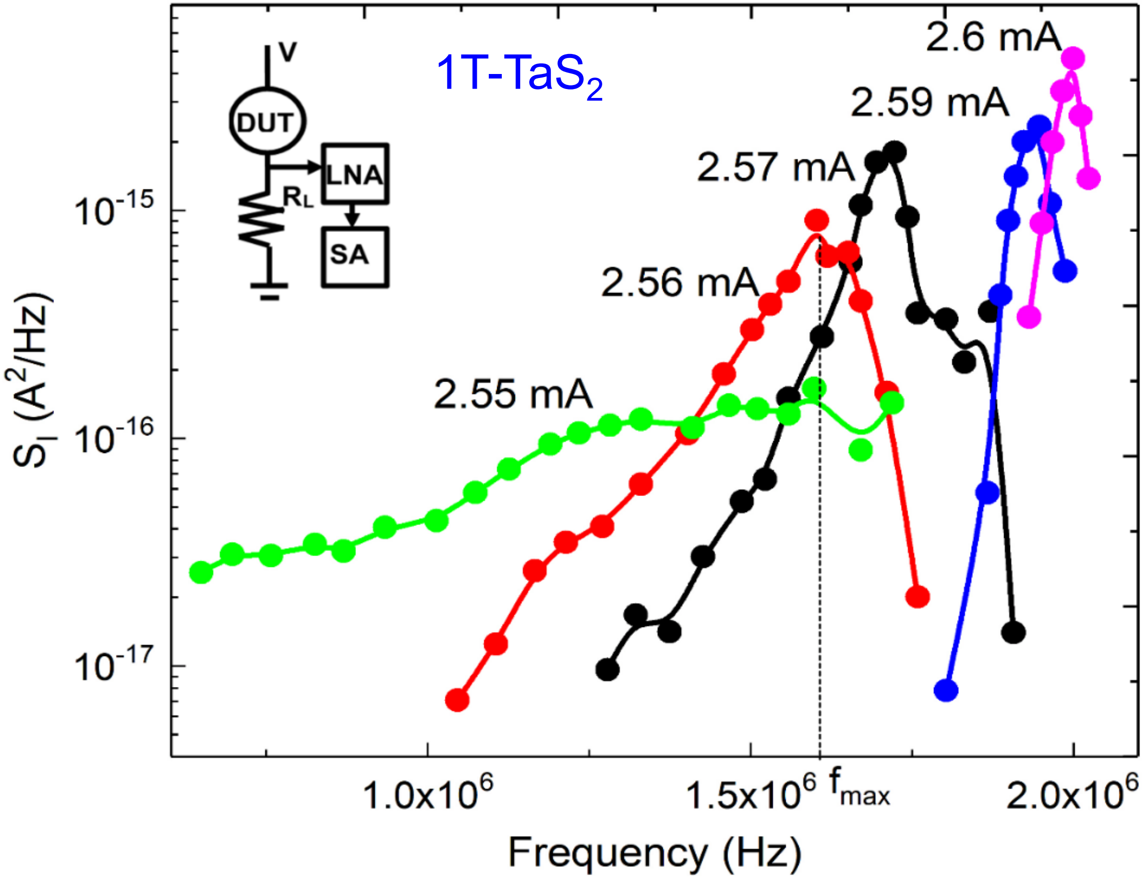


Noise is more sensitive than I-Vs for monitoring CDWs in quasi-2D materials



G. Liu, S. Rumyantsev, M. A. Bloodgood, T. T. Salguero, and A. A. Balandin, Nano Letters, 18, 3630 (2018).

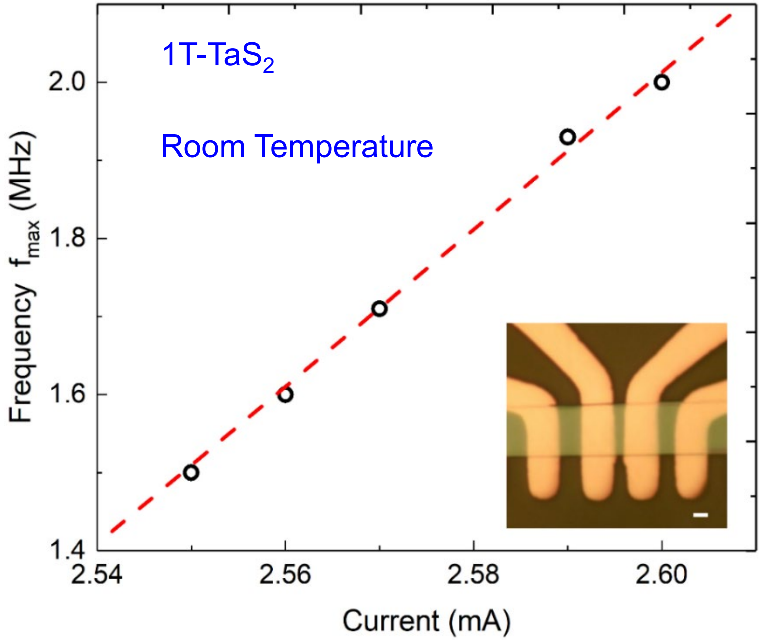
The Signatures of the "Narrow Band Noise" in Quasi-2D CDWs

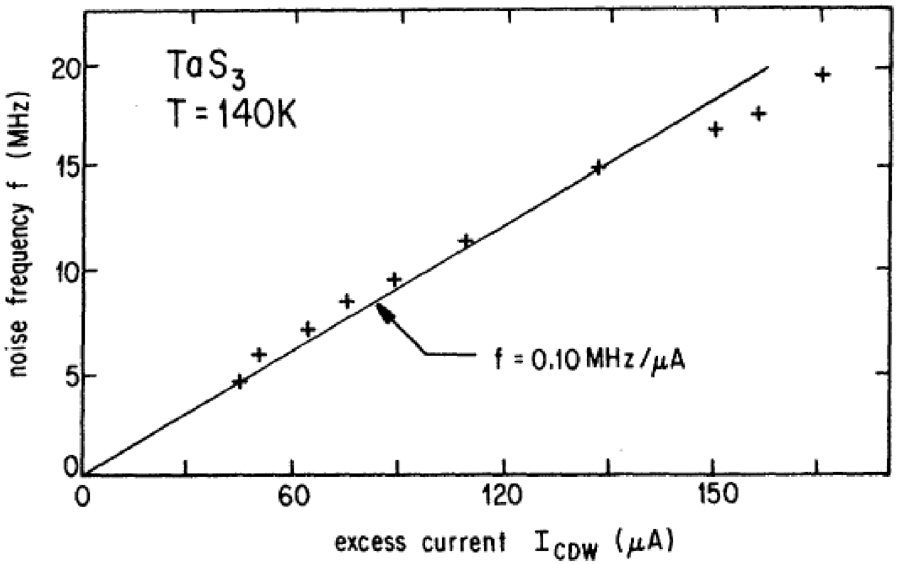


In bulk quasi-1D CDW materials: $I_{CDW}=nef\Lambda A$, where n is the charge carrier density, e is the charge of an electron, and A is the cross-sectional area, one obtains: $f=v_D/\Lambda=(1/ne\Lambda A)\times I_{CDW}$

A. K. Geremew, S. Rumyantsev, B. Debnath, R. K. Lake, and A. A. Balandin, High-frequency current oscillations in charge-density-wave 1T-TaS_2 devices: Revisiting the "narrow band noise" concept, Appl. Phys. Lett., 116, 163101 (2020).

Have We Found the "Narrow Band Noise" in Quasi-2D CDWs?

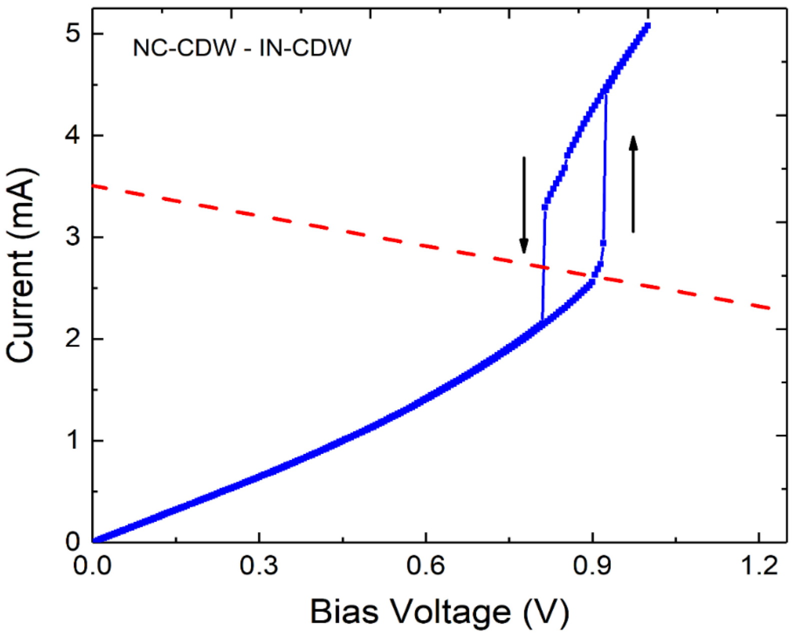




G. Gruner, *et al*., Phys. Rev. B, 23, 6813 (1981).

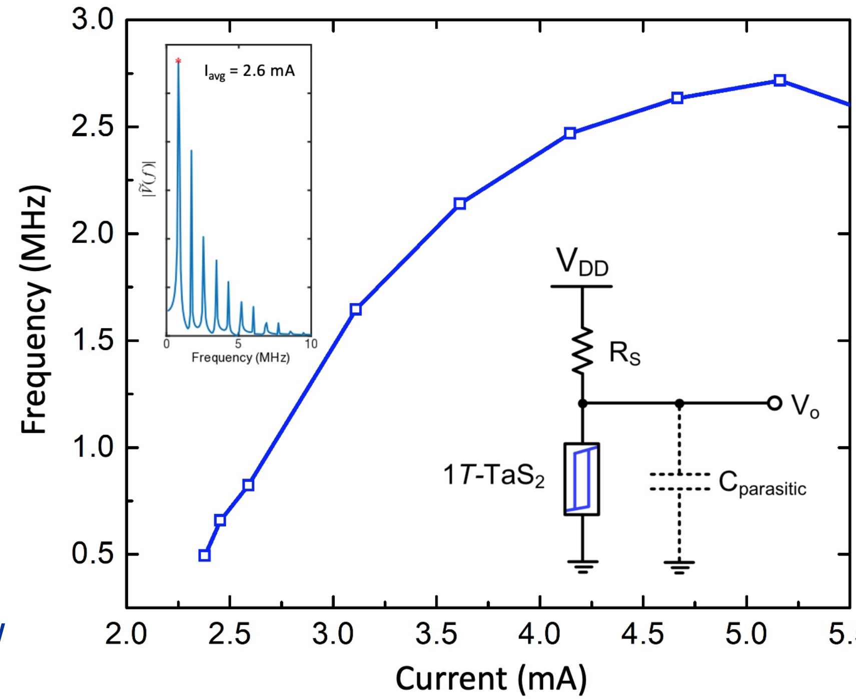
Frequency, f_o of the noise peaks as a function of the current through 1T-TaS_2 device channel. The inset shows a microscopy image of a representative 1T-TaS_2 device structure with several metal contacts.

The Current Oscillations are due to Hysteresis at the NC-CDW – IC-CDW Transition



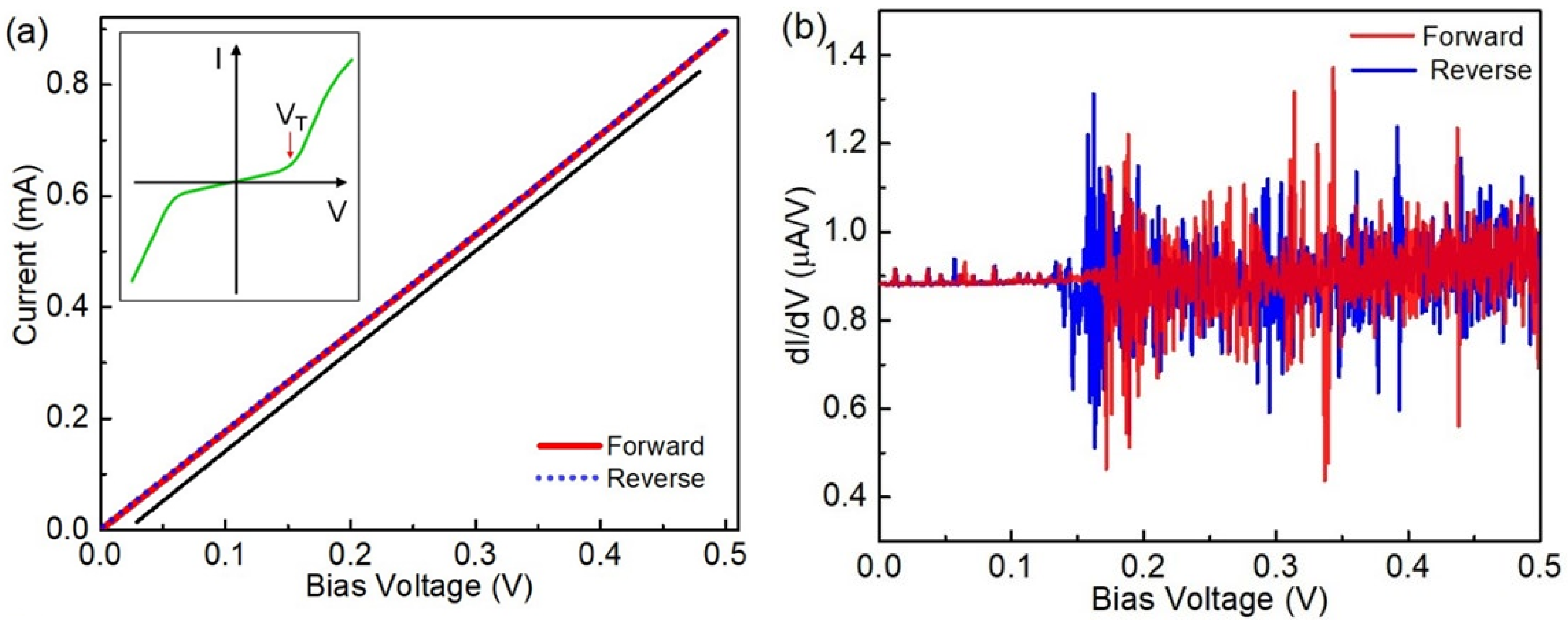
I-Vs of tested 1T-TaS_2 device which revealed "narrow band noise". The hysteresis loop at the bias voltage V = 0.9 V corresponds to the transition from the NC-CDW phase to the IC-CDW phase induced the applied electric field.

