

Low-Frequency Noise in Low-Dimensional van der Waals Materials

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Abstract – The emergence of graphene and two-dimensional van der Waals materials renewed interest to investigation of the low-frequency noise in the low-dimensional systems. The layered van der Waals materials offers unique opportunities for studying the low-frequency noise owing to the properties controlled by the thickness of these materials, and tunable carrier concentration. In this review, we describe unusual low-frequency noise phenomena in quasi-2D and quasi-1D van der Waals materials. We also demonstrate that the low-frequency noise spectroscopy is a powerful tool for investigation of the electron transport and charge-density-wave phase transitions in this class of materials.

Keywords – low-frequency noise, charge density waves, van der Waals materials, 2D materials, 1D materials

I. INTRODUCTION

The emergence of graphene and two-dimensional (2D) *van der Waals* materials renewed interest to investigation of the low-frequency noise in the low-dimensional systems [1-3]. This type of materials offers unique opportunities for studying the low-frequency noise phenomena owing to their properties, controlled by the film thickness, and their widely tunable charge carrier concentration. Practical applications depend on the ability to understand and reduce the noise in this new type of materials. From the other side, these materials offer new opportunities for addressing the fundamental problems of noise and fluctuations.

II. NOISE IN GRAPHENE

The first material of this class – graphene – revealed a number of interesting properties in the context of $1/f$ noise owing to its 2D nature, unusual linear energy dispersion for electrons and holes, zero-energy bandgap, specific scattering mechanisms and metallic-type conductance [1-15]. From one side, graphene is an ultimate surface where conduction electrons are exposed to the traps, e.g. charged impurities in a substrate or on its top surface, which can result in strong carrier-number fluctuations. From the other side, graphene can be considered a zero-bandgap metal, where mobility fluctuations resulting from the charged scattering centers in the substrate or surface can also make a strong contribution to $1/f$ noise. The ability to change the thickness of few-layer graphene conductors by one atomic layer at a time opened up opportunities for examining surface and volume contributions to $1/f$ noise directly [14-15]. Independent studies have shown that noise in graphene reveals an unusual gate-bias dependence [5-13]. In the vicinity of the Dirac point, the noise amplitude follows a V-shape dependence, attaining its

minimum at the Dirac point where the resistance is at its maximum [10]. The unusual gate dependence of the noise amplitude in graphene supported the conclusion that $1/f$ noise in graphene devices does not follow the conventional McWhorter model used for complementary metal-oxide-semiconductor (CMOS) devices and other metal-oxide-semiconductor field-effect transistors (MOSFETs) (see Figure 1).

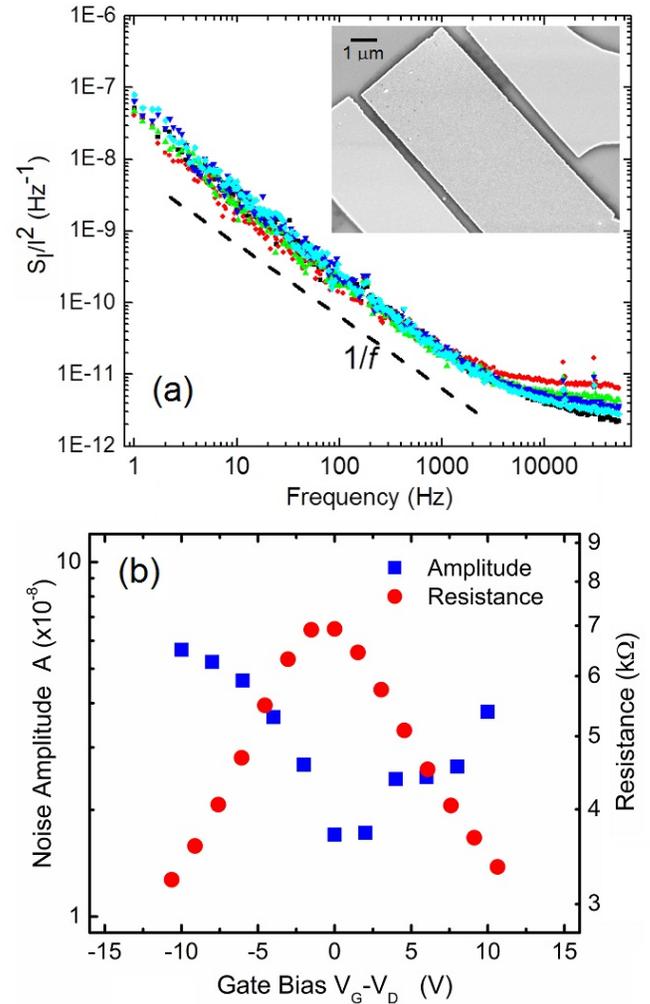


Fig. 1 Low-frequency noise in graphene. (a) Typical $1/f$ noise spectra in a graphene device. The inset shows a scanning electron microscopy image of a representative graphene device. (b) Unusual V-shape bias dependence of $1/f$ noise in graphene. The figures are reproduced from Ref. [1] with permission from the Nature Publishing Group.

