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MBE-grown Mn-doped $SnSe_2$ 2D films on GaAs (111)B substrates.

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Intensive research is currently being aimed at understanding both the growth and the physical properties of a wide range of two-dimensional (2D) materials [1], since this class of materials is expected to lead to entirely new types of devices on the nanoscale. Additionally, the introduction of magnetic dopants into a 2D lattice can bring out new functionalities, providing new opportunities for spintronic applications. In this work we explore this area by introducing Mn ions into the 2D lattice of $SnSe_2$. The growth of Mn-doped $SnSe_2$ films was carried out by molecular beam epitaxy (MBE) on GaAs (111)B substrates by varying the flux of Mn during the growth. Rigorous characterization of the physical properties of this material was carried out by a wide range of complementary studies, including RHEED, XRD, electric-transport and Raman spectroscopy.

The Mn-doped $SnSe_2$ film specimens were grown using a dual-chamber Riber 32 MBE system, and the growth process was monitored by RHEED (Figs. 1a and 1b). The growth sequence was as follows. First, an epi-ready GaAs (111)B substrate was deoxidized by heating to 600°C. A 50 nm GaAs buffer layer was then deposited on the GaAs substrate in the III-V MBE chamber, which was subsequently transferred to the II-VI chamber for the $SnSe_2$ deposition. The wafers were annealed in that chamber at 600°C in Se_2 flux, resulting in improved surface flatness. Additionally, the inert Se surface termination resulting from this process allows growth of 2D systems on top of a 3D material with practically no defects. The growth of Mn-doped $SnSe_2$ was then performed at the substrate temperature ~150°C, with nominal Mn content ranging from 5 to 20 percent as determined by the Mn flux and the growth rate. The RHEED (Fig. 1c) shows that single-crystal $SnSe_2$:Mn film can be grown layer-by-layer on a GaAs(111)B substrate, with a typical growth rates of ~2 ML/min. RHEED images also indicate that the in-plane lattice constant of the $SnSe_2$:Mn films is about 3.8Å, which is close to the lattice constant of 3.811 Å of bulk $SnSe_2$ [2].

The high crystalline quality of the films was confirmed by XRD measurements on a series of Mn doped $SnSe_2$ films grown on GaAs (111)B substrates. In Fig. 2, XRD spectra reveal many reflections from {003}-type lattice planes, indicative of highly directed *c*-axis growth of the films. The layer distances obtained from the observed XRD data are larger than the value of 6.137 Å of bulk $SnSe_2$ [2]; and they increase as the Mn flux increases. Electric transport measurements show that semiconducting behavior and the resistivity of the films strongly depends on the Mn concentration. High-field and low-temperature magneto-transport measurements on these films are planned for determining the conductive type of these 2D films. Raman spectroscopy of the 2D films was also performed (see Fig. 1d) using a 488 nm laser for excitation (at power ~0.76mW), showing similar peaks as bulk $SnSe_2$ [3].

In summary, we have grown high quality epitaxial films of Mn-doped $SnSe_2$ on GaAs (111)B substrates. The films are highly uniform and the crystallinity is comparable to that of films without the Mn dopant. Future studies, including high-field magneto-transport, TEM and magnetometry should contribute to a better understanding of magnetically-doped 2D chalcogenides, with an eye on exploring the opportunities which these materials open for spin-based devices. This work was supported by the National Science Foundation (NSF).

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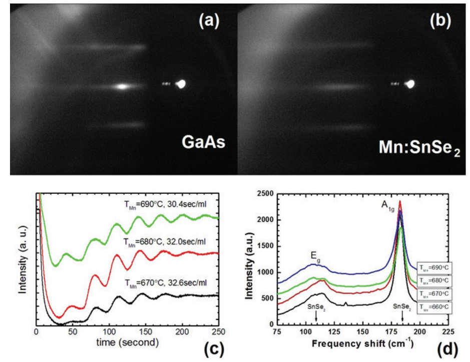

Figure 1. RHEED images of (a) GaAs (111)B surface after removal of oxide at 600°C with Se_2. (b) after deposition of 70ML Mn doped $SnSe_2$. (c) RHEED oscillations of three samples with different Mn concentrations. (d) Representative Raman spectra measured in Mn doped $SnSe_2$ films.

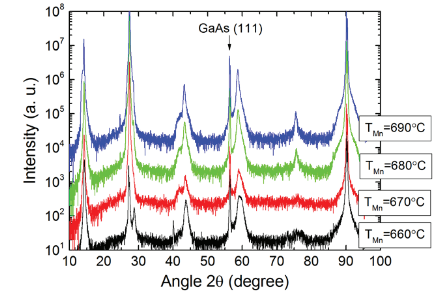

Figure 2. X-ray diffraction data of Mn-doped $SnSe_2$ films grown on GaAs (111)B substrate by MBE.