The current oscillations appear to be similar to our earlier result – this is not the "narrow band noise."



Alexander A. Balandin, University of California, Los Angeles

Derivatives of the I-V Characteristics of 1T-TaS_2 CDW Devices at Room Temperature



(a) The current in the forward (red) and reverse (blue) sweeping overlaps. The straight black line is shown for comparison. No deviations from the non-linearity are observed in this bias range. (b) The derivative of current-voltage characteristics revealing a strong change in the electron transport.

→ The threshold in 2D is ~1 kV/cm while in 1D systems it is ~ 40 mV/cm – 4 V/cm

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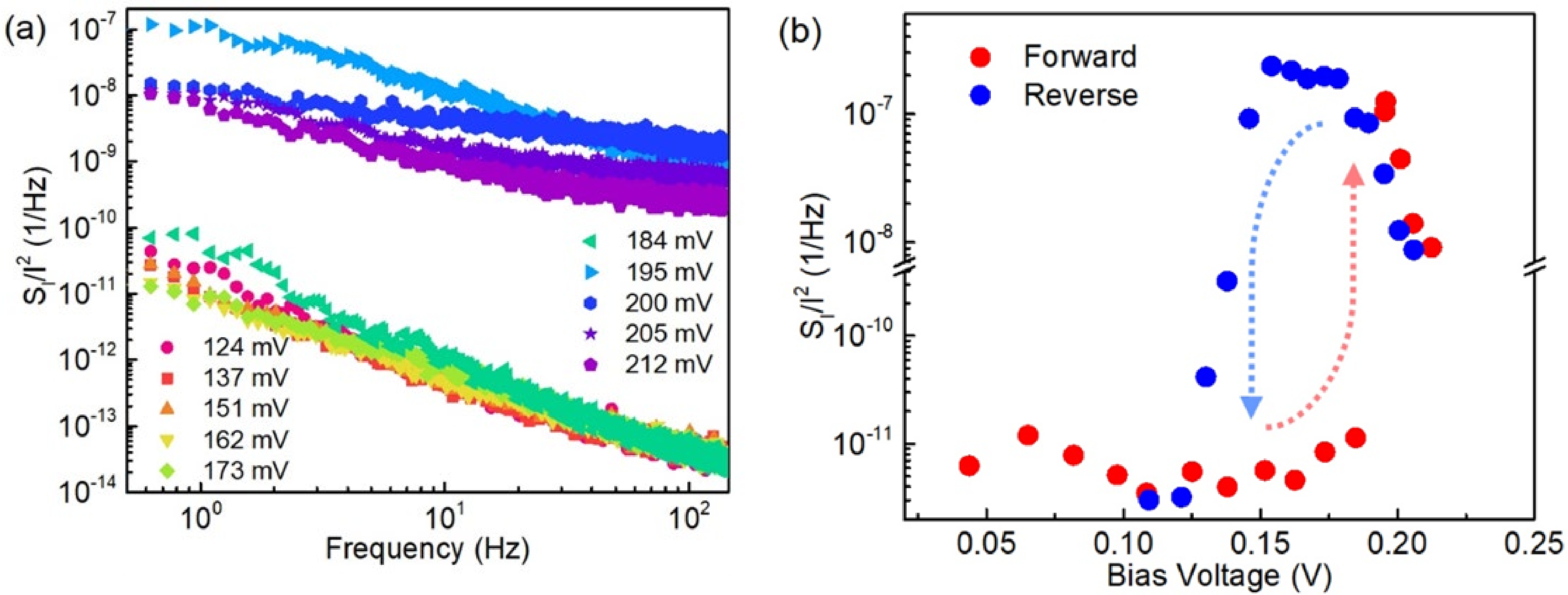
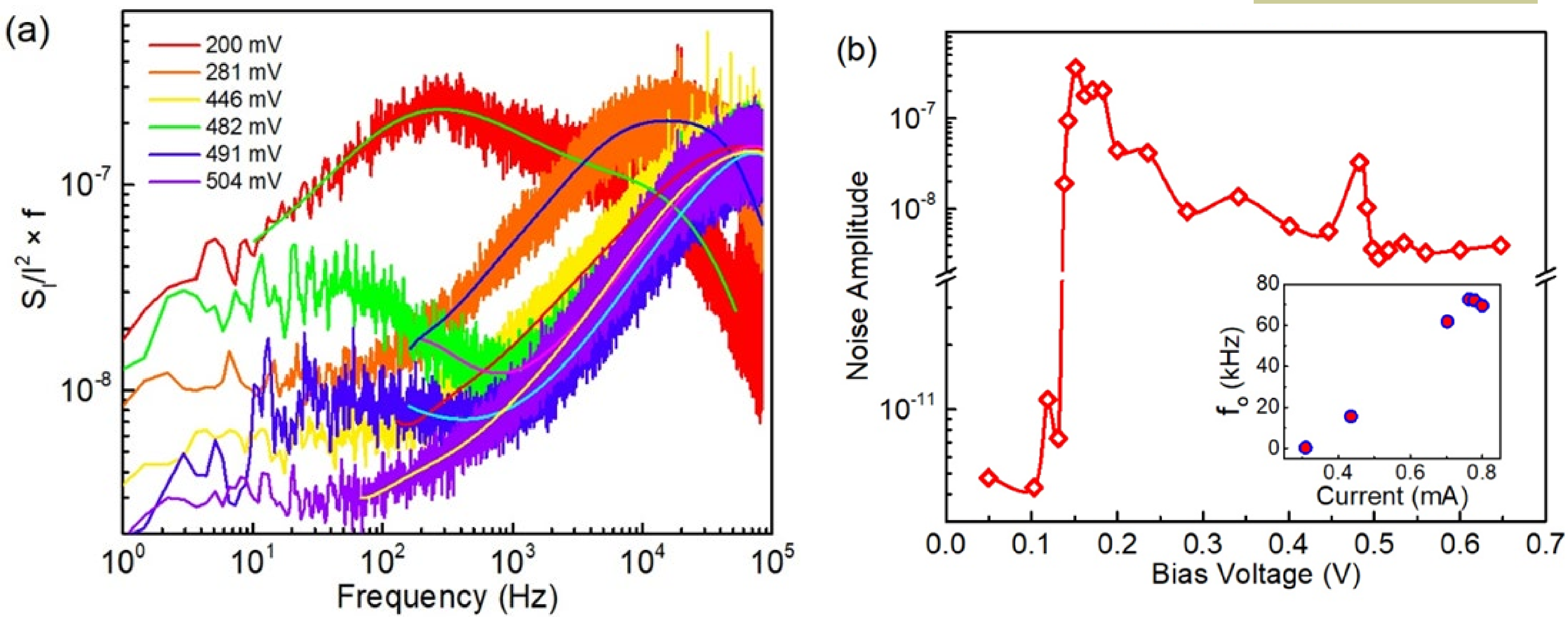
Noise Spectroscopy Reveals the CDC "Domain Depinning" in 1T-TaS_2 Devices



A. Mohammadzadeh, A. Rehman, F. Kargar, S. Rumyantsev, J. M. Smulko, W. Knap, R. K. Lake, and A. A. Balandin, "Room-temperature depinning of the charge-density waves in quasi-2D 1T-TaS2 devices", Appl. Phys. Lett., 118, 223101 (2021).

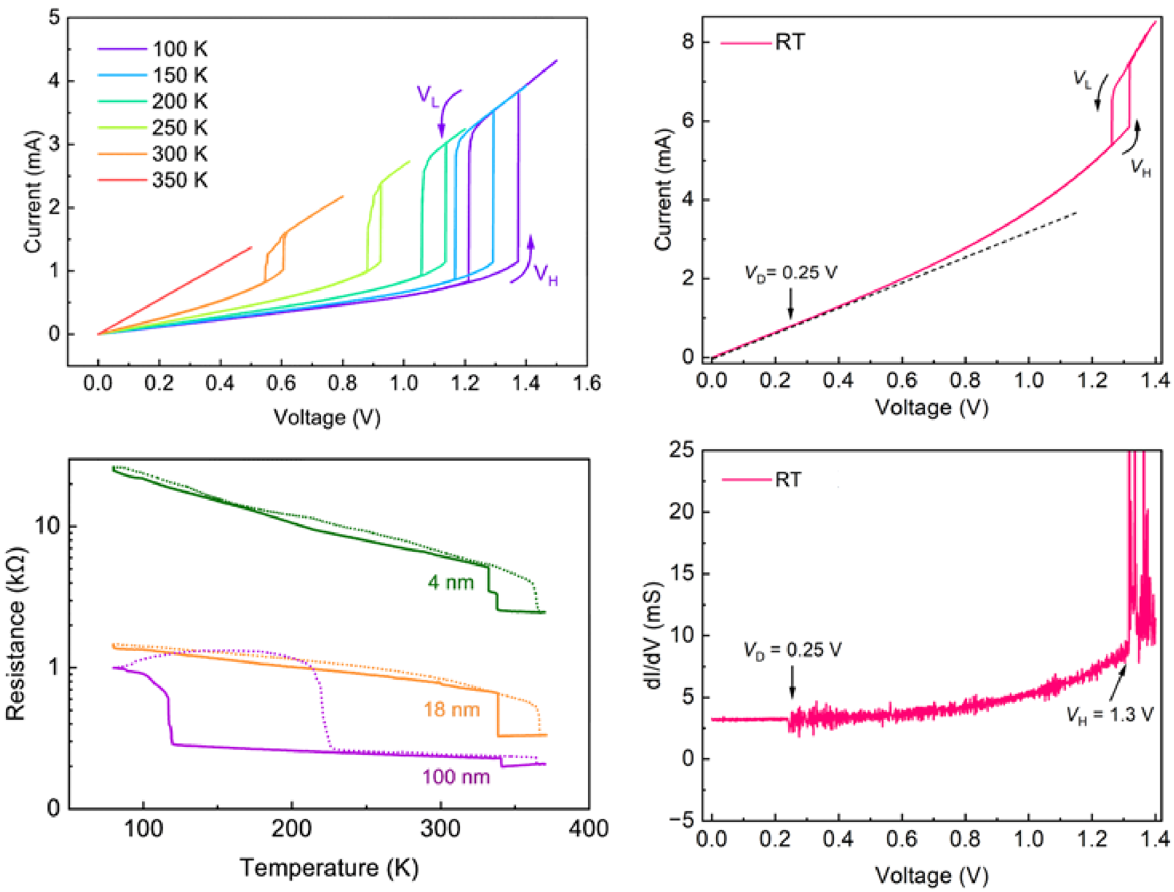
Something is Sliding in Quasi-2D CDW in Materials without Strong Increase in Current



(a) Normalized noise spectral density multiplied by the frequency, $S_I/I^2 \times f$, as a function of frequency at different applied bias voltages. (b) The noise amplitude as a function of the bias voltage. Note the break in the y-axis. The noise level experiences a drastic increase at the depinning point. The inset shows the dependence of the corner frequencies with the current in the device channel.

