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Acoustically-driven femtosecond laser ablation of atomically thin molybdenum disulfide

Malte J. M. J. Becher^{1*}, Anton Saetchnikov¹, Leander Vogel², Ralf Nett¹, Yannis Laplace³, Tingwen Guo³, Pavel Varlamov³, Charlie Massé³, Claudia Bock², Andreas Ostendorf¹, Evgeny L. Gurevich^{4,5} and Vasily V. Temnov^{3*}

Abstract: Femtosecond (fs) time-resolved microscopy is employed to investigate the dynamics of transient Newton rings generated during fs-laser ablation of nanometer-thin films of MoS₂, AuPd and hybrid AuPd/MoS₂ bilayers. By systematically varying the film thickness L , a thickness-independent ablation behavior is revealed, characterized by a constant absorbed energy density at the ablation threshold. Expansion velocities of the ablating films are extracted from the temporal evolution of the Newton ring fringes. These velocities are largely independent of film thickness, consistent with a thermoelastic model explaining the acoustic delamination at the film-substrate interface. This study provides quantitative insight into ultrafast thin film ablation mechanisms and outlines new approaches for engineering transient 2D material architectures with potential applications in nanophotonics and ultrafast quantum optics.

Keywords: femtosecond laser ablation; thin films; 2D materials; ultrafast microscopy; photo-acoustics

Introduction

In accordance with Moore's law, recent research has focused on the continued miniaturization of transistor structures. In parallel with these developments, flexible electronic devices are increasingly gaining market relevance due to their integration into wearable and conformal technologies. The combination of the exceptional electronic, mechanical, optical, and quantum-optical properties of 2D materials^{1–3} with deformable substrates has the potential to unlock new application spaces inaccessible to conventional silicon (Si) technology⁴. Molybdenum disulfide (MoS₂), one of the most widely studied 2D materials, is an indirect bandgap semiconductor with a gap of approximately 1.3 eV in the bulk, which transitions to a direct bandgap of around 1.9 eV in the monolayer limit⁵. Such layers can be prepared by low-temperature atomic layer deposition (ALD), which is a scalable and precise technique that enables the uniform deposition of MoS₂ over large areas on different substrates, including glass⁶. In addition to being a scalable and precise technique, ALD allows layer-by-layer control of film thickness across wide deposition areas. This not only opens opportunities for large-scale

electronic applications, but also enables fundamental studies, since the precise control down to the monolayer limit (~0.65 nm for MoS₂) introduces an entirely new regime for investigating physical mechanisms.

Among the various techniques for precision nanopatterning of thin films, an essential requirement for most applications, ultrashort (femtosecond to picosecond) laser nanofabrication is particularly valuable due to its non-contact operation and minimal heat-affected zone^{7–10}. As the primary mechanism for laser-induced material removal, femtosecond (fs) laser ablation of thin films and multilayer structures remains a topic of ongoing interest in both fundamental and applied research. However, the fs-laser ablation behavior of ultrathin films, i.e., those with thicknesses significantly below the optical absorption length, remains largely unexplored.

Thermodynamic, photo-chemical, photo-mechanical and photo-acoustic ablation mechanisms have been proposed to explain the majority of fs-laser nanofabrication regimes^{11–14}. The use of fs-laser pulses for ablation and structuring of exfoliated MoS₂ flakes has been demonstrated by several groups, but the ablation mechanism, especially for

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ALD-grown thin films and multilayer systems, remains poorly understood. The high optical transparency of such layers alters the laser coupling with the material, leading to the formation of a spatially homogeneous heating profile in the film, in contrast to exponential profiles usually observed in thicker samples due to the combined action of finite skin depth and hot electron diffusion¹⁵. In this study, we show that this homogeneous profile fundamentally modifies the physics of fs-laser ablation.

Femtosecond time-resolved pump-probe microscopy, which was developed to study laser-induced melting and ablation of bulk silicon on the sub-nanosecond time scale¹⁶, also has proven especially effective for studying processes on the nanosecond time scale when combined with high-resolution optics¹⁷. This technique has since been widely applied to investigate ablation dynamics in a range of materials, including thin film systems. In these experiments, the observation of transient interference fringes (Newton rings) revealed non-equilibrium phase transitions, including the formation of a thin, semitransparent shell of laser-melted material expanding into a vacuum¹⁸.

