Superconductivity in two-dimensional η -Mo₃C₂ films

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ABSTRACT Two-dimensional (2D) superconductors have intriguing physical properties and abundant potential applications. Recently, 2D superconducting α -Mo₂C and face-centered cubic Mo₂C have been controllably prepared and they bring new viewpoints to carbon-based superconductivity. Although molybdenum carbides (Mo-Cs) have multiple crystal-line stacking orders, there are still few structures reported for the lack of higher energy supply during growth. In this study, we report a two-step vapor deposition method to grow superconducting η -Mo₃C₂ films with different thicknesses, with the assistance of controllable plasma power. The grown η -Mo₃C₂ films show polycrystalline characteristics, but they still present superior superconductivity. The 3.0-nm-thick film has the superconducting transition temperature of 5.38 K, and its electrical performances follow truly 2D superconducting transitions. This study will not only exhibit a robust superconducting η -Mo₃C₂ ultrathin film, but also provides a convenient growth way to realize more carbide-based heterostructures for future device applications.

Keywords: 2D superconductor, η -Mo₃C₂, superconducting film, two-step vapor deposition, MXene

INTRODUCTION

Two-dimensional (2D) superconductors have abundant physical properties including localization of electrons, Berezinskii-Kosterlitz-Thouless (BKT) transition, and quantum phase transitions at zero temperature [1]. The realization of 2D superconductivity usually requires 2D superconductors, which are mostly amorphous films with nanometer-scale thickness (since 80 years ago) [2,3], molecular beam epitaxy grown crystalline films [4,5], or mechanical exfoliated flakes [6,7] since the development of micromechanical cleavage method in 2004 [8]. The 2D superconductivity is strongly correlated to their thickness, and thicker samples usually have higher superconducting

transition temperatures (T_c). Among kinds of electronic properties, BKT transition becomes the criterion for the 2D superconductivity, which results from bounded vortex-antivortex pairs by the unpaired vortices and antivortices [1]. Recently, magic-angle twisted bilayer graphene flakes are found to be superconducting, which should be the first realization of pure carbon-based superconductor and brings in much more interesting phenomena, like Mott insulating and superconducting phases [9]. As another kind of carbon-based superconductors, transition metal carbides (TMCs) have been investigated since half century ago [10,11], and the 2D TMC superconducting films have been prepared for more than 30 years [12–16]. Different from other 2D superconductors, TMCs, also known as MXenes, usually show highly stable properties, such as high thermal stability, strong mechanical properties, high melting point and high superior corrosion resistance [17].

As a typical and early-studied superconducting TMC, molybdenum carbide (Mo-C) has multiple crystalline structures [18,19]. Orthorhombic α -Mo₂C, in a carbon-ordered form along with metal ABAB stacking order, often exists at the phase transformation temperature below 1430°C [12]. According to the statistics in Table S1 (Supplementary information), the corresponding T_c ranges for their bulk materials are usually below 7.3 K (mostly below 4.1 K). The hexagonal β -Mo₂C and η -Mo₃C₂ are also stable crystalline structures with the T_c below 7.2 and 8.9 K for bulks, respectively [19]. β -Mo₂C is in a carbon-disordered form in contrast with α -Mo₂C, and it is usually formed at the temperature of above 1200°C [20]. η -Mo₃C₂ often appears at a higher temperature of above 1660°C, with metal layer stacking AB-CACB [21]. Recently, chemical vapor deposition (CVD) method has been used to successfully grow single-crystal orthorhombic α -Mo₂C domains with the growth tem-

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perature of 1085°C, and the 5.1-nm-thick crystals start to show 2D superconductivity [12]. Plasma-enhanced pulsed laser deposition (PEPLD) and reactive sputter have been also adopted to grow Mo₂C or Mo-C superconducting films, but their accurate crystalline structures are not reported [16,22]. Benefitting from the different energy source during the growth process, these films have different superconducting behaviors, including higher T_c , which indicates that they should have different crystalline structures. Therefore, we believe there should be other kinds of Mo-C superconducting films if continuing to increase the growth temperature or using different energy source.

In this study, we grow wafer-sized Mo-C film with controllable thickness by a two-step vapor deposition method, which combines a physical vapor deposition (PVD) and CVD processes. The growth method is similar to our previously reported process except the carbonization [23]. We can well control the carbonization degree and energy supply through this two-step process, which is different from the previous CVD, PEPLD or reactive sputter. From the X-ray photoelectron spectroscopy (XPS) analysis for element ratio and the atomic structure by transmission electron microscope (TEM), we consider the two-step grown Mo-C films on c-plane sapphire are hexagonal η -Mo₃C₂. The 2D superconductivity appears when the thickness of the two-step grown films reaches 2.1 nm, and the physical performances are highly stable and nearly unchanged after harsh treatment.

