Materials Research Express

PAPER

High-conductivity flexible Ag films formed by low-temperature and short-time sintering of PVP-modified silver oxalate composite ink

PeiYuan Fan ©, WenHua Zhang ©, Xianglei Yu and GuoYou Gan
Kunming University of Science and Technology - Lianhua Campus: Kunming University of Science and Technology, Kunming 650000, People’s Republic of China
E-mail: ganguoyou@kust.edu.cn

Keywords: Ag complex ink, flexible Ag films, low-temperature, PVP

Abstract

Attaining low-temperature sintering and high electrical conductivity is vital in the field of flexible electronics. Inks with silver oxalate as the precursor have recently received significant attention in this field; however, the high sintering temperature and long sintering time limit commercial applicability. High sintering temperature can shorten the sintering time but lead to porous and uneven film morphology; thus, reducing the conductivity. On the other hand, low sintering temperature prolongs the sintering time; thus, reducing the production efficiency. To solve the abovementioned problems, a silver composite conductive ink modified by polyvinylpyrrolidone (PVP) was prepared in this study. The ink used silver oxalate as the precursor, methanol and acetone as the solvent, and 1, 2-diaminopropane as the complexing agent, and could reduce the sintering temperature and time to 160 °C and 20 min, respectively. After sintering, the silver film showed good electrical conductivity, and low resistivity (4.56 μΩ·cm). Furthermore, the impact of sintering temperature on the surface morphology and electrical conductivity were also studied, and the results showed that PVP had a positive influence on the nucleation of silver and the microstructure of the sintered silver film.

1. Introduction

The technology of flexible electronic substrate printing has received extensive research attention. Various methods are employed to print inks on flexible substrates such as polyester (PET) and polyimide (PI) films. The electronic components produced by this technology have the advantages of deformability, large area, small size, and low cost, which provide the possibility of making smaller, lighter, and higher-performance electronic products. At present, this technology has been widely used in circuit printing [1], flexible electrodes [2], solar cells [3], flexible displays [4], and electronic transistors [5]. The core of this technology is the conductive ink. Currently, the main composition of conductive ink is the combination of an organic carrier and metal nanoparticles, such as copper [6] and silver nanoparticles [7, 8]. Copper nanoparticles face two main problems, i.e., the high sintering temperature and the oxidation of copper nanoparticles during storage and application. By contrast, silver nanoparticles have relatively low sintering temperature and are seldom oxidized during storage and application. However, there are generally two major difficulties in the application of nanoparticle printing ink, i.e., it is challenging to synthesize high-performance nanoparticles at large scale, and the agglomeration of nanoparticles is significant, leading to difficulties in the storage of nanoparticles and the production and storage of the ink.

To solve the abovementioned problems, particle-free silver-based inks have been developed. This particle-free ink is composed of an organic silver precursor and a volatile solvent. It is a pure liquid phase, and silver exists in the ink in the form of ions. Consequently, this kind of ink does not undergo agglomeration during storage and application, and its preparation process is much simpler than that with nanoparticles. Moreover, the sintering time is short, and other elements can be volatilized in the form of gas in the sintering process, leaving only the precipitated silver nanoparticles to be sintered into the silver film, which has excellent electrical conductivity.
This kind of particle-free ink was proposed by Wu et al in 2007, wherein silver acetate, ethanolamine, and long-chain carboxylic acids (such as heptanoic acid, folic acid, undecenoic acid, and lauric acid) were dissolved in n-butanol to prepare particle-free ink [9]; however, the conductivity of the prepared ink was not ideal. Subsequently, many researchers have carried out studies on the precursors and complexation agents for the development of particle-free ink. The ever-used precursors include octyl decanoate silver [10], silver nitrate [11], silver acetate [12], silver oxalate [13], and silver citrate [14], and complexing agents such as n-butylamine, ethylenediamine, 1,2-diaminopropane, ammonia, and ethanolamine. For instance, Nie et al prepared an ink using 1,2-diaminopropane as the complexing agent and silver citrate as the precursor, and obtained a silver film with a resistivity of 17.8 µΩ·cm after sintering at 150 °C for 1 h [14]. Chen et al obtained an ink that could be sintered at 50 °C by mixing diethanolamine with a silver ammonia solution [15]. Mou et al prepared an ink composed of a silver isopropanolamine complex, formic acid reductant, and ethyl cellulose, and obtained a silver film with a resistivity of 12.1 µΩ·cm after sintering at 110 °C for 2 h [16]. The abovementioned studies show that the electrical conductivity improved by reducing the sintering temperature and prolonging the sintering time. However, it is still challenging to generate silver films with high electrical conductivities at lower temperatures rapidly.