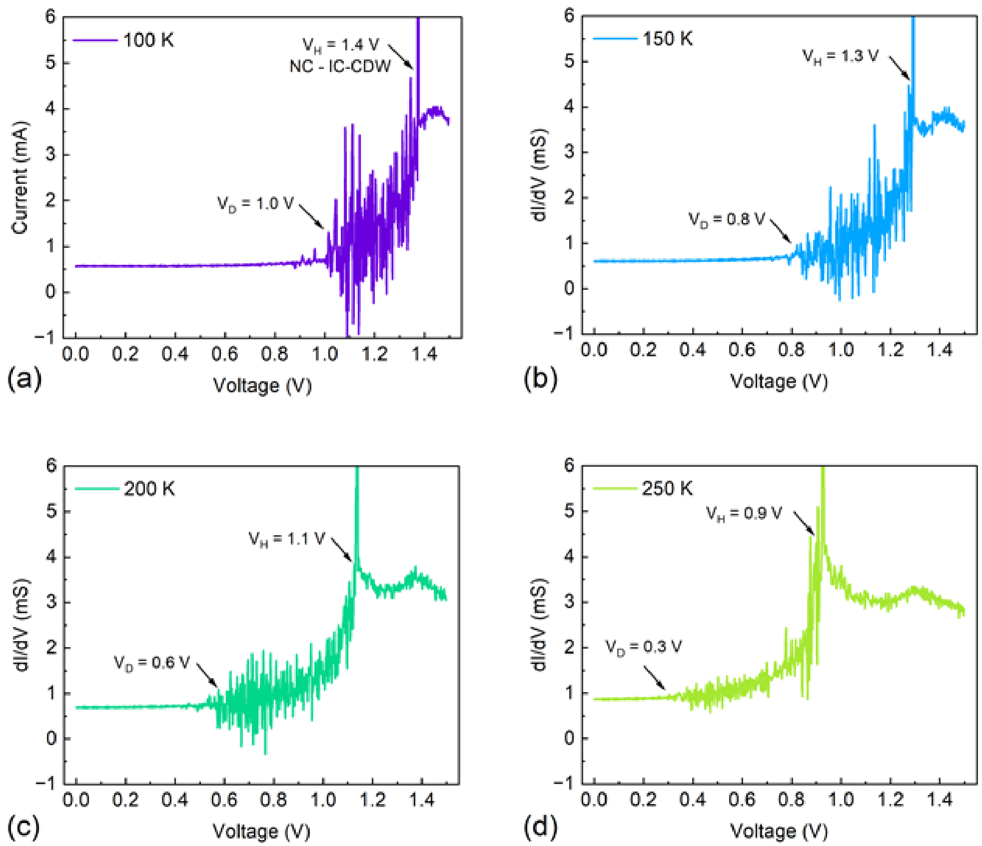
→ Extremely small contribution of CDW current to the total current in 2D systems

Resistive Fluctuations for Monitoring the CDW Domain Depinning in Quasi-2D Materials



- The deviation from the linearity is due to self-heating and hysteresis at 1.2 V due to the NC-CDW – IC-CDW transition.
- The NC-CDW – IC-CDW hysteresis is present in all devices. The C-CDW – NC-CDW hysteresis appears clearly only in a thicker device. Solid lines is the cooling cycle.
- The onset of current fluctuations, dI/dV, at V_D=0.25 V indicating the CDW domain de-pinning and large spikes in dI/dV at V_H=1.3 V corresponding to the NC-CDW – IC-CDW phase transition.

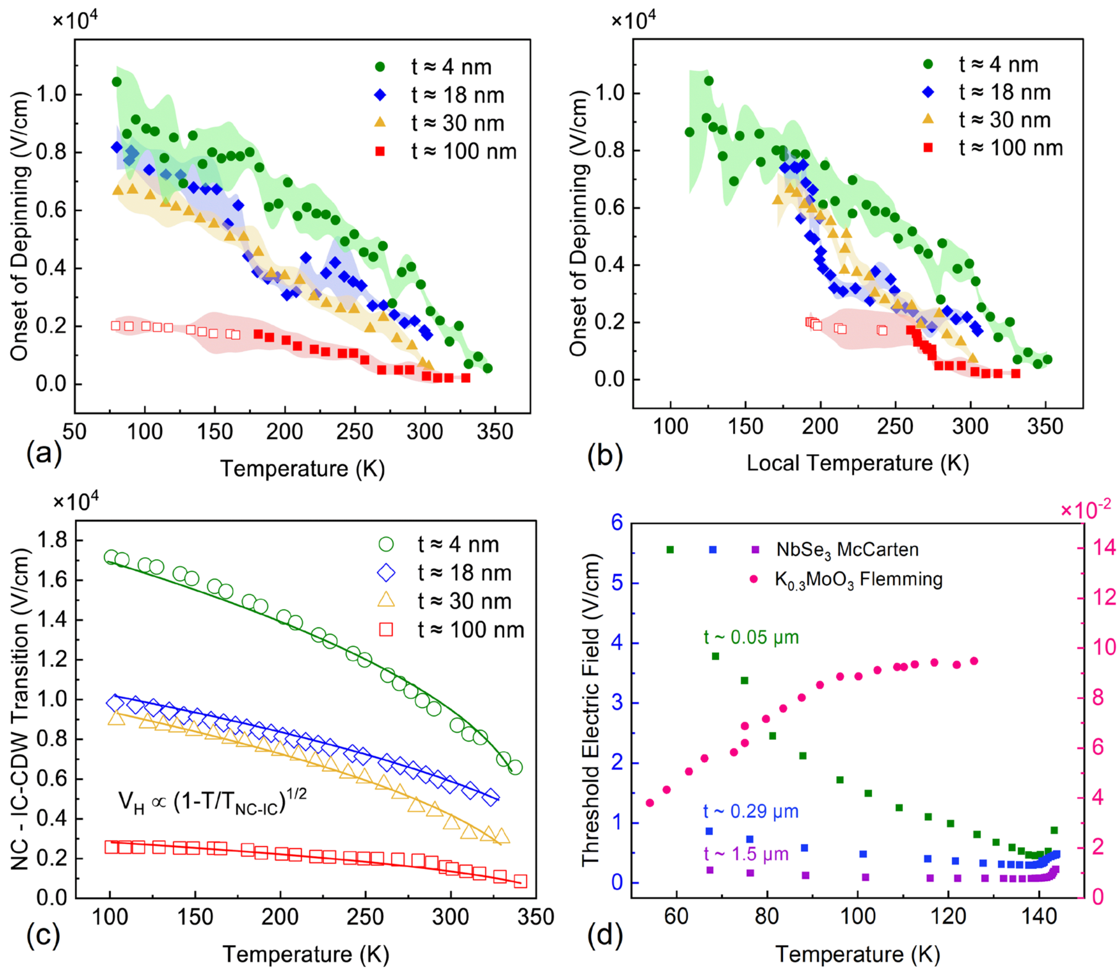
CDW Domain Depinning in Quasi-2D Materials at Different Temperatures



- The device with the channel thickness of ~30 nm.
- The large spike at ~ 1.4 V at 100 K corresponds to the NC-CDW – IC-CDW phase transition, labeled by V_H.
- The burst of the current fluctuations at smaller biases, V_D, indicates the CDW domain depinning.
- At higher temperatures, the onset of the current fluctuations and the voltage of the NC-CDW – IC-CDW phase transition shift to smaller bias voltages.

J. O. Brown, M. Taheri, F. Kargar, R. Salgado, T. Geremew, S. Rumyantsev, R. K. Lake, and A. A. Balandin, Current fluctuations and domain depinning in quasi-two-dimensional charge-density-wave $1T\text{-}TaS_2$ thin films, Appl. Phys. Rev., 10, 041401 (2023).

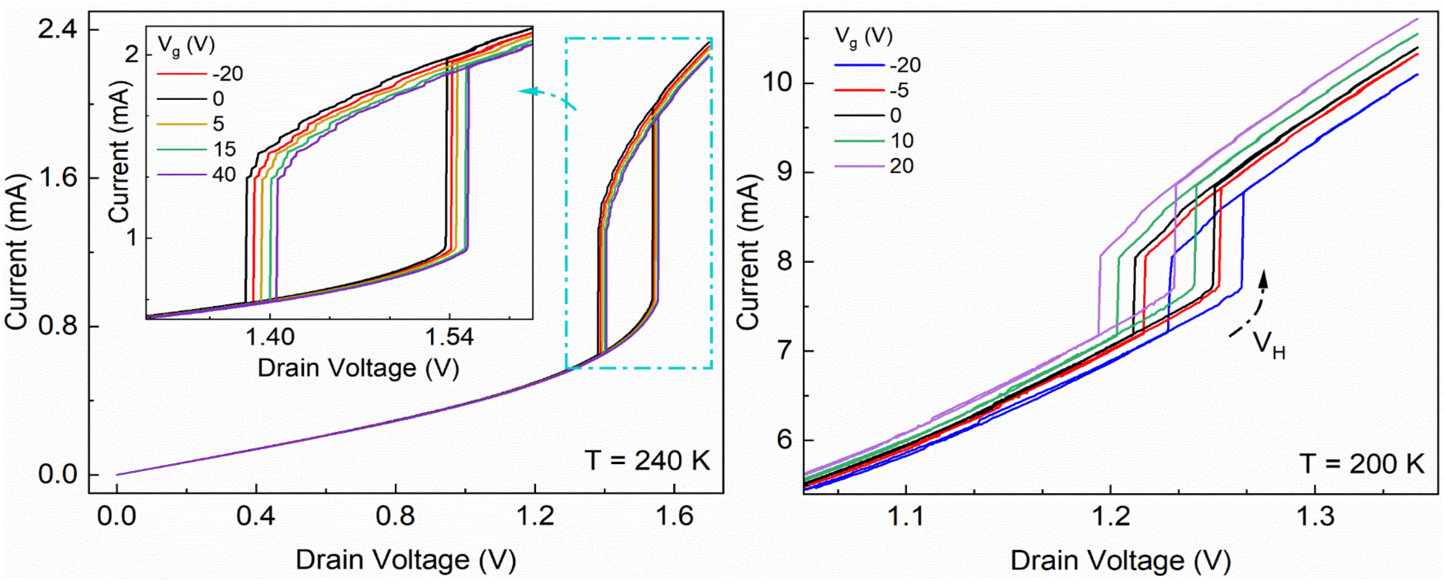
CDW Domain Depinning Threshold Dependence on Temperature in 2D Materials



- (a) The CDW domain depinning field, E_D, as a function of the measurement temperature.
- (b) The E_D as a function of the estimated local temperature of the 1*T*-TaS_2 channel.
- (c) The field of the NC-CDW – IC-CDW phase transition as a function of the measurement temperature.
- (d) The threshold field of the CDW depinning in materials with the quasi-1D crystal structure.

J. O. Brown *et al.*, Appl. Phys. Rev., 10, 041401 (2023).

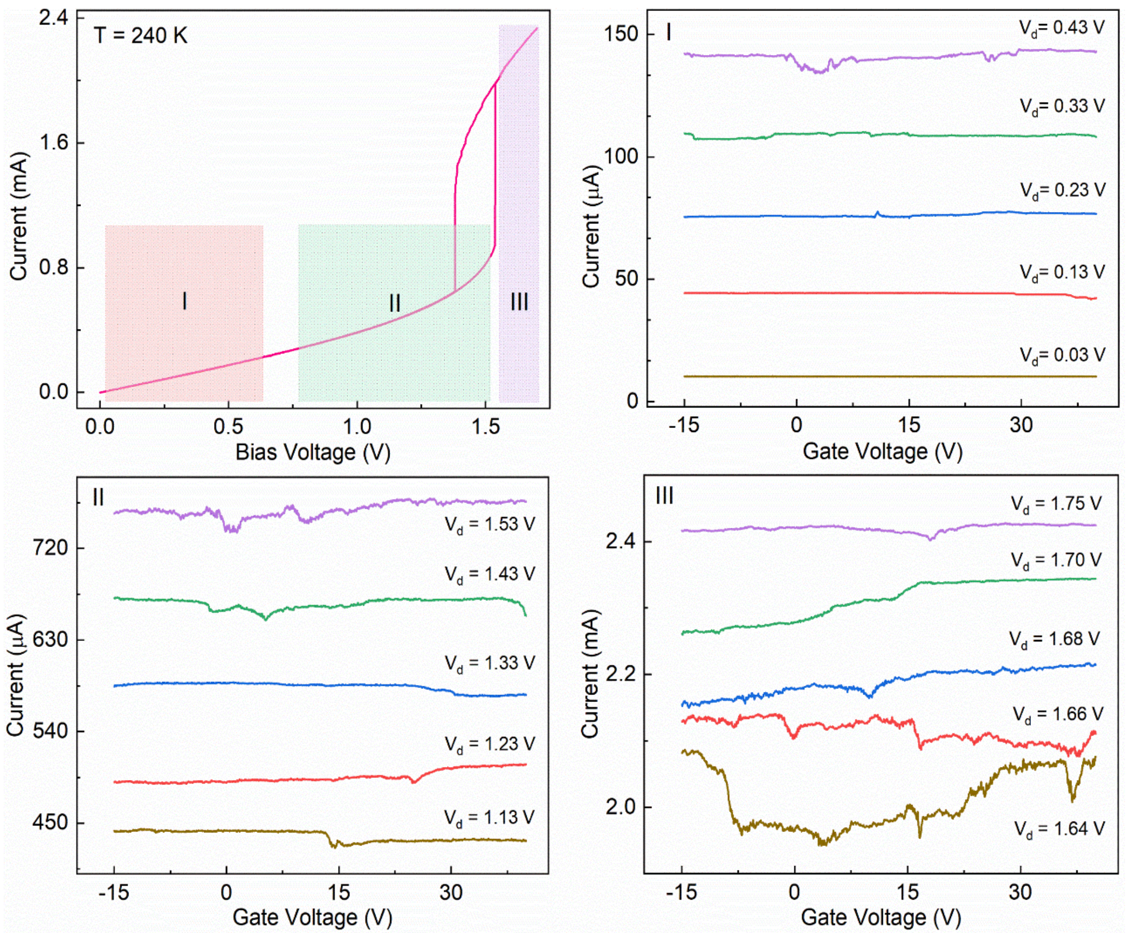
Electrical Gating of CDW Phases in *h*-BN / 1*T*-TaS_2 Heterostructure Devices



- I-V characteristics of the *h*-BN capped 1T-TaS_2 device (H ~ 15 nm) under the fixed gate biases V_g, at T = 240 K. The size of hysteresis remain unchanged under the gate bias.
- Drain-source I-V characteristics of another device (H ~ 35 nm), demonstrating the shift in the threshold voltages V_H, as the V_g takes values from -20 V to 20 V at T = 200 K.

