

Laser-Induced Surface Structuring of Silicon for Enhanced Antibacterial Performance of Silver Thin Films

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Abstract

Influence on the properties of silver thin films deposited on deep femtosecond laser-induced periodic surface structures (LIPSS) was investigated. LIPSS with a spatial period of 850 ± 20 nm and an amplitude of 650 ± 50 nm were fabricated on N-doped silicon (100) using femtosecond laser beam to be used as a substrate. Silver thin films (~ 100 nm) were deposited by magnetron sputtering and pulsed laser deposition on both flat (100) Si single crystal and LIPSS-structured (100) Si substrates. Morphological and structural analyses performed by scanning electron microscopy and X-ray diffraction revealed non-conformal growth of silver on LIPSS, characterized by preferential deposition at the top of the structures and crystallization in a face-centered cubic structure. Antibacterial activity assays against *Escherichia coli* (*E. coli*) showed that silver films deposited on LIPSS significantly delayed the growth of bacteria compared to those on flat substrates. The influence of the LIPSS structures and film deposition technique toward anti-bacterial activity is discussed.

Highlights

- Physical vapor deposition of films on deep-laser-induced periodic structures
- PLD and magnetron sputtered silver thin films on Deep-LIPSS structural properties
- Enhancement of antibacterial activity of silver thin films using LIPSS substrate
- Non-conformal growth toward reduced delamination of the films

1. Introduction

Over the past two decades, laser induced periodic surface structures (LIPSS) have attracted significant attention due to their ability to tailor surface properties. LIPSS can be formed on almost all types of materials such as metals [1], semiconductors [2], insulators [3], polymers [4], and thin films [5]. Depending on the spatial period (Λ) and the polarization of the laser beam, they are mainly classified into two categories namely low spatial frequency LIPSS (LSFL) with a spatial period larger than half the laser wavelength and high spatial frequency LIPSS (HSFL) with a spatial period smaller than half the wavelength [6], [7], [8], [9]. LIPSS have been extensively studied since their discovery in the 1960s by Birnbaum, during the irradiation of semiconductors using a pulsed ruby laser [10]. They have attracted significant scientific interest due to their potential applications in surface functionalization, including tribological properties [11], wettability [12], [13] and antibacterial performance [14], [15], [16], [17]. For example, Cunha et al. [15] demonstrated that laser structuring of titanium significantly reduces *Staphylococcus aureus* (*S. aureus*) adhesion and biofilm formation compared to polished samples. Additionally, Lutey et al. [16] showed that LIPSS, with feature sizes comparable to bacterial dimensions, limit the adhesion of both *Escherichia coli* (*E. coli*) and *S. aureus*. These studies highlight the effectiveness of laser structuring in the fabrication of antibacterial surfaces. The fabrication of nanostructured surfaces capable of killing attached bacteria was initially inspired by nature surfaces.

Indeed, the unique nanostructures of cicada wings can mechanically rupture the membranes, providing an affective mechano-bactericidal effect [18], [19].

Two main strategies are employed to control bacterial growth on material surfaces. In the physical or contact killing approach, bacteria are mechanically damaged through direct interaction with surface structures that can disrupt their membranes or prevent biofilm formation. In the chemical or release killing process, antibacterial agents such as metal ions (Cu, Zn, Ag, ...), organic molecules or reactive oxygen and nitrogen species are locally released from the surface to inhibit bacterial growth or directly kill microorganisms [20].

Ag thin films offer significant potential for a variety of engineering applications [21], [22], [23], [24]. Moreover, silver exhibits remarkable antibacterial activity, attributed to the release of Ag^+ ions that can penetrate bacterial cells, inhibit DNA replication, and induce cell lysis [25], [26]. The antimicrobial effectiveness of silver is closely related to the amount of Ag^+ ions released over time [25].

The deposition of thin films is widely studied to modify the surfaces of materials or for functional applications [27]. Several studies have focused on films deposited onto pre-patterned substrates, some of them dealing with deposition onto LIPSS. Among the few examples, Garcia-Valenzuela et al. [28] investigated the deposition of SiO_x films by reactive magnetron sputtering at oblique angles on LIPSS substrates with an amplitude of approximately 250 nm and a period of 700 nm. They found that the structured substrates induce nanometric 2D compositional patterns in the films, showing that the surface topography can control the lateral organization of the film's composition. Hotovy et al. [29] studied the deposition of NiO thin films on LIPSS formed on a Si_3N_4 insulating layer. They showed that these structured substrates support the fabrication of gas sensor elements and highlighted the potential of LIPSS to enhance the performance of NiO based gas sensor. Thomann et al. [30] investigated the conformality of aluminium thin films deposited on micro-patterned silicon substrates using different deposition techniques. They showed that all physical deposition techniques result in non-conformal films on pre-patterned substrates.

In this study, the influence of using LIPSS silicon substrates on the structural and antibacterial properties of silver thin films, compared with atomically flat (100) Si substrates is investigated. Ag thin films were obtained using two physical deposition methods: magnetron sputtering (MS) and pulsed laser deposition (PLD). The two physical techniques were used in order to compare the influence of the process on the conformality of films in the deep LIPSS and the other properties (morphology and grain size, crystallinity) that may influence the antibacterial properties. The morphology of the films was examined using scanning electron microscopy (SEM) in both top and cross-sectional views and X-ray diffraction (XRD) was used to investigate the crystalline structure. Also, surface wettability was evaluated through contact angle measurements. To assess antibacterial activity, several groups have proposed simple tests to evaluate or compare the activity of films [31], [32], [33], [34], [35], focusing on bacterial adhesion, chemical release or performance under dry or wet conditions. In this study, the

antibacterial activity against *Escherichia coli* was assessed using a protocol similar to that described by Chu et al. [31] due to its relevance to the type of deposited film.

2. Materials and Methods

2.1. Elaboration of silver thin films

Silver thin films were deposited by magnetron sputtering and pulsed laser deposition onto (100) Si single-crystal substrates and laser-structured (100) Si substrates, referred to as P-Si and LIPSS-Si, respectively. The LIPSS-Si substrates were fabricated on N-doped Si(100) using Yb:YAG femtosecond laser beam (350 fs pulse duration, 1030 nm wavelength, 100 kHz repetition rate) with linear polarization. The structuring process was performed under 1 mbar N₂ atmosphere to avoid redeposit linked to the ablative deep LIPSS formation. The structuring led to the formation of unusual deep low spatial frequency LIPSS (D-LSFL) with a spatial period around 850 ± 20 nm and an amplitude (δ) of 650 ± 50 nm with about 200 nm of redeposited SiO_x. Morphology of the structured substrates is shown in Fig. 1 and more details on the laser structured substrates are available in a previous work [36] with experimental details. Before each deposition step, the substrates were cleaned in isopropanol ultrasonic baths. To discriminate between the chemical effects from the possible physical effects related to the morphology of the samples, silicon was chosen as a substrate material. Indeed, since silicon does not exhibit any antibacterial properties [37], [38], its use allows the antibacterial activity of the Ag film to be clearly highlighted.

Direct current (DC) magnetron sputtering was carried out using an Ag (99.99% purity) target and a power of 200 W under an argon working pressure of 7×10^{-3} mbar (20 sccm). The distance between the target and the substrate was 12 cm. The deposition was carried out for 1 minute to achieve a film thickness of approximately 100 nm. During deposition, the substrate holder was rotated to ensure uniform film thickness across the surface. Ag films deposited using magnetron sputtering process on P-Si and LIPSS-Si are referred to Ag^{MS}-P and Ag^{MS}-LIPSS, respectively.

For PLD process, a Nd:YAG laser (Powerlite 9010 from Amplitude Technology company), with a pulse width of 10 ns, a wavelength of 355 nm (third harmonic) and a repetition rate of 10 Hz was used to ablate the Ag target. The films were grown by adjusting the laser fluence on the target at $2-3 \text{ J.cm}^{-2}$. The target to substrate distance was fixed at 50 mm. The deposition was performed at room temperature (about 20°C) under argon atmosphere at a pressure of 10^{-2} mbar. The deposition time was 60 min to obtain thin films of around 100 nm thick. For these conditions, the deposition rate is therefore $\sim 1.7 \text{ nm/min}$. The Ag films deposited by PLD on P-Si and LIPSS-Si are referred to as Ag^{PLD}-P and Ag^{PLD}-LIPSS, respectively.

2.2. Characterization of silver thin films

Surface morphologies were observed by SEM (Zeiss SUPRA 40). Structural characteristics were investigated by XRD by using a diffractometer (D8 Discover, Bruker) equipped with a monochromatized $\text{Cu } K_{\alpha 1}$ wavelength ($\lambda = 1.54056 \text{ \AA}$) in the θ - 2θ Bragg-Brentano geometry.

To investigate the wettability properties of the samples, water contact angle (CA) measurements were performed. A droplet volume of 6 μL of water was deposited on the sample surfaces using the DigiDrop system, and the resulting images were analysed using ImageJ software with the LB-ADSA plugin.

