MODIFICATION OF ADHESION FORCES IN MULTIPLE LAYERS OF TRANSITION METAL DICHALCOGENIDES USING ILLUMINATION FOR MICRO-ACTUATORS

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ABSTRACT

Surface adhesion forces in few layers of layered transition metal dichalcogenides (ReS_2, NbS_2, n-type WSe_2, MoS_2, p-type $MoSe_2$, TaS_2) hexagonal BN (hBN) and graphene were determined using atomic force microscope with conducting silicon tip in dark and under illumination to identify material for integrated optical sensor in NEMS/MEMS switches. In all cases the surface adhesion forces increased under illumination. WSe_2, an indirect band gap with 1.66 eV energy, showed the largest change of ~165% in its adhesion force. Hexagonal BN, a wide band gap energy material of 5.5 eV, showed the smallest change of 7.2% comparable to changes in our control samples of 90 nm SiO_2 on Si and 100 nm Au on SiO_2/Si. NbS_2 and graphene, samples with the smallest energy band gaps, respectively showed 54.8% and 8.4% increase in surface adhesion forces under illumination.

KEYWORDS

Surface adhesion force, stiction force, 2D materials, transition metal dichalcogenides, and Atomic force microscopy.

INTRODUCTION

Surface adhesion forces play an important role in nano and micro-electromechanical system devices where stiction forces can potentially render them inoperable or increase their operating voltages. 2D layered materials offer unique optical and electronic properties for applications in NEMS as well as in low threshold light emitting diodes and lasers, chemical sensors, and electronic devices [1]-[6]. Graphene and MoS_2 MEMS switch and resonators have been demonstrated [7]. However, there are a large number of transition metal dichalcogenides with potentially better properties. Surface stiction forces are affected by surface roughness [8] and may also be affected by surface states that are important in electronic devices.

Here we report the optical modification of adhesion force between two material systems in close proximity. The adhesion force in atomic length scale is dictated by van der Waals [9] and Casimir forces [10]. Casimir force between two materials depends on their electromagnetic properties, the properties of their intervening medium, and their geometry. By changing electromagnetic properties of their constituent materials and their geometries, it is possible to fashion mechanical switches controlled by the Casimir force [10]. Motivation for this work arises from interest to identify suitable materials and geometries using 2D materials for NEMS and MEMS switches with programmable characteristics. We are also interested in finding materials with reduced surface adhesion forces to design scaled [11]-[12] NEMS switches with negligible hysteresis or memory.

Here we compare the surface adhesion forces measured using a Si AFM probe of ReS_2, NbS_2, WSe_2, MoS_2, $MoSe_2$, hexagonal BN, TaS_2, graphene, SiO_2 and Au thin film. The last two materials were used as control samples to ensure that the illumination of the AFM system's quad-detector or the Si AFM probe do not dominate the measured change in the surface stiction forces. As expected, the illumination increased the surface stiction forces in all samples with the highest change of 165% in WSe_2.

EXPERIMENTAL DETAILS

The experimental setup for the AFM measurement of the surface adhesion force is shown in Fig. 1. The samples were prepared using mechanical exfoliation [13] using adhesive tape from bulk layered materials. The samples were then mounted on magnetic discs and placed in a Bruker AFM system for measurement. The AFM scan and height profile of four samples are shown in Fig. 2. From the height profiles, the number of layers in all the samples ranged from 6 to 20 layers with 0.7 nm per atomic layer [13]. The spring constant of the silicon cantilever beam was calibrated using thermal tuning in dark and under illumination and was calibrated to eliminate the effect of the illumination in the elastic properties of the AFM probe. Si cantilever spring constant effectively increased by ~10% (from 0.16 nN to 0.175 nN) when illuminated. Stiction forces were then extracted from "force versus displacement" plots. Recently it has been shown that photothermal effect can generate nanometer scale actuation in AFM cantilever beams [14]. The apparent change in the AFM-measured probe's spring constant is a combination of thermal effects and the effect of external illumination on the quad-detector of the AFM's displacement sensor. The effective and apparent change in the probe's Hooke constant was accounted for in analyzing the AFM-measured surface stiction forces of the samples.

