Monitoring and Controlling Charge-Density-Waves in 2D Materials

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Outline

→ Background and motivations: CDW and noise

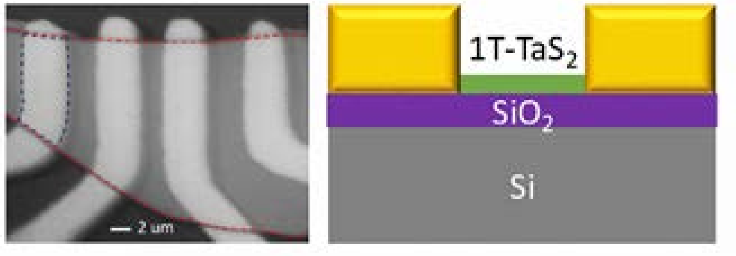
→ From bulk quasi-1D CDW to thin films of quasi-2D CDW materials

→ Room temperature operation of quasi-2D CDW devices

→ Electronic low-frequency noise as a signal

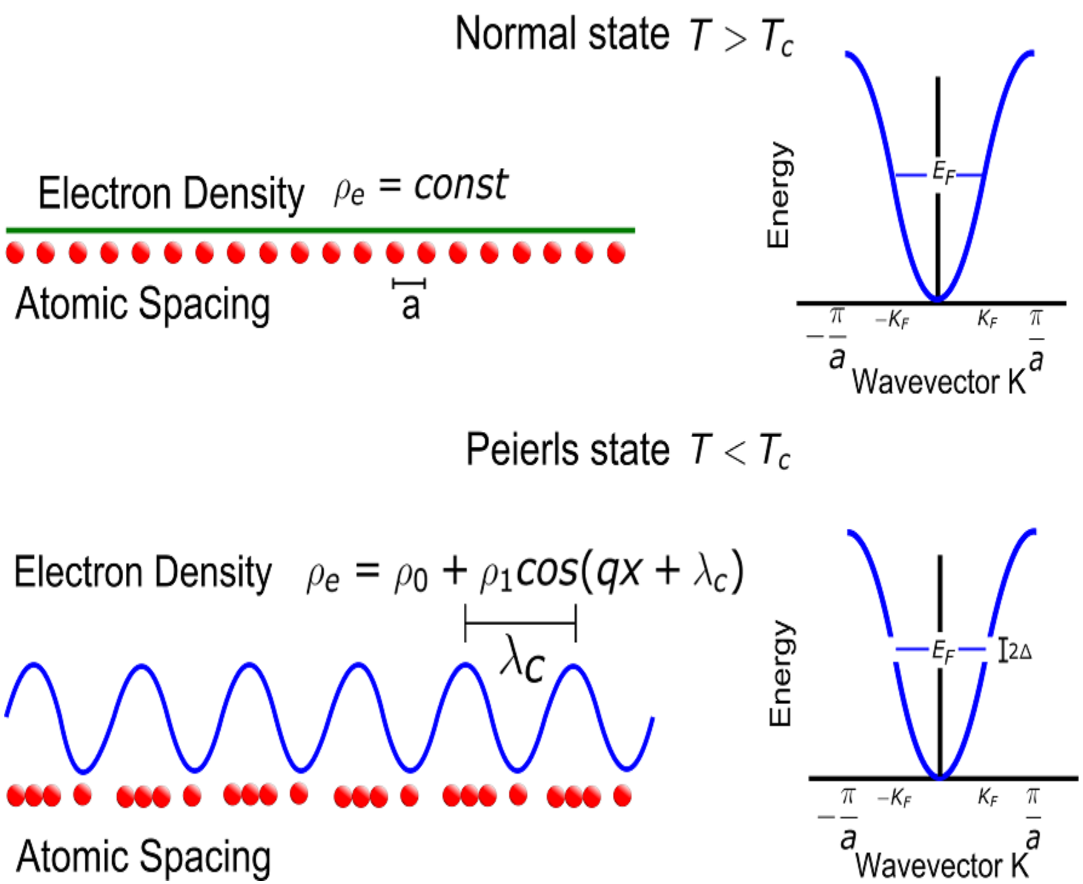
→ The search for the “narrow band noise”

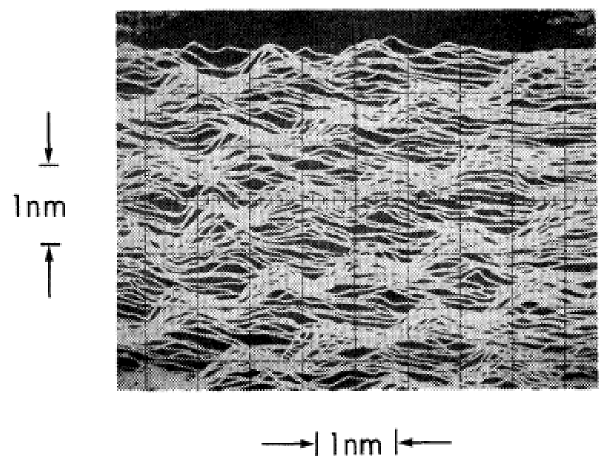
→ Conclusions



Alexander A. Balandin, University of California - Riverside

Charge Density Waves: Quasi-1D Crystals



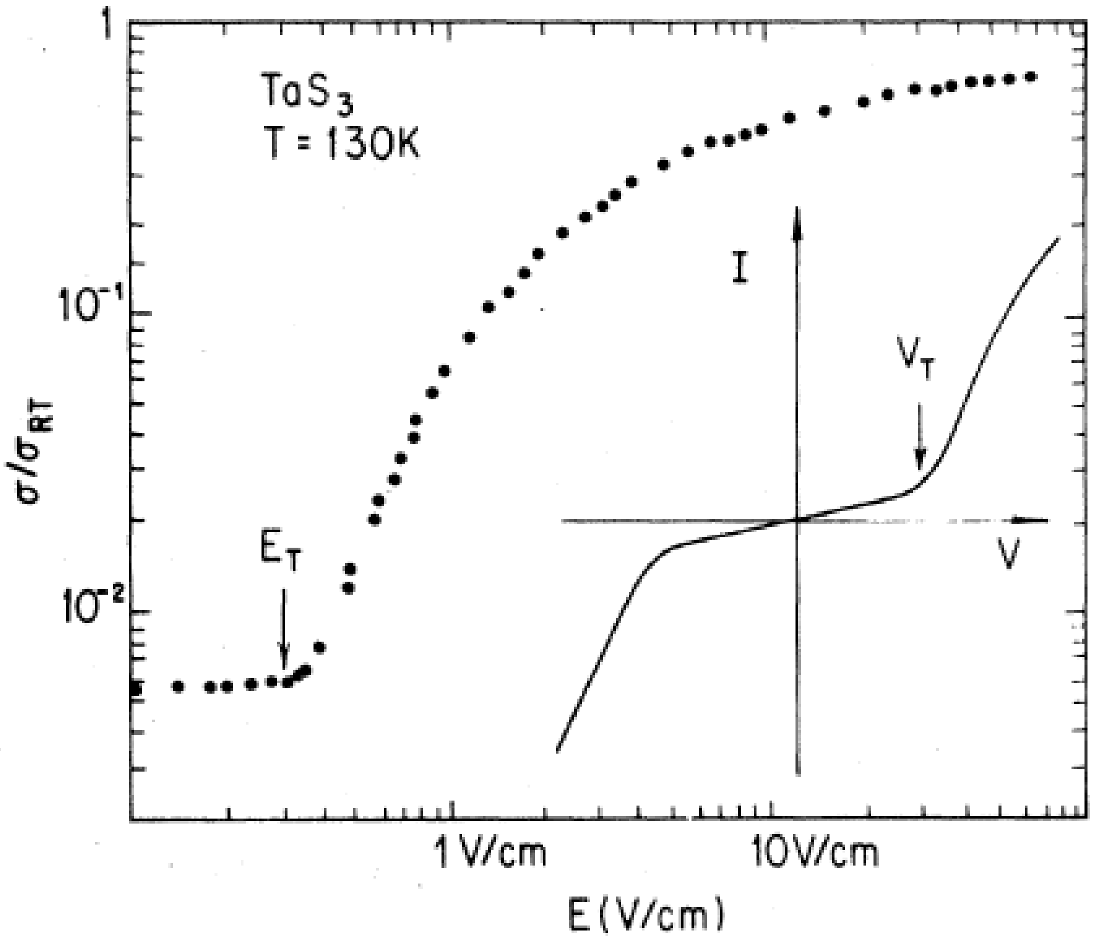


R.V. Coleman, *Phys. Rev. Lett.*, **55**, 394 (1985).

Macroscopic quantum phenomena: coherence length >1 μm

Quantum materials

Charge Density Waves: Early Devices



→ Electric-field-dependent conductivity normalized to RT conductivity.

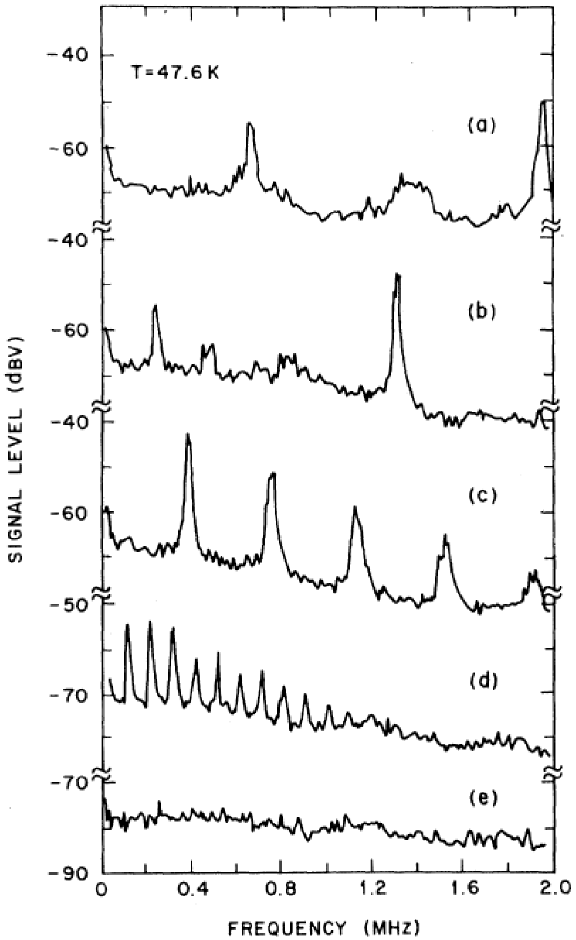
→ The inset shows typical DC I-V characteristics of the same material.

→ CDW de-pinning was the main mechanism for device operation.

→ One can get oscillations at output with DC input.

The image is after G. Gruner, *Rev. Mod. Phys*., **60**, 1129 (1988).

Current Oscillations in Bulk Quasi-1D CDW Materials



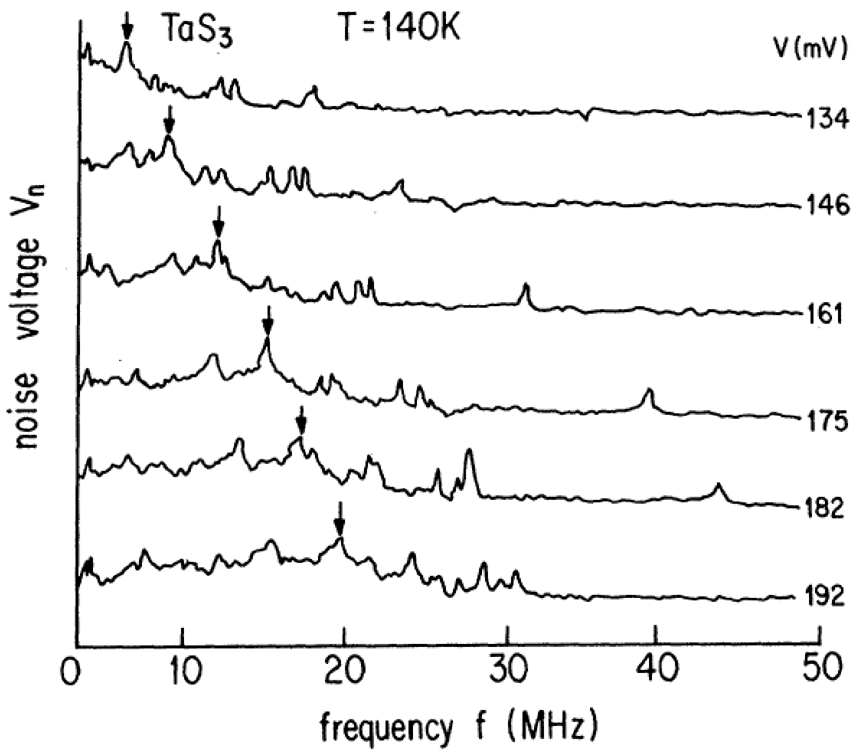
Sliding-Mode Conductivity in $NbSe_3$: Observation of a Threshold Electric Field and Conduction Noise

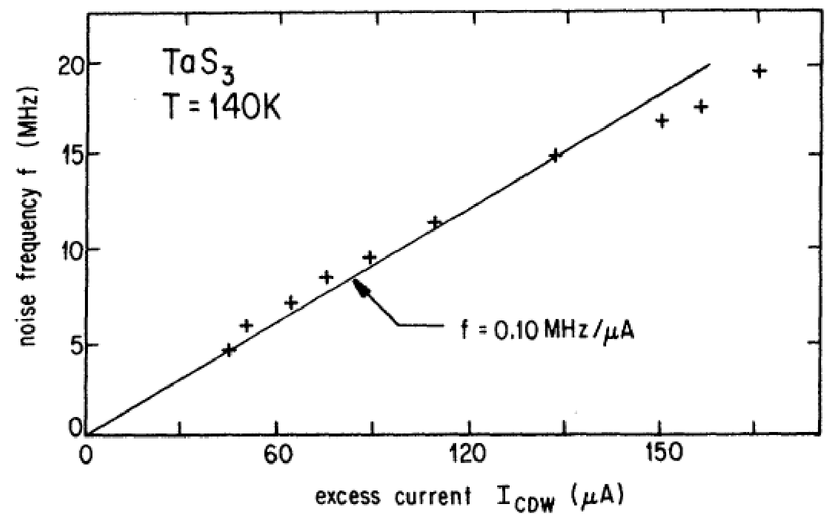
R. M. Fleming and C. C. Grimes
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 15 March 1979)

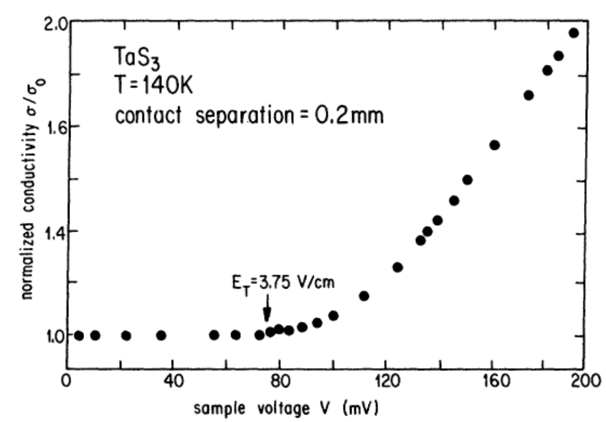
FIG. 3. Output of on-line spectrum analyzer for selected values of current. Increasing current from zero (e) to a value above threshold (d) results in an increase of broad-band noise plus a discrete frequency with numerous harmonics. The frequency increases with current and at higher currents (b) a second frequency appears. Currents and dc voltages (a) $I = 270\ \mu A$, $V = 5.81$ mV, (b) $I = 219\ \mu A$, $V = 5.05$ mV, (c) $I = 154\ \mu A$, $V = 4.07$ mV, (d) $I = 123\ \mu A$, $V = 3.40$ mV, (e) $I = V = 0$. Sample cross section $\approx 136\ \mu m^2$.

