An Integrated 1T-TaS_2 – h-BN – Graphene Oscillator: A Charge-Density-Wave Device Operating at Room Temperature

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A charge-density-wave oscillator based on an integrated tantalum disulfide–boron nitride–graphene device operating at room temperature

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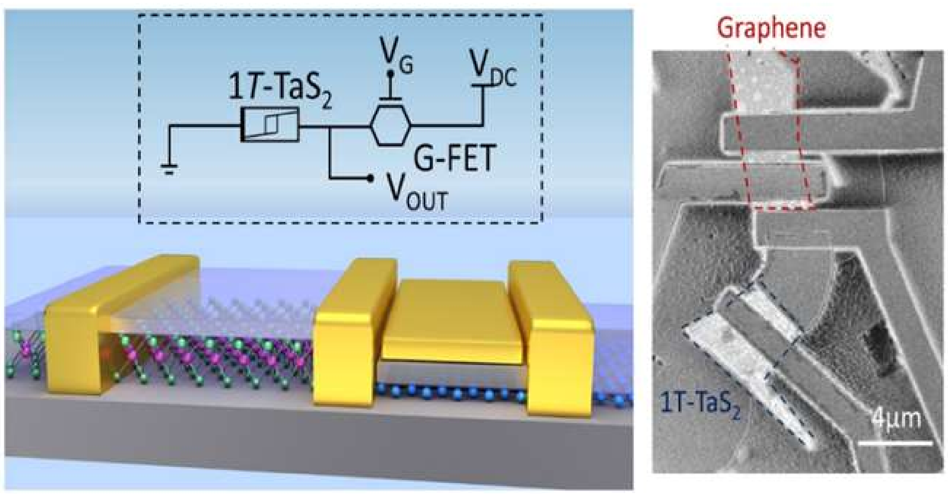
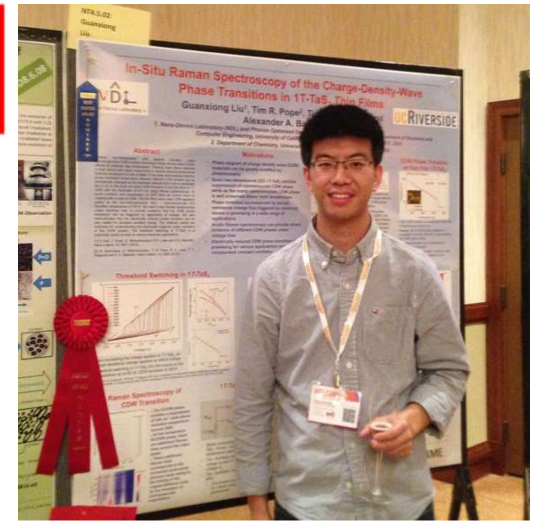
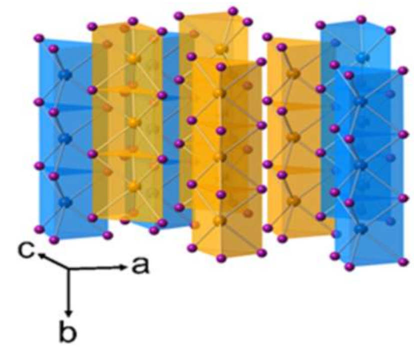


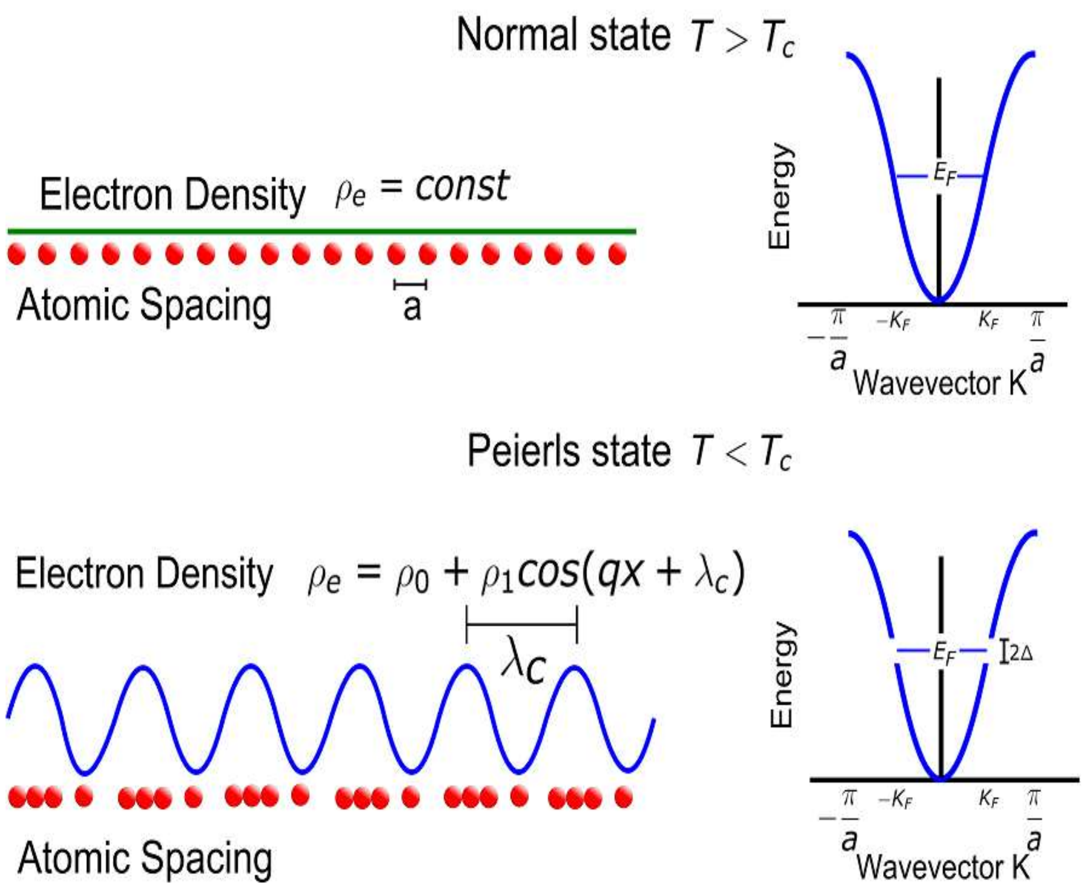


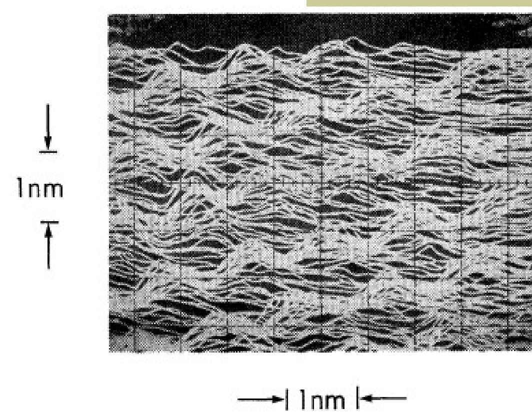
Dr. Guanxiong Liu
MRS Best Poster Award (2016)

From 2D to 1D Materials



Charge Density Waves: Basics

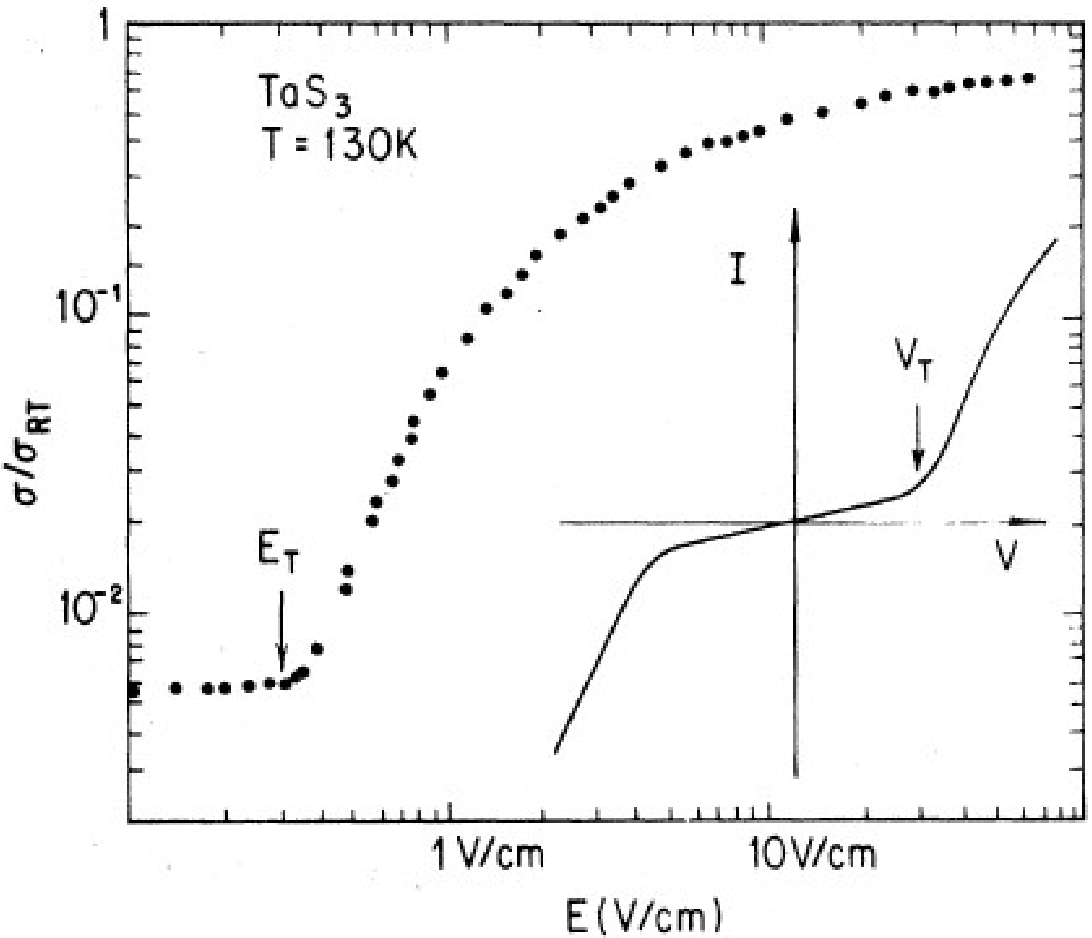




R.V. Coleman, *Phys. Rev. Lett.*, **55**, 394 (1985).

