

Laser direct patterning of two-dimensional MoS₂ for photoelectric sensing arrays

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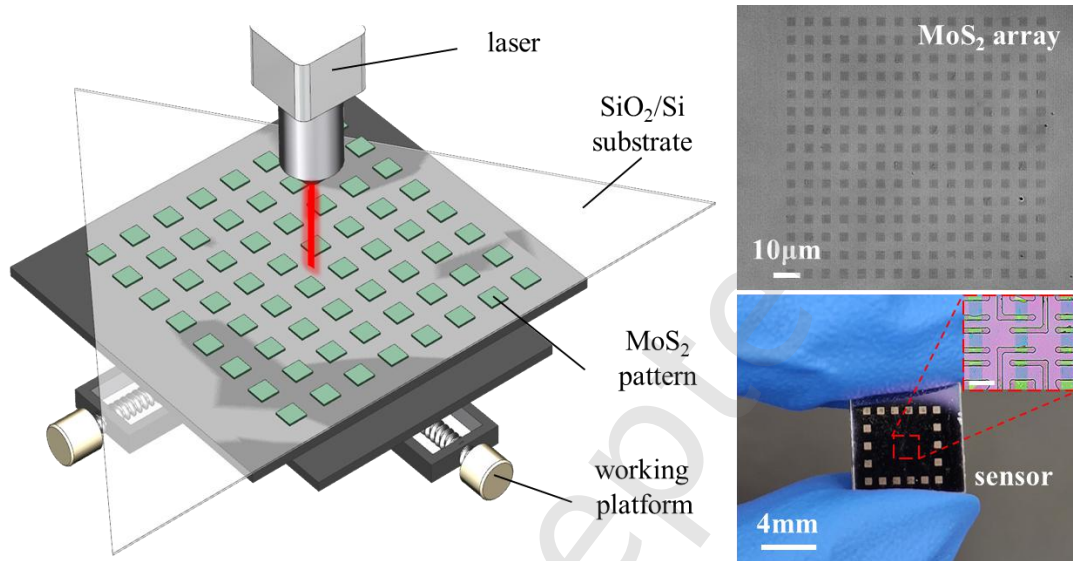
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We investigate the etching-free fabrication of the MoS₂ photoelectric sensing array via a simple laser direct patterning method. The structural density of the fabricated MoS₂ array pattern can reach 107 units/mm², and the size of each pattern unit is about 3.5 μm. The photoelectric sensing array constructed by this method has no obvious trailing effect.

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ABSTRACT: Two-dimensional MoS₂ photoelectric sensing array has shown great application potential in the image sensing field, and the fabrication of the pattern structure is the foundation for the construction of MoS₂ array devices. However, the traditional ion etching patterning technology easily leads to the shedding and residue of MoS₂ materials, which affects the quality of the pattern structure and the performance of the devices. Here, through a simple laser direct patterning method, we investigate the etching-free fabrication of the two-dimensional MoS₂ pattern structure and the construction of the photoelectric sensing array. The research results show that for monolayer MoS₂ materials, the removal rate of the laser direct patterning method can reach about 98%, the structural density of the fabricated array pattern can reach 107 units/mm², and the size of each pattern unit is about 3.5μm. Moreover, this fabrication method rarely introduces ion trap defects, and the photoelectric response of the MoS₂ sensing array has no obvious trailing effect. This work provides a reference for high-quality patterning of two-dimensional materials into array devices without etching.

KEYWORDS: two-dimensional MoS₂, laser patterning, etching-free fabrication, array structure, photoelectric sensing

1 Introduction

Due to the high carrier mobility, switching ratio and mechanical strain, two-dimensional MoS₂ devices have great application potential in the field of the photoelectric sensing[1-4]. In particular, the two-dimensional MoS₂ photoelectric sensor array, which has shown excellent capabilities in the image sensing, neuromorphic simulation and information processing, is a favorable candidate for the next generation of optoelectronic components[5-10].

The controllable fabrication of pattern structures is a key step in the construction of two-dimensional MoS₂ photoelectric array devices[11-14]. However, due to the unique structural characteristics of two-dimensional MoS₂ materials (where the molecular layers are bonded by van der Waals forces rather than molecular bonds), the traditional ion etching technique easily leads to the shedding of two-dimensional MoS₂ and the residual of chemical reagents in the pattern structure processing[15-18]. Additionally, the ion etching processing easily introduces ion trap defects, resulting in the response current of two-dimensional MoS₂ photoelectric sensing arrays slowly recovers to the initial state after the illumination disappears[19-22]. That is, the tailing effect occurs.

The laser patterning technology, as an emerging processing technique, has the advantages of no mask, fewer steps and diversity[23-27]. It does not require etching,

which can significantly prevent the processing defects and contamination of two-dimensional materials, thereby providing a new technical route for the pattern processing of the layered nano-devices[28-32]. For instance, Li[33] proposed a method of laser patterning two-dimensional materials to realize the preparation of VS₂/MoS₂ heterojunctions, which reduced the difficulty of constructing lateral/vertical heterojunctions. Park[28] successfully fabricated the arrays of MoS₂ field-effect transistors via the laser patterning technology, while keeping the surface pristine. However, the conventional laser processing technology suffers from limitations in both pattern accuracy and structure density, making the high-quality patterning of MoS₂ array structures a persistent challenge[34-36].

Here, we investigate the etching-free fabrication of two-dimensional MoS₂ pattern structures and the construction of photoelectric sensing arrays through a laser direct patterning method based on confocal microscopy. Specifically, the pattern structure is processed directly on the monolayer MoS₂ through the micro-area positioning and laser continuous ablation. In an area of 2.1mm², 225 MoS₂ pattern units (15×15) are fabricated, with each unit having a size of about 3.5μm. Then, based on the laser patterning structure, a 3×3 two-dimensional MoS₂ photoelectric sensing array is fabricated. In the photoelectric test, the response current of the device can recover quickly, and no obvious trailing effect is observed.