The antibacterial properties of the films were investigated using a protocol designed to maximize interactions between the sample surfaces and the bacteria. The protocol is summarized in Fig. 2 and was inspired from protocol previously reported in the literature, for example Chu et al. [31]. First (Step 1), a droplet of an *E. coli* solution with a controlled concentration of 10^8 cells/mL was deposited on the different samples. The volume of the droplet was chosen as 40 μL to ensure the solution remains in contact with the 1 cm^2 sample even in the case of hydrophilic films. Then (Step 2), the samples were maintained for three hours at 37°C to allow bacterial proliferation. The samples were rinsed ten times with the same volume of 460 μL of nutrient medium to recover as many bacteria as possible (Step 3). Then (Step 4), 200 μL of each solution were collected in wells and the evolution of bacterial concentration was observed over 10 hours at 37°C . This was performed using an UV/Visible spectrophotometer adjusted on $600 \pm 5 \text{ nm}$ (VICTOR Nivo Multimode Microplate Reader). Absorbance was determined as the ratio between the light intensity passing through 1 cm^3 of nutrient solution and that passing through 1 cm^3 of bacterial suspension. As bacteria absorb light at this wavelength, lower measured values correspond to lower bacterial concentrations, indicating a greater effect of the coating on growth.

The protocol was adapted and optimized to enable the comparison of the prepared samples. Therefore, absorbance between 0.1 and 1 is proportional to the bacterial concentration in the solution for concentration between 10^8 and 10^9 cells/mL. A value of 0.1 corresponds to a solution with 10^8 cells/mL and a value 1 corresponds to a concentration of 10^9 cells/mL. Absorbance values under 0.1 or over 1, despite being representative of concentration under 10^8 cells/mL and over 10^9 cells/mL respectively, are not proportional to the cell concentrations. The spectrometer measures the absorbance every 20 minutes, corresponding to the theoretical doubling time of the *E. coli* population. Finally, the remaining culture obtained after incubation (Step 3) was serially diluted by 10, 10^2 , 10^3 and 10^4 in nutrient medium. Then, 10 μL of each dilution was spread on Luria Broth (LB) agar in Petri dishes. The plates were incubated at 37°C for 24 hours to allow bacterial growth, enabling comparison of bacterial proliferation at different concentrations.

3. Results and discussion

Morphological, Structural, and Wettability Properties of the Samples

Figure 3 displays the top view and cross-section SEM images of the silver thin films. $\text{Ag}^{\text{MS-P}}$ and $\text{Ag}^{\text{PLD-P}}$ exhibit morphologies typical of silver thin films [39]. The appearance of the grains suggests a crystallization of the film, crystallized silver films at room temperature being already reported in literature [40], [41]. The main difference observed is that the grain size on $\text{Ag}^{\text{MS-P}}$ seems significantly smaller than the one on $\text{Ag}^{\text{PLD-P}}$ possibly due to the very different growth rate (about 100 nm/min and 1.7 nm/min for MS and PLD respectively) and the deposition conditions between the two techniques. Top view SEM images show homogeneous growth on the LIPSS with similar morphologies with both techniques. Cross-section images evidence that the growth is not conformal with silver film mostly deposited on the top of the SiO_x layer LIPSS. The results are therefore in agreement with previous works on Al deposition processes including PLD and magnetron sputtering [30]. It is, however, interesting to notice that silver grains still appear in the valleys of the LIPSS and on the edges with positive angles with both techniques and despite a quite high aspect ratio of about 1:6. Even if the films are not conformal, Ag is present all over the surface of the trenches between the protrusions.

$\theta/2\theta$ X-ray diffraction patterns are presented in Fig. 4. In the $35\text{--}47^\circ$ 2θ range, the two peaks located at 38.1° and 44.3° are attributed to the (111) and (200) planes, respectively, and are related to the face centered cubic (fcc) phase of metallic silver (space group : Fm-3m), in agreement with the ICDD file (#00-004-0783). No other phase was detected in any of the samples. This result confirms that even at room temperature, the energetic conditions of the process enable for the Ag films to crystallize. A main difference concerns the change in preferential orientation of crystallites of the Ag films. Both films grown on P-Si exhibit a (200) preferential orientation since the ratio of intensities between the (200) and (111) planes is about 3 compared to a ratio of 0.4 for a silver powder (ICDD file #00-004-0783). Such modification of the preferential orientation for silver films have already been reported linked to the process parameters, for example the presence of nitrogen gas in the sputtering process [42] or the substrate temperature for thermal deposition [43]. In our case, both techniques, despite their differences, lead to a similar orientation crystallites in the film. In contrast, on LIPSS-Si both samples exhibit no particular preferential orientation as the intensities of the two peaks respect the ones of randomly distributed crystallites of a powder. This supposition is in agreement with the SEM observation of the film covering along the LIPSS.

After the deposition of the silver thin film, the wettability of the surfaces was evaluated by contact angle measurements. The results are presented in Fig. 5. Figure 5(a) and 5(b) show the contact angle measurements for P-Si and LIPSS-Si, respectively. The measured contact angles are $70^\circ \pm 5^\circ$ and $26^\circ \pm 5^\circ$, showing that after laser structuring, the hydrophilic character of Si surface is enhanced (for more details, including the role of the SiO_x redeposited layer, see the previous study [36]).

After Ag deposition (Fig. 5(c–f)), all surfaces show hydrophobic behavior, whether the films were deposited on bare silicon ($\text{Ag}^{\text{MS-P}}$ and $\text{Ag}^{\text{PLD-P}}$) or on LIPSS-structured substrates ($\text{Ag}^{\text{MS-LIPSS}}$ and $\text{Ag}^{\text{PLD-LIPSS}}$). However, $\text{Ag}^{\text{MS-LIPSS}}$ and $\text{Ag}^{\text{PLD-LIPSS}}$ show a more pronounced increase of the contact angle compared to the unstructured samples, indicating that LIPSS enhances hydrophobicity through

changes in surface morphology. For deposition on bare silicon, Ag^{MS}-P has a contact angle of $96^\circ \pm 2^\circ$, a little bit lower than that of Ag^{PLD}-P ($108^\circ \pm 2^\circ$). In contrast, when the films are deposited on LIPSS, both techniques display similar contact angles of $119^\circ \pm 2^\circ$ for Ag^{MS}-LIPSS and $117^\circ \pm 2^\circ$ for Ag^{PLD}-LIPSS. These observations are consistent with the results reported by Dutheil et al. [39], who investigated the deposition of silver thin films on silicon substrates via magnetron sputtering using the same deposition system as in the present work. Their results show that for low film thicknesses (a few nanometers), the surfaces exhibit hydrophobic behavior with contact angles exceeding 90° .

Antibacterial properties of the samples

The antibacterial properties of the samples were investigated using the protocol described in the Experimental section. After three hours of interaction between the samples and the bacterial solutions, *in situ* absorbance (optical density) measurements at 600 nm were performed to monitor bacterial growth over time. The obtained results are shown in Fig. 6, illustrating the bacterial growth curves. As shown in Fig. 6, for bare silicon, an exponential behavior is observed from the start of the analysis, indicating that the growth of the bacteria is not inhibited. On LIPSS substrates, bacterial growth is slightly delayed by approximately one hour compared to bare silicon. The bacterial growth after interaction with the Ag^{PLD}-P sample exhibits a behaviour very similar to that of bare Si, indicating that the Ag deposit has no detectable activity in our conditions of test. In contrast, the solution recovered after interaction with Ag^{MS}-P shows pronounced delay of approximately four hours, suggesting that it initially contained a much lower concentration of viable bacteria.

The antibacterial effect is even more pronounced when silver was deposited on LIPSS-structured substrates. Both Ag^{PLD}-LIPSS and Ag^{MS}-LIPSS surfaces show a prolonged latency phase of approximately eight hours, which demonstrates a greater inhibition of bacterial proliferation compared to the other surfaces tested.

These results obtained from the absorption measurements can be confirmed by the Petri dishes shown in Fig. 7. This figure shows a series of Petri dishes divided into four quadrants, each corresponding to a different dilution level, where quadrant A represents a dilution by 10, quadrant B by 10^2 , quadrant C by 10^3 and quadrant D by 10^4 . Each quadrant displays the bacterial colonies obtained after incubation, providing a direct visual confirmation of the differences in bacterial growth observed across dilutions and between the tested samples. The top plate outlined in purple represents a sample containing copper (Cu) used as a reference, as copper is known for its strong antibacterial activity [44].

From these figures, only a slight difference in bacterial growth is observed between bare silicon and LIPSS substrates. Bacterial growth appears clearly reduced on the Ag^{MS}-P surface compared to Ag^{PLD}-P, in agreement with the observations shown in Fig. 6. When silver is deposited on LIPSS, growth is further reduced in both Ag^{MS}-LIPSS and Ag^{PLD}-LIPSS samples, reaching levels comparable to the Cu reference. Growth is slightly lower on Ag^{MS}-LIPSS, suggesting it has the stronger antimicrobial effect. In order to

understand the differences in the antibacterial activity of surfaces, it is necessary to examine the underlying mechanisms more closely.