EXPERIMENTAL SECTION

Growth of η -Mo₃C₂ films

Two-step vapor deposition, which includes the typical PVD (magnetron sputter) and CVD processes, was adopted to grow the carbide films. In this study, the magnetron sputter was used to deposit the molybdenum films, which consisted of a main sputter chamber (base pressure $<10^{-4}$ Pa) and a loadlock chamber (base pressure $<10^{-1}$ Pa). The commercial molybdenum target with high purity (>99.95 at.%) was pre-sputtered to eliminate the surface contamination. The standard sputtering procedure was conducted under the following conditions: c-plane sapphires as growth substrates at $\sim 100^\circ\text{C}$, deposition rate of $\sim 0.2 \text{ \AA s}^{-1}$ and chamber pressure of 10 Pa. After the sputtering, the as-sputtered molybdenum films were stored in the glovebox before further experiments. The controllable carbonization was realized in a customized inductively coupled plasma (ICP) CVD system, and the typical growth parameter was as follows: growth

temperature of 650°C, pressure of 6 Pa, CH₄/H₂/Ar ratio of 5:180:10, plasma power of 30 W and growth time of 5 min. The insufficient carbonization had the same growth parameters except the growth time of 1 min, and the excessive carbonization had the growth time of 10 min.

ICP-RIE

The decarbonization was also conducted in the ICP-CVD system, and the typical reactive ion etching (RIE) parameter was as follows: substrate at room temperature, pressure of 6 Pa, pure Ar of 180 sccm, plasma power of 50 W for 5 min.

Transfer

After growth, η -Mo₃C₂/sapphire was spin-coated with polymethyl methacrylate (PMMA, M_w 996k, 4 wt.% in ethyl lactate) at 2000 r min^{-1} for 1 min. NaOH aqueous solution (1 mol L^{-1}) was used to delaminate η -Mo₃C₂ from sapphire, and the floating η -Mo₃C₂/PMMA was cleaned by deionized water for three times. Then, the η -Mo₃C₂/PMMA was pulled off by TEM grids or other substrates. Finally, PMMA was completely removed by acetone.

Characterizations

TEM and scanning transmission electron microscopy (STEM) images were captured by FEI Titan 80-300 and Tecnai F30, which were both operated at 300 kV. Atomic force microscope (AFM) images were taken using the Bruker Dimension Fastscan in a tapping mode. The crystal structures of the grown Mo-C films were examined by a high-resolution single crystal X-ray diffractometer (XRD, Bruker D8 Discover). The incident X-ray was from Cu-K α emission with a wavelength of $1.5418 \text{ \AA}$. Raman spectra were performed by using a Witec/alpha 300R confocal microscope with a 532-nm laser at atmospheric conditions. The XPS was performed using a PHI 5000 X-ray photoelectron spectrometer equipped with a monochromatic using Al K α radiation ($h\nu=1486.6 \text{ eV}$), and the peaks were fitted by the approximation of Lorentzian-Gaussian mixed function.

Electrical measurements

The variable electrical properties with temperature were measured in ^4He cryostat with superconducting magnets (Oxford Teslatron 8 and 12 T), and electrical measurements were performed by using a standard lock-in amplifier (Stanford SR830) with currents of 1–10 μA . For all the measurements, four-probe contacts were used by e-

beam evaporated 5 nm Cr/80 nm Au array (200 μm dots with 500 μm spacing).

RESULTS AND DISCUSSION

During the growth processes, we used AFM to measure the thickness and smoothness at each growth stage, as shown in Fig. 1a. The upper image is a typical AFM image of the as-sputtered 3.6-nm-thick Mo film, and the films appear homogenous in large scale, indicating this metal depositing process could be an effective method. The middle is an *ex-situ* AFM image of the Mo-C film after carbonization by ICP-CVD, and it has a clean surface and is also homogenous in large scale. After the carbonization, the thickness detected at the same position shows a slight decrease from 3.6 to 3.0 nm. This thickness change is different from the layered materials, like transition metal dichalcogenides (like MoS_2 , NbSe_2 , etc.), of which

the thickness will increase after chalcogenisation [23]. The van der Waals interaction between layered materials will introduce interlayer spaces with thickness of about 0.65 nm [24], and thus increase their thickness when transition metal changes into chalcogenides. Relatively, there is no layered structure among all the typical Mo-C crystals. Moreover, carbon sources of methane will be decomposed with the assistance of plasma even at lower temperature, so the carbonization by ICP-CVD will inevitably bring in amorphous carbon films onside. After growth, we usually remove the amorphous carbon films by ICP-RIE, and their morphology was measured by AFM, as shown in the bottom image of Fig. 1a. The thickness collected at the same position decreases to 2.6 nm, indicating there is ~ 0.4 -nm-thick amorphous carbon film on the Mo-C films after the carbonization process. It is worth noting that this two-step deposition