- →Macroscopic quantum phenomena: coherence length >1 μm
- →State variables: phase, frequency and amplitude can be used for information encoding and processing
- →Wavelength can be as small as ~ 1.4 nm

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).

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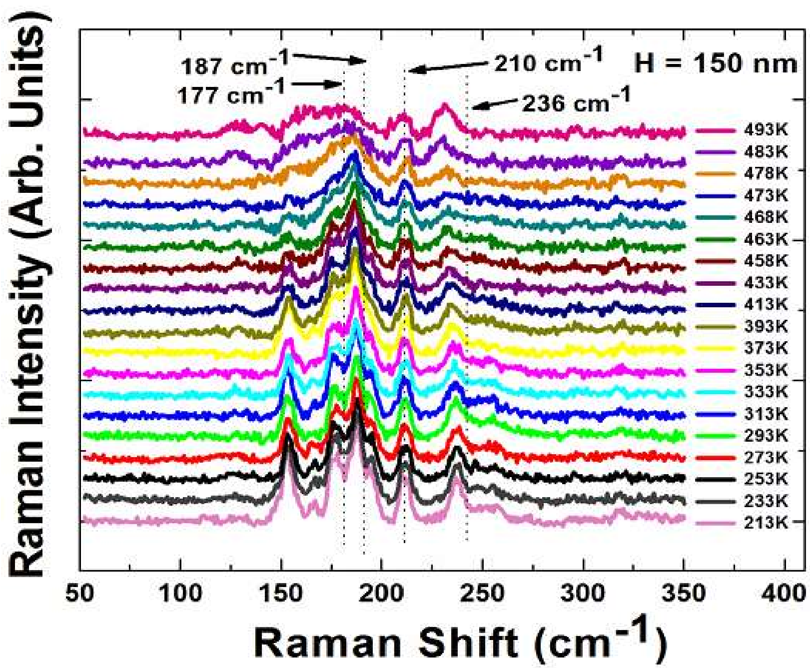
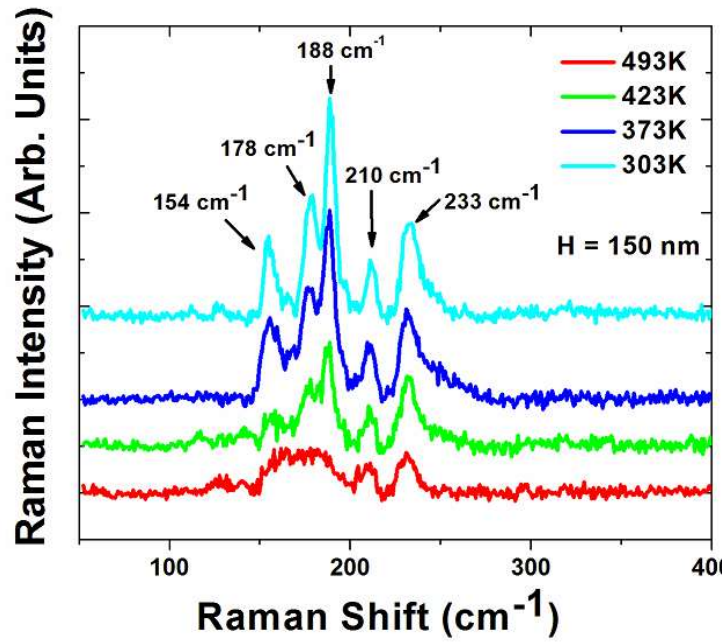
C-CDW – IC-CDW Transition in $TaSe_2$ Films

1T-$TaSe_2$

RT — Commensurate CDW — 473 K — Incommensurate CDW — 600 K — Normal Metal



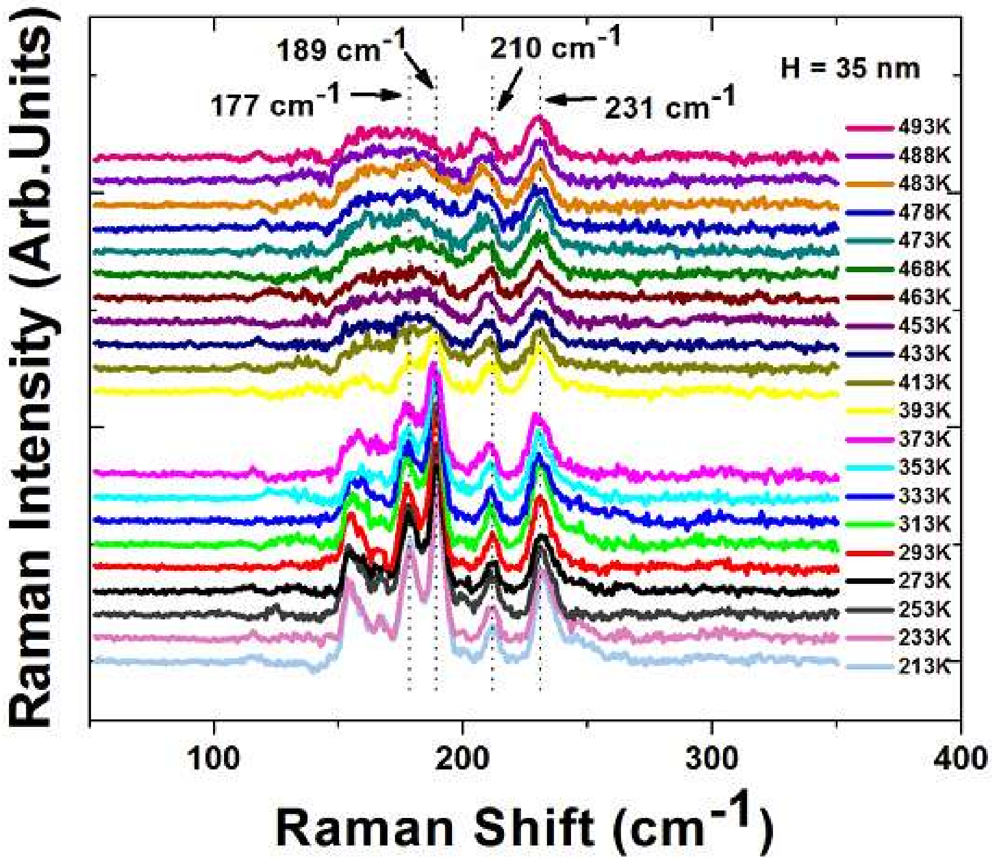


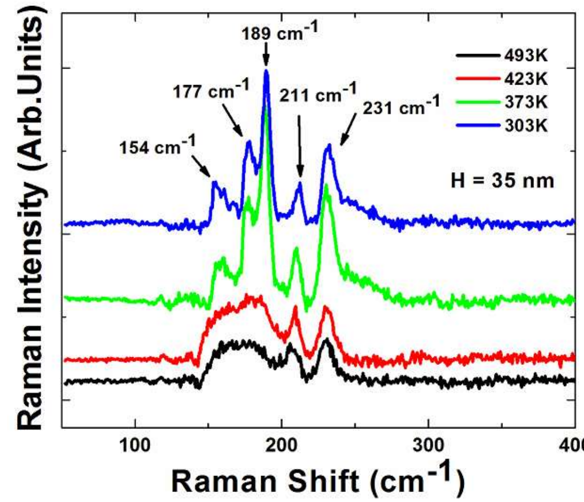
E_g and A_{1g} for 1T and 2H $TaSe_2$ + folded peak at 154 cm^{-1}

The measurements are performed in Ar atmosphere

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

Tuning Commensurate – Incommensurate CDW Transition Temperature

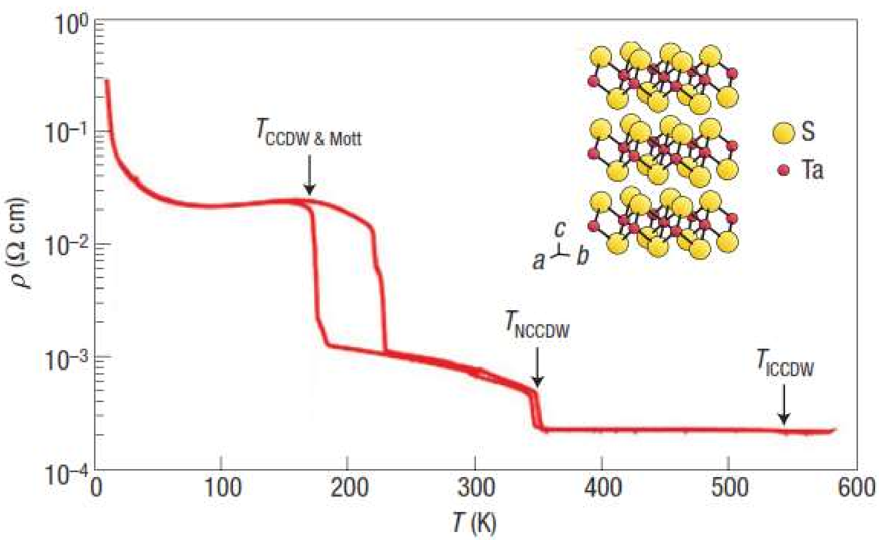




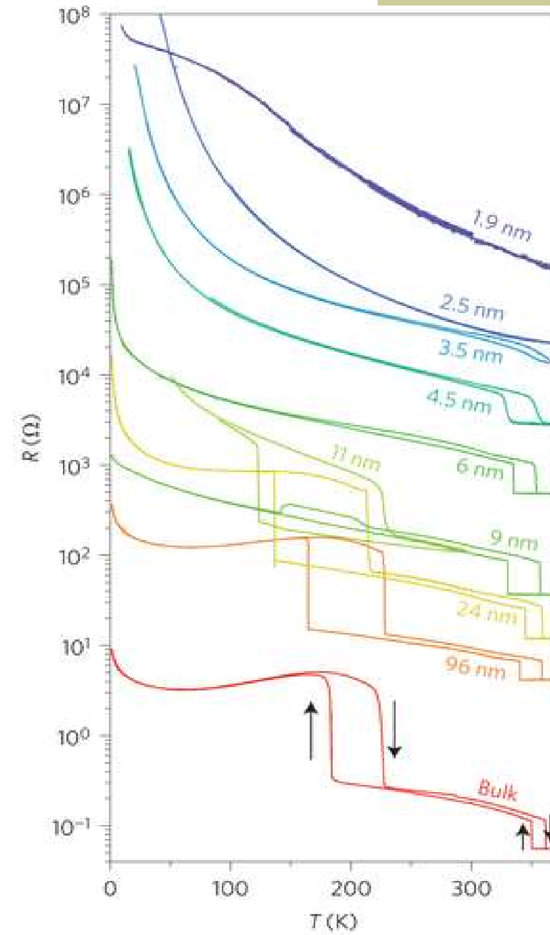
Sample Thickness (nm)	Transition Temperature (K)
150	468-473
41	403-423
35	393-413
18	~353