Silicon is chemically inert and does not have the ability to kill bacteria or inhibit their growth. On LIPSS-structured substrates, the slight delay in bacterial proliferation is not due to a chemical effect but is most likely caused by a physical effect induced by the structured surface. On a stainless steel surface, Lutey et al. [16] reduced *E. coli* adhesion by nearly 99.8%. This reduction is attributed to the morphology of the microstructures, whose size and periodicity limit bacterial attachment points. Similarly, Cunha et al. [15] observed that femtosecond laser texturing of titanium significantly reduces *S. aureus* adhesion and biofilm formation compared to a polished surface. It was observed that Ag^{MS}-P exhibited higher antibacterial activity than Ag^{PLD}-P. This difference can be attributed to variations in grain size, as the results presented above indicate that the only difference between Ag^{PLD}-P and Ag^{MS}-P is the larger grain size of Ag^{PLD}-P. Korched et al. [45] showed that silver nanoparticles with an average size (less than 19 nm) have more effective antibacterial activity than larger ones. The smaller size has a larger surface area and therefore greater contact with bacterial cells [46]. Moreover, as the protocol used in this work is developed to be able to discriminate between these specific samples, it can exhibit a threshold under which the antibacterial activity cannot be observed [38].

Both Ag^{MS}-LIPSS and Ag^{PLD}-LIPSS surfaces exhibit antibacterial activity, which can be attributed to the chemical properties of silver. Silver is chemically active and releases ions that interact with bacterial cell membranes, ultimately causing bacterial death or inhibiting their growth [47]. Furthermore, as indicated above, silver deposited on LIPSS surfaces has a stronger antibacterial effect than silver deposited on bare silicon. This enhancement could be attributed to the spreading of the *E. coli* droplet along the LIPSS orientation as shown in Fig. 9, which increases bacterial contact with the surface and promotes the release of silver ion. In fact, the projected area of the droplet on LIPSS surfaces is approximately two times larger than on bare surfaces, where the droplet maintains a nearly circular shape (see the two rightmost images in Fig. 9). This increased spreading on LIPSS surfaces would induce a stronger interaction between bacteria and silver. It should be noted that these observations differ from the wettability results obtained by contact angle measurements. The difference can be attributed to the fact that measurements are recorded at $t = 0$ using a smaller droplet volume (6 μL), compared to the 40 μL used in the bacterial tests. These results enlighten that standard wettability tests, despite being quite relevant to compare and classify surface properties through literature, are not always reliable to interpret antibacterial activity, depending on the testing conditions. In addition to the macroscopic spreading of the droplet, the stronger antibacterial activity observed for Ag^{PLD}-LIPSS and Ag^{MS}-LIPSS could also be attributed to the increase of the specific surface area, which is up to three times that of a flat surface. The specific surface area was estimated according to the geometric model proposed by Karim et al. [48]. The detailed procedure is presented in the supplementary data. A larger surface area increases the contact between the bacterial solution and the material, allowing more Ag⁺ ions to be released into the solution and enhancing the antibacterial action [49]. Indeed, the antibacterial effectiveness of silver is therefore closely related to the total amount of silver present [25]. These results indicate that silver

deposited on structured surfaces has a strong chemical antibacterial effect and that the surface morphology further enhances the release of silver ions.

It is also interesting to note that the films on LIPSS (Ag^{PLD} -LIPSS and Ag^{MS} -LIPSS) exhibited better adhesion to the substrate than those on flat silicon, as presented in Fig. 9. Indeed, the films on flat silicon often peeled off from the substrates after the rinsing step of the samples (see Fig. 9, first two rows). This result was to be expected, as it is well known that Ag thin films require the use of a buffer layer, such as Cr or Ti, for example [50], to improve adhesion to the silicon substrate. In the case of Ag^{PLD} -LIPSS and Ag^{MS} -LIPSS however, no peeling off was observed at all. It can be explained by the discontinuity in the film resulting from the non-conformal growth on LIPSS substrate. It is indeed well documented that discontinuities in films enable a release of the stress [51]. These results enlighten that the use of LIPSS may serve as an alternative in applications where the incorporation of another chemical element as buffer layer could be detrimental. Moreover, in this study these observations demonstrate that LIPSS increase the adhesion of the silver thin film, ensuring its stability during antibacterial testing steps.

4. Conclusion

This study investigates how femtosecond laser-induced periodic surface structures on silicon substrates influence the morphology, crystallography, properties and antibacterial performance of silver thin films. The obtained LIPSS are characterised by a spatial period of approximately 850 ± 20 nm and an amplitude of about 650 ± 50 nm. Silver was deposited using two techniques: magnetron sputtering and pulsed-laser deposition exhibiting non-conformal coverage, accumulating mainly at the tops of the structures with partial deposition inside the trenches and crystallizes in an fcc structure. Contact angle measurements indicate that the presence of LIPSS significantly enhances surface hydrophobicity after silver deposition, regardless of the deposition technique.

Antibacterial tests show that silver films deposited on LIPSS substrates have a stronger effect compared to flat silicon, with effects comparable to a copper reference. This enhancement is attributed to the increased contact between the bacterial solution and the sample surfaces due to the spreading of *E. coli* droplets and the high surface area of the LIPSS. Together, these effects tend to increase Ag^+ ion release and reinforce the release-killing. The results also show that films deposited by MS have a slightly stronger antibacterial effect than films deposited by PLD. Finally, the non-conformal growth on LIPSS display significantly improved adhesion compared to films on flat silicon, demonstrating that these nanostructures enhance film stability during antibacterial testing.

Declarations

Conflict of interest:

The authors declare no conflict of interest.

Author Contribution

L. L. and B. A. wrote the first draft of the manuscript and prepared the figures. A.-L. T., E. M., B.A. and F. B.-M. were in charge of the conceptualization and the methodology. Formal analysis and investigations were performed by L. G., H. R., L. L., P. B., A. S., E. M. and B. A.; Funding acquisition: B. A., E. M., A.-L. T., N. S. also did funding acquisition and supervision. All authors reviewed the manuscript.

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. K. Ahmmed, C. Grambow, A.-M. Kietzig, « Fabrication of Micro/Nano Structures on Metals by Femtosecond Laser Micromachining », *Micromachines*, vol. 5, n° 4, pp. 1219–1253, 2014, 10.3390/mi5041219
2. A. Talbi, S. Kaya-Boussougou, A. Sauldubois, A. Stolz, C. Boulmer-Leborgne, N. Semmar, « Laser-induced periodic surface structures formation on mesoporous silicon from nanoparticles produced by picosecond and femtosecond laser shots ». *Appl. Phys. A* **123**, 463 (2017). n° 710.1007/s00339-017-1075-2
3. K.D. Arun Kumar, B. Aspe, M. Depardieu, A.-L. Thomann, N. Semmar, « Influence of thin film for LIPSS formation on soda-lime glass using SHG femtosecond laser beam », *AIP Advances*, vol. 14, n° 10, p. 105105, 2024, 10.1063/5.0230358
4. O. Shavdina, H. Rabat, M. Vayer, A. Petit, C. Sinturel, N. Semmar, « Polystyrene Thin Films Nanostructuring by UV Femtosecond Laser Beam: From One Spot to Large Surface », *Nanomaterials*, vol. 11, n° 5, p. 1060, 2021, 10.3390/nano11051060
5. W. Labbe, B. Aspe, A. Stolz, C. Cachoncinlle, N. Semmar, « Formation of decorated LIPSS on GaN thin film by UV picosecond laser beam in air and under vacuum ». *Appl. Phys. A* **130**, 745 (2024). n°

6. J.E. Sipe, J.F. Young, J.S. Preston, H.M. Van Driel, « Laser-induced periodic surface structure. I. Theory », *Phys. Rev. B*, vol. 27, n° 2, pp. 1141–1154, 1983, 10.1103/PhysRevB.27.1141
7. J. Reif, O. Varlamova, S. Uhlig, S. Varlamov, M. Bestehorn, « On the physics of self-organized nanostructure formation upon femtosecond laser ablation ». *Appl. Phys. A* **117**, 179–184 (2014). n° 110.1007/s00339-014-8339-x
8. Y. Zhang et al., « Femtosecond laser-induced periodic structures: mechanisms, techniques, and applications », *OES*, vol. 1, n° 6, pp. 220005–220005, 2022, 10.29026/oes.2022.220005
9. J. Bonse, « Quo Vadis LIPSS?—Recent and Future Trends on Laser-Induced Periodic Surface Structures », *Nanomaterials*, vol. 10, n° 10, p. 1950, 2020. 10.3390/nano10101950
10. M. Birnbaum, « Semiconductor Surface Damage Produced by Ruby Lasers ». *J. Appl. Phys.* **36**, 3688–3689 (1965). n° 1110.1063/1.1703071
11. R. Mareus et al., « Effect of femtosecond laser microstructuring on tribological properties of CrN coatings under engine lubricants ». *Tribol. Int.* **219**, 111741 (2026). 10.1016/j.triboint.2026.111741
12. O. Varlamova, J. Reif, M. Stolz, R. Borcia, I.D. Borcia, M. Bestehorn, « Wetting properties of LIPSS structured silicon surfaces ». *Eur. Phys. J. B* **92**, 91 (2019). n° 510.1140/epjb/e2019-90672-2
13. F.R. Weber, C. Kunz, S. Gräf, M. Rettenmayr, F.A. Müller, « Wettability Analysis of Water on Metal/Semiconductor Phases Selectively Structured with Femtosecond Laser-Induced Periodic Surface Structures », *Langmuir*, vol. 35, n° 47, pp. 14990–14998, 2019, 10.1021/acs.langmuir.9b02406
14. Y. Zhong et al., « Advancing Mechano-Bactericidal Surfaces: Mechanisms, Fabrication, and Synergistic Antimicrobial Strategies ». *Adv. Mater. Inter.* **12**, e00792 (2025). n° 2310.1002/admi.202500792
15. A. Cunha et al., « Femtosecond laser surface texturing of titanium as a method to reduce the adhesion of *Staphylococcus aureus* and biofilm formation ». *Appl. Surf. Sci.* **360**, 485–493 (2016). 10.1016/j.apsusc.2015.10.102
16. A.H.A. Lutey et al., « Towards Laser-Textured Antibacterial Surfaces ». *Sci. Rep.* **8**, 10112 (2018). n° 110.1038/s41598-018-28454-2
17. S.D. Puckett, E. Taylor, T. Raimondo, T.J. Webster, « The relationship between the nanostructure of titanium surfaces and bacterial attachment », *Biomaterials*, vol. 31, n° 4, pp. 706–713, 2010, 10.1016/j.biomaterials.2009.09.081
18. E.P. Ivanova et al., « Natural Bactericidal Surfaces: Mechanical Rupture of *Pseudomonas aeruginosa* Cells by Cicada Wings », *Small*, vol. 8, n° 16, pp. 2489–2494, 2012, 10.1002/smll.201200528
19. G.S. Watson et al., « Insect Analogue to the Lotus Leaf: A Planthopper Wing Membrane Incorporating a Low-Adhesion, Nonwetting, Superhydrophobic, Bactericidal, and Biocompatible Surface ». *ACS Appl. Mater. Interfaces*. **9**, 24381–24392 (2017). n° 2810.1021/acsami.7b08368