"Narrow band noise" was considered to be a direct evidence of CDW de-pinning and sliding.

Other Examples of Current Oscillations in Bulk Quasi-1D CDW Materials

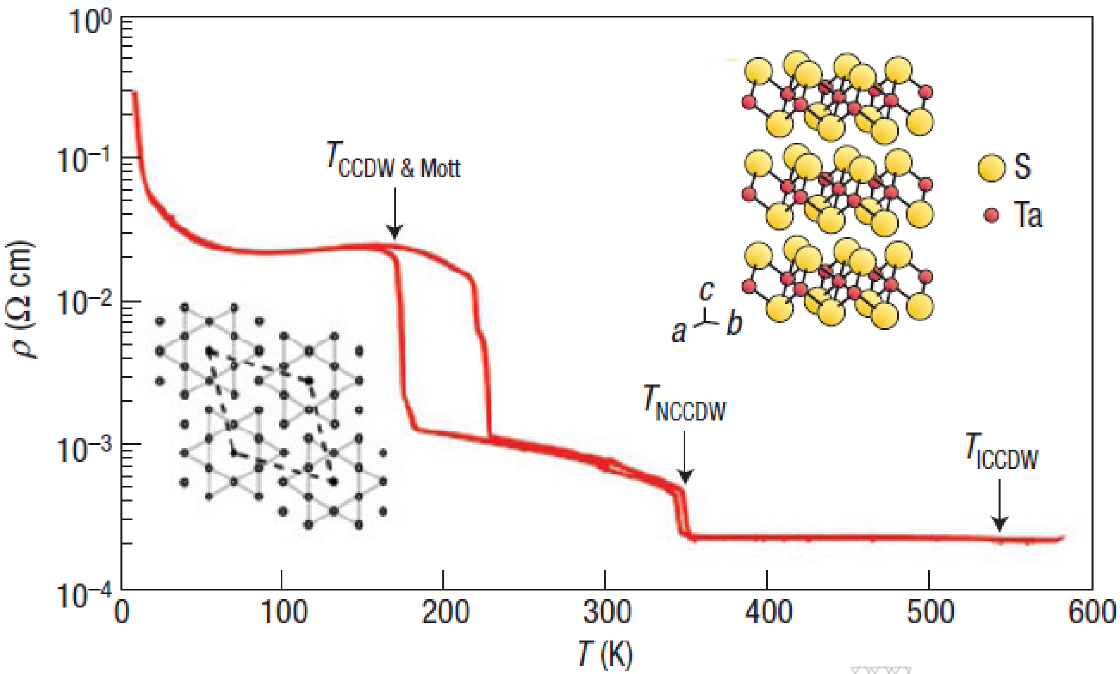


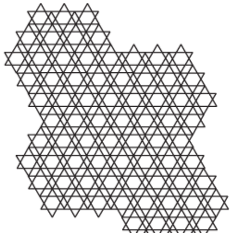


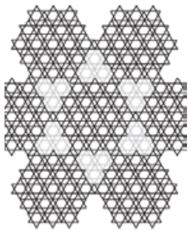


G. Gruner, et al., Phys. Rev. B, 23, 6813 (1981).

Rebirth of the Field of CDW Materials: Quasi-2D Films of 1T-TaS_2







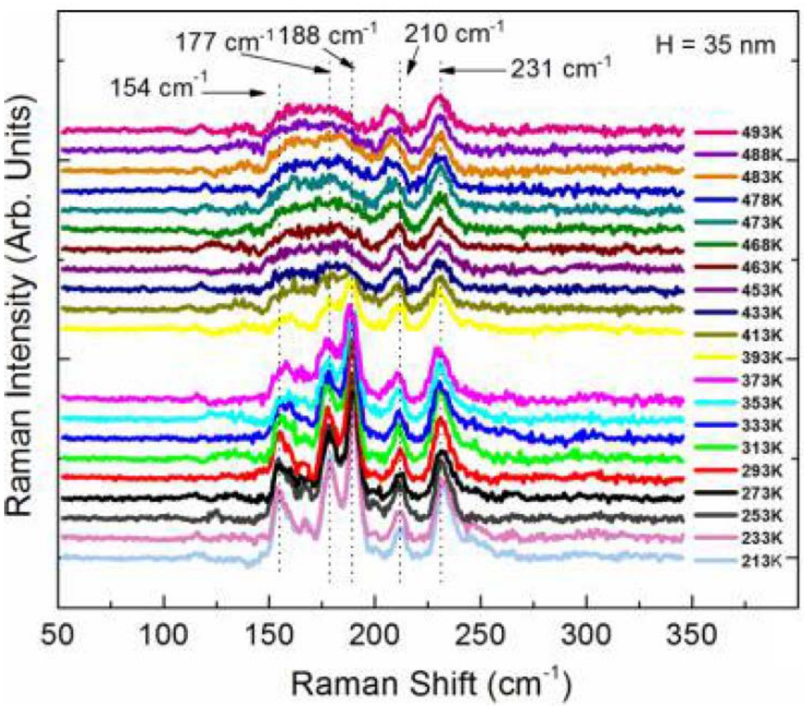
Ambient-pressure phases of 1T-TaS_2. The phases are: a metallic phase at temperatures above 550 K; an IC-CDW phase above 350 K; an NC-CDW phase above 190 K; a C-CDW Mott phase below 190 K. Also shown are the Ta atom distortions in the fully commensurate phase and the crystal structure of 1T-TaS_2.

B. Sipos, A.F. Kusmartseva, A. Akrap, H. Berger, L. Forró, and E. Tutiš, Nature Mater., 7, 960 (2008).

There are multiple phase transition points – some of them are above RT

Dimensionality Effects on CDW Transitions in Quasi-2D Films of TMDs

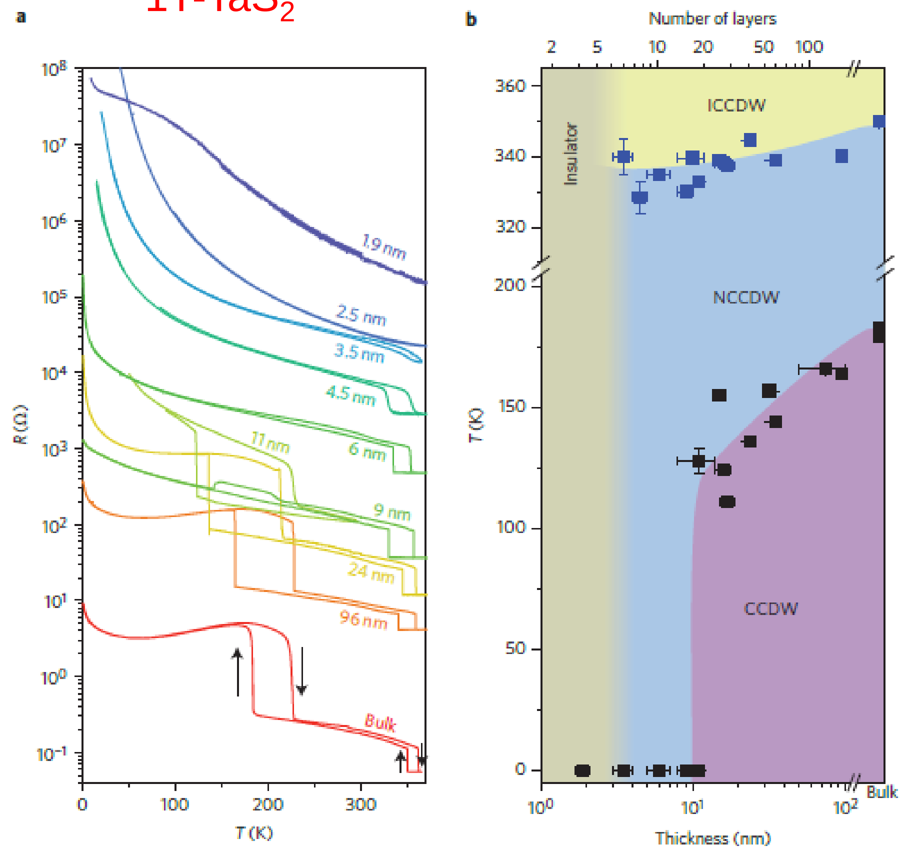
1T-$TaSe_2$



R. Samnakay, D. Wickramaratne, T. R. Pope, R. K. Lake, T. T. Salguero, and A. A. Balandin, Nano Lett., 15, 2965 (2015).

P. Goli, et al., Nano Lett., 12, 5941 (2012).

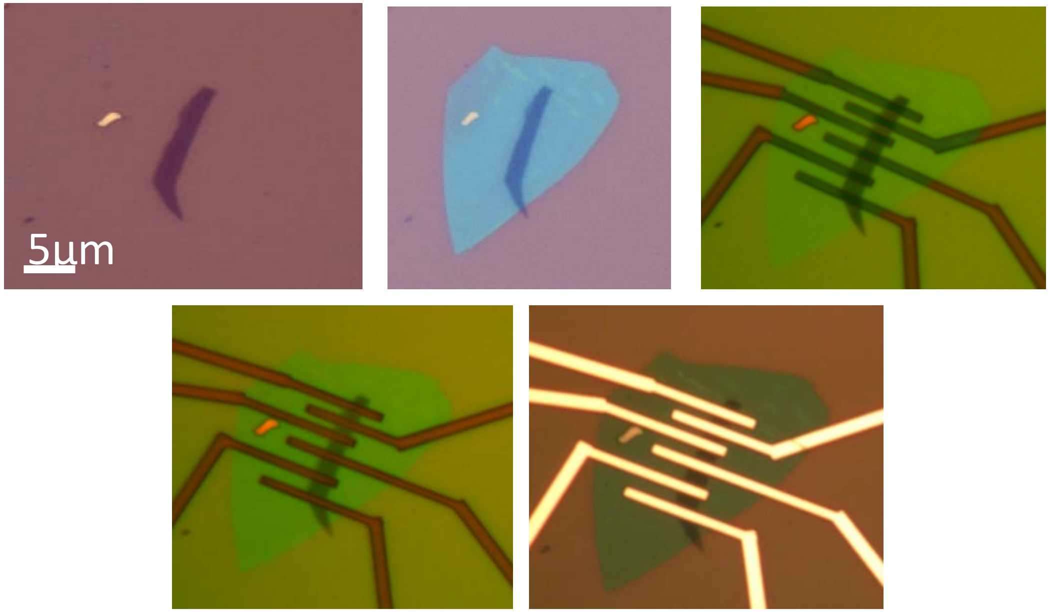
1T-TaS_2



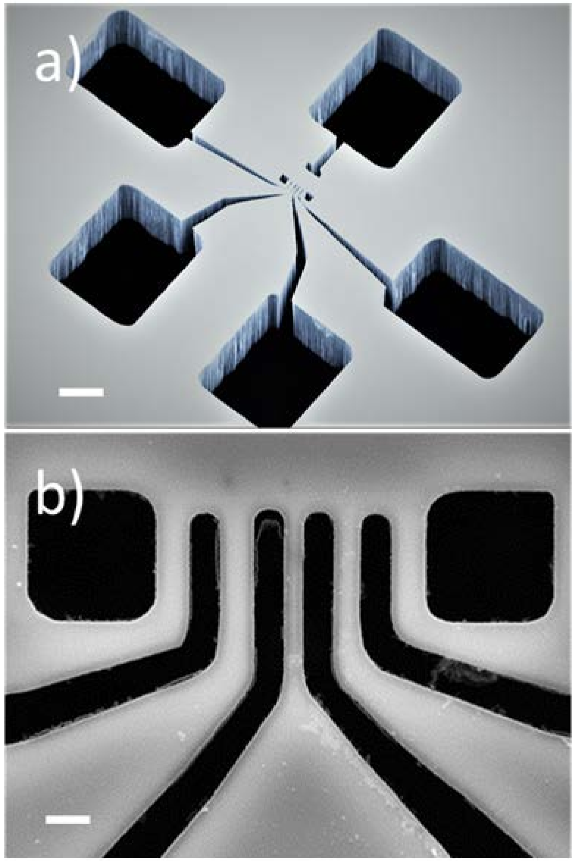
Y. Yu et al, Nature Nano, 10, 270 (2015)

Fabrication of Quasi-2D CDW Devices

E-Beam Lithography



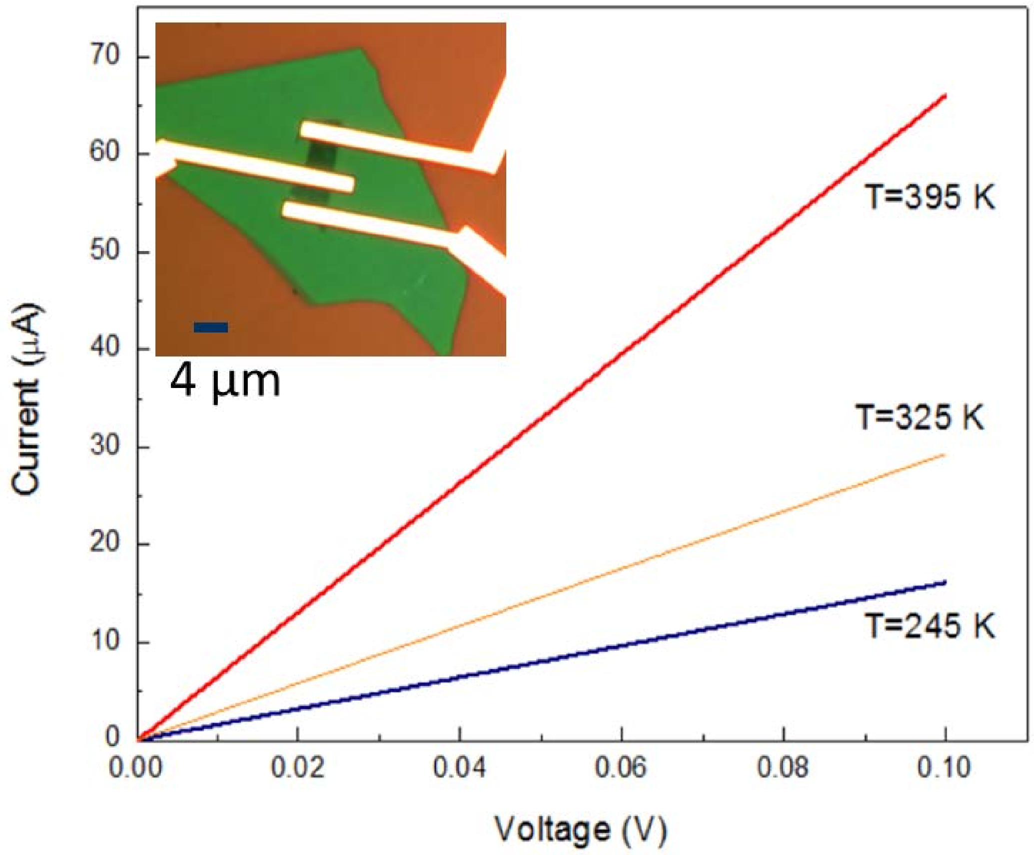
Shadow Mask Method

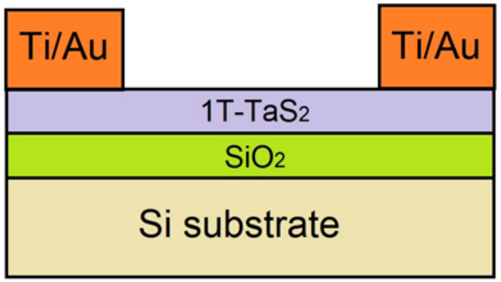


Boron Nitride (h-BN) films are used to cap the 1T-TaS_2.

h-BN layer is dry transferred with the PDMS assisted technique which allows for accurate alignment.

