The High Coercivity Fields in Chemically Bonded $WSe_2/MoSe_2$ Powders

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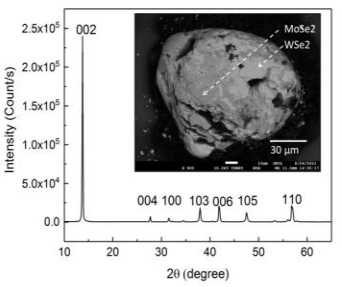
Abstract

- The dilute magnetic semiconductor (DMS) is one of the promising materials for spintronic applications. The basic idea is doping magnetic elements into a semiconductor host, thereby making a material possessing both semiconductor and magnetic feature.
- However, weak ferromagnetism and low coercivity field at room temperature; low Curie temperatures and intrinsic/extrinsic mechanism disputation limit its application potential.
- It is reported the bound edge defect would induce the ferromagnetism in 2D transition metal dichalcogenide, 2D TMDs single crystal. To increase the bound edge defect and enhance the ferromagnetism, the magnetism of chemically bonded $WSe_2/MoSe_2$ powder were studied.
- Our studies reveal the highest coercivity field at room temperature, and this characteristic originates from the chemical bonding-induced structure defect at WSe_2 and $MoSe_2$ interface.

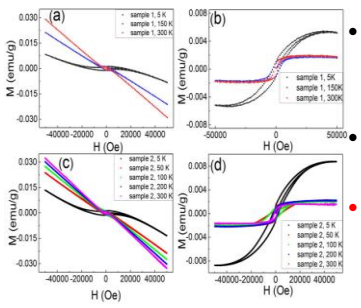
Experiment method

The mixed $WSe_2/MoSe_2$ powder is a commercial product and was purchased from SixCarbon Technology. Co. (ShenZhen, China) The purchased $WSe_2/MoSe_2$ powder was vacuum-sealed in a glass tube with a pressure of 10^{-3} torr, and then further thermally annealed. The $WSe_2/MoSe_2$ powder was heated up to 1000°C by a rate of 2.7°C/min and maintained at 1000°C for 1 hour. After thermal annealing, it was naturally cooled down to room temperature.

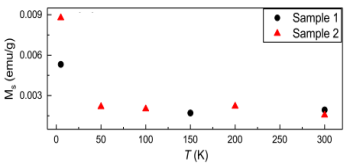
Results and Discussions



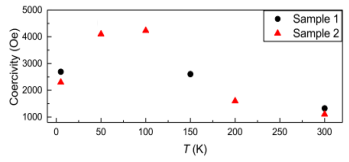
- The X-ray diffraction spectrum of the $WSe_2/MoSe_2$ powder. The peak position is consistent with the database. The sharp peaks imply that the sample is highly crystallized.
- The top-right inset shows that SEM image in the backscattering emission image mode. The light area is the WSe_2, and the dark area is the $MoSe_2$, which confirmed by the energy dispersive spectroscopy mode in SEM. It shows the phases of WSe_2 and $MoSe_2$ are separated.
- The EPMA supports that W:Se = 1:2 in the light zone and Mo:Se = 1:2 in the dark zone, and $MoSe_2$:WSe_2 ≈ 1:1.

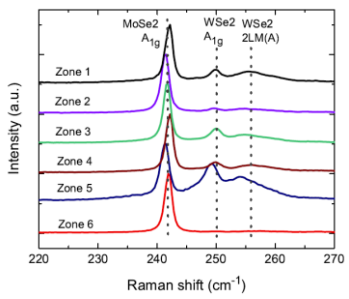


- (a,c) The M–H curves at temperatures for sample 1 and sample 2. They exhibit hysteresis loops at low magnetic fields and diamagnetism at high magnetic fields.
- (b,d) The M–H curves at temperature for sample 1 and sample 2; the diamagnetic contribution was subtracted.
- The extracted coercivity field of sample 1 is 2600 Oe at at 5 K and 1300 Oe at 300 K. The extracted coercivity field of sample 2 is 2299 Oe at 5 K and 1100 Oe at 300 K.

