Structural characteristic of vanadium(V) oxide/sulfur composite cathode for magnesium battery applications

E. SHEHA^{1,*}, E.M. KAMAR²

¹Physics Department, Faculty of Science, Benha University, Benha, Egypt

²Chemistry Department, Faculty of Science, Benha University, Benha, Egypt

Magnesium batteries are regarded as promising candidates for energy storage devices owing to their high volumetric capacity. The practical application is hindered, however, by strong electrostatic interactions between Mg^{2+} and the host lattice and due to the formation of a passivation layer between anode and electrolyte. V_2O_5 is a typical intercalation compound with a layered crystal structure ((0 0 1) interlayer spacing $\sim 11.53 \text{ \AA}$), which can act as a good host for the reversible insertion and extraction of multivalent cations. Herein, we have presented an investigation of the effects of S injection on the structure, electrochemical performance and Mg^{2+} diffusion in V_2O_5 cathode materials for Mg-ion batteries. The $\text{V}_2\text{O}_5/\text{S}$ composite structure was investigated using X-ray diffraction, field-emission scanning electron microscope and energy dispersive X-ray spectroscopy. The integrated electrode exhibits an improvement in the electrical and electrochemical properties compared to the V_2O_5 electrode. The as-prepared $\text{V}_2\text{O}_5/\text{S}$ composite has an initial discharge capacity of $310 \text{ mAh}\cdot\text{g}^{-1}$ compared to $160 \text{ mAh}\cdot\text{g}^{-1}$ for the V_2O_5 electrode. The $\text{V}_2\text{O}_5/\text{S}$ composite is a promising cathode material for magnesium-ion battery applications.

Keywords: V_2O_5 ; SEM, conductivity; magnesium batteries

1. Introduction

Lithium-based batteries power everything from phones to electric cars, and while the lithium metal does the job for now, there are plenty of rooms for improvement in terms of efficiency and price. Magnesium, on the other hand, has a higher energy density than lithium and is far more abundant in the natural world, which might deliver batteries with higher density of energy storage and transformative advances in safety, cost and performance compared to lithium-ion (Li-ion). Mg is the eighth most earth-abundant metal on the earth's crust [1]. However, advancement of magnesium rechargeable batteries has been hampered by limited choice of electrolyte and cathode materials in view of facile passivation of Mg surface and sluggish solid-state diffusion of highly polar divalent cation in lattices [2–4]. The prototype magnesium rechargeable batteries were developed in 2000, utilizing solutions comprising Mg organo-halo-aluminate complexes and ether solvents (THF, glymes) that are convenient

with both magnesium metal anodes and Mo_6S_8 cathodes [5]. Different types of Chevrel phase ($\text{Mg}_x\text{Mo}_6\text{T}_8$, $\text{T} = \text{S, Se}$) cathodes for rechargeable Mg batteries have been thoroughly explored [6, 7]. Various candidates have been suggested in recent years for magnesium battery cathode materials with capacity and redox voltage higher than those of Chevrel phases ($120 \text{ mAh}\cdot\text{g}^{-1}$; 1.1 V vs. Mg) [8, 9]. Layered transition metal oxides are favorable because they may possess the structural flexibility [10] needed to follow the expected severe structural deformations upon insertion of bivalent ions such as Mg^{2+} of high charge density. Orthorhombic V_2O_5 is one such material that offers exciting prospects of being a reversible intercalating cathode for Mg batteries [5, 11, 12]. The theoretical energy density of a cathode based on Mg intercalation into V_2O_5 is $\sim 660 \text{ Wh/kg}$ [13], which approaches the practical energy densities of current commercial Li-ion chemistries ($\sim 700 \text{ Wh/kg}$ for LiCoO_2) [14]. Such a layered framework host is of great interest in Mg intercalation mostly owing to its ability to adapt to the geometry of the intercalated guest species by adjusting the interlayer

