# Observation of the Amontons-Coulomb law on the nanoscale: Frictional forces between $MoS_2$ flakes and $MoS_2$ surfaces

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# Observation of the Amontons-Coulomb law on the nanoscale: Frictional forces between $MoS_2$ flakes and $MoS_2$ surfaces

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**Abstract.** – The $MoS_2$ flake moves on $MoS_2$ in such a way that the stacking of the sulphur basal plane of $MoS_2$ is maintained. The frictional forces between $MoS_2$ surfaces are clearly proportional to the loading force although they depend strongly on the movement of the $MoS_2$ flake. The Amontons-Coulomb law is excellently satisfied at loading forces in the range of 1–120 nanonewtons. The frictional coefficient between $MoS_2$ surfaces along the direction $[10\bar{1}0]$ of the $MoS_2(0001)$ surface is estimated to be approximately 0.003.

It has long been known that the layer materials such as graphite, muscovite mica and $MoS_2$ exhibit small friction. However, the reason why they exhibit small friction has not been clarified in full because the friction occurring at layer materials involves grains in the interface and surface deformations. In the case of $MoS_2$, with the exception of a paper [1] indicating that ultralow friction occurs at $MoS_2$ flakes on $MoS_2$, there are few experimental studies on friction between $MoS_2$ surfaces despite the fact that $MoS_2$ is a very important lubricant. In this paper [1], it has been reported that ultralow friction with a friction coefficient of $10^{-3}$ order is caused by the friction-induced orientation of easy shear basal planes of the $MoS_2$ crystal structure parallel to the sliding direction.

In this letter, we report that a $MoS_2$ flake moves on $MoS_2$ in such a way that the stacking between sulphur layers of $MoS_2$ is maintained. These frictional-force maps from the $MoS_2$ flake on $MoS_2$ (surface friction) exhibit a pattern quite different from that of a tip on $MoS_2$ [2] (henceforth called tip friction). We here demonstrate, for the first time, that the Amontons-Coulomb law is excellently satisfied at loading forces in the range of 1–120 nanonewtons, based on the atomic-scale movement of a $MoS_2$ flake.

A $MoS_2$ substrate was prepared by cleaving a natural $MoS_2$ block. A $MoS_2$ flake with an area of 1mm square and a thickness of several micrometers was used. Normal and lateral forces were measured simultaneously under a relative humidity of below 50% at room temperature, using a commercially available instrument (Seiko Instruments Inc., SPI-3700). There was not a prominent difference between the lateral forces measured under different relative humidities. The scan speed was 0.13 $\mu$m/s. The lattice orientations of the upper $MoS_2$ flake and lower $MoS_2$ substrate were not specified with respect to the sliding direction because the scan direction for a $MoS_2$ flake on the $MoS_2$ substrate was arbitrarily taken. A rectangular silicon cantilever with a $Si_3N_4$ tip (a normal spring constant: 0.75 N/m) was used. Zero normal

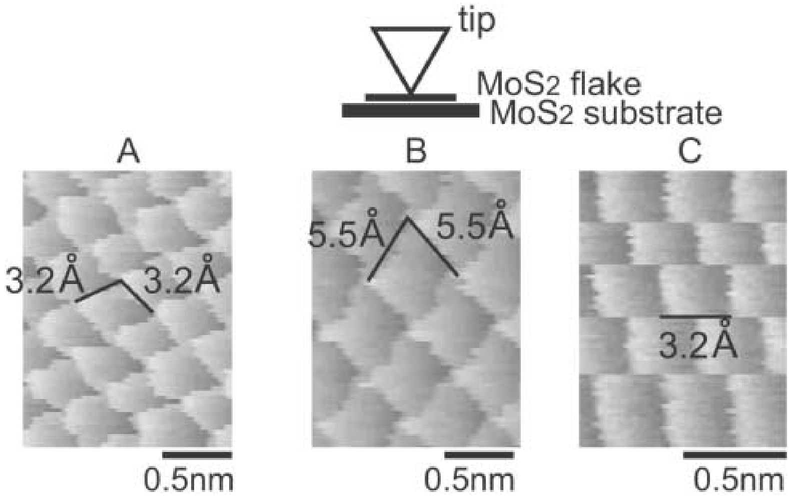


Fig. 1 – Three $x$ frictional-force maps at different areas from a $MoS_2$ flake on $MoS_2$ obtained by scanning along the $x$-direction.

