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[1]	Please check the sentence beginning “However, in the methods involving lithography…” for clarity.	OK
[2]	Please check the sentence beginning “To evaluate the electronic properties of the prepared…” for clarity.	修改
[3]	Please check whether the edits made to Supporting Information section are correct.	修改

Maskless Micro/Nanopatterning and Bipolar ~~Electrical Rectification~~ Electrical Rectification of MoS_2 Flakes Through Femtosecond Laser Direct Writing

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Abstract

~~MoS~~Molybdenum disulfide (MoS_2) micro/nanostructures are desirable for tuning electronic properties, developing required functionality, and improving the existing performance of multilayer MoS_2 devices. This work presents a useful method to flexibly microprocess multilayer MoS_2 flakes through femtosecond laser pulse direct writing, which can directly fabricate regular MoS_2 nanoribbon arrays with ribbon widths of 179, 152, 116, 98, and 77 nm, and arbitrarily pattern MoS_2 flakes to form micro/nanostructures such as single nanoribbon, labyrinth array, and cross structure. This method is mask-free and ~~simple,~~simple and has high flexibility, strong controllability, and high precision. Moreover, numerous oxygen molecules are chemically and physically adsorbed on laser-processed MoS_2, attributed to roughness ~~defect-sites~~ defect sites and edges of micro/nanostructures that contain numerous unsaturated ~~edge-sites~~ edge sites and highly active ~~centres.~~centers. In addition, electrical tests of the ~~field-effect~~ field-effect transistor fabricated from the prepared MoS_2 nanoribbon arrays reveal new interesting features: output and transfer characteristics exhibit a strong rectification (not going through zero and bipolar conduction) of ~~drain–source~~drain–source current, which is supposedly attributed to the parallel structures with many ~~edge-defects~~ edge defects and p-type chemical doping of oxygen molecules on MoS_2 nanoribbon arrays. This work demonstrates the ability of femtosecond laser pulses to directly induce micro/nanostructures, property changes, and new ~~device-properties~~ device properties of ~~two-dimension~~two-dimensional materials, which may ~~future~~ enable new applications ~~at~~in electronic devices based on MoS_2 such as logic circuits, complementary circuits, chemical sensors, and ~~p–n~~p–n diodes.

Keywords

MoS_2 flakes; femtosecond laser direct writing; micro/nanopatterning; oxygen bonding; electrical rectification

~~INTRODUCTION~~Introduction

ASSOCIATED CONTENT Supporting Information.AUTHOR INFORMATIONCorresponding AuthorAuthor ContributionsFunding SourcesNotesThe authors declare no competing financial interest.For Table of Contents Only~~Transition metal~~ Transition-metal dichalcogenides (TMDCs), representative layered materials like graphene, have been widely studied as a family of new-type semiconducting materials with extraordinary mechanical, electrical, optical properties, and great promise for extensive applications.[1–6] Molybdenum disulfide (MoS_2), representative material belonging to the TMDC group, has layered structures composed of a layer of molybdenum atoms sandwiched between two layers of sulfur atoms.[7,8] Unlike graphene with ~~zero-band-gap,~~ a zero band gap, MoS_2 is a ~~band-gap~~ band gap semiconductor with a sizable energy band gap:[5,9] bulk MoS_2 has an indirect energy gap of ~~~1.2~~ ~1.2 eV and monolayer MoS_2 has a direct band gap of ~~~1.8~~ ~1.8 eV.[3] Hence, MoS_2 can serve as a promising candidate of ~~graphene,~~graphene and has excellent potential in semiconductor-related applications of layered materials such as thin-film transistors,[1,10] integrated circuits,[11,12] complementary inverter,[13] photodetectors,[14] light-emitting diodes,[15,16] photovoltaics,[17,18] superconductors,[19,20] and chemical/biological sensors.[21,22]

