

Parameter-dependent oxidation of physically sputtered Cu and the related fabrication of Cu-based semiconductor films with metallic resistivity

Jiangbin Su^{1,2*}, Jianhua Zhang², Yang Liu¹, Meiping Jiang¹ and Lei Zhou¹

ABSTRACT In this paper, we report the parameter-dependent oxidation of physically sputtered Cu and the related fabrication of Cu-based semiconductor films with metallic resistivity. It was found that various Cu-based (oxide) films such as pure Cu, Cu₂O, CuO films and Cu/Cu₂O, Cu₂O/CuO composite films could be obtained by simply adjusting the deposition parameters during physical sputtering deposition. The main oxygen source for the oxidation of Cu and the parameter-dependent oxidation mechanisms were explored. Further, the electrical and optical testing results show that the obtained pure Cu film and Cu/Cu₂O composite film both present an intriguing combination of metal and semiconductor characteristics.

Keywords: copper, oxidation, high mobility semiconductor, physical sputtering deposition, thin film

INTRODUCTION

In literature, the study of Cu film has been generally centered on the optimization of film properties under various deposition techniques [1–3] for specific applications such as interconnection of ultra-large-scale integrated circuits (ULSIC). However, it should be noted that the surface of Cu film, especially that of nanoscale size, is susceptible to oxygen and gets oxidized spontaneously not only when exposing to air but also during film growing. For the former cause, we can package the Cu interconnection-based chips to keep away from air and water as much as possible; for the latter cause, we often try to deposit Cu film in a pre-pumped high vacuum chamber with (e.g., physical sputtering) or without (e.g., thermal or electron-beam evaporation) high purity working rare gas such as Ar. In physical sputtering, the base pressure of chamber is generally up to 10⁻⁴–10⁻⁵ Pa and the working gas is often of 99.999 wt.% high purity [3,4]. However, according to our calculation results (in later sections), the residual O₂ in such high purity conditions is still sufficient for a full oxidation of the sput-

tered Cu atoms. It thus can be imaged that the sufficient oxygen source would lead to a partial or even full oxidation of the growing Cu film. Obviously, such undesirable oxidation would influence the performance, stability and lifetime of Cu film used as interconnection in ULSIC. Moreover, the parameter-dependent oxidation of Cu during physical sputtering deposition has not been investigated systemically yet. Thus, study on the parameter-dependent oxidation of physically sputtered Cu is crucial not only to mechanism understanding but also to practical avoidance of the undesirable oxidation.

On the other hand, one recent interest in material research is the fabrication of high mobility semiconductors such as graphene-like MoS₂ [5] for the application in optoelectronic devices. Among Cu-based family, Cu is a typical metal material with a low resistivity of 1.67×10⁻⁶ Ω cm, while its oxide Cu₂O is a representative p-type semiconductor material with a band gap of 2.17 eV and a high resistivity of 3×10⁶ Ω cm. Switzer *et al.* [6] found that the resistivity of layered Cu/Cu₂O film could be tuned from 3.0×10⁶ to 8.1×10⁻⁵ Ω cm. In spite of this, the optical property of the layered Cu/Cu₂O film with a metallic resistivity was not studied in Ref. [6]. Thus, it is imperative to fabricate a certain structure of Cu-based films which can exhibit both metal and semiconductor characteristics.

With the above considerations, we particularly studied the parameter-dependent oxidation of physically sputtered Cu and fabricated Cu-based semiconductor films with metallic resistivity. It was found that various Cu-based (oxide) films such as pure Cu, Cu₂O, CuO films and Cu/Cu₂O, Cu₂O/CuO composite films could be obtained by simply adjusting the deposition parameters during physical sputtering deposition. The main oxygen source for the oxidation of Cu and the parameter-dependent oxidation mechanisms were explored. Further, the electrical and op-

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tical testing results showed that the obtained pure Cu film and Cu/Cu₂O composite film both present an intriguing combination of metal and semiconductor characteristics.