The role of h-BN: physics vs. technology

Changing the Charge-Density-Wave Current with the Electric Gate



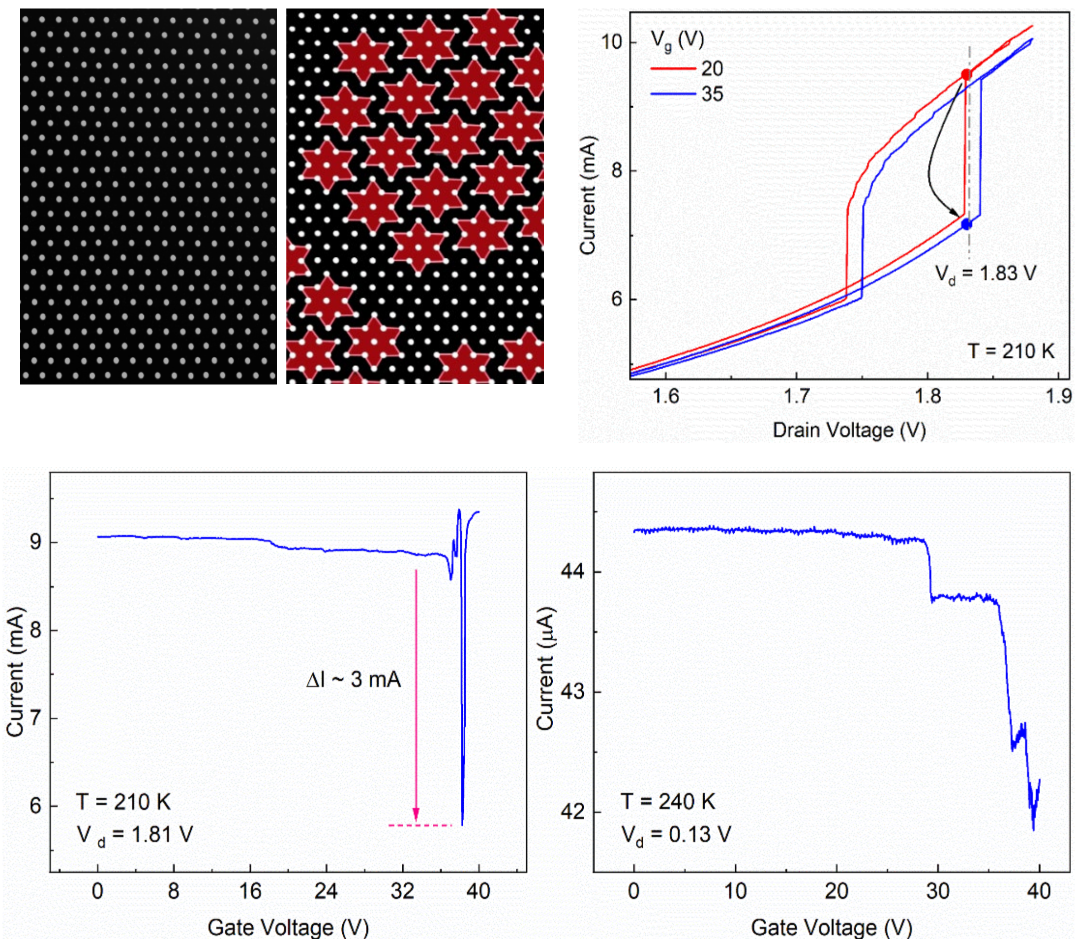
(a) I-V characteristics of the *h*-BN/1T-TaS_2 heterostructure device, without applied gate bias, at 240 K. The shaded regions I, II and III represent linear, super-linear and near-V_H IC-CDW regions, respectively. The current traces measured with the gate sweep rate of 500 mV/S for fixed V_d values for three regions.

→ The effect is electrical rather then thermal

→ We soften the domains with current and then affect them electrically

Alexander A. Balandin, University of California, Los Angeles

Switching the Charge-Density-Wave Phases with the Electrical Gate

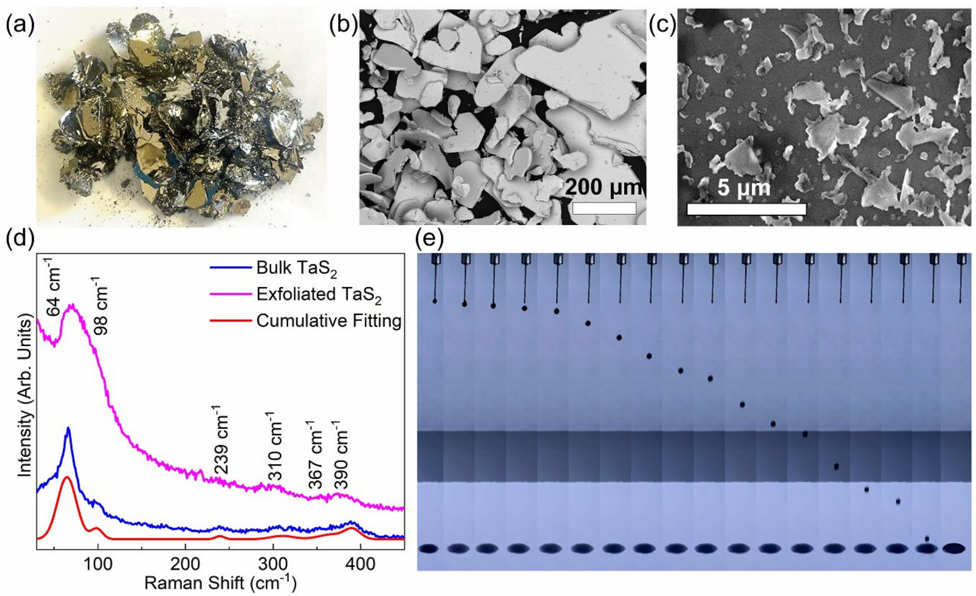


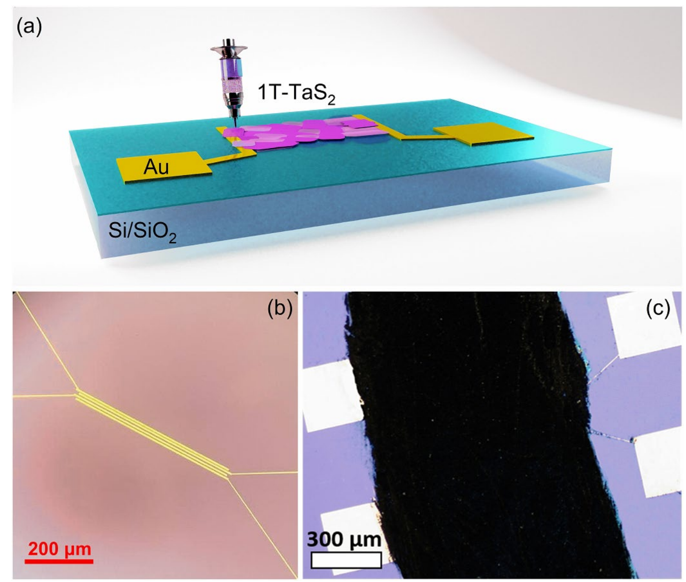
(a) Current as a function of the source-drain voltage at two fixed gate biases, measured at T = 210 K. In this device the transition from IC-CDW to NC-CDW phase, depicted with the red and blue dots, occurs at the voltage close to V_d = 1.83 V.

(b) Current as the function of the gate bias at the V_d = 1.83 V. The current change of ΔI ~ 3 mA, induced by the gate, corresponds to the 1T-TaS_2 channel switching between IC-CDW and NC-CDW phases.

(c) Current switching by the gate within the same NC-CDW phase for small, fixed bias of V_d = 0.13 V.

Solution-Processed CDW Devices

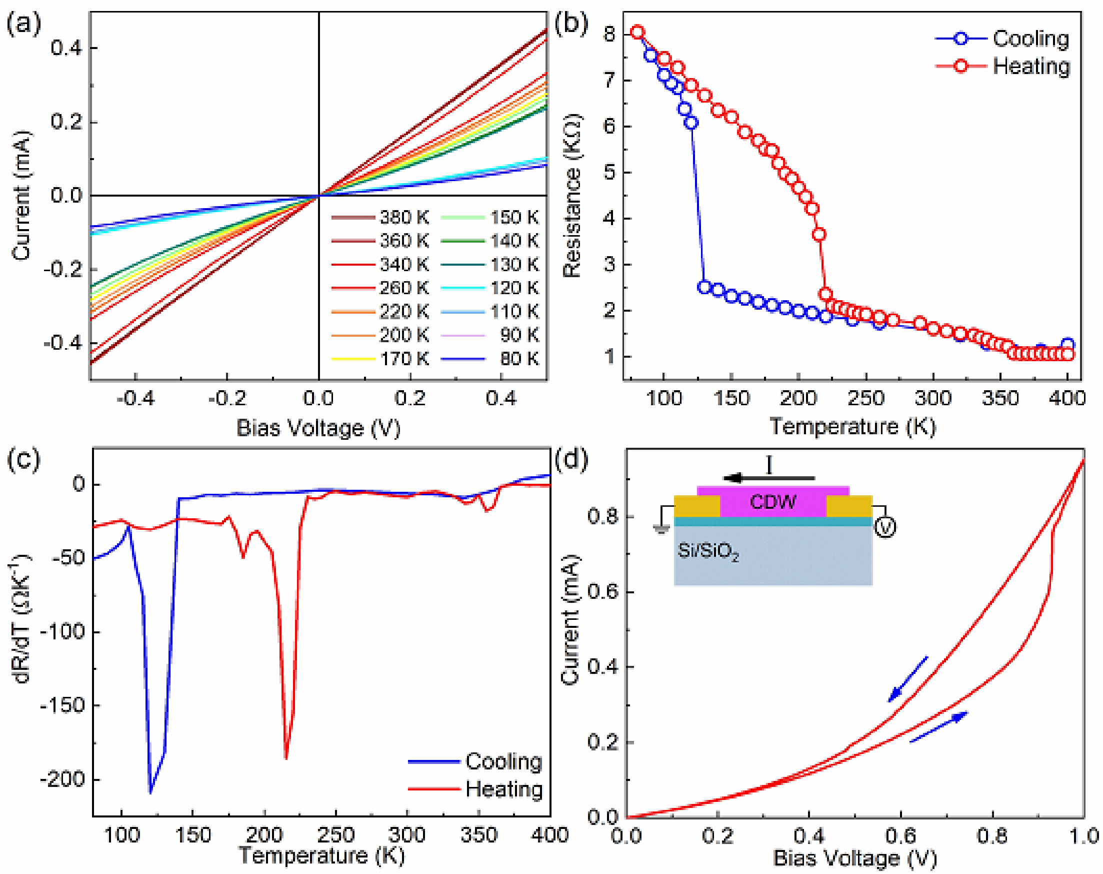


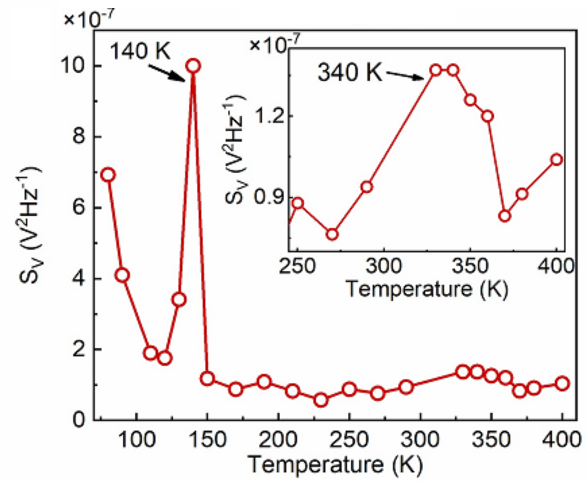


Time-lapse optical image of the ink droplet formation, release, and trajectory to the substrate. Optical microscopy images of the fabricated electrodes and actual printed device.

S. Baraghani, Z. Barani, Y. Ghafouri, A. Mohammadzadeh, T. T. Salguero, F. Kargar, and A. A. Balandin, “Charge-Density-Wave Thin-Film Devices Printed with Chemically Exfoliated 1T-TaS$_2$ Ink", ACS Nano, 16, 4, 6325 (2022).