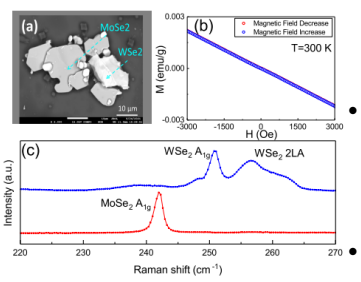


- The saturation magnetization, M_S, as a function of temperature for two $WSe_2/MoSe_2$ powders.
- The temperature dependent coercivity fields of two $WSe_2/MoSe_2$ powders.
- The coercivity is orders higher than all reported values in 2D TMDs. Please Refer to the Table 1.





- The Raman spectrometer, a sensitive tool for detecting lattice bonding, was used to identify the chemical bonding at the interface between WSe_2 and $MoSe_2$.
- The $WSe_2/MoSe_2$ mix powder size is two order larger than the Raman laser spot. The Raman spectra might have detected the signal of only WSe_2, $MoSe_2$ or chemically bonded $WSe_2/MoSe_2$. The scan step is much smaller than the possible shift of the peals.
- The peak of $MoSe_2$ is A_{1g} (242 cm^{-1}), and the peaks of WSe_2 are A_{1g} (250 cm^{-1}) and 2LA(M) (256 cm^{-1}) were labeled with dotted lines.
- The Raman shifts of two $WSe_2/MoSe_2$ powders in different zones. It exhibited the standard peaks of WSe_2 and $MoSe_2$.
- Red shifts of WSe_2 peaks and are shown in zone 5. It is the evidence of interface chemical bonding between WSe_2 and $MoSe_2$.



- To further identify the source of the observed ferromagnetism, another mixed WSe2 and MoSe2 powder from the same raw materials was prepared without 1000°C thermal annealing.
- (a) The SEM image in the backscattering emission imaging mode. The light area is the WSe_2 and the dark area is the $MoSe_2$. The sample was a mixture of WSe_2 and $MoSe_2$ flakes containing only one material within each flake.
- (b) The M–H curve shows the diamagnetism feature, and no hysteresis loops were detected.
- (c) The 242 cm^{-1} for MoSe2, and 250 cm^{-1} and 256 cm^{-1} for WSe_2, are shown in the Raman spectra. No mixed peaks or red-shifted peaks were observed.