To achieve ~~desirable~~ the desired electronic properties and required functionality or improve the existing performance of MoS_2 devices, a microfabrication process is usually required to fabricate large arrays of orderly arranged MoS_2 micro/nanostructures, commonly involving patterning and etching.[3,23] Hence, it is crucial to conduct research on MoS_2 patterning with ordered micro/nanostructures, controlled ~~structure-size,~~ structure size, and new features for device application. Several approaches have been attempted to pattern MoS_2 materials or fabricate micro/nanostructures of MoS_2 deposited on substrates, including tape exfoliation,[24,25] chemical vapor deposition (CVD),[26,27] thermal decomposition of thiosalts,[28] van der Waals epitaxial growth,[29,30] patterned MoO_3 sulfurization,[31,32] CVD in plasma-treated areas,[33,34] block ~~copolymer~~copolymer lithography,[35] reactive ion etching (RIE) combined with deposition in plasma-treated areas,[3] lithography combined with stamping,[23] lithography combined with RIE,[36,37] and ~~continue~~continuous wave (CW) laser direct writing.[38,39] Among them, CVD in plasma-treated areas, block ~~copolymer~~copolymer lithography, lithography combined with deposition in plasma-treated areas, lithography combined with stamping, lithography combined with RIE, and CW laser direct writing can realize control for the location, shape, and size of MoS_2 micro/nanostructures. ~~Whereas,~~However, in the methods involving [AQ1]lithography, plasma surface treatment, and RIE, chemical organics (such as photoresist) and inorganic or organic masks are used, combined process are required, and the integral

process is relatively complex. CW laser direct writing is a simple one-step ~~process and is simple,~~ process, needs no special atmosphere system and ~~mask are needed, cost is~~ mask, has a relatively ~~low,~~ low cost, and has high flexibility and ~~controllability are high. Whereas,~~ controllability. However, the CW laser processing is a thermal process, and the strong thermal effect would cause thermal oxidization of materials and large recasting layer, hence processing precision is insufficient. Femtosecond (ultrafast) laser pulse processing is another kind of laser processing technology.[40,41] Femtosecond laser pulses have a n ultrashort pulse width, a n ultrahigh power density, and ~~nonlinear-nonequilibrium~~ a nonlinear–nonequilibrium processing feature, and multiphoton absorption and nonthermal ~~effect~~effects can be ~~realized, hence except~~ realized; hence, almost all the advantages of CW laser ~~processing,~~ processing and femtosecond laser processing ~~also possesses~~ are expected as well as a high processing precision.[42–44]

In this work, we proposed a useful method of utilizing femtosecond laser direct writing to modify the multilayer MoS_2 flakes, directly fabricate regular MoS_2 nanoribbon arrays with different ribbon widths, and arbitrarily pattern MoS_2 flakes to form different MoS_2 micro/nanostructures. Moreover, the laser-fabricated MoS_2 structures were chemically and physically bonded with numerous oxygen molecules in the air, attributed to the roughness ~~defect-sites~~ defect sites and long edges of the nanoribbons that may contain numerous unsaturated ~~edge-sites~~ edge sites and highly active ~~centres.~~centers. At last, electronic properties of MoS_2 nanoribbon arrays fabricated to be ~~field-effect~~ field-effect transistor (FET) were tested, and the output and transfer characteristics exhibited a strong rectification (not went through zero and exhibited bipolar conduction) of ~~drain−source~~drain–source current. This rectification was supposedly attributed to the parallel structures with many ~~edge-defects~~ edge defects and p-type chemical doping of oxygen molecules on MoS_2 nanoribbon arrays, which may cause transition of n-type channel to p-type channel or properties similar to ~~pn~~ the p–n junction. The proposed method had advantages of simplicity, ~~maskless,~~masklessness, strong controllability, high flexibility, and high ~~precision,~~precision and indicated the ability of femtosecond laser pulses to directly induce ~~two-dimension~~two-dimensional micro/nanostructures/patterns, property changes of ~~two-dimension~~two-dimensional material, and new device features.

