DC bias dependent nanoscale carrier distribution on a few-layer WSe$_2$ on SiO$_2$ observed by scanning nonlinear dielectric microscopy

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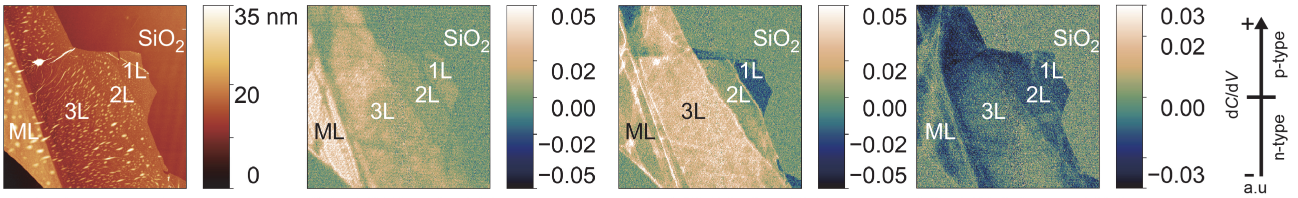
WSe$_2$ is one of transition metal dichalcogenides and has attracted much interest because of its semiconductor properties even in few atomic-layer sheets. Field effect transistor devices using WSe$_2$ have already been demonstrated, showing ambipolar characteristics. In addition, monoatomic layer WSe$_2$ is a direct-transition bandgap semiconductor, which is promising for optoelectronic applications. For investigating electronic properties of WSe$_2$ and its devices, spatial distribution of dominant carriers is important. In this paper, we demonstrate that scanning nonlinear dielectric microscopy (SNDM) [1] can image dc bias dependence of dominant carrier distribution in WSe$_2$ mechanically exfoliated on SiO$_2$/Si substrates. SNDM measures tip-sample capacitance variation to applied voltages (dC/dV). The polarities of dC/dV reflect the polarities of dominant carriers. dC/dV is positive (negative) if the dominant carrier is p-type (n-type). Since the amplitude of dC/dV depends on carrier concentration, we can obtain information on the spatial distribution of dominant carriers in nanometer resolution.

The sample was prepared by a so-called Scotch tape method. WSe$_2$ was mechanically exfoliated on thermally oxidized Si substrates. The oxide layer thickness was 300nm and the substrates were highly doped (0.001Ωcm to 0.005 Ωcm). We used Pt-Ir coated cantilevers with a tip radius of 25nm and measured samples in air at a room temperature. In order to control tip-sample contact force at 2nN and avoid the damages of sample, we combined SNDM with peak-force tapping mode atomic force microscopy. For dC/dV imaging, ac modulation voltage of 3V$_{pk}$ at 1MHz was applied to the sample. Figure below shows topographic and dC/dV image at different dc bias voltages. As shown in Fig. (a), the imaged area includes single layer (denoted by “1L” in the figure), bi-layer (“2L”), and multilayer (“ML”) WSe$_2$. For zero dc bias voltage (not shown), image contrast is very weak, showing that WSe$_2$ is an almost intrinsic semiconductor. When we applied the dc sample voltage of -5V$_{dc}$, a dC/dV image shows dominant carrier on WSe$_2$ was p-type at all layer-numbers, as shown in Fig. (b). This is because, by applying negative dc bias, holes are induced on WSe$_2$. Then, for +5V$_{dc}$, only a part of WSe$_2$ showed the conversion to n-type but the other parts remain p-type (Fig. (c)). During repeated scan of surface at the same condition, we observed gradual change of dominant carrier types. Furthermore, by increasing dc bias voltage up to +10V$_{dc}$, all layer numbers became totally n-type, as expected (Fig. (d)). The observed gradual image contrast changes are possibly attributed to charge injection and interfacial charge states at a WSe$_2$/SiO$_2$ interface. The results here indicate that SNDM will be a useful tool for the investigation of WSe$_2$ and devices. 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 and the Cooperative Research Project Program of the Research Institute of Electrical Communication, Tohoku University.

References: [1] Y. Cho, A. Kirihara, and T. Saeki, Rev. Sci. Instrum. 6, 2297 (1996).



(a) Topography (b) dC/dV at -5V$_{dc}$ (c) dC/dV at +5V$_{dc}$ (d) dC/dV at +10V$_{dc}$

Figure: SNDM images of WSe$_2$ mechanically exfoliated on SiO$_2$