We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

4,200
Open access books available

116,000
International authors and editors

125M
Downloads

154
Countries delivered to

TOP 1%
Our authors are among the most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
Molecular Precursor Method for Fabricating \( p \)-Type \( \text{Cu}_2\text{O} \) and Metallic Cu Thin Films

Hiroki Nagai and Mitsunobu Sato

Abstract

Functional thin films are used in various fields of our life. Many different methods are used to fabricate these films including physical vapor deposition (PVD) and chemical processes. The chemical processes can be used to manufacture thin films in a relatively cheap way, as compared to PVD methods. This chapter summarizes the procedures of the molecular precursor method (MPM), a chemical process, for fabrication of both metal oxide semiconductor \( \text{Cu}_2\text{O} \) and metallic Cu thin films by utilizing Cu(II) complexes in coating solutions. The MPM, recently developed and reported by the present authors, represents a facile procedure for thin film fabrication of various metal oxides or phosphates. This method pertinent to the coordination chemistry and materials science including nanoscience and nanotechnology has provided various thin films of high quality. The MPM is based on the design of metal complexes in coating solutions with excellent stability, homogeneity, miscibility, coatability, etc., which are practical advantages. The metal oxides and phosphates are useful as the electron and/or ion conductors, semiconductors, dielectric materials, etc. This chapter will describe the principle and recent achievement, mainly on fabricating the \( p \)-type \( \text{Cu}_2\text{O} \) and metallic Cu thin films of the MPM.

Keywords: molecular precursor method, thin film, \( p \)-type \( \text{Cu}_2\text{O} \), copper

1. Introduction

A sustainable society requires innovative technology where many disciplines interact. Highly functionalized thin films in various devices such as computers, which were developed mainly for the semiconductor industry in the last century, are now widely used in various fields of our daily life. For example, the touch panel in mobile phone uses a transparent conductive thin film and an antireflection thin film on the glass. A product with various thin films makes
life more comfortable. Many different methods are used to fabricate such thin films including physical vapor deposition (PVD) such as laser ablation, molecular beam epitaxy, sputtering, and chemical processes [1]. The chemical processes can be used to manufacture thin films in a relatively cheap way compared to PVD methods. The chemical process is a processing technique for preparing thin films, ceramic coatings, and powders. However, it is usually difficult to fabricate high-quality thin films using chemical processes.

Transparent metal oxide thin films of $p$-type semiconductors deposited directly on various substrates offer several advantages in the design of heterojunctions with $n$-type oxide films for fabricating thin film devices [2, 3]. Over the past years, the quest to obtain high-quality cuprous oxide films has fueled the development of many physical processing techniques including sputtering, thermal oxidation, vacuum evaporation, molecular beam epitaxy, and electrodeposition [4–9]. However, reproducible formation of cuprous oxide films, uncontaminated by copper or the CuO phase, is a formidable challenge from the technical perspective. Most of the aforementioned physical processing techniques are not economically viable in large area applications. The chemical procedures, which save both energy and resources, have therefore emerged as an attractive alternative because of cost-effective production capabilities.

Recently, we achieved the fabrication of $p$-type Cu$_2$O transparent thin films by means of a chemical process, the molecular precursor method (MPM), using the thermal reaction of molecular precursor films spin-coated on a Na-free glass substrate. A stable precursor solution for the spin-coating process was facilely prepared by reacting an isolated Cu(II) complex of ethylenediamine-$N, N', N''-tetraacetic acid (EDTA, $H_4$edta) with dibutylamine in ethanol [10, 11]. The MPM is one of the chemical processes used for thin film formation of metal oxides or phosphates [12–22]. The method is based on the formation of excellent precursor films involving anionic metal complexes and the alkylammonium cation. The stability, homogeneity, miscibility, and other characteristics of the precursor solutions, which can be used for various coating methods, are practical advantages, in contrast to the conventional sol-gel method.

This chapter summarizes the procedures used in the MPM for the fabrication of both metal oxide semiconductor Cu$_2$O and metallic Cu thin films by utilizing Cu(II) complexes in coating solutions.