*E-mail: islam.shihah@fsc.bu.edu.eg

separation. Several studies specified the possibility that this compound may insert Mg ion in conventional nonaqueous Mg salt solutions with some degree of reversibility. However, none of these studies explains performance that would make it possible to consider V_2O_5 as a cathode material for rechargeable Mg batteries. Too low capacity and slow rates of Mg-ion insertion into this host material could be referred to strong Coulombic interactions of the bivalent cations within the host lattice. Sulfur is one of the most promising candidates for conversion cathodes because of its high theoretical capacity ($1672 \text{ mAh}\cdot\text{g}^{-1}$), volumetric capacity ($3459 \text{ mAh}\cdot\text{cm}^{-3}$) as well as its reserve abundance [15]. V_2O_5 with added sulfur has been studied as a cathode material for lithium batteries because of the unique charge-discharge properties of this material [16]. However, the addition of sulfur requires a highly precise and well-controlled synthesis [16]. Magnesium batteries could be safer and more efficient than the lithium ones. The major difference as compared to lithium is that Mg metal does not form dendrites during deposition, which makes it potentially longer lasting and substantially safer than a Li metal anode [17, 18].

In the work reported herein, an attempt was made to study the impact of S doping on the structural, morphological, electrical and electrochemical properties of vanadium pentoxide via sonochemical method. The goal was to develop a unique cathode material allowing the insertion/extraction of magnesium ions and exhibiting high capacity. The manipulation of the interlayer spacing and amorphization of V_2O_5 can increase Mg^{2+} accommodation sites and offer a cathode with high initial capacity. V_2O_5/S exhibited good properties in hosting magnesium ions and its electrochemical performance.

2. Experimental

Nanosized V_2O_5/S composite was prepared using modified sonochemical technique. Vanadium pentoxide (99.6 % Alfa Aesar) and sulfur (99.5 % Alfa Aesar) were mixed at a molar ratio of 90:10. The powder mixture was grinded for 30 minutes using an agate mortar. After that, the mixture was

uniformly dispersed in 50 mL of deionized water by ultrasonication for 3 h at room temperature. Finally, the mixture was dried in an oven at 90°C for 24 h in air. The X-ray diffraction (XRD) patterns of the prepared samples were obtained using a PANalytical X-ray diffraction system model X'Pert PRO with monochromator, Cu-radiation ($\lambda = 1.542 \text{ \AA}$) at 50 kV, 40 mA and scanning speed of $0.02^\circ/\text{s}$. The morphology was investigated by scanning electron microscope (FE-SEM, Quanta 250 FEG) with an energy-dispersive X-ray (EDX) unit attached. Impedance spectroscopy measurements were performed on the CHI604E electrochemical workstation in the frequency ranging from 1 Hz to 1 MHz at different temperatures. The magnesium rechargeable batteries were assembled into 2032-type coin cells with magnesium foil as the anode, and filter paper as the separator. The Mg foil was mechanically polished to remove the oxide layer. The active material was prepared by mixing the mixture of as-prepared V_2O_5 or V_2O_5/S powder, PVDF binder and super carbon P at a weight ratio of 75:15:10 with a few drops of N-methyl-pyrrolidone. The slurry was coated with a Cu foil and dried for two hours at 100°C . Electrolyte solution was synthesized via dissolving 5 M $\text{MgNO}_3\cdot 6\text{H}_2\text{O}$ in 2,2-dimethoxypropane MHMD [19]. The charge/discharge profiles were measured on a Neware battery tester CT3008. Cyclic voltammograms of MHMD electrolyte solution were performed on the CHI604E Electrochemical Workstation using a two-electrode coin cell, where the working electrode was V_2O_5 or V_2O_5/S composite while the counter and reference electrodes are Mg metal. CV were performed also with a three electrode cell using Al as a working electrode (WE) and Mg foil as counter and reference electrodes. The measurements were carried out at $0.5 \text{ mV}\cdot\text{s}^{-1}$ and ambient conditions.

3. Results and discussion

Fig. 1 shows the XRD patterns of pure V_2O_5 , S and V_2O_5/S composite. The characteristic XRD peaks of pure V_2O_5 at $2\theta = 15.53^\circ, 20.40^\circ, 21.84^\circ, 26.27^\circ, 31.11^\circ, 32.48^\circ, 34.41^\circ, 41.39^\circ, 45.57^\circ, 47.43^\circ$ and 51.29° , which correspond to the (2 0 0),