III. NOISE IN 2D VAN DER WAALS MATERIALS

Recently, the exotic phenomena, such as charge density waves (CDW) in 2D van der Waals materials, attracted interest in the context of the low-frequency noise research [16-18]. The CDW phase is a macroscopic quantum state consisting of a periodic modulation of the electronic charge density accompanied by a periodic distortion of the atomic lattice [19]. One of the most interesting 2D CDW materials is 1T-TaS₂ [17, 20-23]. As the temperature increases above 180 K, the commensurate CDW phase in this material breaks up into a nearly-commensurate CDW phase that consists of ordered commensurate CDW regions separated by domain walls. This transition is revealed as an abrupt change in the resistance with a large hysteresis window in the resistance profile at 200 K. As the temperature increases to 350 K, the nearly commensurate phase melts into an incommensurate phase, in which the CDW wave vector is no longer commensurate with the lattice. This transition is accompanied by a smaller hysteresis window in the resistivity. Only at high temperatures of 500 K – 600 K the incommensurate CDW phase melts into the normal metallic phase of 1T-TaS₂.

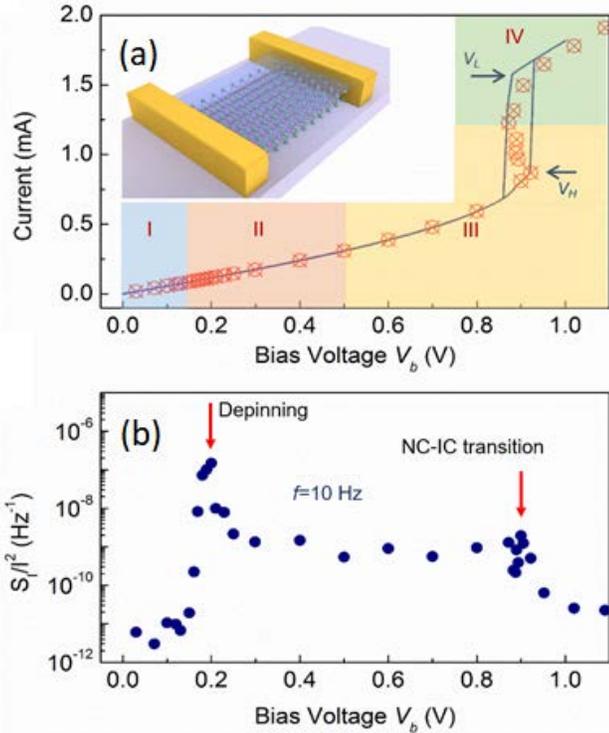


Fig. 2 Low frequency noise in 2D charge-density-wave materials. (a) Current-voltage characteristics of thin-film 1T-TaS₂ device at room temperature. The inset shows the device schematic. The abrupt CDW phase transitions are seen at voltages V_H (up scan) and V_L (down scan). The red circles indicated the biasing points for the low-frequency noise measurements. (b) The normalized noise spectral density, S_I/I^2 at 10 Hz as a function of the bias voltage, V_B . Two pronounced local maxima correspond to the de-pinning of the charge density wave and the phase transition between two CDW phases. The figures are adapted from Ref. [17].

We investigated the low-frequency noise in 1T-TaS₂ thin films as they were driven from the nearly commensurate (NC) to incommensurate (IC) CDW phases by voltage and

temperature stimuli [17]. This study revealed that noise in 1T-TaS₂ has several pronounced maxima at the bias voltages, which correspond to the onset of CDW sliding and to the phase transitions (see Figure 2). The noise spectral density was more sensitive to the phase transitions and changes in the electron transport than the current-voltage (I-V) characteristics. We observed the unusual Lorentzian features and exceptionally strong noise dependence on the electric bias and temperature, leading to the conclusion that electronic noise in 2D CDW systems has a unique physical origin different from known fundamental noise types [17]. It was established that the low-frequency noise spectroscopy can serve as useful tool for understanding electronic transport phenomena in 2D CDW materials characterized by coexistence of different phases and strong pinning. The technique has been also used for the vertical 1T-TaS₂ CDW devices. It was found that the low-frequency noise spectral density revealed strong peaks, below the temperature of the commensurate CDW to nearly-commensurate CDW transition, possibly indicating the presence of the strongly debated *hidden phase* states [18].