EXPERIMENTAL SECTION

All Cu-based films were deposited on glass slides in a JG-P500A magnetron sputtering system. The Cu target was of 99.99 wt.% purity and well-soaked in dilute HCl solution to remove the possible oxide layers formed in air. The glass slide substrates were ultrasonically cleaned in turn by ethanol and deionized water for several times. A base pressure of 5.0×10^{-4} Pa was achieved by a turbo-molecular pump backed by a mechanical pump. Before each deposition, a pre-sputtering of 10 min was regularly performed to remove the possible oxide layers on the target surface again. Then formal physical sputtering deposition was carried out at a pressure of 0.1 Pa in a high purity Ar atmosphere (purity: 99.999 wt.%, flow: 15 sccm). To explore the parameter-dependent oxidation of Cu during film growing, we designed five typical sets of experiments by changing the deposition parameters such as work mode (direct current and radio frequency, DC & RF), sputtering power density, substrate bias voltage and substrate temperature. Since different sputtering deposition conditions are often with different deposition rates, the deposition rate and time were monitored by a quartz crystal oscillator near the substrate to make each set comparable. After the preparation, electrical and optical testing experiments were carried out in turn by using a four-point probe instrument (SDY-4) and an ultraviolet-visible (UV-vis) spectrophotometer (SHIMADZU UV-2450). Further, a scanning electron microscope (SEM, ZEISS SUPRA55) and a powder X-ray diffractometer (XRD, RIGAKU D/Max 2500 PC) were also applied subsequently for the surface morphology and texture characterizations respectively.

RESULTS AND DISCUSSION

The deposition parameters and the corresponding XRD analysis results are listed in Table 1. (i) For different work modes (Set 1), the deposit obtained by DC mode displays a pure phase of Cu while the deposit obtained by RF mode displays a mixed oxidation phase of CuO/Cu₂O. (ii) For different sputtering power densities p (Set 2), the deposit obtained at $p = 2.19 \text{ W cm}^{-2}$ exhibits a pure phase of Cu while the deposit obtained at $p = 0.88 \text{ W cm}^{-2}$ exhibits a partial oxidation phase of Cu/Cu₂O. (iii) For different work modes and sputtering power density (Set 3), the deposit gained at RF 1.76 W cm^{-2} demonstrates a single oxidation phase of Cu₂O while the deposit gained at DC 0.88 W cm^{-2} demonstrates a partial oxidation phase of Cu/

Cu₂O. (iv) For different substrate bias voltages V_s (Set 4), the deposit gotten at $V_s = 0 \text{ V}$ presents a mixed oxidation phase of CuO/Cu₂O while the deposit gotten at $V_s = -100 \text{ V}$ presents a single oxidation phase of CuO. (v) For different substrate temperatures T_s (Set 5), the deposit acquired at $T_s = 20^\circ\text{C}$ (room temperature) shows a pure phase of Cu while the deposit acquired at $T_s = 400^\circ\text{C}$ shows a partial oxidation phase of Cu/Cu₂O. For further confirmation, the same experiments were repeated several times and similar XRD results were obtained. We thus can conclude that DC sputtering mode, larger sputtering power density, smaller substrate bias voltage and lower substrate temperature are more suitable for the fabrication of pure Cu film; inversely, RF sputtering mode, smaller sputtering power density, larger substrate bias voltage and higher substrate temperature are more feasible to prepare Cu film with Cu₂O component or even totally Cu₂O and/or CuO film(s).

As experimentally demonstrated above, partial or even entire sputtered Cu atoms can be oxidized into Cu₂O or CuO during physical sputtering deposition in the pre-pumped high vacuum chamber backfilled with high purity Ar gas. Generally, there are two possible oxygen sources applied for the oxidation of Cu: (1) the O₂ and H₂O (gas) molecules adsorbed on the glass slide surface; (2) the remained O₂ and H₂O (gas) in the sputter deposition chamber. Alternatively, someone may think that the release of O₂ and H₂O (gas) adsorbed on the inner wall of chamber would also supply the O₂ and H₂O (gas). Actually, such release of O₂ and H₂O (gas) should be and is considered here as one part of the second source because the O₂ and H₂O (gas) after releasing would come into the chamber vacuum. Although this viewpoint is well-known, to our best knowledge, the quantitative contributions of the above possible oxygen sources are still not given to the oxidation of physically sputtered Cu film.