2 Results and discussion

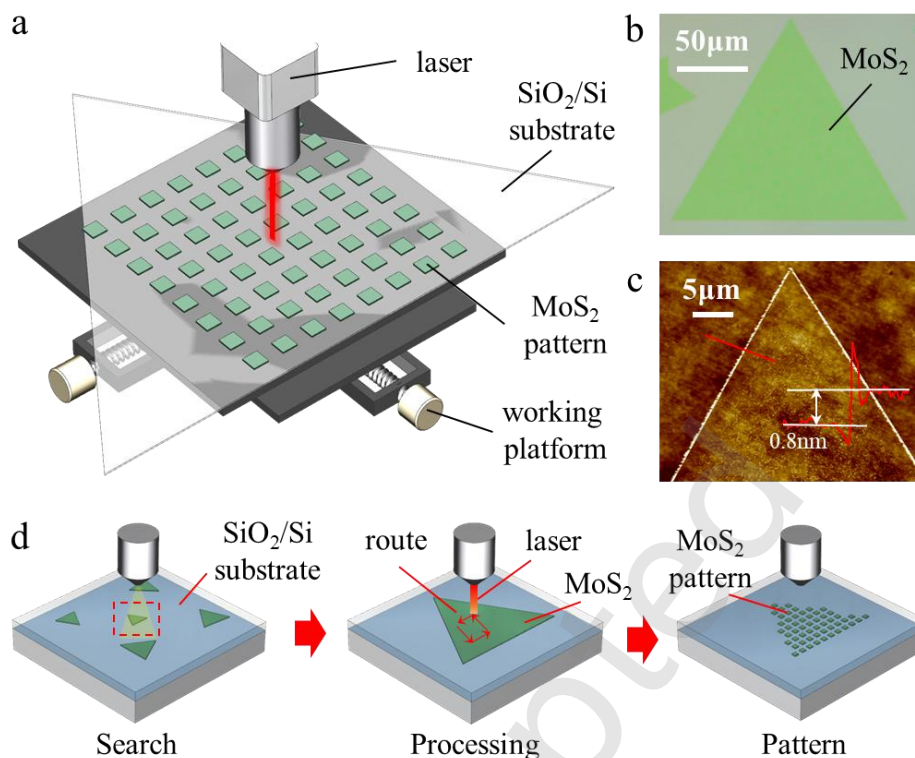


Figure 1 (a) The schematic diagram of the laser direct patterning method; (b) the optical image of the monolayer MoS₂; (c) the AFM image of the monolayer MoS₂; (d) the schematic diagram of the patterning processing of MoS₂.

2.1 The processing effect of laser direct patterning

Figure 1(a) shows the schematic diagram of the laser direct patterning method, which uses a laser to directly pattern the monolayer MoS₂ material without the steps of the lithography, etching and material transfer. Due to the extremely thin thickness of the monolayer MoS₂ film (only one molecular layer), the zone of the MoS₂ film exposed to the laser will be rapidly vaporized under the effect of high-density heat, thereby achieving the removal of excess materials.

The MoS₂ film used for processing is synthesized by the chemical vapor deposition (CVD) technology. The morphology is a triangular structure of the single layer and single crystal, with a size of about 160 μm, as shown in Figure 1 (b). The test result of the atomic force microscope (AFM) shows that the height difference between the MoS₂ film and the SiO₂/Si substrate is about 0.8 nm, with a thickness of only one atomic layer, as shown in Figure 1(c). The optical test results show that the photoluminescence (PL) curve of the MoS₂ film has a strong A exciton peak and a weak B exciton peak under the excitation light of 532 nm. The Raman shift interval (between the in-plane vibration mode E_{12g} and the out-of-plane vibration mode A_{1g}) is about 20 cm⁻¹, as shown in Figure S1. The fabrication process of the laser direct patterning method is shown in Figure 1(d) (see the experimental section for details). This method, which combines the micro-area positioning with the in-situ laser processing, does not require the transfer of two-dimensional materials and avoids the contamination of chemical reagents. Thereby, it causes very little damage to the two-dimensional MoS₂ film and retains the intrinsic characteristics of

materials.

First, we analyze the influence of the laser direct patterning power and speed on the removal effect of the monolayer MoS₂. Figure 2(a) shows the processing morphology of the monolayer MoS₂ at different laser powers, and the central wavelength of the laser is 532 nm. It can be seen that when the laser power is 30 mW, the MoS₂ in the rectangular processing area (blue dashed line) can be effectively removed, but the processing effect of laser is gradually weakened with the reduction of the power. Even when the laser power is 3 mW and 1.5 mW, the MoS₂ film shows no damage. This is because this patterning method uses the continuous laser, and the removal of MoS₂ is mainly based on the ablation effect, so the processing effect is directly related to the laser energy. If the laser power is reduced, it can not provide enough energy to ablate MoS₂, resulting in the increase of processing residues. When the laser energy is completely lower than the ablation energy of MoS₂, an ineffective processing situation will occur.

Figure 2(b) shows the processing morphology of the monolayer MoS₂ at different processing speeds. It can be seen that when the processing speed is 5 μm/s and 8 μm/s, the MoS₂ can be effectively removed, but with the increase of the processing speed, there are striped MoS₂ residues in the processing area. Moreover, the faster the working platform moves, the more obvious the residual MoS₂ leaves. This is because at high processing speed, the work platform is prone to non-uniform motion in certain areas, resulting in uneven distribution of laser energy on the MoS₂ film, thereby causing the local residue. Although this problem can be optimized by upgrading the hardware equipment of the

working platform, this phenomenon can still not be ignored in the laser fast processing.

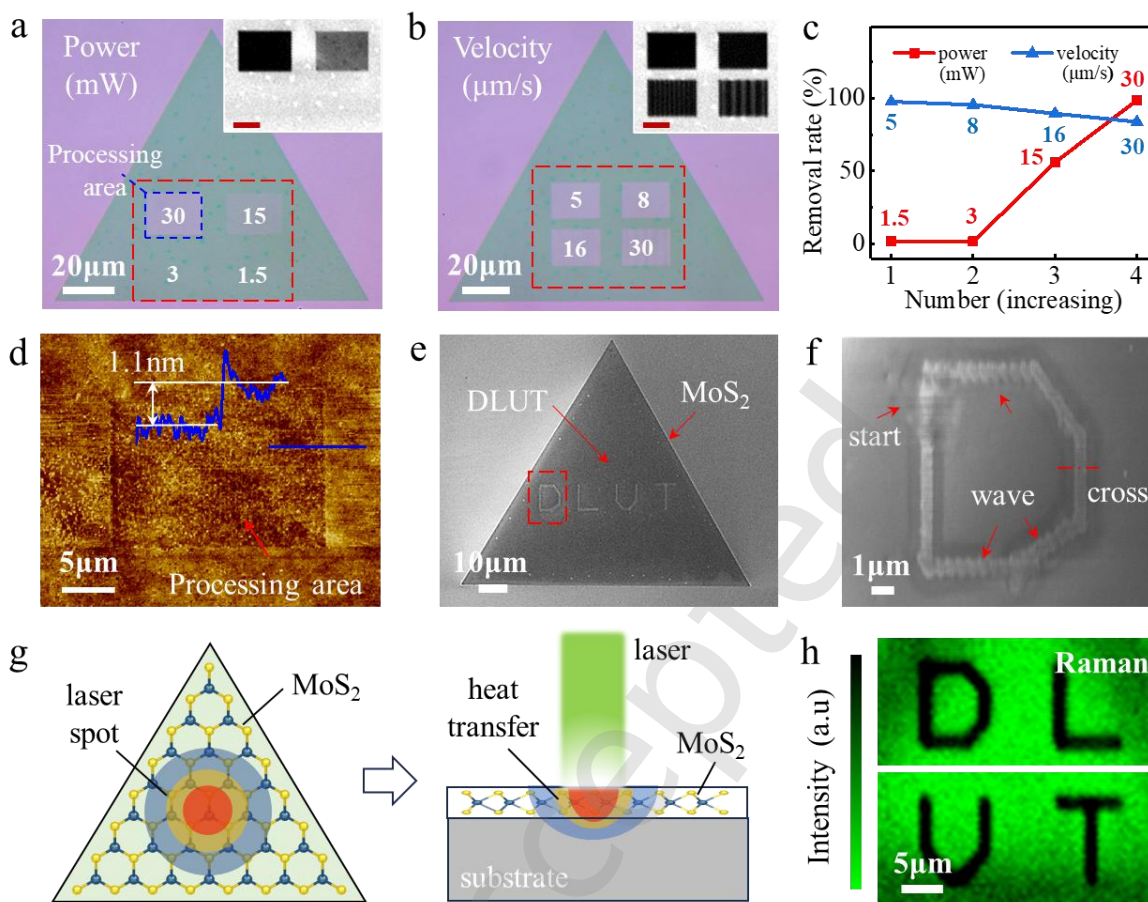


Figure 2 Laser processing morphology of the monolayer MoS₂: (a) the different laser powers, (b) the different processing speeds, and the scale bar of the inset is 10 μm; (c) the removal rate curve of MoS₂; (d) the AFM image of the processing area. The 'DLUT' pattern processed by laser: (e) the SEM image of MoS₂; (f) the magnified SEM image of the 'D' letter; (g) the schematic diagram of the laser spot energy distribution; (h) the Raman spectrum image.