2. Molecular precursor method

The decision by the Nobel Prize committee to award the Nobel Prize for chemistry in 1913 to Alfred Werner met with worldwide approval. In a statement, the committee said that Alfred Werner received the prize in recognition of his work on the linkage of atoms in molecules by which he has thrown new light on earlier investigations and opened up new fields of research especially in inorganic chemistry [23]. Today, the metal complexes are used in various applications such as catalysts, luminescence, and medicine. In 1996, one of the authors, M.S., focused on the thin film fabrication of various metal oxides and phosphate compounds...
using the metal complexes of stable [10–22]. This is the MPM, which is one of the chemical processes used for thin film fabrication. In those days, most of the researchers in the field of thin film formation by chemical processes preferred to use rather unstable metal complexes. It is easy to imagine the capability of polymers to form films because we use polymer films every day. In fact, well-adhered precursor films can be formed on various substrates by coating the solution dispersing the produced oligomers and polymers including metallic species provided by hydrolyzing the unstable metal complexes. These results led us to believe for a long time that only the oligomers and polymers can form precursor films, but the stable metal complexes having discrete molecular weight would not be useful in the formation of such thin films. The MPM was a challenge to this central belief.

The MPM, pertinent to coordination chemistry and materials science including nanoscience and nanotechnology, has been used to fabricate various high-quality thin films with appropriate film thicknesses. As a result, the MPM represents a facile procedure for thin film fabrication of various metal oxides or phosphates, which are useful as electron and/or ion conductors, semiconductors, dielectric materials, etc [24, 25].

**Figure 1** shows the Co$_3$O$_4$ thin films, which were first fabricated using the molecular precursor solutions. To date, more than 40 kinds of metal oxides or phosphates have been easily fabricated. **Figure 2** shows the general protocol for fabricating the titanium dioxide thin films. First, a water-resistant coating solution was prepared by the reaction of a neutral [Ti(H$_2$O)(edta)] complex with dipropylamine in ethanol, where edta represents ethylenediamine-$N$, $N'$, $N''$, $N'''$-tetraacetate anion. Molecular precursor solutions can be used in spin, dip, or spray coating on various material surfaces to form precursor thin films. To obtain the precursor film, the coated film was dried at around 70°C. The precursor films involving metal complexes should be amorphous, just as with the metal/organic polymers in the sol-gel processes; otherwise, it would not be possible to obtain the resulting metal oxide thin films spread homogeneously on substrates by using the following heat treatment. After this, the precursor film was heat-treated at appropriate temperatures for eliminating the components in the organic ligand from the metal complexes involved in the precursor films and to fabricate thin films of crystallized metal oxides or phosphates. The heat treatment of a well-adhered precursor film at 450°C in air is useful for the fabrication of transparent titania thin films.

**Figure 1.** The Co$_3$O$_4$ thin films which were first time to fabricate the thin film using the molecular precursor solutions.
Cuprous oxide, Cu$_2$O, with a cubic structure is a potential candidate for $p$-type semiconductors having a band gap of 2.0 eV, which is the band gap of its single crystal. The thin films of Cu$_2$O can be grown generally by dry processes in a vacuum chamber at high temperature, such as sputtering, thermal oxidation, and pulsed laser deposition [26–28]. Over the past years, the quest to obtain high-quality Cu$_2$O films has fueled the development of many physical processing techniques including sputtering, thermal oxidation, vacuum evaporation, molecular beam epitaxy, and electrodeposition. However, reproducible formation of Cu$_2$O films uncontaminated by the CuO phase is a formidable challenge from the technical perspective [29, 30]. In addition, most of the aforementioned physical processing techniques are not economically viable in large area applications. Solution-based processes have, therefore, emerged as attractive alternatives because of the ability for cost-effective production [31]. Armelao and coworkers have successfully employed a sol-gel solution containing dissolved copper acetate to produce a Cu$_2$O thin film [32]. The semiconductive nature of the thin film was, however, unclear owing to the lack of Hall effect measurements in their work.