20. A. Nikiforov, C. Ma, A. Choukourov, F. Palumbo, « Plasma technology in antimicrobial surface engineering ». *J. Appl. Phys.* **131**, 011102 (2022). n° 110.1063/5.0066724
21. L.-P. Chang, J.-J. Wang, T.-H. Hung, K.-N. Chen, F.-Y. Ouyang, « Direct metal bonding using nanotwinned Ag films with (1 1 1) surface orientation under air atmosphere for heterogeneous integration ». *Appl. Surf. Sci.* **576**, 151845 (2022). 10.1016/j.apsusc.2021.151845
22. C. Zhang et al., « An Ultrathin, Smooth, and Low-Loss Al-Doped Ag Film and Its Application as a Transparent Electrode in Organic Photovoltaics ». *Adv. Mater.* **26**, 5696–5701 (2014). n° 3210.1002/adma.201306091
23. M. Nur-E-Alam et al., « Multifunctional prospects of physical vapor-deposited silver-based metal-dielectric nanocomposite thin films ». *J. Science: Adv. Mater. Devices.* **10**, 100871 (2025). n° 210.1016/j.jsamd.2025.100871
24. G. Ding, C. Clavero, D. Schweigert, M. Le, « Thickness and microstructure effects in the optical and electrical properties of silver thin films ». *AIP Adv.* **5**, 117234 (2015). n° 1110.1063/1.4936637
25. R. Rebelo, N.K. Manninen, L. Fialho, M. Henriques, S. Carvalho, « Morphology and oxygen incorporation effect on antimicrobial activity of silver thin films ». *Appl. Surf. Sci.* **371**, 1–8 (2016). 10.1016/j.apsusc.2016.02.148
26. O. Lyutakov, I. Goncharova, S. Rimpelova, K. Kolarova, J. Svanda, V. Svorcik, « Silver release and antimicrobial properties of PMMA films doped with silver ions, nano-particles and complexes ». *Mater. Sci. Engineering: C* **49**, 534–540 (2015). 10.1016/j.msec.2015.01.022
27. S. Sakthinathan et al., « A Review of Thin-Film Growth, Properties, Applications, and Future Prospects », *Processes*, vol. 13, n° 2, p. 587, 2025, 10.3390/pr13020587
28. A. García-Valenzuela et al., « 2D compositional self-patterning in magnetron sputtered thin films ». *Appl. Surf. Sci.* **480**, 115–121 (2019). 10.1016/j.apsusc.2019.02.206
29. I. Hotovy et al., « Preparation of laser induced periodic surface structures for gas sensing thin films and gas sensing verification of a NiO based sensor structure ». *J. Electr. Eng.* **75**, 24–28 (2024). n° 110.2478/jee-2024-0004
30. A. Thomann et al., « Conformity of Aluminum Thin Films Deposited onto Micro-Patterned Silicon Wafers by Pulsed Laser Deposition, Magnetron Sputtering, and CVD », *Chemical Vapor Deposition*, vol. 17, n° 10–12, pp. 366–374, 2011, 10.1002/cvde.201106936
31. J.-H. Chu et al., « Antimicrobial characteristics in Cu-containing Zr-based thin film metallic glass ». *Surf. Coat. Technol.* **259**, 87–93 (2014). 10.1016/j.surfcoat.2014.05.019
32. H. Kawakami, K. Yoshida, Y. Nishida, Y. Kikuchi, Y. Sato, « Antibacterial Properties of Metallic Elements for Alloying Evaluated with Application of JIS Z 2801:2000 », *ISIJ Int.*, vol. 48, n° 9, pp. 1299–1304, 2008, 10.2355/isijinternational.48.1299
33. S. Comby-Dassonneville et al., « ZrCuAg Thin-Film Metallic Glasses: Toward Biostatic Durable Advanced Surfaces ». *ACS Appl. Mater. Interfaces.* **13**, 17062–17074 (2021). n° 1410.1021/acsami.1c01127

34. G.I. Nkou Bouala, A. Etiemble, C.D. Loughian, C. Langlois, J.-F. Pierson, P. Steyer, « Silver influence on the antibacterial activity of multi-functional Zr-Cu based thin film metallic glasses ». *Surf. Coat. Technol.* **343**, 108–114 (2018). 10.1016/j.surfcoat.2017.10.057
35. J. Hasan et al., « Selective bactericidal activity of nanopatterned superhydrophobic cicada *Psaltoda claripennis* wing surfaces ». *Appl. Microbiol. Biotechnol.* **97**, 9257–9262 (2013). n° 2010.1007/s00253-012-4628-5
36. L. Lounis et al., « Physico-Chemical characterization of D-LIPSS formation by femtosecond laser beam on N-doped (100) silicon under controlled atmospheres ». *Appl. Surf. Sci. Adv.* **30**, 100860 (2025). 10.1016/j.apsadv.2025.100860
37. H. Kawakami, K. Yoshida, Y. Nishida, Y. Kikuchi, Y. Sato, « Antibacterial Properties of Metallic Elements for Alloying Evaluated with Application of JIS Z 2801:2000 », *ISIJ Int.*, vol. 48, n° 9, pp. 1299–1304, 2008, 10.2355/isijinternational.48.1299
38. D. Boivin et al., « Contribution to the understanding of antibacterial properties of CuTiZn thin film: From crystalline alloy to metallic glass ». *Surf. Coat. Technol.* **499**, 131879 (2025). 10.1016/j.surfcoat.2025.131879
39. P. Dutheil, A.L. Thomann, T. Lecas, P. Brault, M. Vayer, « Sputtered Ag thin films with modified morphologies: Influence on wetting property ». *Appl. Surf. Sci.* **347**, 101–108 (2015). 10.1016/j.apsusc.2015.04.052
40. G.S. Jang, S.M. Ahn, N.-M. Hwang, « Effects of Sputtering Power, Working Pressure, and Electric Bias on the Deposition Behavior of Ag Films during DC Magnetron Sputtering Considering the Generation of Charged Flux ». *Electron. Mater. Lett.* **18**, 57–68 (2022). n° 110.1007/s13391-021-00314-8
41. A. Rizzo, M.A. Tagliente, M. Alvisi, S. Scaglione, « Structural and optical properties of silver thin films deposited by RF magnetron sputtering », *Thin Solid Films*, vol. 396, n° 1–2, pp. 29–35, 2001, 10.1016/S0040-6090(01)01242-1
42. Y. Hu et al., « Understanding the Preferred Crystal Orientation of Sputtered Silver in Ar/N₂ Atmosphere: A Microstructure Investigation », *Advances in Materials Science and Engineering*, vol. 2019, pp. 1–8, 2019. 10.1155/2019/3079393
43. J.-D. Grunwaldt, F. Atamny, U. Göbel, A. Baiker, « Preparation of thin silver films on mica studied by XRD and AFM », *Applied Surface Science*, vol. 99, n° 4, pp. 353–359, 1996, 10.1016/0169-4332(95)00600-1
44. R.B. Thurman, C.P. Gerba, G. Bitton, « The molecular mechanisms of copper and silver ion disinfection of bacteria and viruses », *Critical Reviews in Environmental Control*, vol. 18, n° 4, pp. 295–315, 1989, 10.1080/10643388909388351
45. P. Korshed, L. Li, Z. Liu, A. Mironov, T. Wang, « Size-dependent antibacterial activity for laser-generated silver nanoparticles ». *J. Interdiscip Nanomed.* **4**, 24–33 (2019). n° 110.1002/jin2.54
46. T. Bruna, F. Maldonado-Bravo, P. Jara, N. Caro, « Silver Nanoparticles and Their Antibacterial Applications », *IJMS*, vol. 22, n° 13, p. 7202, 2021, 10.3390/ijms22137202