Table 1

our works

Material	Coercivity	Saturation Magnetization	Temperature	Treatment
$WSe_2/MoSe_2$ powder	2695 Oe	0.0053 emu/g	5 K	interface
$WSe_2/MoSe_2$ powder	2606 Oe	0.0017 emu/g	150 K	interface
$WSe_2/MoSe_2$ powder	1324 Oe	0.0019 emu/g	300 K	interface
$WSe_2/MoSe_2$ powder	2299 Oe	0.0087 emu/g	5 K	interface
$WSe_2/MoSe_2$ powder	4100 Oe	0.0022 emu/g	50 K	interface
$WSe_2/MoSe_2$ powder	4233 Oe	0.0020 emu/g	100 K	interface
$WSe_2/MoSe_2$ powder	1600 Oe	0.0022 emu/g	200 K	interface
$WSe_2/MoSe_2$ powder	1100 Oe	0.0015 emu/g	300 K	interface
WSe_2 nanosheet	414 Oe	211 emu/cm^3	20 K	edge
WSe_2 naosheet	106 Oe	70 emu/cm^3	300 K	edge
WSe_2 few-layer	578 Oe	0.078 emu/g	10 K	zigzag
WSe_2 few-layer	200 Oe	0.0073 emu/g	300 K	zigzag
WS_2 nanosheet	1115 Oe	0.0046 emu/g	3 K	zigzag
WS_2 nanosheet	92 Oe	0.0052 emu/g	300 K	zigzag
WS_2 nanosheet	240 Oe	0.39 emu/g	10 K	zigzag and structure defect
WS_2 nanosheet	140 Oe	0.2 emu/g	300 K	zigzag and structure defect
WS_2 exfoiled nanosheet	400 Oe	0.004 emu/g	10 K	zigzag or vacancy
WS_2 exfoiled nanosheet	125 Oe	0.002 emu/g	300 K	zigzag or vacancy
WS_2 few-layer	295 Oe	0.098 emu/g	10 K	zigzag
WS_2 few-layer	130 Oe	0.009 emu/g	300 K	zigzag
WS_2 powder	~60 Oe	0.002 emu/g	300 K	vacancy
WS_2 nanoflake	293 Oe	3.67 emu/g	60 K	
WS_2 nanoflake	171 Oe	1.82 emu/g	300 K	
WS_2 nanoflake	967 Oe	7.59 emu/g	60 K	
WS_2 nanoflake	239 Oe	3.08 emu/g	300 K	
$MoSe_2$ nanoflake	100 Oe	1.39 emu/g	300 K	zigzag
$MoSe_2$ few-layer	435 Oe	0.013 emu/g	10 K	zigzag
$MoSe_2$ few-layer	40 Oe	0.0026 emu/g	300 K	zigzag
$MoSe_2$ nanoflowers	50 Oe	0.027 emu/g	300 K	thermal vacancy
$MoSe_2$ nanoflowers	80 Oe	0.017 emu/g	300 K	thermal vacancy
$MoSe_2$ nanoflowers	60 Oe	0.003 emu/g	300 K	thermal vacancy
MoS_2 nanosheet	150 Oe	1 emu/g	300 K	vacancy
MoS_2 1T phase	150 Oe	12.5 emu/g	300 K	structure phase
MoS_2 nanosheets	50~200 Oe	0.1 emu/g	5 K	thermal vacancy
MoS_2 nanosheets	20~50 Oe	0.008 emu/g	300 K	thermal vacancy
MoS_2 film	260 Oe	0.00125 emu/cm^3	300 K	proton irradiation
MoS_2 film	700 Oe	0.0015 emu/cm^3	10 K	proton irradiation
MoS_2 film	276 Oe	0.0486 emu/g	300 K	web buckle-mediated strain
MoS_2 nanoparticles	20.8 Oe	0.1 emu/g	5 K	thermal vacancy
MoS_2 nanosheet	241.3 Oe	1.08 emu/g	10 K	zigzag and structure vacancy
MoS_2 nanosheet	~80 Oe	0.8 emu/g	300 K	zigzag and structure vacancy
MoS_2 single crystal bulk	400 Oe	0.004 emu/g	50 K	zigzag
MoS_2 single crystal bulk	100 Oe	0.0038 emu/g	300 K	zigzag
MoS_2 pyramid (films)	~200 Oe	3 emu/g	2 K	zigzag
MoS_2 pyramid (films)	~50 Oe	2.9 emu/g	300 K	zigzag
MoS_2 nanosheet	~55 Oe	0.01 emu/g	300 K	S vacancy and substitutional dopants
MoS_2 1T phase	200 Oe	0.057 emu/g	5 K	electron beam formed defects
MoS_2 nanosheet	~200 Oe	0.0073 emu/g	300 K	un-paired Mo or edge
MoS_2 few-layer	517 Oe	0.019 emu/g	10 K	zigzag
MoS_2 few-layer	146 Oe	0.0043 emu/g	300 K	zigzag
MoS_2 nanoribbons	~250 Oe	0.032 emu/g	2 K	zigzag
MoS_2 nanoribbons	~250 Oe	0.026 emu/g	300 K	zigzag

- A slight magnetic or transition element dopant might lead to strong ferromagnetism in 2D TMDs .
- Our energy dispersive spectroscopy, EDS, analysis supports that there were no un-avoided magnetic or transition elements in our system.
- The saturation magnetization was 0.001 emu/g. If this magnetism originated from Ni, Co or/and Fe, the magnetic elements would have reached a 0.01% atomic ratio, which is within the detectable range of the EMPA.
- Our EMPA, XPS and ICPM experiment showed no detectable magnetic elements in our samples.
- These support that the external element dopants are not the main mechanism of the observed ferromagnetism in $WSe_2/MoSe_2$ powder.

Conclusions:

- The magnetism of chemical bounded $WSe_2/MoSe_2$ powder was studied.
- The coercivity field reaches 2600 Oe at 5 K, 4233 Oe at 100 K and 1300 Oe at 300 K. These values are orders higher than all reported values in 2D TMDs. The physics mechanics behind is different from the widely reported vacancy and zigzag structure-induced ferromagnetism.
- A Raman spectrum reveals a red shift which supports the chemical bonding at the interface of WSe_2 and $MoSe_2$.
- The large coercivity field originates from the chemical bonding-induced structural distortion at the interface between WSe_2 and $MoSe_2$.