The removal rates of MoS₂ under different laser powers and processing speeds are evaluated by the Raman spectroscopy, as shown in Figure 2(c) and Figure S2. It can be seen that at the laser power of 30 mW, as the processing speed increases from 5 μm/s to 30 μm/s, the MoS₂ removal rate gradually decreases from about 98% to 84%. At the processing speed of 5 μm/s, as the laser power decreases from 30 mW to 1.5 mW, the MoS₂ removal rate drops significantly from about 98% to 0%. Thus, the results indicate that the energy distribution is the primary factor determining the removal rate of MoS₂, and low laser power or high processing speed will reduce the removal rate of MoS₂. In addition, the AFM test results show that under the working conditions of 30 mW and 5 μm/s, the shape of the rectangular processing area is regular and the surface is smooth. The height difference between the edge of the processed area and the unprocessed MoS₂ film area is only 1.1 nm, indicating that the laser processing has a very good removal effect on the MoS₂ and causes very little damage to the substrate, as shown in Figure 2(d).

Then, we further analyze the processing effect of the laser on the pattern structure of the monolayer MoS₂. Figures 2(e) and Figure S3(a) show the line structures processed by laser on a monolayer MoS₂, and it can be seen that they form a

very clear "DLUT" pattern. The pattern is located in the middle of the MoS₂ film, and the size of each letter is about 10 μm × 8 μm, which is highly recognizable and complete.

Among them, the letter "D" is magnified for observation, revealing more details of the processing morphology, as shown in Figure 2(f). It can be seen that along the laser processing path, the obvious wavy undulations can be clearly observed. This is a typical morphological feature after laser processing, which is caused by the movement of the molten pool and the temperature difference between the front and back of the molten pool[37]. At the initial position of the path, due to the activation and adjustment of the laser, an additional energy impact is exerted on the material, resulting in a concave area appearing at the starting position of the processing. Furthermore, in the cross section of the laser processing path, there are clearly inconsistent colors, as shown at the marked 'cross' position in Figure 2(f). This is because the laser energy is the Gaussian distribution, the center energy is the highest, and the energy gradually decreases along the center, thus showing different processing effects on the MoS₂ film, as shown in Figure 2(g). According to the light and dark of the color, the cross section of the laser processing path is divided into the processing zone and the heat-affected zone. The processing zone is light,

which is in the center of the processing path, and the MoS₂ material in it is vaporized by laser at high temperature, so as to be effectively removed. The heat-affected zone is dark, which is on both sides of the processing path, and the laser energy in this zone is not enough to vaporize the MoS₂ film, so only dark hot processing marks are left. Besides, as can be seen from Figure 2(f), under the 2 μm laser spot, the actual line width of the letter "D" after processing is less than 2 μm , which also indirectly confirms the existence of the heat-affected zone.

In order to analyze the residual situation of MoS₂ after laser processing, the Raman and PL tests are conducted on the "DLUT" pattern, as shown in Figure 2(h) and Figure S3(b). It can be seen that the morphology of the whole "DLUT" pattern is complete, and there is no obvious optical spectrum signal (the optical spectrum is black), indicating that there is no MoS₂ film material in the area. Therefore, it can be concluded that the laser direct patterning method has the excellent processing effect and high removal rate for the MoS₂.

2.2 The patterning of MoS₂ array structures

Next, we have fabricated various-sized monolayer MoS₂ array structures by the laser direct patterning method. The number of rows and columns for these structures are 3 $\times$ 3, 8 $\times$ 8, and 15 $\times$ 15, respectively, as shown in Figures 3(a) - (f) and Figure S4. It can be seen that the letter pattern is processed with grooves on the MoS₂, while the array pattern is left with protrusions on the MoS₂. In the processing, the triangular monolayer MoS₂ film is first processed into a rectangular shape along the designed path. Then, the

rectangular shape is divided into individual array units according to the number of rows and columns, thereby obtaining the designed array structure, as shown in Figure S5.

Figure 3 (a) and Figure 3(b) show the morphology of the 3 $\times$ 3 array structure. It can be seen that the morphology of the MoS₂ array is regular and uniform after the laser processing, and the size of each unit is about 10 $\mu\text{m} \times 10 \mu\text{m}$. It is worth noting that the edges of the MoS₂ array units processed by laser are shown as standard right angles, rather than arc shapes. Compared with the MoS₂ arrays processed by the ion etching technology in our previous study[38], the laser processing performs even better in the processing of corner details of array structures. When the number of arrays increases to 8 $\times$ 8, the size of each unit is reduced to 5 $\mu\text{m} \times 5 \mu\text{m}$. It can be seen that the arrangement of the arrays is still arranged neatly and each unit remains complete, as shown in Figure 3(c) and Figure 3(d). If the row and column number of the MoS₂ array continues to increase, while the unit size continues to decrease, it is more test the ability of the laser processing. Figure 3(e) and Figure 3(f) show a 15 $\times$ 15 MoS₂ array processed by the laser direct patterning method. The total area of the array is about 2.1 mm², and the density of the MoS₂ unit structures is about 107 units/mm². The size of each unit is about 3.5 μm , which is already close to the diameter of the laser spot. It can be seen that even at such a small size, the morphology and consistency of each MoS₂ unit still perform exceptionally well.