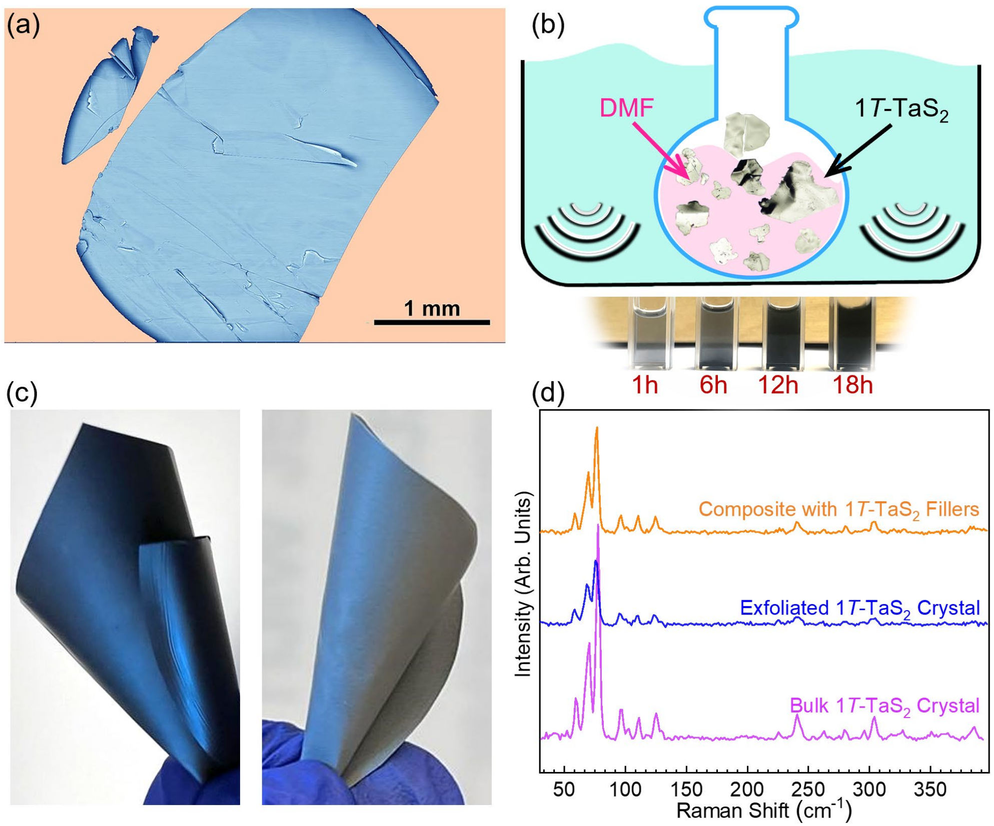
Inkjet Printed CDW Thin-Film Devices – Enhancing Functionality





S. Baraghani, Z. Barani, Y. Ghafouri, A. Mohammadzadeh, T. T. Salguero, F. Kargar, and A. A. Balandin, "Charge-Density-Wave Thin-Film Devices Printed with Chemically Exfoliated 1T-TaS_2 Ink", ACS Nano, 16, 4, 6325 (2022).

Toward Quantum Composites - Preserving CDW Phases in Disordered Materials

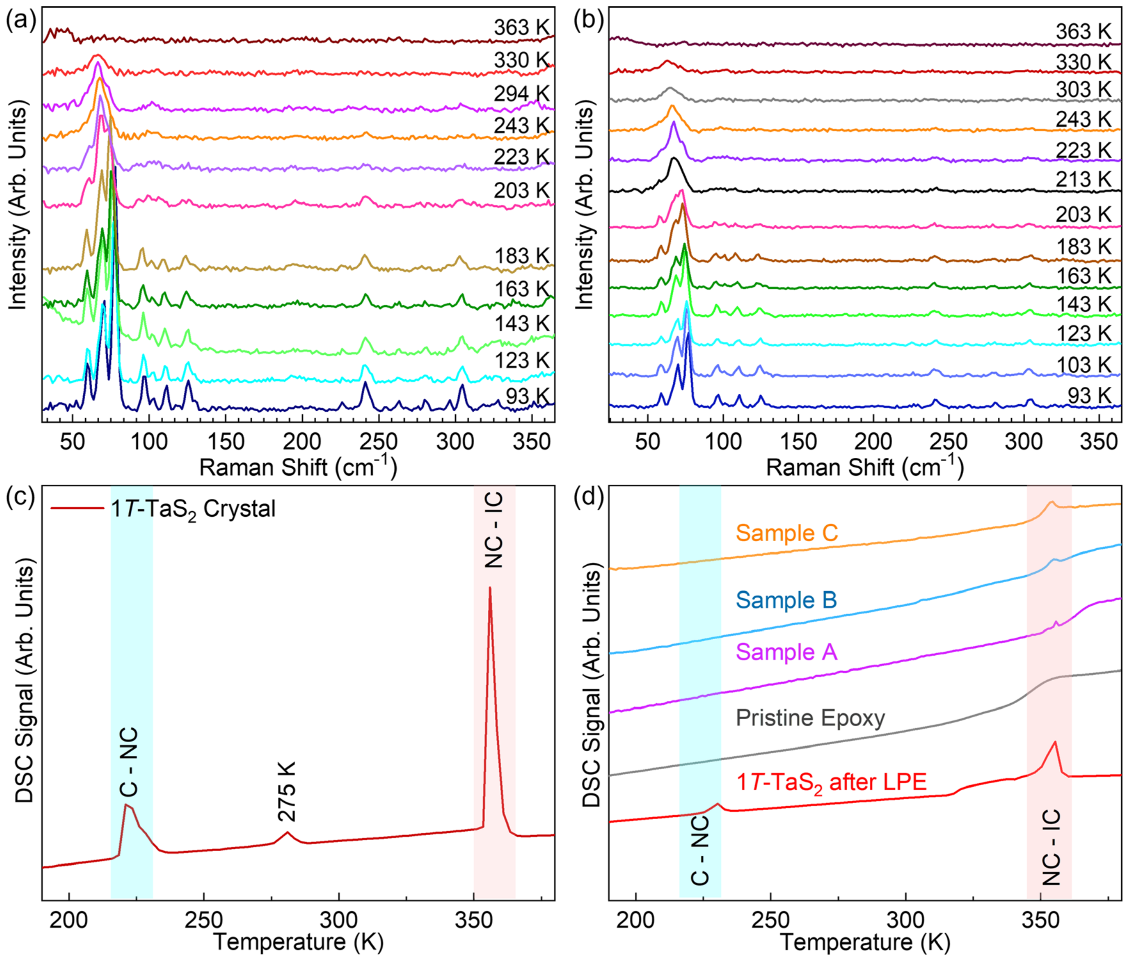


a) SEM image (false color) of 1T-TaS_2 crystals synthesized by the CVT method. (b) Illustration of the chemical exfoliation method using low-power bath sonication in DMF solvent. The vials with DMF solutions of 1T-TaS_2 fillers are shown at different exfoliation times.

(c) Flexible PVDF composite films with 1T-TaS_2 fillers (left) and dual 1T-TaS_2 and h-BN fillers (right).

Z. Barani, et al., T. Geremew, M. Stokey, N. Sesing, M. Taheri, M. J. Hilfiker, F. Kargar, M. Schubert, T. T. Salguero, and A. A. Balandin, “Quantum composites with charge-density-wave fillers”, Adv. Mater., 2209708 (2023).

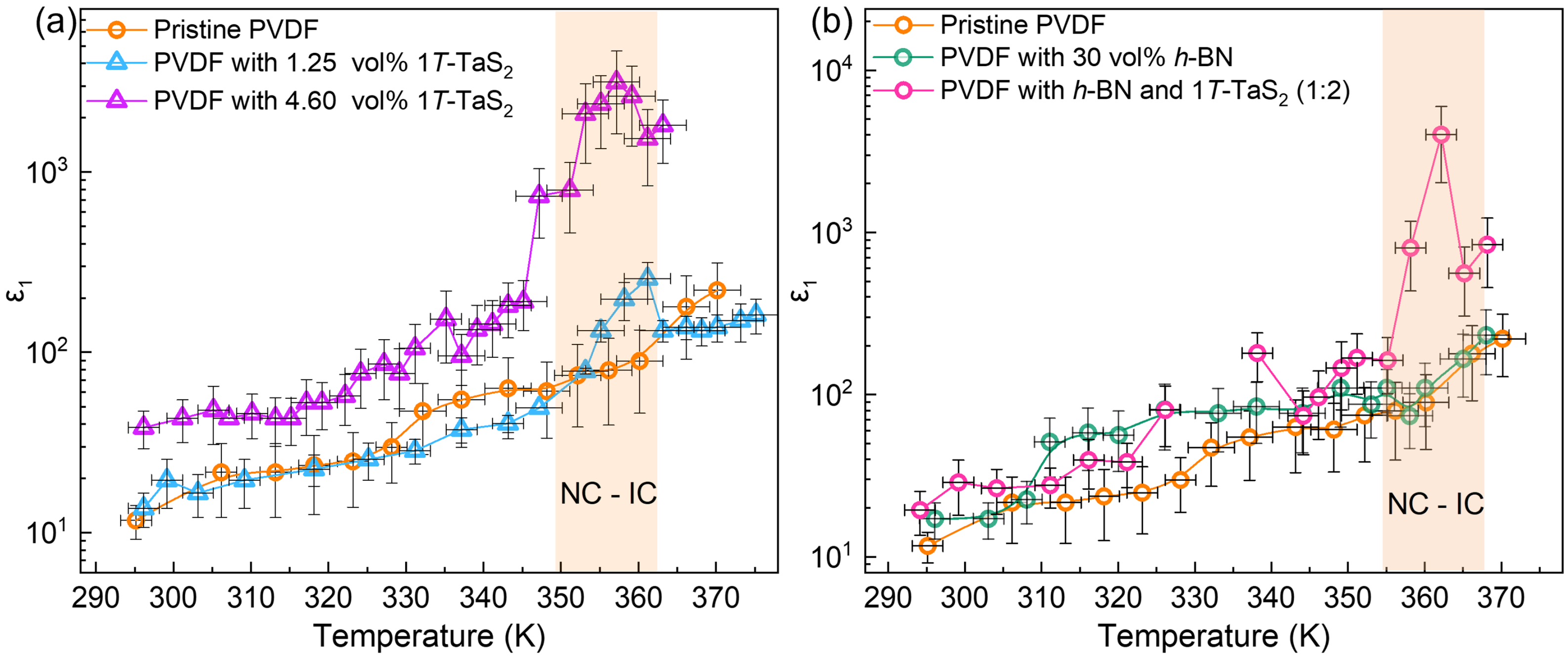
CDW Phase Transitions are Preserved after Chemical and Mechanical Processing



The peaks in the ~100 cm^{-1} to 125 cm^{-1} range disappear at ~213 K as a result of the C-CDW to NC-CDW transition. All Raman peaks disappear after T~355 K as a result of the loss of translation symmetry in the IC-CDW phase.

Z. Barani, T. Geremew, M. Stokey, N. Sesing, M. Taheri, M. J. Hilfiker, F. Kargar, M. Schubert, T. T. Salguero, and A. A. Balandin, “Quantum composites with charge-density-wave fillers”, Adv. Mater., 35, 2209708 (2023).

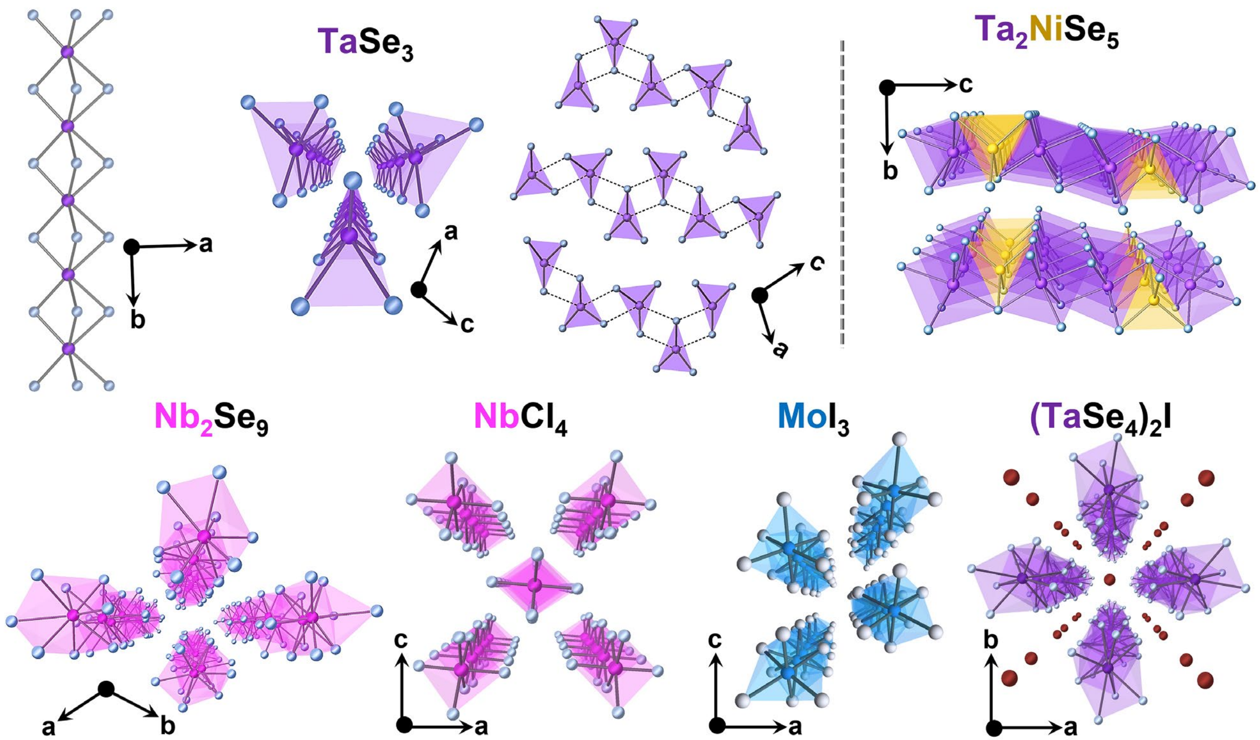
Enhancement of Dielectric Constant in Electrically-Insulating CDW Composites



Dielectric constant, ε_1, measured by the parallel capacitance method as a function of temperature for the pristine PVDF and PVDF composites with low-concentration of 1*T*-TaS_2 fillers. Note a strong enhancement of the dielectric constant at the CDW transition temperature.