For each sample, at least six measurements were performed. Light intensity was controlled by a fiber optical illuminator (incandescent light source). Its highest intensity setting, used here, generated a photon flux of 2.47×10^{17} $cm^2 s^{-1}$ at 600 nm wavelength. The AFM chamber humidity was maintained at 34% and all the measurements were carried out at room temperature and atmospheric pressure.

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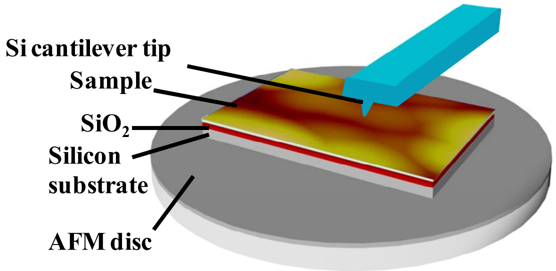

Figure 1: Experimental setup for measuring the stiction force of various materials.

RESULTS

Experimental results showed that, graphene had the maximum adhesion force (46 nN) while n-type WSe_2 (16 nN) and TaS_2 (15 nN) were smallest among all the samples in dark (Fig. 3). Under illumination, the maximum increase was observed in WSe_2 while the minimum increase was observed in hBN. The increase in adhesion forces are summarized in Table. 1. NbS_2 and TaS_2 are metallic and showed very little change due to illumination. Hexagonal BN is an insulator and showed no change due to illumination probably because of lack of energetic photons needed to generate carriers in it. N-type WSe_2 can be used as optically active layer on NEMS/MEMS optical actuator with activation vphotons of h>1.66 eV.

Fig. 3 shows the change in the adhesion forces in the above samples under in dark. The maximum increase was observed in WSe_2 while the minimum increase was observed in hBN (Fig. 4). The increase in adhesion forces are summarized in Table. 1 and Fig. 5. To calculate the percentage increase, we used mean values of stiction forces measured over many cycles.

DISCUSSION

The interaction between the AFM probe (assumed to be spherical) and the planar sample is approximately given by [15]-[16]:

$$F_{vdW} = \frac{A_{Hamaker} r}{6l^2} \qquad (1)$$

where, $A_{Hamaker}$ is the Hamaker constant that depends on the material properties of the two interacting system, "r" is the radius of the sphere and "l" is the distance between the sphere and the plane. In our case, the tip is considered spherical and the sample is considered planar. The radius of the tip was ~10 nm. To explain the experimental observation of adhesion forces, we take graphene as a model system because most of its relevant parameters are reported in the literature. The Hamaker constant for graphene is reported [17] to be 1.49 x 10^{-19}J. Using this value, and the measured surface force, we estimated that the effective tip-graphene distance was around 0.2 nm when the tip touched the sample. The surface adhesion force of graphene can vary depending on its substrate, surface conditions, and thickness. As shown in Fig. 3, illumination increased the stiction force in all the samples. Illumination also increased the apparent spring constant of the cantilever beam by 10%. For a spherical tip, the Casimir force can be calculated as follows [18]:

$$F_{Casimir} = \frac{r(\hbar)\omega_p}{32\sqrt{2}l^2} \qquad (2)$$

where, $\hbar$ is the Planck's constant, "r" is the radius of the spherical tip, ω_p is the plasma frequency which is as high as ~10^{16} rad/s for most metals [19] and "l" is the distance between the tip and sample (0.2 nm).