(0 0 1), (1 0 1), (1 1 0), (3 0 1), (0 1 1), (3 1 0), (0 0 2), (4 1 1), (6 0 0) and (0 2 0) lattice planes of the V_2O_5 orthorhombic structure [20] (JCPDS Card No. 41-1426), were detected in both pure V_2O_5 and V_2O_5 -S composite. The identified diffraction peaks can be indexed to the orthorhombic V_2O_5 phase (space group: Pmmn (No. 59); $a = 11.516$ Å, $b = 3.565$ Å, $c = 4.372$ Å. According to Londero et al. [21], the structure of V_2O_5 has an orthorhombic layered structure, which forms intercalation layers. As a result, it offers a possibility of reversible intercalation of different atoms, molecules or ions. The interlayer separation of V_2O_5 changes depending on the size and shape of intercalated particles [22]. Also, it can be seen that the crystal structure of pure V_2O_5 has the strongest intensity of the (0 0 1) plane at $2\theta = 20.40^\circ$, with a d-spacing of 4.34 Å, while V_2O_5 /S composite has the same peak with a d-spacing of 4.35 Å. It was confirmed that small ratio of sulfur expanded the interlayer spacing of V_2O_5 in (0 0 1) direction, shielded the powerful polarization effect of divalent Mg^{2+} ions and could facilitate the intercalation process of Mg^{2+} ions [23]. The sulfur insertion succeeded in expanded interplanar distance of (0 0 1) plane from 4.34 Å to 4.35 Å. This unique architecture can provide abundant active sites for Mg^{+2} ion insertion/extraction and conversion. Furthermore, compared to the relative intensities of the (0 0 1) and (1 1 0) diffraction peaks in Fig. 1, it is clear that the as-prepared V_2O_5 /S composite demonstrates higher relative intensity of (1 1 0) plane. This peak intensity shift can be attributed to the enlarged interlayer distance value. As well, (1 1 0) crystal planes of V_2O_5 /S composite provide channels for facile Mg^{2+} ion insertion and extraction [24]. The morphologies of the pure V_2O_5 and as-prepared V_2O_5 /S composite were studied using field-emission scanning electron microscope (SEM) as displayed in Fig. 2. The low and high magnification FE-SEM images of the pure V_2O_5 (Fig. 2a and Fig. 2b) show uniform rod-like structures with the width ranging between 60 nm and 100 nm.

These nanorods tend to assemble to form bundles in the same direction. The as prepared V_2O_5 /S composite (Fig. 2c and Fig. 2d) exhibits similar

Fig. 1. XRD patterns of pure V_2O_5 , V_2O_5 /S and sulfur element.

Fig. 2. FE-SEM images of pure V_2O_5 (a) and (b) and V_2O_5 /S composite (c) and (d).

morphology of rod-like shapes. However, high magnification FE-SEM image of the V_2O_5 /S composite reveals that decreased and more homogeneously distributed aggregates appear. Fig. 3 shows EDS spectra of V_2O_5 /S composite. The results confirm the presence of sulfur with V_2O_5 particles. The molar ratio of V:S is 34.48:0.29 (in at.%), in addition, the elemental mapping in Fig. 4, showing uniformity of the V, O, and S elements, indicates that the V_2O_5 nanoparticles and sulfur are homogeneously distributed in V_2O_5 /S

composite, which is consistent with the SEM images. Fig. 5a shows the relationship between the electrical conductivity and the reciprocal temperature of the V_2O_5 and V_2O_5/S electrodes at frequency 1 kHz. It is clear from the figure that the electrical conductivity increased after doping with sulfur element and can be attributed to the consecutive O/S exchange reactions which led to formation of sulfur/vanadium oxide cluster anions $VO_3S_2^-$ and $VO_4S_1^-$ [25]. The existence of $VO_3S_2^-$ and $VO_4S_1^-$ acts as a co-bridge which can facilitate the translational charge carrier motion, enhancing the ions diffusion and the electrical conductivity. The Arrhenius equation was used to calculate activation energy and the results showed that the activation energy decreased from 0.83 eV to 0.39 eV after doping with the sulfur element. The reduction in the activation energy confirms the role of sulfur in improving the mobility of ions and its effect in improving the electrochemical performance. Fig. 5b illustrates the Mg plating/stripping behavior of the MHMD electrolyte. It is seen that the reduction process begins from 0.2 V. In the subsequent oxidation step, the onset of the oxidation voltage is about 1.5 V. The oxidation peak at about 1.75 V is attributed to the electrochemical dissolution of Mg. The CV clearly shows that the as-synthesized electrolyte enables reversible Mg deposition/dissolution. Fig. 5c shows a CV of cell 1 (Mg/electrolyte/ V_2O_5) and cell 2 (Mg/electrolyte/ V_2O_5/S) acquired between -0.8 V and 2.2 V at a low scan rate of $1 \text{ mV} \cdot \text{s}^{-1}$ and ambient condition.