~~RESULTS AND DISCUSSION~~Results and Discussion

In this work, multilayer MoS_2 flakes were mechanically exfoliated from a natural crystal and deposited on 300 nm-SiO_2/Si substrates. The thickness of MoS_2 flakes selected for experiments was several to dozens of nanometers. Schematic of our method of fabricating MoS_2 nanoribbons/patterns is shown in Figure 1a, which is based on the formation of regular nanostructures and the material removal by femtosecond laser pulse irradiation. When focused femtosecond laser beam is irradiated on material surface, surface plasmons (SPs) of material can be induced, interference of which with incident laser field can lead to the formation of initial grating structures on material, then these initial grating structures can assist the coupling of SPs and incident laser field, leading to the further formation of final grating structures with deeper gaps.[45] The depth of gaps of laser-induced grating structures is influenced by the number and energy of ultrafast laser pulses on the unit area of material, and can be on a micrometer scale.[42,46,47] The MoS_2 used in our experiment was ~~nano-scale~~ a nanoscale thin ~~flake, therefore controlling~~ flake; therefore, keeping the scan speed of laser beam ~~enough~~ slow enough (laser pulse number on unit area of MoS_2 ~~enough large)~~large enough) can control the gaps penetrating the whole MoS_2 thin flake, enabling surface nanogratings to become independent nanoribbons. Figure 1b shows the optical comparison of pristine MoS_2 with femtosecond laser-processed (FLP-) MoS_2, which showed ~~obviously~~ an obvious optical color change of the MoS_2 flake after femtosecond laser irradiation, indicating ~~the~~ change in the thickness or surface roughness. Figure 1c shows the atomic force ~~microscope~~microscopy (AFM) results of the MoS_2 flake in Figure 1b, which indicates the reduction of the outline height of the FLP-MoS_2 flake, suggesting a thinning effect femtosecond laser processing on MoS_2. Figure 1d shows the ~~high-resolution~~ high-resolution AFM image of FLP-MoS_2, which indicated the formation of MoS_2 grating structures.

1~~.~~. Principle and preliminary characterization of this method. (a) Schematic of femtosecond laser direct wiring to induce MoS_2 nanoribbons array. (b) Optical comparison of pristine MoS_2 (upper part) with FLP-MoS_2 (lower part). (c) AFM and (d) ~~high-resolution~~ high-resolution AFM of the FLP-MoS_2 flake.

To further investigate the FLP-MoS_2 micro/nanostructures, scanning electron ~~microscope~~microscopy (SEM) was carried out to characterize its physical morphology, as shown in Figure 2. Figure 2~~a–e show~~a–e shows regular MoS_2 nanoribbon arrays with different ribbon widths of ~~approximate~~approximately 179, 152, 116, 98, and 77 nm, respectively. Figure 2f shows two independent MoS_2 nanoribbons with small and big ~~width~~widths of 56 and 420 nm, respectively. Figure 2g,h ~~show~~shows two ~~kind~~kinds of MoS_2 patterned structures obtained through material removal by femtosecond laser direct writing, which were a labyrinth array and a cross structure, indicating the flexible processing capability of femtosecond laser for arbitrary patterns. The formation ~~way~~ of MoS_2 micro/nanostructures and the dependence of widths of nanoribbons on laser processing parameters (pulse energy and scan speed) are analyzed in the Supporting Information.

2~~.~~. FLP-MoS_2 micro/nanostructures and patterns. ~~(a–e)~~(a–e) SEM images of regular MoS_2 nanoribbon arrays with widths of 179, 152, 116, 98, and 77 nm, respectively. (f) SEM images of two independent MoS_2 nanoribbons with ~~width~~widths of (above) 56 and (below) 420 nm. SEM images of (g) MoS_2 labyrinth array and (h) MoS_2 cross structure. The laser processing parameters for MoS_2 micro/nanostructures are shown in Table S1.

To investigate the formation of MoS_2 nanoribbons rather than surface structures on MoS_2, ~~energy-dispersive~~ energy-dispersive X-ray (EDX) analysis was performed. Figure 3~~a–c show~~a–c shows the SEM images of the edge of a FLP-MoS_2 flake, and its S and Si EDX mapping images. The ~~grey~~gray part denotes MoS_2, black part denotes the substrate, and regular ~~stripe~~striped structures were obtained through femtosecond laser processing (Figure 3a). Figure 3b shows clearly separated MoS_2 nanoribbons, and Figure 3c shows ~~the~~ clear gaps between these MoS_2 nanoribbons. Figure 3~~d–f~~d–f shows the SEM image of MoS_2 nanoribbon array, and its S and Si EDX mapping images, which also indicated the separation of MoS_2 nanoribbons, thus evidencing the formation of MoS_2 nanoribbons.