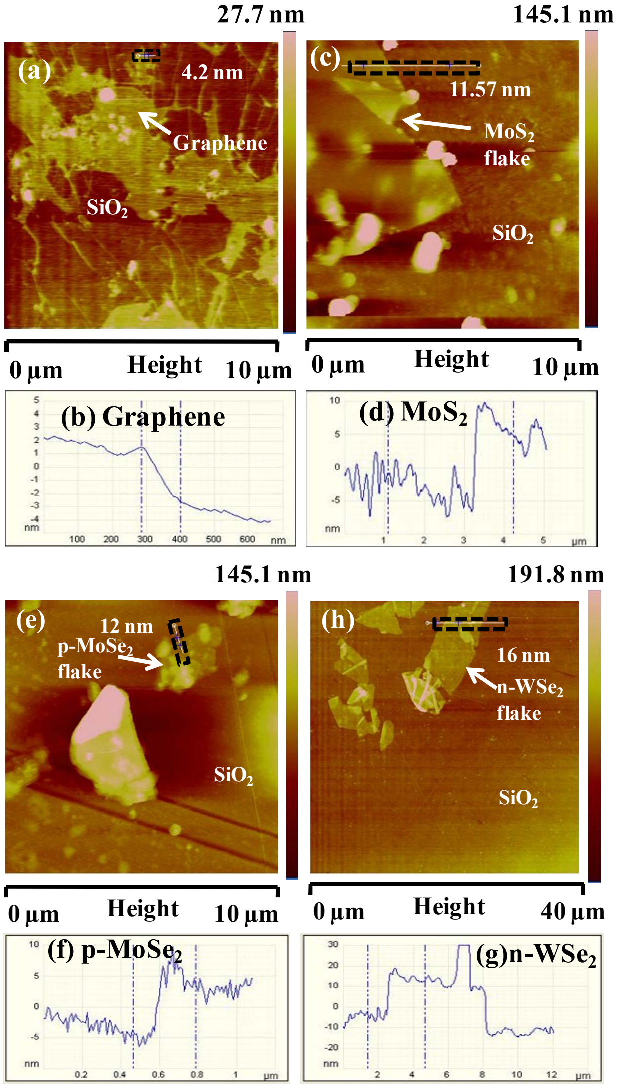

Figure 2: AFM image of the samples prepared by mechanical exfoliation and corresponding height profile.

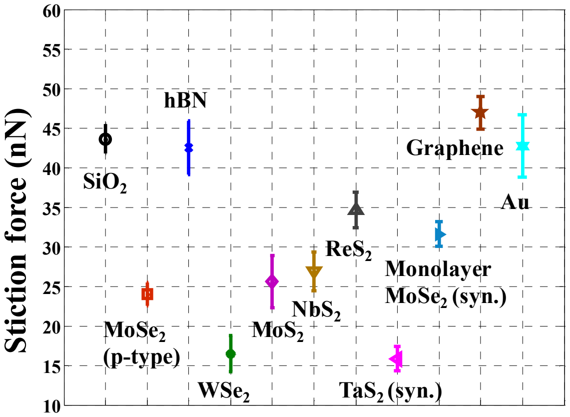

Figure 3: Stiction/adhesion force in dark.

The plasma frequency of graphene is taken to be ~7x10^{16} rad/s for our calculations [19]-[20]. According to equation (2), the Casimir force is 42 nN (in dark) which is in good agreement with 47 nN measured using the AFM probe (Fig. 2) and in agreement with the Hamakar coefficient of 1.49x10^{-19} J.

Plasma frequency can change due to electron-hole pair generation according to the following equation [19]:

$$\omega_p = \sqrt{\frac{N_{e,h}q^2}{m^*_{e,h}\varepsilon_0}} \qquad (3)$$

where $N_{e,h}$ is the carrier concentration, q is the electron charge, $m^*_{e,h}$ is the effective mass of electron or hole and ε_0 is the permittivity of the medium. Taking $m^*_{e,h}$~0.8 m_0 (m_0 is the electron mass) and $N_{e,h}$~3x10^{20} cm^{-3}. A change from 47 nN to 52 nN surface adhesion force, indicates that the $N_{e,h}$ was increased from 3x10^{20} cm^{-3} to 3.6x10^{20} cm^{-3} under the illumination.