For cell 1 (V_2O_5), the reduction current (magnesium insertion) with an onset potential of 0.6 V shows an increasing trend up to -0.8 V. This behavior can be attributed to the reduction of V^{5+} to V^{4+} forming $Mg_xV_2O_5$. In the subsequent anodic scan, a substantial oxidation current (magnesium extraction) with an onset potential of 0.8 V still increases linearly until 2 V. This anodic current can be attributed to the phase transition of $Mg_xV_2O_5$ to V_2O_5 and extraction of Mg^{2+} . For cell 2 (V_2O_5/S), it can be seen a high reduction and oxidation current comparing to pure V_2O_5 electrode. This can be attributed to the redox of elemental sulfur to Mg polysulfides (MgS_x): $2Mg^{2+} + S_8 + 4e^- \leftrightarrow$

Fig. 3. EDS spectrum of V_2O_5/S .

Fig. 4. EDS elemental mappings of V_2O_5/S composite. The elements of sulfur (a), oxygen (b), and vanadium (c), (d) V, O and S (d), respectively, are characterized.

$2MgS_4$ [26, 27]. Generally, doping V_2O_5 cathode with S might introduce more active sites accommodating Mg^{2+} comparing to pure V_2O_5 cathodes.

Fig. 6a displays the first and second charge and discharge curves of pure V_2O_5 , and the V_2O_5/S electrodes. As shown in this figure, pure V_2O_5 exhibits a quasi-plateau located at 0.7 V, while V_2O_5/S exhibits a quasi-plateau located at 0.4 V in the initial discharge curve. In case of the charge curves, V_2O_5/S electrode exhibits one plateau located at 1.75 V and continued up to 1.8 V (the cut off voltage), corresponding to reversible extraction of Mg^{2+} . The initial charge potential plateau and the cut off voltage for V_2O_5/S electrode of 1.75 V and 1.85 V, respectively, are much lower than for V_2O_5 electrode. Additionally, V_2O_5/S electrode delivered high initial charge and discharge capacities of $300 \text{ mAh} \cdot \text{g}^{-1}$ which are higher than the values of V_2O_5 electrode of $100 \text{ mAh} \cdot \text{g}^{-1}$ and $183 \text{ mAh} \cdot \text{g}^{-1}$, respectively. The 2nd discharge/charge capacities of V_2O_5 and V_2O_5/S electrodes are $80/20 \text{ mAh} \cdot \text{g}^{-1}$ and $120/190 \text{ mAh} \cdot \text{g}^{-1}$, respectively. Fig. 6b presents the cycling performance of the pure V_2O_5 , and V_2O_5/S electrodes.

Fig. 5. (a) ionic conductivity versus reciprocal temperature of the V_2O_5 and V_2O_5 composite cathode; (b) CVs in MHMD electrolyte on Al electrodes at a scan rate of $0.5 \text{ mV} \cdot \text{s}^{-1}$; (c) CV curves of V_2O_5 and V_2O_5/S composite cathode.

It can be seen that the reversible capacity suffers from fast fading after the first two cycles. The V_2O_5/S electrode, however, shows high capacity at the first two cycles comparing to pure V_2O_5 electrode. This can be attributed to the extra active surface area obtained due to introduction of sulfur.

Fig. 6. (a) galvanostatic magnesiation/demagnesiation potential profiles of Mg/V_2O_5 , $\text{Mg}/(V_2O_5/S)$ coin cells; (b) cycling performances of Mg/V_2O_5 , $\text{Mg}/(V_2O_5/S)$ coin cells.

Fig. 7a shows the Nyquist plots of Mg/V_2O_5 and $\text{Mg}/(V_2O_5/S)$ coin cells. The data were analyzed on the basis of the Randles equivalent circuit given in Fig. 7a. The semicircle in the high frequency region represents the charge transfer resistance at cathode-electrolyte interface R_{ct} and the lower frequency inclined line represents Warburg impedance W_s corresponding to the magnesium ion diffusion into the bulk of the electrode. The EIS data were fitted using the EIS spectrum analyzer software and the equivalent electrical circuit is shown in the inset of Fig. 7a. R_Ω corresponds to the ohmic resistance of the whole stack. CPE represents the double-layer capacitive effects. The values of the impedance parameters are listed in Table 1.