Recently, $p$-type Cu$_2$O transparent thin films were fabricated using the thermal reaction of molecular precursor films spin-coated on a Na-free glass substrate [10]. A stable precursor solution for the spin-coating process was easily prepared by reacting an isolated Cu(II) complex of EDTA with dibutylamine in ethanol. The 50-nm-thick Cu$_2$O thin film resulting from heat treatment of the precursor film at 450°C for 10 min in Ar gas at a flow rate of 1.0 L min$^{-1}$ was characterized by X-ray diffraction (XRD). Figure 3 shows the XRD pattern of the resultant thin film deposited on the Na-free glass substrate after heat treating the precursor film. The XRD pattern of the resultant thin film indicated a precise cubic lattice cell parameter with $a = 0.4265(2)$ nm, with a crystallite size of 8(2) nm. No additional peaks from any possible contaminants such as Cu and CuO appeared in the XRD pattern of the Cu$_2$O film. X-ray
photoelectron spectroscopy (XPS) peaks attributed to the O 1s and Cu 2p_{3/2} level of the Cu_2O film were observed at 532.6 and 932.4 eV, respectively. The peak position of the Cu 2p_{3/2} level is identical to the reported values, which were observed for Cu_2O thin films prepared by other methods [31, 33]. In addition, no peak for the CuO phase was observed at its typical value of 944 eV [31]. The average grain size of the deposited Cu_2O particles was ~200 nm, observed via field-emission scanning electron microscopy (FE-SEM). The optical band edge evaluated from the absorption spectrum of the transparent Cu_2O thin film was 2.3 eV, assuming a direct transition semiconductor. The tensile strength of the films on the glass substrate was measured by a stud pull adhesion test. The tensile strength of the adhesion of the Cu_2O thin film to the substrate was 83(2) MPa, indicating strong adhesion to the glass substrate.

Figure 4 shows the Arrhenius plot of the Cu_2O thin film on the Na-free glass substrate over the temperature range 160–300 K. Hall effect measurements of the thin film indicated that the single phase Cu_2O thin film is a typical p-type semiconductor with a hole concentration of 1.7 × 10^{16} cm^{-3} and hole mobility of 4.8 cm^2 V^{-1} s^{-1} at ambient temperature. The activation energy from the valence band to the acceptor level was determined as 0.30 eV by least-square fitting using the free carrier concentration spectroscopy (FCCS) method [34].
The resistivity of the Cu$_2$O thin film fabricated using the MPM was lower than that of both films obtained by the oxidation of a copper film and by the dc reactive magnetron sputtering process [26–28]. It was observed that the carrier concentration tends to be high and the carrier mobility is low for the Cu$_2$O thin film fabricated by the MPM, compared to the thin films formed by previously reported processes (Table 1).

The method described is the first example of fabrication and characterization of $p$-type Cu$_2$O transparent thin films using a coating solution prepared from a starting Cu$^{2+}$ complex of the H$_2$edta$^{2-}$ ligand. Reduction of the Cu$^{2+}$ species occurred unambiguously through the heating process under Ar gas flow. The CuO phase could be found in the thin film by the prolonged reactions after fabricating the Cu$_2$O thin film at the identical atmospheric condition and temperature. This result indicates that the formation mechanism of Cu$_2$O in the MPM differs from that of the sol-gel method, in which the Cu$_2$O phase was derived from the CuO phase in N$_2$ atmosphere at 90°C. It is notable that the quality of the resultant thin film fabricated

![Figure 4](image_url)
The XPS spectra of the films are shown in Figure 5. The peak positions of the Cu 2p_{3/2} level in spectra (a)–(d) are 933.5, 932.7, 932.5, and 933.2 eV in Figure 5A, respectively. The peaks observed in (a) and (d) can be assigned to the Cu^{2+} ion, and the broad peak at 944 eV observed in (d) is typical of CuO. In contrast, the peaks observed in (b) and (c) can be assigned to metallic Cu and/or Cu^{+} ions. These XPS results are consistent with the XRD results.
In Figure 5B and C, the XPS spectra of the C1s and N1s peaks, respectively, are shown. No impurities such as nitrogen or carbon atoms can be found in the XPS spectra of the resultant Cu$_2$O thin films, although the metallic Cu$_0$ thin film includes a certain amount of nitrogen and carbon atoms. It was thus clarified that single phase Cu$_2$O formation was completed by the removal of organic residues in the Cu$_0$ thin film. The co-presence of nitrogen and carbon atoms was thus shown to have an important role in preventing the oxidation of the produced Cu$_2$O phase. The presence of nitrogen and carbon atoms may also help in organizing the stepwise reactions.