Figure 1 Two-step vapor deposition growth of Mo_3C_2 film. (a) AFM images and the corresponding height profiles of the as-sputtered Mo film, Mo-C film and decarbonized Mo-C film by Ar plasma. Their thicknesses have slight reduction (~ 0.6 nm) after carbonization, and there is thin amorphous carbon film onside (~ 0.4 nm). (b) Typical Raman spectra of the grown Mo-C films with different thicknesses, in which there exists a characteristic vibration mode at $\sim 171 \text{ cm}^{-1}$. (c) XPS spectra of Mo 3d and C 1s from a 3.0-nm-thick Mo-C film. Mo has bivalence and C has two different binding statuses of amorphous carbon at 284.3 eV and Mo-C at 282.5 eV. From their relative intensity, we estimate their relative element ratio of Mo:C is 1.483:1, indicating the existence of Mo_3C_2 .

method is convenient to grow Mo-C films with different thicknesses by simply changing the thickness of the as-sputtered molybdenum film, and all the thicknesses of carbonized Mo-C films show a reduction by 20%–30%.

Raman spectroscopy is a powerful tool to probe the structural characteristics and properties of nanostructure materials, and it is sensitive to the vibration of different chemical bonds [25,26]. The Raman spectra of Mo-C films with different thicknesses are shown in Fig. 1b, and there exists an obvious characteristic vibration mode at 171 cm^{-1} . This peak is consistent with the theoretically calculated Raman modes of Mo_3C_2 [27], and we assume it should be E_{2g} mode on the basis of that $\eta\text{-Mo}_3\text{C}_2$ belongs to a highly symmetrical space group of $P63/mmc$ [21] and only E_{2g} is weakly polarized among its four main Raman tensors of A_{1g} , A_{2g} , E_{1g} and E_{2g} . The intensity of E_{2g} mode becomes stronger when the film thickness increases, and the frequencies are slightly blue shifted. This characteristic vibration mode is quite different from the reported $\alpha\text{-Mo}_2\text{C}$ [28], also indicating that they should have different Mo-C bonds. Moreover, Raman peaks at ~ 1350 and $\sim 1590\text{ cm}^{-1}$ can also be used to detect the existence of covered carbon films. After the decarbonization by ICP-RIE, those peaks disappear, indicating the complete etching of carbon films.

To further identify the chemical compositions and crystalline phases of the grown Mo-C films, XPS analysis for chemical bonds was conducted. The XPS spectra of Mo 3d and C 1s core levels, acquired on the 3.0-nm-thick Mo-C films before decarbonization, are shown in Fig. 1c. The core levels of Mo 3d have two individual peaks at 228.0 and 231.7 eV, corresponding to the $3d_{5/2}$ and $3d_{3/2}$. The core levels of C 1s also have two dominant peaks around 282.5 and 284.3 eV, corresponding to Mo-C bonds and pure carbon films. From their relative intensity, we can calculate their element ratios in the grown Mo-C films, and the atomic ratio of Mo to C is estimated to be 1.483:1. Among the reported Mo-C structures, the grown 3.0-nm-thick Mo-C films are likely to be Mo_3C_2 . The reported stable structure for Mo_3C_2 is in hexagonal close-packed (hcp) stack form, which is $\eta\text{-Mo}_3\text{C}_2$ (standard identification card JCPDS No. 42-0890) [21].

To further investigate the crystallinity of the Mo_3C_2 film, high-resolution XRD was performed, as shown in Fig. 2a. The sharp peak at 41.9° belongs to sapphire (0006), so-called c-plane, which we used as the growth face [22,29]. The peak at around 36.5° belongs to the low miller index of (111) in $\eta\text{-Mo}_3\text{C}_2$, and its broadened width indicates that this crystalline film has mostly nano-sized grains inside.