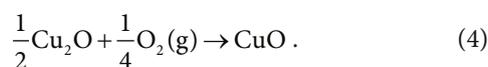
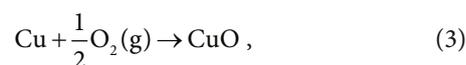
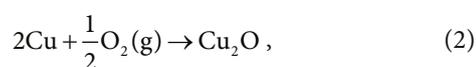
In the following, we analyze and compare the respective contents of O and Cu atoms at the above mentioned two specified locations. For the first possible source, we compare the surface densities of the adsorbed O₂ and H₂O (gas) molecules on the glass slide surface with that of the as-deposited Cu atomic layer. According to Ref. [7], we know that the surface densities of the adsorbed O₂ and H₂O (gas) molecules on glass surface are about 10^{14} and 10^{15} molecules/cm² respectively, which are similar or comparable to that of Cu film (7.7×10^{14} atoms/cm²). Nevertheless, the numbers of adsorbed O₂ and H₂O (gas) molecule layers are 4.5 and 7 (90°C) [7] respectively, which are expected to oxidize only the initially-deposited several Cu atomic layers. Accordingly, we can almost ignore the little influence of the adsorbed O₂ and H₂O (gas) molecules on the surface

of glass slide substrates. For the second possible source, the partial pressure of O atoms in the chamber (including three parts: the remained O₂ and H₂O (gas) in the pre-pumped vacuum, and the impurity O₂ in the working gas Ar) is 2.185×10^{-4} Pa. In this calculation, for the sake of simplicity, we assume that the volume fractions of O₂ and H₂O (gas) in the pre-pumped high vacuum are 21% and 1.2% (2.34 kPa saturated vapor pressure and 50% relative humidity at 20°C), which are the same as the typical composition of air. In addition, all the impurity in working gas Ar is supposed to be O₂. Due to the low pressure, we can apply the state equation of an ideal gas to obtain the concentration of O₂ in the chamber. The calculation result is 5.4×10^{10} atoms/cm³, in which, the atomic ratio of O originating from the remained O₂ and H₂O (gas) in the pre-pumped vacuum and the impurity O₂ in the working gas Ar is 84:2.4:1. It indicates that the main oxygen source is the remained O₂ in the pre-pumped high vacuum, whose oxygen concentration is about 5.2×10^{10} atoms/cm³, rather than the remained H₂O (gas) in the pre-pumped high vacuum and the impurity O₂ in the high purity working gas. It can be further verified by the fact that there is no any copper hydroxide in the XRD patterns. On the other hand, provided no or little reflection occurs for simplicity during the incident Cu flux striking the substrate, we can achieve the following equation:

$$n_{\text{Cu}} = \frac{\rho_{\text{Cu}} v_d N_A}{\nu M}, \quad (1)$$

where n_{Cu} is the concentration of incident Cu atoms near the glass substrate, ρ_{Cu} is the density of Cu film (about 8.4 g cm^{-3}) [4], v_d is the deposition rate of Cu atoms with a typical value of $0.01\text{--}0.2 \text{ nm s}^{-1}$ in this paper, N_A is the Avogadro constant, ν is the average velocity of the travelling Cu atoms before reaching the substrate, M is the atomic weight of Cu. After a detailed calculation like Ref. [8], we find that the average retained kinetic energy of a sputtered Cu atom in this work is 1.24 eV. Thus the average velocity ν of Cu atoms near the substrate is about $1.9 \times 10^3 \text{ m s}^{-1}$. According to Equation (1), the concentration of the incident Cu atoms near the substrate is about $(0.44\text{--}8.8) \times 10^9$ atoms/cm³. Since the concentration of O₂ remained in the pre-pumped chamber is much larger than that of Cu atoms near the substrate (5.2×10^{10} vs. $(0.44\text{--}8.8) \times 10^9$ atoms/cm³), the residual O₂ in the pre-pumped high vacuum chamber is fully sufficient in quantity and should be the main source for the oxidation of Cu atoms.

Based on thermodynamic data, the reactions between Cu and O₂ are as follows.



The changes in free energy at room temperature given by Equations (2-4) are -147.69 , -128.12 and $-54.27 \text{ kJ mol}^{-1}$ [9] respectively, all of which are much lower than zero. It indicates that Cu can be oxidized spontaneously at room temperature under an atmosphere containing sufficient O₂. It should be noted that, different from the oxidation of bulk Cu, the oxidation of gaseous Cu atoms during sputtering deposition would be greatly enhanced due to a much higher energy and a much more full exposure to O₂. In addition, the oxidation of Cu into Cu₂O (Equation (2)) seems the easiest to occur due to the biggest change in free energy. In spite of this, Cu and Cu₂O can also be oxidized or further oxidized into CuO due to that the changes in free energy given by Equations (3 and 4) are both much lower than zero.