Z. Barani, *et al.*, Quantum composites with charge-density-wave fillers, Adv. Mater., 35, 2209708 (2023).

Quasi-1D *vs.* True-1D van der Waals Materials



The top panel shows quasi-1D vdW materials. The bottom panel shows true-1D vdW materials.

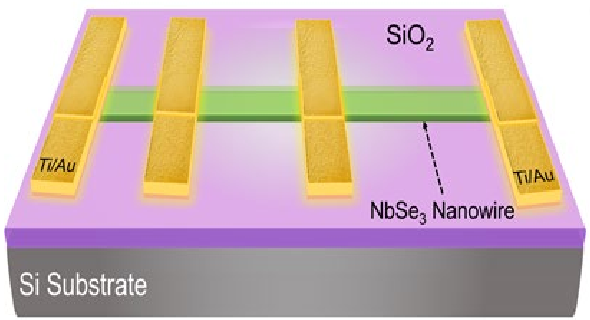
Possible other meaning: Quasi-1D can indicate a bundle of the atomic chains.

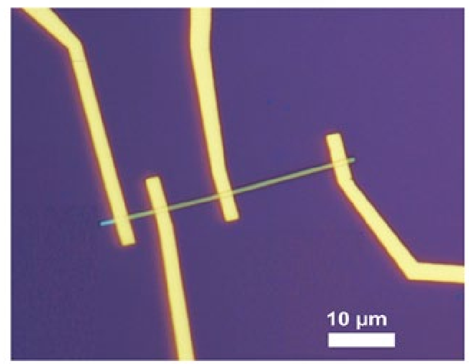
Terminology: 1D but not CNTs

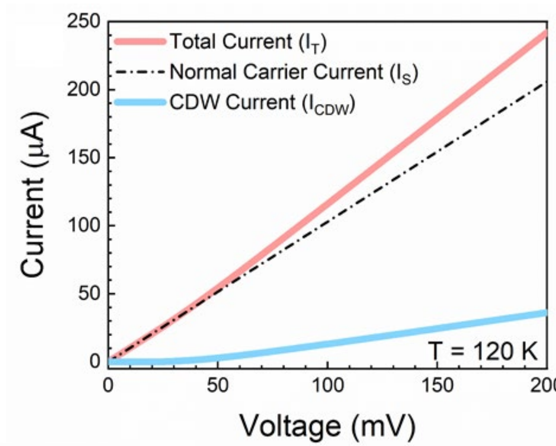
DOD/ONR: The Vannevar Bush Faculty Fellowship (VBFF) award for One-Dimensional Quantum Materials

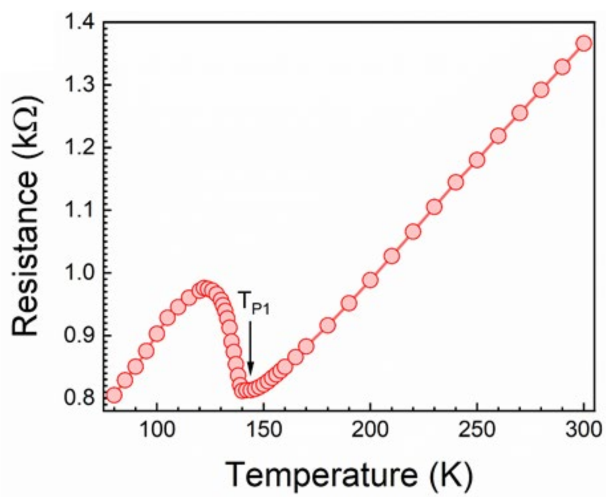
A. A. Balandin, F. Kargar, T. T. Salguero, and R. Lake, “One-dimensional van der Waals quantum materials”, Mater. Today, 55, 74 (2022).

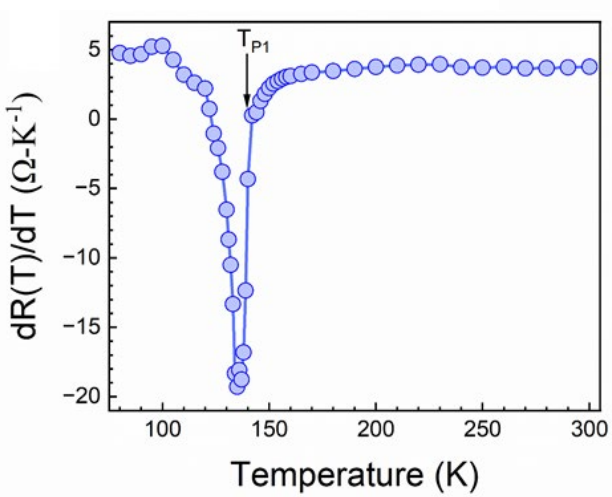
Sliding CDWs in 1D Materials with Non-Fully Gapped Fermi Surface – $NbSe_3$ Nanowires





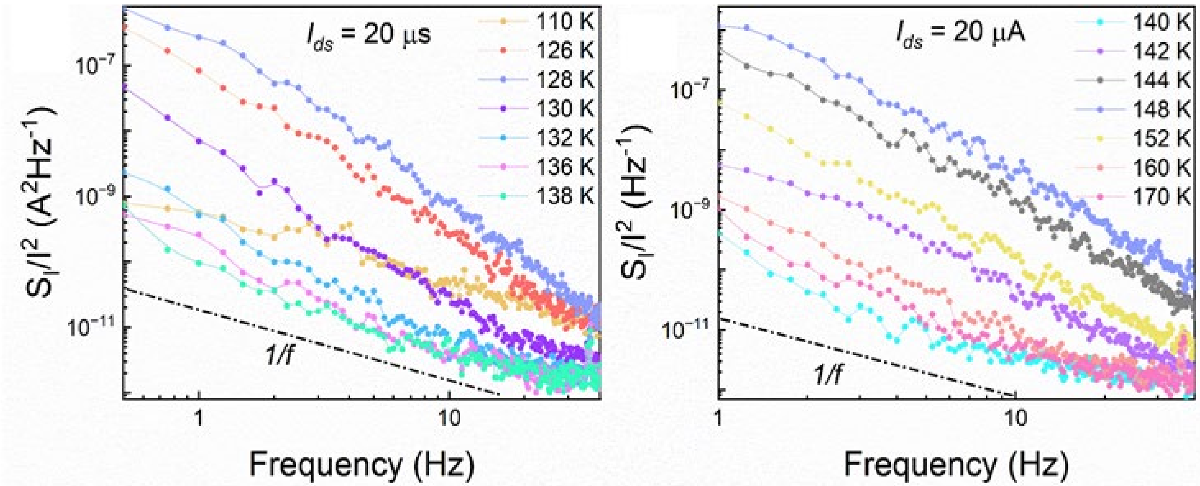


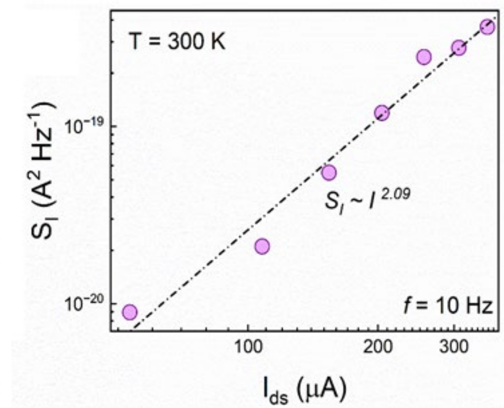




Resistance of the $NbSe_3$ device as a function of temperature measured in the heating cycle. The device shows a pronounced resistive anomaly near the CDW phase transition temperature $T_{P1} \approx 145K$.

Noise in CDW $NbSe_3$ Nanowires





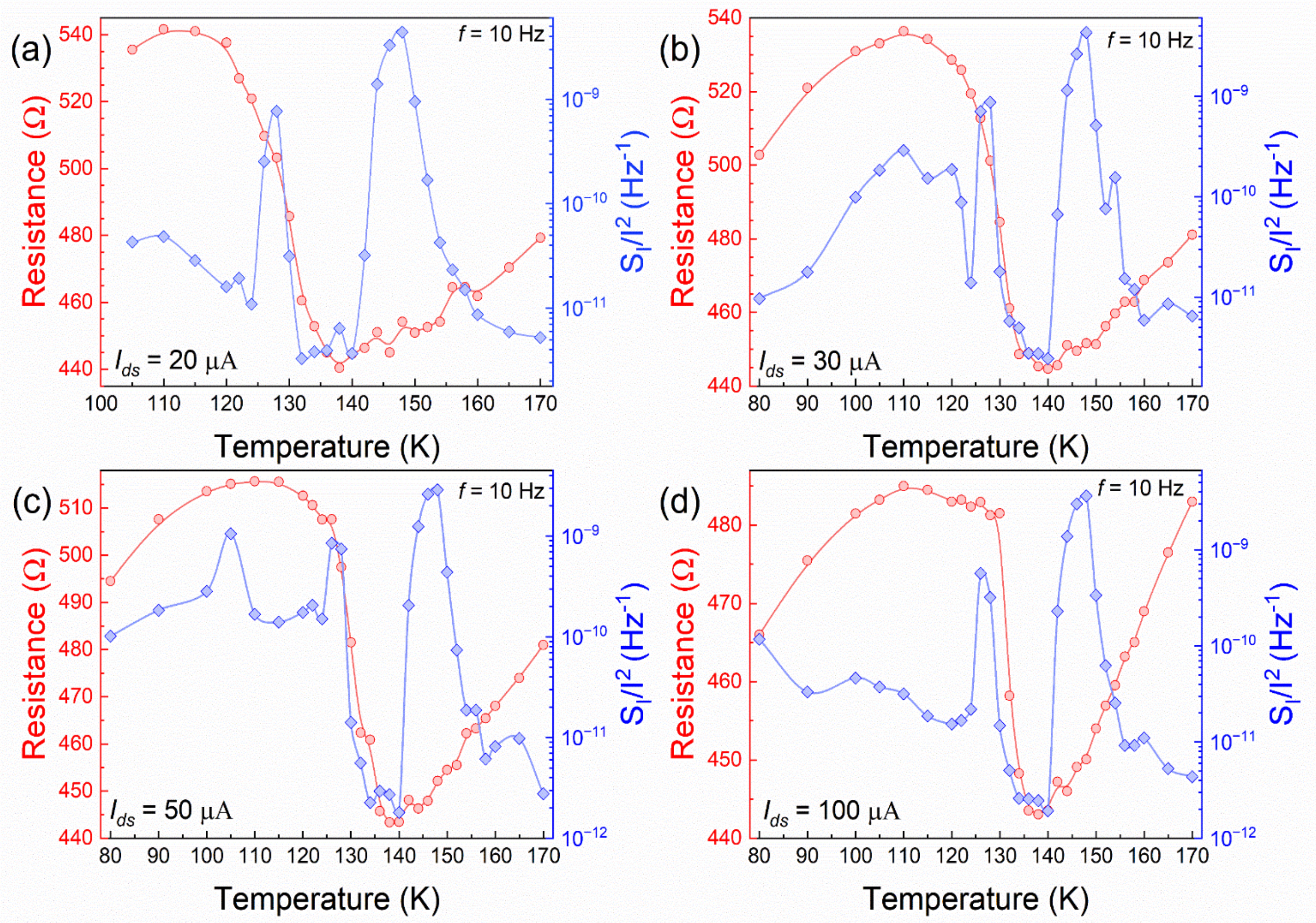
S_I at f = 10 Hz and T = 300K as a function of the device current.

S_I/I^2 vs. frequency measured at the fixed device current of Ids = 20 μA and temperatures in the range from 110 K to 138 K. (d) The same as in panel (c) but for a different temperature range from 140 K to 170 K. Note the evolution of the noise spectrum shapes as a function of temperature.

S. Ghosh, S. Rumyantsev, and A. A. Balandin. “The noise of the charge density waves in quasi-1D NbSe3 nanowires — contributions of electrons and quantum condensate ” Appl. Phys. Rev., 11, 021405 (2024).

