齊魯工業大學

QILU UNIVERSITY OF TECHNOLOGY

本科毕业设计(论文)

Synthesis of $MoTe_2$ carbon cloth self-supporting flexible electrodes and performance study of lithium-sulphur batteries

学院名称 化学与制药学部

专业班级 应化（国际班）19-1

学生姓名 于耀

学　　号 201904300358

导师姓名 顾少楠

2023 年 06 月 01 日

Synthesis of $MoTe_2$ carbon cloth self-supporting flexible electrodes and performance study of lithium-sulphur batteries

$MoTe_2$ 碳 布 自 支 撑 柔 性 电 极 的 合 成 及 锂 硫 电 池 性 能 研 究

作 者 姓 名 于耀

专 业 班 级 应用化学（国际班）19-1

指导教师姓名 顾少楠

专业技术职务 副教授

齐鲁工业大学本科毕业设计（论文）原创性声明

本人郑重声明：所呈交的毕业设计（论文），是本人在指导教师的指导下独立研究、撰写的成果。设计（论文）中引用他人的文献、数据、图件、资料，均已在设计（论文）中加以说明，除此之外，本设计（论文）不含任何其他个人或集体已经发表或撰写的成果作品。对本文研究做出重要贡献的个人和集体，均已在文中作了明确说明并表示了谢意。本声明的法律结果由本人承担。

毕业设计（论文）作者签名：________________

2022 年 5 月 26 日

齐鲁工业大学关于毕业设计（论文）使用授权的说明

本毕业设计（论文）作者完全了解学校有关保留、使用毕业设计（论文）的规定，即：学校有权保留、送交设计（论文）的复印件，允许设计（论文）被查阅和借阅，学校可以公布设计（论文）的全部或部分内容，可以采用影印、扫描等复制手段保存本设计（论文）。

论文作者签名：______________________ 日期：2022 年 5 月 26 日

导 师 签 名：____________________

目录

ABSTRACT

Lithium-sulphur batteries, which has been studied by scientist for two decades, has high theoretical specific capacity of 1675mAh·g^{-1}, and high theoretical energy density of 2600Wh·kg^{-1}. However, the downside of lithium-sulphur batteries seriously limited the development of the lithium-sulphur batteries in last two decades. That is mainly because elemental sulfur and lithium sulfide has low conductivity, shuttle effect of lithium-sulphur batteries, and the sulfur anode volume change during the charging and discharging processes. Therefore, it is crucial to create a new cathode material that could release the problems above. Herein, in this paper we reported a $MoTe_2$/CC material by pretreatment of the carbon cloth and synthesis the $MoTe_2$ compound onto the carbon fiber. The SEM photo shows the $MoTe_2$/CC material was well synthesized, and the new Lithium-sulphur battery we prepared in the lab shows extreme high electrochemical properties from electrochemical workstation test.　Therefore, the $MoTe_2$/CC material is a fantasist solution for the new　lithium-sulphur batteries, and this material can be extended to apply for many different electrodes.

Key words: Lithium-sulfur battery; Characterization; Electrochemical performance, $MoTe_2$/CC; Cyclic voltammetry

摘　要

锂硫电池经过科学家二十年的研究，理论比容量高达 1675mAh·g^{-1}，理论能量密度高达 2600Wh·kg^{-1}。然而，近二十年来，锂硫电池的缺点严重制约了锂硫电池的发展。这主要是由于单质硫和硫化锂的电导率低、锂硫电池的穿梭效应以及在充放电过程中硫阳极体积的变化所致。因此，创造一种新的阴极材料来解决上述问题是至关重要的。在此，我们通过预处理碳布，并在碳纤维上合成 $MoTe_2$ 化合物，提供了一种 $MoTe_2$/CC 材料。SEM 照片表明，$MoTe_2$/CC 材料得到了很好的合成，电化学工作站测试表明，我们在实验室制备的新型锂硫电池具有极高的电化学性能。因此，$MoTe_2$/CC 材料是新型锂硫电池的理想解决方案，这种材料可以扩展适用于许多不同的电极。