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

CDW Effects in 1T-TaS_2



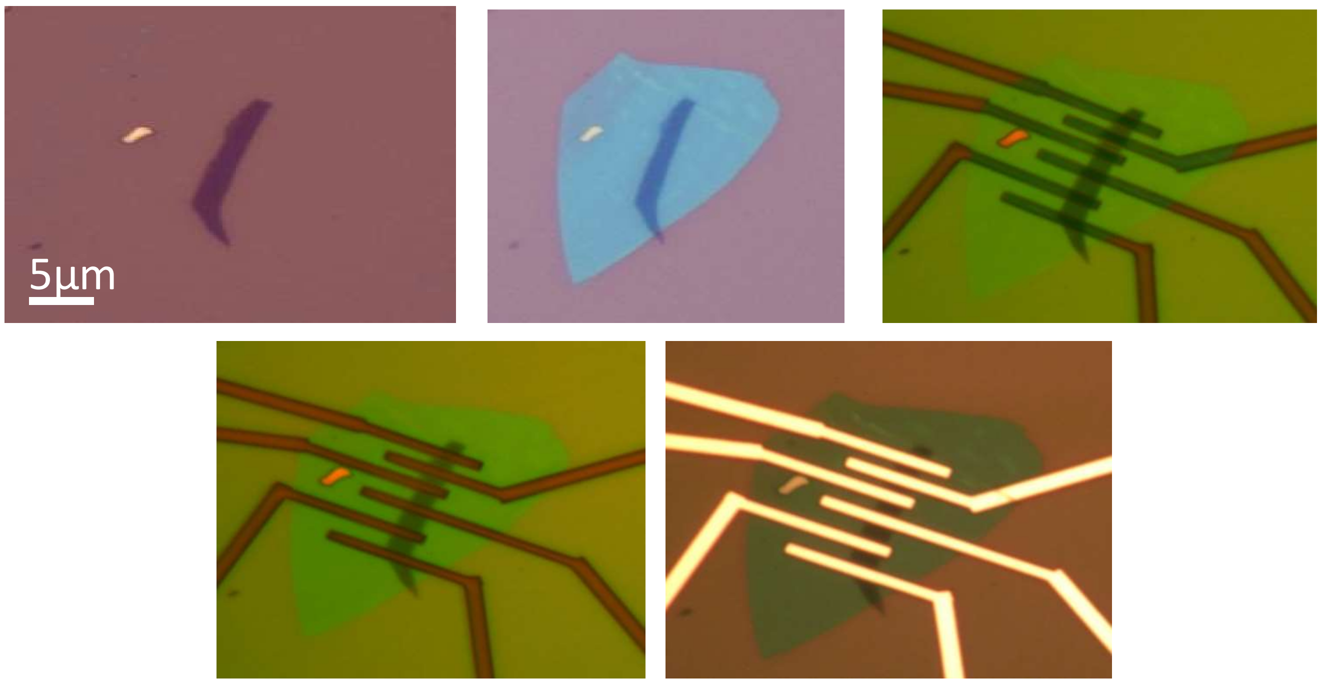
B. Sipos et al, Nature Mat., 7, 960 (2008)



Y. Yu et al, Nature Nanotech (2015)

→ 1T-TaS_2 experiences several CDW transitions
→ CDW phase transition is accompanied by an abrupt resistance change
→ C-CDW to NC-CDW transition (~180 K) appears in thick film but absent in thin films (H<9 nm)
→ NC-CDW to IC-CDW phase transition at 350-360 K is preserved as the thickness reduced

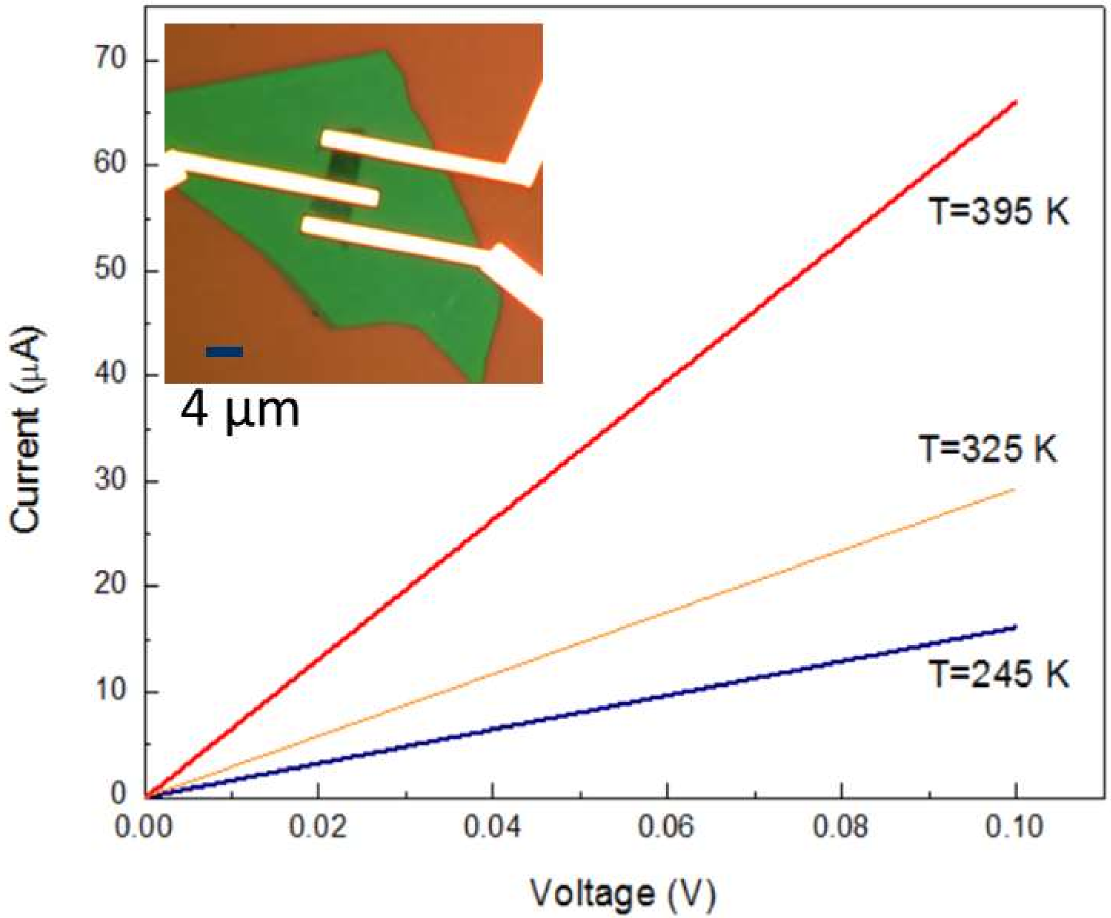
Boron Nitride Capping and Contacts



→ Hexagonal 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.