Noise in CDW $NbSe_3$ Nanowires – Multiple Peaks in Temperature Dependence

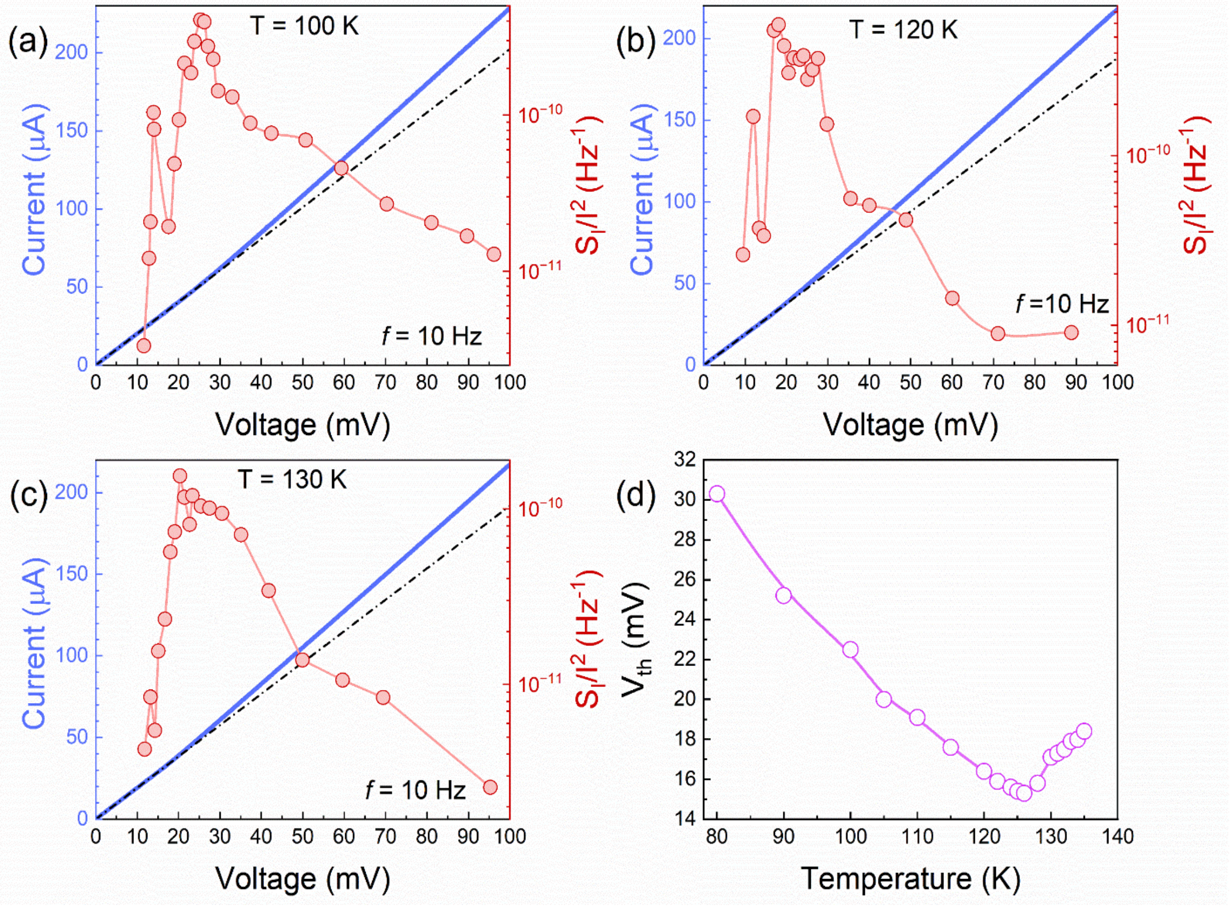
UPON: Nature of the peaks



(a) Resistance (left axis) and S_I/I^2 (right axis) as the functions of temperature in the range that includes the CDW phase transition. The noise *vs.* temperature data shows well-defined peaks at and below the CDW transition temperature. The panels (b), (c), and (d) are the same as panel (a) but show data for the different current levels I_{ds} = 30 μA, 50 μA, and 100 μA, respectively.

Noise in CDW $NbSe_3$ Nanowires – Double Peaks in Voltage Dependence

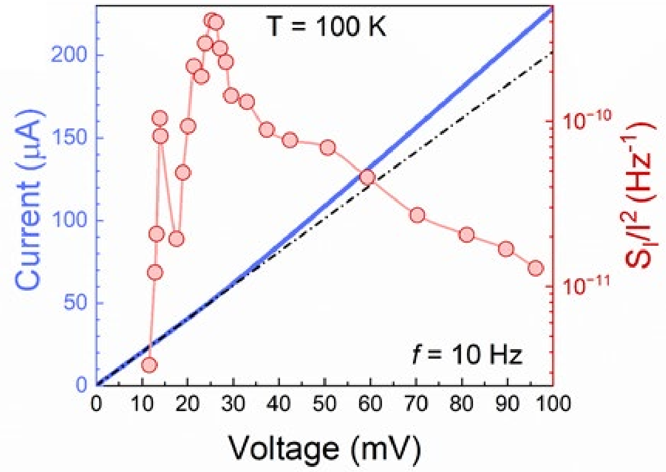
UPON: Nature of the peaks



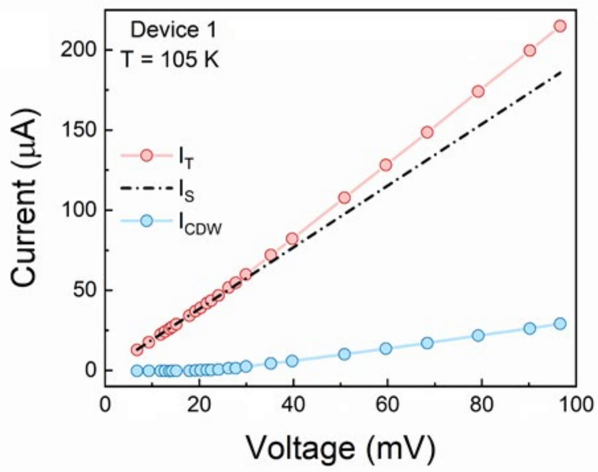
(a) *I-V* characteristics (left axis) and S_I/I^2 at f =10 Hz (right axis), as a function of applied voltage. The onset of the non-linear current corresponds to CDW the depinning and sliding. The noise spectra reveal two peaks – the smaller one slightly below the depinning field and the larger one at the onset of depinning (I_{CDW} > 0). The panels (b) and (c) are the same as panel (a) but show the data for temperatures T=120 K and 130 K, respectively. (d) The threshold voltage dependence on the temperature in the incommensurate CDW phase.

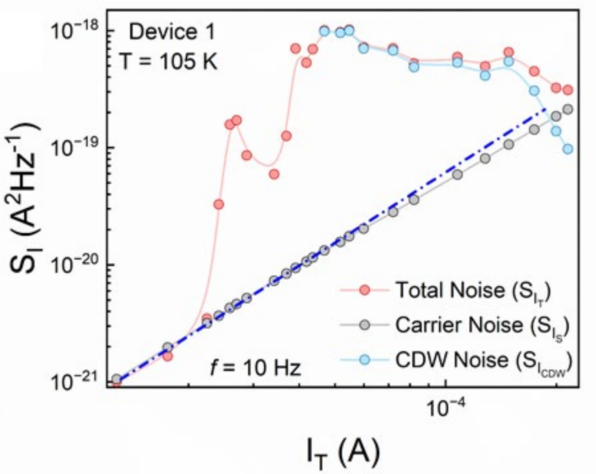
The Noise of Sliding CDW Condensate in Quasi-1D Materials

UPON: Noise level of collective currents



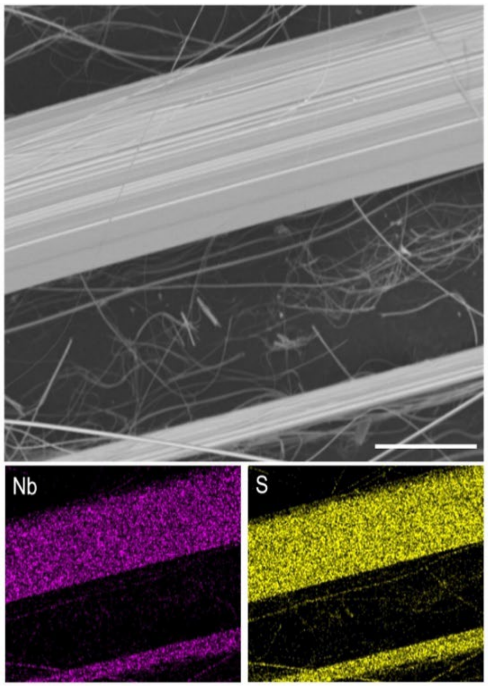
- → *I-Vs* and the normalized noise spectral density, S_I/I^2, at f =10 Hz as a function of applied voltage. The data are shown for T = 100 K, below the CDW phase transition.
- → The onset of the non-linear current corresponds to the depinning and sliding of the CDW quantum condensate.
- → Noise of the sliding CDW condensate decreases with increasing current.
- → The noise of individual electrons shows expected $S \sim I_S^2$ dependence.

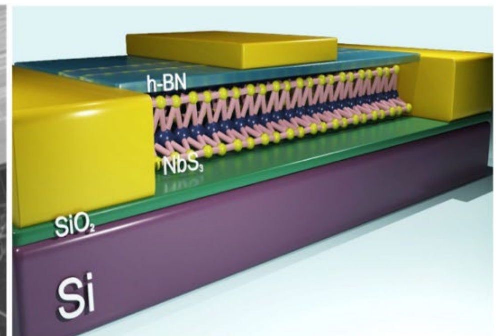


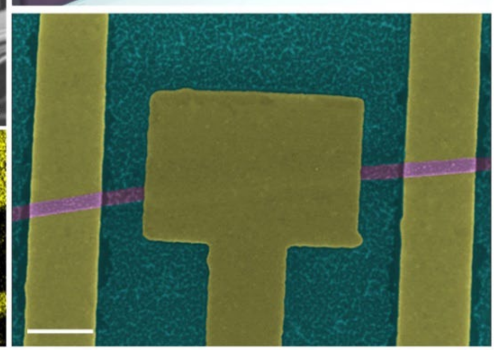


S. Ghosh, S. Rumyantsev, and A. A. Balandin. "The noise of the charge density waves in quasi-1D NbSe3 nanowires — contributions of electrons and quantum condensate " Appl. Phys. Rev., 11, 021405 (2024).

Revisiting Quasi-1D CDW Materials with Sliding CDWs – NbS_3-II Nanowires







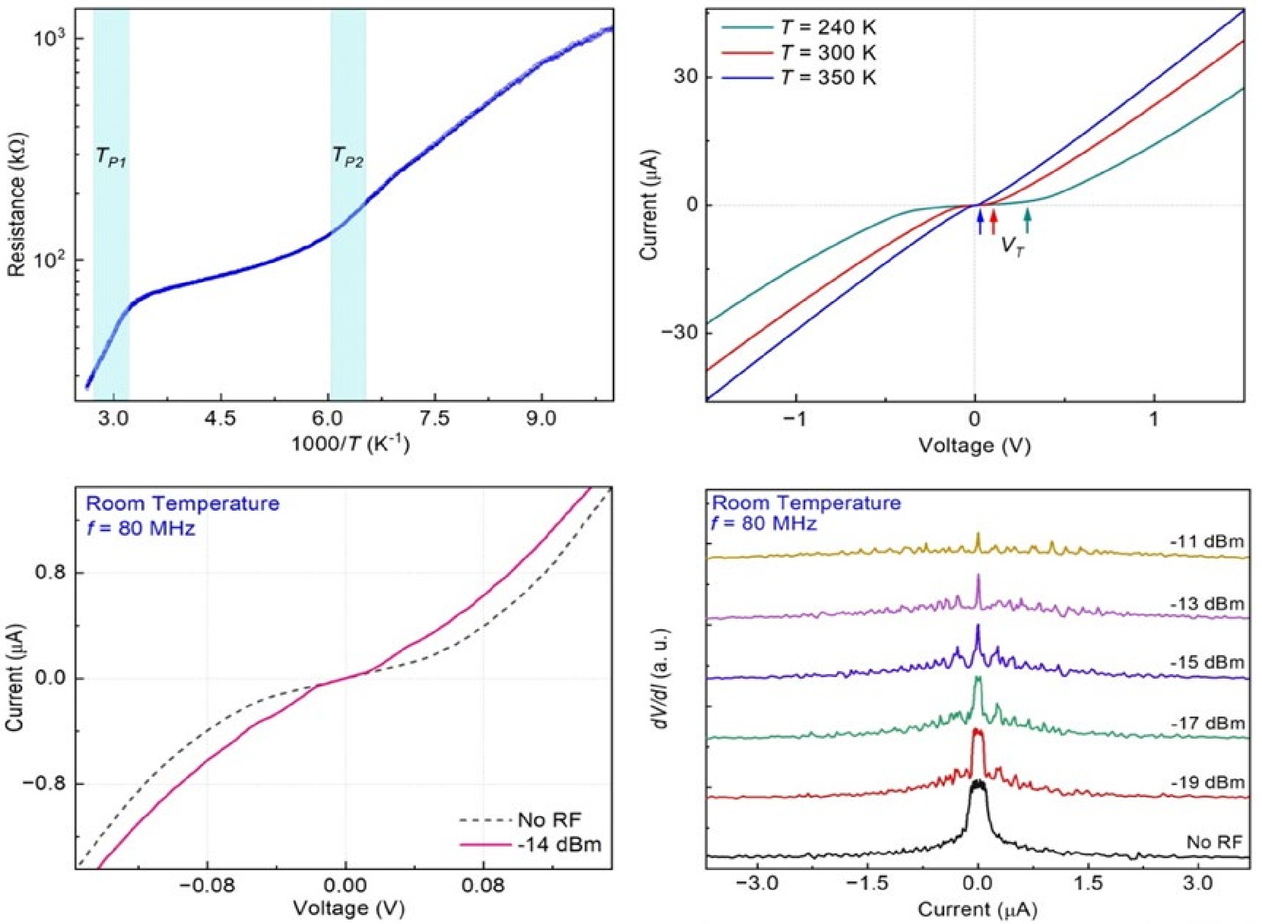
- The monoclinic polymorphs include NbS_3-II, a metal at higher temperature with three CDW phases at Peierls temperatures T_{P0} = 460 K, T_{P1} = 330 to 370 K, and T_{P2} = 150 K.
- The CDW phase below T_{P1} revealed high coherency under microwave irradiation and the potential of synchronization up to the frequency of 200 GHz.