Device Structure and Contacts





Channel thickness:
t = 6 nm - 9 nm

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

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

→ The edge contacts provide good Ohmic contacts to the 1T-TaS_2.

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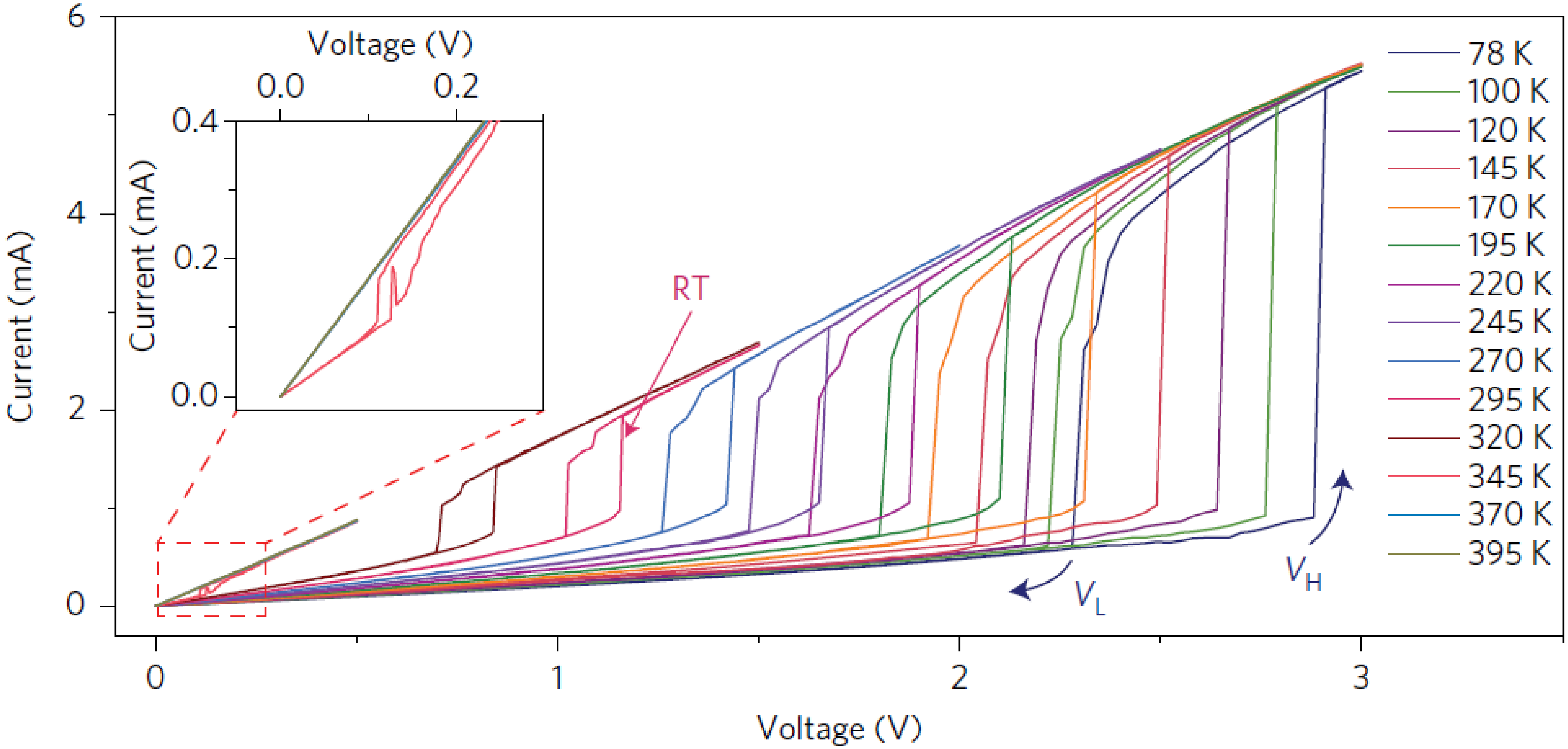
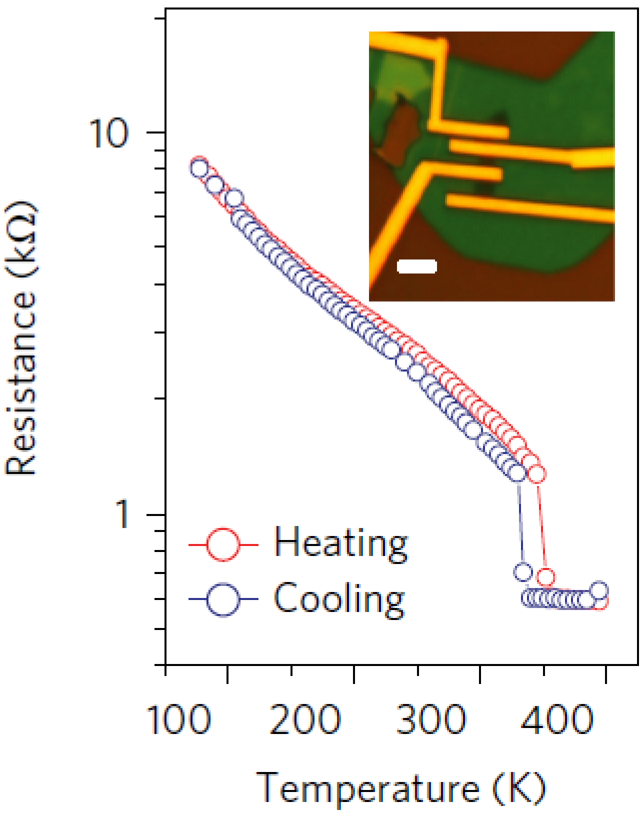
I-V Characteristics of Thin Film 1T-TaS_2



The threshold switching effect is prominent from 78 K to 320 K. The blues arrows indicate the voltage sweep direction for the measurement at 78 K. For all the other temperatures, V_H is always higher than V_L. 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. As T exceeds 350 K, the IV becomes linear.

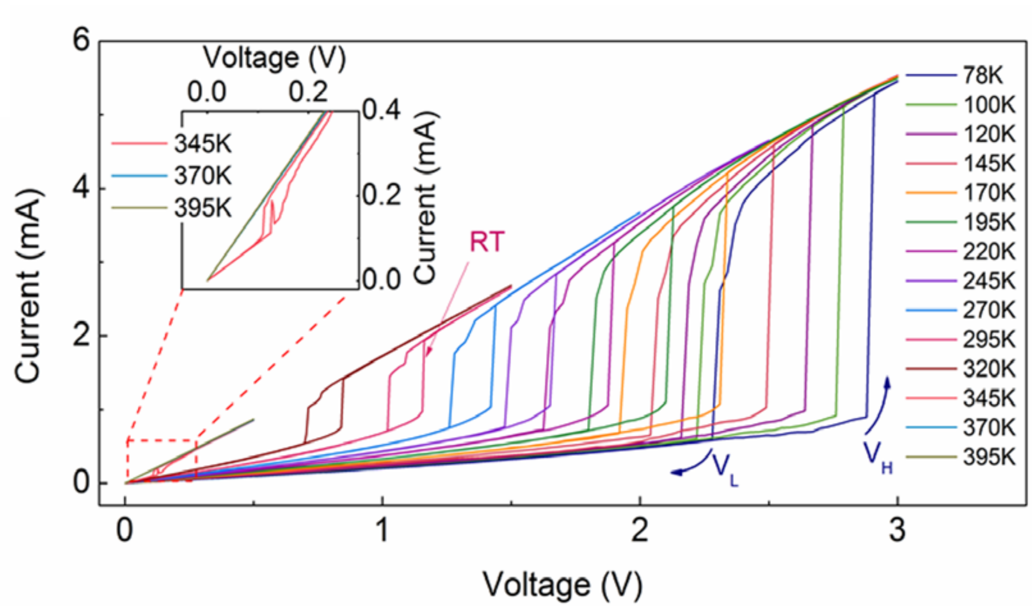
Low-Voltage I-V Characteristics of Thin Film 1T-TaS_2



No transition at 180 K

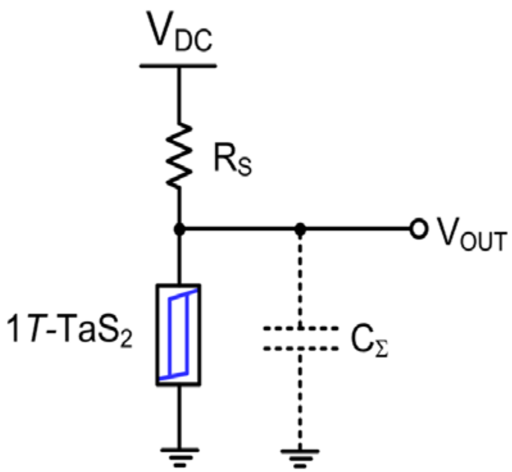
→ Temperature-dependent resistance measurements for 1T-TaS_2. The NC-CDW–IC-CDW and IC-CDW–NC-CDW transitions happen at 350 K and 340 K during the heating and cooling process, respectively. The resistance is measured at low voltage (V=20 mV).

→ Resistances match



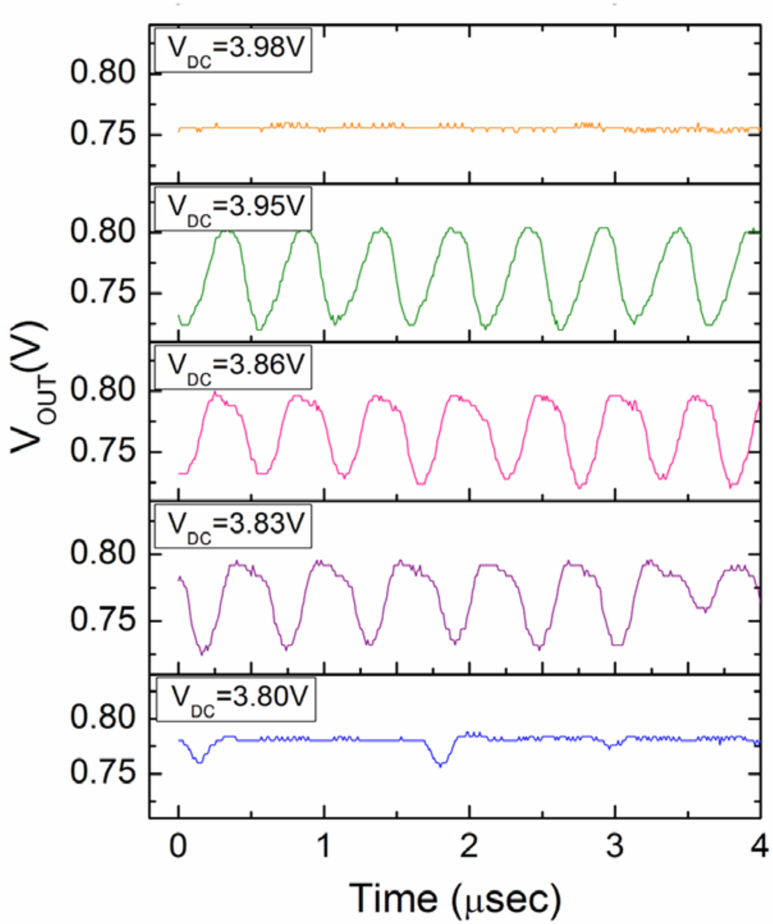
G. Liu, B. Debnath, T. R. Pope, T. T. Salguero, R. K. Lake, and A. A. Balandin, Nature Nano, 11, 845 (2016).

Oscillator Based on 1T-TaS_2 Device



Different operation mechanism from early devices – no de-pinning

Allows for high T operation

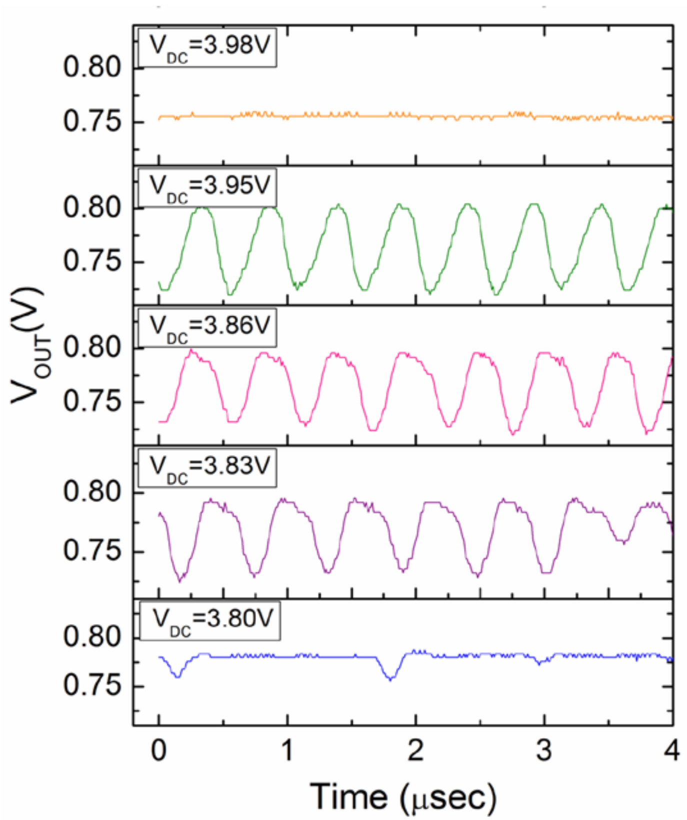


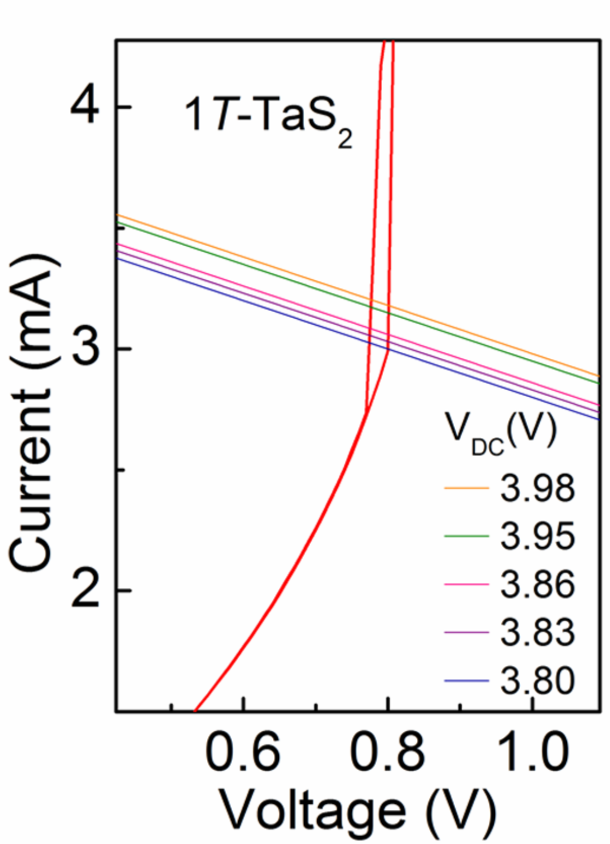
→Circuit schematic of the oscillator consists of the 1T-TaS_2 film, a series connected load resistor, and a lumped capacitance from the output node to ground. The load resistance is 1 kΩ.