Chapter 1.　INTRODUCTION

1.1 Lithium-sulfur batteries background

At present, with the continuous depletion of the earth's energy and environmental pollution, as well as the development of wearable electronic devices, AI smart grid, intelligent textiles and artificial electronic skin, it is particularly important to develop a clean energy chemical energy storage system with high energy density.[1] Among various electrodes, flexible batteries, with excellent characteristics such as flexibility, stability and portability, have outstanding development potential in wearable electronic devices and small medical devices.[1] Recent studies on flexible batteries mainly focus on lithium-ion batteries with high energy density and cycle stability.[2] As a kind of lithium-ion battery, lithium-sulfur battery has sulfur as its cathode, and lithium metal as its anode, which completes the charging and discharging process through the mutual conversion of lithium elemental and lithium sulfide.[2] A high theoretical specific capacity of $1675mAh\cdot g^{-1}$ and a high theoretical energy density of $2600Wh\cdot kg^{-1}$ can be obtained for lithium-sulfur batteries. According to studies, the lithium-sulfur batteries also have the advantages of low cost, abundant sulfur reserves, and environmental friendly. However, the main reason that lithium-sulfur battery has not been applied in practice is that 1. Due to the existence of insulating elemental sulfur and lithium sulfide, the battery has poor conductivity, therefore, the actual discharge capacity of lithium-sulfur battery is low and the capacity attenuation is fast; 2. The polysulfide generated by charging and discharging reaction is easily dissolved in liquid electrolyte, resulting in shuttle effect, which led to reduction of utilization of active sulfur, and the generation of lithium dendrites; 3. In the process of charge and discharge, the sulfur anode produces nearly 80% volume change, which will cause the electrical contact between the electrode material and the collector to deteriorate and increase the internal impedance.[3][4]The factors above will lead to the problems of the lithium-sulfur batteries in short cycle life, fast capacity decay and low coulomb efficiency of lithium-sulfur batteries. The self-supported sulfur electrode has good ion and electron conductive skeleton and more negative sulfur ion carrier sites, so the self-supported material as the sulfur element carrier of lithium sulfur battery can effectively increase the surface load and content of sulfur in lithium sulfur battery.[5] Therefore, the positive sulfur electrode prepared by the self-supporting flexible material is expected to improve the electrochemical activity, reduce the polarization, relieve the volume expansion in charge and discharge, enhance the adsorption of polylithium sulfide to reduce its shuttle effect, and thus significantly increase the actual capacity, rate and cycle stability of the lithium-sulfur battery. Carbon cloth has high electrical conductivity and good mechanical strength, and is a good substitute for traditional aluminum foil, which can be directly used in the fluid collection of self-supporting cathode materials for lithium-sulfur batteries [6]. Based on the pore structure formed by interweaving carbon cloth, the carbon cloth impregnated with active sulfur and then heat-treated at 155℃ has good chemical properties, high cycle, high specific electric capacity and so on. These advantages make carbon cloth a promising electrode material.[2]

Carbon cloth has the characteristics of high conductivity and good mechanical strength, so it can be used to replace the traditional aluminum foil as a collecting fluid in the self-supporting sulfur anode material of lithium sulfur batteries.[1] From this perspective, more and more carbon cloth self-supporting electrodes are used in lithium-sulfur batteries based. Recent research related to self support lithium-sulfur batteries based on carbon cloth material is multiple. Elazari Prepared ACF-S anode material by soaking the carbon cloth into active sulfur. The material has advantages of high sulfur surface load, good electrochemical performance, and high specific discharge capacity; Miao prepared CFC/S anode material by carbonizing the carbon cloth with nitrogen environment. Which has 96% of capacity retention ratio. Lei grew the WS2 nanosheet on carbon cloth by hydrothermal method to get the self-supporting collection fluid (C@WS2). This material could efficiently adsorb poly-sulfide, and result in the improval of electronic conductivity.

However, the non-polar surface of carbon-based materials has a very limited adsorption effect on polar lithium polysulfide, which makes the intermediate lithium polysulfide hinder the conductivity of the battery, resulting in the decrease of the final positive electrode sheet conductivity and lower battery performance than estimated.[8] Therefore, it is one of the major challenges in the field of lithium-sulfur batteries to design and prepare anode materials that can effectively inhibit the shuttle effect.

1.2 Cyclic voltammetry

Cyclic voltammetry (CV) is a potentiodynamic measurement in electrochemistry.

Which is generally used to test the electrochemical properties of molecule that is adsorbed onto the electrode[11]. While the cyclic voltammetry is operating at a electrochemical workstation. During the experiment, the current at the working electrode is plotted versus the applied voltage. In the cyclic voltammetry method experiment, the electric potential increases as the time goes. Which causes the redox reaction in both cathode and anode of the battery. The current in cathode decreases as the concentration of reducible analyte reduced, and the reduced analyte would begin to be reoxidized during the reverse current. The redox reaction of lithium-sulfur battery shows in equation 1. During this process, the electric potential between the working electrode and the reference electrode, and the current between the working electrode and the reverse electrode are measured by the electrochemical workstation. These data can be used to draw the current-potential figure. On the cyclic voltammetry figure, the more similar the shape of the oxidation peak to the reduction peak means the higher reversibility of the charging and recharging process. Therefore, the cyclic voltammetry figure could show the information of redox potential and electrochemical reaction rate.[10,11]

$$S + 2Li^{+} + 2e^{-} \rightleftharpoons Li_2S \ (E^{\circ} \approx 2.15 \text{ V vs Li / Li}^{+})$$

Equation 1. Redox reaction of lithium sulfur battery

1.3 Battery cycle life and its affection

Battery cycle refers to the number of charge and discharge cycles that a battery can complete before losing proper performance. The battery cycle life is affected by discharge rate, temperature, and cut-off voltage. However, due to internal oxidation reaction, which can cause the internal resistance increase. Therefore, the battery could not release the stored energy, the battery life gradually ends. There are several reasons that could shorten the lithium-sulfur battery cycle life. 1. Lithium metal deposition. For some reason, partial of the lithium ion could not form the stable compound during the charging process. Instead, lithium ion obtain one electron and become lithium metal. This phenomenon could reduce the electric capacity of the battery. 2. Shuttle Effect. In the charging and discharging processes, polysulfide compound appear as by product on the anode of the battery. These polysulfide could move freely to the cathode, and react with lithium metal. Which could seriously reduce the conductivity of battery, and cause short battery life. 3. Electrolyte depletion. In the process of continuous circulation, due to the limitation of chemical and thermal stability electrolyte decomposition and volatilization will occur. Which cause the electrolyte could not be fully infiltrated into anode and cathode material, reduce the battery cycle life. [12]