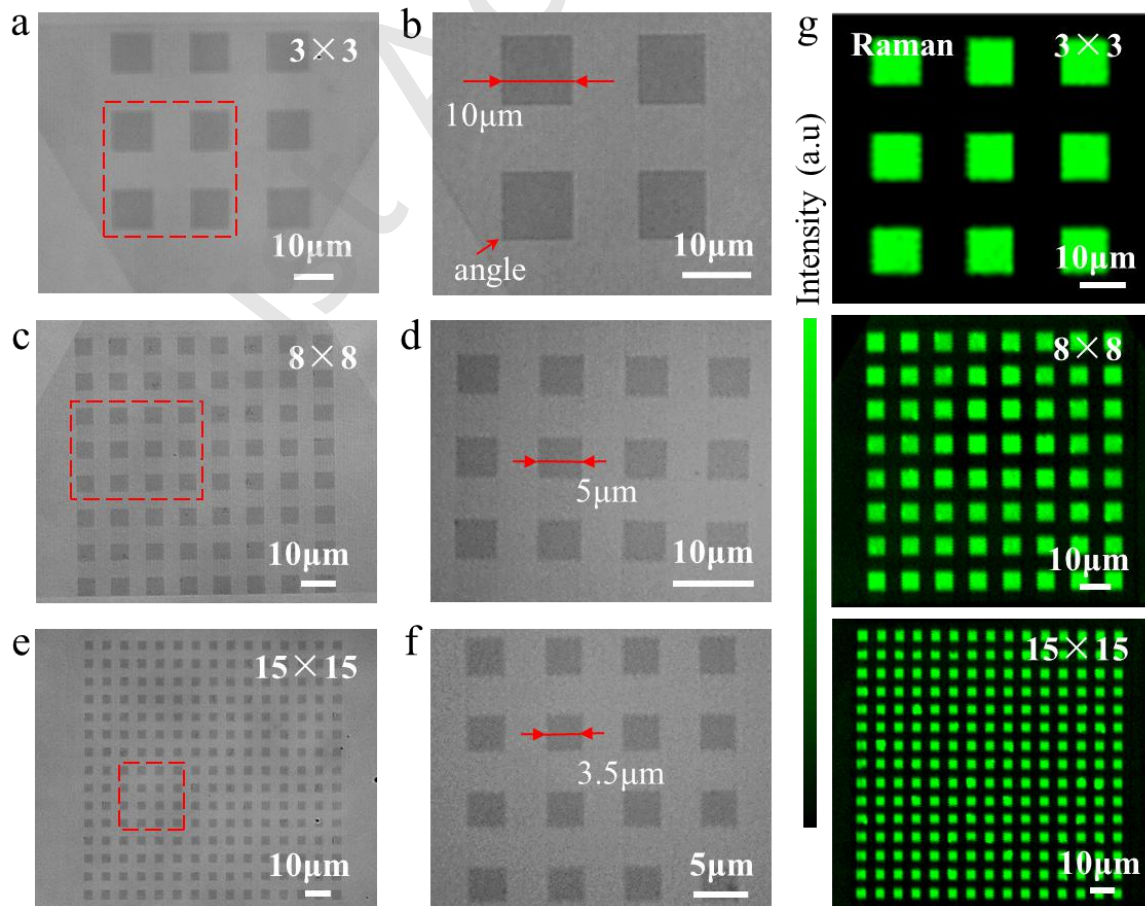


Figure 3 The monolayer MoS₂ arrays via the laser direct patterning: (a) the overall morphology of the 3×3 structure; (b) the local magnified morphology of the 3×3 structure; (c) the overall morphology of the 8×8 structure; (d) the local magnified morphology of the 8×8 structure; (e) the overall morphology of the 15×15 structure; (f) the local magnified morphology of the 15×15 structure; (g) the Raman spectra of the above three MoS₂ arrays.

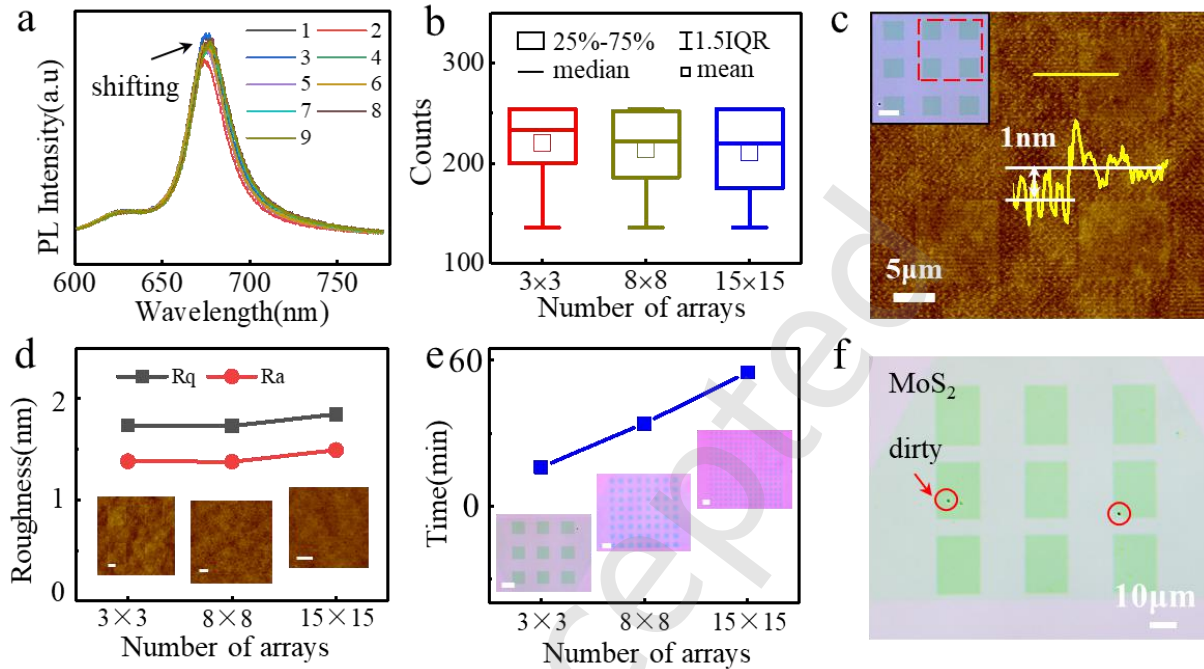


Figure 4 (a) the PL curve of the 3×3 array; (b) the box plot of the PL spectral intensity; (c) the AFM test morphology of the 3×3 array, and the inset scale bar is 10μm; (d) the roughness curves of three MoS₂ array structures (3×3, 8×8, and 15×15), and the inset scale bar is 5μm; (e) the processing time of three MoS₂ array structures, and the inset scale bar is 10μm; (f) the dirt spots on a 3×3 MoS₂ array structure.

The Raman and PL spectra of the above three monolayer MoS₂ array structures are shown in Figure 3(g) and Figure S6. For the 3×3 array structure, the Raman shift (about 403.5 cm⁻¹) and PL (about 680 nm) scan images show that the internal units have uniform luminescence and similar intensity, indicating that the array structure is complete and the optical performance are consistent. However, as the size of the array units decreases, in the 8×8 array structure, although the Raman image shows that the shape of the array is complete, the PL spectral intensities of some units are inconsistent. Especially in the 15×15 array structure, the PL spectra of some array unit parts are directly black, resulting in the absence of the spectral pattern, as shown in Figure S6(c). This is because the PL spectrum is particularly sensitive to the number of MoS₂ layers. When the single layer changes to the multi-layer structure, the energy valley of the conduction band bottom of MoS₂ changes from the K valley to the Λ valley (that is, from the direct band gap to the indirect band gap), thereby causing a sudden decrease in the PL[39]. In the CVD synthesis of the monolayer MoS₂ film, there are usually some microscopic defects, such as large crystal nucleus particles or localized blocky multilayers[40, 41]. After processing, these defects in the raw materials still remain in the array structure. When the unit size of the MoS₂ array is similar to the size of the defect, the local bandgap variation of the material caused by the defect cannot be

ignored, thereby resulting in a decline in the PL performance.