SEM image and EDS elemental mapping of NbS_3 crystals. The scale bar is 25 μm.

A representative SEM image of the *h*-BN/NbS_3 device. The pseudo colors are used for clarity. The scale bar is 1 μm.

M. Taheri, … and A. A. Balandin. "Electric-field modulation of the charge-density-wave quantum condensate in h-BN/NbS_3 quasi-2D/1D heterostructure devices." Appl. Phys. Lett., 123, 233101 (2023).

Verification of the CDW Phases in NbS_3 Nanoribbons

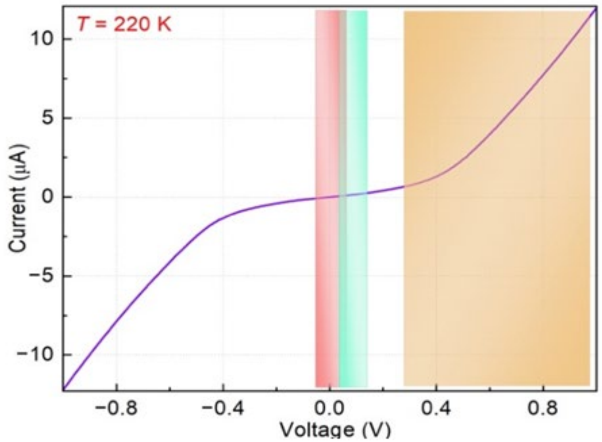


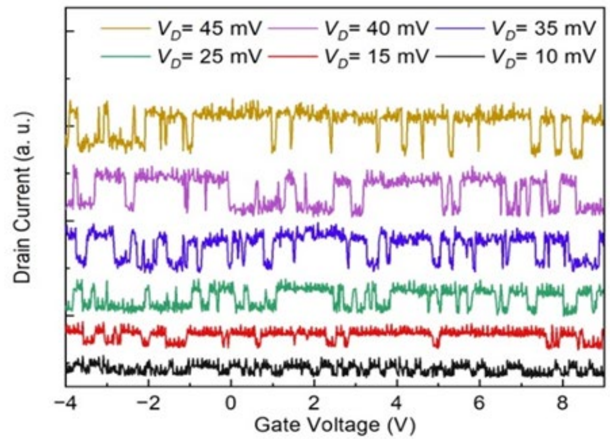
The CDW phase transitions: T_{P1} = 320 K to 375 K, and T_{P2} = 154 K – 164 K.

The RT I-V characteristics without RF (dashed-black curve) and with RF (red curve) radiation. The ripples (red curve) are the Shapiro-like steps).

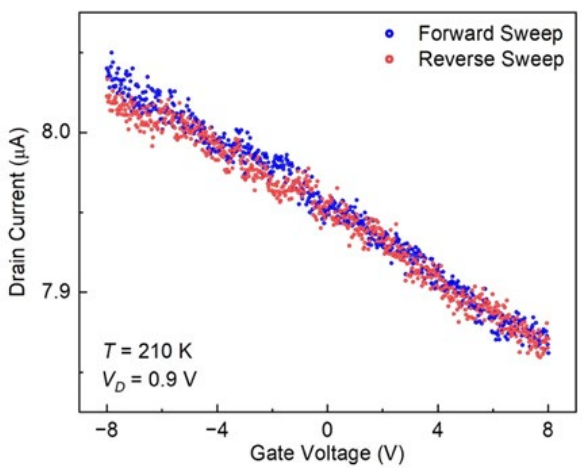
M. Taheri, et al., "Electric-field modulation of the charge-density-wave quantum condensate in h-BN/NbS_3 quasi-2D/1D heterostructure devices." Appl. Phys. Lett., 123, 233101 (2023).

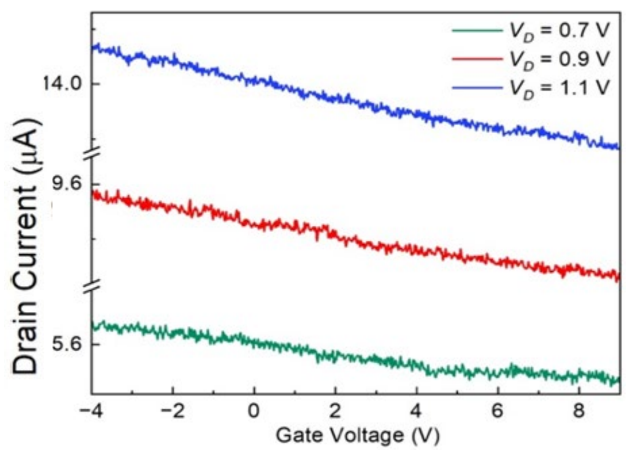
Reversible Gating of the Sliding CDW Collective Current in NbS_3 Nanoribbons





I-Vs of *h*-BN/NbS_3 quasi-2D/1D devices with the regions of the single electron current (red), intermediate near-threshold (green), and collective current (yellow).





Increasing the gate effect: interplay between depinning and screening

M. Taheri, et al., "Electric-field modulation of the charge-density-wave quantum condensate in h-BN/NbS_3 quasi-2D/1D heterostructure devices." Appl. Phys. Lett., 123, 233101 (2023).

Take-Home Messages

- *We can play with the charge-density-wave condensate phases even at room temperature*
- *Low-frequency noise spectroscopy is a useful tool for investigating electron transport in CDW materials*
- *Electron transport and noise in quasi-1D and quasi-2D materials are different*
- *There is a hope for the noise of collective current suppression – theory help is needed*
- *The practical applications of new materials may be absolutely not what we initially anticipated*

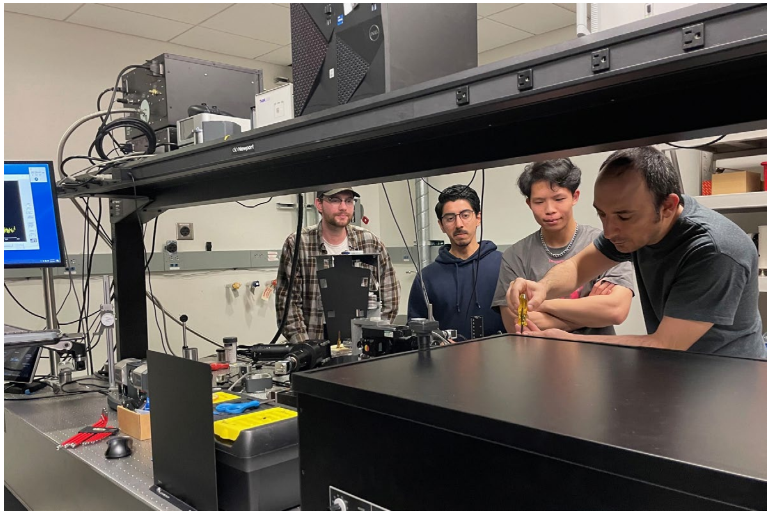
A. A. Balandin, E. Paladino, and Pertti J. Hakonen. "Electronic noise—From advanced materials to quantum technologies" Appl. Phys. Lett., 124, 050401 (2024).

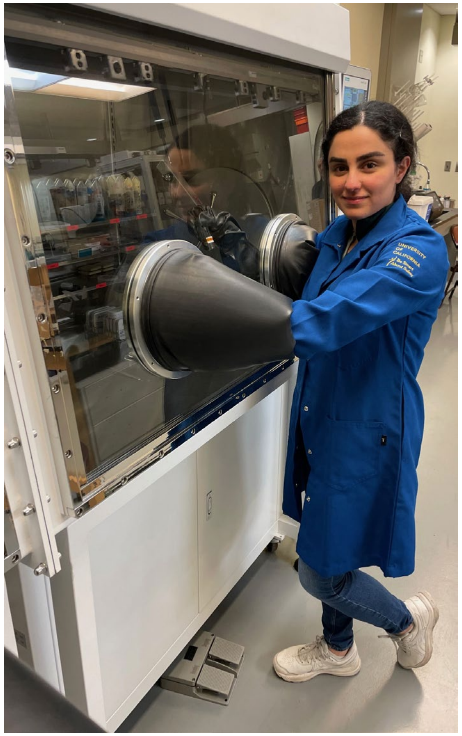
`Everything's got a moral, if only you can find it.'

"Alice's Adventures in Wonderland"
Lewis Carroll

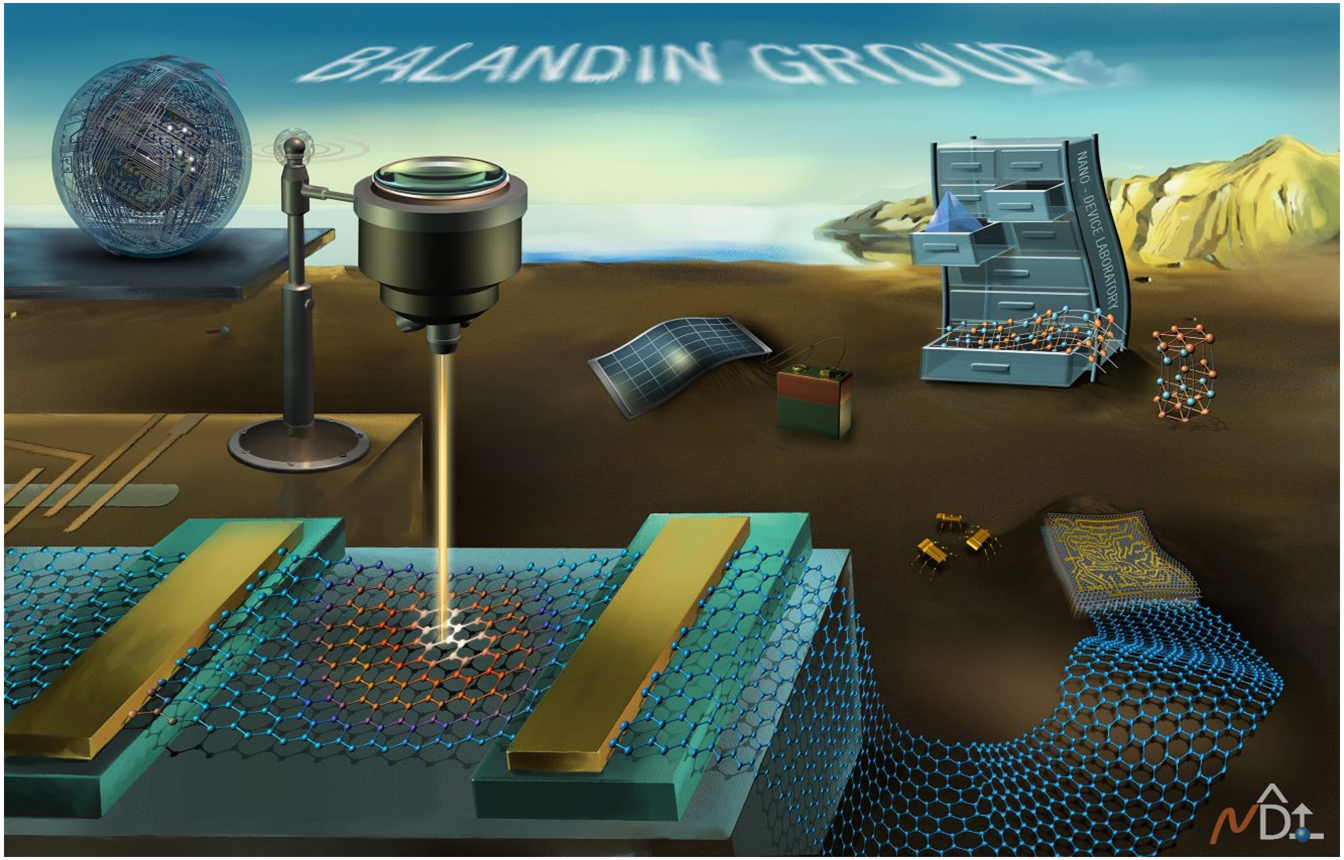
Acknowledgments of Students

https://balandin-group.ucla.edu/





Group members aligning the Brillouin – Mandelstam spectrometer, CNSI; Tekwam and Zahra exfoliating and transferring 1D van der Waals materials, MSE, UCLA, 2024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