In the sol-gel method for Cu$_2$O thin film formation, the CuO film is annealed at 900°C for 5 h in nitrogen for the partial removal of oxygen atoms from the initial oxide thin film. In contrast, the MPM eliminates the organic components in order to form the Cu$_2$O thin film at the abovementioned lower temperature. It is interesting that the difference between these two methods is in the kind of atoms that must be removed. Furthermore, it is important that the formation route of the $p$-type Cu$_2$O thin films determines the quality of the thin films, as mentioned above. The MPM is additionally preferable in terms of saving energy by reducing the formation temperature.

It was first shown that the expected Cu$_2$O formation using the MPM occurred via an unexpected intermediate Cu$_0$ phase formed by the thermal decomposition of the molecular precursor involving a Cu(II) complex salt. The XRD measurement of the crystallized thin films was useful in determining the activation energies of the redox reactions from the Cu(II) complex to Cu$_0$, from Cu$_0$ to Cu$_2$O, and from Cu$_2$O to CuO (Figure 6). The redox reactions of the metals and organic ligands occurred stepwise with annealing of the thin films under moderate conditions. Consequently, the ligand in the molecular precursor plays an important role in fabricating excellent $p$-type Cu$_2$O thin films. It is also suggested that kinetic studies on the thermal reactions of metal complexes in the solid state are essential for revealing the reaction mechanism of thin film fabrication.

**Figure 5.** XPS spectra of (A) Cu 2p$_{3/2}$, (B) C 1s, and (C) N 1s of the thin films heat-treated in Ar gas flow. The films were fabricated by heat treating the precursor film at (a) 200°C for 10 min, (b) 400°C for 0 min, (c) 450°C for 10 min, and (d) 450°C for 60 min.
4. Fabrication of copper thin films

From the kinetic study of the Cu$_2$O thin film formation, it was elucidated that the Cu$^{II}$ species formed as an intermediate was oxidized to the resultant Cu$_2$O thin film during the heat treatment, and the oxidizing agent is the oxygen present in the commercially available Ar gas as an impurity (<2 ppm) [11]. However, the intermediate Cu thin film obtained through the reaction using the precursor film is not electrically conductive. Therefore, in order to fabricate transparent metal copper thin films, we examined novel precursor solutions [35, 36]. A novel precursor solution containing a Cu$^{II}$ complex of EDTA and a Cu$^{II}$ complex of propylamine derived from formic acid, and the amine was prepared by mixing the two precursor solutions. The concentration of total copper in the ethanolic precursor solution was adjusted to 0.35 mmol g$^{-1}$. The spin-coating method was used for precursor film formation on a Na-free glass substrate. The spin-coated precursor films were preheated in a drying oven at 70°C for 10 min.

Figure 6. A kinetics study was performed in order to clarify the reaction mechanism for fabricating the excellent p-type Cu$_2$O thin films by using the molecular precursor method.
and then, heat-treated at 350°C for 15 min under an Ar gas flow of 1.5 L min⁻¹ to fabricate thin films in a tubular furnace with a quartz glass tube. The resultant thin film is hereby denoted as A. The rate of temperature increase was controlled by a proportional-integral-derivative program preinstalled in the furnace. Before increasing the temperature, the tubular furnace was filled with Ar gas. The thickness of the resultant films was measured using a stylus profilometer. A flat- and same-sized quartz glass plate was placed on the resulting thin film A in the tubular furnace and then post-annealed at 350°C for 20 and 40 min in an Ar gas flow of 1.5 L min⁻¹. The resulting thin film is hereby denoted as APn (n = post-annealing time). The XRD patterns of the resultant thin films A, AP20, and AP40 with a thickness of 40 nm over the 2θ range 30°–50° are shown in Figure 7. The peaks at 2θ = 36.6° and 42.5° for A can be assigned to the (111) and (200) phases of Cu₂O, respectively, and an additional peak at 43.5° for A is assigned to the (111) phase of copper (JCPDS card No. 04–0836). The peak at 2θ = 36.9° for AP20 is assigned to the (111) phase of Cu₂O and that at 43.7° can be assigned to the (111) phase of copper.