Thermodynamically, as demonstrated above, the sputtered Cu atoms can react spontaneously at room temperature with the sufficient O₂ molecules retained in vacuum. Nevertheless not all the sputter deposits are Cu₂O or CuO as imaged, which are observed to be dependent kinetically on the deposition parameters (see Table 1). In the following, we discuss the influence of deposition parameters on the oxidation behavior and result of Cu atoms during physical sputtering deposition.

For different work modes, the DC mode leads to a much higher deposition rate relative to the RF mode (see Set 1 of Table 1). Similarly, as shown in Set 2 of Table 1, a larger sputtering power density can also cause a much higher deposition rate. Generally speaking, a higher deposition rate can shorten the required deposition time which will prevent Cu atoms from sufficiently exposing to O₂. This should be the main reason why the DC mode with larger sputtering power density tends to achieve pure Cu film while RF mode or smaller sputtering power density tends to form Cu film with Cu₂O component or even totally Cu₂O and/or CuO film(s). However, relative to the DC 0.88 W cm^{-2} , as shown in Set 3 of Table 1, the RF 1.76 W cm^{-2} with a higher deposition rate (0.045 vs. 0.03 nm s^{-1}) and a shorter period of deposition time (1.5 vs. 2 h) seem to obtain a more fully oxidized film (Cu₂O vs. Cu/Cu₂O) inversely. It further indicates that there may be other factors influencing the oxidation of Cu besides the deposition rate and time. We believe that the different work modes DC and RF result in such different oxidation effect. As is known to all, similar to the working gas Ar, the residual O₂ between two elec-

trodes would also be ionized into plasma (including O_2^+ , O^+ , e^- , O , O_2) during sputtering. For the DC sputtering, the O_2^+ and O^+ travel directionally to the target surface (cathode). While for the RF sputtering, the O_2^+ and O^+ travel back and forth between two electrodes which may increase the opportunity of reaction with the sputtered Cu atoms. In addition, as we experimentally observed, the color of plasma in DC and RF sputtering was greatly different (DC: green; RF: purple). It indicates that the ion density or plasma component including Ar plasma and O_2 plasma should be different. It is expected that the different component of O_2 plasma such as O_2^+ and O^+ may lead to different oxidation reactivity of Cu. For different substrate bias voltage or different substrate temperature, as shown in Sets 4 and 5 of Table 1, the work mode, deposition rate and time between two typical experiments are the same or nearly the same. However, the obtained sputter deposits are more fully oxidized under larger substrate bias voltage (CuO vs. CuO/Cu₂O) or higher substrate temperature (Cu/Cu₂O vs. Cu). This is probably due to the additional energy supplied to Cu atoms and O_2 molecules under larger substrate bias voltage or higher substrate temperature promoting the oxidation of Cu or further oxidation of Cu₂O.

We further studied the electrical resistivities and band gaps of the obtained Cu-based films. Among these, it is found that the pure Cu film and the Cu/Cu₂O composite film both display an intriguing combination of metal and semiconductor characteristics. For example, the electrical resistivities of a 31 nm-thick pure Cu film and a 72 nm-thick Cu/Cu₂O (~10 at.% Cu₂O) composite film are 1.2×10^{-4} and 6.2×10^{-5} Ω cm respectively; while the band gaps E_g , which were estimated according to the prolongation (dotted lines) of linear sections of $(Ah\nu)^2 - h\nu$ curves (solid lines) in Fig. 1, are 1.54 and 2.48 eV respectively for the 31 nm-thick pure Cu film and 72 nm-thick Cu/Cu₂O

