# Thermal and Electrical Properties of Quasi-1D van der Waals Nanowires


**CNF Project Number: 2698-18**

**Principal Investigator(s): Deyu Li**

**User(s): Yang Zhao, Lin Yang**

*Affiliation(s): Department of Mechanical Engineering, Vanderbilt University*


*Primary Source(s) of Research Funding: National Science Foundation*

*Contact: deyu.li@vanderbilt.edu, yang.zhao@vanderbilt.edu, lin.yang@vanderbilt.edu*

*Primary CNF Tools Used: Heidelberg mask writer DWL2000, Autostep i-line stepper, LPCVD Nitride - B4, GSI PECVD, AJA sputter deposition, AJA ion mill*


## Abstract:

**Using the CNF cleanroom, we have successfully fabricated microdevices for nanowire electrical and thermal conductivity measurements. These microdevices allow for experimental studies of the transport properties of various types of van der Waals nanowires, including $NbSe_3$ and $Ta_2NiSe_5$. Interesting observations such as record long ballistic phonon transport in $NbSe_3$ nanowires have been obtained. Systematic studies are being conducted to understand the underlying physical mechanisms.**


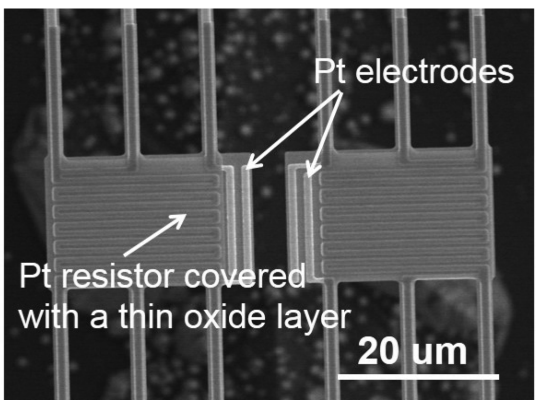


*Figure 1: A scanning electron microscopy (SEM) image of the microdevice consisting of two suspended membranes integrated with serpentine Pt coils as both resistance heaters and thermometers for transport property measurements of individual nanowires.*

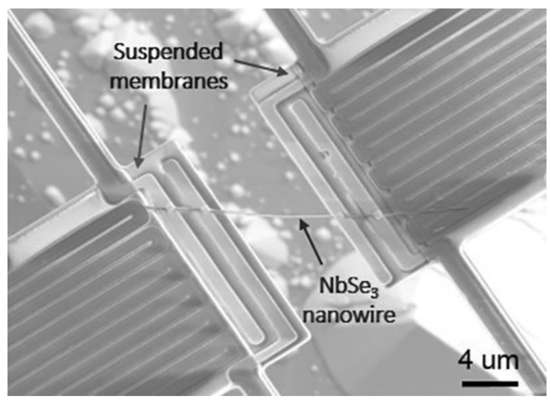


*Figure 2:An SEM micrograph of an individual 135 nm-diameter $NbSe_3$ nanowire placed between the two suspended membranes.*

## Summary of Research:

Two Ph.D. students, Yang Zhao and Lin Yang have been trained and used CNF cleanroom facilities to fabricate microdevices as shown in Figure 1. The microdevice consists of two side-by-side suspended $SiN_x$ membranes integrated with serpentine Pt coils serving as both resistance heaters and thermometers. Yang Zhao made three trips to CNF and spend a total of about five weeks to fabricate the devices while Lin Yang only joined the first trip and spent about ten days at CNF.

The nanofabrication process involves LPCVD $SiN_x$ film growth, sputtering deposition of Pt films, PECVD $SiO_2$ film deposition, photolithography and etching, and the students have got extensive experience of using various nanofabrication tools to prepare the microdevices. In about half year time frame, the students have successfully fabricated a few wafers of devices, which have been used to measure the electrical and thermal conductivities of $NbSe_3$ and $Ta_2NiSe_5$ nanowires.