1.4 Electrochemical impedance spectroscopy (EIS)

Lithium sulfur battery has higher potential on anode and lower potential on cathode compared with other batteries. During the charging and discharging processes, the lithium ion remove from cathode and embed on the cathode. As a result, the charge-discharge capacity, cycle stability and charge-discharge ratio of anode and cathode materials for lithium-ion batteries are closely related to the process of lithium ion removal and embedding in chimeric electrode materials. Electrochemical impedance spectroscopy could easily show the process of removal and embedding of lithium ion. An EIS is consisted of 4 parts. 1. high frequency area: the semi-circle related to the diffusion and migration of lithium ions through SEI film on the surface of active material particles. 2. medium and high frequency area: A semicircle relating to electron transport within a particle of an active materia. 3. Medium frequency area: The semicircle associated with a charge transfer process. And 4. low frequency area: An line related to the solid diffusion process of lithium ions within the active material particles. By analyzing the intercept point of EIS spectroscopy we can conclude that the lower medium intercept shows the better cyclic stability and electrochemical performance.[13][14]

1.5 $MoTe_2$ material

Molybdenum ditelluride (MoTe2) is compound of molybdenum and tellurium. The MoTe2 could crystallize in two dimensional sheets, which can be thinned down to flexible and transparent monolayers. MoTe2 materila is a semiconductor, and its band gap is in the infrared region, which increases the possibility of using as a semiconductor in electronics or an infrared detector. N-type MoTe2 material has a electrical conductivity of 8.3 Ω-1cm-1 with 5×1017 mobile electrons per cubic centimeter. P-type MoTe2 shows conductivity of 0.2 Ω-1 cm-1 and hole concentration of 3.2×10 16 cm-3. Powder MoTe2 has more resistance. In the high current situation, MoTe2 material shows negative resistance. As the current increases, the voltage at both ends of the material decreases. Which means as the increase of current, the potential between the material could decrease.[17] As a result, attaching the

MoTe2 material to the cathode of the lithium sulfur battery could increase the conductivity of the battery, rise the energy capacity and increase the battery stability and cycle life. These features of MoTe2 material could also release the lithium sulfur battery problems on cathode, reduce the impact of shuttle effect on the battery.[18]

Chapter 2. METHOD

2.1 Preparation of lithium-sulfur battery electrode

2.1.1 Hydrophilic treatment of carbon cloth

The carbon cloth (1x1 cm2) was cleaned three times with deionized water, acetone and isopropanol respectively via ultrasonic treatment. Then the carbon cloth was put into a flask, and soaked in a homogeneous 1:1 volume mixture of concentrated sulfuric acid and concentrated nitric acid for 2 hours. Followed by refluxing the flask at 80 °C in water bath for 1 hour. After that, the carbon cloth was rinsed with deionised water and ethanol till pH is 7, and dried at room temperature.

2.1.2 Synthesis of $MoTe_2$/CC material

0.346g Tetrahydrate and ammonia molybdate ((NH4)2Mo7O244H2O) and 26ml N,N-dimethylformamide (O=C(N(CH3)2)2) were added into reaction kettle, then the carbon cloth was added. The reaction kettle was heated at 200℃ in a hydrothermal oven for 12 hours. Element Molybdenum (Mo) was connected to the carbon cloth after this reaction. The carbon cloth was cooled down until room temperature. Ethanol was used to rinse the carbon cloth to get rid of the impurities on the surface of carbon cloth. Until no red impurities drop off from the carbon cloth, it is dried at room temperature. The carbon cloth was carried by a porcelain boat, and put into a tube furnace in air conditions. Meanwhile, the carbon cloth was heated at a rate of 5℃ per minute, until the temperature rises to 400℃, keep the temperature for 2 hours. Molybdenum oxide was formed on the carbon cloth during this process. The carbon cloth was cooled down at room temperature. 0.2g tellurium powder (Te) was add on the both sides of carbon cloth. The carbon cloth was put back to the tube furnace on a porcelain boat. The tube furnace was vacuumized by argon and hydrogen for 3 times to remove the air. After which, the carbon cloth was heated in the argon and hydrogen condition at 620℃ for 3 hours. MoTe2 was formed on the carbon cloth during this reaction.

1 mg sublimed sulfur and carbon cloth was put into the reaction kettle. The carbon cloth was rinsed by carbon disulfide solution (CS2) to dissolute the solid sulfur. Stand the reaction kettle for 5 minutes. After that, the disulfide solution was volatilized in a hydrothermal oven. The reaction kettle was put into a container, and heated at 155℃ for 12 hours. The MoTe2/CC material was obtained. The MoTe2/CC material that obtained was scanned by scanning electron microscopy to observe the characterization of the material.

2.2 SEM

The scanning electron microscope (SEM) is a scanning microscope that could produce the images by scanning the sample by using the electrons high energy beam.[20] When the electrons interact with the scanning sample, characteristic X-rays was produced as a signal. Then the signal is collected by the detectors and form the images. The resolution of SEM depends on many factors. For instance, the electron spot size and interaction volume of the electron beam with the sample. Some of SEM could provide less than 1 nm resolution. However, typical modern SEM could provide the resolution of 1-20 nm. The SEM is one of the most widely used methods used for the examnation and analysis of the micro and nanoparticles. [15] The characterization analysis of MoTe2/CC was observed by scanning electron microscope.