In thin film geometry, transient Newton rings revealed the dynamics of 100 nm and 500 nm fused silica layers driven by thermal expansion of a fs-laser-excited, absorbing silicon substrate¹⁹: the expansion velocity was found to decrease for thicker fused silica layers. In another experiment, during fs-laser ablation of a 20 nm-thick Ni layer on glass, the observation of multiple Newton ring patterns revealed complex ablation dynamics, featured by the separation of the film into two sub-layers propagating at different velocities²⁰.

These prior studies demonstrate the sensitivity of Newton ring analysis to nanoscale film dynamics, providing a foundation for extending this approach to the ultra-thin, 2D material regime investigated here.

Results

In this study, we performed time-resolved microscopy in transmission geometry (Fig. 1(a)) on ablating thin films and multilayers. We observed the formation of transient Newton rings on nanoscale thin films of semiconducting MoS₂ with thicknesses ranging between $1.8 \text{ nm} \leq L_{\text{MoS}_2} \leq 11.6 \text{ nm}$, thin films of gold-palladium (Au₈₀Pd₂₀) alloy with thicknesses between $10 \text{ nm} \leq L_{\text{AuPd}} \leq 35 \text{ nm}$ and hybrid systems consisting of MoS₂ coated with gold-palladium (Au₈₀Pd₂₀) alloy. Figure 1(a) shows a schematic setup and build-up of the process. The build-up of Newton rings during laser ablation indicates the formation of a transient cavity where light is partially reflected by the ablating front¹⁷, which enabled systematic measurements of ablation velocities as a function of film thickness and composition (Fig. 3S and Fig. 4S). In addition, we compared the expansion velocities of pristine MoS₂ with those of the bilayer MoS₂/AuPd system. Our analysis revealed that the expansion velocities are independent of film thickness (or mass)

for equal absorbed energy densities. This implies a nontrivial conversion pathway of the absorbed laser energy into kinetic energy, where the mass increase for thicker (heavier) films is compensated by spatially distributed compression forces generated within the homogeneously excited layer resulting in the thickness-independent expansion velocity. In order to explain this counterintuitive experimental observation, we proposed a simple phenomenological model that calculates the center-of-mass dynamics of fs-laser-excited thin films based on the resulting acoustic transients. Nondestructive acoustic measurements in the low-intensity regime confirmed the generation of picosecond acoustic pulses in all investigated samples. The developed phenomenological model is in qualitative agreement with Newton ring analysis. Application of the thermo-acoustic model allowed us to elucidate the ablation mechanism and quantify the expansion velocity after the separation from the substrate, see the schematic in Fig. 1(b).

In the low-fluence regime, the optically transparent substrate remains unperturbed and the cavity is formed by (possibly melted) thin films delaminated from the surface²¹.

By counting dark rings of the interference pattern, the distance between the film and substrate can be accurately measured. With the probe wavelength $\lambda = 400 \text{ nm}$ minimum (dark) or maximum (bright) ring appears every 200 nm of traveled distance. The transient position of the ablating film in the center $X = (n_{\text{dark}} - 1/2) \cdot \lambda/2$ is calculated by counting the number of dark rings n_{dark} . Here, $X(t)$ denotes the effective displacement of the film front. In experiments it is extracted from Newton ring counting, while in the thermo-acoustic model (V) it corresponds to the center-of-mass displacement of the film. We use this notation consistently throughout the manuscript. The expansion velocity v_x is plotted as a function of the incident fluence in Fig. 3S. The velocities for different thicknesses of the layers appear to be linear functions of incident fluence and stay below 250 m/s, see also Fig. 4S for AuPd films.

At first glance, the experimental data in Fig. 2S seem to strongly depend on the material and their thickness (MoS₂ or AuPd-loaded MoS₂). However, the incident laser fluence F_{inc} does not represent a relevant physical quantity. Neither does the absorbed laser fluence $F_{\text{abs}} = A \cdot F_{\text{inc}}$ (where A denotes the absorption coefficient), since it does not account for the film thickness L . In this paper we claim that the absorbed energy density $W = F_{\text{inc}} \cdot (A(L)/L)$ in [kJ·cm⁻³] represents a relevant parameter, which i) defines the ablation threshold and ii) facilitates the theoretical interpretation of the experimental data.

