Two-Dimensional Charge-Density-Wave Quantum Materials

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The charge density wave (CDW) phase is a quantum state consisting of a periodic modulation of the electronic charge density accompanied by a periodic distortion of the atomic lattice in quasi-one-dimensional (1D) or quasi-two-dimensional (2D) metallic crystals. Several layered transition metal dichalcogenides (TMDs) exhibit unusually high transition temperatures to different CDW symmetry-reducing phases, opening possibility for practical device applications. One of the most promising materials, 1T-TaS_2, has the CDW transition between the nearly-commensurate (NC-CDW) and the incommensurate (IC-CDW) phases at 350 K. The transition from the IC-CDW phase to the normal metal phase is observed at even higher temperature. In this keynote talk, I will review our recent experimental results on controlling the CDW phase transitions in quasi-2D materials with an applied electric field, and discuss possible device applications of quasi-2D CDW materials.

We have demonstrated the room-temperature voltage-controlled oscillators and logic circuits, which operate on the basis of the NC-to-IC CDW transition in the quasi-2D 1T-TaS_2 channels, triggered by the applied voltage [1-2]. We found that the quasi-2D 1T-TaS_2 CDW devices reveal exceptional hardness against X-ray and proton radiations [3-4]. We explained this property of the CDW devices by the high carrier concentration in all their phase states, two-terminal design, and the quasi-2D channel geometry. The low-frequency electronic noise spectroscopy has been used as an effective tool for monitoring the CDW phase transitions, particularly the switching from the IC-CDW phase to the normal metal phase in the quasi-2D 1T-TaS_2 channels [5]. The noise spectral density exhibits sharp increases at the phase transition points, which correspond to the step-like changes in resistivity. The noise spectroscopy was instrumental in revealing the “hidden phase transitions” in vertical 1T-TaS_2 devices [6].

The data on the “narrow-band noise” in quasi-2D CDW devices [7] and the switching speed of the CDW phases will also be presented [8]. Despite the similarities of the “narrow-band noise” in quasi-1D and quasi-2D CDW materials, we argue that the nature of the current oscillations in quasi-2D 1T-TaS_2 is different from the “narrow-band” noise. Analysis of the biasing conditions and electrical current indicates that the observed oscillations are related to the current instabilities due to the voltage-induced transitions between the NC-CDW and IC-CDW phases [7]. By combining the results of our experiments with a numerical analysis of the transient heat diffusion in the quasi-2D 1T-TaS_2 devices on Si/SiO_2 substrates, we clearly reveal the thermal origins of the CDW phase switching in such devices [8]. In spite of this thermal character, our numerical modelling suggests that a suitable reduction of the size of these CDW devices should allow their operation at GHz frequencies.

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