2.3 XRD

X-ray diffraction analysis (XRD) is a X-ray technology wildly using in material science. By irradiating the sample material with incident X-ray, use the detector to receive and measure the scattering angles and intensities of the X-rays that transmits the material. The spectrum that shows on screen could determine the crystallographic structure of a material. X-ray diffraction analysis method could determine multiple of the material structure properties, that includes attice parameters , strain, grain size, epitaxy. Phase composition, and preferred orientation. In addition, the XRD method could also be used to identify crystalline phases and orientation, determine atomic arrangement, and measure thickness of thin films and multi-layers.[16] On the spectrum of XRD, the broad humped peak position refers to the amorphous material with short range ordering. Instead, a sharp peak on the XRD spectrum means the material is crystalline. By compare the XRD spectrum with typical orthorhombic phase of the material, the synthetic material could be analyzed. [19]

2.4 Assembly of lithium sulfur battery and its electrochemical performance test

Positive electrode shell, MoTe2/CC material, 20ul of electrolyte, membrane, 20ul of electrolyte, lithium tablet, and cathode shell were assembled separately from top to bottom of the lithium-sulfur battery in the glove compartment in argon and hydrogen condition. The battery was pressed by 500N once after its finishing assemble. After which, a voltammeter was used to test the electric tension of the lithium-sulfur battery. 2 to 3 volt means the battery is proper functioning. LAND battery testing system was used to do the constant current charge-discharge test of the battery in room temperature. Scanning speed of 0.1 mVs-1 to 0.5 mVs-1 of cyclic voltammetry curve were tested separately by electrochemical workstation. The impedance spectrum of the lithium-sulfur battery was tested as well.