Thickness-dependent optical constants for MoS₂⁵ have been measured ellipsometrically and used to calculate $A(L)$ (see the Supplementary Information (SI)) and obtain W for all samples. The inset in Fig. 2(a) shows that the absorbed laser density at the ablation threshold $W_{\text{thr}}(L) \sim 12 \text{ kJ/cm}^3$ appears to be L -independent. We attribute this

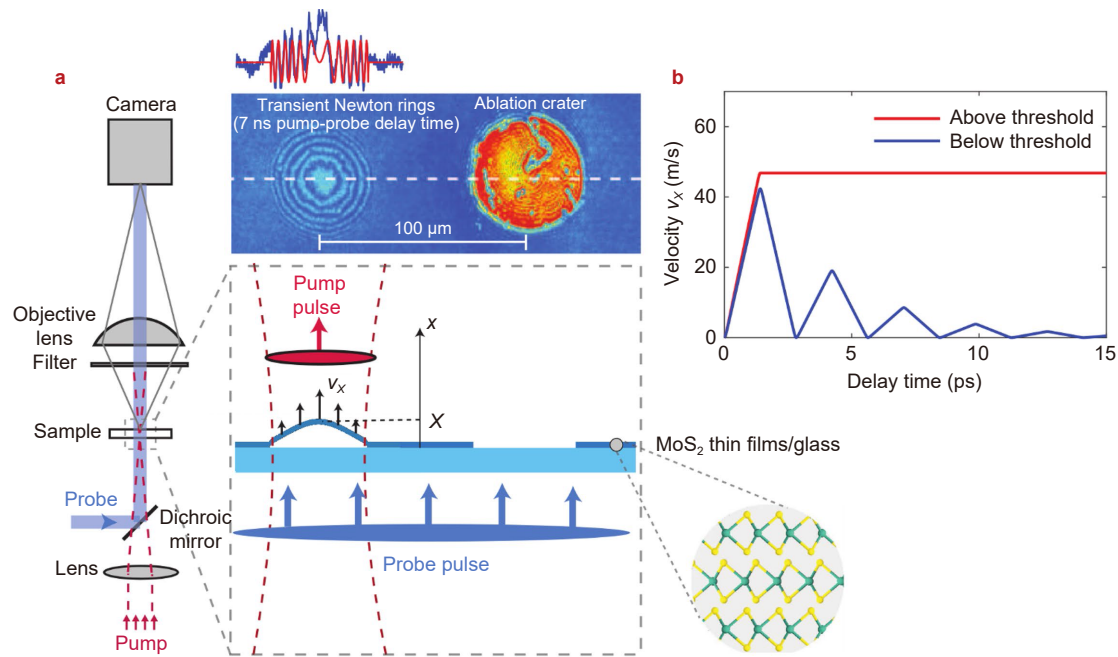


Fig. 1 | (a) Imaging pump-probe microscopy in the transmission geometry captures the dynamics of ablating thin film. The time-delayed probe pulse generates Fabry-Perot-type interference fringes formed by light reflection from the substrate and a nanometer-scale semi-transparent ablating thin film moving at a maximum velocity v_x . The horizontal cross-section (along the white dashed line) of the probe image (blue) can be accurately reproduced using a two-beam interference model (red). (b) Schematics of velocity dynamics $v_x(t)$ below and above the ablation threshold (see Fig. 5S and text for calculation details). This unified interpretation of both nondestructive (acoustic) and destructive (ablation) regimes demonstrates that the expansion dynamics of the film are governed by the same underlying thermoelastic processes across a broad range of excitation conditions. In this way, our study bridges the gap between nondestructive photo-acoustic response and ablation behavior in fs-laser-excited thin films. The observation of transient Newton rings in films as thin as 1.8 nm highlights the capability of this metrology to resolve ultrafast dynamics in few-layer 2D materials.

L -independent behavior to the fact that all investigated films remain significantly thinner as compared to the laser absorption depth $h \sim 100$ nm ($h \approx \lambda_{\text{pump}}/4\pi k$) resulting in the spatially homogeneous excitation of the film. The relation between the spatial profile of the absorbed energy density and the ablation threshold for much thicker AuPd thin films is provided in the SI.

Let us turn to the analysis of expansion velocities, which represent the main subject of this paper. The dependence of expansion velocities from Fig. 3S on W for different L is presented in Fig. 2(a). The surprising result is that for MoS₂ also the expansion velocity v_x is nearly independent of the layer thickness. AuPd-loaded MoS₂ samples display much slower expansion velocities, an expected result due to the spatially inhomogeneous heating of a 80 nm-thick AuPd overlayer, in agreement with previous experimental observations on thicker SiO₂ films¹⁹. It is instructive to analyze the expansion dynamics below the ablation threshold. Nondestructive femtosecond time-resolved pump-probe measurements on a AuPd(80 nm)/MoS₂(7.5 nm)/glass sample reveal photo-acoustic oscillations induced by the propagation of acoustic pulses inside the film. Figure 2(b) demonstrates that the time-resolve reflectivity signal can be accurately reproduced by acoustically induced oscillations of the film thickness $\Delta L(t)$ occurring at a period $2L/c_s \sim 50$