→The output terminal is monitored by an oscilloscope.

→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.

Oscillator Based on 1T-TaS_2 Device





Load lines of the resistor at different V_{DC}. The blue line, which represents V_{DC}=3.8 V, intersects with V_H of 1T-TaS_2. This is the condition at which the circuit is about to oscillate.

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

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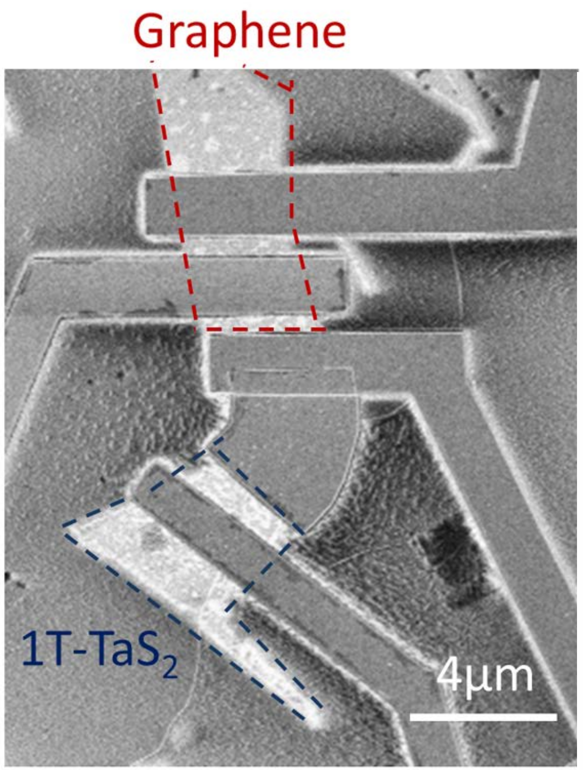
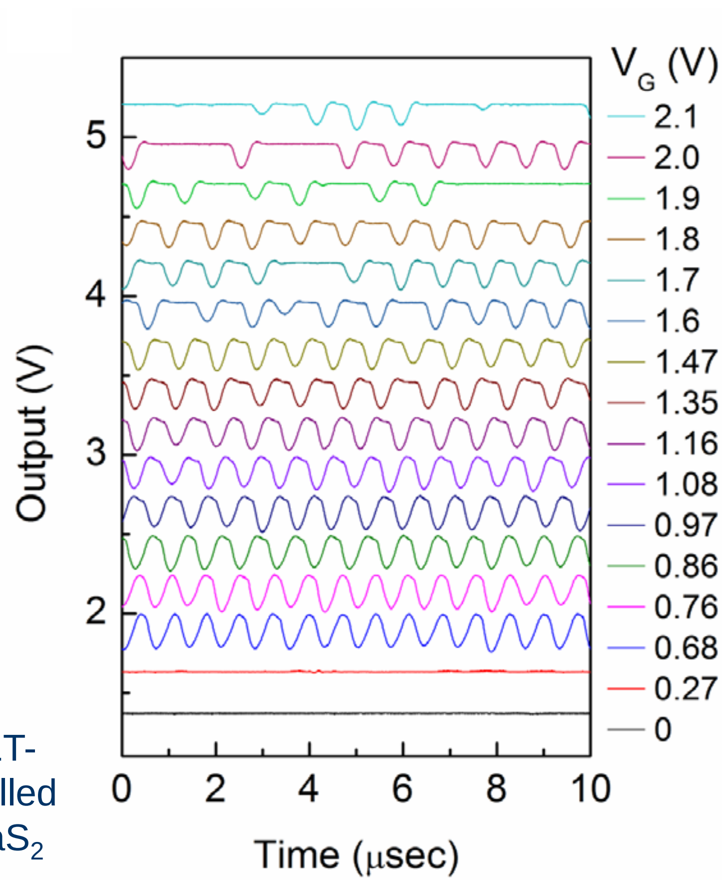
An Integrated 1T-TaS_2 – h-BN – Graphene Oscillator



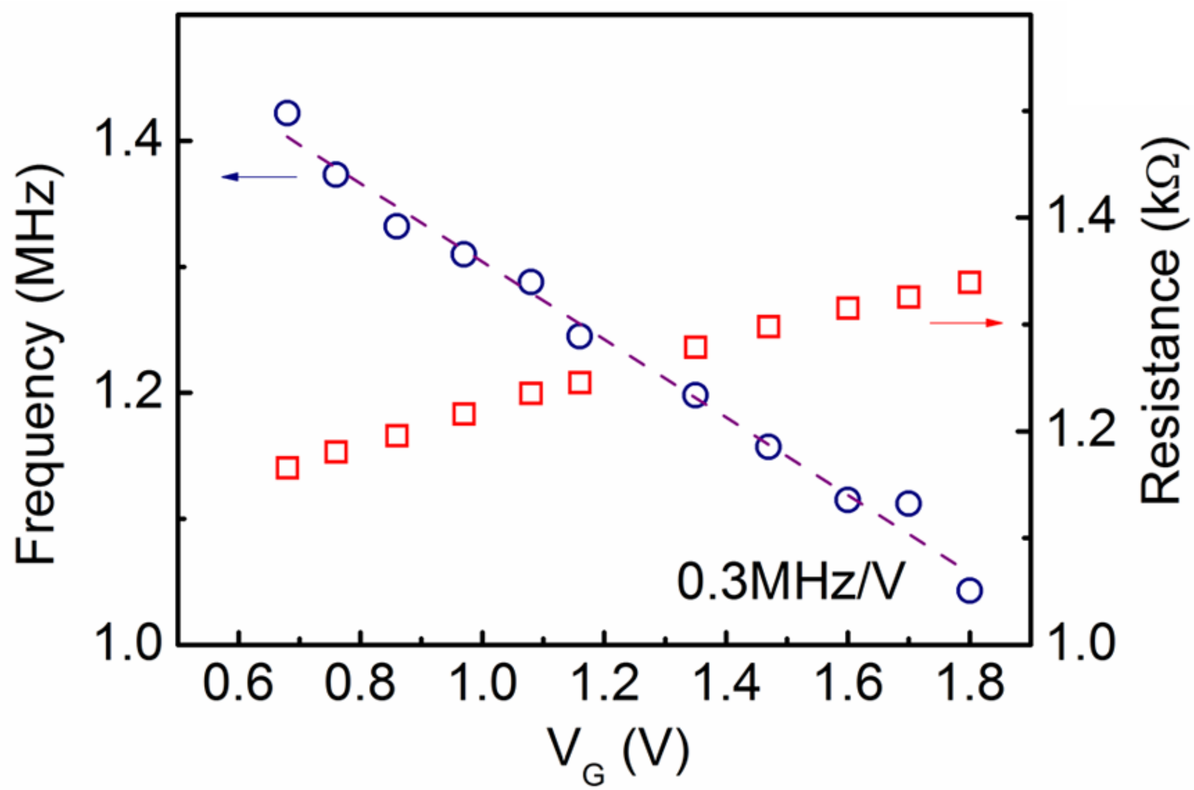
The SEM image of the integrated 1T-TaS_2–BN–graphene voltage controlled oscillator. The graphene and the TaS_2 are highlighted by dashed lines.



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. R. Pope, T. T. Salguero, R. K. Lake, and A. A. Balandin, Nature Nano, 11, 845 (2016).

1T-TaS_2 – h-BN – Graphene CDW VCO



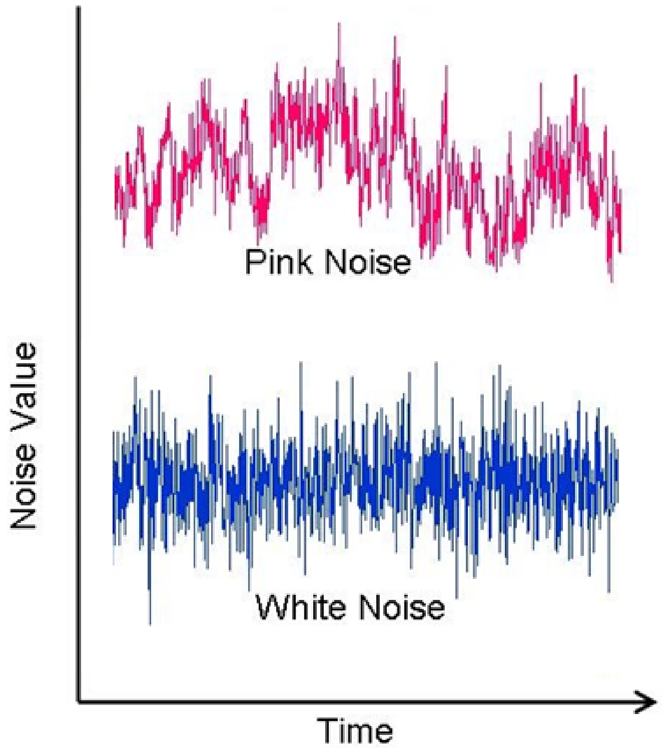
The dependence of oscillation frequency as function of gate bias.

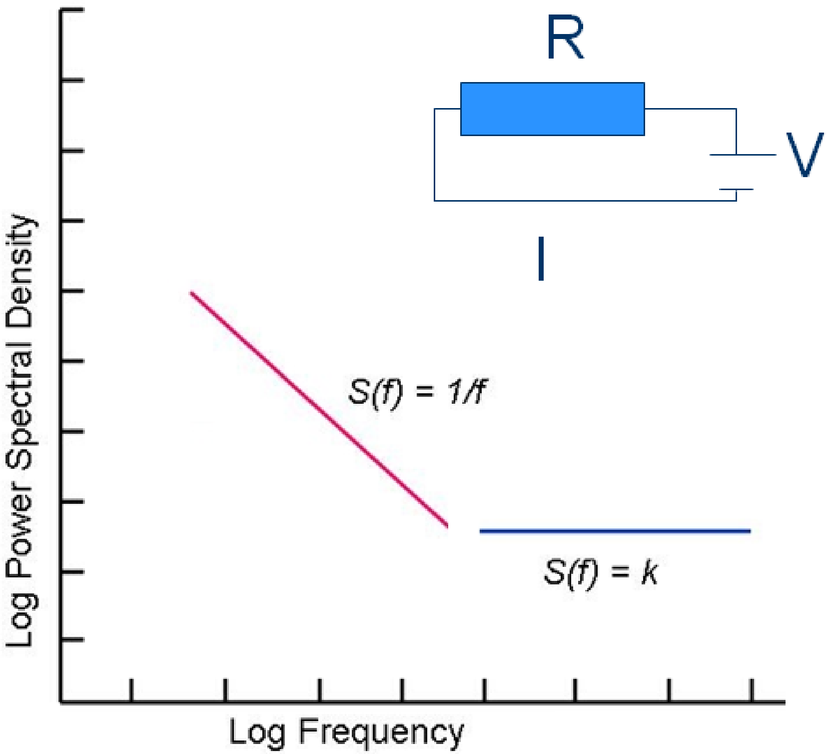
Blue circles show the frequency of the oscillation under increased gate bias. The frequency can be adjusted monotonically with the tuning sensitivity of 0.3M Hz/V.

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

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

Basics of Electronic Noise





Low-frequency noise was discovered in vacuum tubes - J. B. Johnson, Phys. Rev. 26, 71 (1925).

Fundamental Types of Electronic Noise

Electronics: noise is a random fluctuation in an electrical signal characteristic for all electronic devices.

Different Types of Intrinsic Electronic Noise:

Thermal noise:

$S_I = 4k_BT/R$

Shot noise:

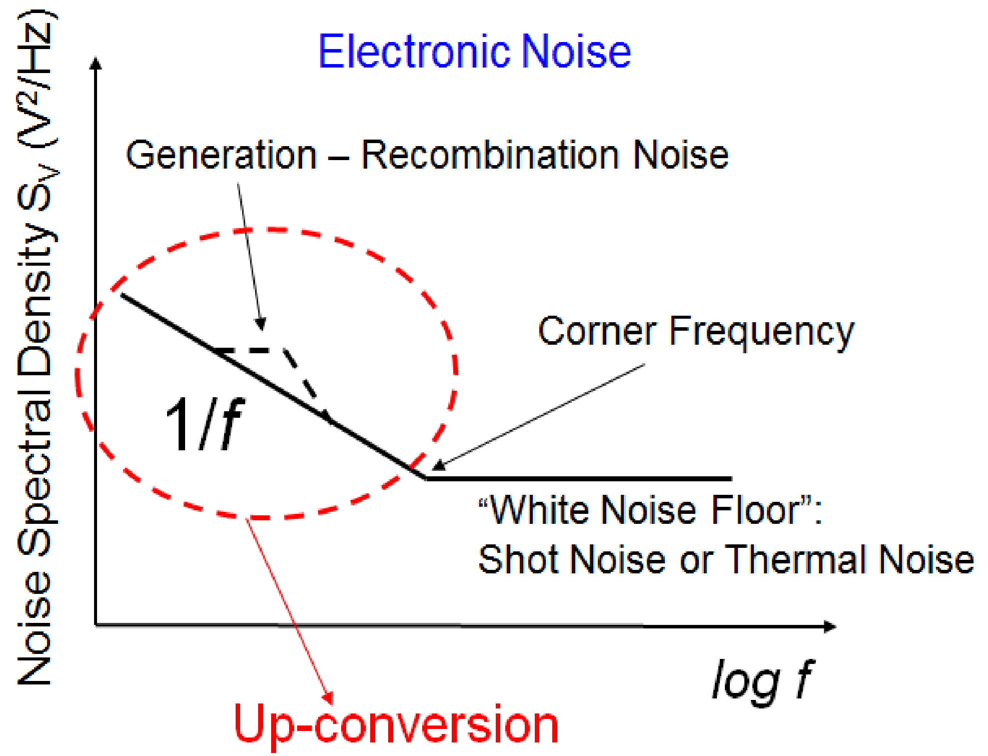
$S_I = 2e\langle I\rangle$

Flicker 1/f noise:

$S_I \sim I^2/f$

G-R noise:

$S_I \sim 1/(1+f^2\tau^2)$

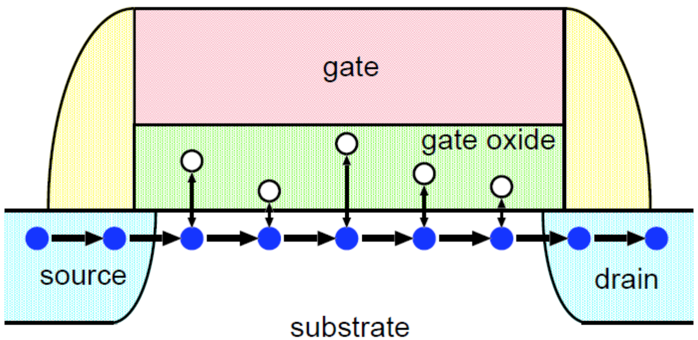


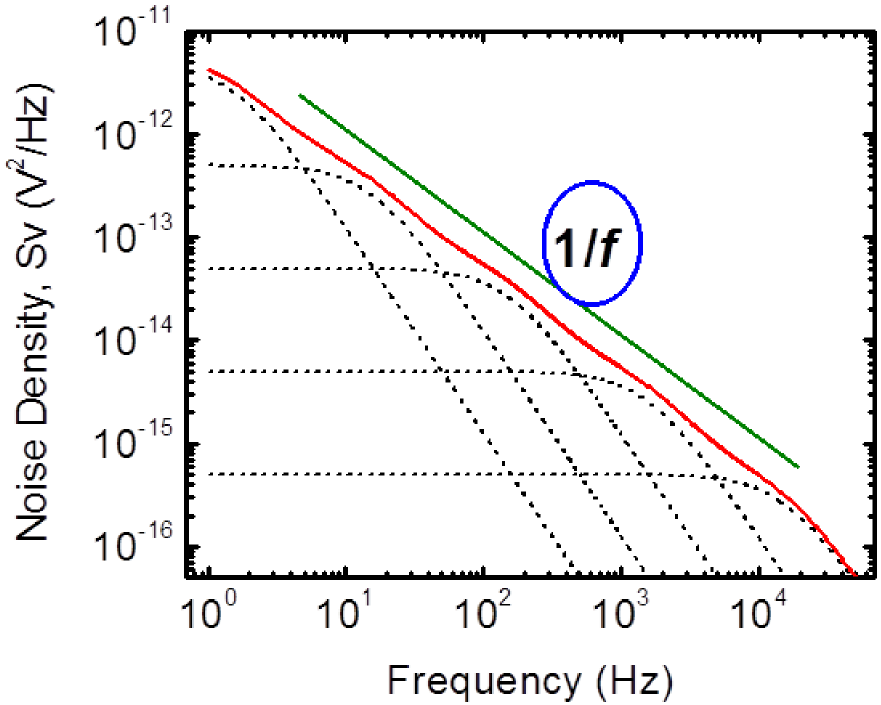
In the context of CDW research, the low frequency noise was referred to as the "broad band noise".

Low-Frequency Noise in Semiconductors

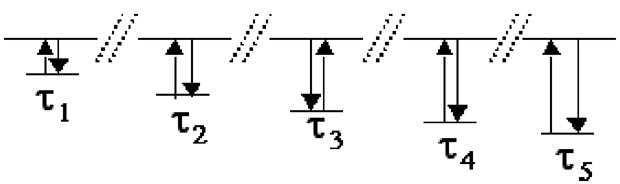
$$I = qN\mu$$

$$\delta I = q(\delta N)\mu + qN(\delta\mu)$$





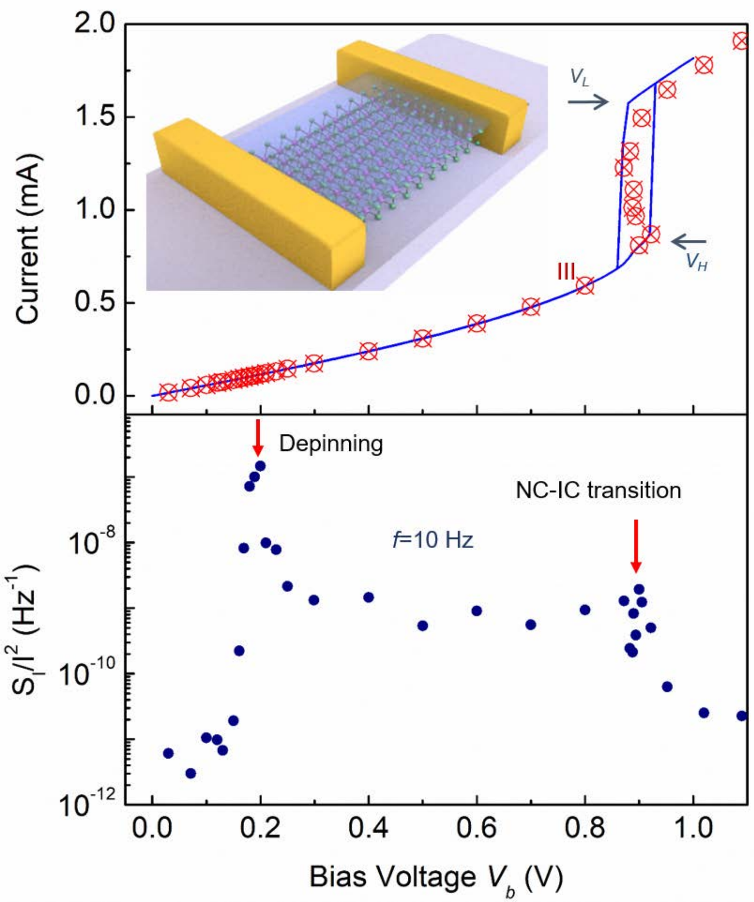
Series of levels

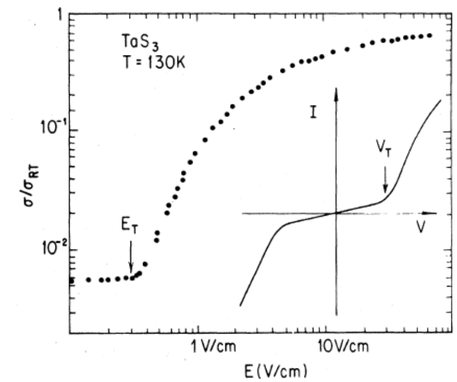


McWhorter's model: $g(\tau_N) = [\tau_N \ln(\tau_2/\tau_1)]^{-1}$

$$S_N(\omega) = 4\overline{\delta N^2}\int_{\tau_1}^{\tau_2} g(\tau_N)\frac{\tau_N}{1+(\omega\tau_N)^2}d\tau_N$$

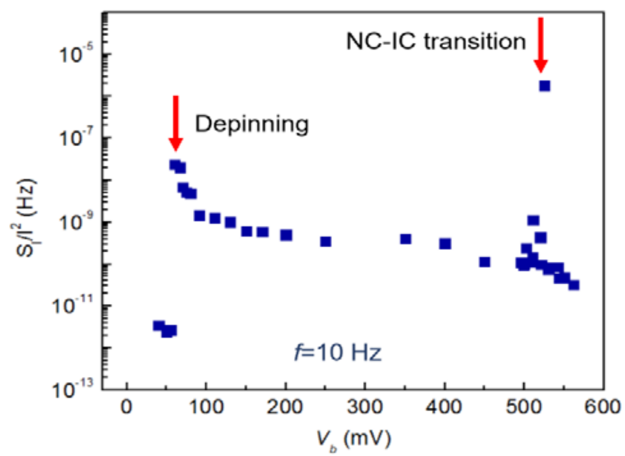
Low-Frequency Noise in Quasi-2D CDW Materials





IV-characteristics of 2D CDW materials are different from those of bulk 1D CDW.

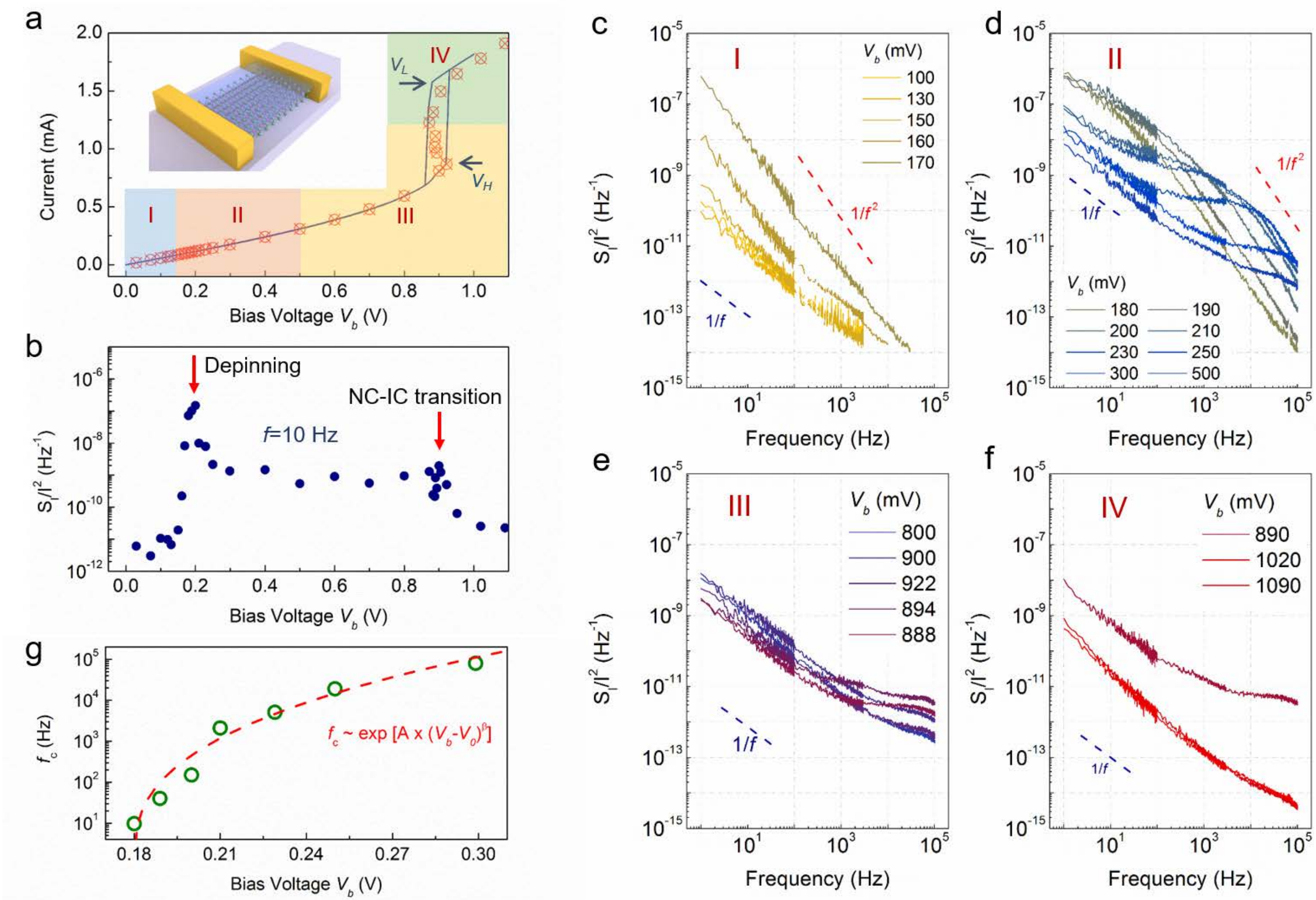
G. Gruner, Rev. Mod. Phys., 60, 1129 (1988).



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).

Unusual Features of Low-Frequency Noise in CDW Materials

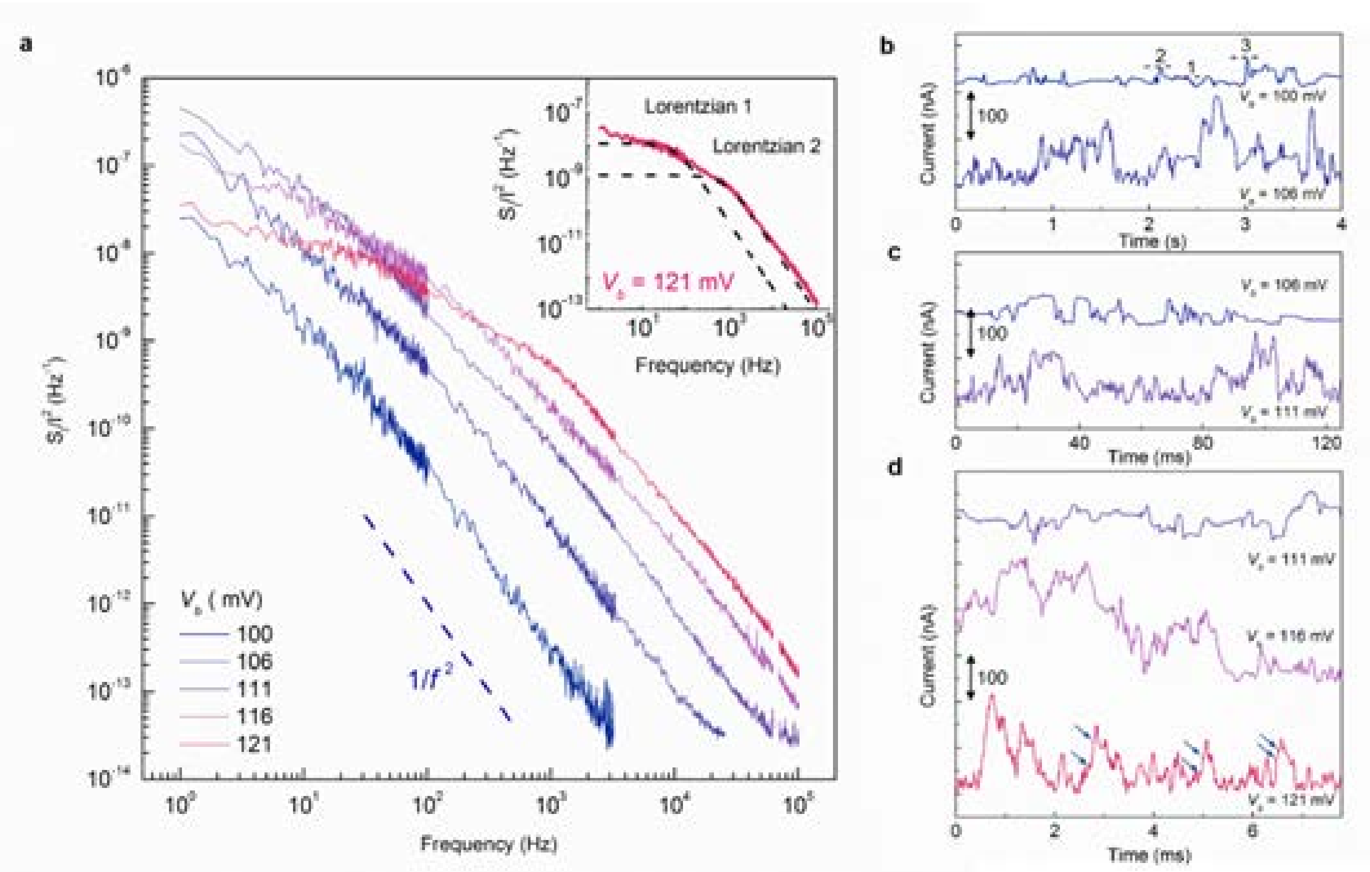


A voltage increase of only 120 mV results in a four orders-of-magnitude change in f_c.