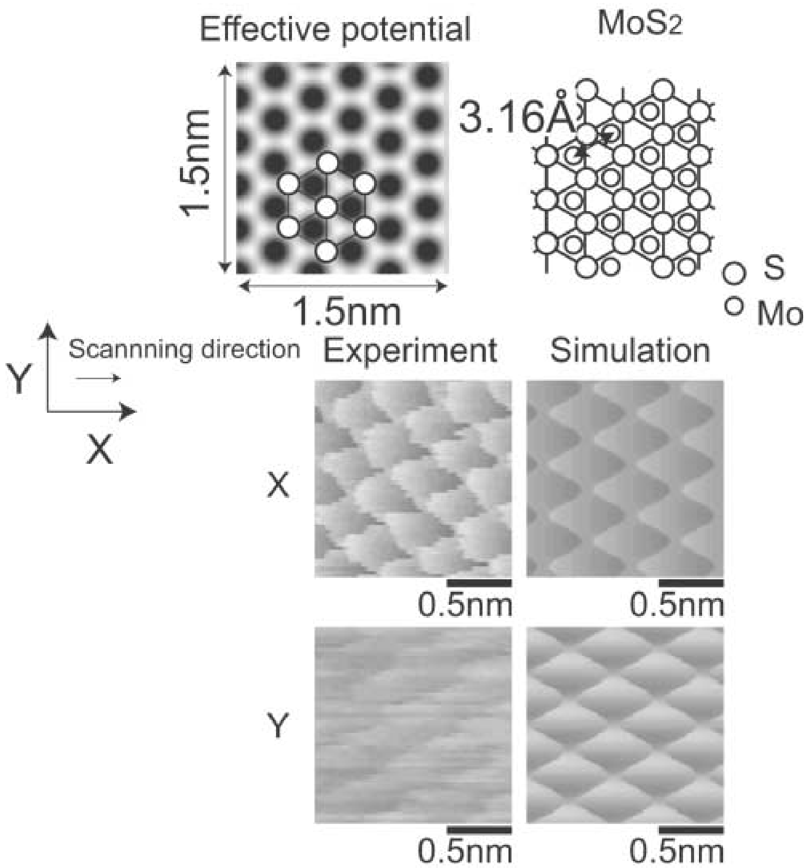


Fig. 2 – Experimental data and theoretical simulation for type A of fig. 1.

force is defined as the position at which the cantilever is not bent. The frictional forces were calibrated by using the method of Meyer *et al.* [3].

Figure 1 shows three different $x$ frictional-force maps from a $MoS_2$ flake on $MoS_2$ scanned along the $x$-direction. It should be noted that these exhibit scaled (types A and B) and square (type C) patterns, clearly different from that of a tip on $MoS_2$ from the standpoint of a periodic pattern and contrast (see figures on the left-hand side of fig. 4 below). Noting that this system consists of friction between a tip and a $MoS_2$ flake and that between a $MoS_2$ flake and $MoS_2$, it was found that the friction from this system includes two different mechanisms. However, it can be concluded that the frictional features of a flake on $MoS_2$ exhibit only friction between a $MoS_2$ flake and $MoS_2$ because they do not include the frictional-force map from a tip on $MoS_2$. This means that the friction between a tip and a $MoS_2$ flake is greater than that between a $MoS_2$ flake and $MoS_2$. Now, we consider type A of the frictional-force map, which is the standard pattern appearing in this experiment. The movement of the flake on $MoS_2$ is substituted into the movement of a single particle moving with a constant velocity in the effective potential for type A, as follows: $V = V_0 \left\{ 2\cos\left(\frac{2\pi}{a}x\right)\cos\left(\frac{2\pi}{a\sqrt{3}}y\right) + \cos\left(\frac{4\pi}{a\sqrt{3}}y\right)\right\}$,