3~~.~~. ~~The formation~~ Formation of separated MoS_2 nanoribbons. (a) SEM image of the edge of a FLP-MoS_2 ~~flake,~~flake and its (b) S and (c) Si EDX mapping images. (d) SEM image of MoS_2 nanoribbon ~~arrays,~~arrays and its (e) S and (f) Si EDX mapping images. The laser processing parameters were pulse energy of 0.015 ~~μJ,~~μJ, scan interval of 0.5 ~~μm,~~μm, and scan speed of 5 ~~μm/s.~~μm/s.

To investigate the change in chemical property of FLP-MoS_2 ~~flaks,~~flakes, Raman and X-ray photoelectron spectroscopy (XPS) characterizations were conducted. Figure 4~~a–d show~~a–d shows the Raman spectra of pristine (P-) MoS_2 and FLP-MoS_2. There was no Raman ~~peak~~peaks at 820 ~~cm^{-1}~~cm^{-1} originating from MoO_3, which ~~indicted~~indicated no formation of MoO_3, thus no ~~obviously~~obvious thermal oxidation for FLP-MoS_2,[48] due to the ~~non-thermal~~nonthermal effect of femtosecond laser processing.[42] No Raman peak of SiO_2 at 520 ~~cm^{-1}~~cm^{-1} was detected on the P-MoS_2 ~~flake,~~flake; however, an ~~obviously~~obvious Raman peak of SiO_2 was detected on the FLP-MoS_2 flake, which indicated that the substrate was also detected on the FLP-MoS_2 flake.[49,50] This result also proved the separation of MoS_2 nanoribbons and penetrating gaps between them, consistent with the results in Figure 3. XPS Mo and O spectra of P-MoS_2 and FLP-MoS_2 are also shown in Figure 4, and their S 2p spectra are shown in Figure S8. The Mo 3d spectra of P-MoS_2 ~~is~~are shown in Figure 4b, which reveals three peaks (227.2, 229.3, and 232.4 ~~eV) respectively~~eV), respectively, assigned to the S 2s orbital of the divalent sulfur, and the Mo^{4+} $3d_{5/2}$ and $3d_{3/2}$ orbitals of the tetravalent molybdenum. However, in Mo 3d spectra of FLP-MoS_2 (Figure 4e), except the three peaks as shown in pristine MoS_2, there is a new peak at ~~~ 235~~~235 eV, which is assigned to the Mo^{6+} $3d_{3/2}$ orbital of the hexavalent molybdenum (calculated content of Mo^{6+} in all Mo is shown in Table S2). The Mo^{6+} in FLP-MoS_2 was attributed to ~~Mo–O~~the Mo–O bonds formed through the combination of oxygen ~~combined~~ with unsaturated Mo bonds, ~~defect-sites,~~defect sites, or edge of nanoribbons that are generated from the damage and material removal of MoS_2 induced by femtosecond laser pulses.[51,52] Figure 4c shows the O 1s spectra for P-MoS_2, which reveals two peaks (532.6 and 533.4 eV) respectively assigned to divalent oxygen from ~~Si–O~~Si–O bonds and oxygen (zero valent) molecules that physically adsorbed on MoS_2 surface (O_2/MoS_2).[53–55] The divalent oxygen from ~~Si–O~~Si–O bonds came from the 300 nm SiO_2/Si substrate, and oxygen (zero valent) molecules adsorbed on the MoS_2 surface should be attributed to the intrinsic defect and edge of the ~~flake,~~flakes, which were active sites with physical adsorption capacity. However, in the O 1s spectra for FLP-MoS_2 (Figure 4f), except the strong and dominant peak assigned to divalent oxygen from ~~Si–O~~Si–O bonds as shown in P-MoS_2, it revealed a stronger peak of a zero-valent oxygen of O_2/MoS_2, indicating the physical adsorption of more oxygen molecules on the MoS_2 surface; it also revealed a new peak at ~~~ 530.5 eV that~~~530.5 eV, which is assigned to the divalent oxygen from ~~Mo–O~~Mo–O bonds,[56,57] in ~~accord~~accordance with the result of XPS Mo 3d spectra (calculated content of O_2 and ~~O–Mo~~O–Mo in all O is shown in Table S2). These results indicated that more oxygen atoms/molecules were chemically and physically combined with FLP-MoS_2. This can be attributed to the roughness surface ~~defect-sites~~defect sites on MoS_2 nanoribbons and long edges of nanoribbons (the defects generated by femtosecond laser ablation are elaborated in the Supporting Information), for they contained numerous unsaturated edge sites, ~~were~~had numerous highly active ~~centres,~~centers, and hence can physically and chemically bonded with adsorbates such as O_2 molecules (the chemical and physical reaction ~~mechanism~~mechanisms of the laser-processed MoS_2 with oxygen molecules are speculated in the Supporting Information).[58–60] The oxygen absorption on MoS_2 not only led to the change in chemical valence of MoS_2~~,~~ but also, according to previous reports, can lead to p-type doping effect on MoS_2 with O_2 as an electron acceptor and MoS_2 as an electron donor (the schematic of the charge-transfer process is shown in Figure S9).[58]