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

Boron Nitride Capping and Contacts



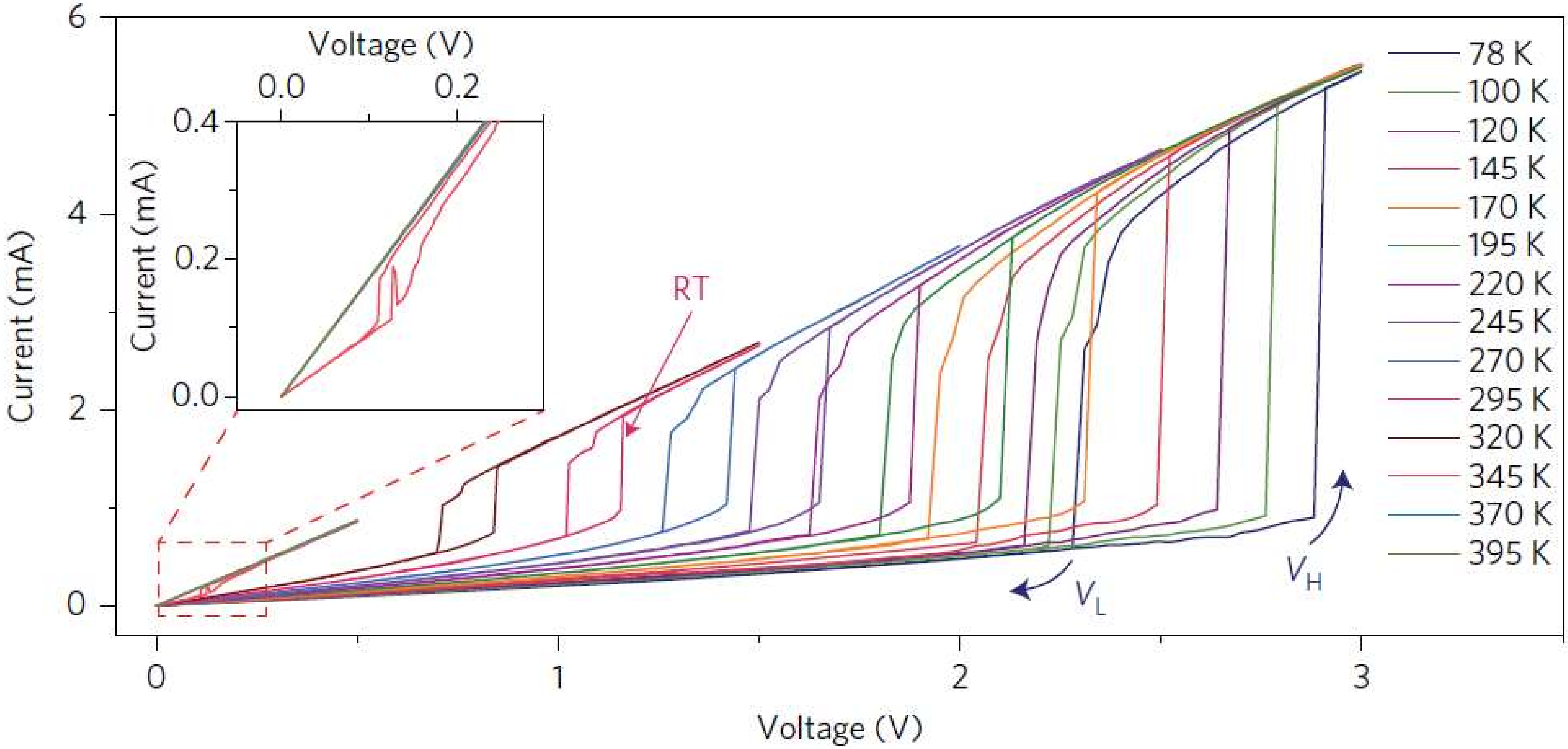
Channel thickness:
t = 6 nm - 9 nm

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

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

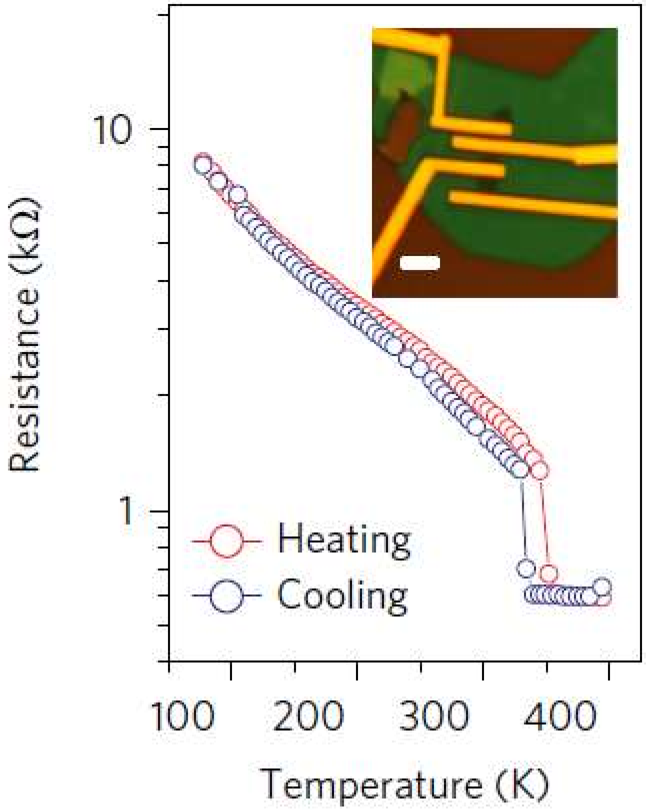
→ The edge contacts provide good Ohmic contacts to the 1T-TaS_2.

I-V Characteristics of Thin Film 1T-TaS_2



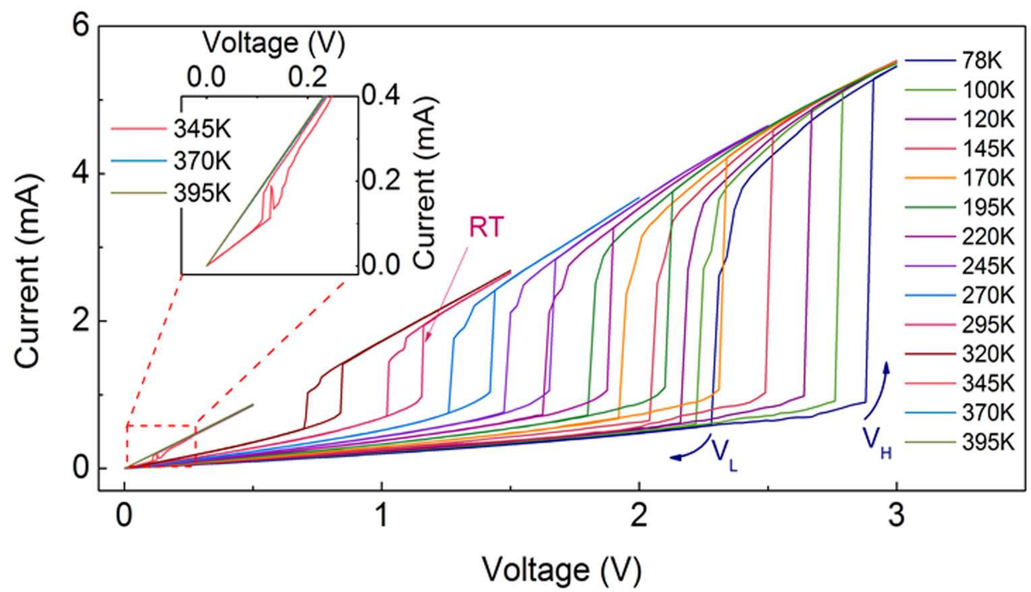
The threshold switching (TS) effect is prominent from 78 K to 320 K. The blues arrows indicate the voltage sweep direction for the measurement at 78 K. For all the other temperatures, V_H is always higher than V_L. The TS is prominent up to 320 K, and becomes less pronounced as the temperature approaches the NC-CDW–IC-CDW transition at 350 K. As shown in the inset, at 345 K (red curve), the TS is still measurable. As T exceeds 350 K, the IV becomes linear.

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



→ 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



No transition at 180 K

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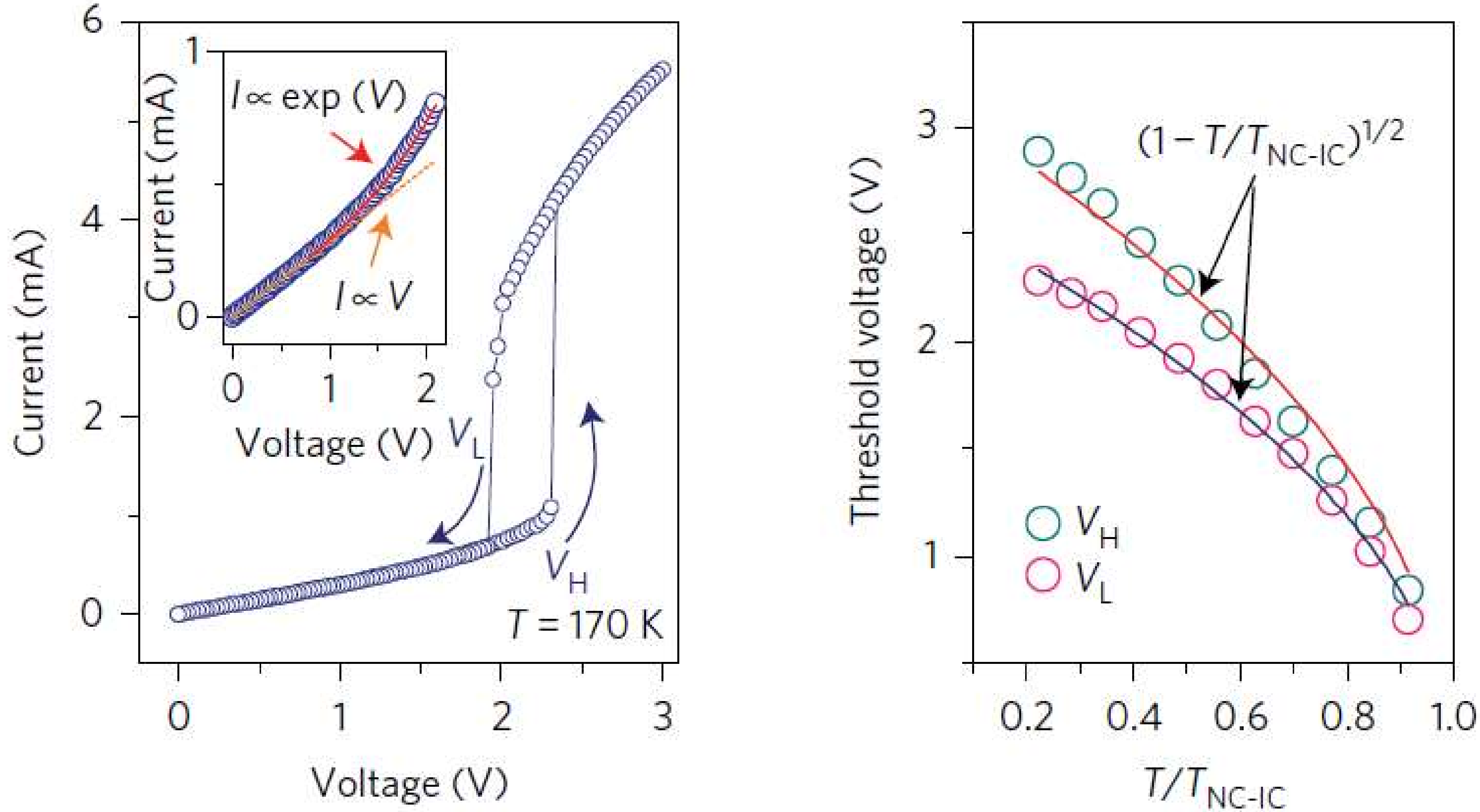
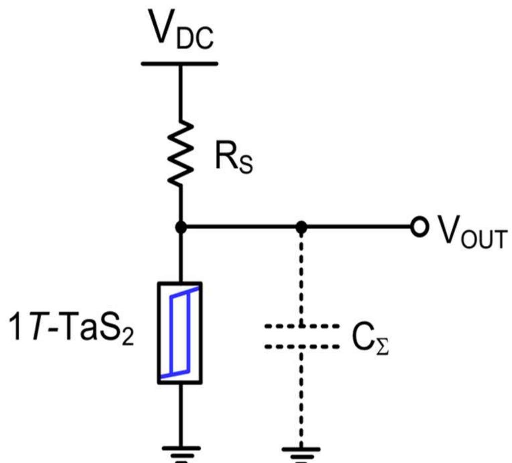
Additional Evidence of the NC-CDW–IC-CDW