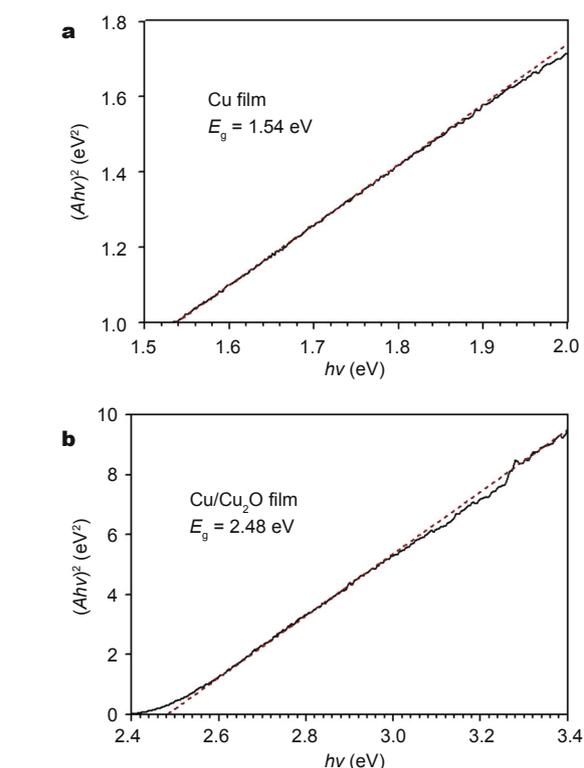


Figure 1 $(Ah\nu)^2-h\nu$ curves of the obtained Cu (a) and Cu/Cu₂O (b) films.

composite film.

Generally, the electrical resistivities of metal and semiconductor thin films are decided by the concentration and mobility of carriers, which is similar to bulk materials. However, the scattering factors of thin film which decide the carrier mobility are much more complicated. It is well known that the electrical resistivity of thin film increases with decreasing film thickness and is greater than that of bulk materials. It indicates that there are some other scat-

Table 1 Five typical sets of experiments under different deposition parameters, where p is sputtering power density, V_s is substrate bias voltage, T_s is substrate temperature, v_d , t and D are deposition rate, time and film thickness respectively. Remark: different from the RF mode in Sets 1 and 4, the RF mode in Set 3 with a stronger magnetic field (~6 vs. ~4.5 kG s) causes a higher deposition rate (0.045 vs. 0.02 nm s⁻¹) even under a lower sputtering power density (1.76 vs. 2.19 W cm⁻²)

Sets	Work modes	p (W cm ⁻²)	V_s (V)	T_s (°C)	v_d (nm s ⁻¹), t (h or s), D (nm)	Phases
1	DC	2.19	0	20	~0.2, 155 s, 31	Cu
	RF	2.19	0	20	~0.02, 1.5 h, 108	CuO, Cu ₂ O
2	DC	2.19	0	20	~0.2, 288 s, 58	Cu
	DC	0.88	0	20	~0.03, 2400 s, 72	Cu, Cu ₂ O
3	RF [*]	1.76	0	20	~0.045, 1.5 h, 243	Cu ₂ O
	DC	0.88	0	20	~0.03, 2 h, 216	Cu, Cu ₂ O
4	RF	2.19	0	20	~0.02, 1.5 h, 108	CuO, Cu ₂ O
	RF	2.19	-100	20	~0.02, 1.5 h, 108	CuO
5	DC	2.19	0	20	~0.2, 155 s, 31	Cu
	DC	2.19	0	400	~0.2, 155 s, 31	Cu, Cu ₂ O

tering mechanisms in thin film such as the well-known Fuchs-Sondheimer (FS) surface scattering [10,11] and Mayadas-Shatzkes (MS) grain-boundary scattering [12]. For the FS surface scattering, the key influence parameters are the film thickness D and the specularity factor p_s . In this paper, the film thicknesses of the Cu and Cu/Cu₂O films taken for examples are 31 nm and 72 nm respectively and the surface morphologies are shown in Fig. 2. According to the simplified FS equation [10,11],

$$\Delta\rho_s / \rho_b \approx \frac{3\lambda_b}{8D}(1-p_s), \quad (5)$$

where $\Delta\rho_s$ is the surface scattering caused-excess resistivity, ρ_b is the resistivity of bulk materials and λ_b is the mean free path of bulk materials (for Cu, $\lambda_b \approx 40$ nm). Since $p_s \geq 0$, the $\Delta\rho_s$ of the Cu and Cu/Cu₂O films cannot be larger than $0.5\rho_b$ and $0.3\rho_b$, respectively. While for the MS grain-boundary scattering, Fig. 3 shows the textures of the achieved Cu and Cu/Cu₂O films. By applying Scherrer Equation, we obtained that the average sizes of Cu grains in the Cu film and the Cu/Cu₂O film are 5 and 7 nm respectively (for simplicity, we only consider the main component Cu grains in the Cu/Cu₂O film first). According to the simplified MS equation [12]