To measure the electrical and thermal properties of nanowires, individual nanowire samples are placed to bridge the two suspended membranes as shown in Figure 2. The device is then put into a cryostat for electrical and thermal transport measurements, during which one suspended membrane is heated up by resistance Joule heating and a portion of the heat is transferred to the other suspended membrane. Through monitoring the resistance change of the Pt coils, the temperature of both membranes can be simultaneously obtained. This allows for extraction of the thermal conductivity of the nanowire. In addition, the four extra Pt electrodes at the inside of the two membranes allow for four-point measurements of the nanowire electrical conductivity.

Our group has used this approach to conduct extensive measurements of various nanowires, nanotubes and nanoribbons. To date, the newly fabricated microdevices have been adopted to study thermal properties of two kinds of van der Waals nanowires made of $NbSe_3$ and $Ta_2NiSe_5$. van der Waals nanowires are a class of materials composed of covalently bonded molecular chains assembled together via weak van der Waals interactions, which renders interesting electrical and thermal transport properties as demonstrated by some of our recent studies [1,2].

For example, the measured thermal conductivity of a 135 nm-diameter $NbSe_3$ nanowire is displayed in Figure 3 together with the contributions from both electron and phonon as energy carriers. $NbSe_3$ nanowires demonstrate two spontaneous charge density waves (CDW) as the temperature drops to 145 K and 59 K, respectively, which correspond to condensation of a large portion of free electrons and lead to variations in their electrical conductivity and electron contribution to the thermal conductivity. The unusual peaks in the lattice thermal conductivity are attributed to electron-phonon scattering, which provide direct and unambiguous evidence for the importance of electron-phonon scattering in lattice thermal transport, which has been lacking so far. In addition, we have used the newly fabricated devices to probe ballistic transport of phonons in $NbSe_3$ nanowires and observed record long ballistic transport distance and currently we are probing the underlying physical mechanisms for this unexpected ballistic phonon transport.

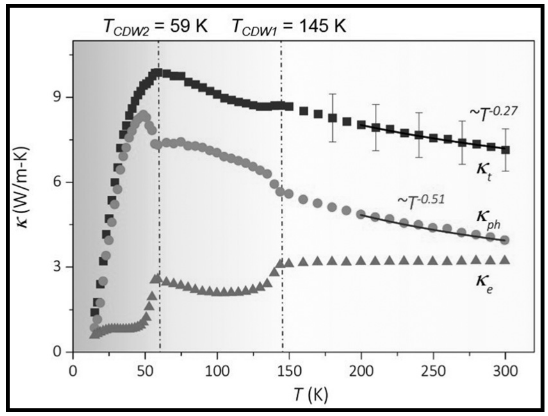


*Figure 3: Distinct signatures of electron-phonon scattering in the lattice thermal conductivity of a 135 nm-diameter $NbSe_3$ nanowire in the temperature range of 15-300 K. The electron and phonon contributions are labelled as $\kappa_e$ and $\kappa_{ph}$, respectively, and the total thermal conductivity is denoted as $\kappa_t$.*

## References:


[1] Q. Zhang, C. Liu, X. Liu, J. Liu, Z. Cui, Y. Zhang, L. Yang, Y. Zhao, T. T. Xu, Y. Chen, J. Wei, Z. Mao, and D. Li, "Thermal Transport in Quasi-1D van der Waals Crystal $Ta_2Pd_3Se_8$ Nanowires: Size and Length Dependence," ACS Nano 12, 2634-2642 (2018).

[2] L. Yang, Y. Tao, J. Liu, C. Liu, Q. Zhang, M. Akter, Y. Zhao, T. T. Xu, Y. Xu, Z. Mao, Y. Chen, and D. Li, "Distinct Signatures of Electron-Phonon Coupling Observed in the Lattice Thermal Conductivity of $NbSe_3$ Nanowires," Nano Lett. 19, 415-421 (2019).