Chapter 3. RESULT

3.1 Characterization analysis of $MoTe_2$/CC

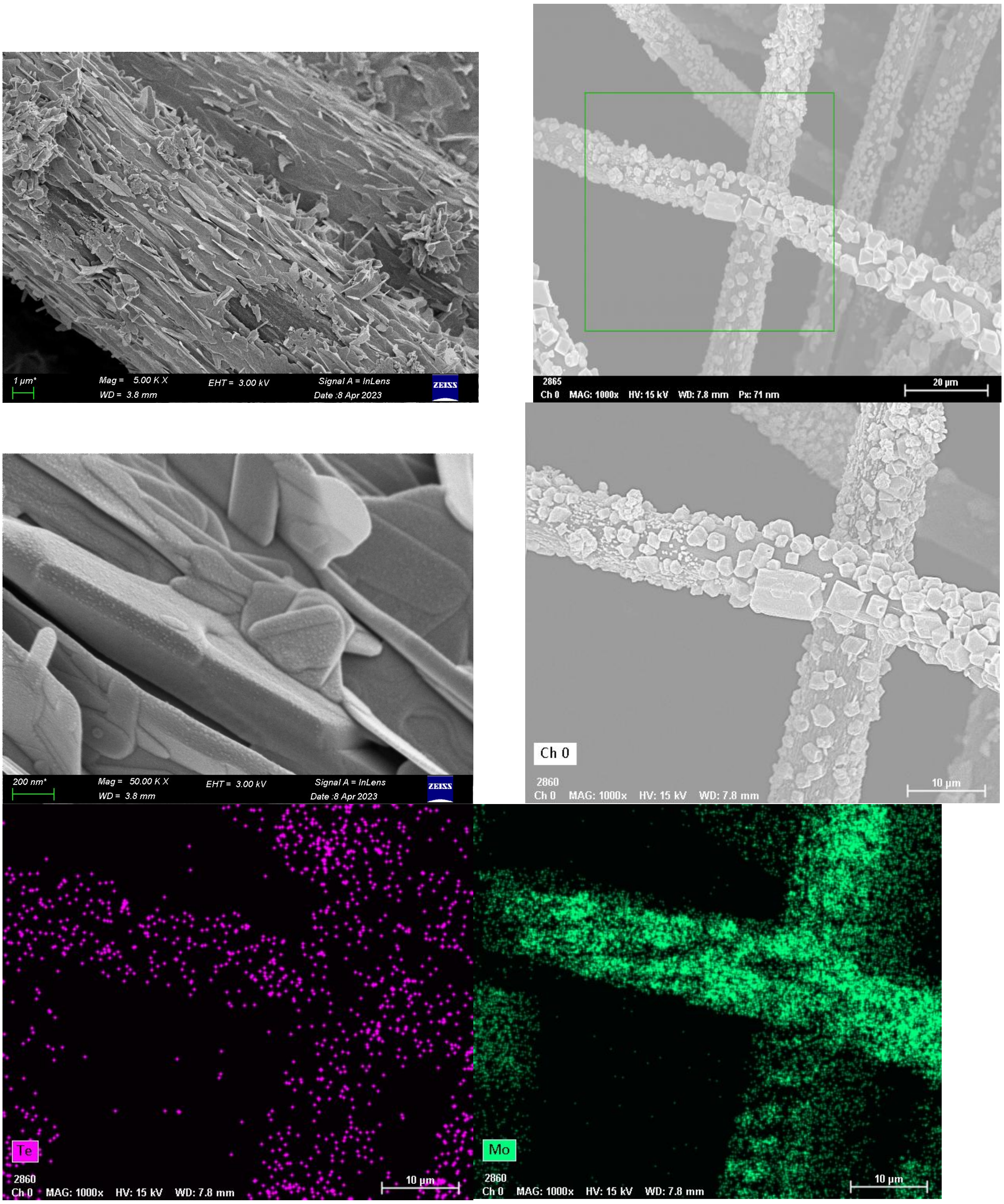

FIGURE 1. (a,b) High magnification SEM images of MoTe2 coated on carbon cloth

fiber. (c) SEM image and photograph of carbon cloth material fiber. (d-f) HAADF-STEM image of single MoTe2/CC fiber and Ch O, Te, and Mo elemental mapping.

As displayed in the high-magnification SEM images in Figure 1a, 1b, many of MoTe2 two-dimensional sheet like aggregation nanocones self assembled on the carbon cloth fiber. Fiugre 1c show the SEM image of carbon cloth fiber fully covered with the MoTe2 compound. Figure 1(d-f) show the HAADF-STEM image and Ch O, Te, and Mo elemental mapping results in each MoTe2/CC nanocone. As a result, the MoTe2 compound were formed onto the carbon cloth fiber properly. The structure and morphology of MoTe2/CC material is favorable for electron transfer.

In addition, the structure features of MoTe2/CC can be further demonstrated by a representative X-ray diffraction (XRD) pattern. The XRD pattern that determined shows in figure 2. The MoTe2/CC characteristic diffraction peaks can be proper match to the typical orthorhombic phase of MoTe2 compound. Which is well match to the SEM images.

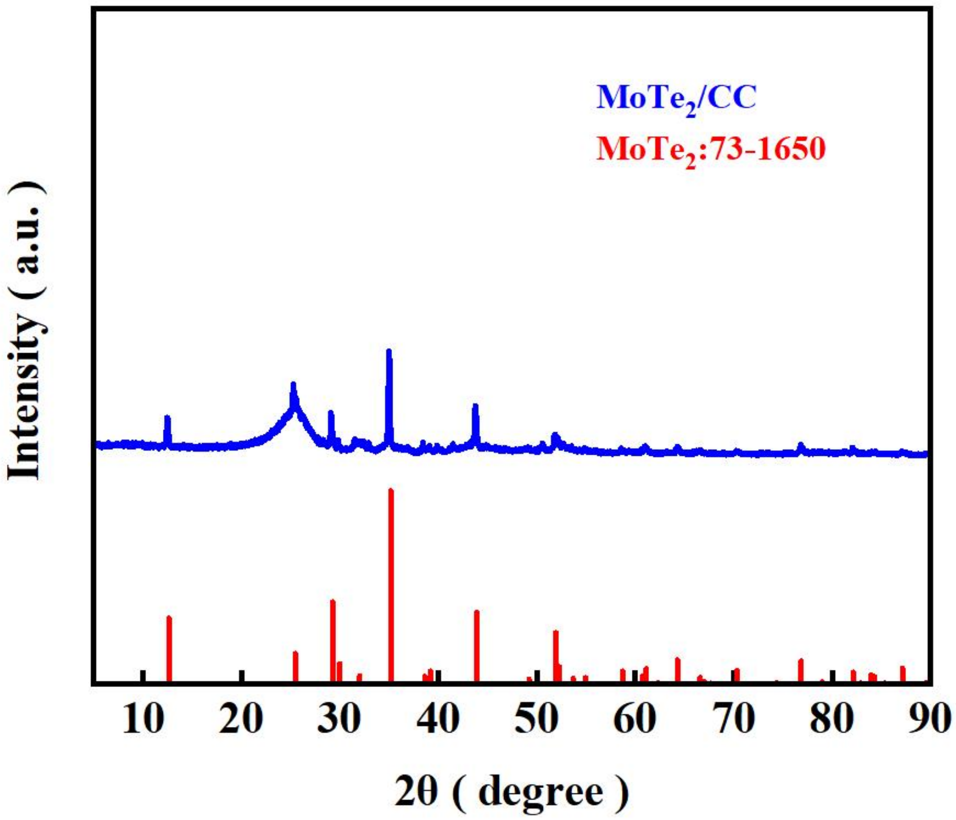

FIGURE 2. Representative X-ray diffraction (XRD) pattern of MoTe2/CC material.

3.2 Electrochemical performance of $MoTe_2$/CC

According to figure 3, the electrochemical impedance spectroscopy (EIS) plots of MoTe2/CC lithium sulfur battery and blank sample display an inclined line at low frequency (less than 1Hz). That is because diffusion of the solid state protons in the protons electrode. In the medium frequency and high frequency, the EIS curves consist of a semicircle, which means the charge transfer resistance. The intercept at higher frequency means the ohmic resistance. Based on the fitting of equivalent, the battery uses MoTe2/CC material has less charge transfer resistance than the blank CC lithium sulfur battery, which decreases from 76.91 ohm to 58.58 ohm. Due to the good electrical conductivity properties of MoTe2, the lithium-sulfur cells can get fast electron conduction and fast ion transport properties. As a result, using MoTe2/CC material can enhance the rate capacity and recycle stability.