To further analyze the influence of the laser direct patterning on the spectral uniformity of the monolayer MoS₂ array structure, we extract the PL curves of each unit point in the 3×3 array, as shown in Figure 4(a) and Figure S7. It can be seen that the PL curve of some unit points has a little decline and blue shift, but the PL curve of the 3×3 array structure has little difference on the whole. Due to the excessive number of units in the 8×8 and 15×15 arrays, we adopt box plots for the PL analysis, as shown in Figure 4(b). The distance between the upper quartile (75%) and the lower quartile (25%) can reflect the dispersion of a set of data. It can be seen that as the number of MoS₂ arrays increases, the box gradually becomes longer, indicating that the degree of data dispersion increases. The calculation of the relative standard deviation of the PL for the three MoS₂ array structures is shown in equation (1):

$$RSD = \frac{s}{\bar{x}} \times 100\% \quad (1)$$

where, the *RSD* is the relative standard deviation of the data, the *s* is the standard deviation of the data, and the $\bar{x}$ is the arithmetic mean of the data. The calculated results show that the *RSD* of the PL for the 3×3, 8×8 and 15×15 array structures are 16.3%, 17.3% and 18.9%, respectively, indicating that the PL consistency of the 8×8 and 15×15 arrays gradually becomes worse. Meanwhile, due to the

advantage of the larger unit size, the PL average and median values of the 3×3 array are also higher than those of the other two arrays. Thus, it can be seen that in the laser direct patterning, the quality of the raw materials and structure design, especially the unit size, are very importance to the optical performance of the MoS₂ array structure.

Besides, the surface roughness is also an important factor affecting the processing quality of MoS₂ array structures. The AFM test morphology of the 3×3 array structure is shown in Figure 4 (c), and it can be seen that there is no obvious processing boundary line between the array structure unit and the substrate after the laser direct patterning. The height difference between the MoS₂ and the SiO₂/Si substrate is only about 1nm, indicating that the laser does not produce an effective processing depth on the substrate. This is because the energy density of the laser is concentrated, and its impact on the non-processing area is very small. Moreover, the melting point of the SiO₂ layer on the substrate surface is relatively high, approximately 1700°C, and the laser ablation effect on it is limited, so the substrate remains relatively flat as a whole. But compared with the unprocessed MoS₂ film (as shown in Figure 1(c) inset), the fluctuations of the AFM test curves after processing are significantly larger (as shown in Figure 4(c) inset). The root mean square roughness R_q and the average roughness R_a are used to further evaluate the processing surface quality of the three MoS₂ array structures, as shown in Figure 4(d). It can be seen that the R_q values of the 3×3, 8×8 and 15×15 array structures are about 1.7nm to 1.9nm, and the R_a values are about 1.3nm to 1.5nm, which is relatively low.

As the number of arrays increases, the laser patterning time of the array structures gradually becomes longer, as

shown in Figure 4(e). In addition, due to the ablation splash, the MoS₂ array structure is easy to have some dirt spots, as shown in Figure 4 (f). However, these dirt spots of the laser direct patterning are very small and cannot cause significant morphological damage to the overall structure of the array. Compared with the traditional ion etching method, which can easily result in the loss of the MoS₂ array structure (Figure S8), the laser patterning technology has the advantages of no chemical reagent contamination, no residual photoresist, and no material shedding during the processing. Therefore, it can be concluded that at the micron scale, the laser direct patterning method has the extremely high accuracy, controllability and surface quality for the fabrication of the monolayer MoS₂ array structures.

2.3 The fabrication and testing of the MoS₂ photoelectric sensing array

Based on the monolayer MoS₂ structure via the laser direct patterning, we fabricate a 3×3 photoelectric sensing array. The MoS₂ photoelectric sensor array is built on a SiO₂/Si substrate with the size of about 8mm×8mm, and the test contacts are made around the substrate for the photoelectric testing of each photosensitive unit, as shown in Figure 5 (a) (see the experimental section for details). The optical image shows that within the photoelectric sensing array, the morphologies of the 9 MoS₂ photosensitive units processed by the laser patterning are regular and neatly arranged. There is no cross-interference between the electrodes, and the size of each unit is about 10μm×20μm, as shown in Figure 5(b). The metal electrodes are placed at both ends of each MoS₂ photosensitive unit, and the SiO₂ layer is the insulating layer with a thickness of about 500nm, as shown in Figure 5(c).

