Nanoscale carrier distribution imaging of layered semiconductor materials using scanning nonlinear dielectric microscopy

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Layered materials are nowadays rising class of materials owing to their various superior and anomalous properties. In particular, layered semiconductors have recently attracted much interest. For example, since molybdenum disulfide (MoS_2), one of layered semiconductors, can maintain relatively high carrier mobility even for atomic monolayer of this material, its electronic device applications have been studied extensively. Optoelectronic applications of MoS_2 are also explored, because a monolayer MoS_2 has a direct transition bandgap. For boosting research and development of layered semiconductor materials and devices, we need tools for characterization and analysis of carrier and charge distribution in a nanoscale. A promising candidate is scanning nonlinear dielectric microscopy (SNDM), which is a scanning probe microscopy method based on the detection of tip-sample capacitance. By measuring tiny variation in tip-sample capacitance to an applied voltage ($\mathrm{d}C/\mathrm{d}V$), SNDM can obtain information on dominant carrier (electrons or holes) and its spatial distribution in a nanoscale (See, Fig. 1(a)). In this talk, we demonstrate SNDM is even applicable to few- to mono-layer of layered semiconductors. Figures 1(b) -1(e) shows topographic ((b) and (d)) and SNDM images ((c) and (e)) of n-type and p-type MoS_2 flakes exfoliated on SiO_2(300nm)/Si substrates, respectively. SNDM was combined with atomic force microscopy for simultaneous topographic imaging, which suggests both of the n- and p-type flakes included few-layer MoS_2. $\mathrm{d}C/\mathrm{d}V$ images show n- and p-type MoS_2 flakes were clearly distinguished as regions with negative and positive signals, respectively. In particular, we could obtain significant $\mathrm{d}C/\mathrm{d}V$ intensity even for a monolayer MoS_2. Interestingly, for a bilayer p-type flake in (d) and (e), signal was almost zero probably due to strong carrier depletion or high concentration in this area. These results suggest that SNDM will be useful for nanoscale characterization of carrier distribution in layered semiconductor materials. This work was partly supported by a Grant-in-Aid for Scientific Research (Nos. 15K04673, 16H02330) from the Japan Society for the Promotion of Science.

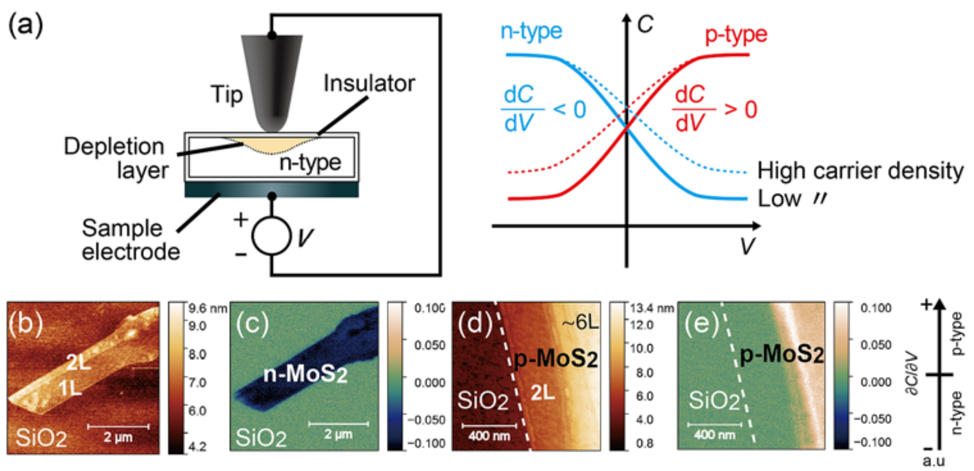

Figure 1 Principle of majority carrier determination by SNDM and SNDM images of n- and p-type few-layer MoS_2.

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In the main text, we focus on dominant carrier distribution imaging by SNDM working in air. In addition to this, we can also utilize another mode of SNDM, called ultrahigh vacuum noncontact SNDM (UHV-NC-SNDM). Higher sensitivity of UHV-NC-SNDM to capacitance variation allows us to obtain atomic scale charge distribution (dipole moment) of layered materials as well as nanoscale carrier distribution as shown in Fig. 2. Here we note that these images are currently obtained for bulky MoS_2 but not for few-layer MoS_2. However, this is just due to technical limitations in our experimental setup and sample preparation. Actually, the same method has previously achieved atomic resolution imaging of atomic-scale charge states on monolayer graphene on SiC [K. Yamasue et al., Phys. Rev. Lett. 114, 226103(2015)].

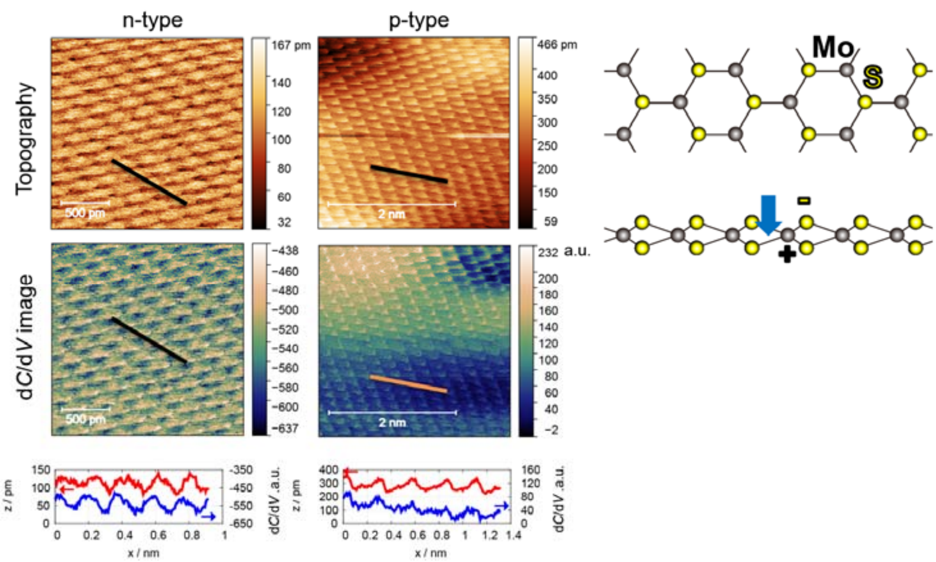

Figure 2 Atomic resolution images of n- and p-type MoS_2 by NC-SNDM