$$\Delta\rho_g / \rho_b \approx 1.33 \frac{\lambda_b R}{d(1-R)}, \quad (6)$$

where $\Delta\rho_g$ is the grain-boundary scattering caused-excess resistivity, d is the average grain size and R (≈ 0.38 [13]) is the average reflection coefficient. We analyzed that the $\Delta\rho_g$ of the Cu and Cu/Cu₂O films are $6.5\rho_b$ and $4.7\rho_b$, respectively. In summary, the as-calculated resistivities of the pure Cu film and Cu/Cu₂O composite film should be $8\rho_b$ ($= 1.3 \times 10^{-5} \Omega \text{ cm}$) and $6\rho_b$ ($= 1.0 \times 10^{-5} \Omega \text{ cm}$) respectively. Obviously, both the calculation results are much smaller than their corresponding experimentally measured values: 1.3×10^{-5} vs. $1.2 \times 10^{-4} \Omega \text{ cm}$ for the pure Cu film; 1.0×10^{-5} vs. $6.2 \times 10^{-5} \Omega \text{ cm}$ for the Cu/Cu₂O composite film. It indicates that the conventional FS and MS scattering theories cannot fully account for the excess resistivity. It is expected that there are some other factors which cause more carrier scattering and thus increase the resistivity: (1) the loose feature of films with many nanoscale slits (see Fig. 2) that carriers cannot get across would increase the scattering and migration distance of carriers. It is expected that larger slits in the Cu/Cu₂O composite film would make more contribution to the excess resistivity than that in the pure Cu film. (2) The quantum size or nanosize effect of two-dimensional thin film and its building nanoparticles and nanoslits

would result in discrete energy levels or widen the band gap. As shown in Fig. 2, thinner film and smaller building blocks in the pure Cu film would cause more pronounced quantum size or nanosize effect and thus greatly increase the resistivity. This should be the main reason why the pure Cu film exhibits an abnormal higher resistivity relative to the Cu/Cu₂O composite film. (3) For the Cu/Cu₂O composite film, the doping of semiconductor Cu₂O in metallic Cu film could also increase the resistivity. Although the real resistivities of the Cu and Cu/Cu₂O films increase by 1 or 2 order(s) of magnitude relative to bulk Cu, they still present a typical metal or alloy resistivity characteristic.

While the band gap of semiconductor film is mainly decided by the band structure and affected by some factors such as quantum size or nanosize effect, doping and defect. For the pure Cu film, the quantum size or nanosize effect of two-dimensional metallic thin film and its building nanoparticles and nanoslits (see Fig. 2a) would result in discrete energy levels and thus it displays a semiconductor band gap characteristic. While for the Cu/Cu₂O composite film, the similar quantum size or nanosize effect (see Fig. 2b) would also result in discrete energy levels of the metallic Cu component. Meanwhile, the massive doping of p-type Cu₂O in semiconductor Cu film (i.e., Cu/Cu₂O composite film with ~ 10 at.% Cu₂O) results in the increase in the optical band gap of Cu film from 1.54 to 2.48 eV (also larger than that of pure Cu₂O of 2.17 eV) due to the well-known Burstein-Moss shift [14,15]. In addition, it is expected that the defected nanocrystalline features of the pure Cu film (5 nm-grain size) and the Cu/Cu₂O composite film (7 nm-grain size) would further influence their band gaps.

For a final confirmation, we repeated the same experiments several times and obtained the similar results for the electrical resistivity and optical band gap of pure Cu films

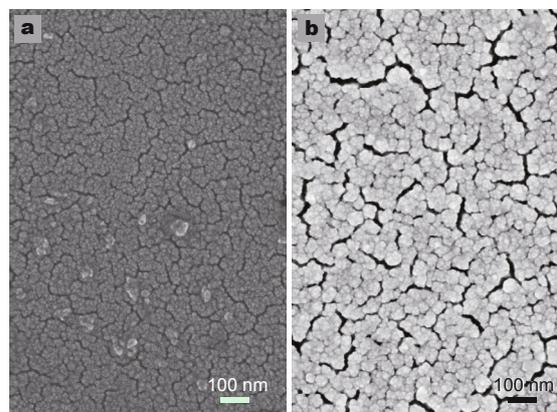


Figure 2 SEM images showing the surface morphologies of the obtained Cu (a) and Cu/Cu₂O (b) films.