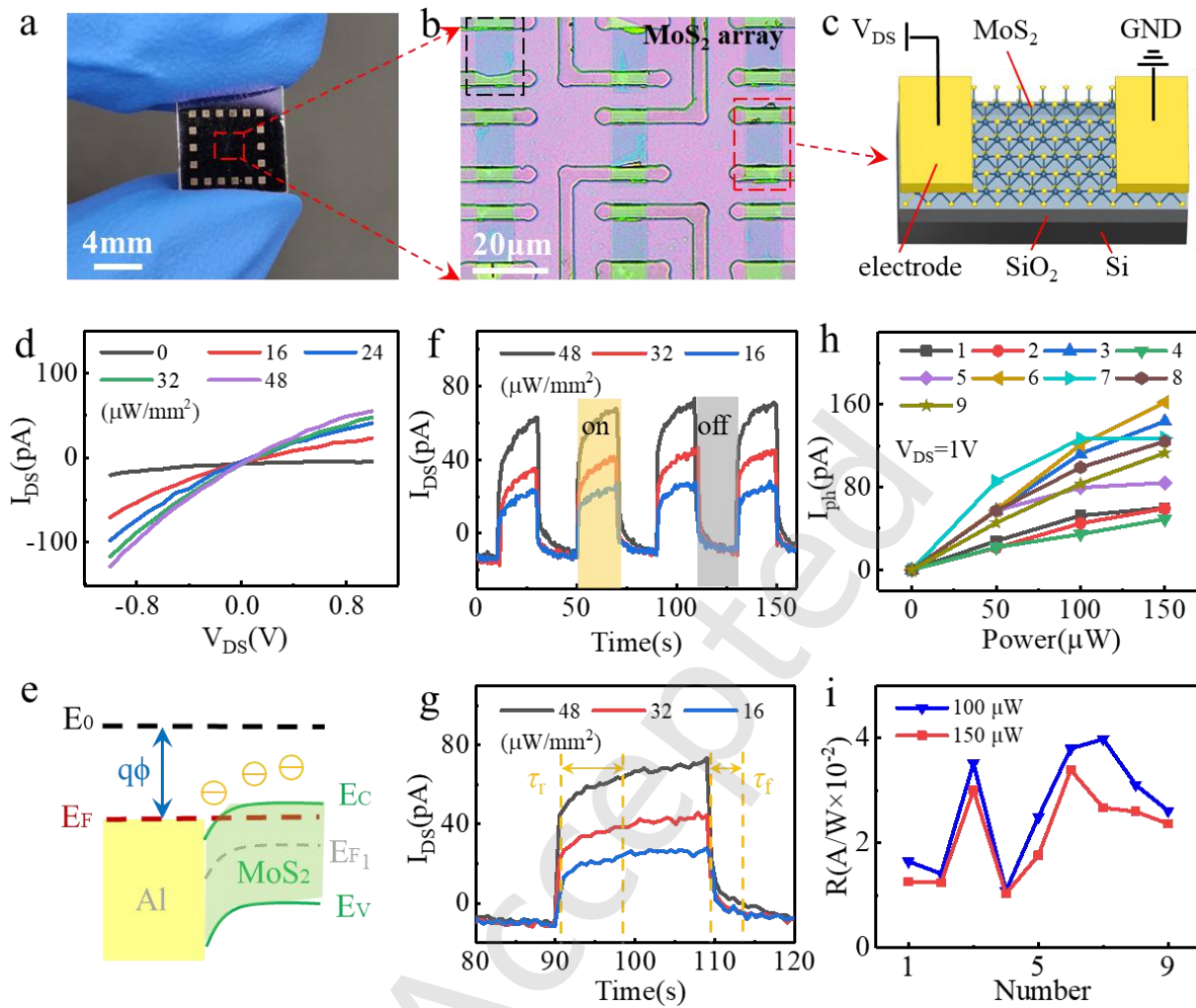


Figure 5 The two-dimensional MoS₂ photoelectric sensing array: (a) the physical image; (b) the optical microscopic image of the internal structure; (c) the schematic diagram of the photosensitive unit structure; (d) the photoelectric output curves (I_{DS} - V_{DS}) of the tested photosensitive unit (marked by a black box in Figure 5 (b)) under different incident light intensities; (e) the schematic diagram of the energy band structure of the contact between the Al electrode and the MoS₂; (f) the time response curve of the tested photosensitive unit; (g) the response rise/fall time of the tested photosensitive unit; (h) the variation curves of photocurrent versus incident power for nine photosensitive units; (i) the response rate R of nine photosensitive units.

The photoelectric test results show that under the incident light of 532nm, with the increase of the light power, the output current of the MoS₂ photosensitive unit in the array gradually increases, and the photoelectric output curve (I_{DS} - V_{DS}) is an inclined straight line, showing an approximate ohmic contact characteristic, as shown in Figure 5 (d). This is because the electrode material of the MoS₂ array is the Al, and the work function of the Al is about 4.28eV, while the work function of the monolayer MoS₂ is about 4.36eV[42]. When they form a metal-semiconductor contact, the energy band of the monolayer MoS₂ near the metal side will bend downward, allowing charges to pass through the contact area smoothly, as shown in Figure 5(e), so the response current of the device changes linearly with the light power.

Figure 5(f) shows the time response curve of the MoS₂ photosensitive unit, and as the incident light is turned on/off, the response current rises/falls rapidly. Under the illumination of the 16μw/mm², 32μw/mm², and 48μw/mm², the response rise time τ_r (the time range for the output

current change from 10% to 90%) is 6.6s, 6.6s, and 6.8s respectively, and the response fall time τ_f is 2.2s, 3.1s, and 3.9s, respectively, as shown in Figure 5(g). It can be seen that the response fall current of the MoS₂ array device fabricated by the laser direct patterning method can recover quickly, without showing the obvious trailing effect. This is because the diameter of the laser spot is about 2μm, and compared with the ion etching, it is more difficult to form ion trap defects on the substrate and MoS₂ material, thereby avoiding the situation where charges are captured by the trap states and undergo delayed recombination in the transmission process.

The variation curve of the photocurrent and incident power of the two-dimensional MoS₂ photoelectric sensing array is shown in Figure 5(h). It can be seen that as the incident light power increases, the photocurrent of all MoS₂ photosensitive units gradually increases until the saturation is reached. The response rate R is used to evaluate the photoelectric response ability of each photosensitive unit, which is calculated as shown in equation (2):

$$R = \frac{I_{DS} - I_{Dark}}{\rho \times A} \quad (2)$$

where, the I_{DS} is the output current of the device, the I_{Dark} is the dark current of the device, the ρ is the incident light power density, and the A is the effective channel area of the device. It can be seen that as the incident power increases, the R decreases due to the saturation of the photoelectric output of some photosensitive units. Overall, the R of the photosensitive units in the MoS₂ sensing array is about 0.01A/W to 0.04A/W, as shown in Figure 5(i). Therefore, it can be concluded that the laser direct patterning method has the excellent intrinsic processing characteristics, and the fabricated two-dimensional MoS₂ sensing array has no obvious trailing effect.

3 Conclusions

In summary, we investigate the etching-free fabrication effect of the laser direct patterning method on the two-dimensional MoS₂ pattern structure, and construct a 3×3 photoelectric sensing array. The research results show that the laser direct patterning method has the excellent manufacturing accuracy, surface quality, and inherent processing characteristics at the micrometer scale. For fabricating the MoS₂ pattern structure, the removal rate can reach about 98%. The structural processing density can reach about 107 units/mm², and the size of each array unit is about 3.5μm. The root mean square roughness is about 1.7nm to 1.9nm, and the average roughness is about 1.3nm to 1.5nm. Furthermore, the laser direct patterning method rarely introduces ion trap defects. The response fall time of the fabricated two-dimensional MoS₂ photoelectric sensing array is short, and no obvious trailing effect occurs. This work provides a reference for the etching-free fabrication of high-quality two-dimensional patterned structures for photoelectric array devices.

4 Experimental Section

4.1 The CVD synthesis of MoS₂ films

The monolayer MoS₂ film is prepared by the CVD. The molybdenum source is the MoO₃ (25mg), the sulfur source is the sublimated S (1g), the carrier gas is the Ar (15sccm), and the substrate is the SiO₂/Si wafer (with the SiO₂ layer of 500nm). The molybdenum source is placed in the middle of the heating zone, and a catalyst NaCl (0.5mg) is added to promote the low-temperature nucleation. The sulfur source is placed at the upper edge of the heating zone, which is heated and evaporated through the thermal radiation. During the synthesis process, the temperature change gradients of the CVD tubular furnace are the room temperature - 670°C - 670°C - 740°C - 740°C - room temperature, and the corresponding time periods are the 22 minutes - 3 minutes - 2 minutes - 10 minutes - natural cooling.

4.2 The laser direct patterning of the MoS₂ structure

The laser direct patterning device is a self-assembling equipment, which has been modified from a confocal Raman spectrometer, including a laser, an xy-axis coordinate control platform, a microscope, and a lens group. The observation center point coincides with the laser optical path, enabling precise positioning and processing for the MoS₂ films. The laser spot of the equipment is the Gaussian

distribution, and the size of the spot can be adjusted by the lens group. In the processing, the SiO₂/Si substrate (with the monolayer MoS₂) is placed on the workbench platform, and the position of the MoS₂ film is sought through the microscope; then, based on the pattern structure of the two-dimensional MoS₂, different processing schemes are designed; finally, under the action of laser heat, the working platform moves along the designated path, thereby obtaining the designed MoS₂ structure. When fabricating the MoS₂ line structure and array structure, the effective laser power is about 30mW, the effective spot diameter is about 2μm, and the movement speed of the working platform is about 10μm/s.

4.3 The fabrication and testing of the MoS₂ photoelectric sensing array

On the basis of the 3×3 MoS₂ array structure patterned by the laser direct patterning, the metal electrodes of the photoelectric sensing array are constructed through the photolithography (Suss-MJB4) and the magnetron sputtering (Kurt J. Lesker-PVD75). The photoresist is the S1818, the exposure time is 1s, and the development time is 60s. The power of the magnetron sputtering is 100W, the time is 50s, and the sputtering material is Al. In addition, the test contacts are constructed around the substrate in the same way to conduct photoelectric tests on the MoS₂ photosensitive units. In the test, the wavelength of the test light is 532nm, the light blocker is used to control the on/off of the optical path, and the semiconductor analyzer (Keithley 4200A) is used to collect the response signal of the MoS₂ photoelectric sensor array.