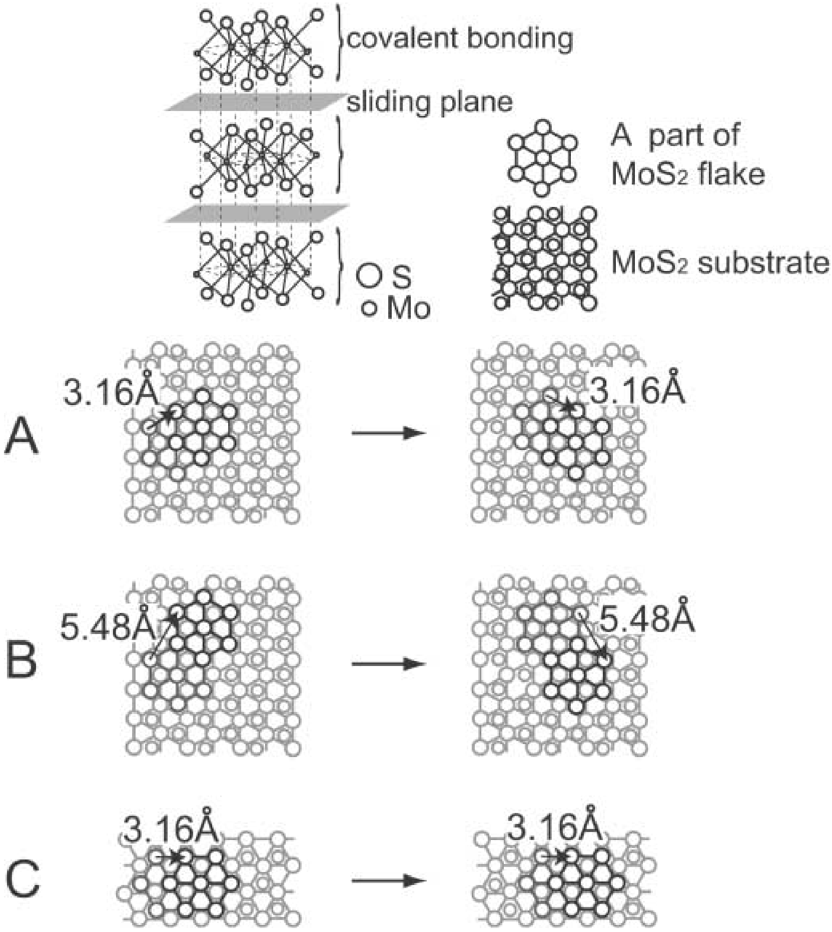


Fig. 3 – The three types (A, B and C) of the $MoS_2$ flake movement are shown; the arrows represent the scanning direction.

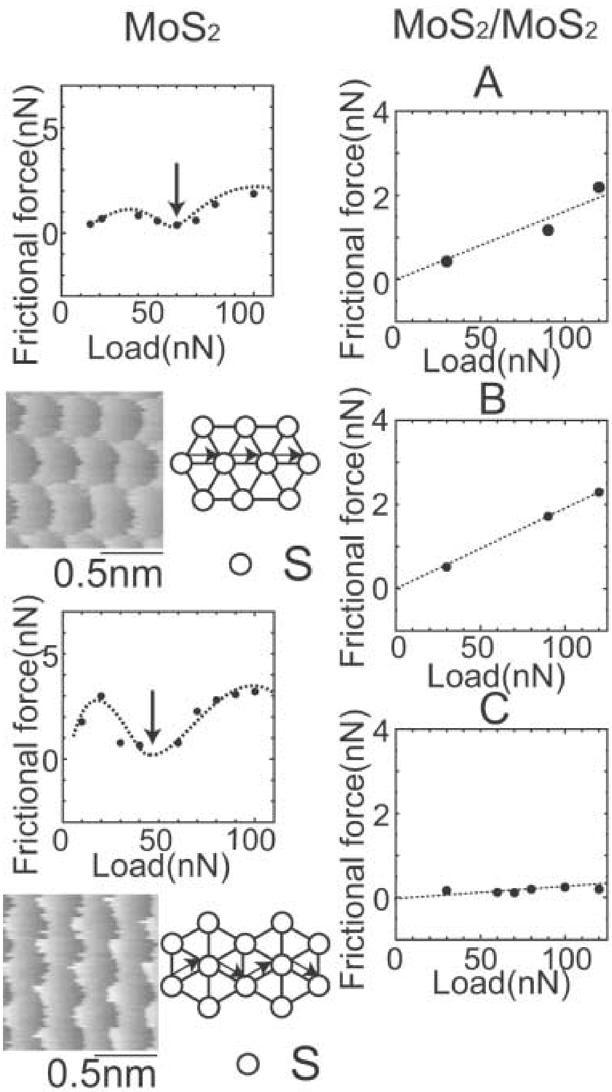


Fig. 4 – The frictional forces in relation to the loading force for the surface friction (right-hand side) and for the tip friction (left-hand side). Images and arrows on the left-hand side represent frictional-force maps and the tip movement, respectively.