In this paper, we propose to add polyvinyl pyrrolidone (PVP) into ink. The PVP could adhere to the complex on the decomposed silver nanoparticles [17], which homogenized the growth of nanoparticles, reduced the adverse influence of temperature on sintering, and made the sintered silver film denser. Herein, we prepared the original ink and PVP-modified ink, and then sintered them within a temperature range of 140 °C–190 °C. The results showed that PVP could improve the surface morphology and thus increase the conductivity of the sintered silver film. A high-conductivity silver film with a resistivity of 3.42 µΩ·cm was obtained after sintering at 160 °C for 20 min.

2. Experimental section

2.1. Materials
In this study, the silver nitrate (AgNO₃), oxalate dihydrate, methanol (MT), and polyvinylpyrrolidone (PVP) used were all purchased from Aladdin Reagent Co., Ltd. Acetone (chemically pure, CP) and 1,2-diaminopropane were purchased from Sinopharm Chemical Reagent Co., Ltd No further purification was carried out for the materials used.

The substrate was a polyimide (PI) film, which was purchased from Guangzhou Beilong Electronics Co., Ltd. Before use, the PI films were cleaned with ethanol and deionized water.

2.2. Preparation of silver oxalate precursor
First, 10.2 g of AgNO₃ and 3.78 g of oxalic acid dihydrate were respectively dissolved in 60 ml deionized water to obtain an AgNO₃ solution and oxalic acid solution. After complete dissolution, silver nitrate solution was slowly added to the oxalic acid solution to form a silver oxalate precipitate. The precipitation was washed with deionized water, collected and dried at 60 °C for 10 h in a vacuum drying oven. Finally, a white powdered silver oxalate was obtained, as shown in figure 2(a).

2.3. Preparation of PVP-modified ink
The PVP-modified ink is referred to as the AgV ink in this procedure. First, 3 ml MT, 2 ml CP, and 4.44 g of 1, 2-diaminopropane were mixed at 300 rpm for 10 min in a beaker to obtain Solvent 1. To study the modification effect of PVP, 0.108 g of PVP was mixed into Solvent 1 to obtain Solvent 2. The AgV ink was prepared by mixing silver oxalate powder into Solvent 1 and Solvent 2, respectively. The specific preparation scheme is shown in figure 1, and the prepared ink is shown in figure 2(b).

2.4. Characterization
The thermal behaviors of silver oxalate powder and ink from 50 °C to 300 °C were studied by a synchronous thermogravimetric analyzer (TG-DSC) at a heating rate of 10 °C min⁻¹ under a nitrogen atmosphere. The UV–vis absorption spectrum of the ink with water as the solvent was measured by a UV–vis spectrophotometer. Fourier transform infrared (FT-IR) spectroscopy was used to measure the FT-IR spectral image of the ink. The surface morphology and composition of the sintered Ag films were studied by a scanning electron microscope (SEM) and an attached energy dispersive spectroscopy (EDS). The crystal structure of the sintered Ag films was analyzed by an x-ray diffractometer (XRD). The resistivity of the sintered Ag films was measured by a four-probe resistivity tester and a stylus profilometer.
3. Results and discussion

Silver oxalate has relatively a high silver content, which is significantly higher than that of silver acetate, silver citrate, or other precursors. Moreover, it has a simple structural formula, and can be decomposed into metallic silver and carbon dioxide at lower temperatures. Hence, silver oxalate is an ideal precursor for preparing ink\(^{18–20}\). The 1,2-diaminopropane was selected as the complex agent because of its high amino content. Furthermore, 1, 2-diaminopropane also shows high volatility at room temperature, indicating weak bond energy, which can lead to a lower decomposition temperature of the final complex.