Figure 7. XRD patterns of A, AP20, and AP40 thin films. Parallel beam optics (θ = 0.3°) was employed for calculations. The lines indicate the following: ……A, ----AP20, and ━ AP40. The peaks are denoted as follows: ▽ Cu; | Cu₂O.
The single peak at $2\theta = 43.7^\circ$ for AP40 is attributed to the (111) phase of copper. Thus, the Cu$_2$O phase decreased gradually with increasing post-annealing time, and no peak owing to any impurity phase such as Cu$_2$O and CuO could be detected in the annealed AP40 film. The cell parameter of the Cu cubic lattice in A, which was determined by the Wilson & Pike method, is $a = 3.71(3) \, \text{Å}$, and the crystallite size of Cu crystals formed in the film can be determined as 11(1) nm; the estimated standard deviations are presented in parentheses. The cell parameter of the Cu cubic lattice in AP40 is $a = 3.72(3) \, \text{Å}$, and the crystallite size of the Cu crystals can be determined as 13(1) nm. The surface morphology of the A and AP40 thin films was observed using FE-SEM. The grain size of the Cu particles also increased from 50 nm (A) to 70 nm (AP40) upon annealing. Figure 8 shows the Auger spectra of A, AP20, and AP40 thin films. Broad peaks were observed at 264 eV for carbon, 509 eV for oxygen, and 764, 835, and 914 eV for copper atoms. The kinetic energies of the copper atoms are identical to those in other films fabricated by the MPM. The result indicates that the amount of carbon atoms in the AP40 thin film was reduced to half by the post-annealing treatment of A. Figure 9 shows

![Figure 8](image-url)

Figure 8. The Auger spectra of A and A20, and AP40 thin films. The lines indicate the following: ……A, ----AP20, and ━AP40, respectively.
the curve fitting results of the Auger spectrum for A over the range 230–300 eV, corresponding to the carbon atoms, along with the curves of the neutral and tetravalent carbon atoms. The curve fitting results suggest that the carbon atom in A was 85% agreement to the neutral. The electrical resistivity of the A, AP20, and AP40 thin films is $7.5 \times 10^{-4}, 2.8 \times 10^{-4},$ and $4.7 \times 10^{-5}$ Ω cm, respectively. Thus, highly conductive translucent copper thin films could be obtained in commercially available Ar gas. A plausible scheme for copper lattice formation, which can be deduced from the XRD and Auger spectra, is presented in Scheme 1.

**Figure 9.** The curve fitting results of carbon state in AP40 thin film. The lines indicate the following: ……A, —Carbon (neutral), ----Carbon (tetravalent), respectively.

**Scheme 1.** Plausible scheme for the formation of a Cu thin film from the precursor film.
The scheme indicates that four Cu complexes are required to construct one FCC copper unit cell. During the heat treatment of the precursor complexes in Ar gas flow containing <2 ppm of oxygen as impurity, neighboring complexes react with each other. The valency of copper was reduced from +2 to 0 by the thermal decomposition of the complexes of EDTA and butyl-amine ligands in Ar gas. In the process, Cu$_2$O involving Cu and the neutral carbon atom is produced in the A thin film. During the reaction from the A thin film to the resultant AP40 thin film by post-annealing, when the oxygen content is below 2 ppm in the Ar gas, it cannot react with the film, because the quartz glass plate placed on the A thin film can prevent the film from encountering the oxygen molecule. In fact, the copper thin film, which was separately prepared by a vacuum plating method, was not oxidized by post-annealing under an identical condition. Thus, it is accepted that the reduction reaction occurred because of the materials inside the A thin film. Under these conditions, only one candidate that can act as a reductant for Cu$^{2+}$ ion remains on the carbon atoms in film A.

