Monolayer Molybdenum Diselenide

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Abstract:

We fabricated a device based on few-layer molybdenum diselenide ($MoSe_2$), a unique two-dimensional (2D) semiconducting material in the family of transition metal dichalcogenides. Unlike its sister material, molybdenum disulfide (MoS_2), monolayer $MoSe_2$ is largely unexplored [1]. Here, we employed the same exfoliation technique developed by the winners of the 2010 Nobel Prize in Physics for their work with graphene [2]. In this method, scotch tape is used to exfoliate $MoSe_2$ crystals. These crystals are then deposited on the surface of a silicon dioxide/silicon chip. Using an optical microscope, few-layer $MoSe_2$ pieces are identified. A precise measurement of the thickness of each $MoSe_2$ piece is determined using atomic force microscopy. By combining these methods with electron-beam lithography to create a transistor, we can ultimately examine the unexplored optical and electronic properties of monolayer $MoSe_2$.

Introduction:

In recent years 2D semiconducting materials have been produced that exhibit interesting electrical and optical properties. In monolayer materials, electrons behave differently than in bulk materials. As electrons move through monolayer materials, they are confined to two dimensions, thus resulting in different properties. Graphene is a 2D material that has been greatly explored. One interesting property of graphene is that it has a very high electron mobility of 200,000 cm2 $V^{-1}s^{-1}$ [3]. However, graphene does not have a naturally existing band gap and its on/off current ratio of five is very low [4]. Due to this lack of a naturally existing band gap, graphene is not an ideal material for making transistors. For the fabrication of 2D transistors, it is essential to find new 2D semiconducting materials. Recently, a family of compounds known as the transition metal dichalcogenides has been of interest in monolayer form. One transition metal dichalcogenide, molybdenum disulfide (MoS_2), has been studied widely in monolayer form. This material has a band gap of 1.8 eV, an on/off current ratio of 10^8, and an electron mobility of 380 cm^2 $V^{-1}s^{-1}$ [5].

We explored another transition metal dichalcogenide, molybdenum diselenide ($MoSe_2$), with the hopes of finding a material with similarly high on/off ratio, but with a lower band gap, and a higher electron mobility.

$MoSe_2$, shown in Figure 1, is an inorganic compound that has been used in bulk form for many years as a dry lubricant. The predicted band gap of a monolayer based on the band structure of a bulk crystal is 1.6 eV. The approximate height of a single layer of $MoSe_2$ is 0.65 nm, as determined from a bulk crystal. Once these layers are exfoliated and isolated, then electrical and optical properties of this unexplored monolayer material may be investigated.

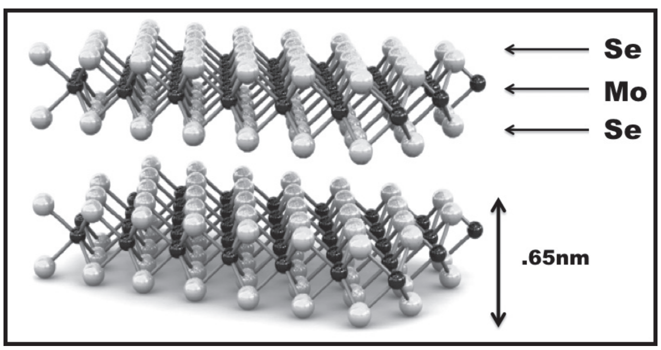

Figure 1: Structure of $MoSe_2$, after [1].

Experimental Procedure:

First, we deposited $MoSe_2$ crystals on Scotch™ tape and then ripped the tape apart several times until the crystals were very fine. Due to van der Waals interactions, this material's layers could be easily ripped apart. Second, the tape containing the exfoliated $MoSe_2$ crystals was placed on top of a silicon chip with 285 nm of thermally grown SiO_2. Then we rubbed the tape against the chip to transfer the exfoliated crystals from the tape onto the chip. Next, an optical microscope was used to scan the chip for possible monolayer, bilayer, and trilayer pieces of $MoSe_2$. This process took advantage of the way that $MoSe_2$ absorbs light to determine if a piece could possibly be one to a few layers thick. Typically, a monolayer to bilayer of $MoSe_2$ appears pink to light purple in color.