3.1. Characterization of silver oxalate

The silver oxalate used in this study was prepared by the reaction of oxalic acid and silver nitrate, and the reaction equation is as follows:

\[
\text{AgNO}_3 + \text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{AgC}_2\text{O}_4 + \text{NaNO}_3
\]

The prepared powder was scanned by TG-DSC at a heating rate of 10 °C min\(^{-1}\), as shown in figure 3. Figure 3(a) shows the DSC curve of the silver oxalate. Two peaks were observed at 202 °C and 210 °C, which can be ascribed to the decomposition of silver oxalate. The position and intensity of the two peaks are related to the size and structure of silver oxalate\(^{21}\). Figure 3(b) shows the TG curve of silver oxalate. The decomposition of silver oxalate is shown to begin at 150 °C, and that the maximum weight loss occurred at 225 °C. These results are consistent with the DSC results. Meanwhile, the decomposition products of silver oxalate are only Ag and
CO₂. The weight loss calculated from the TG curve is 28%, and the remaining weight accounts for 72%, which is consistent with the silver content in silver oxalate.

3.2. Characterization of ink

Generally, it is difficult for silver oxalate to dissolve in common solvents. However, after the formation of the coordination bond between silver ions and amino groups (–NH₂), the ionic bonds in silver oxalate are weakened, so that the complex can dissolve in the solvents with high hydroxyl content such as deionized water and methanol. The possible formation mechanism of the silver complex is illustrated in figure 4.

The morphology of the silver film after ink sintering directly affects the conductivity of the Ag film. Thus, we added PVP to the ink to improve the final morphology of the sintered silver film. The amine itself has a certain reducibility, and the reaction process can produce a significant amount of heat, which easily promotes the direct decomposition of the generated complex into silver nanoparticles and silver oxide. Hence, we used UV–vis and FT-IR to characterize the inks.

Since the amine has weak reducibility, it may lead to the direct precipitation of silver nanoparticles from the ink. Moreover, the reaction involved in the ink preparation is exothermic, which may cause the decomposition of the complex into silver oxide. In view of this, we investigated the prepared ink by UV–vis spectroscopy, which is highly sensitive to metallic nanoparticles. The spectral results are shown in figure 5. Here, the different absorption intensities are relative intensities, so the data lines can be moved upwards or downwards. There are no peaks corresponding to silver oxide and silver nanoparticles [22]. The ink is colorless and transparent, indicating that the ink was successfully prepared.

Figure 6 shows the FT-IR results of the ink. In the infrared spectrum of 1,2-diaminopropane, the peaks at 3380 and 3300 cm⁻¹ correspond to the asymmetric vibration and tensile vibration of the –NH₂ groups, and the peaks at 2949, 2920, and 2870 cm⁻¹ correspond to the –CH₃ groups and –CH₂ groups [23]. In the infrared spectrum of the mixed solution of CP and MT, there is a wide peak at 3402 cm⁻¹, which is attributed to the hydroxyl groups in MT, which form hydrogen bonds. Moreover, MT and CP can form a six-membered ring structure through nonlinear hydrogen-bond combination. The positive charges on the carbon atoms of the

![Figure 3. (a) DSC and (b) TG curves of silver oxalate.](image)

![Figure 4. Schematic of the reaction process of Ag complex.](image)
Carbonyls in CP are dispersed due to the participation of neighboring methyl groups, which shifts the infrared frequency to a lower wave number, resulting in the appearance of carbonyl peaks at 1740 and 1655 cm\(^{-1}\) [24]. In the infrared spectrum of the ink, the carbonyl peak becomes stronger and narrower because of the addition of carbonyls in silver oxalate. Meanwhile, the hydroxyl peak at 3334 cm\(^{-1}\) from the solution containing CP and MT, as well as the peaks of the CH\(_3\) and CH\(_2\) groups in 1,2-diaminopropane at 2964, 2934, and 2877 cm\(^{-1}\), were also observed.

Figure 7 shows the DSC-TG results of the ink. As shown in figure 7(a), it can be observed that an endothermic peak appears at 71 °C due to the volatilization of methanol and acetone. An exothermic peak appears at 115 °C, which is attributed to the decomposition of the Ag complex, indicating that the decomposition temperature of the silver complex is much lower than that of silver oxalate. An obvious endothermic peak appears at 130 °C, which is due to the escaped amines and carbon dioxide after the
decomposition of the silver complex. Figure 7(b) is similar to figure 7(a), the initial endothermic peak is due to the volatilization of the solvent. The first exothermic peak is due to the decomposition of the complex, and the second endothermic peak is due to the escape of gas produced by the decomposition of the complex. Combined with the TG curve, it can be concluded that the decomposition of the ink begins at 115 °C and finishes at 134 °C.