ps. The photo-acoustic model used to obtain theoretical fits in Fig. 2(b) can be also used to calculate the oscillating dynamics of the center-of-mass motion $v_x(t)$ of the film below the ablation threshold in Fig. 2(c). These dynamics clearly demonstrate photo-acoustic oscillations with the same period and peak expansion velocities of a few meters per second suggesting that the acoustical model might be also useful to interpret the irreversible dynamics of ablating thin films shown in Fig. 2(a).

Discussion

This experimental observation of thickness-independent expansion velocities and ablation thresholds quantified using the concept of the absorbed energy density, stimulated the development of a theoretical model explaining the ablation mechanism. To explore the underlying physics of the observed expansion velocities, we first evaluated a phenomenological approach based on Gurney theory, which describes the conversion of absorbed energy into kinetic energy in ablating films²³. This theory assumes the energy conversion without losses, so that the velocity of flying film depends on the square root of the ablated mass m as $v = \sqrt{2E/m}$. Substituting the mass of the film m as the film density ρ multiplied by the thickness L and the laser spot area, one can see that in the frames of this theory the

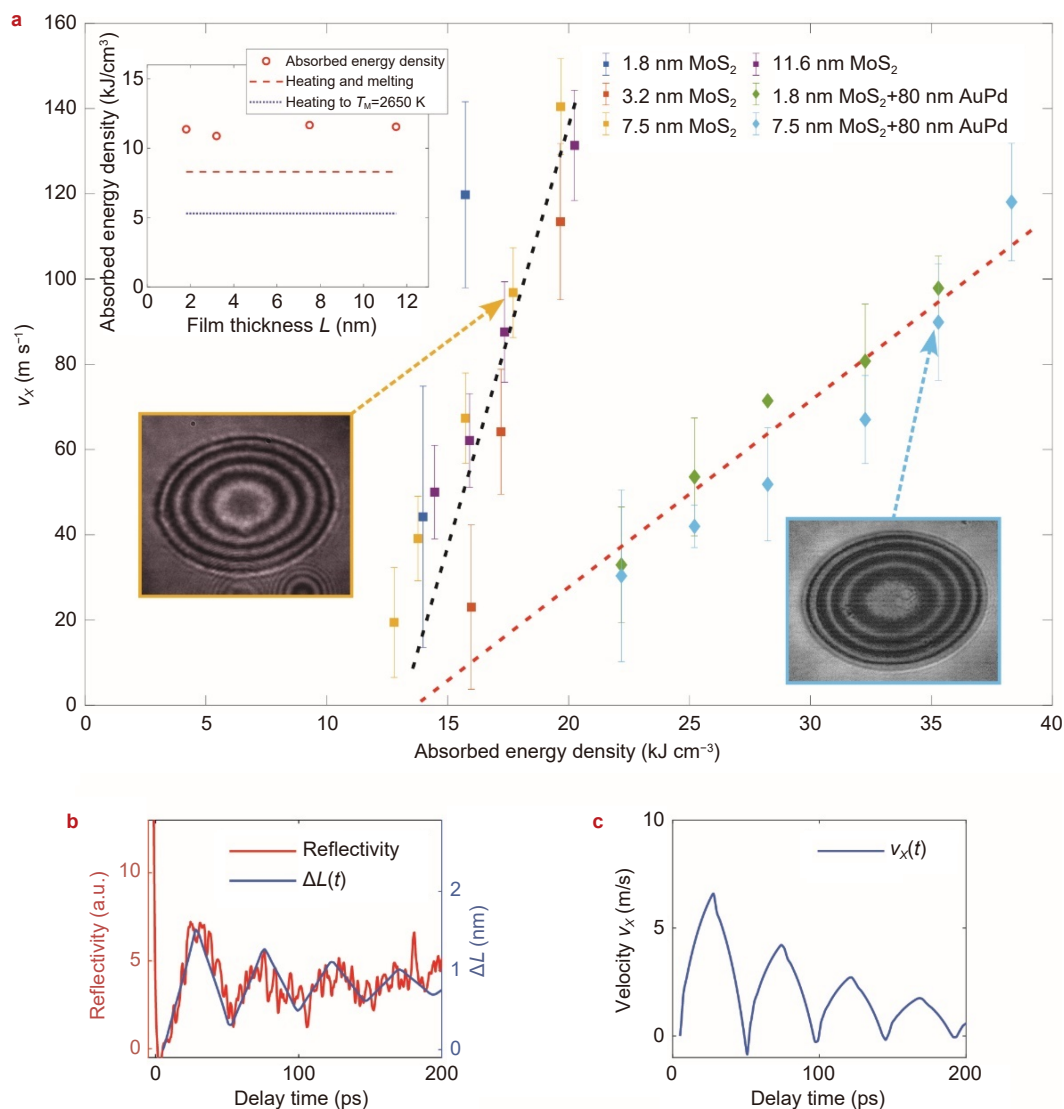


Fig. 2 | (a) Above the ablation threshold: the expansion velocity v_x as a function of the absorbed energy density in MoS₂ and MoS₂ loaded with Au₈₀Pd₂₀ thin films, with two examples of transient Newton rings for a 7.5 nm thin MoS₂ film and a (7.5 nm)MoS₂/(80 nm)AuPd bilayer. The inset shows the absorbed energy density at the ablation threshold $W_{\text{abs}}^{\text{thr}}$ for MoS₂ thin films of different thickness $L=1.8$ nm, 3.2 nm, 7.5 nm and 11.6 nm. Being thickness-independent, it slightly exceeds the value required for heating up to the melting point and melting but remains below the vaporization limit^{21,22}, suggesting that ablation occurs in a liquid phase. (b) Below the ablation threshold: background-free time-resolved reflectivity signal from a 7.5 nm MoS₂/ 80 nm AuPd bilayer excited with 400 nm pump pulses and probed with 800 nm probe pulses at the AuPd/air interface. Damped oscillations are accurately reproduced with the calculated photo-acoustic oscillations of the film thickness $\Delta L(t)$. (c) The expansion velocity $v_x(t)$ obtained from the acoustic fit in panel (b). See the Discussion Section for details of acoustic simulations and the Supplementary Information for the calculations of the absorbed energy density.