The polycrystalline Cu lattices were gradually structured by reducing the valency of the Cu$^{2+}$ ion with carbon atoms, and the Cu grains were simultaneously grown by annealing. This reaction mechanism involving the reduction reaction caused by carbon atoms may be comparable to the modern and indirect steel-making system using corks. The tensile strength of the AP40 adhered onto the Na-free glass substrate was 36(12) MPa as determined from the stud pull adherence tests, indicating strong adhesion to the glass substrate. The tensile strength of the Cu film deposited onto an identical Na-free glass substrate by a vacuum plating method was 1.7(5) MPa after an identical heat treatment of the AP40 thin film. Thus, the tensile strength of the AP40 thin film on the Na-free substrate was more than 20 times higher than that of the Cu thin film deposited by the vacuum plating method. The covalent bonds between the trace amounts of Cu$^{2+}$ ion present locally at the interface between the thin film AP40 and the O$^{2-}$ ions belonging to the Na-free glass molecules may assist in the formation of a robust interface between the Na-free glass substrate and the AP40 thin film. In fact, the tensile strength of the adhesion of the Cu$_2$O thin film to the substrate fabricated using the MPM was 83(2) MPa.

Figure 10 presents the transmittance and reflectance spectra of the thin films. The transmittance spectra of A, AP20, and AP40 are not significantly different in the UV-Vis region, and the transparency of AP40 is more than ~30% in the visible region. The infrared reflectance of AP40 is higher than 40% and reached 100% in the far-infrared region, whereas the reflectance of A was low, 20–30%, over this region. The MPM can facilely control the film thickness by adjusting the concentration of Cu ion in the precursor solution under identical spin-coating conditions. When the Cu thin film is 100-nm-thick, the conductivity is 1.8 × 10$^{-5}$ Ω cm, and the transparency in the visible region is below 5%. Thus, a thicker film indicates higher conductivity, but reduced transparency.

Recently, we attempted to embed copper in narrow trenches (0.2–1.0 μm wide and 5.0 μm deep) by using the MPM. A new precursor solution was prepared by dispersing the Cu nanopowder (20–40 nm) into the abovementioned Cu precursor solution. Si substrates with the trenches were immersed in this precursor solution under ultrasonic vibration for 1 min and then slowly withdrawn from the solution. The dip coating and heat treatment steps were repeated twice. The cross-sectional FE-SEM images of the treated substrate indicate that the embedded copper fills the trenches without voids.
5. Conclusion

Thermal reactions of metal complex films useful for ceramic thin film production such as \( \text{Cu}_2\text{O} \) did not attract much attention for a long time, with the exception of the CVD procedure. However, we indicated that the MPM provides facile and unique routes to obtain \( p \)-type \( \text{Cu}_2\text{O} \) and metallic Cu thin film with excellent adhesion to glass substrates, through the thermal reactions of metal complexes.

The importance of the metal complex in the MPM was presented by using the unprecedented thin film fabrication of \( p \)-type \( \text{Cu}_2\text{O} \), along with the recently elucidated reaction mechanism. In general, impurities such as nitrogen and carbon atoms interfere seriously with the functions of semiconductor devices. However, the present molecular precursor involving nitrogen and carbon atoms is necessary for fabricating an excellent \( p \)-type \( \text{Cu}_2\text{O} \) thin film using this solution-based process. Additionally, in the chemical fabrication of copper thin films with high conductivity, an organic ligand that reacts with the central Cu(II) ion is essential, and the atoms derived from the ligand, which can act as a reductant, prevent the produced copper from oxidation.

It is important that most of the originally included atoms in the MPM system are not involved in the resultant thin films if the amounts and treatment are appropriate. Therefore, the role of the ligand of the metal complex resembles that of auxiliary lines to solve geometrical problems in mathematics. In the sol-gel process, the similarity of the gel composition and the final oxides is desirable and is supposed to be an advantage of the method, though the rearrangement of the polymerized amorphous species to the crystalline requires much energy. From this point of view, the concept of the MPM is quite different from that of the conventional sol-gel method and has many potential applications.
Author details

Hiroki Nagai and Mitsunobu Sato*

*Address all correspondence to: ft10302@ns.kogakuin.ac.jp

Department of Applied Physics, School of Advanced Engineering, Kogakuin University, Tokyo, Japan

References