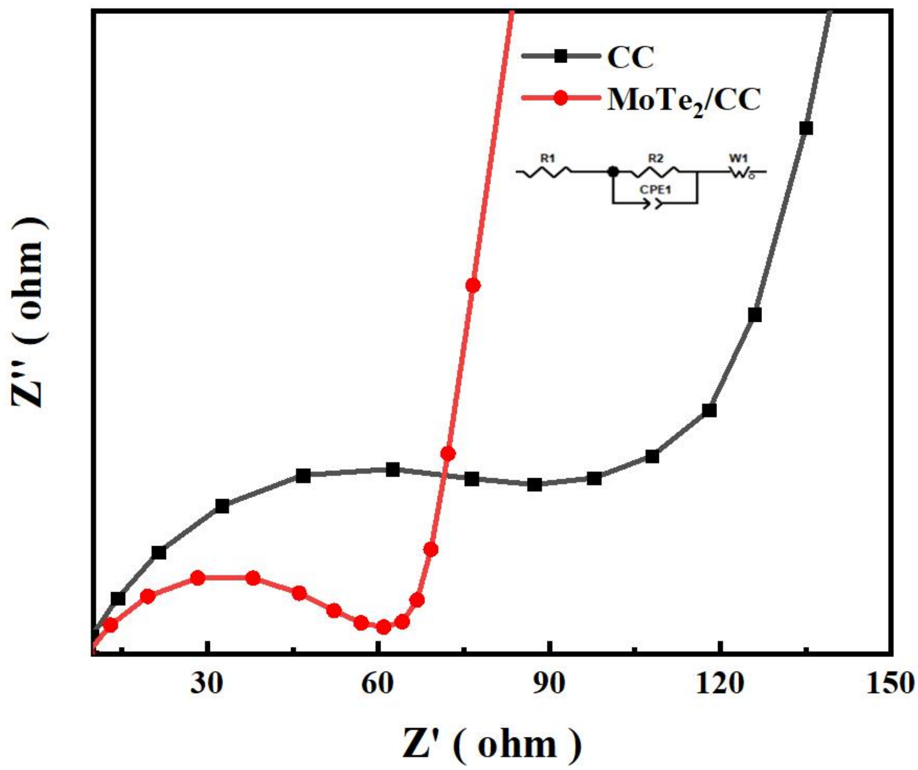

FIGURE 3. The (EIS) plots of MoTe2/CC lithium sulfur battery and blank sample (CC/S).

Figure 4 and 5 shows the cyclic voltammogram of MoTe2/CC battery and CC/S battery at a scanning rate of 0.1-0.5 mVs-1. It is easy to conclude that the both od the samples have stronger peaks on cyclic voltammogram when the scanning rate is higher. The peak of　MoTe2/CC battery that shows on the cyclic voltammogram is stronger than the peaks shows on blank sample CC/S battery. Which indelicate that the　MoTe2/CC battery has fast kinetics for lithium sulfide conversion in the cathode. Compared with CC/S battery, the anodic peak of MoTe2/CC battery has a trend of moving to lower potential in general. Instead, the cathode peak of MoTe2/CC battery move to the higher potential compared with CC/S battery. This phonomonal shows that the MoTe2/CC battery support efficient lithium sulfide redox reactions and faster kinetics throughout cycling.

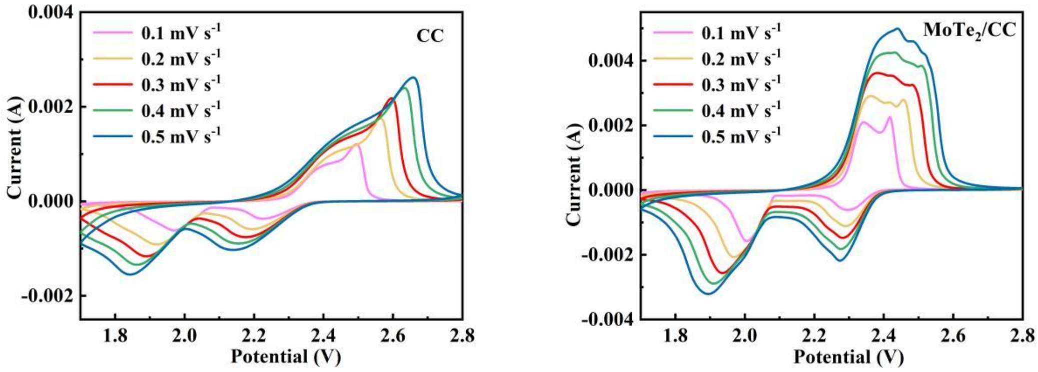

FIGURE 4,5. Cyclic voltammetry curve of MoTe2/CC lithium sulfur battery and CC/S lithium sulfur battery as blank sample.

MoTe2/CC lithium sulfur battery shows the favourable cycling performance at 1C in figure 6. In which the initial discharge specific capacity of 917 mAhg-1. The discharge specific capacity decreases to 645 mAhg-1 after 100 cycles. The coulombic efficiency has a high level of over 99.27 percent. Due to the the activation of sulfur material of MoTe2, the specific capacity is gradually increase. Compared with the blank carbon cloth sample shows in figure 7, the MoTe2/CC lithium sulfur battery shows more specific capacity in general. As a result, MoTe2 compound attached on the carbon cloth could significantly increase the specific capacity of the battery.

