Light emission from MoS2 on various substrates for application to photonic nanostructures

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MoS2 is attracting intense research interest because it evolves into a direct bandgap semiconductor only when an MoS2 crystal is reduced to monolayer thickness. We studied monolayer fabrication and identified the number of layers exactly using Raman spectra. The measured photoluminescence (PL) intensity for a monolayer was about 30 times stronger than that for a bilayer. In addition, we transferred MoS2 to various substrates, and evaluated the optical property from the PL intensity. The PL intensity on graphene was enhanced more than 10-fold compared with the intensity at a fiber tip. Our study indicates that a graphene substrate is a satisfactory candidate for MoS2 application.

Key words: 2D materials; molybdenum disulfide; monolayer exfoliation; PL enhancement

1. Introduction

It is well-known that graphite-like 2D materials can be exfoliated by using a Scotch tape method [1]. More than 60 different types of 2D materials have been investigated with this method, and MoS2 is one that has been garnering intense research interest because of its outstanding optical properties. As the number of layers is reduced from bulk to monolayer, this 2D material evolves from an indirect to a direct bandgap semiconductor [2]. This interesting material property is used in many fields including light-emitting devices [3], and photodetectors [4].

A problem is that the quantum efficiency of MoS2 is not high. This is mainly due to [the/its?] thickness of under 1 nm and the small light emission region. It remains a great challenge to enhance the quantum efficiency and thus enable MoS2 to be applied to light emitting devices. A number of laboratories have engaged energetically in enhancing the quantum efficiency by such means as exploiting the strong Purcell effect in a photonic crystal, and fabricating quantum dots in a monolayer. In terms of the Purcell effect, spontaneous emission is enhanced by the Purcell factor \( F \) in Eq. (1).

\[
F = \frac{3Q\lambda_c}{4\pi^2V}
\]  

(1)

This equation indicates that a cavity with a high \( Q \) and a small mode volume \( V \) is required for quantum efficiency enhancement. For this reason, monolayer MoS2 is often integrated with nanocavities. However, since the state of the substrate surface can have a negative effect on the optical property of MoS2, the enhancement can be quenched.

In this research, we study how to fabricate and transfer monolayer MoS2, and then we collect photoluminescence (PL) spectra from monolayers on different substrates.

2. Fabrication of monolayer and measurement of optical properties

Nitto N-380 tape and Gel-Pak PF film \( \times 4 \) were used to fabricate the monolayer. The way to exfoliate a monolayer is shown in Fig. 1. First, bulk MoS2 (SPI Supplies) is placed on Nitto tape and covered with a second piece of the same tape. Then we mechanically cleave the crystal by pulling the tapes apart. This process is repeated about 10 times. After that, the tape is attached to a 5-mm-square piece of polydimethylsiloxane (PDMS). Finally, after cleaving at an appropriate speed, a monolayer is fabricated on the PDMS. The fabricated structure is shown in Fig. 2(a). The monolayer is indicated with a white arrow.

Raman spectroscopy is used to identify the number of layers. As shown in Fig. 2(b), the left peak is attributed to the in-plane vibration of MoS2 and the right peak results from out-of-plane vibration. Previous research demonstrated that there is a relationship between the Raman spectrum and the number of layers. The left peak undergoes a red shift while the right peak undergoes a blue shift as the number of layers decreases [5]. This is mainly due to the decrease in the van der Waals force along the c-axis of the
material. Fig. 2(b) shows that the number of layers is identified, and this agrees well with previous research.

The measured PL intensity for a monolayer and a bilayer differ greatly as shown in Fig. 2(d). As mentioned above, the former are direct bandgap semiconductors and the latter are indirect bandgap semiconductors. This figure indicates that the PL peak is about 660 nm and the intensity increases about 30-fold when the MoS$_2$ crystal is thinned to a monolayer. We also mapped the PL intensity inside the yellow frame in Fig. 2(c) with the PL at 660 nm. It is clear from Fig. 2(c) that only the monolayer becomes bright.

3. Transfer monolayer to fiber tip and compare PL for various substrates

We described how to fabricate a monolayer on PDMS. Here, we introduce how to transfer a monolayer to a fiber tip shown in Fig. 3(a).

The monolayer can be transferred by attaching the fiber to the monolayer and then detaching it very slowly. Since the adhesive force of the PDMS is lower than the van der Waals force between the monolayer and the fiber, the monolayer is attached to the fiber tip. The monolayer shown in Fig. 2(a) is transferred as shown in Fig. 3(b). It is clear that the monolayer can be transferred without breaking the structure.

To clarify the influence of the substrate on PL intensity, we transferred a monolayer to 10-layer graphene and a fiber tip. Fig. 3(c) shows the PL intensity on these substrates, and reveals that the PL intensity on graphene is more than 10 times stronger than that on the fiber tip. The increased PL intensity is mainly attributed to the dangling bond on the substrate surface and the surface roughness. In terms of the dangling bond, previous research has indicated theoretically that an O-dangling bond at the SiO$_2$ surface modifies the electronic properties of the MoS$_2$ and causes a transition from a direct to an indirect bandgap semiconductor [6]. Since 2D materials have no dangling bond, it is appropriate to use graphene as a substrate so that the optical property of MoS$_2$ can be fully utilized.

4. Conclusion

We studied how to fabricate and transfer monolayer MoS$_2$. The number of layers was exactly identified from changes in PL intensity and Raman spectra. We also evaluated the substrate according to the PL intensity of the monolayer. It is important to use 2D materials as the substrate because they have no dangling bonds.

References