Electronic Supplementary Material: Supplementary material (the optical morphology, spectral images, and processing route of the laser patterned MoS₂) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94909164>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Long Chen: Data curation, project administration, validation, writing manuscript, experimental design, funding acquisition. Yi Wang: Data curation, validation, experimental design. Xiaobo Liao: Project administration, experimental design. Xuan Liao: Data curation, validation. Lingyu Zang: Data curation, validation. Jinhui Song: Project administration, writing manuscript, experimental design. All the authors have approved the final manuscript.

Informed consent

Not applicable.

Ethics statement

Not applicable.

Use of AI statement

None.

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Electronic Supplementary Material

Laser direct patterning of two-dimensional MoS₂ for photoelectric sensing arrays

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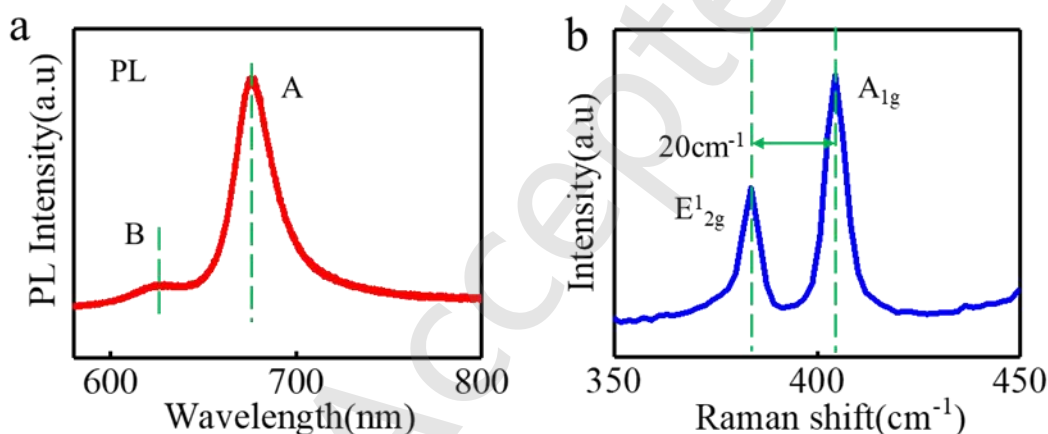


Figure S1 The spectral curve of the MoS₂ material synthesized by the CVD: (a) the photoluminescence (PL); (b) the Raman shift.

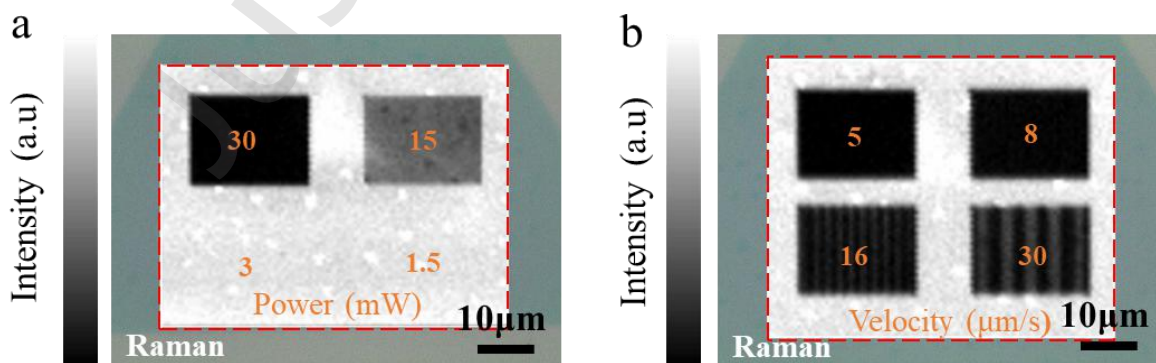


Figure S2 The MoS₂ Raman spectroscopy after the laser processing: (a) the different laser powers; (b) the different processing speeds.

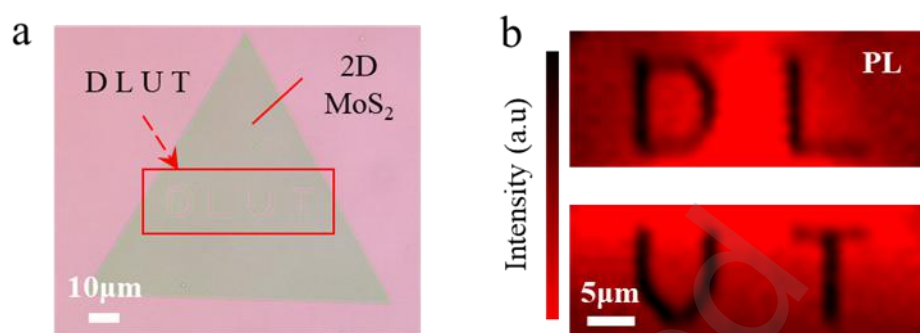


Figure S3 The 'DLUT' pattern processed by laser: (a) the optical microscopic morphology; (b) the PL spectrum.

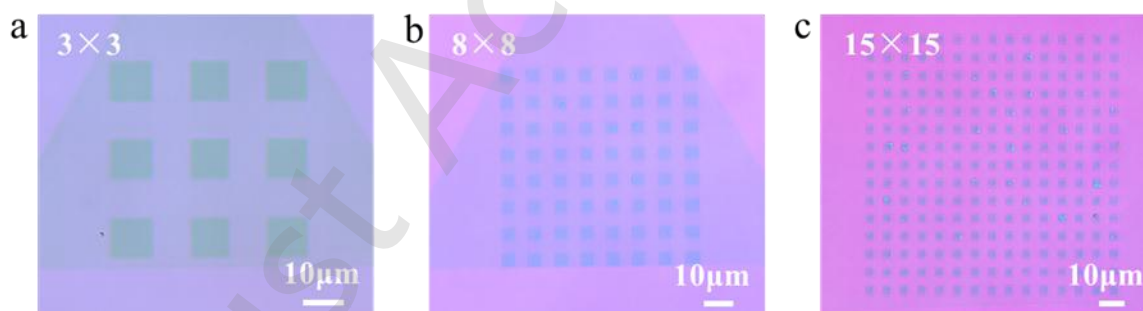


Figure S4 The MoS₂ arrays via the laser direct patterning: (a) the 3×3 pattern structure; (b) the 8×8 pattern structure; (c) the 15×15 pattern structure.