Figure 2 Crystalline structure of the 2.4-nm-thick $\eta\text{-Mo}_3\text{C}_2$ film. (a) High-resolution XRD, showing the hexagonal crystalline structure of $\eta\text{-Mo}_3\text{C}_2$. (b) Low-magnification STEM image of the transferred $\eta\text{-Mo}_3\text{C}_2$ film (the inset is the SAED pattern), showing a polycrystalline structure. (c) A high-magnification TEM image of the $\eta\text{-Mo}_3\text{C}_2$ films (the inset is the related FFT image), indicating the average grain size of $\sim 5\text{ nm}$. (d) Atomic structure image of the area marked out by a red square in (c), showing that the (006) and (110) orientations both exist in the film.

Then, we performed TEM and STEM to confirm the crystal structures for the 2.4-nm-thick $\eta\text{-Mo}_3\text{C}_2$ film. It is worth noting that the TEM and STEM images were captured under the operation voltages of 300 kV, and the amorphous carbon films on the surface of $\eta\text{-Mo}_3\text{C}_2$ can be completely etched after e-beam irradiation in dozens of seconds. Fig. 2b shows a typical STEM image of the transferred $\eta\text{-Mo}_3\text{C}_2$ film at a low magnification, and the inset is the corresponding selected area electron diffraction (SAED) pattern at $\sim 140\text{ nm}$ region. The transferred film appears homogenous and shows a polycrystalline structure. After further magnification, the atomic resolution TEM images were captured, shown in Fig. 2c. The TEM image shows that the polycrystalline structures mainly have two kinds of atomic lattices, and their average lateral grain sizes are about 5 nm. The inset in Fig. 2c is the related fast Fourier transformation (FFT) image, which also indicates their polycrystalline feature. After enlarging a typical atomic structure region marked out by the red square in Fig. 2c, we obtain the accurate spacing distance of ~ 0.24 and $\sim 0.15\text{ nm}$, which are respectively consistent with the lattice parameters of β and η phases, but not with α phase. The lattice spacing dis-

tances and angles correspond well with their hexagonal crystalline stacks. We illustrate the atomic models for the (111) and (100) faces of η - Mo_3C_2 in the inset for reference [21]. The growth surface of sapphire (0001), carbon-rich growth condition, high energy supply, their element ratio by XPS and the characteristic Raman mode, all indicate the η - Mo_3C_2 structure. Although the two-step vapor deposition can easily grow the homogenous films with controllable thickness and robust lattices in grains and grain boundaries, these grown films always present nanocrystalline [23]. Therefore, more parameters should be added in to further improve their crystallinity.

Although the bulk η - Mo_3C_2 has been prepared by solid-state phase transition under 6 GPa and confirmed to be a type-II superconductor with a T_c of 7.4 K [21,30], there are still no thin superconducting η - Mo_3C_2 films reported. After fabricating standard four-probe contacts, we measured the temperature-dependent resistances of these grown η - Mo_3C_2 films with different thicknesses. Moreover, amorphous molybdenum films are reported to present superconducting characteristic [31], so we firstly confirm the temperature dependence of the resistance of the as-sputtered 3.6-nm-thick molybdenum film. In Fig. 3a, the molybdenum film exhibits semiconductive but not superconducting behavior, due to its increased resistance along with the decreased temperature, which also indicates this molybdenum film is relatively high crystalline (details refer to Fig. S1 in Supplementary information). Then, we compare the electrical performances of the 3.6-nm-thick molybdenum films after different carbonization conditions. All these Mo-C films show superconducting characteristics— T_c of the insufficient (i- Mo_3C_2), suitable (η - Mo_3C_2) and excessive carbonized (e- Mo_3C_2) films are 3.10, 5.38 and 4.25 K,

respectively. Here, T_c is defined as the temperature where the resistance of the film drops to 10% of its resistance at normal state.