4~~.~~. Raman and XPS spectra of P-MoS_2 and FLP-MoS_2. (a) Raman spectra of P-MoS_2. XPS peak-split results of (b) Mo 3d and (c) O 1s spectra of P-MoS_2. (d) Raman spectra of FLP-MoS_2, indicating no thermal oxidation for MoS_2 processed by femtosecond laser. XPS peak-split results of (e) Mo 3d and (f) O 1s spectra of FLP-MoS_2. The laser processing parameters were pulse energy of 0.015 ~~μJ;~~μJ, scan interval of 0.5 ~~μm;~~μm, and scan speed of 5 ~~μm/s;~~μm/s.

To evaluate the electronic properties of the prepared[AQ2] MoS_2 nanoribbon arrays, we fabricated a back gate FET ~~by~~ using MoS_2 nanoribbon arrays (NrA) on SiO_2/~~p~~$_p$ + Si substrate as a channel, with 5 nm Ti/ 75 nm Au as a source and drain electrodes, through electron beam lithography (EBL), metal evaporation deposition, and a lift-off process. The electrical measurements of fabricated FET were performed ~~by~~ using a Keithley 4200 semiconductor characterization system in air and at room temperature. The schematic of the structure and measurement of the fabricated MoS_2 NrA-FET is shown in Figure 5~~a,b shows~~a,b, where the SEM image of MoS_2 nanoribbon arrays used for fabricating ~~the~~ FET with channel length of L ~~≈~~≈ 3.4 ~~μm;~~μm, integral channel width of W ~~≈~~≈ 6.6 ~~μm;~~μm, ribbon number of about 38, and gate dielectric thickness of d = 300 ~~nm.~~ nm is given. For comparison, P-MoS_2 flake was also fabricated as a back-gated FET. Figure 5c shows ~~drain–source~~ the drain–source current (I_{DS}DS) versus ~~drain–source~~drain–source voltage (V_{DS}DS) characteristics of this NrA-FET under gate voltages (V_{GG}) ranging from ~~–15~~15 to 15 V. For this output characteristic curve, the ~~drain–source~~drain–source current changed linearly with ~~drain–source~~ the drain–source voltage, indicating a nearly ohmic contact for this FET device. In addition, the output curve did not go through zero and exhibited a strong rectification of ~~drain–source~~ the drain–source current, which was different from the output characteristic curve of the FET fabricated ~~by~~ using pristine/undamaged MoS_2 flake as shown in Figure S10a. This may be attributed to the parallel structures with many ~~edge-defects~~ edge defects and p-type chemical doping of oxygen molecules on MoS_2 nanoribbon arrays, which might cause transition of n-type channel to p-type channel or properties similar to ~~pn~~ the p–n junction.[3,61]