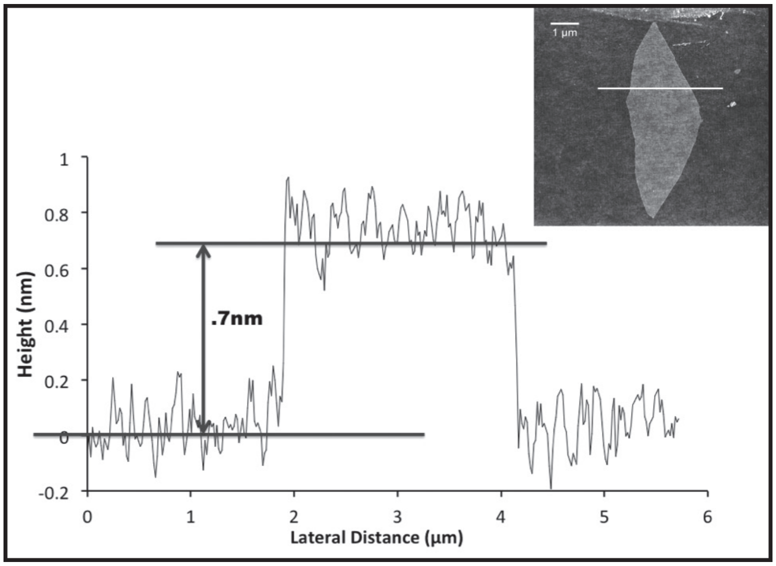

Figure 2: Cross-sectional plot of a monolayer of $MoSe_2$. The AFM image is in the upper-right corner; the cross-section is indicated by the white line.

Then an atomic force microscope (AFM) was used to confirm the height of interesting $MoSe_2$ pieces. By looking at a cross-sectional plot of the $MoSe_2$ sample, shown in Figure 2, we were able to measure the height of each piece. Keeping in mind that a single layer of $MoSe_2$ as measured from a bulk crystal is 0.65 nm thick, we used the AFM cross-sections to determine if a given piece was a monolayer, bilayer, or trilayer. Our device fabrication process is illustrated in Figure 3.

Fabrication started with a thin piece of exfoliated $MoSe_2$ on the silicon chip (Figure 3a). Next, the chip was spun with resist. Exposure to the chip via electron-beam lithography and development followed (Figure 3b). Finally, 50 nm of Au were evaporated for electrodes (Figure 3c). The transistor device was completed upon lift-off of the Au (Figure 3d).

Figure 4 shows the fine features one of the several devices that were successfully fabricated.

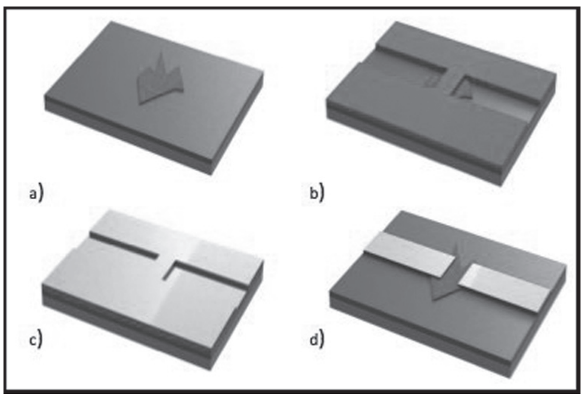

Figure 3: Device fabrication process.

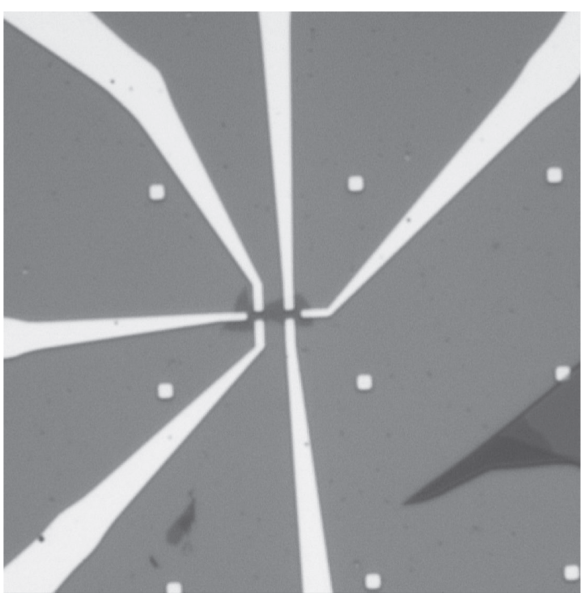

Figure 4: Completed device made from a trilayer piece of $MoSe_2$.

Summary and Future Work:

We successfully exfoliated and isolated few-layer $MoSe_2$. Sixty thin samples of $MoSe_2$ were exfoliated and measured using AFM, and several few-layer $MoSe_2$ devices were successfully fabricated. We are currently working towards measuring the electrical and optical properties of $MoSe_2$. The devices we fabricated will be used specifically to look at the band gap, on/off current ratio, and mobility of monolayer $MoSe_2$.

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