Fig. 3b shows the effect of thickness on the temperature-dependent resistances (R - T) for the grown η - Mo_3C_2 films by suitable carbonizations. The 1.5- and 1.8-nm-thick films both display semiconductive characteristics, and the films become superconducting only when the thickness increases to 2.1 nm. The 3.0-nm-thick film shows superconductivity with the superconducting onset temperature (T_{onset}) of 5.57 K and the temperature of zero resistance (T_{zero}) is 5.27 K, in contrast with T_c of 3.0 K for the CVD-grown 7.5-nm-thick α - Mo_2C [12] and T_c of 4.2 K for the PEPLD-grown 5.5-nm-thick Mo_2C with fcc structure [22]. With increasing thickness of η - Mo_3C_2 , their T_c will also increase to 6.7 K for the 6.5-nm-thick films. Furthermore, all the grown superconducting α - Mo_2C domains show obviously metallic characteristics, and the superconducting bulk η - Mo_3C_2 and fcc-structured Mo_2C films show weak metallic features. In contrast, the resistances of all these superconducting η - Mo_3C_2 films are constant and nearly unchanged even at varied temperatures. The features of constant resistivity are considered to result from the enhanced phonon scattering along with the increasing density of carriers when lowering the temperature. We assume this feature may come from the existence of huge density of grain boundaries or hydrogen bonds during the ICP-CVD process [32], and it may be able to bring more potential applications.

Then, we further studied the superconducting behaviors of the 3.0-nm-thick η - Mo_3C_2 film. Fig. 4a shows its R - T curves under an out-of-plane magnetic field. The magnetic field gradually suppresses the super-

Figure 3 Superconductivity in thin η - Mo_3C_2 films. (a) Temperature-dependent resistance of the 3.6-nm-thick Mo films before and after carbonization (the inset is the zoom-in curves), indicating that the insufficiently (i- Mo_3C_2) and excessively (e- Mo_3C_2) carbonized films show worse behaviors than the suitable one (η - Mo_3C_2). (b) Thickness-dependent superconductivity in η - Mo_3C_2 films (the inset is the zoom-in curves), showing that their T_c increases with increasing thickness.

Figure 4 2D superconductivity. Superconducting resistance transition of the 3.0-nm-thick η -Mo₃C₂ film under out-of-plane (a) and in-plane (b) magnetic fields. (c) Temperature dependence of the upper critical field H_{c2} under out-of-plane (red spots) and in-plane (green spots) magnetic fields, and the gray lines are fitted following the GL theory. (d) V - I characteristics at different temperatures in logarithmic scale. Inset: temperature dependence of the exponent α deduced from the power-law behavior, $V \propto I^\alpha$, which is extracted from V - I , and the fitted temperature for BKT transition is 5.38 K.

conductivity, and the critical fields are higher than those of ultrathin α -Mo₂C phase [12]. The electrical performances under an in-plane magnetic field are shown in Fig. 4b. Fig. 4c shows the influences of external out-of-plane and in-plane magnetic fields on the superconducting characteristics for this 3.0-nm-thick η -Mo₃C₂ film. As for the out-of-plane case, the critical field ($H_{c2\perp}$) shows a linear behavior close to T_c . The behaviors of $H_{c2\perp}$ and $H_{c2\parallel}$ are in accordance with the standard Ginzburg-Landau (GL) theory for 2D superconductors [33], as follows:

$$H_{c2,\perp}(T) = \frac{\phi_0}{2\pi\xi_{GL}(0)^2} \left(1 - \frac{T}{T_c}\right),$$

$$H_{c2,\parallel}(T) = \frac{\phi_0\sqrt{12}}{2\pi\xi_{GL}(0)d_{sc}} \left(1 - \frac{T}{T_c}\right)^{1/2},$$

where $\xi_{GL}(0)$ is the GL in-plane coherence length at zero temperature, ϕ_0 is the magnetic flux quantum and d_{sc} is the out-of-plane superconducting effective thickness. After fitting with the above equations, we can estimate the corresponding coherence length $\xi_{GL}(0)$ is 7.32 nm, which is similar to the average grain size. The effective thickness

d_{sc} is 3.16 nm, which is slightly larger than its real thickness of 3.0 nm. The grain boundaries in the η -Mo₃C₂ film could affect the data of d_{sc} together. The voltage-current (V - I) characteristics of this film were also measured at selected temperatures ranging from 4.0 to 5.5 K without applying external magnetic field. The measurements present the power-law dependence, $V \propto I^\alpha$, corresponding with the 2D superconducting theory model on the basis of BKT transition [33,34]. The results are plotted logarithmically in Fig. 4d, and the V - I characteristics follow BKT transition, indicating true 2D superconductivity in this 3.0-nm-thick η -Mo₃C₂ film. When exponent α reaches to 3, we obtain the BKT transition temperature T_{BKT} of 5.38 K, shown in the inset of Fig. 4d, which is nearly the same to the T_{zero} of 5.27 K for this film. Moreover, the 3.3- and 6.5-nm-thick η -Mo₃C₂ films also perform truly 2D superconductivity, and their V - I characteristics are shown in Fig. S2.