3.3. Characterization of the Ag film after sintering

The silver film was coated on the PI substrate by a spin coater and then sintered in a drying oven at low temperatures, as shown in figure 8. At the beginning of sintering, the solvent escapes and the complex decomposes to produce CO₂, 1,2-diaminopropane. The silver nanoparticles begin to precipitate and grow. As the sintering progresses, the solvent volatilizes, the complex is resolved to produce nano-silver, and the nano-silver is sintered to form a silver film.

The SEM images obtained after sintering at different temperatures for 20 min are shown in figures 9 and 10. Figure 9 shows the SEM images of the Ag films after the Ag ink was sintered. As shown in figure 9(a), the decomposition of the ink was completed at 140 °C, and the complex decomposed into silver, which forms nanoparticles. With the increase in sintering temperature, the size of the silver nanoparticles increases in size, and the adjacent nanoparticles begin to fuse slowly, leading to neck growth. From 160 °C, with the increase of sintering temperatures, it can be seen clearly from the images that holes appear in the film. On the one hand, with the increase of temperature, the decomposition reaction becomes stronger, and the escape of gas products and the evaporation of the solvent become more intense accordingly. On the other hand, with an increase in temperature, the higher activation energy can promote surface diffusion and grain boundary diffusion, so the diffusion is more efficient. As a result, the smaller silver nanoparticles tend to completely fuse into larger nanoparticles before they have time to grow [25].

Figure 10 shows the SEM images of the Ag films after the AgV ink was sintered. The decomposition of the ink was completed at about 140 °C, and neck growth between the silver nanoparticles was observed. Notably, the Ag grains became more uniform. Moreover, the high-magnification images show that the holes were observed until the sintering temperature increased to 190 °C. This can be attributed to PVP wrapping the (111) and (100)
crystal planes of silver [26], slowing down the high-speed diffusion at higher temperatures. Thus, the grains became more uniform and the sintered planes became smoother.

From the low-magnification images, when the temperature was not higher than 180 °C, Ag films with good morphology were obtained after the AgV ink was sintered. However, when the sintering temperature was higher than 180 °C, the rapid evaporation of the solvent and the rapid decomposition of the complex into Ag and CO₂ produced numerous holes. Furthermore, the growth rate of the silver grains was fast and the growth time was short; thus, the holes could not be effectively covered by the growth of the Ag grains.

The sintering of Ag and AgV inks at 160 °C endowed the Ag films with good electrical conductivity, as shown in the XRD patterns in figure 11. Only the peaks of the (111), (200), (220), (311), and (222) planes of Ag were observed, and there were no other obvious peaks in the XRD pattern. Thus, it can be concluded that the inks had completely decomposed into Ag at 160 °C [27, 28].

The wafer resistance was measured with four probes and then multiplied by the film thickness to obtain the resistivity. Figure 12 shows the resistivity curves of the Ag films after the inks were sintered at different temperatures. By comparison, it can be found that the resistivity of the Ag film after the AgV ink was sintered was lower than that after the Ag ink was sintered. The resistivities of the two sintered inks were relatively high when sintered at 140 °C and 190 °C, and overall, the resistivity first decreased and then increased. The lowest resistivities for the sintered AgV ink (4.56 μΩ·cm) and sintered Ag ink (16.44 μΩ·cm) appeared at 160 °C and 170 °C, respectively. The resistivity of the sintered Ag ink changed very little when the Ag ink was sintered within the range 140 °C–170 °C.
The high resistivity of the inks sintered at 140 °C can be attributed to the untight connection of the necks of silver grains and the incomplete evaporation of some solvents and free amines. With the increase in the sintering temperature, the growth of the necks of the nanoparticles can increase the contact area between particles and thus improve the electrical conductivity. Furthermore, as the temperature continues to rise, the decomposition reaction of the inks becomes increasingly intense. For the Ag ink, the escaping gas destroys the overall structure of the film, and the large nanoparticles tend to fuse into small nanoparticles, forming numerous holes. By contrast, for the AgV ink, the PVP was found to cover some crystal planes of the silver, and weaken the fusion reaction of the larger nanoparticles with smaller nanoparticles; thus, making the grain size more uniform. Moreover, the newly generated nanoparticles could fill the holes produced by the escaping gas. Despite this, when the sintering temperature was higher than 170 °C, the decomposition reaction of the ink was violent and beyond the control limit of PVP. As a result, the sintered silver film had too many holes, which decreased its resistivity.