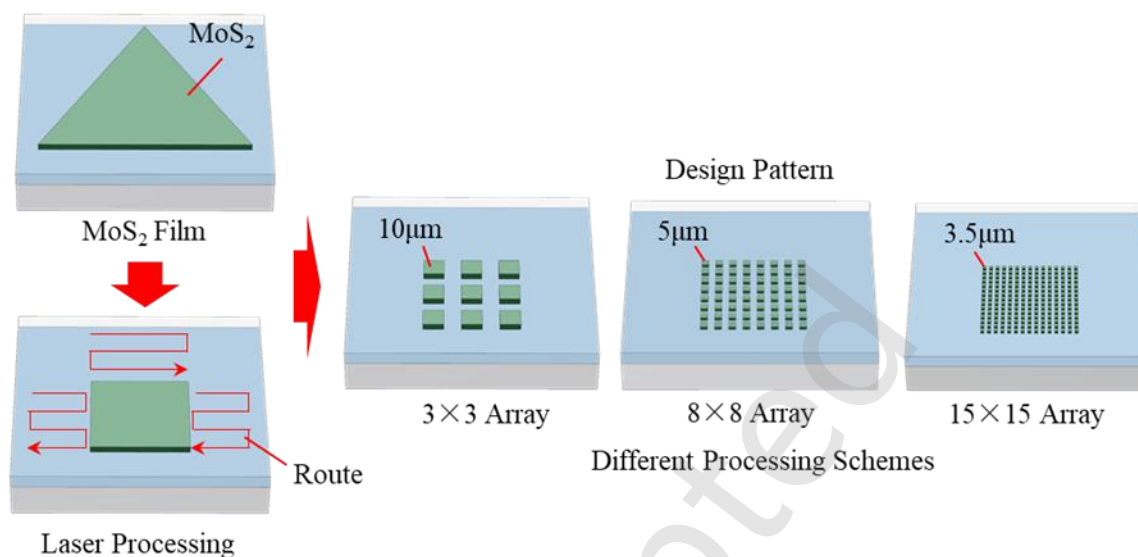


Figure S5 The schematic diagram of the laser direct patterning process for the MoS₂ array structures.

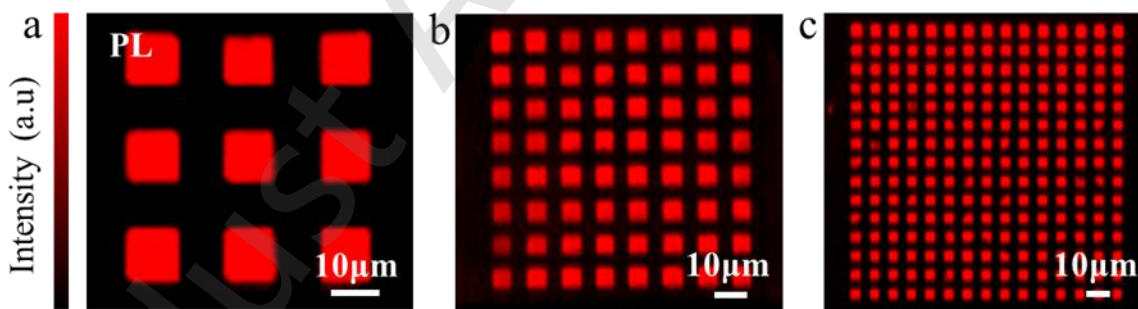


Figure S6 The PL spectra of the MoS₂ array structures: (a) the 3 × 3 pattern; (b) the 8 × 8 pattern; (c) the 15 × 15 pattern.

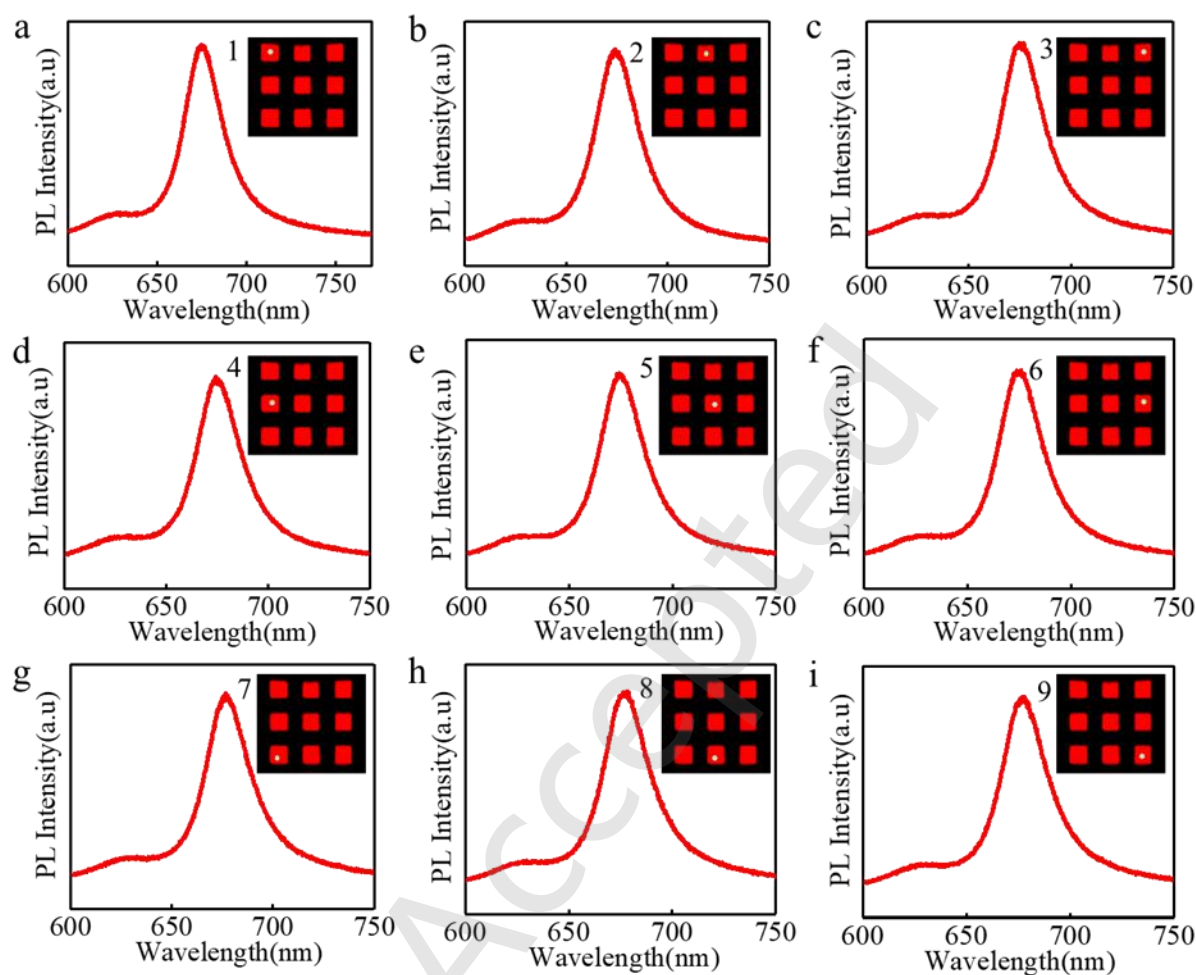


Figure S7 The PL curves of each photosensitive unit in the 3×3 array.

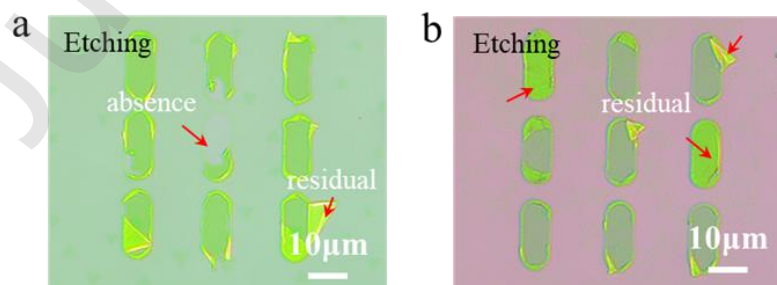


Figure S8 The MoS₂ array pattern structures fabricated by the ion etching method: (a) the absence of the array units; (b) the residual of the photoresist.