where $a = 0.316$ nm. This effective potential is determined so that it takes the minimum values at the natural stacking relation of $MoS_2$. The result of this simple preliminary simulation is in excellent agreement with the experimental data shown in fig. 2. Here, the spacing of $a = 0.316$ nm indicates a jump to the next stable position maintaining the stacking of $MoS_2$, as shown in fig. 3. Similarly, it is also revealed that the movements for types B and C are performed in such a way that the natural stacking relation of $MoS_2$ is maintained, as shown in fig. 3.

The mean frictional forces for different movements in relation to the loading force are shown on the right-hand side in fig. 4. These are all proportional to the loading force although they depend strongly on the movement of the $MoS_2$ flake. Thus, the proportional coefficients

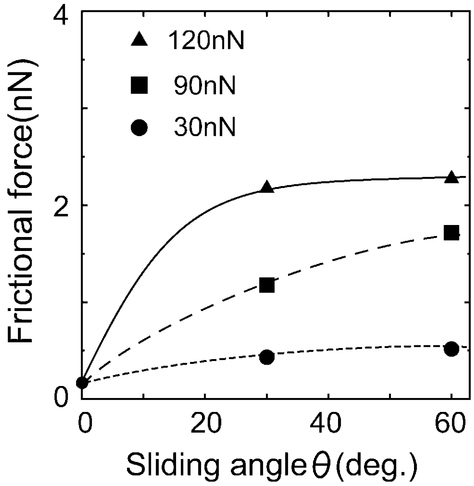


Fig. 5 – The frictional forces *vs.* the sliding angle deduced from the data of fig. 4, where the sliding angles for cases A, B and C are 30°, 60° and 0°, respectively.

defined as $\mu_{\mathrm{A}}$, $\mu_{\mathrm{B}}$ and $\mu_{\mathrm{C}}$ for the cases A, B and C are estimated to be approximately 0.01, 0.02 and 0.003, respectively. The proportional coefficient $\mu_{\mathrm{C}}$ for the case C is much smaller than $\mu_{\mathrm{A}}$ and $\mu_{\mathrm{B}}$ for the cases A and B, which corresponds to the frictional coefficient $\mu_{10\bar{1}0}$ and is close to the experimental value (below 0.002) obtained by Martin *et al.* [1]. Thus, it is found that the $MoS_2$(0001) flake is easy to shear along the direction [10$\bar{1}$0] of the $MoS_2$(0001) surface. Surprisingly, the frictional coefficient for the case B is eight times larger than that for the case C. Proportionality of the frictional forces in relation to the loading force also reveals that the contact area between $MoS_2$ surfaces $S$ is proportional to the loading force $F_N$, using the relationship $F = \mu F_N = \tau S = \tau\alpha F_N$, where $\alpha$ represents the proportional constant. This indicates that surface deformation is significantly smaller in $MoS_2$ than in graphite because the lamellar $MoS_2$ consists of covalent bonding, which behaves like a hard plate. Along the different scanning directions of the $MoS_2$(0001) surface, a tip performs one-dimensional stick-slip and zigzag stick-slip motions, shown on the left-hand side in fig. 4. This behavior is similar to that of ionic surfaces [4]. In the case of an ionic surface, the minimum points (shown by the arrows) appear before large distortions of the surface occur. Thus, it is inferred that large distortions of the surface occur even in $MoS_2$ triple layers after the minimum points shown by the arrows. Furthermore, it is interesting to note that these results are in good agreement with a recent computer simulation result by Wenning *et al.* [5], *i.e.*, shear forces for tip friction have a strongly oscillatory component and shear forces for surface friction obey the Amontons-Coulomb law of friction.