The stability of the conductivity of the Ag film during bending is a very important performance. Figure 13 shows the conductivity of the sintered silver film in different states. Write a bulb into the circuit through the Ag film and use a 3 V DC voltage. It can be seen that the bulb can emit light normally even when the PI film is bent, which proves the effective conductivity of the flexible Ag film.
4. Conclusions

In this paper, using PVP as a modifier, a AgV composite ink was prepared with silver oxalate as the precursor, acetone and methanol as the solvent, and 1,2-diaminopropane as the complexing agent. Conductive silver films were obtained by sintering the ink under temperatures ranging from 140 °C to 190 °C for 20 min. A highly conductive silver film, with a resistivity of 4.56 μΩ·cm, was obtained when the ink was sintered at 160 °C. Compared with the unmodified Ag ink, the conductivity of the Ag film obtained with the AgV ink was significantly improved. The morphologies and resistivities of the films sintered on the PI substrate, within a certain temperature range, were analyzed. The surface morphology of the sintered ink was found to affect the final conductivity of the film. High sintering temperature could produce large nanoparticles, which increased the contact area between the nanoparticles through neck growth; thus, improving the conductivity. On the other hand, a high sintering temperature promoted the decomposition reaction and led to rapid evaporation of the solvent, producing excessive holes in the silver film. PVP had a positive effect on the surface morphology of the ink. PVP was found to be coated on the (100) and (111) crystal planes of the silver, which slowed down the fusion degree of the small-particle silver nanometer grains into larger-particle grains. As a result, the morphology of the Ag grains became more uniform, increasing the electrical conductivity. In our subsequent research, we will focus on increasing the adhesion of the Ag film after ink sintering and improving the pattern making process of the silver films.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51771084) and Technology Projects of Yunnan Province (Grant No. 202002AB080001-1 and Grant No. 202102AB080008).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

ORCID iDs

PeiYuan Fan  
https://orcid.org/0000-0002-9485-0377
WenHua Zhang  
https://orcid.org/0000-0001-8687-5876

Figure 13. The conductivity of silver film at different conditions. (a) Silver film before bending (b) Silver film after 50 times of bending (c) Silver film access circuit before bending (d) Silver film access circuit after bending.
References