This drastic change in f_c with the bias is highly unusual for conventional materials, where a Lorentzian spectrum is associated G-R noise with f_c independent from the bias.

G. Liu, S. et al. Nano Letters, 18, 3630 (2018).

Random Telegraph Signal Noise in CDW Materials

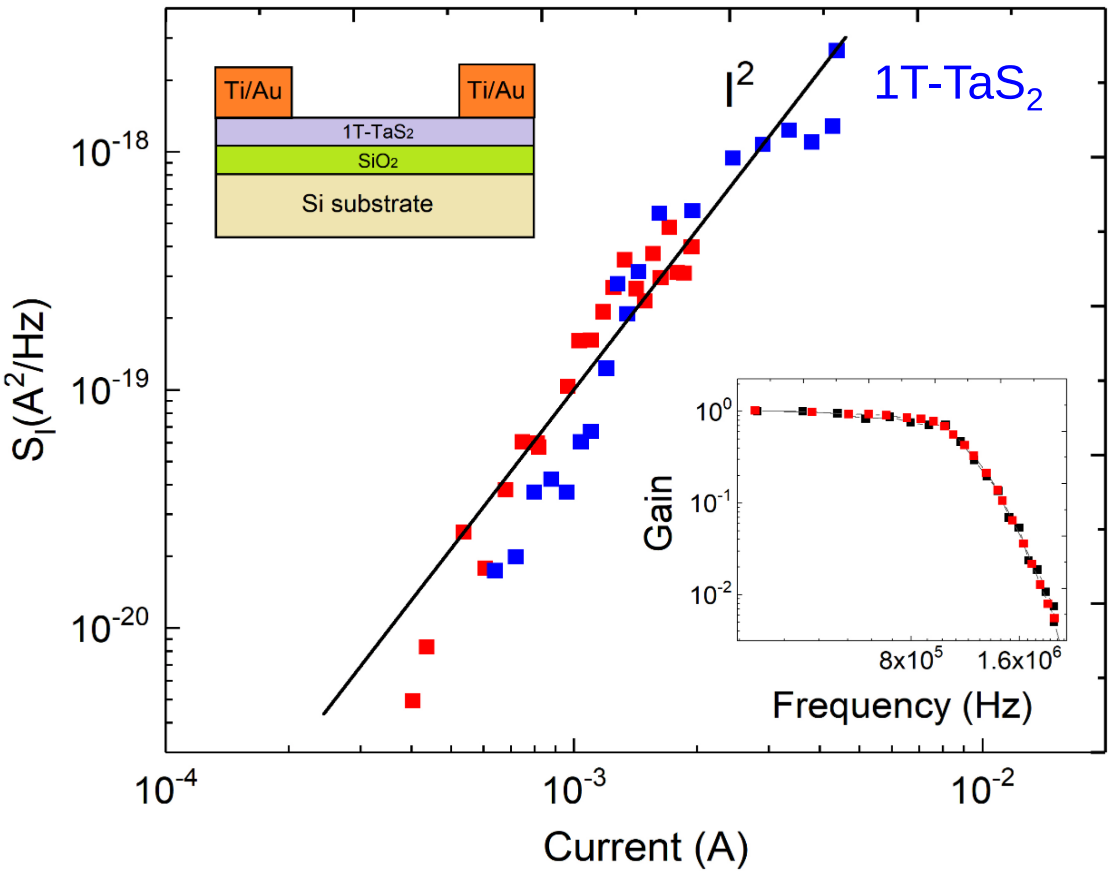


The noise spectral density after onset of sliding at different V_b. The corner frequency increases with increasing V_b.

Time-domain signals at V_b and time scales. Note that a small increase of the bias results in a significant change in the noise. The amplitude of the pulses increases and number of fluctuators becomes lager. This is different from classical RTS noise in semiconductor devices.

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

The Search for the "Narrow Band Noise" in Quasi-2D CDWs

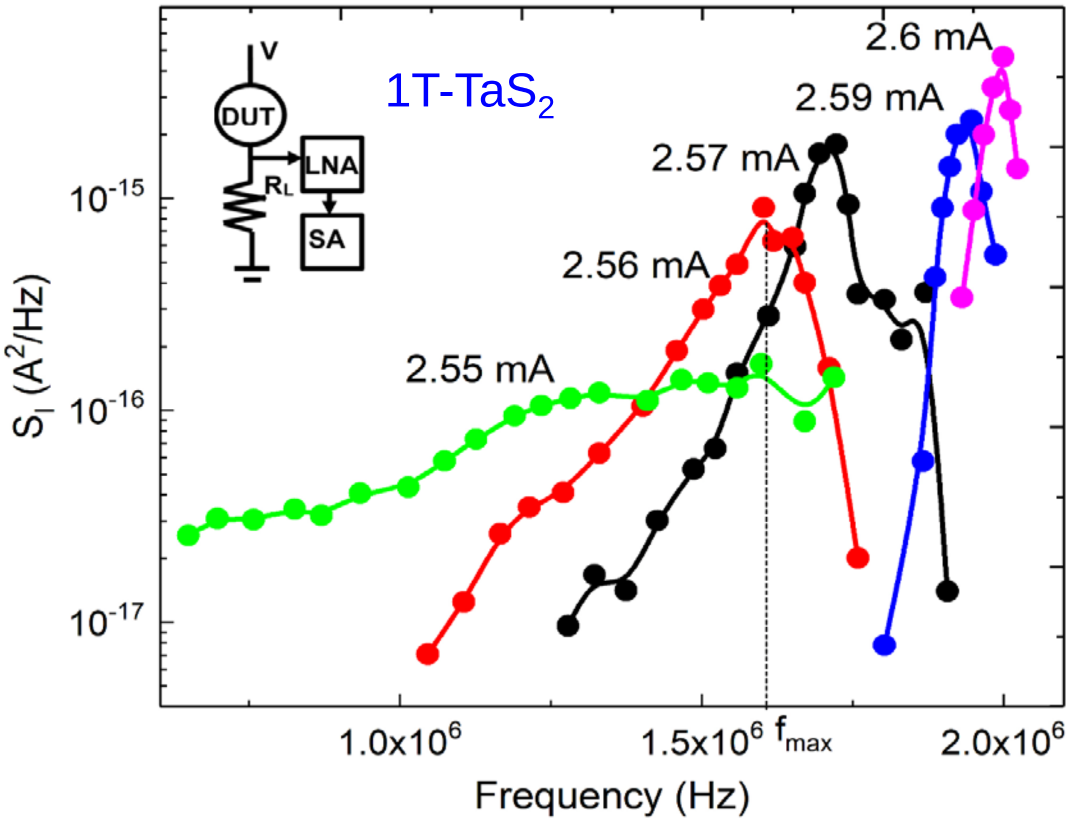


Noise power spectral density, S_I, as a function of the current through 1T-TaS_2 device channel measured at frequency *f*=760 kHz. The red and blue data points correspond to two tested devices.

The lower inset shows the gain, normalized to the gain at *f*=30 kHz, as a function of frequency.

Adane K. Geremew, Sergey Rumyantsev, Roger Lake, Alexander A. Balandin, Current Oscillations in Quasi-2D Charge-Density-Wave 1T-TaS_2 Devices: Revisiting the "Narrow Band Noise" Concept, arXiv:2003.00356 (2020)

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



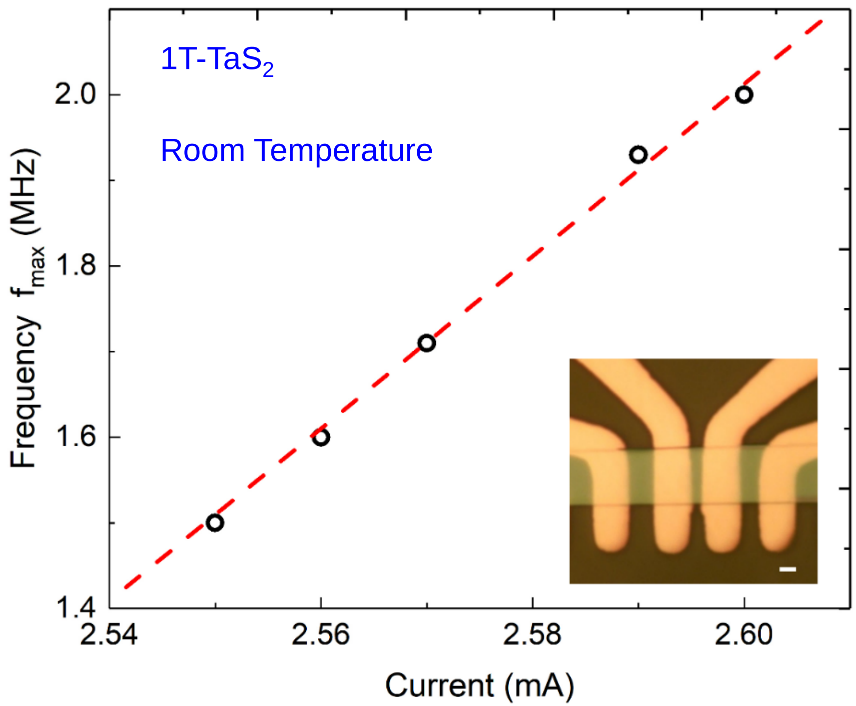
Noise as a function of frequency for several value of the current through the device channel. The peak shifts to the higher frequency f_o with the increasing current.

In bulk quasi-1D CDW materials, the linear relationship was explained assuming that f is proportional to the CDW drift velocity, v_D, so that $f=v_D/\Lambda$, where Λ is the characteristic distance.

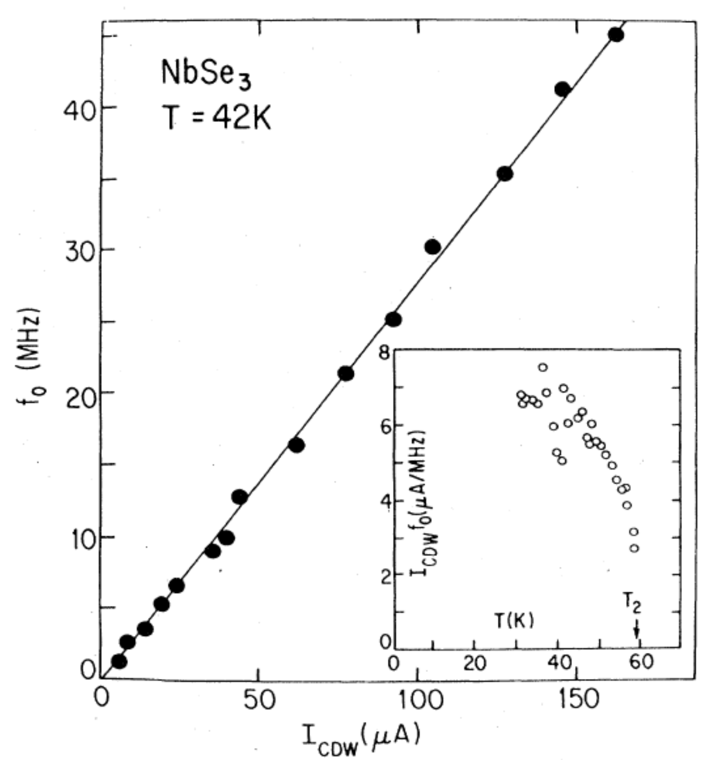
Since $I_{CDW}=nef\Lambda A$, where n is the charge carrier density, e is the charge of an electron, and A is the cross-sectional area, one obtains: $f=(1/neLA)\times I_{CDW}$

Adane K. Geremew, Sergey Rumyantsev, Roger Lake, Alexander A. Balandin, arXiv:2003.00356 (2020)

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

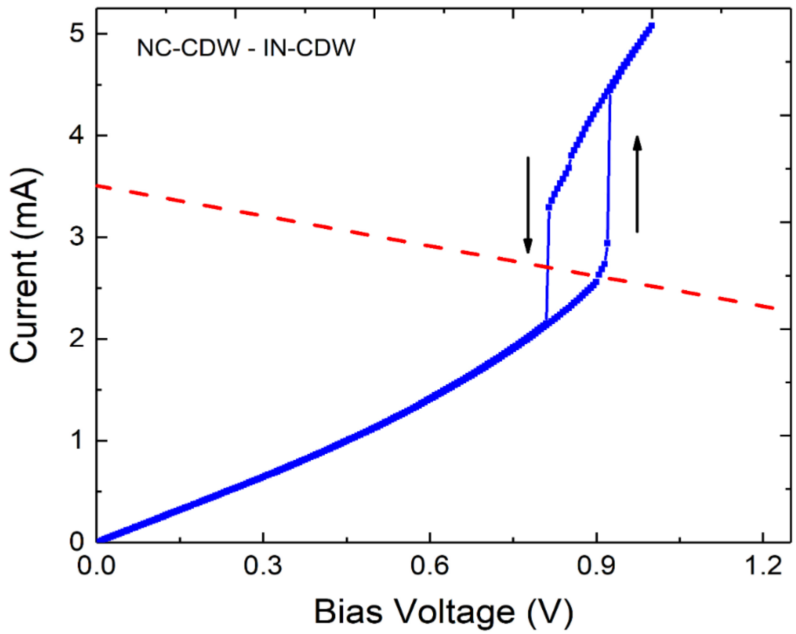


Frequency, f_o of the noise peaks as a function of the current through 1T-TaS_2 device channel. The inset shows a microscopy image of a representative 1T-TaS_2 device structure with several metal contacts.

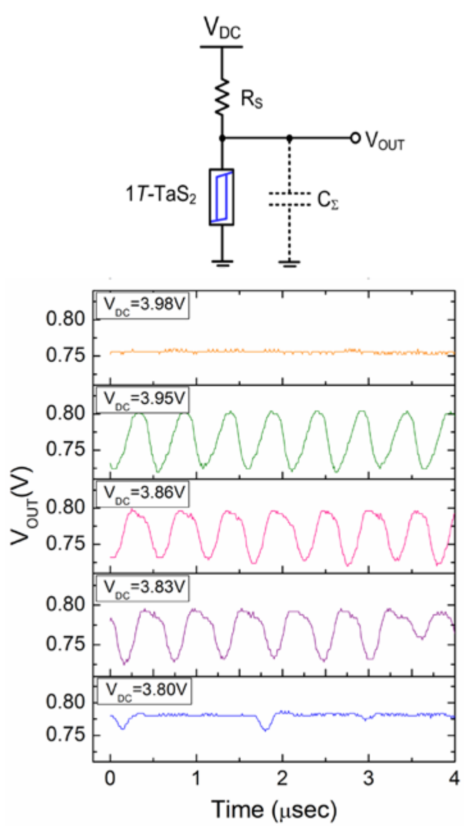


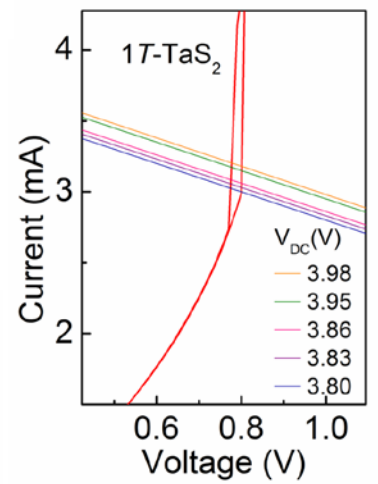
Relation between the COW current and fundamental oscillation frequency in $NbSe_3$. The inset shows I_{CDW}/f_o vs. temperature. After Bardeen et al. (1982).