47. M.F. Aizamddin, M.M. Mahat, Z.Z. Zainal Ariffin, I. Samsudin, M.S.M. Razali, et M. 'Abid Amir, « Synthesis, Characterisation and Antibacterial Properties of Silicone–Silver Thin Film for the Potential of Medical Device Applications », *Polymers*, vol. 13, n° 21, p. 3822, 2021, 10.3390/polym13213822
48. W. Karim, A. Petit, H. Rabat, M. Tabbal, A.-L. Thomann, N. Semmar, « Picosecond laser beam nanostructuring of GDC thin films: exchange surface enhancement by LIPSS ». *Appl. Phys. A* **128**, 731 (2022). n° 810.1007/s00339-022-05866-6
49. J.-J. Wang et al., Antibacterial efficacy of ultrafast laser-induced periodic structures on SUS304 surfaces with Ag and Cu coatings. *Thin Solid Films*. **825**(140740) (2025). 10.1016/j.tsf.2025.140740
50. D. Lu, J. Yang, X. Wang, S. Gao, M. Li, H. Ji, « Effect of sputtering power on the microstructure and properties of silver films prepared by magnetron sputtering ». *Mater. Today Commun.* **42**, 111288 (2025). 10.1016/j.mtcomm.2024.111288
51. G. Abadias, E. Chason, E. Keckes, M. Sebastiani, G. Thompson, E. Barthel, G. Doll, C. Murray, C. Stoessel, L. Martinu, Stress in thin films and coatings: Current status, challenges, and prospects. *J. Vacuum Sci. Technol. A* **36**(020801) (2018). 10.1116/1.5011790

Figures

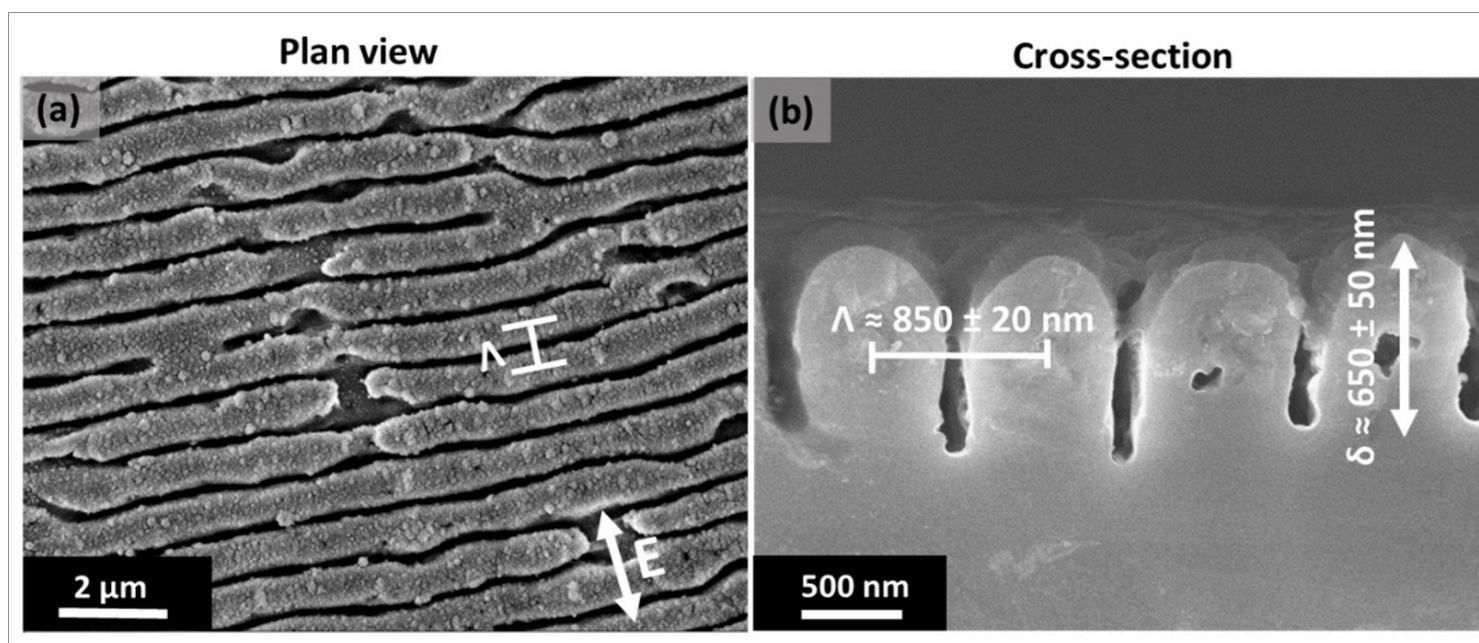


Figure 1

SEM images of the morphological features of the irradiated surface: (a) top view and (b) cross-sectional view, obtained by irradiating the target surface with a fluence of $190 \pm 7 \text{ mJ/cm}^2$. The reported values in (b) represent the mean spatial period (Λ) and amplitude (δ) measured at several points on the sample.

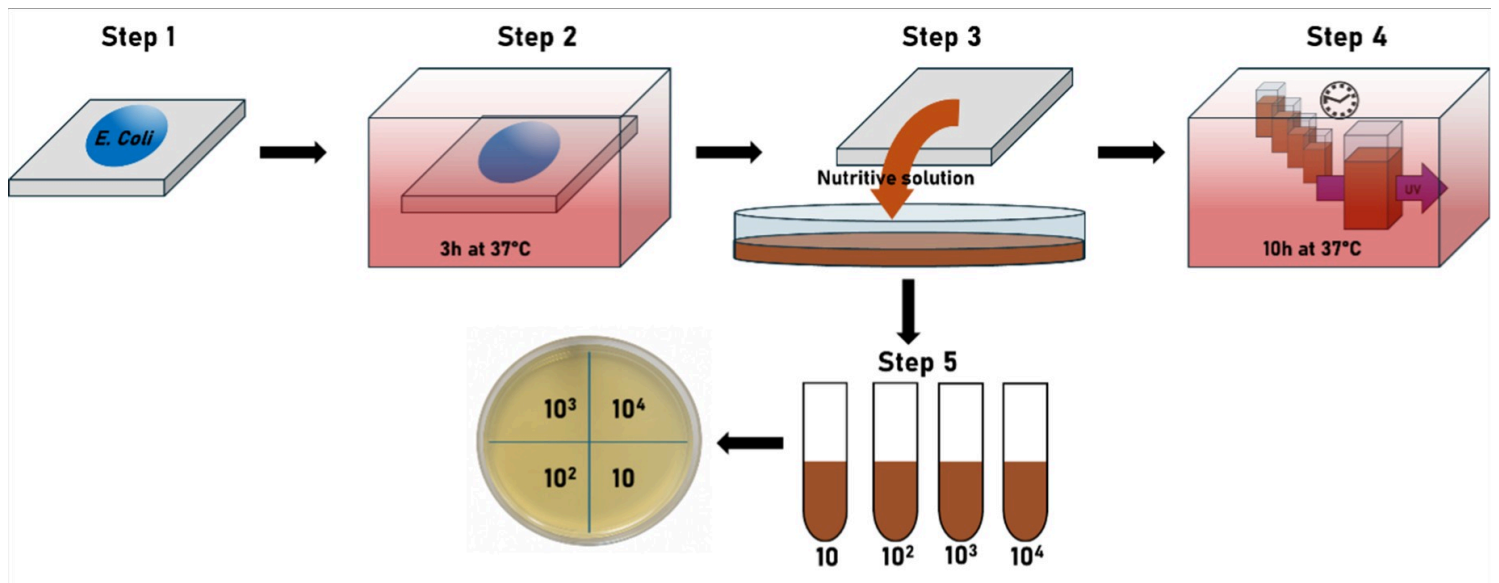


Figure 2

Schematic of the bacterial culture and analysis protocol.