5~~.~~. Electrical test of MoS_2 NrA-FET. (a) Schematic of the structure and measurement of fabricated MoS_2 NrA-FET. (b) SEM image of MoS_2 nanoribbon arrays used for fabricating FET. (c) Output and (d) transfer characteristic curve of the fabricated MoS_2 NrA-FET. The laser processing parameters for NrA are pulse energy of 0.015 ~~μJ;~~μJ, scan interval of 0.5 ~~μm;~~μm, and scan speed of 10 ~~μm/s;~~μm/s.

Figure 5d shows ~~drain–source~~ the drain–source current (I_{DS}DS) versus gate voltages (V_{GG}) characteristics of this NrA-FET under ~~drain–source~~drain–source voltage (V_{DS}DS) ranging from 6 to 10 V. The trend of this transfer curve was non-monotone variation and exhibited a strong rectification of ~~drain–source~~ the drain–source current, which was different from the transfer characteristic curve of FET fabricated ~~by~~ using pristine/undamaged MoS_2 flake. As shown in Figure S10b, transfer characteristic curve of pristine/undamaged MoS_2 FET exhibited a n-type conduction. However, the transfer characteristic curve of MoS_2 NrA-FET exhibits a bipolar conduction, similar to ~~p-n~~ the p–n type transfer conduction (Figure 5d), with current chopping by a small voltage range. To further evaluate the electronic properties of this device, on/off ratio, carrier mobility ~~(μ);~~(μ), and subthreshold swing (SS) were calculated. The on/off ratio of the device was calculated to be 1.2 ~~×~~× 10^2 (p-type segment) and 1.7 ~~×~~× 10^3 (n-type segment) at ~~drain–source~~ the drain–source voltage (V_{DS}DS) of 10 V. The carrier mobility ~~(μ)~~(μ) was calculated according to equation from reported reports,[23] as shown in eq 1

$$\mu = \frac{L}{W}\frac{d}{\varepsilon_0\varepsilon_r}\frac{1}{V_{DS}}\frac{\partial I_{DS}}{\partial V_G} \quad (1)$$

where L and W are length and width of the FET channel, respectively; d, $\varepsilon\varepsilon_0$, and $\varepsilon\varepsilon_r$ are thickness, vacuum permittivity, and relative permittivity of the grid dielectric layer, respectively; $\frac{\partial I_{DS}}{\partial V_G}$ can be calculated from the I_{DS}–V_G curve. For this FET device, the length and width of the channel were L ≈ 3.4 μm and W ≈ 6.6 μm; μm, respectively; the grid dielectric layer was SiO_2, its thickness, vacuum permittivity, and relative permittivity were d ≈ 300 nm, $\varepsilon\varepsilon_0$ ≈ 8. 85 × 10^{-12} F/m, and $\varepsilon\varepsilon_r$ ≈ 3.9 F/m,[23] respectively. Hence, carrier mobility of this device was calculated to be approximately 2.6 × 10^{-3} cm^2 V/V/s. s^{-1}. The SS was calculated according to equation from previous reports,[62] as shown in eq 2,

$$SS = \frac{\Delta V_G}{\Delta \log I_{DS}} \quad 2$$

and SS of this device was calculated to be ~21 V/dec according to eq 2. The obvious strong rectification behavior of I_{DS}–V_{DS} and I_{DS}–V_G of the MoS_2 NrA-FET indicated the property change of material and new device properties, which may enable new applications at electronic devices based on MoS_2 such as logic circuits, complementary circuits, chemical sensors, and p–n diodes. In addition, moderate surface modification of MoS_2 flakes by femtosecond laser pulses would also tune the n-type electronic properties of MoS_2 FET: as shown in Figure S10, the on/off ratio of MoS_2 FET was increased by two magnitude; as shown in Figure S11, the drain–source current (I_{DS}) increased quicker and reached saturation faster with the increase of gate voltages (V_G).