velocity must depend on the layer thickness as $v = \sqrt{2F/\rho L}$. However, our experiments show that the velocity does not depend on L . Thus, this model did not satisfactorily account for our experimental observations leading us to adopt the photo-acoustic model²⁴, which describes the initial stage of absorbed energy conversion in acoustic waves. Note that ultrafast photo-acoustics has been successfully applied to quantify the heat penetration depth h in fs-laser-excited thin films²⁵ and also applied to interpret fs-laser spallation^{26,27} and ablation²¹ thresholds.

The photo-acoustic model provides a simple yet quanti-

tative framework for simulating the expansion dynamics of fs-laser-excited thin films²⁴. Driven by a complex interplay between the (nearly instantaneous, deeply sub-picosecond) hot electron pressure and the subsequent electron-phonon relaxation and thermal expansion, the photo-generated stress generates propagating acoustic strain pulses^{28,29}. The dynamics of propagating strains are governed by the acoustic wave equation and provide direct access to the mechanical motion of laser-excited thin film. For our model calculations presented in Fig. 3(a) we assume that a 10 nm MoS₂ thin film (characterized by an acoustic impedance

($Z_{\text{MoS}_2} = c_s \rho_0 = 36 \times 10^6 \text{ kg}/(\text{m}^2 \cdot \text{s})$) on glass ($Z_{\text{glass}} = 13 \times 10^6 \text{ kg}/(\text{m}^2 \cdot \text{s})$) is laser-heated to the melting point. Figure 3(a) shows the dynamics of the displacement $u_x(x, t)$ of atoms with respect their equilibrium position at room temperature, see Ref.³⁰ for calculation details. As such, it should generate the compressional thermal strain of $\varepsilon_{xx} = \partial u_x / \partial x = -2.4\%$, which splits into two counter-propagating compressive acoustic pulses with an amplitude of 1.2%. The finite acoustic reflection coefficient $(Z_{\text{MoS}_2} - Z_{\text{glass}}) / (Z_{\text{MoS}_2} + Z_{\text{glass}}) = 0.47$ at the MoS₂/glass interface determines the decay of damped oscillations of the film due to the energy leakage in the substrate. Figure 3(b) shows the evolution of the displacement u_x of the MoS₂/air and MoS₂/glass interfaces together with the center-of-mass (COM) position of the film:

$$X(t) = \frac{1}{L} \int_0^L u_x(x, t) dx, \quad (1)$$

which describes the COM motion of a vibrating thin film. Figure 3(b) clearly demonstrates that the laser-heated MoS₂ thin film expands in both directions resulting in a much weaker oscillation of the COM motion $\langle u_x(t) \rangle$. We explain this unusual, almost symmetric expansion dynamics of a film (resembling the symmetric dynamics of a free-standing membrane) by a large acoustic impedance mismatch between MoS₂ and the glass substrate $Z_{\text{glass}}/Z_{\text{MoS}_2} \simeq 0.36$, which is closer to a free interface ($Z_{\text{vacuum}}/Z_{\text{MoS}_2} \simeq 0$). The corresponding COM-velocity

$$v_X(t) = \frac{dX(t)}{dt}, \quad (2)$$

reaches the value of 46 m/s, much smaller as compared to the velocities at both film interfaces. In fact, it roughly matches the measured expansion velocity slightly above the ablation threshold in Fig. 2(a). The thermo-acoustic model predicts that all velocities in Fig. 3(c) are independent of the film thickness L . The agreement with L -independent expansion velocities presented in Fig. 2(a) makes us believe that the thermo-acoustic model plays a key role in understanding the origin in fs-laser ablation of thin films. It is equivalent to an intuitive macroscopic toy model - an initially compressed spring of length L (corresponding to film thickness) attached to a substrate, which is released instantaneously at one end at time zero. On the one hand, the distributed force accelerating the spring is proportional to its length. On the other hand, the accelerated mass is also proportional to L . Thus, longer springs are heavier, but the accelerating force is also higher, so that the maximum acquired COM-velocity of the spring becomes L -independent.

To clarify the mechanism of thin film delamination we examined the dependence of the acoustic strain at the MoS₂-glass interface $\varepsilon_{xx}^{\text{MoS}_2/\text{glass}}$ on time, see Fig. 3(d). The initial compressional strain of -0.6 % changes the sign upon the acoustic reflection at the delay time $L/c_s \approx 1.4$ ps, i.e.

exactly at the time when the average film velocity reaches its maximum value of 46 m/s. At the same time the film becomes homogeneously stretched with the potential energy density $\left(0.5c_s^2\rho_0 \int_0^L \varepsilon_{xx}^2 dx\right)/L \simeq 0.5c_s^2\rho_0\varepsilon_{xx}^2 = 0.035 \sim \text{kJ}/\text{cm}^3$.

If the tensile stress $c_s^2\rho_0\varepsilon_{xx}$ (~ 80 MPa for $\varepsilon_{xx} = 1\%$) at the MoS₂/glass interface exceeds the adhesion strength, the film will detach from the surface. The work (per unit surface area) done by this tensile force is estimated to be $c_s^2\rho_0(\varepsilon_{xx}^2/2)a$, where $a = 0.65$ nm is the interlayer distance⁵. In terms of energy conservation, in order to separate the film from the substrate this work should exceed the adhesion strength. To overcome the typical adhesion strength (~ 0.02 mJ/cm²) reported for MoS₂ thin films on glass³¹ one would need to assume the threshold strain amplitude $\varepsilon_{xx}^{(\text{thr})} \sim 2.5\%$, which exceeds values in Fig. 3(c). However, since (i) the absorbed energy density at the threshold significantly exceeds the value needed to reach the melting threshold (see the inset in Fig. 2(a)), the strain in Fig. 3(c) is underestimated and (ii) the adhesion energy at the liquid MoS₂/glass interface is likely to be lower. As such, the potential energy stored in a small fraction of the acoustically stretched film should be sufficient to overcome the adhesion strength.

The above qualitative analysis assumes the nearly instantaneous jump of the strain at a MoS₂ interface. A more realistic modeling would be required to account for finite strain rates, which, indeed, are shown to be relevant in fs-laser-induced spallation experiments with macroscopically thick samples²⁶.

The presented thermo-acoustic ablation model can be useful to quantify more sophisticated ablation mechanisms at higher laser excitations, particularly for systems with significantly stronger mechanical adhesion to the substrate³², as, for example nickel thin films^{20,27}. As mentioned in the introduction, the 20 nm thin ablating nickel film is spalled into two distinct layers²⁰: the large tensile deformation in the middle of the film is responsible for the spallation in the middle of the thin metal layer³³. As a result, there is a significant difference in the COM velocities of the two parts of the film, which qualitatively explains the experimental results reported in Ref.²⁰.

Since the internal spallation and separation from the substrate are expected to occur at different times, the application of imaging time-resolved interferometric microscopy^{34,35} will be essential for obtaining a quantitative understanding of this thin-film ablation in the high-fluence regime.