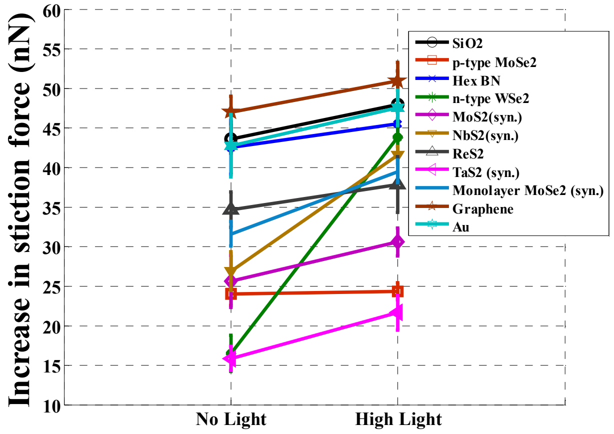

Figure 4: Increase in stiction/adhesion force due to illumination.

This is quite reasonable given the large absorption coefficient of the graphene that absorbs a wide range of wavelengths (due to its near zero energy band gap) and the fact that our illumination source was wide-bandwidth (incandescent) light.

An optical micro-actuator can be devised using WSe_2 as one of its plates and a cantilever beam in stiction with WSe_2. Upon illumination of the WSe_2 layer the stiction force will increase causing the cantilever beam to move closer to the WSe_2 substrate. This actuator can be used in valves and switches.

Table 1: Increase in adhesion force due to illumination (mean values are used for calculation).

Sample	*F (nN)*	*ΔF (nN)*
SiO2	*43.6*	*4.4*
P-type $MoSe_2$	*24*	*0.3*
Hex BN	*42.5*	*3*
n-type WSe_2	*16.5*	***27.3***
MoS_2 *(synthetic)*	*25.6*	*5*
NbS_2 *(synthetic)*	*26.8*	*14.7*
ReS_2	*34.6*	*3.2*
Syn. TaS_2	*15.8*	*5.8*
Monolayer $MoSe_2$ *(syn.)*	*31.6*	*8*
Graphene	*47*	*4*
Au	*42.7*	*4.8*

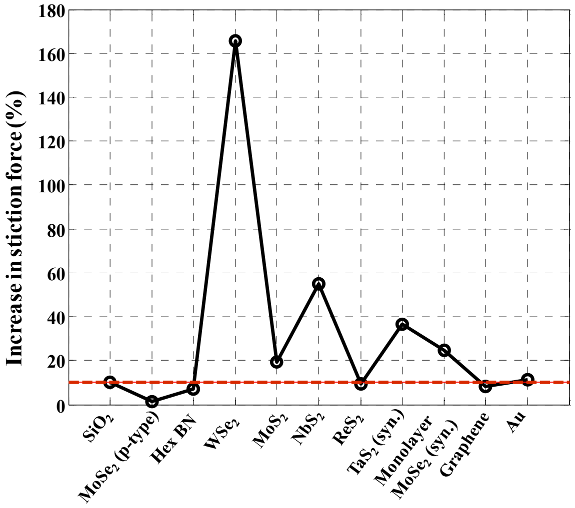

Figure 5: Percentage increase in stiction force due to illumination.

For an effective spring constant of 0.01 N/m, the increase in the WSe_2 surface adhesion force of 27 nN, will result in a change in displacement of $\Delta x \sim 3\ \mu m$.

CONCLUSION

Surface adhesion force of eight layered materials (ReS_2, NbS_2, WSe_2, MoS_2, $MoSe_2$, hexagonal BN, TaS_2 and graphene) were examined and were found to increase under illumination with white light. The largest change was measured in WSe_2 and the smallest change was in MoS_2 followed by ReS_2, graphene and hBN. Photoconductivity is responsible for the observed increase in the surface adhesion force. The change in the surface adhesion force of these layered materials can be used in photoactuators to generate appreciable forces and displacements.

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