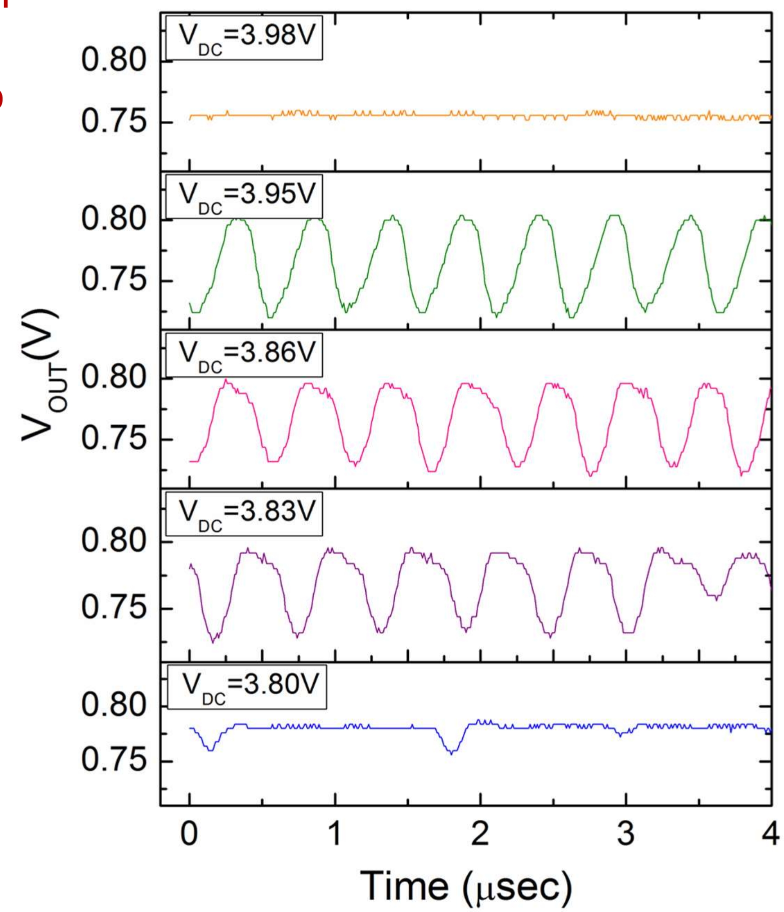
→ Super-linear current dependence on voltage and temperature dependence of the threshold voltage are consistent with the analytical theories of CDW effects.

Oscillator Based on 1T-TaS_2 Device



Different operation mechanism from early devices – no de-pinning

Allows for high T operation

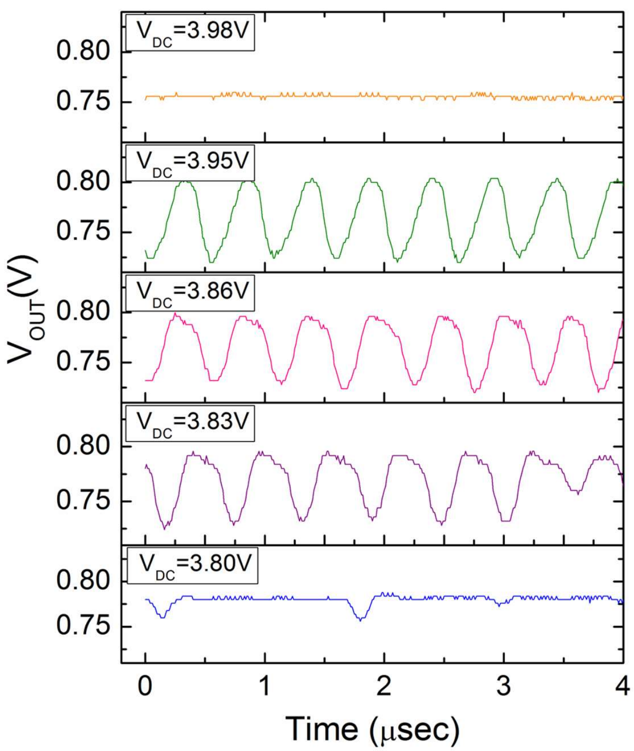


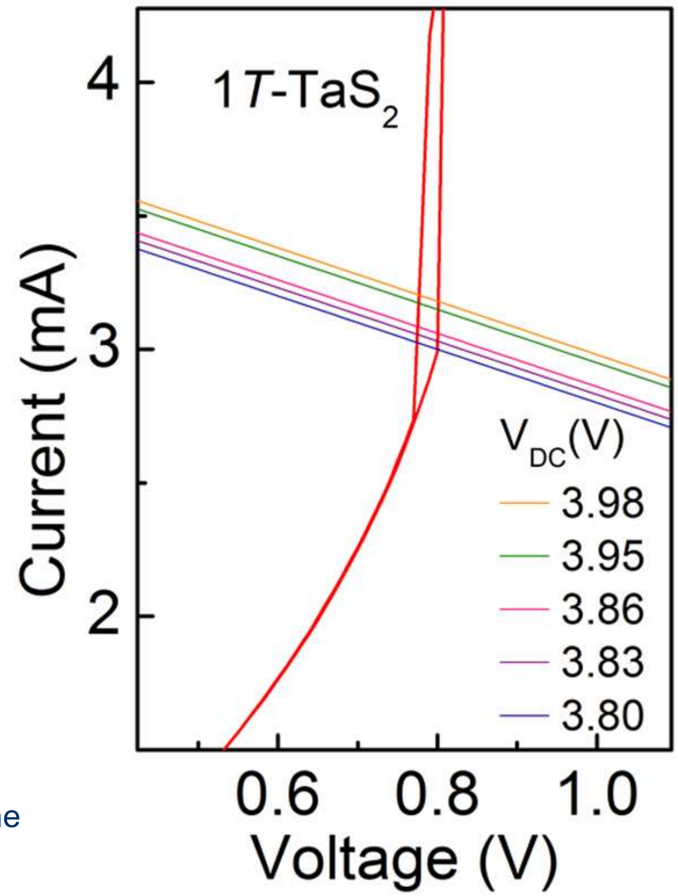
→Circuit schematic of the oscillator consists of the 1T-TaS_2 film, a series connected load resistor, and a lumped capacitance from the output node to ground. The load resistance is 1 kΩ.

→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.

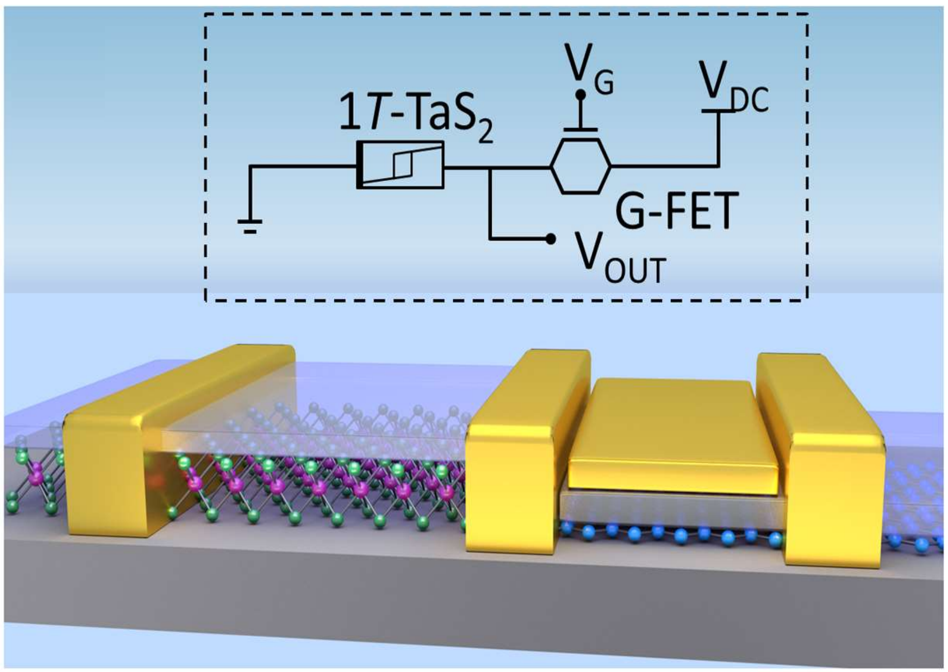
Oscillator Based on 1T-TaS_2 Device





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.

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



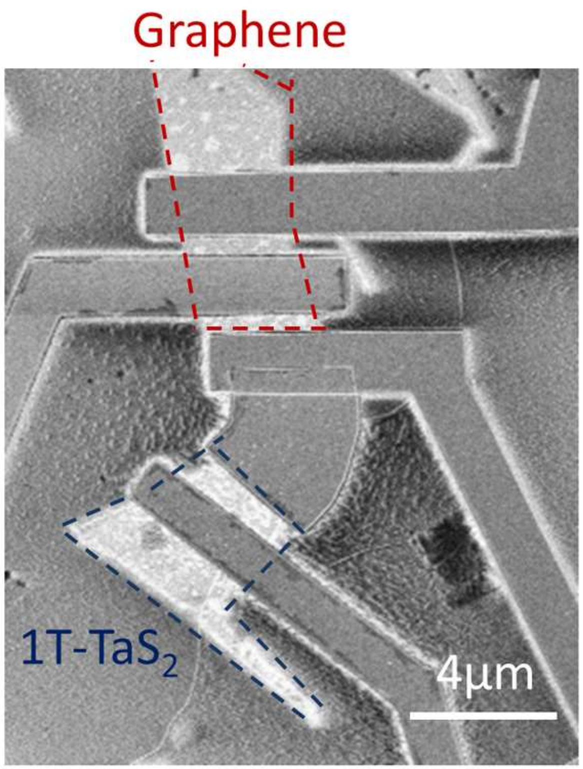
The device structure of the integrated oscillator consists of a graphene FET series connected to 1T-TaS_2.

Both the graphene and TaS_2 are fully covered with h-BN which acts as a protection layer against oxidation for the 1T-TaS_2 and as a gate dielectric for the G-FET.