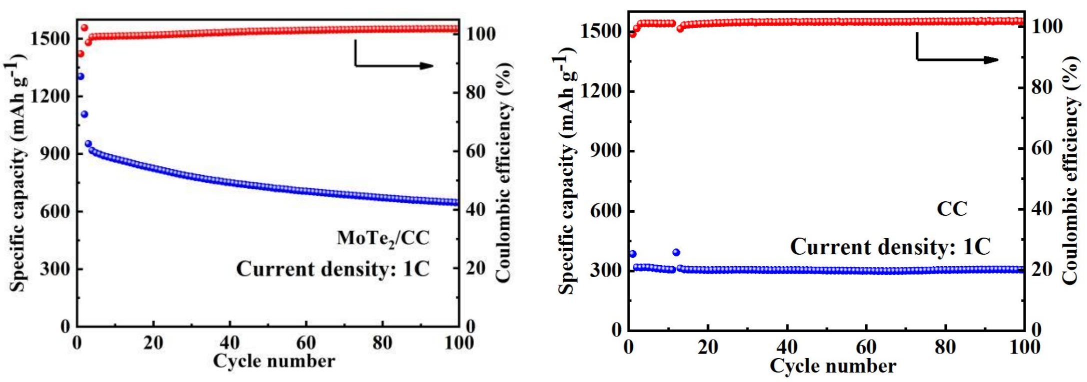

FIGURE 6,7. Battery cycle of MoTe2/CC lithium sulfur battery and the CC lithium sulfur battery as blank sample.

The constant current charge and discharge curve of lithium sulfur battery samples shows in figure 8. The charge and discharge plateau of the MoTe2/CC lithium sulfur battery at 0.2C is considerably long compared with the blank carbon cloth sample. The MoTe2/CC lithium sulfur battery shows the greater capacity of 1304 mAhg-1 compared with blank sample at 424 mAhg-1. Besides, the battery has MoTe2 shows lower oxidation potential plateaus, and smaller potential gap between the oxidation and reduction plateaus. Furthermore, the battery with MoTe2 shows lower interlayer than the blank sample battery (ΔE). Which means when the conductive interlayer used in lithium sulfur battery, the transfer between electrodes becomes effective. Besides, in figure 8, the lithium sulfide nucleation point of MoTe2/CC battery shows higher than CC/S battery (2.2V). Which indicates MoTe2/CC battery is more stable, and can store more electric energy.

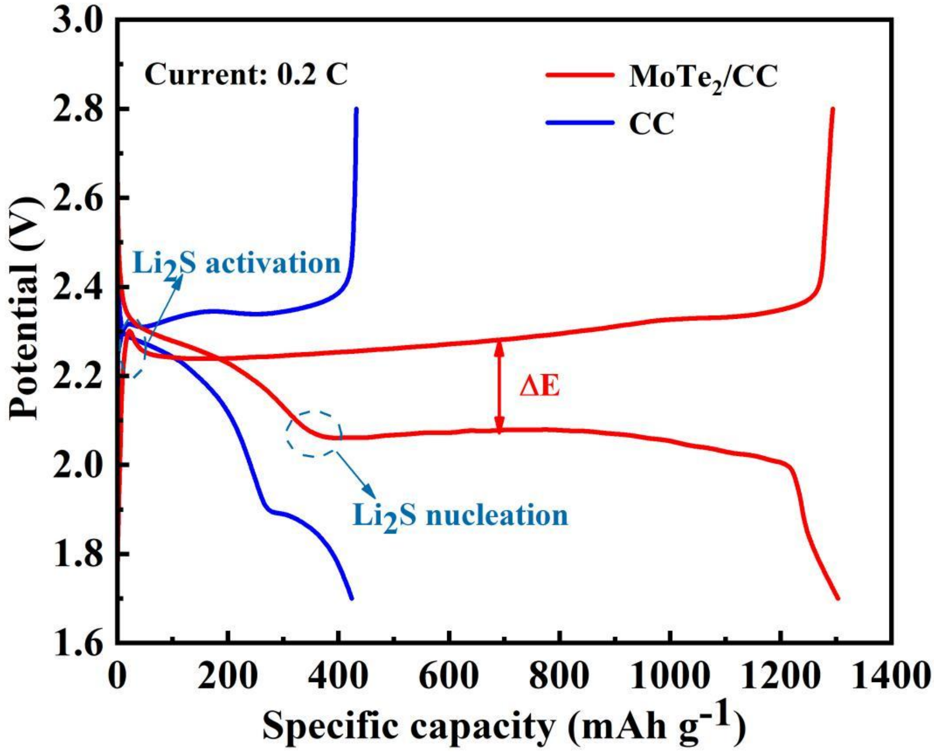

FIGURE 8. Constant charge and discharge of MoTe2/CC lithium sulfur battery and its blank sample in 0.2C.

Chapter 4. CONCLUSION AND DISCUSSION

In this experiment, MoTe2 was successfully attached on to the carbon cloth fiber after pretreatment and synthesis of MoTe2/CC material. The characteristic SEM image and X-ray diffraction (XRD) pattern can prove the successful of the syntheses of the MoTe2 material, and the material was well grew on the carbon cloth fiber. And the MoTe2/CC material is favorable for electron transfer and has good electrical conductivity properties. Besides, the electrochemical test was successfully done with the electrochemical workstation. The result of electrochemical impedance spectroscopy (EIS), battery cycles, clavanostatic charge and discharge, and cyclic voltammetry curve were determined. The MoTe2/CC battery has less charge transfer resistance, high capacity and recycle stability, longer battery cycle life, have faster kinetics of cycling and effective transfer between electrodes.