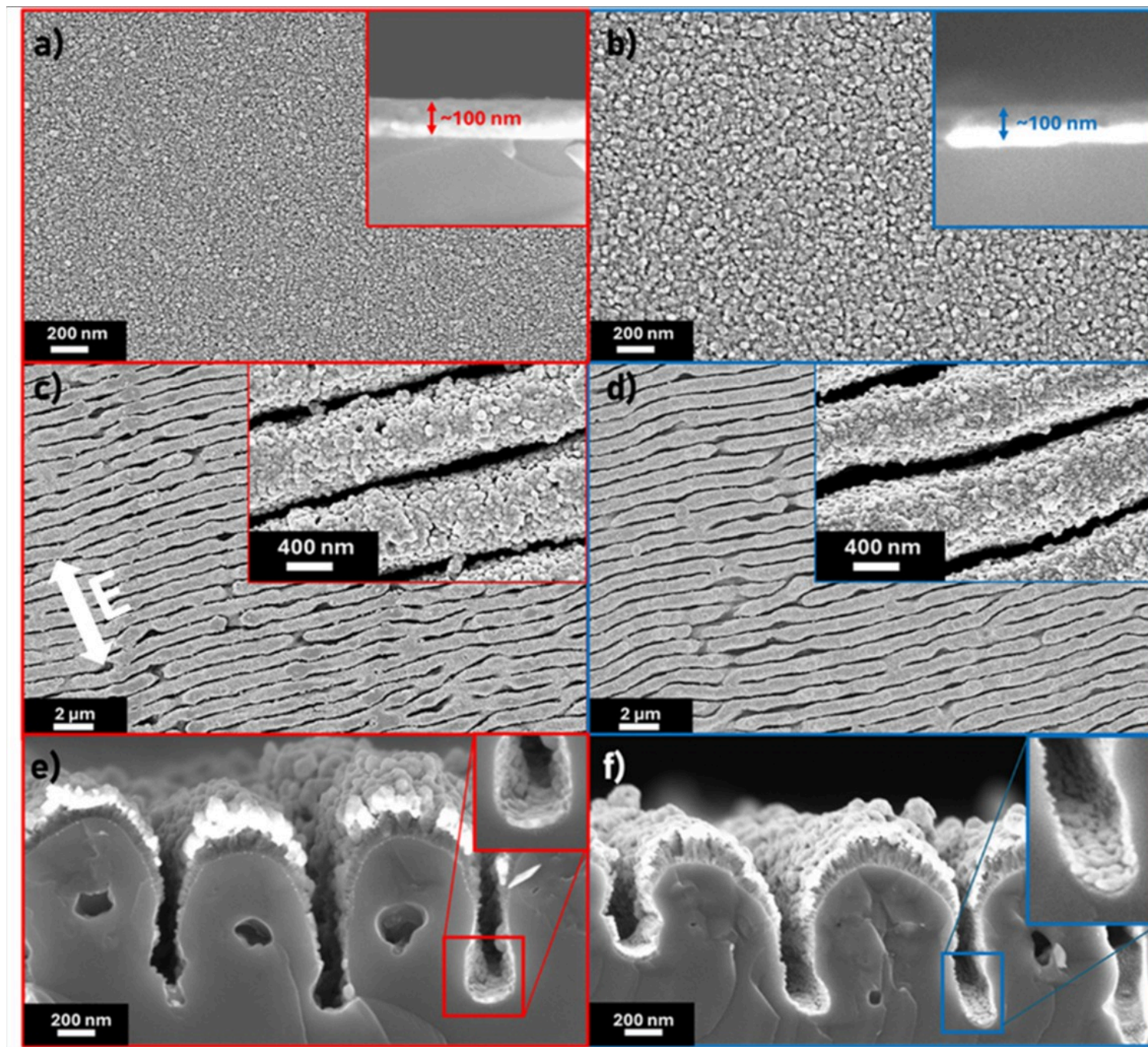


Figure 3

SEM images of the surfaces after silver deposition using magnetron sputtering (left) and PLD (right): (a–d) top-view and (e–f) cross-sectional view. (a) $\text{Ag}^{\text{MS-P}}$, (b) $\text{Ag}^{\text{PLD-P}}$, (c, e) $\text{Ag}^{\text{MS-LIPSS}}$, and (d, f) $\text{Ag}^{\text{PLD-LIPSS}}$.

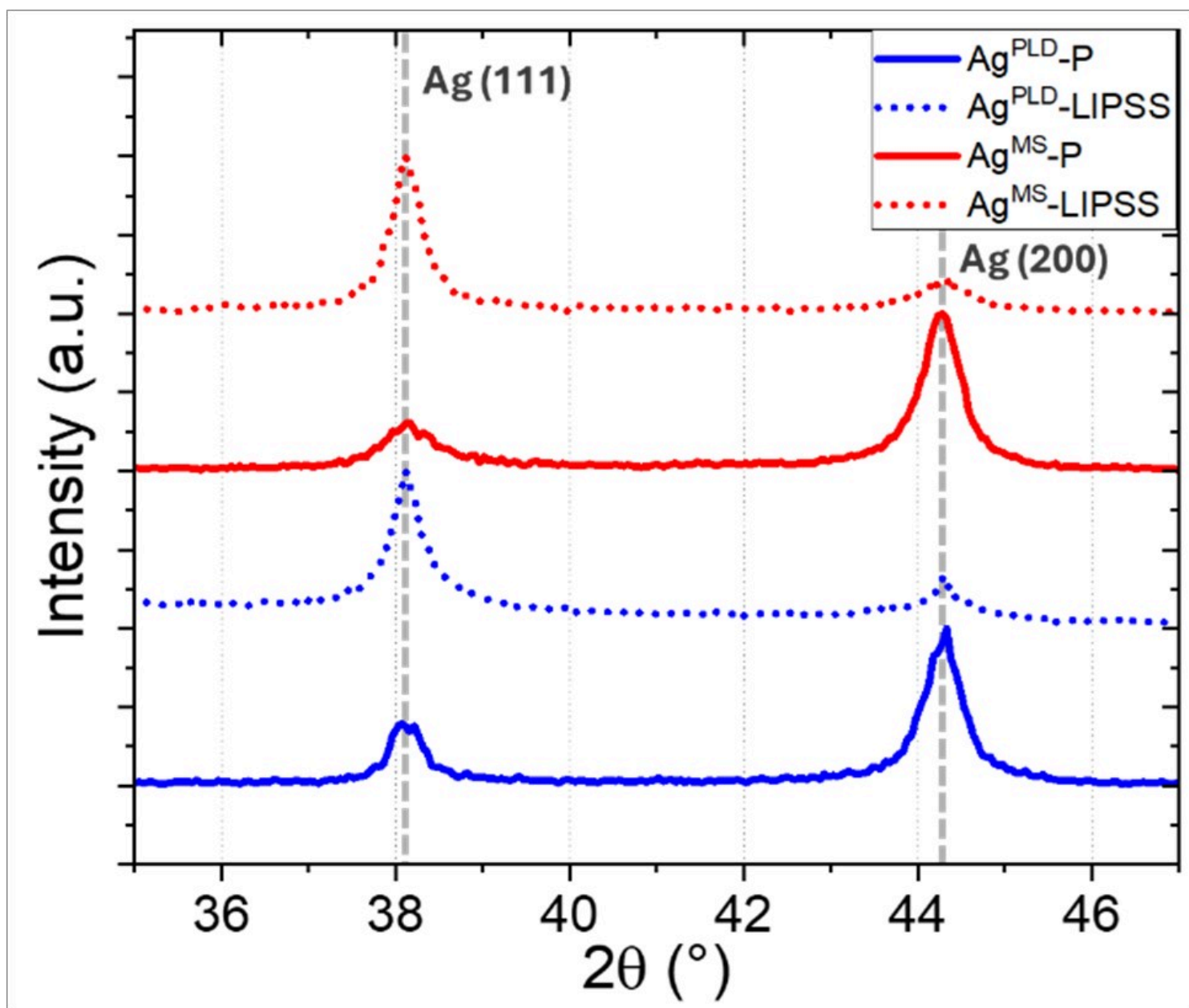


Figure 4

q/2q X-ray diffraction patterns of (a) $\text{Ag}^{\text{MS-P}}$, (b) $\text{Ag}^{\text{PLD-P}}$, (c) $\text{Ag}^{\text{MS-LIPSS}}$, (d) $\text{Ag}^{\text{PLD-LIPSS}}$.