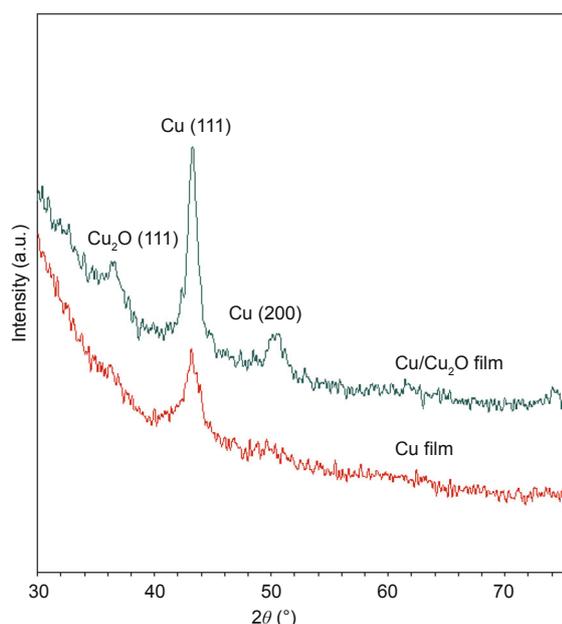


Figure 3 XRD patterns showing the textures of the obtained Cu and Cu/Cu₂O films.

and Cu/Cu₂O composite films. Although the quantitative mechanisms are still unclear, such Cu-based films with a superior conductivity and a solar-window band gap may have some fascinating applications such as in high electron mobility transistors [5], electrodes [16] and solar cells [17,18].

CONCLUSIONS

In this work, the oxidation of Cu during physical sputtering deposition was studied systematically by varying the deposition parameters including work mode, sputtering power density, substrate bias voltage and substrate temperature. Quantitative calculation results show that the main oxygen source for the oxidation of Cu is the residual O₂ in the pre-pumped high vacuum. It is demonstrated that the DC mode with a large sputtering power density such as 2.19 W cm⁻² at room temperature tends to deposit pure Cu film, while the DC mode with a small sputtering power density such as 0.88 W cm⁻² or at an elevated temperature such as 400°C tends to deposit Cu/Cu₂O composite film. It is also demonstrated that the RF mode normally with a low deposition rate is more suitable for the fabrication of Cu₂O and/or CuO film(s) rather than the pure Cu film or Cu/Cu₂O composite film. The electrical and optical testing results show that the obtained pure Cu film and Cu/Cu₂O composite film both present an intriguing combination of metal and semiconductor characteristics. For the pure Cu

film, the electrical resistivity and the optical band gap are 1.2×10⁻⁴ Ω cm and 1.54 eV respectively; while for the Cu/Cu₂O composite film, the electrical resistivity and the optical band gap are 6.2×10⁻⁵ Ω cm and 2.48 eV respectively. Based on these findings, it provides not only an effective route to avoid the possible oxidation of physically sputtered Cu atoms but also a flexible and low-cost new method to prepare Cu-based semiconductor films with metallic resistivity.

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Author contributions Su J designed the experiment and wrote the man-

uscript; Zhang J revised the manuscript and helped to analyze the results together with Jiang M; Liu Y performed the experiments with the support from Zhou L. All authors contributed to the general discussion.

Conflict of interest The authors declare that they have no conflict of interest.



Jiangbin Su is a PhD candidate at Xiamen University (since 2013) and a lecturer at Changzhou University (since 2010). His current interests are focused on the controllable fabrication of Cu-based nanostructured thin films and low dimensional nanostructures (LDNs), and the nanoinstability and nanoprocessing of LDNs under electron beam irradiation.

依赖于参数物理溅射铜的氧化以及相关金属电阻率铜基半导体薄膜的制备

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摘要 本文研究了依赖于参数物理溅射铜的氧化以及相关金属电阻率铜基半导体薄膜的制备. 研究发现, 在物理溅射过程中, 通过简单地调节沉积参数可以得到各种各样的铜基(氧化)薄膜, 如纯Cu、Cu₂O、CuO薄膜和Cu/Cu₂O、Cu₂O/CuO复合薄膜. 文中揭示了物理溅射铜氧化的主要氧来源和依赖于参数的氧化机制. 进一步地, 电学和光学测试结果表明, 所得的纯Cu薄膜和Cu/Cu₂O复合薄膜均表现出奇异的金属、半导体双特性.