CONCLUSIONS Conclusions

Femtosecond laser direct writing was used to nonthermally modify the multilayer MoS_2 flakes, induce separated MoS_2 nanoribbon arrays, and arbitrarily pattern MoS_2 flakes to form different MoS_2 micro/nanostructures. Optical microscope, microscopy, AFM, and SEM were performed to characterize the physical micromorphology of laser processed MoS laser-processed MoS_2 flakes. EDX mapping indicated the separation of MoS_2 nanoribbons, proving the formation of MoS_2 nanoribbons rather than surface structures on MoS_2. Raman spectra indicated the non-thermal nonthermal effect of the femtosecond laser processing, also proved the separation of MoS_2 nanoribbons and penetrating gaps between them. XPS spectra indicated that more oxygen molecules were chemical chemically and physical physically bonded to FLP-MoS_2, which was attributed to the roughness defect sites on MoS_2 nanoribbons and the long edges of nanoribbons that contained numerous unsaturated edge sites and highly active centres. centers. A MoS_2 NrA-FET was fabricated and electrical tests were conducted to evaluate the electronic properties of the prepared MoS_2 nanoribbon arrays. Results indicated that output and transfer characteristic curves exhibited a strong rectification (not going through zero and bipolar conduction) of drain–source drain–source current, which were different from that of FET fabricated by using pristine/undamaged MoS_2 flake. This may be attributed the parallel structures with many edge-defects edge defects and p-type chemical doping of oxygen molecules on MoS_2 nanoribbon arrays, which might cause transition of n-type channel to p-type channel or properties similar to pn p–n junction. At last, the on/off ratio, carrier mobility, and SS were also calculated. The proposed method indicated the ability of femtosecond laser pulses to directly induce two-dimension nanostructures, property two-dimensional nanostructures and change in material, the properties of the material and new device properties, device, which may future enable new applications at as electronic devices based on MoS_2 such as logic circuits, complementary circuits, chemical sensors, and p–n p–n diodes.

METHODS Methods

Femtosecond laser processing system: Laser Processing System

The light path setup of our femtosecond laser processing system was reported in our previous study.[8] The microscope objective (50 ×, (50×, NA = 0.5) was used to focus laser beam.

Characterization of MoS_2 nanostructures: Nanostructures

The optical images were obtained utilizing an Olympus microscope. The AFM characterization was carried out utilizing a SPM-960 AFM. The SEM images and EDX mapping spectra were obtained utilizing a Hitachi scanning electron microscope. Raman spectra were obtained utilizing a Renishaw InVia Reflex spectrometer (532 nm light source). XPS spectra was performed utilizing a PHI Quantera X-ray photoelectron spectrometer.

Device fabrication Fabrication and electrical characterization: Electrical Characterization

Multilayer MoS_2 flakes were placed on p + Si/SiO_2 (300 nm) substrates and processed by femtosecond laser pulse. Then Then, the substrates were spin-coated with poly-methyl polymethyl methacrylate (PMMA) solution. The source and drain electrodes were fabricated through three main steps: standard electron-beam lithography (EBL) was performed by a Zeiss Supra55 SEM and Raith pattern generator to pattern the PMMA masks; 5 nm Ti/75 nm Au were deposited through electronic beam evaporation; a lift-off process was performed in acetone. The electrical measurements of the fabricated MoS_2 FET were performed b y using a Keithley 4200 semiconductor characterization system in air and at room temperature.

Supporting information

The Supporting Information is available free of charge on the ACS Publications website. Supplementary table of laser Laser processing parameters for parameters; [AQ3] MoS_2 micro/nanostructures; supplementary analysis for the formation way of MoS_2 micro/nanostructures, micro/nanostructures; dependence of widths of nanoribbons on laser processing parameters, parameters; defects generated by femtosecond laser ablation, and ablation; chemical/physical reaction mechanism of laser-processed MoS_2 with oxygen molecules; table of quantitative XPS results; supplementary electrical test results of MoS_2 FETs with moderate surface modification by femtosecond laser pulses (PDF)

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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