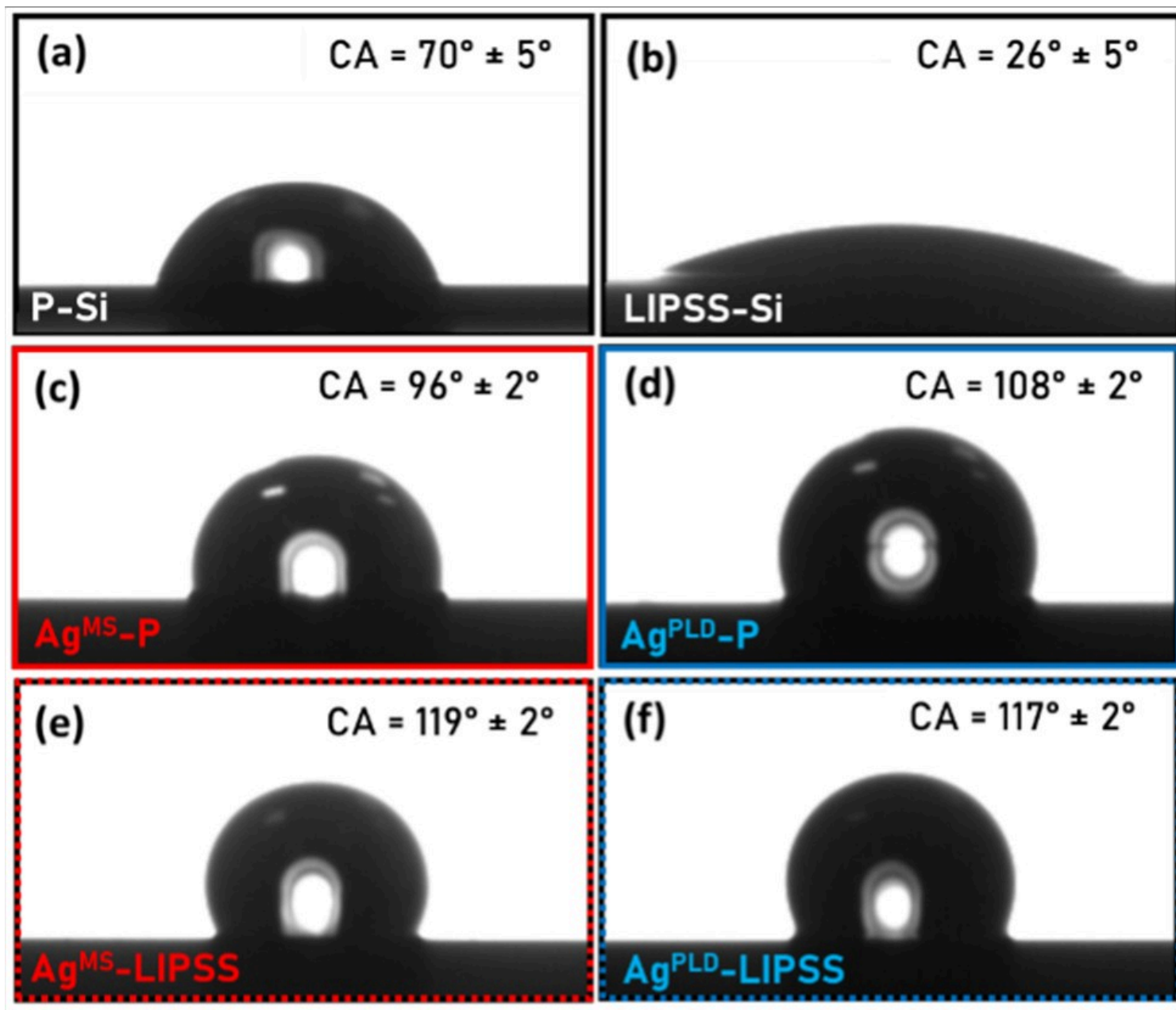


Figure 5

Contact angle measurements using 6 μL water droplets deposited on various surfaces. (a) P-Si, (b) LIPSS-Si, (c) $\text{Ag}^{\text{MS}}\text{-P}$, (d) $\text{Ag}^{\text{PLD}}\text{-P}$, (e) $\text{Ag}^{\text{MS}}\text{-LIPSS}$, and (f) $\text{Ag}^{\text{PLD}}\text{-LIPSS}$.

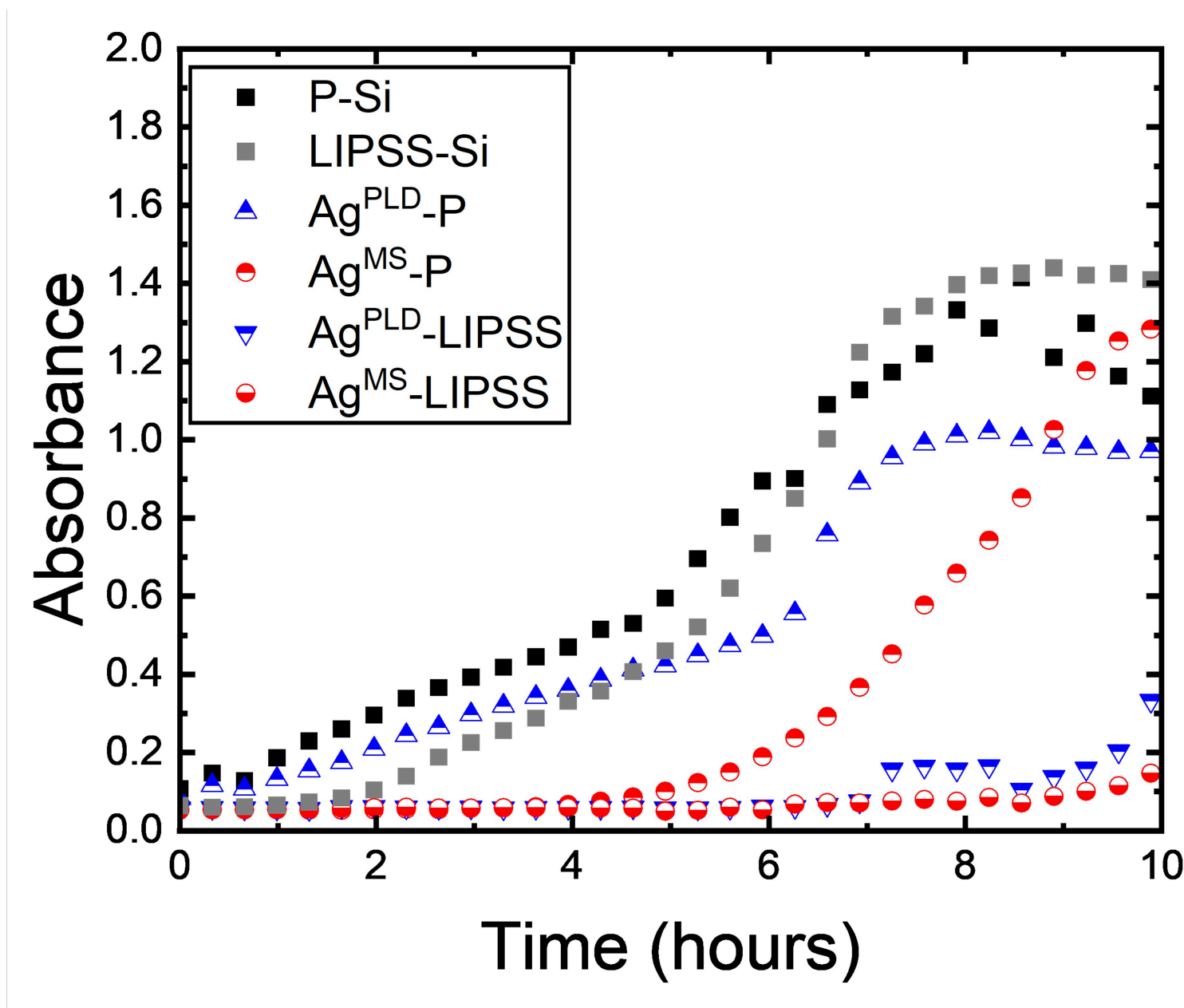


Figure 6

Bacterial growth curve for different surfaces obtained by optical density measurement at 600 nm.

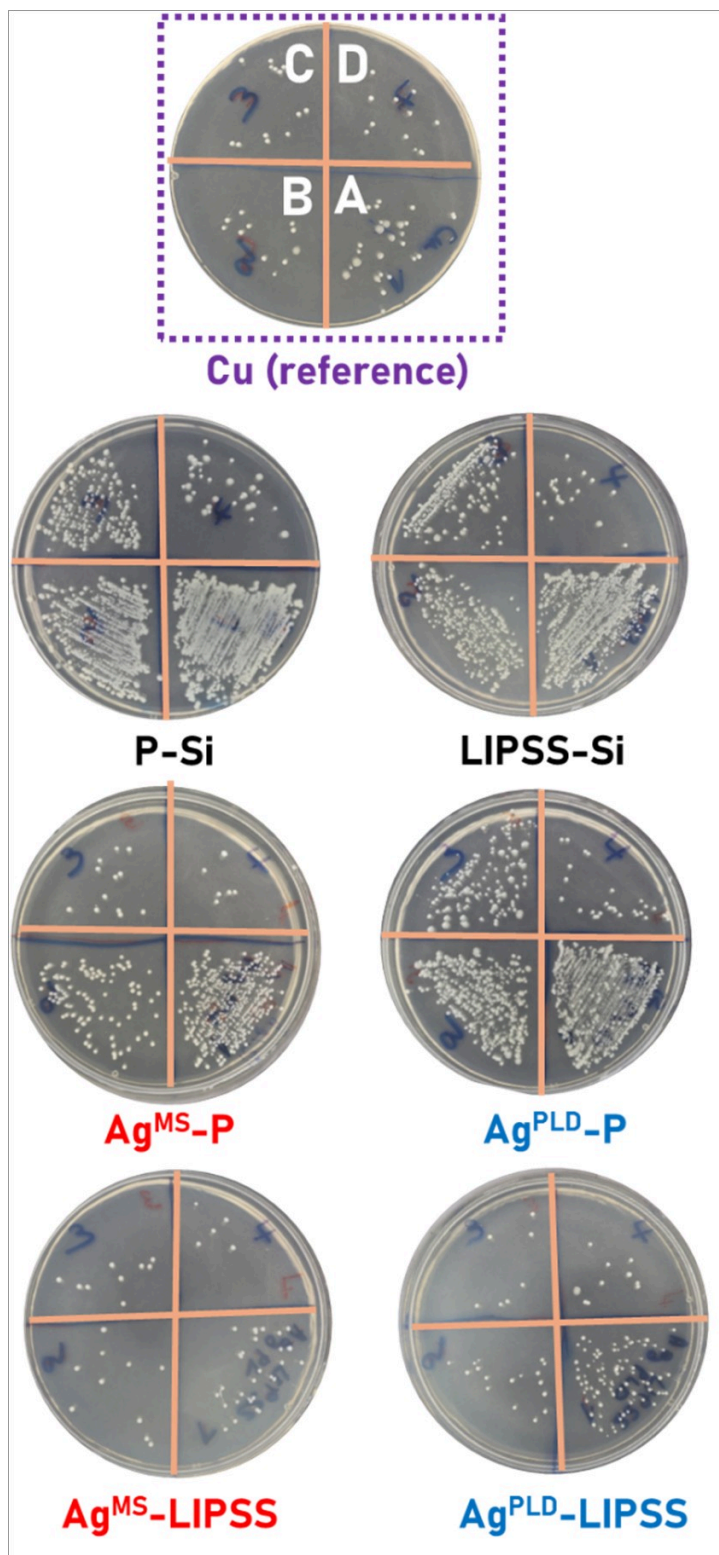


Figure 7

Images of a Petri dish divided into four quadrants containing bacterial colonies after 24 h of incubation at 37 °C with various dilutions: quadrant A represents a dilution divided by 10, quadrant B divided by 10², quadrant C divided by 10³, and quadrant D by 10⁴.