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



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



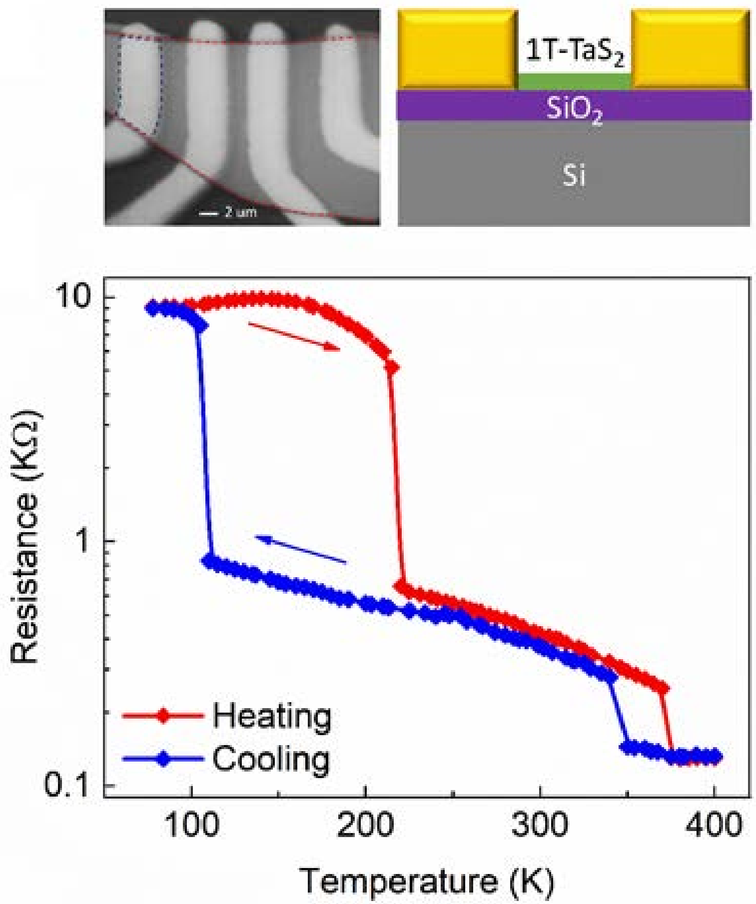


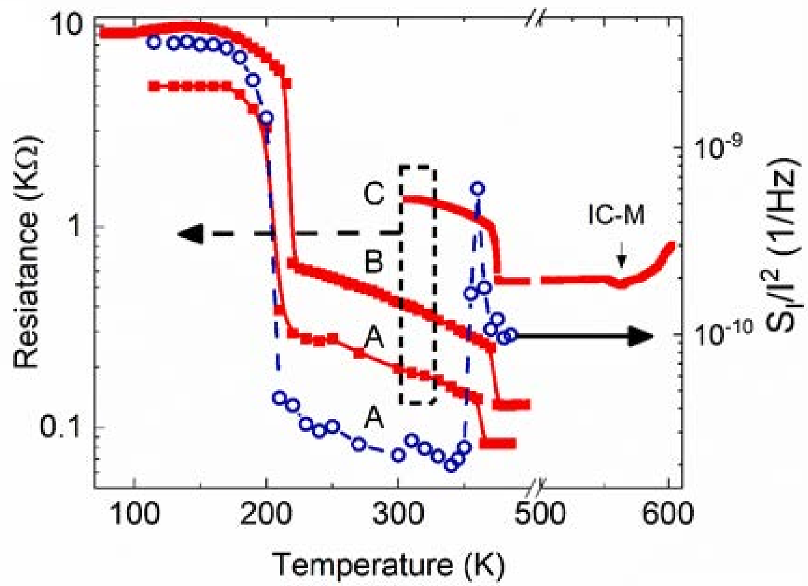
I-Vs of tested 1T-TaS_2 device which revealed "narrow band noise". The hysteresis loop at the bias voltage V = 0.9 V corresponds to the transition from the NC-CDW phase to the IC-CDW phase induced the applied electric field.

Adane K. Geremew, Sergey Rumyantsev, Roger Lake, Alexander A. Balandin, arXiv:2003.00356 (2020)

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

IC CDW – Metal Transition in Quasi-2D CDW Materials

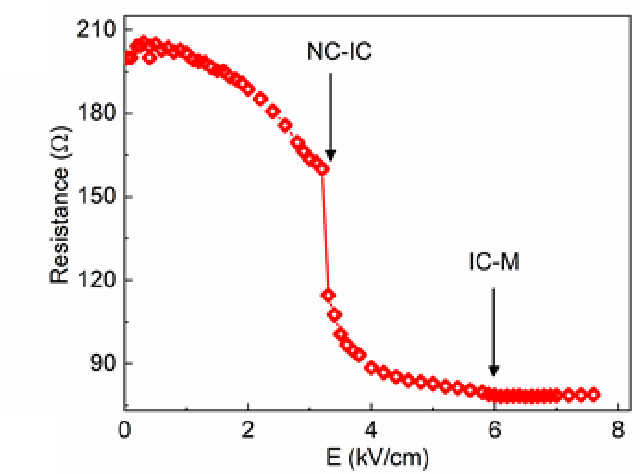


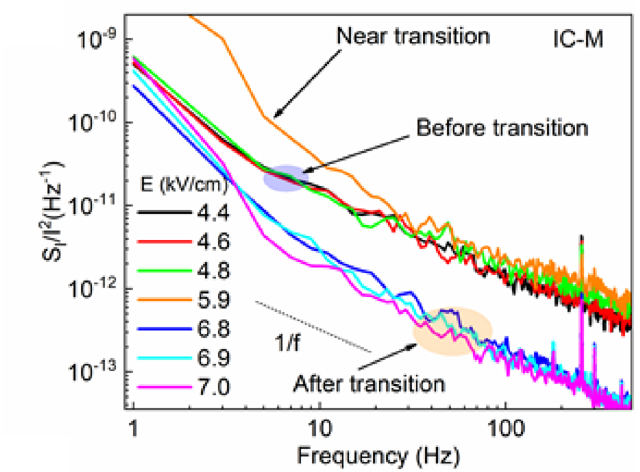


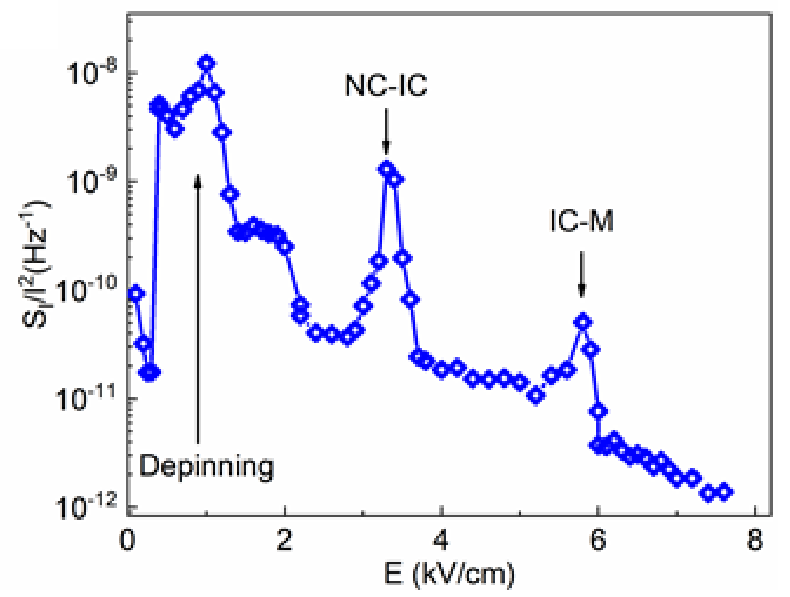
→ Optical image of a representative device (left panel) and a schematic of the device layered structure (right panel). The scale bar is 2 µm.

→ Resistance as function of temperature for cooling (blue curve) and heating (red curve) cycles conducted at the rate of 2 K per minute.

Noise Spectroscopy of CDW Transitions







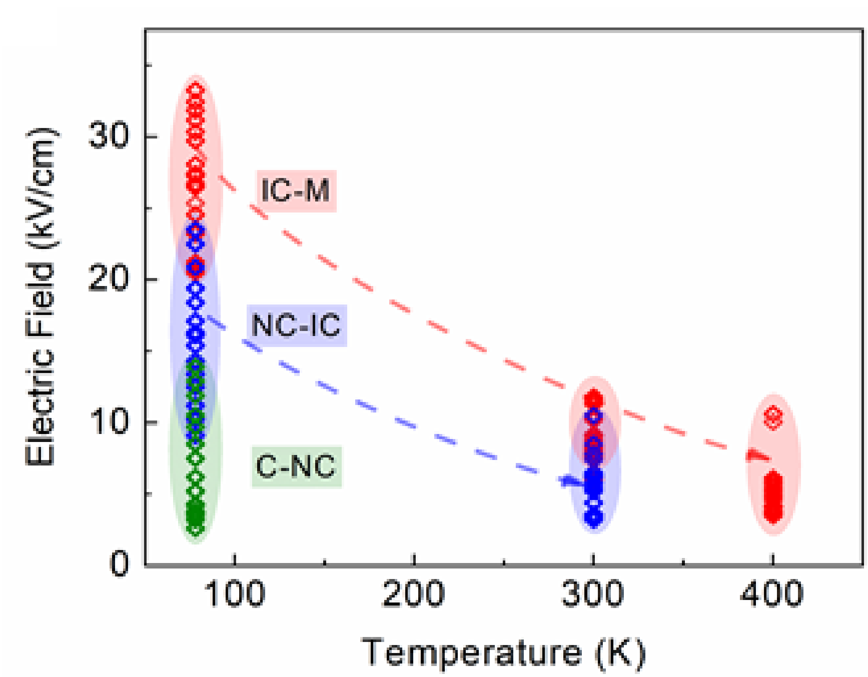
→ Resistance as a function of the applied electric field measured at RT.

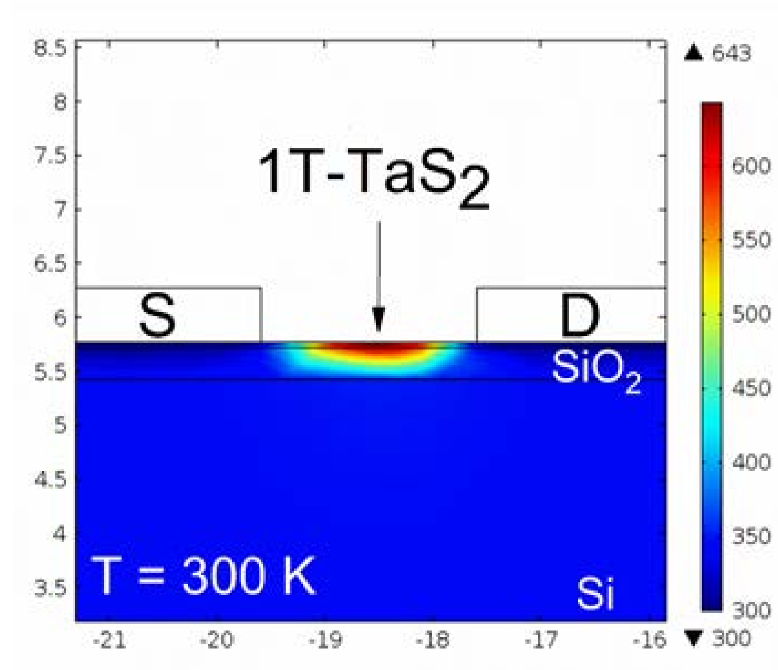
→ Noise spectral density as the function of frequency for several values of the electric field, which include the point of transition from the IC-CDW to the normal metallic phase.

→ Noise spectral density, measured at f=10 Hz, as the function of the electric field.

A. K. Geremew, S. Rumyantsev, F. Kargar, B. Debnath, A. Nosek, M. A. Bloodgood, M. Bockrath, T. T. Salguero, R. K. Lake, and A. A. Balandin, ACS Nano, 13, 7231 (2019).

Electric Field vs Self-Heating in CDW Devices

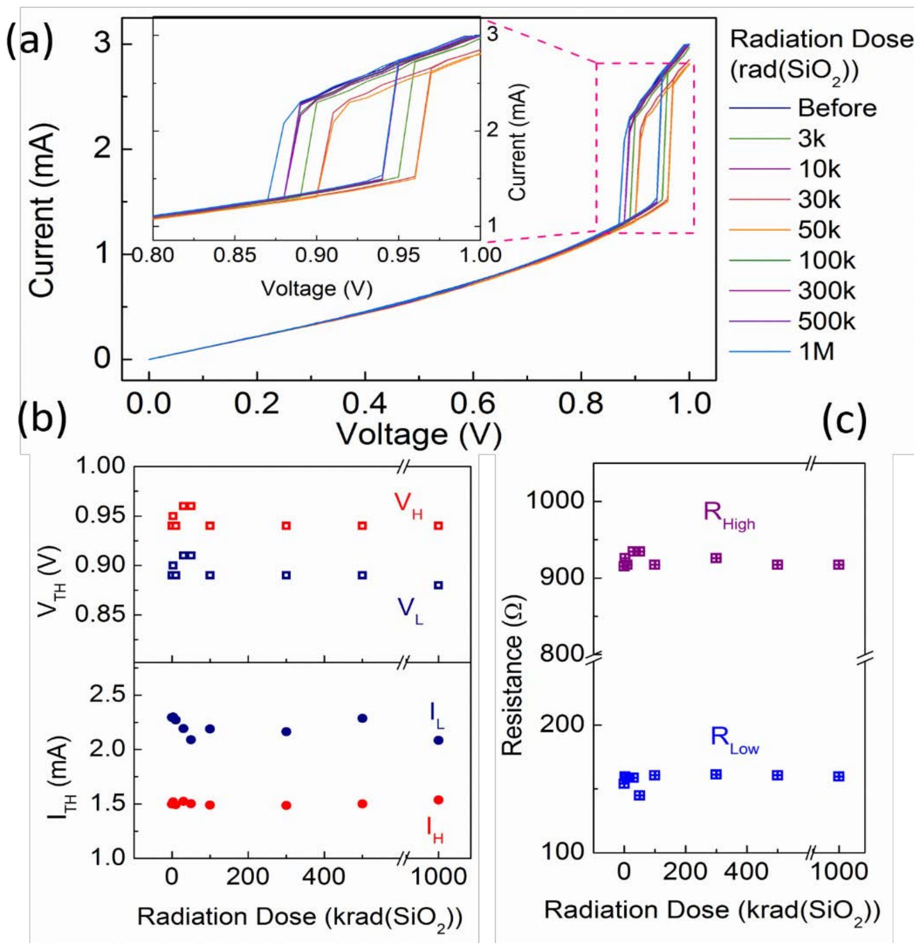




Summary of electric field induced phase transitions at different temperatures for 1T-TaS_2 devices. The variation in the electric field required to include the phase transitions is due to different device geometries, thickness of the layers in the device structures, and other variations in the device designs.