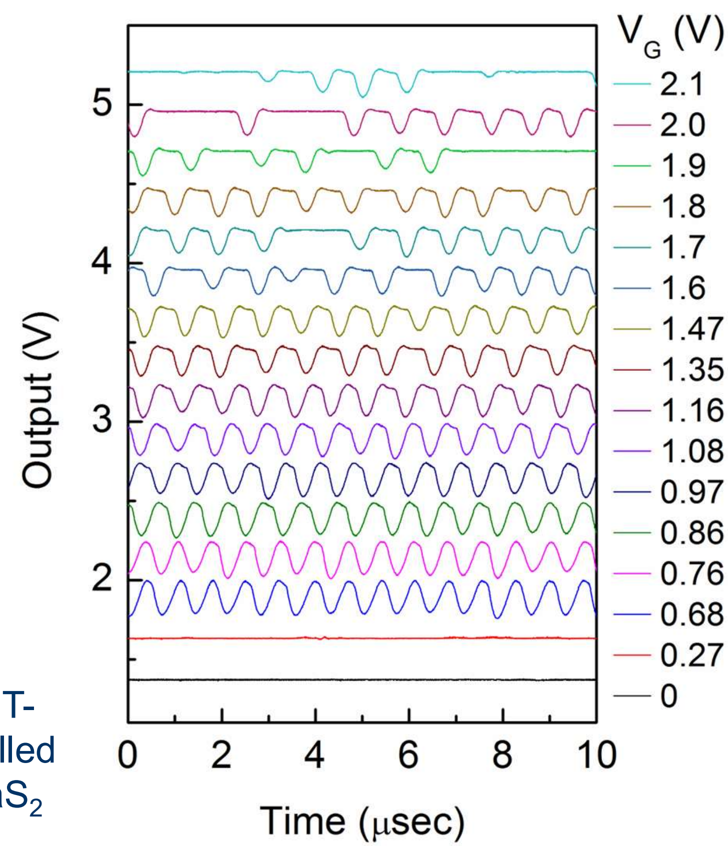
The equivalent circuit is shown in the inset. The V_{DC} bias is applied at the drain terminal of the G-FET and the V_G bias is connected to the gate terminal of G-FET.

Ground is connected to one terminal of 1T-TaS_2 device, while the common terminal of the two devices is the output port.

An Integrated $1T\text{-}TaS_2$ – h-BN – Graphene Oscillator

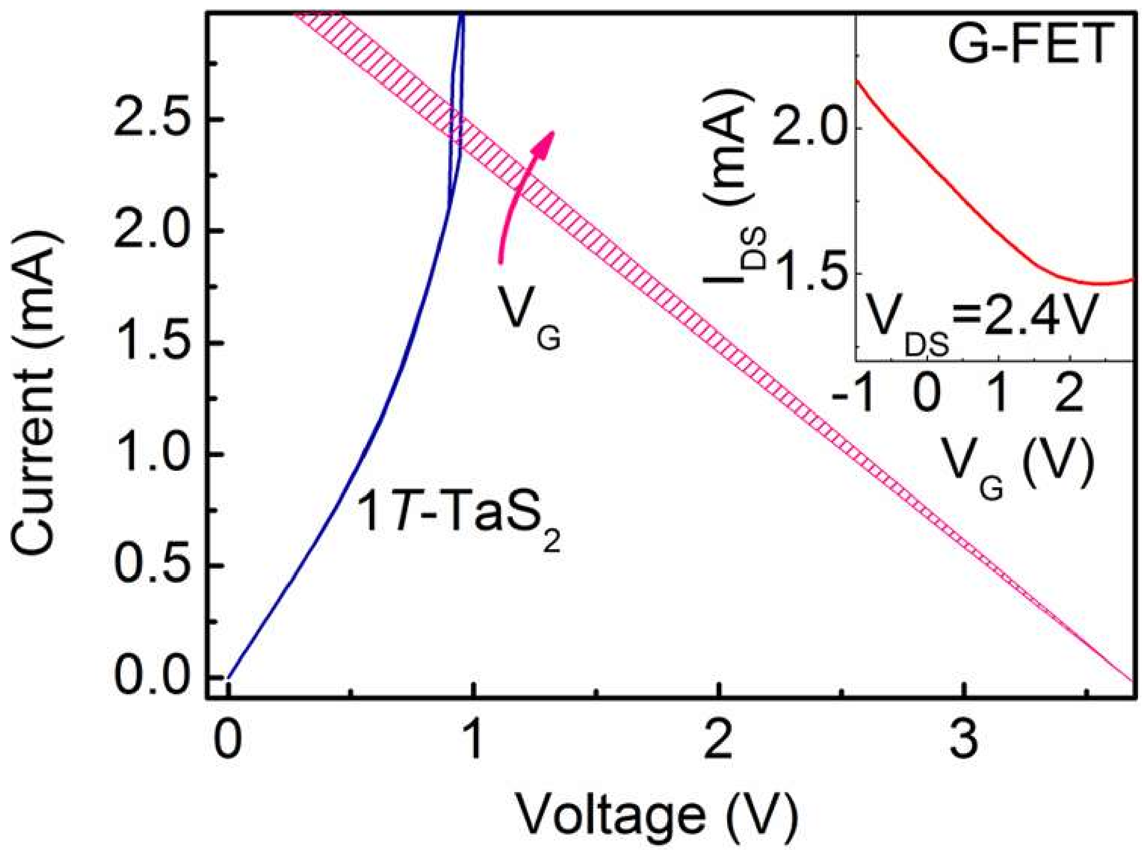


The SEM image of the integrated 1T-TaS_2–BN–graphene voltage controlled oscillator. The graphene and the TaS_2 are highlighted by dashed lines.



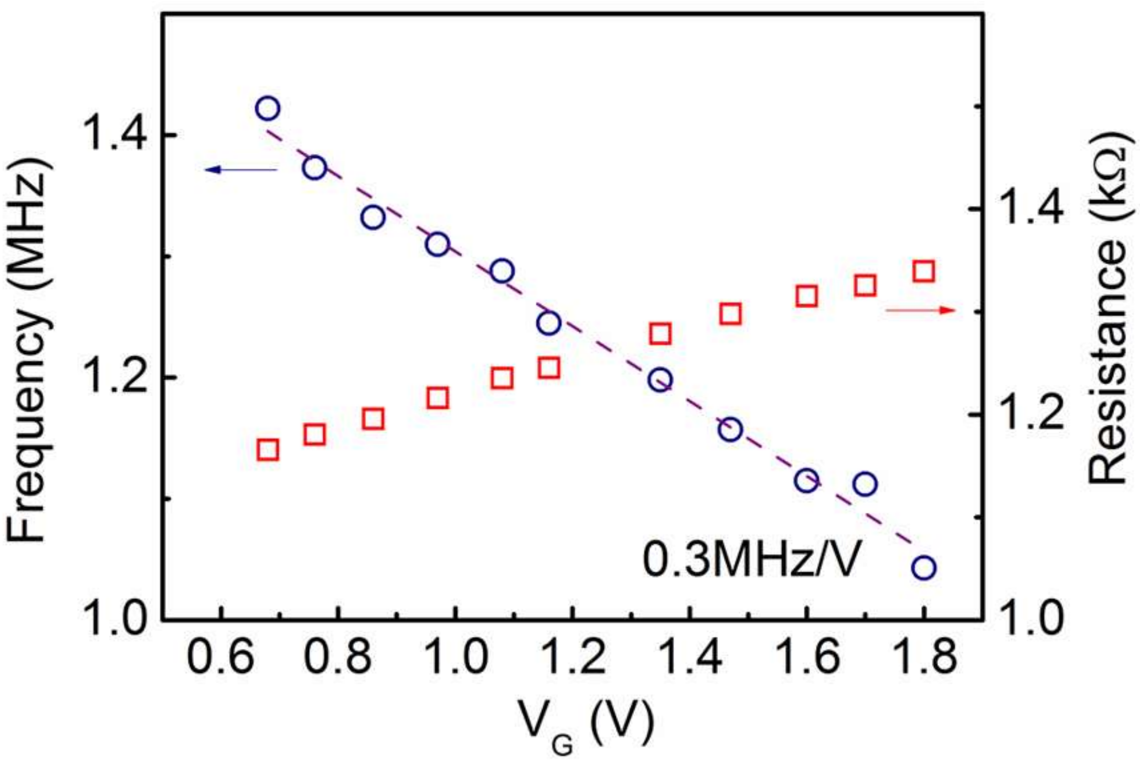
Output waveforms at different gate biases when V_{DC} is fixed at 3.65 V. The oscillation frequency is tunable with gate biases in the range of 0.68 V to 1.8 V. The different waveforms are vertically offset of 0.25 V for clarity.

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



The load line representing the resistance range of the G-FET intersects with the I-V of 1T-TaS_2 device. The arrow indicates the slope change of the load line with VG. The inset shows the transfer characteristic (I_{DS} - V_G) of G-FET under source drain bias at 2.4 V.

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



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.

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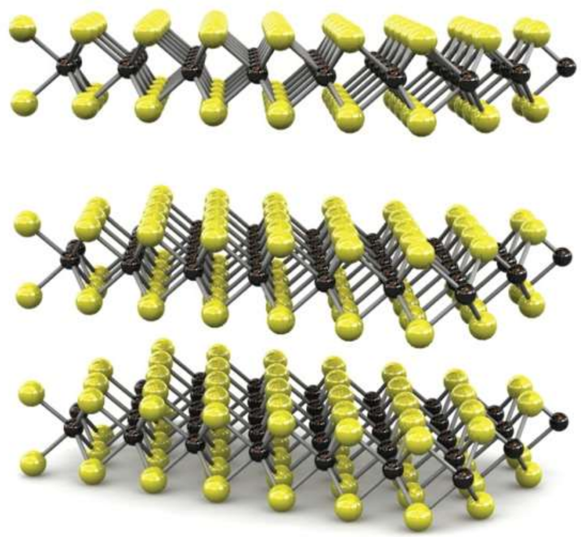
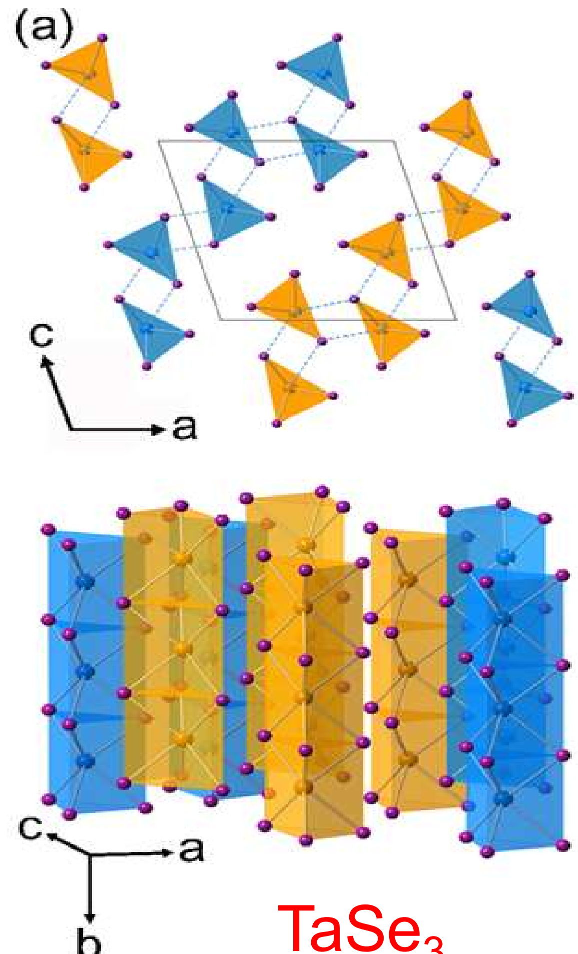
Fundamental Science Motivation: From Quasi-2D to Quasi-1D van der Waals Materials

Can we exfoliate Quasi-1D atomic threads like we do quasi-2D atomic planes?