Fig. 7. (a) electrochemical impedance spectra (EIS) of the V_2O_5 and V_2O_5/S composite, (b) linear fitting of Warburg impedance of the V_2O_5 and V_2O_5/S composite.

The ohmic resistances are similar in the two cells ($\approx 23 \text{ } \Omega$). Meanwhile, the V_2O_5/S electrode exhibits a little larger R_{ct} than the V_2O_5 , suggesting the formation of solid electrolyte interphase (SEI) a bit thicker than in V_2O_5/S electrode. The kinetic ion-diffusion coefficients of the two electrode materials could be calculated from equation 1 [28, 29]:

$$D_{Mg^{2+}} = \left[\frac{R^2 T^2}{2A^2 n^4 F^4 C^2 \sigma^2} \right] \quad (1)$$

Table 1. Comparison of the evaluated electrochemical impedance parameters, A_W and D_{Mg}^{+2} values of Mg/V_2O_5 , $Mg/(V_2O_5/S)$.

EIS parameters	V_2O_5	V_2O_5/S
R_Ω [Ω]	23.46	23.74
CPE-T	0.00045	0.00050
CPE-P	9.05×10^{-5}	0.00011
R_{ct} [Ω]	146.94	169.75
W_s	206.9	218.29
D_{Mg}^{+2} [$cm^2 \cdot s^{-1}$]	2.3×10^{-12}	2×10^{-12}

where $R = 8.314$ J/mol, K is the universal gas constant, T is the absolute temperature, A is the surface area of the cathode (1.5 cm^2), n is the number of the electrons transferred in the electronic reaction, F is the Faraday constant 96485 $C \cdot mol^{-1}$, C is the concentration of magnesium ions $\sim 4 \times 10^{-4}$ $mol \cdot cm^{-3}$, σ is the Warburg factor which is related to Z_{re} :

$$Z_{re} = R_s + R_{ct} + \sigma \omega^{-\frac{1}{2}} \quad (2)$$

where Z_{re} is the real part of the resistance in the low frequency region, ω is the corresponding frequency. Fig. 7b shows the plot between Z_{re} the reciprocal square root of frequency $\omega^{-1/2}$ in the low frequency region. The diffusion coefficients D_{Mg}^{+2} of magnesium ion in different cathodes were calculated by equation 1 and presented in Table 1. The value of D_{Mg}^{+2} is slightly higher in the V_2O_5 (2.3×10^{-12} $cm^2 \cdot s^{-1}$) than in the V_2O_5/S (2×10^{-12} $cm^2 \cdot s^{-1}$) electrode, and this can be attributed to that the activation energy (E_a) barrier for the migration of interstitial Mg^{+2} to be overcome is a bit higher in the V_2O_5/S compared with the pristine V_2O_5 .

4. Conclusions

The as-prepared sheet-like V_2O_5/S composites prepared by sonochemical method were employed as a cathode in a magnesium battery. This material exhibits a nanorod morphology. The orthorhombic structure of V_2O_5 was not affected by modification with sulfur. However, sulfur caused a small expansion of interplanar distances of (0 0 1) crystal planes from 4.34 Å to 4.35 Å which may improve

Mg^{2+} ion diffusion and storage. Generally, modification of V_2O_5 with sulfur can improve its electrical and electrochemical performance as magnesium battery cathode. The V_2O_5/S cathode delivered a high initial capacity ~ 310 $mAh \cdot g^{-1}$ enlightening the promising future of high capacity cathode for magnesium ion batteries.

Acknowledgements

This work is partial financially supported by the Support Development of Scientific Research Center of Benha University (SDSRC) (Grant No. 1076) and the Science Technology Development Fund (Grant No. 12564).