A. K. Geremew, S. Rumyantsev, F. Kargar, B. Debnath, A. Nosek, M. A. Bloodgood, M. Bockrath, T. T. Salguero, R. K. Lake, and A. A. Balandin, ACS Nano, 13, 7231 (2019).

1T-TaS_2 CDW Devices Under X-Ray Irradiation

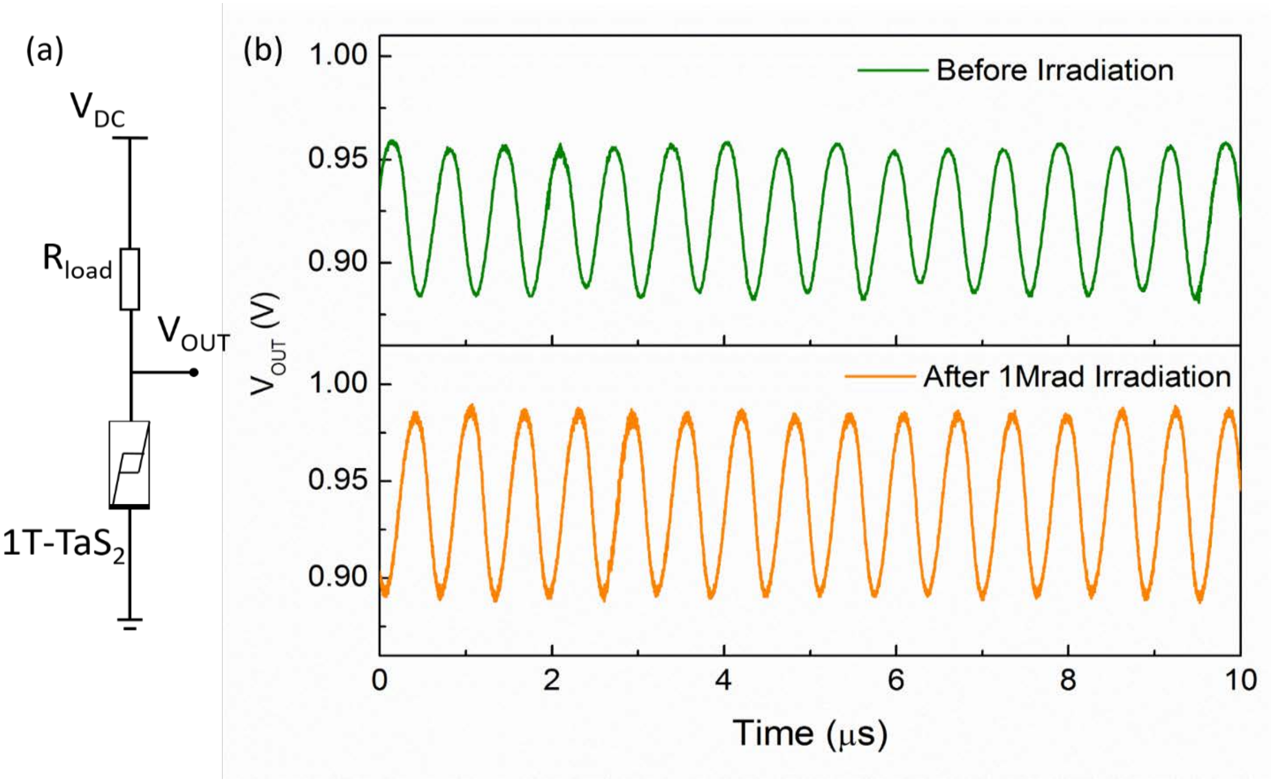


TID response of 1T-TaS_2 devices up to 1 M rad (SiO_2). (a) I-V curves measured after each X-ray irradiation step. (b) Threshold voltages, V_H and V_L, threshold currents, I_H and I_L as function of dose. (c) Extracted resistance at the high resistance and low resistance states as a function of dose.

Carrier concentration:
10^{21} cm^{-2} - 10^{22} cm^{-2}

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).

Radiation Hardness of CDW Devices

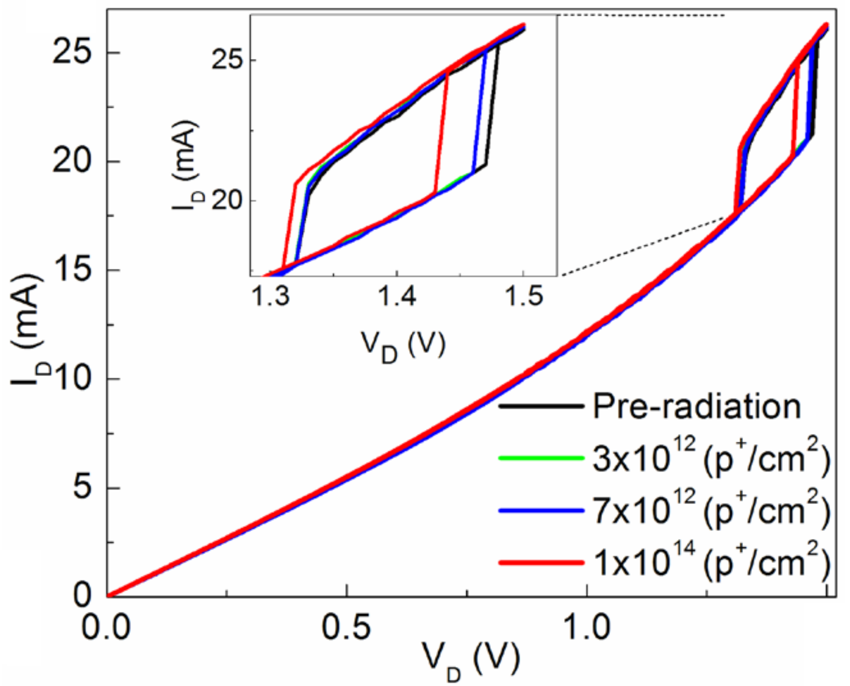


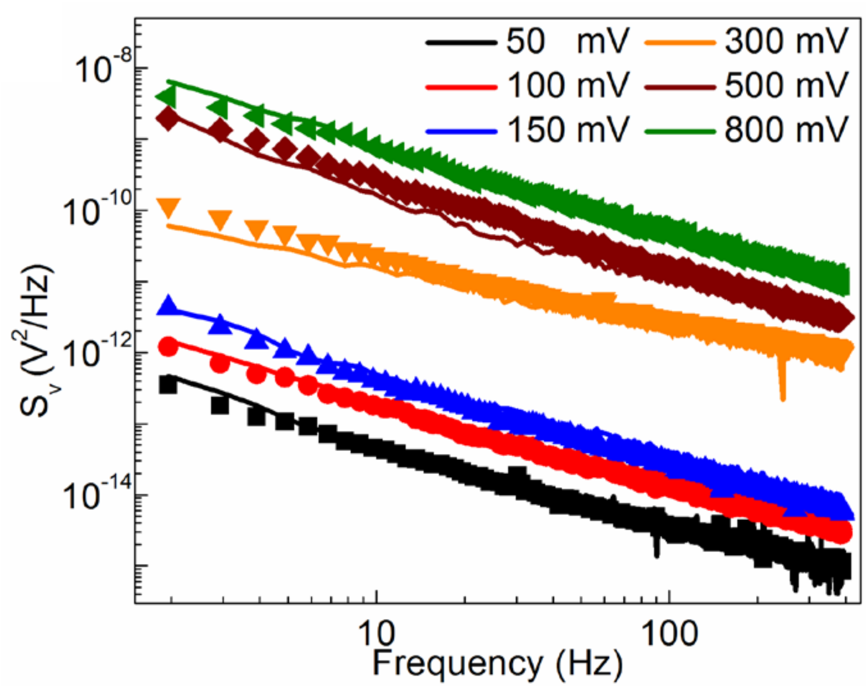
(a) Circuit schematic diagram of a self-sustaining oscillator implemented with one 1T-TaS_2 device and a load resistor.

(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 Effect on 1T-TaS_2 CDW Devices

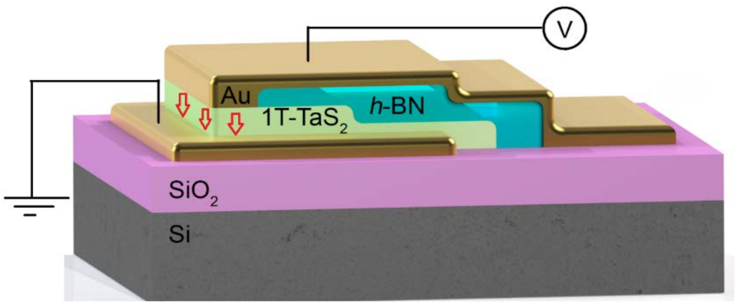


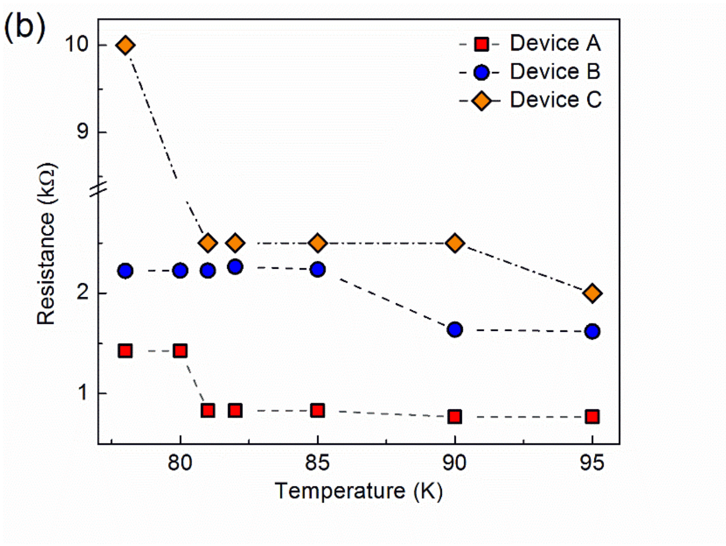


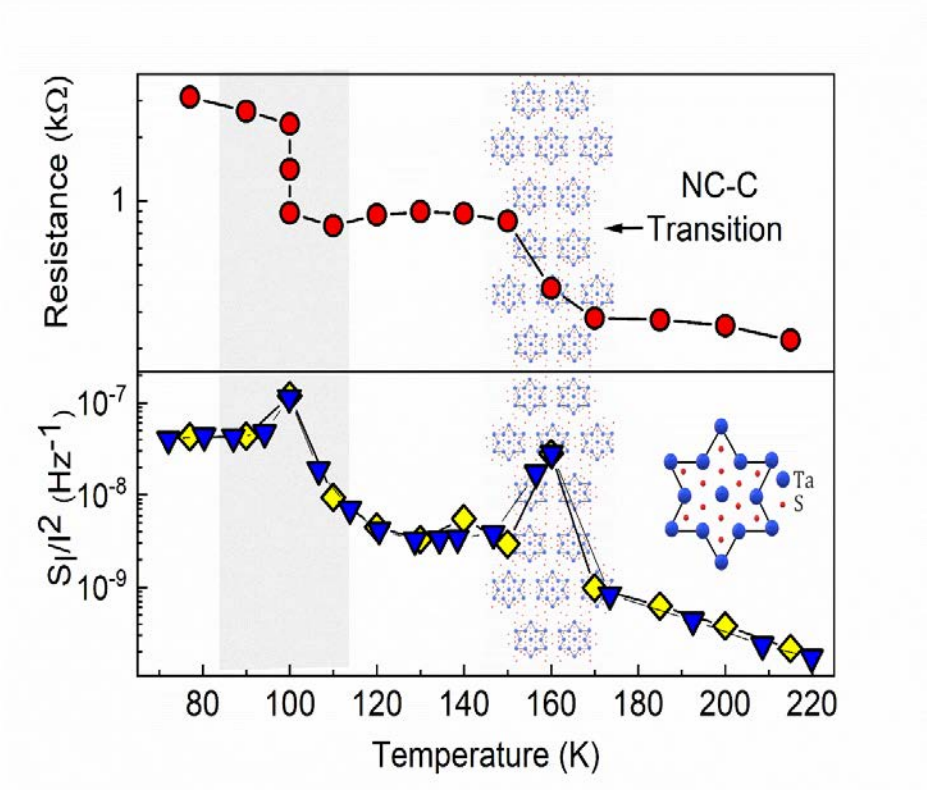
The quasi-two-dimensional (2D) 1T-TaS_2 channels show a *remarkable* immunity to bombardment with the high-energy 1.8 MeV protons to, at least, the irradiation fluence of 10^{14} H^+cm^{-2}.

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).

Vertical CDW Devices







R. Salgado, et al., "Low-frequency noise spectroscopy of charge-density-wave phase transitions in vertical quasi-2D 1T-TaS_2 devices," Applied Physics Express, vol. 18, no. 3, pp. 037001, 2019.

Conclusions

→ Voltage controlled NC-CDW to IC-CDW transition in two-dimensional 1T-TaS_2 channels can be utilized for switching at RT

→ Low-frequency noise spectroscopy is a powerful tool to investigate electronic transport phenomena in CDW material systems

→ No signatures of the “narrow band noise” in 2D CDW materials

→ Self-heating effects are important in 2D CDW materials

→ Radiation hardness of 2D CDW materials and devices

→ There are other 2D and 1D materials which may have superior CDW properties

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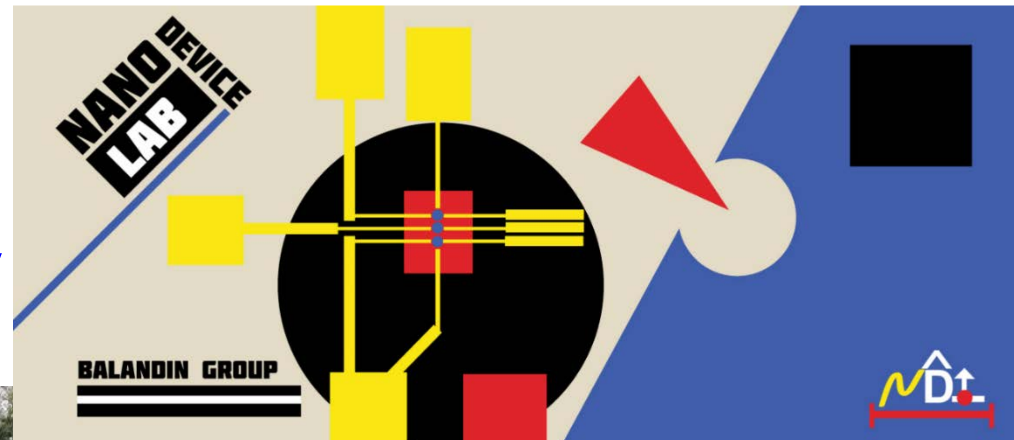
- Dr. Adane Geremew (Intel, Portland)
- Dr. Ruben Salgado (Intel, Portland)

Cooperation with Dr. Sergey Rumyantsev (Polish Academy of Sciences; formerly of Ioffe Institute, St. Petersburg, Russia)



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