MoS_2



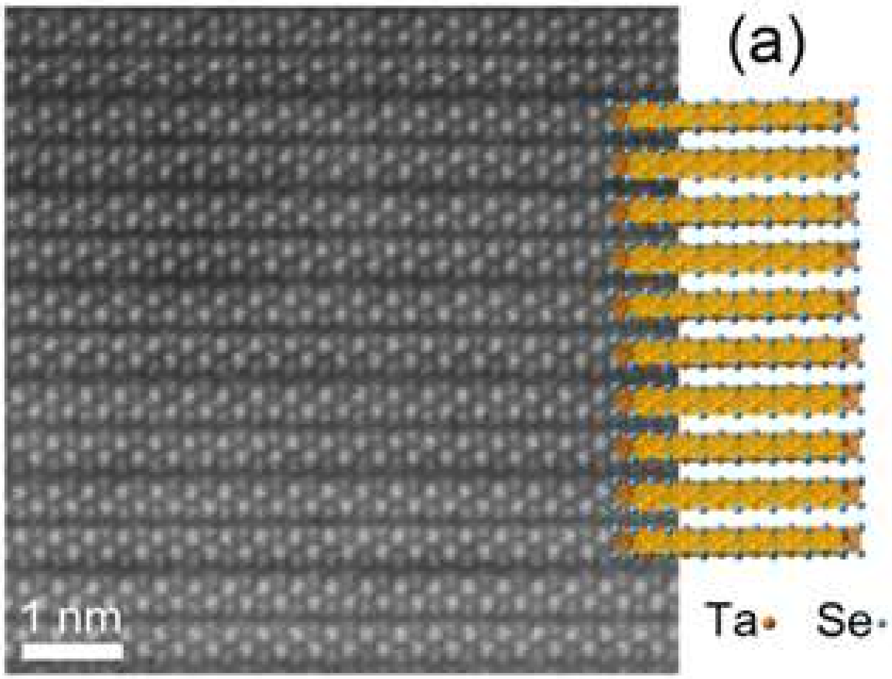
$TaSe_3$

→ Crystal structure of monoclinic $TaSe_3$, with alternating layers of $TaSe_3$

→ Cross section of the unit cell, perpendicular to the chain axis (b axis).

→ The side view: 1D nature of $TaSe_3$ chains along the b axis.

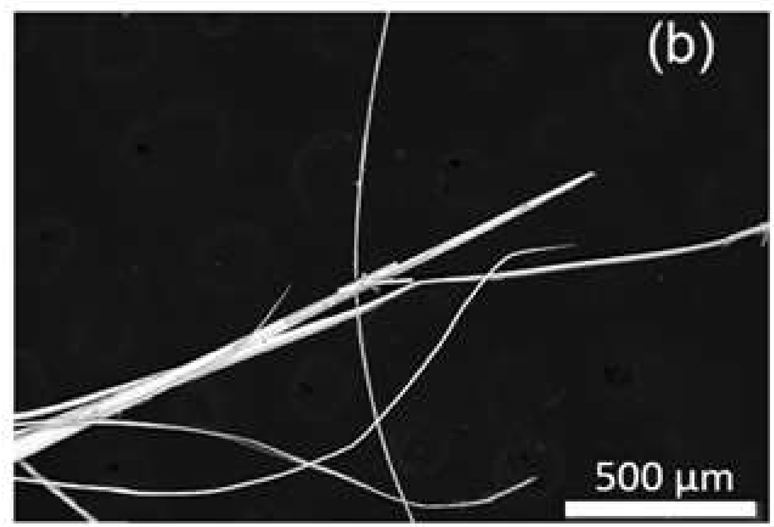
Quasi-1D Crystals Can be Mechanically and Chemically Exfoliated from Bulk $TaSe_3$



High resolution scanning transmission electron microscopy image of exfoliated $TaSe_3$ showing pristine metal trichalcogenide chains that extend along the b axis.

Collaboration:
Prof. Tina T. Salguero
University of Georgia

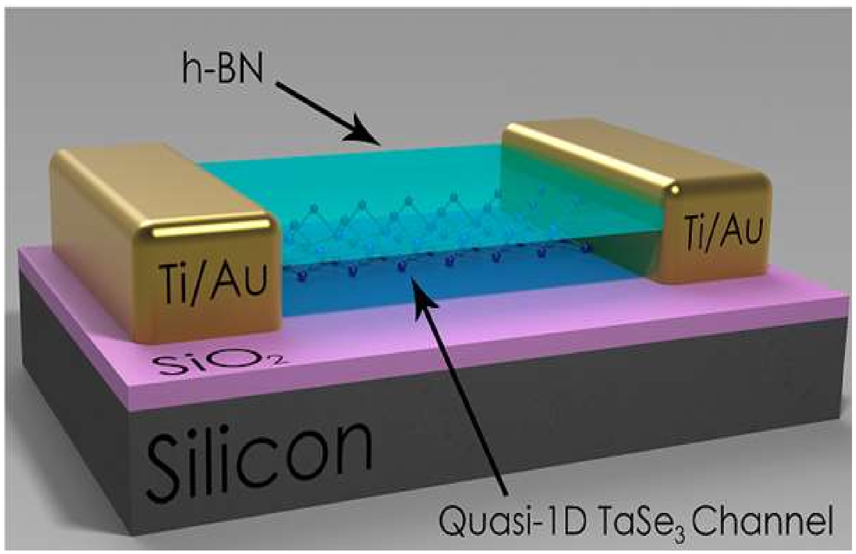
Chemical Vapor Transport (CVT) Method



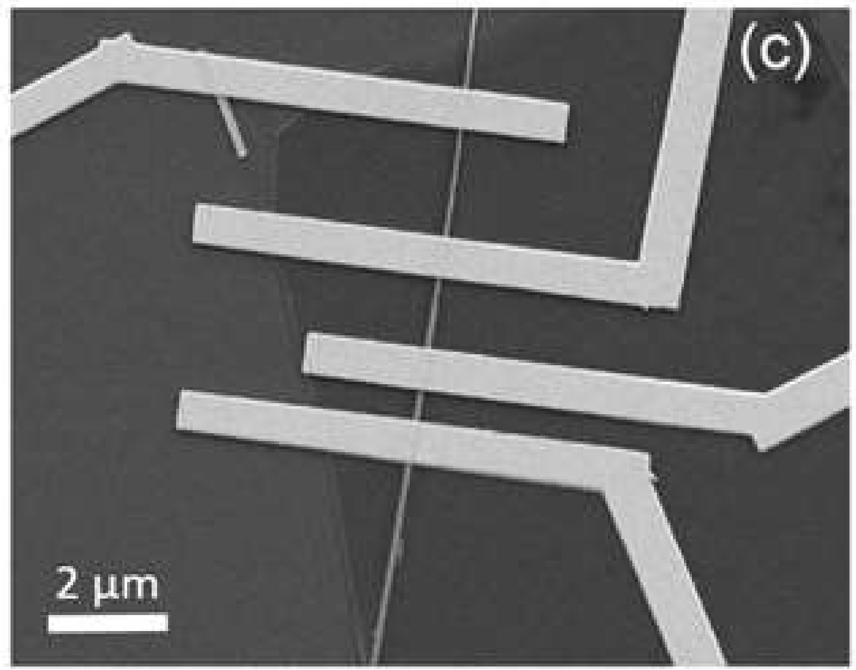
Scanning electron microscopy image of $TaSe_3$ crystals prepared by CVT method.

Boron Nitride Capped Devices with Quasi-1D $TaSe_3$ Channels

Boron Nitride capping is essential for device fabrication.



Schematic of the $TaSe_3$/h-BN quasi-1D / quasi-2D nanowire heterostructures used for the I-V testing.