There are amorphous carbon films inevitably formed on the grown η -Mo₃C₂ surface, so we further investigated whether these amorphous carbon films will affect their electrical performance. Fig. 5 compares the superconducting behaviors of the 2.8-nm-thick η -Mo₃C₂ film

Figure 5 Robust 2D superconductivity for η - Mo_3C_2 . R - T curves under out-of-plane (a, d) and in-plane (b, e) magnetic fields for the as-grown 2.8-nm-thick η - Mo_3C_2 film (a, b), and the film after decarbonization by ICP-RIE (d, e), whose superconducting behaviors are slightly affected. (c, f) Temperature dependence of the upper-critical-field H_{c2} for the as-grown 2.8-nm-thick η - Mo_3C_2 film (c), and the film after decarbonization (f) under out-of-plane (blue spots) and in-plane (red spots) magnetic fields, where the gray lines are fitted following the GL theory.

before and after decarbonization by ICP-RIE. Their R - T curves under the out-of-plane and in-plane magnetic fields are plotted in Fig. 5a, b and Fig. 5d, e, respectively. After long-term Ar plasma irradiation to remove the covered carbon films, the conductivity is reduced, along with the slightly decreased T_c by about 0.2 K. Their fitted H_{c2} are also plotted in Fig. 5c and e according to the GL theory. Before decarbonization, $\xi_{\text{GL}}(0)$ and d_{sc} for the 2.8-nm-thick η - Mo_3C_2 film are 8.32 and 3.07 nm, respectively. After decarbonization, $\xi_{\text{GL}}(0)$ and d_{sc} become 8.47 and 3.05 nm, which does not make much difference. Based on the above comparisons, we consider the covered amorphous carbon film has only modest effect on the electrical performance, and the electrical performances of these thin superconducting η - Mo_3C_2 films are robust even after harsh treatment.

Considering the growth parameters, structural characterizations and electric performances, we assume the previously reported PEPLD- and reactive-sputter-grown Mo-C films should also be η - Mo_3C_2 or β - Mo_2C [16,22,29], even though most of their characterizations did not point it out directly (Table S1). As an important supplement, this two-step vapor deposition method has already presented a much effective way to obtain more

kinds of Mo-C films with good superconducting behaviors. The compatible and controllable growth processes, along with the grown stable 2D η - Mo_3C_2 superconductors, will accelerate MXene-based van der Waals heterostructures or junctions in superconducting electronics or other potential applications [35].

CONCLUSIONS

In summary, we develop a two-step vapor deposition method to grow 2D superconducting η - Mo_3C_2 films with controllable thicknesses. Through the detailed structural and spectroscopic characterizations, we confirm the stacking order for the thin films. Although having polycrystalline structures, the thin η - Mo_3C_2 films still exhibit good superconductivity. The 3.0-nm-thick η - Mo_3C_2 film has the superconducting transition temperature of 5.38 K, which is the highest for this thickness so far. Through the in-depth electrical measurement, these thin η - Mo_3C_2 films show true 2D characteristics of superconducting transitions. Moreover, amorphous carbon films on the grown films have slight effect on their superconductivity, and their superconductivities are robust even after harsh treatment. This study has not only offered a new superconducting Mo-C film, but also provides a new growth

method to realize more 2D carbide-based hetero-structures for future device applications.

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二维超导 η - Mo_3C_2 薄膜的可控制备

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摘要 二维超导体具有丰富的物理特性和非常广泛的潜在应用。最近, 有报道制备出具有二维超导特性的 α - Mo_2C 和面心立方 Mo_3C , 这些材料为碳基超导的研究带来了新的方向。碳化钼具有多种晶体结构, 除了目前已经被制备的种类外, 二维碳化钼尚没有新的晶体结构被制备出来, 这或许是因为在制备过程中缺乏额外的能量供给。在本工作中, 我们进一步发展了两步气相沉积法, 通过有效调控等离子体作为外加能量供给, 成功制备出具有不同厚度和超导特性的二维 η - Mo_3C_2 薄膜。虽然这种方法生长出的 η - Mo_3C_2 薄膜是多晶, 但这些薄膜仍然可以表现出良好的超导特性。其中, 3.0 nm厚的薄膜具有5.38 K的超导转变温度, 而且其电学性能很好地与二维超导特性吻合。这项工作不仅证明了二维 η - Mo_3C_2 薄膜具有稳定和良好的超导特性, 而且还提供了一种更为便捷的生长方法, 这将进一步促进更多基于二维碳化物异质结构的应用性器件的便捷制备。