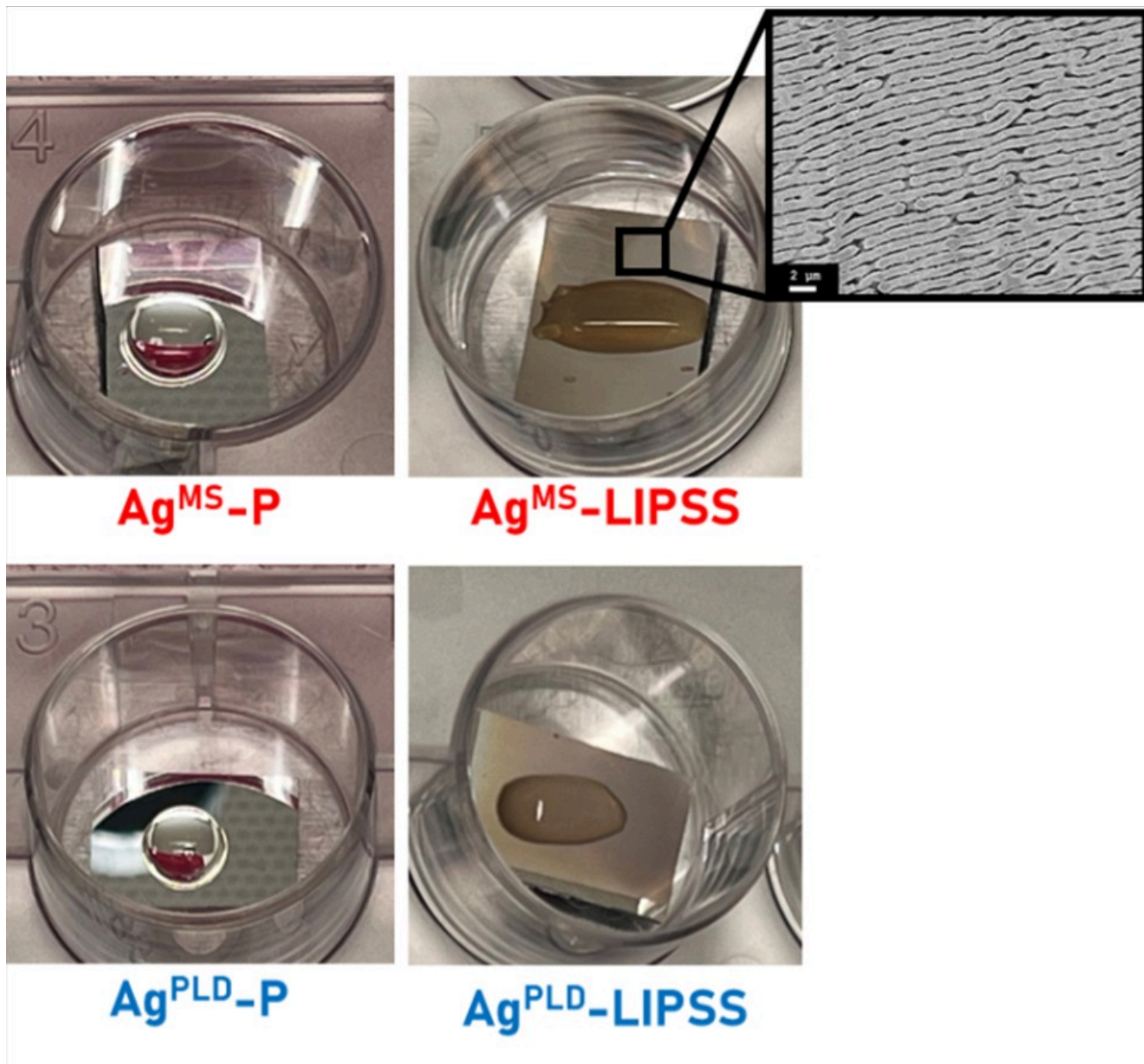


Figure 8

Images of the samples after the deposition of 40 μL of *E. coli* solution. The images show significant droplet spreading along the LIPSS orientation on $\text{Ag}^{\text{PLD}}\text{-LIPSS}$ and $\text{Ag}^{\text{MS}}\text{-LIPSS}$ surfaces. In contrast, on $\text{Ag}^{\text{PLD}}\text{-P}$ and $\text{Ag}^{\text{MS}}\text{-P}$ surfaces, the droplet maintains a nearly circular shape throughout the bacterial proliferation step.

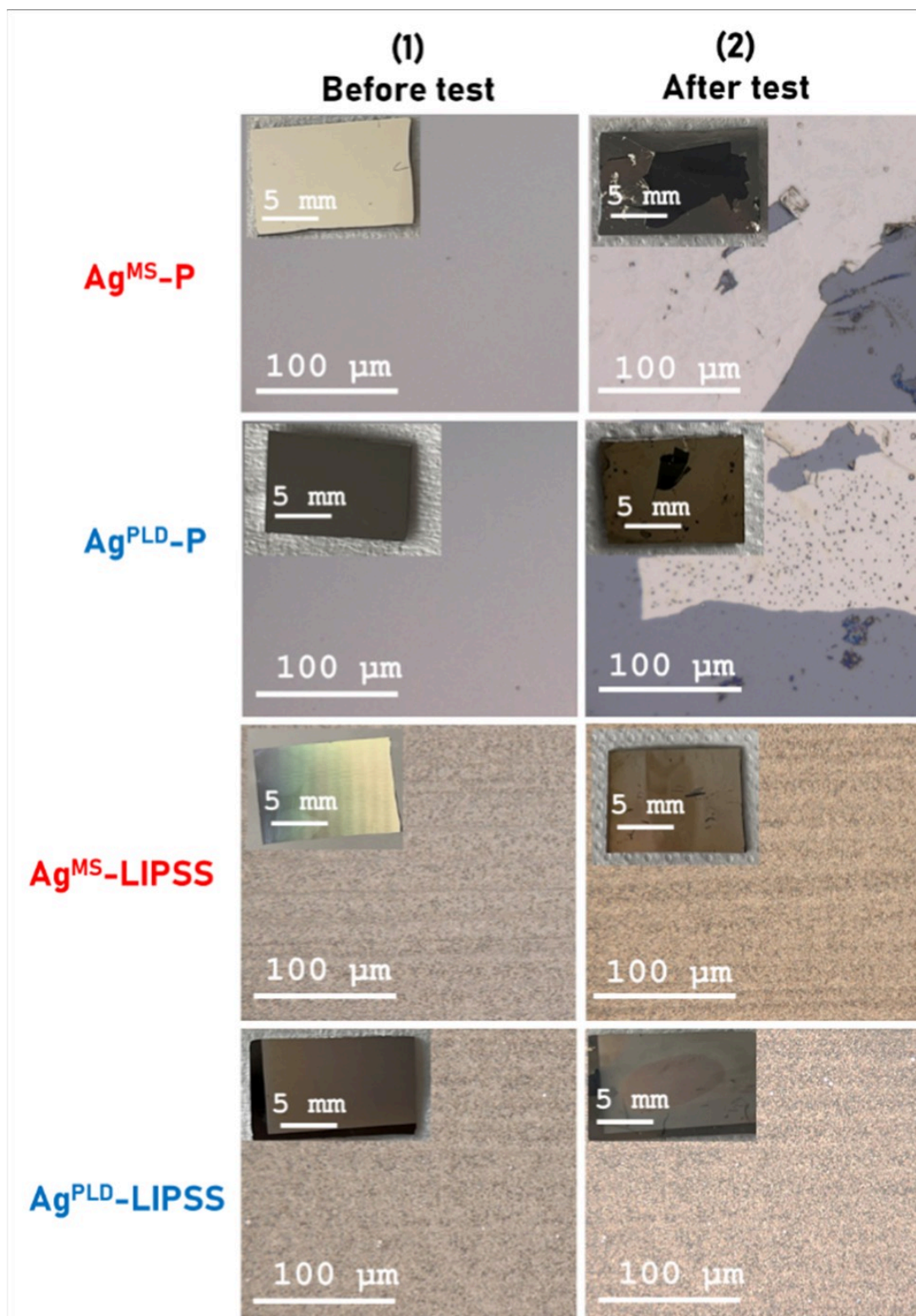


Figure 9

Real images of the samples shown in the corner and their corresponding optical microscope images: (1) shows the samples before antibacterial testing, and (2) shows the samples after the rinsing step.

Supplementary Files

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