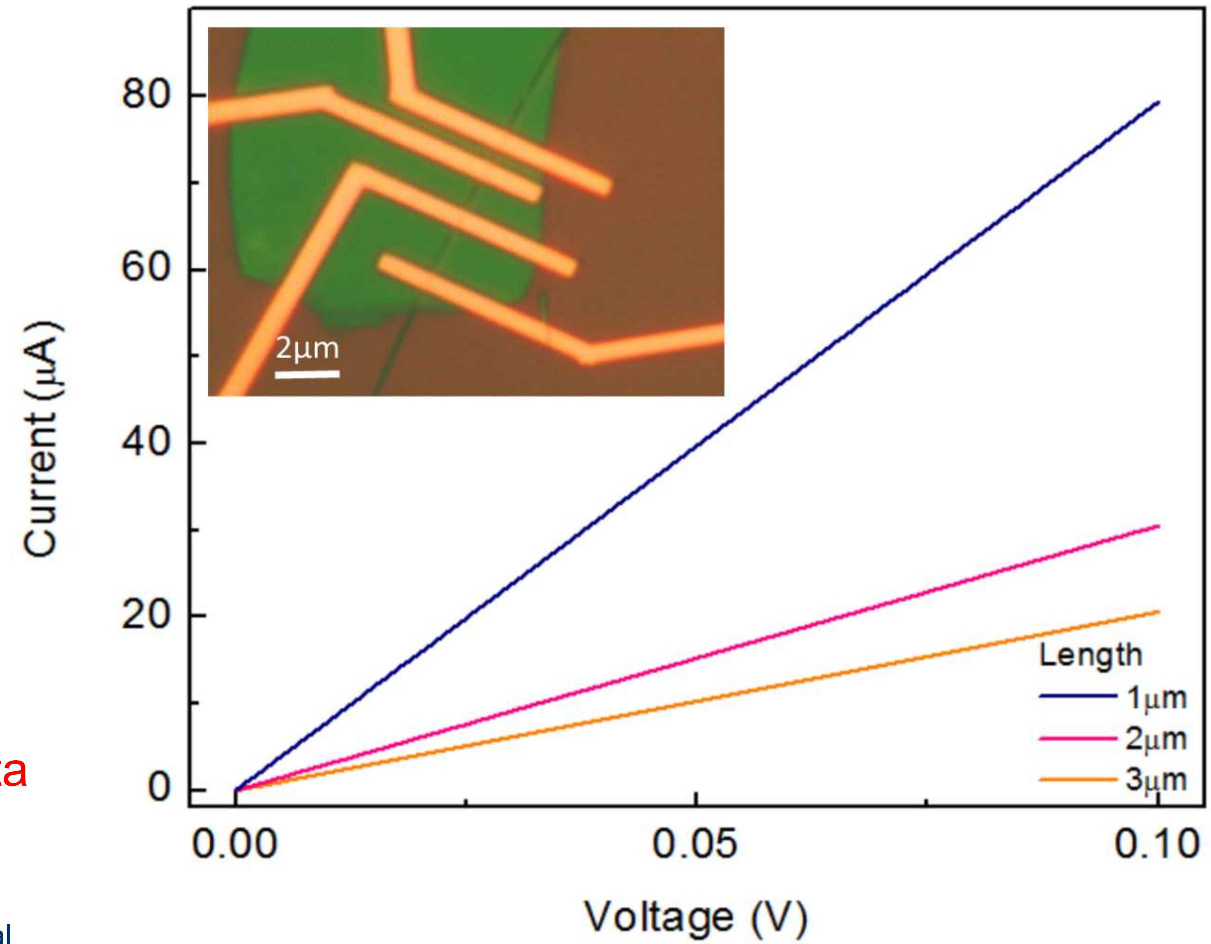
The metals tested for fabrication of Ohmic contacts included combinations of thin layers of Cr, Ti, Au, Pd together with a thicker Au layer.

Low-Field Electrical Characteristics of Devices with Quasi-1D $TaSe_3$ Channels

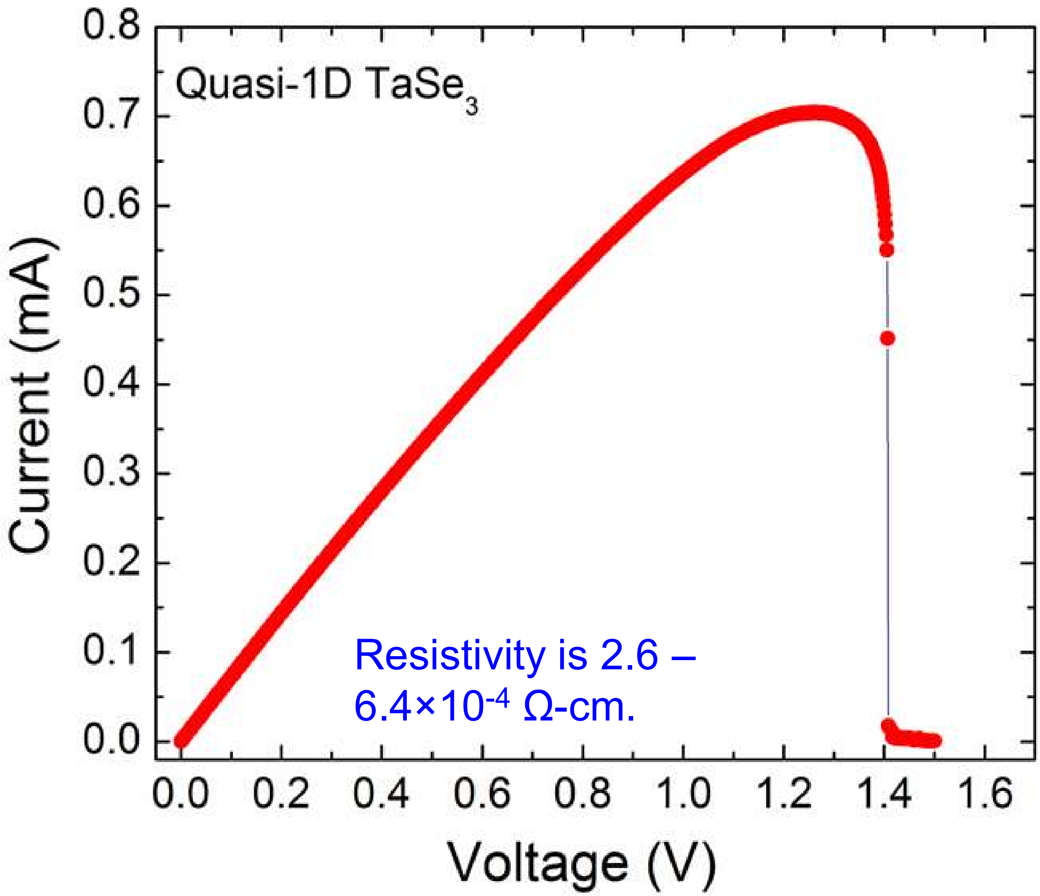
→ Current-voltage characteristics of $TaSe_3$ devices with different channel length.

→ Linear characteristics at low voltage indicates good Ohmic contact of $TaSe_3$ channel with the metal electrodes.

The contact resistance extracted from TLM data is $2R_C$=22 Ω-µm



Current Density in Quasi-1D $TaSe_3$ Nanowires

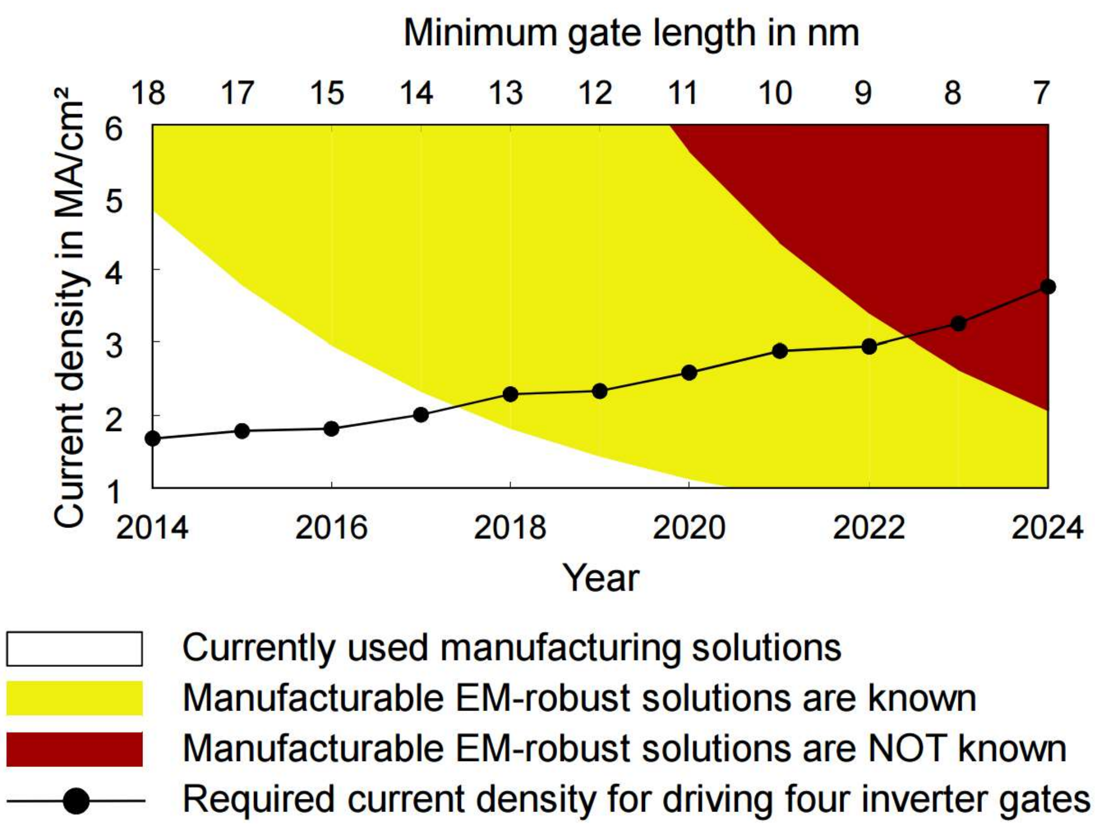


→ High-field I-V characteristics showing the breakdown point. In this specific device the breakdown is gradual.

→ Breakdown current density of about 32 MA/cm^2 — an order-of-magnitude higher than that for copper.

M.A. Stolyarov, G. Liu, M.A. Bloodgood, E. Aytan, C. Jiang, R. Samnakay, T.T. Salguero, D.L. Nika, S.L. Rumyantsev, M.S. Shur, K.N. Bozhilove and A.A. Balandin, Breakdown current density in h-BN-capped quasi-1D $TaSe_3$ metallic nanowires: prospects of interconnect applications, *Nanoscale*, **8**, 15774 (2016)

Practical Motivations for Quasi-1D Metals: Search of New Interconnect Materials



According to ITRS:

→ Current density ~1.8 MA/cm^2 at the half-pitch width of 28.5 nm will increase to ~5.35 MA/cm^2 at the width of 7 nm.

→ There is no existing technology with the breakdown current density high enough to sustain such currents.

→ The layer thicknesses will decrease from 57.0 nm in 2016 to 15.4 nm by 2028

Conclusions

→ Voltage controlled NC-CDW to IC-CDW transition in two-dimensional 1T-TaS_2 channels utilized for switching.

→ An integrated graphene transistor provides a voltage tunable, matched, low-resistance load, enabling precise voltage control of the oscillator frequency.

→ Hexagonal boron nitride capping of 1T-TaS_2 provides protection from oxidation.

→ Low capacitance, low resistivity, small intrinsic time constants → intrinsic RC-limited frequency is in THz regime.

→ Quasi-2D van der Waals Materials are not the limit: Quasi-1D can also be interesting and useful

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