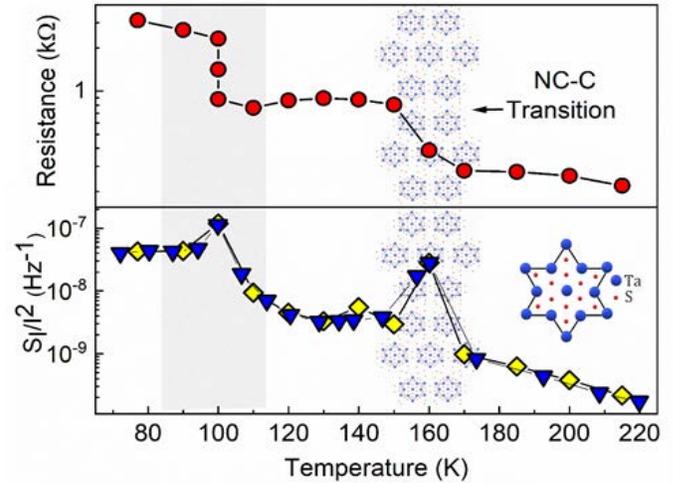


Fig. 3 Electrical resistance (upper panel) and normalized current noise spectral density (lower panel) as functions of temperature. The noise data were measured at the bias of $V_{SD}=13$ mV and frequency $f=10$ Hz. The decrease in resistance at $T_C=160$ K corresponds to the well-known commensurate to nearly-commensurate CDW transition. A diagram, depicting the reconstruction of Ta atoms into hexagonal clusters, is shown to illustrate the phase transition. A distinctive noise peak is observed at the same temperature T_C . Below the commensurate CDW – nearly-commensurate CDW phase transition temperature, one can see another step in the resistance with the corresponding peak in the noise spectral density. The figure is adapted from Ref. [18]

The low-frequency electronic noise spectroscopy has been instrumental in monitoring the electric-field induced transition from the incommensurate CDW phase to the normal metal phase. The noise spectral density, S_I/I^2 , exhibits sharp increases at the phase transition points, which correspond to the step-like changes in resistivity. Assignment of the phases was consistent with low-field resistivity measurements over the temperature range from 77 K to 600 K. The transition to the metallic phase of 1T-TaS₂ is not accompanied by a large change in the resistivity. However, noise spectrum undergoes substantial

changes, which allow to accurately determine the transition (see Figure 4).

IV. NOISE IN 1D VAN DER WAALS MATERIALS

The concept of van der Waals materials has been extended to one-dimensional (1D) systems. In contrast to the layered quasi-2D crystals, quasi-1D materials, such as MX_3 (where M = transition metals; X = Se and Te) consist of the atomic threads, which are weakly bound in bundles by van der Waals forces. As a consequence, the exfoliation of the MX_3 crystals results not in 2D layers but rather in quasi-1D nanowires [24–28]. It has been shown that some of quasi-1D van der Waals materials reveal exceptionally high electrical current densities [24, 27]. These materials are very interesting from the low-frequency noise prospective as well (see Figure 5).