Furthermore, a combined experimental and theoretical investigation of thin films with varying adhesion strengths - conducted across a broad range of laser fluences - could provide access to the ultimate limit of thermoelastic ablation. This limit is characterized by the maximum expansion velocity $v_X = c_s \ln(\rho_0/\rho_1)$, where ρ_1 is the density of

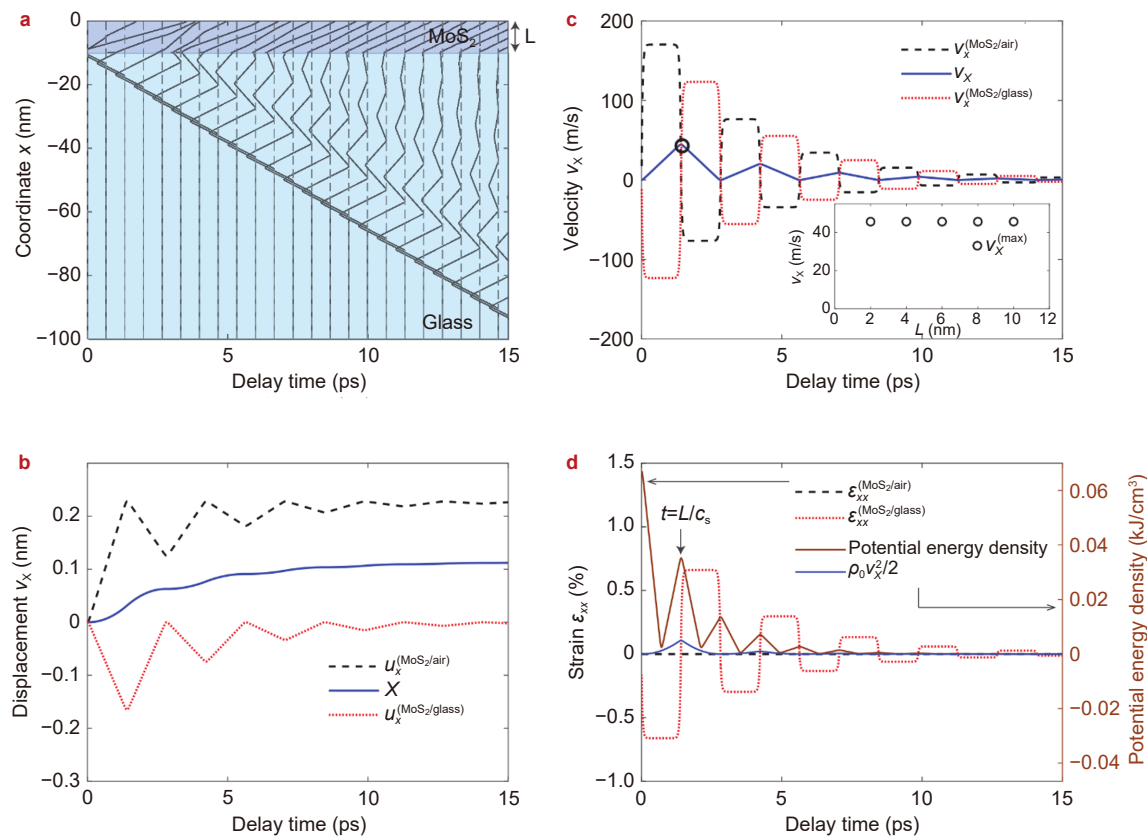


Fig. 3 | (a) The calculated elastic displacement $u_x(x,t)$ of a $L=10$ nm MoS₂ thin film instantaneously heated to the melting point generates acoustic waves inside the film decaying in the glass substrate. (b) Both film interfaces oscillate out of phase with a period $2L/c_s$, resulting in much weaker oscillations of the center-of-mass-motion $X(t)$. (c) The time-derivatives of the curves in panel (b) represent velocities at both interfaces and the COM-velocity $v_X(t)$. The inset shows $v_X(t)$ does not depend on the film thickness L . (d) The negative compressive strain at the MoS₂/glass interface becomes tensile (changes the sign) at $t = L/c_s$, resulting in the maximum of the potential energy density of a stretched film (The arrows indicate which axis each curve corresponds to, providing visual guidance). Film separation (ablation) should occur at this moment, see the schematics in Fig. 1(b). The maximum value of the kinetic energy of the translational motion $\rho v_X^2/2$ at $t = L/c_s$ is much smaller, suggesting that the energy for film separation is taken from the potential energy.

the liquid film at the binodal line of the liquid–gas phase transition on the thermodynamic phase diagram^{17,18}.