References

- [1] SON S.-B., GAO T., HARVEY S.P., STEIRER K.X., STOKES A., NORMAN A., WANG C., CRESCE A., XU K., BAN C., *Nat. Chem.*, 1 (2018) 1.
- [2] AURBACH D., LU Z., SCHECHTER A., GOFER Y., GIZBAR H., TURGEMAN R., COHEN Y., MOSHKOVICH M., LEVI E., *Nature*, 407 (6805) (2000), 724.
- [3] AURBACH D., SURESH G.S., LEVI E., MITELMAN A., MIZRAHI O., CHUSID O., BRUNELLI M., *Adv. Mater.*, 19 (23) (2007), 4260.
- [4] XU M., LEI S., QI J., DOU Q., LIU L., LU Y., HUANG Q., SHI S., YAN X., *ACS Nano*, 12 (2018), 3733.
- [5] BHANDAVAT R., DAVID L., SINGH G., *J. Phys. Chem. Lett.*, 3 (11) (2012), 1523.
- [6] CANEPA P., GAUTAM G.S., HANNAH D.C., MALIK R., LIU M., GALLAGHER K.G., PERSSON K.A., CEDER G., *Chem. Rev.*, 117 (5) (2017), 4287.
- [7] GERSHINSKY G., YOO H.D., GOFER Y., AURBACH D., *Langmuir*, 29 (34) (2013), 10964.
- [8] GREGORY T.D., HOFFMAN R.J., WINTERTON R.C., *J. Electrochem. Soc.*, 137 (3) (1990), 775.
- [9] MATSUI M., *J. Power Sources*, 196 (16) (2011), 7048.
- [10] MITELMAN A., LEVI E., LANCY E., AURBACH D., *ECS T.*, 3 (27) (2007), 109.
- [11] NOVÁK P., IMHOF R., HAAS O., *Electrochim. Acta*, 45 (1–2) (1999), 351.

- [12] NULI Y., YANG J., LI Y., WANG J., *Chem. Commun.*, 46 (21) (2010), 3794.
- [13] SEH Z.W., SUN Y., ZHANG Q., CUI Y., *Chem. Soc. Rev.*, 45 (20) (2016), 5605.
- [14] SHTERENBERG I., SALAMA M., GOFER Y., LEVI E., AURBACH D., *MRS Bull.*, 39 (5) (2014), 453.
- [15] SONG J., SAHADEO E., NOKED M., LEE S.B., *J. Phys. Chem. Lett.*, 7 (9) (2016), 1736.
- [16] WHITTINGHAM M.S., *Chem. Rev.*, 104 (10) (2004), 4271.
- [17] YOO H.D., SHTERENBERG I., GOFER Y., GERSHINSKY G., POUR N., AURBACH D., *Energ. Environ. Sci.*, 6 (8) (2013), 2265.
- [18] ZHANG R., YU X., NAM K.-W., LING C., ARTHUR T.S., SONG W., KNAPP A.M., EHRLICH S.N., YANG X.-Q., MATSUI M., *Electrochem. Commun.*, 23 (2012), 110.
- [19] SHEHA E., EL-DEFTAR M., *J. Solid State Electr.*, 22 (9) (2018), 1.
- [20] DROSOS C., JIA C., MATHEW S., PALGRAVE R.G., MOSS B., KAFIZAS A., VERNARDOU D., *J. Power Sources*, 384 (2018), 355.
- [21] LONDERO E., SCHRÖDER E., *Phys. Rev. B*, 82 (5) (2010), 054116.
- [22] WANG Y., CAO G., *Chem. Mater.*, 18 (12) (2006), 2787.
- [23] TANG H., PENG Z., WU L., XIONG F., PEI C., AN Q., MAI L., *Electrochem. Energ. Rev.*, 1 (2) (2018), 169.
- [24] SU D., DOU S., WANG G., *J. Mater. Chem. A*, 2 (29) (2014), 11185.
- [25] JIA M.-Y., XU B., DENG K., HE S.-G., GE M.-F., *J. Phys. Chem. A*, 118 (37) (2014), 8106.
- [26] ZHAO-KARGER Z., ZHAO X., WANG D., DIEMANT T., BEHM R.J., FICHTNER M., *Adv. Energ. Mater.*, 5 (3) (2015), 1401155.
- [27] VINAYAN B., ZHAO-KARGER Z., DIEMANT T., CHAKRAVADHANULA V.S.K., SCHWARZBURGER N.I., CAMBAZ M.A., BEHM R.J., KÜBEL C., FICHTNER M., *Nanoscale*, 8 (6) (2016), 3296.
- [28] LIU C., WANG X., DENG W., LI C., CHEN J., XUE M., LI R., PAN F., *Angew. Chem. Int. Edit.*, 57 (24) (2018), 7046.
- [29] GHORBANZADEH M., FARHADI S., RIAHIFAR R., HADAVI S., *New J. Chem.*, 42 (40) (2018), 1.

Received 2018-07-14

Accepted 2019-04-23