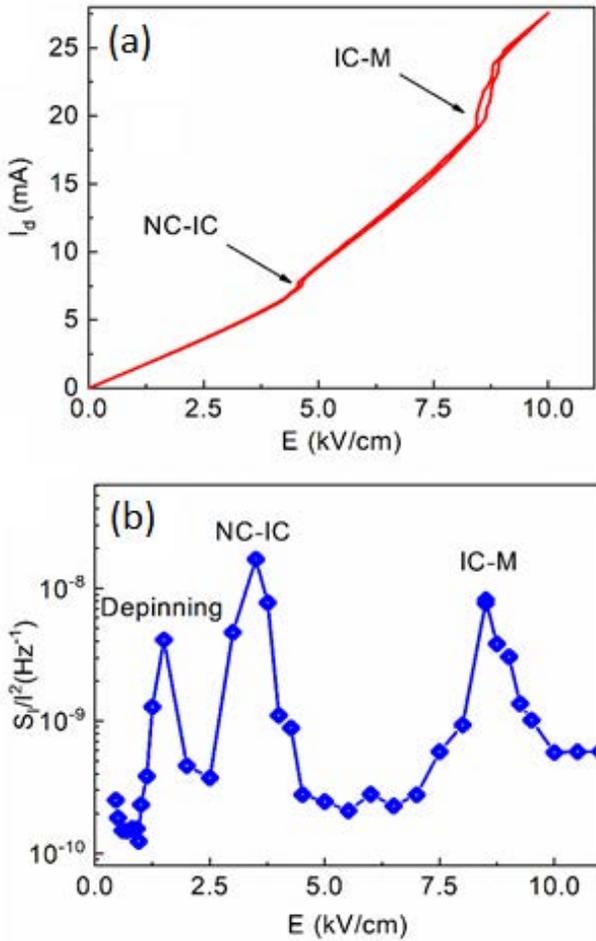


Fig. 4 Noise spectroscopy of CDW – metallic phase transition. (a) Current-voltage characteristics showing two steps in current at the electric field of 4.5 kV/cm and 9 kV/cm corresponding to the nearly-commensurate to incommensurate CDW phase transition and incommensurate to metal transition, respectively. (b) Normalized spectral density as a function of the electric field measured at $f=10$ Hz. The peaks in the noise spectral density at 4.5 kV/cm and 9 kV/cm are in excellent agreement with the resistance steps in (a). Note that the noise spectrum is much more sensitive to the phase transitions than the I-V characteristics.

Specifically, we found that quasi-1D TaSe_3 and ZrTe_3 van der Waals nanowires, which possess exceptionally high current densities, have rather low levels of the low-frequency noise as compared to graphene [25, 28]. In ZrTe_3 nanowires, the noise reveals the $1/f$ behavior near room temperature but becomes dominated by the Lorentzian bulges at low temperature. Unexpectedly, the corner frequency of the Lorentzian peaks shows a strong sensitivity to the applied source–drain bias. The dependence on electric field can be explained by the Frenkel–Poole effect only in the scenario where the bias voltage drop happens predominantly on the defects, which block the quasi-1D conduction channels [28]. In TaSe_3 , $1/f$ noise becomes the $1/f^2$ type as temperature increases to ~ 400 K, suggesting the onset of electromigration. Using Dutta–Horn model, we determined that the noise activation energy for quasi-1D TaSe_3 nanowires is ~ 1.0 eV, comparable to that for Cu and Al interconnects. Our results suggest that quasi-1D van der Waals metallic nanowires have potential for applications in the *ultimately downscaled* local interconnects [25]. While this review emphasized the use of low-frequency noise as a

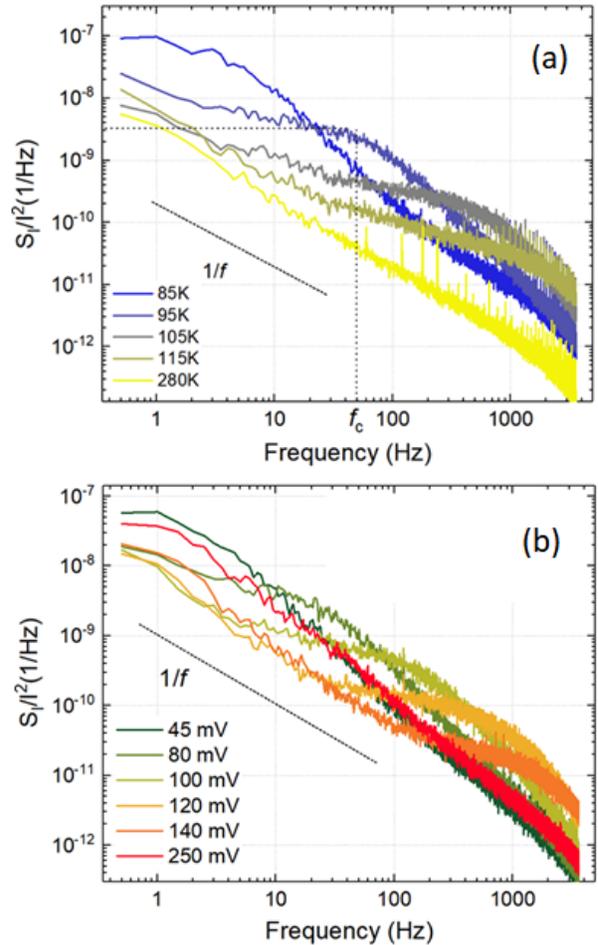


Fig. 5 Noise in 1D van der Waals materials. (a) Normalized noise spectral density, S_I/I^2 , as a function of frequency of quasi-1D ZrTe_3 nanoribbon at temperatures from 85 K to 280 K. (b) Normalized noise spectral density, S_I/I^2 , as a function of frequency of quasi-1D ZrTe_3 nanoribbon at the bias voltage ranging from 45 mV to 250 mV. Adapted from Ref. [28].

spectroscopy tool for understanding the electron transport phenomena, the obtained results are also important for practical applications of 2D and 1D van der Waals materials in sensors or information processing [29-35].

V. CONCLUSIONS

We reviewed our recent results pertinent to the unusual noise phenomena in quasi-2D and quasi-1D van der Waals materials. We also discussed the prospects of the low-frequency noise spectroscopy which is a powerful tool for investigation of the electron transport and charge-density-wave phase transitions in this class of materials.

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