[1] Jahn S F, Blaudeck T, Baumann R R, Jakob A, Ecorchard P, Rüffer T, Lang H and Schmidt P 2010 Inkjet printing of conductive silver patterns by using the first aqueous particle-free MOD ink without additional stabilizing ligands Chem. Mater. 22 3067–71
[2] Vaseem M, McKerricher G and Shamim A 2016 Robust design of a particle-free silver–organocomplex ink with high conductivity and inkjet stability for flexible electronics ACS Appl. Mater. Interfaces 8 177–86
[3] Vanalakar S A, Agawane G L, Shin S W, Yang H S, Patil P S, Kim J Y and Kim J H 2015 Non-vacuum mecanochemical route to the synthesis of CuSxS0 nano-ink for solar cell applications Acta Mater. 85 314–21
[4] Moses O A et al 2021 2D materials inks toward smart flexible electronics Mater. Today 50 116–48
[5] Li CD, Xu JZ, Xu JI, Shen Y and Jin M 2016 Rounded silicon edges on the surface of Al–Si alloy cylinder liner by means of mechanical grinding treatment Tribol. Int. 104 204–11
[6] Jun H Y, Lee E J and Ryu S O 2020 Synthesis and characterization of copper ink and direct printing of copper patterns by inkjet printing for electronic devices Curr. Appl. Phys. 20 853–61
[7] Jiang H, Tang C, Wang Y, Mao L, Sun Q, Zhang L, Song H, Huang F and Zuo C 2021 Low content and low-temperature cured silver nanoparticles/silver ion composite ink for flexible electronic applications with robust mechanical performance Appl. Surf. Sci. 564 150447
[8] Ibrahim N, Akindoye J O and Mariatti M 2021 Recent development in silver-based ink for flexible electronics J. Sci. Adv. Mater. Der. 7 100395
[9] Wu Y, Li Y and Ong B S 2007 A simple and efficient approach to a printable silver conductor for printed electronics J. Am. Chem. Soc. 129 1862–3
[10] Teng K F and Vest R W 1988 Metallization of solar cells with ink jet printing and silver metallo–organic inks IEEE Trans. Compon. Hybrids Manuf. Technol. 11 291–7
[11] Liu Z, Su Y and Varahramyan K 2005 Inkjet-printed silver conductors using silver nitrate ink and their electrical contacts with conducting polymers Thin Solid Films 478 275–9
[12] Mou Y, Zhang Y, Cheng H, Peng Y and Chen M 2018 Fabrication of highly conductive and flexible printed electronics by low temperature sintering reactive silver ink Appl. Surf. Sci. 459 249–56
[13] Zope K R, Cormier D and Williams S A 2018 Reactive silver oxalate ink composition with enhanced curing conditions for flexible substrates ACS Appl. Mater. Interfaces 10 3830–7
[14] Nie X, Wang H and Zou J 2012 Inkjet printing of silver citrate conductive ink on PET substrate Appl. Surf. Sci. 261 554–60
[15] Chen S P, Kao Z K, Lin J L and Liao Y C 2012 Silver conductive features on flexible substrates from a thermally accelerated chain reaction at low sintering temperatures ACS Appl. Mater. Interfaces 6 7064–8
[16] Mou Y, Cheng H, Wang H, Sun Q, Liu J, Peng Y and Chen M 2019 Facile preparation of stable reactive silver ink for highly conductive and flexible electrodes Appl. Surf. Sci. 475 75–82
[17] Chen D, Qiao X, Qiu X, Chen J and Jiang R 2011 Large-scale synthesis of silver nanowires via a solvothermal method J. Mater. Sci., Mater. Electron. 22 6–13
[18] Boldyrev V V 2002 Thermal decomposition of silver oxalate Thermochem. Acta 388 63–90
[19] Dong Y, Li X, Liu S, Zhu Q, Li G and Sun X 2015 Facile synthesis of high silver content MOD ink by using silver oxalate precursor for inkjet printing applications Thin Solid Films 589 381–7
[20] Itoh M, Kakuta T, Nagaoka M, Koyama Y, Sakamoto M, Kawasaki S, Umeda N and Kurihara M 2009 Direct transformation into silver nanoparticles via thermal decomposition of oxalate-bridging silver oleylamine complexes J. Nanosci. Nanotechnol. 9 6655–60
[21] Yang W, Wang C and Arrighi V 2018 Silver oxalate ink with low sintering temperature and good electrical property J. Electron. Mater. 47 2824–35
[22] Flower G L, Latha S V and Rao K V 2016 Novel characterization of nanosilver fluid through ultrasonic studies supported by UV–Vis spectroscopy, DLS and TEM studies J. Mol. Liq. 221 333–8
[23] Yang W, Wang C and Arrighi V 2018 Effects of amine types on the properties of silver oxide ink and the associated film morphology J. Mater. Sci., Mater. Electron. 29 20895–906
[24] Max J J and Chapados C 2005 Infrared spectroscopy of acetone-methanol liquid mixtures: hydrogen bond network J. Chem. Phys. 122 014504
[25] Li J, Zhang X, Liu X, Liang Q, Liao G, Tang Z and Shi T 2020 Conductivity and foldability enhancement of Ag patterns formed by PV/Ag modified Ag complex inks with low-temperature and rapid sintering Mater. Des. 185 108255
[26] Wiley B, Sun Y, Mayers B and Xia Y 2005 Shape-controlled synthesis of metal nanostructures: the case of silver Chem. Eur. J. 11 454–63
[27] Grunwaldt J D, Atamny F, Gobel U and Baiker A 1996 Preparation of thin silver films on mica studied by XRD and AFM Appl. Surf. Sci. 99 353–9
[28] Liu X et al 2021 UV–sinterable silver oxalate-based molecular inks and their application for in-mold electronics Adv. Electron. Mater. 7 2100194