Conclusions

To summarize, in this Letter we observed ultrafast delamination (‘flight’) of few nanometer thick MoS₂ films by recording the transient Newton rings during femtosecond laser ablation. Through careful analysis of the energy balance in terms of the absorbed energy density, we found that ablation in MoS₂ occurs in a liquid phase and the ablation threshold is independent of the film thickness. The expansion velocities slightly above the ablation threshold energy density (~ 10 kJ/cm³) are also independent of the film thickness. These experimental observations are explained by a simple photo-acoustic model, which corroborates the L independent behavior, provides the correct estimation for expansion velocities, and suggests the new method to study the adhesion at liquid/solid interfaces. Since liquid MoS₂ is unstable under stationary conditions³⁶, single-shot ultrafast optical measurements provide an

exclusive route to investigate its non-equilibrium physical properties. All aforementioned phase transitions could have technological importance in thermal management in advanced interconnects. Investigations of fs-laser-induced phase transitions in nanoscaled thin films and their mechanical motion via time-resolved imaging techniques will help reach the speed and energy limits in ultrafast laser-matter interactions in monolayer 2D materials. Implementing the techniques shown in this Letter could resolve the challenge of further miniaturization, resulting in more energy-efficient and faster memory devices, integrated circuits and thin film transistors³⁷.

Experimental section

Preparation of MoS₂ and AuPd thin films

The MoS₂ layers are grown by plasma enhanced atomic layer deposition (ALD) at 300 °C electrode temperature with a Bis(t-butylimido)bis(dimethylamino)molybdenum precursor and a 10 Pa, 200 W H₂S and Ar plasma as

co-reactand⁶. Using 60, 90, 210 and 310 ALD cycles on 200 mm glass (SCHOTT AF32[®]eco) wafers, polycrystalline MoS₂ of 1.83 nm, 3.18 nm, 7.49 nm and 11.58 nm is grown.

Gold (80%) and Palladium (20%) (AuPd) samples were deposited by sputtering (SC7620 Mini Sputter Coater, Quorum Technologies) on 150 µm Menzel Glaser cover glass substrates. Layer thicknesses of 10 nm, 20 nm, 30 nm, 35 nm, 66 nm, 80 nm and 100 nm are achieved by linearly varying deposition times from 60 s to 480 s at a constant current of 18 mA applied to the sputtering target at 0.08 mbar. AuPd bilayers were prepared by sputtering (SC7620 Mini Sputter Coater, Quorum Technologies) 80 nm AuPd on MoS₂ films, generated by ALD.

Time-resolved microscopy in transmission geometry

MoS₂, AuPd and MoS₂ films loaded with AuPd were ablated with single femtosecond Ti: Sapphire pump pulses (Spectra Physics, $\lambda_{\text{pump}} = 800$ nm, $t_p = 110$ fs, $f_{\text{rep}} = 20$ Hz). Pump and probe pulses were separated with a beamsplitter; the probe pulses were time-delayed, frequency doubled and made collinear with pump pulses using a dichroic mirror to enable the illumination of a large surface area of the sample under the normal incidence, see Fig. 1S. Using a probe delay of $t_{\text{delay}} = 7$ ns transient interference fringes (Newton rings) were observed in an incident fluence range of 25–120 mJ/cm² for MoS₂, AuPd and AuPd-loaded MoS₂.

Ellipsometric measurements and absorption of MoS₂ thin films

The refractive index and the film thickness were measured via spectroscopic ellipsometry (SENTECH Instruments GmbH, Model SE800-DUV) under an incident angle of 70° within a wavelength range from 190 nm to 930 nm.

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Author contributions

The original idea was conceived by V.V. Temnov, M. J. M. J. Becher, A. Saetchnikov; The design and theoretical analysis were carried out by V. V. Temnov, M. J. M. J. Becher, E. L. Gurevich, R. Nett which was verified in experiment by M. J. M. J. Becher, A. Saetchnikov, L. Vogel, Y. Laplace, T. Guo, P. Varlamov; writing—original draft by M. J. M. J. Becher, E. L. Gurevich, V. V. Temnov; The writing—review and editing was carried out by C. Massé, E. L. Gurevich, V. V. Temnov; The entire research was supervised by A. Ostendorf, V.V. Temnov, C. Bock; All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing financial interests.

Supplementary information

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