However, the MoTe2/CC material was prepared in the lab, and only characterization and electrochemical experiment was done. None of the practical testing was finished, the MoTe2/CC material is in a theoretical position. Besides, more parallel experiments could be done in the further researches. Therefore, more practical and electrochemical experiment could be done in the future.

REFERENCES

[1] Wei Z, Sarwar S, Azam S, et al. Ultrafast microwave synthesis of $MoTe_2$@ graphene composites accelerating polysulfide conversion and promoting Li2S nucleation for high-performance Li-S batteries[J]. Journal of Colloid and Interface Science, 2023, 635: 391-405.

[2] Wang H, Yang Y, Liang Y, et al. Graphene-wrapped sulfur particles as a rechargeable lithium–sulfur battery cathode material with high capacity and cycling stability[J]. Nano letters, 2011, 11(7): 2644-2647.

[3] 李豫云，李虹，向明武，等. 锂硫电池自支撑正极材料的研究进展[J]. Journal of Functional Materials/Gongneng Cailiao, 2021, 52(5).

[4] 赵梦，许睿，黄佳琦，等. 锂硫电池中柔性正极的研究进展[J]. 储能科学与技术, 2017, 6(3): 360-379.

[5] Chen S, Zhang J, Wang Z, et al. Electrocatalytic NiCo2O4 nanofiber arrays on carbon cloth for flexible and high-loading lithium–sulfur batteries[J]. Nano Letters, 2021, 21(12): 5285-5292.

[6] Yang Y, Sun W, Zhang J, et al. High rate and stable cycling of lithium-sulfur batteries with carbon fiber cloth interlayer[J]. Electrochimica Acta, 2016, 209: 691-699.

[7] Fang R, Chen K, Yin L, et al. The regulating role of carbon nanotubes and graphene in lithium-ion and lithium–sulfur batteries[J]. Advanced Materials, 2019, 31(9): 1800863.

[8] Wang M, Yang H, Shen K, et al. Stable lithium sulfur battery based on in situ electrocatalytically formed Li2S on metallic MoS2–carbon cloth support[J]. Small Methods, 2020, 4(9): 2000353.

[9] Zhao M, Li B Q, Peng H J, et al. Lithium–sulfur batteries under lean electrolyte conditions: challenges and opportunities[J]. Angewandte Chemie International Edition, 2020, 59(31): 12636-12652.

[10] Gu S, Xu S, Song X, et al. Electrostatic Potential-Induced Co–N4 Active Centers in a 2D Conductive Metal–Organic Framework for High-Performance Lithium–Sulfur Batteries[J]. ACS Applied Materials & Interfaces, 2022, 14(45): 50815-50826.

[11] Kissinger P T, Heineman W R. Cyclic voltammetry[J]. Journal of chemical education,

1983, 60(9): 702.

[12] Ning G, Popov B N. Cycle life modeling of lithium-ion batteries[J]. Journal of The Electrochemical Society, 2004, 151(10): A1584.

[13] Chang B Y, Park S M. Electrochemical impedance spectroscopy[J]. Annual Review of Analytical Chemistry, 2010, 3: 207-229.

[14] Chang B Y, Park S M. Electrochemical impedance spectroscopy[J]. Annual Review of Analytical Chemistry, 2010, 3: 207-229.

[15] Raval N, Maheshwari R, Kalyane D, et al. Importance of physicochemical characterization of nanoparticles in pharmaceutical product development[M]//Basic fundamentals of drug delivery. Academic Press, 2019: 369-400.

[16] Whittig L D, Allardice W R. X-ray diffraction techniques[J]. Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 1986, 5: 331-362.

[17] Puotinen D, Newnham R E. The crystal structure of MoTe2[J]. Acta Crystallographica, 1961, 14(6): 691-692.

[18] Vellinga M B, De Jonge R, Haas C. Semiconductor to metal transition in MoTe2[J]. Journal of Solid State Chemistry, 1970, 2(2): 299-302.

[19] Copeland L E, Bragg R H. Quantitative X-ray diffraction analysis[J]. Analytical Chemistry, 1958, 30(2): 196-201.

[20] Crewe A V, Isaacson M, Johnson D. A simple scanning electron microscope[J]. Review of Scientific Instruments, 1969, 40(2): 241-246.

Acknowledgements

Time goes fast. My four-year bachelor life will soon be over. During my four years of bachelor studies, the knowledge and experiences I gained are valuable for my future and life. It guide me to be a better version of myself. I would not be that smooth and success to finish my four years bachelor without the help of my tutors, classmates, and friends.

Here, I would like to thank professor Shaonan Gu for guidance and support on my bachelor thesis. Without his help, I would not be that certain of doing mt thesis in the topic of lithium sulfur battery. He also guide me in doing experiment and analyzing the data. Besides, I would like to thank my master's tutor Meng Guo, who work in the same lab as me. She helped me a lot when I had problems related to the experiments, for which I am very grateful.