Now, the anisotropy of the frictional force for a different directional movement of the flake *vs.* the pulling direction is shown in fig. 5 from the results of fig. 4, which appears depending on the sliding angle $\theta$, denoted as the angle between the direction of the flake movement and the pulling direction. One notes that the frictional forces *vs.* the sliding angle increase strongly with a higher load. Furthermore, the frictional forces are found to increase with the increase of the sliding angle, which, interestingly, is consistent with the frictional mechanism between flat surfaces discussed by Gyalog and Thomas [6]. These results lead to the following two points: i) in the case where the flake movement is parallel to the pulling direction, the frictional force is smallest. ii) In the case where the direction of the flake movement is not parallel to that of the pulling force, the flake does not move toward the next stable point until the projection of the pulling force is coincident with the force necessary to begin moving toward the next stable point. Thus, the larger the sliding angle, the larger the pulling force. In case B, the energetic barrier is supposed to be very large because the path to the next stable point takes the path of the stacking (S atom above S atom). Here, it may make sense to discuss the term "incommensurability" introduced by Hirano *et al.* [7]. They measured the frictional forces of muscovite mica as a function of the lattice misfit angle between the two contacting cleavage lattices and found that the frictional forces are anisotropic with respect to the lattice misfit angle, *i.e.* the frictional forces increase (decrease) when the surfaces approach being commensurate (incommensurate). However, the appearance of the anisotropy of the frictional force in this experiment reveals that a $MoS_2$ flake on $MoS_2$ always takes the initial and final positions so that the stacking of the sulphur basal plane of $MoS_2$ is maintained. Thus, the two contacting $MoS_2$ surfaces are always commensurate and the sliding direction of the $MoS_2$ flake does not always coincide with that of the pulling direction, which may be different from the conclusions of Hirano *et al.*

Furthermore, the results obtained here may give an explanation to the problem why the friction of the system including various flakes is generally small, *e.g.*, a friction force acting on many flakes with different movements may be close to zero, which is consistent with a friction coefficient of 0.001 for two $MoS_2$ surfaces with poly-crystalline microstructures obtained by Le Mogne *et al.* [8].

This study reveals the change in the frictional behavior when the frictional mechanism is transient from a single-atomic tip to a large-area flake tip (compare data on the left-hand side in fig. 4 with those on the right-hand side). There is a prominent difference between frictional-force maps of tip friction and those of surface friction. In this study, we did not treat the flake movement as that of an elastic material but as that of a rigid material; nevertheless, we could understand the movement successfully. The $MoS_2$ flake moves on $MoS_2$ so that the stacking of the sulphur basal plane of $MoS_2$ is maintained. However, the frictional forces between $MoS_2$ surfaces are proportional to the loading force and depend strongly on the movement of a $MoS_2$ flake. The frictional coefficient $\mu_{10\bar{1}0}$ at the sliding angle $\theta = 0°$ is estimated to be approximately 0.003, which indicates that a $MoS_2$ flake is easy to shear along the direction $[10\bar{1}0]$ of the $MoS_2(0001)$ surface. These findings also provide us important information of how to decrease friction between $MoS_2$ surfaces.

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REFERENCES


[1] MARTIN J. M., DONNET C., LE MOGNE TH. and EPICIER TH., *Phys. Rev. B*, **48** (1993) 10583.
[2] FUJISAWA S., KISHI E., SUGAWARA Y. and MORITA S., *Phys. Rev. B*, **51** (1995) 7849.
[3] MEYER E., OVERNEY R. M., DRANSFELD K. and GYALOG T., *Nanoscience: Friction and Rheology on the Nanometer Scale* (World Scientific, Singapore) 1999, p. 347.
[4] ISHIKAWA M., OKITA S., MINAMI N. and MIURA K., *Surf. Sci.*, **445** (2000) 488.
[5] WENNING L. and MÜSER M.H., *Europhys. Lett.*, **54** (2001) 693.
[6] GYALOG T. and THOMAS H., *Europhys. Lett.*, **37** (1997) 195.
[7] HIRANO M., SHINJO K., KANEKO R. and MURATA Y., *Phys. Rev. Lett.*, **67** (1991) 2642.
[8] LE MOGNE T., DONNET C., MARTIN J. M., TONCK A. and MILLARD-PINARD N., *J. Vac. Sci. Technol. A*, **12** (1994) 1998.