Growth of 3-D flower/grass-like metal oxide nanoarchitectures based on catalyst-assisted oxidation method

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Abstract

Cu$_2$O grass-like and ZnO flower-like nanoarchitectures were fabricated directly on Cu powders and Zn powders using a novel thermal oxidation stress-induced (TOS) method based on catalyst assistance at a low temperature of 150°C under moderate humid atmosphere. The experiments of Al powder were also carried out based on TOS method. Overlapping migration (OLM) of Cu and Zn atoms and toothpaste squeezing migration (TSM) of Al atoms caused by different atom densities in metal oxide materials were studied.

Keywords: Flower/grass-like; Nanoarchitecture; Thermal oxidation; Stress gradient; Nickel catalyst

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Background

Cuprous oxide (Cu$_2$O) is a p-type semiconductor metal oxide with a direct band gap of approximately 2.17 eV [1], which has been used as a prospective candidate for low-cost solar energy conversion [2], photocatalysis [3], and sensors [4]. On the other hand, zinc oxide (ZnO) is an n-type semiconductor with a direct band gap of 3.37 eV [5]. Due to its unique optical, electrical, and magnetic properties, it has attracted a great attention and has been widely applied in solar cells and sensors [6-8]. Recently, great efforts have been devoted to fabricate different Cu$_2$O and ZnO nanoarchitectures [9-12] because architectures, including geometry, morphology, and hierarchical structures, were found to have a crucial effect on the fundamental properties of micro/nanostructure semiconductors [13-16]. However, until now, all the fabrication methods of Cu$_2$O flower-like nanoarchitectures belong to chemical solution methods, which are complex and expensive [17-19]. Moreover, ZnO flower-like nanoarchitectures were fabricated by chemical solution routes and hydrothermal method, which either need highly accurate quantitative chemical materials or need complex experimental steps [20,21].

Recently, we have proposed a novel method using thermal oxidation with participation of catalyst and humidity to fabricate the three-dimensional Cu$_2$O flower/grass-like nanoarchitectures (FGLNAs), and the morphology of the Cu$_2$O FGLNAs can be controlled by the heating temperature [22]. Although the growth mechanism has been proposed, experimental investigation is still necessary in order to further verify it. Therefore, in this study, Cu powders were used to replace the Cu foil and Cu film for the fabrication of Cu$_2$O FGLNAs based on thermal oxidation stress-induced (TOS) method. In addition, to verify the generality of the TOS method, Zn powders were also used to fabricate ZnO FGLNAs. Moreover, to investigate the growth mechanism affected by the atom density of metal oxide materials, Al powders were applied to the TOS method. Based on the experimental results, an overlapping migration (OLM) of Cu and Zn atoms and toothpaste squeezing migration (TSM) of Al atoms due to different atom densities of metal oxide materials were proposed in this study. Compared with the fabrication based on the thermal expansion stress-induced method [23,24], the heating temperature of the approach used here is only 150°C which is at least 200°C lower than that of CuO and 250°C lower than that of ZnO nanowire growth [25]. The experimental fact that metal powders can replace metal foil and film for the growth of FGLNAs
further proved that the growth mechanism is based on oxidation extension rather than thermal expansion induced stress.

**Methods**

Commercial silicon wafer with a thickness of 0.50 mm was cut into square samples which were 10 × 10 mm² in size. The substrates were then ultrasonically cleaned (Bransonic 1510, Branson Ultrasonics Corp., Danbury, CN, USA) with acetone and washed with ethanol and de-ionized water sequentially to dissolve the contaminations. Afterwards, Ni catalyst was manually daubed on the surface of samples with a cuboid shape having dimensions of 10 × 3 × 2 mm³ approximately. The nickel catalyst in this experiment was used as a high temperature resistance electrically conductive coating material (service temperature 538°C Pyro-Duct™ 598-C, Aremco, Inc., Valley Cottage, NY, USA). Cu, Zn, and Al powders were dispersed around Ni on the substrate, respectively. Cu, Zn, and Al powder samples were then heated by a ceramic heater in air atmosphere under 55% to 75% humidity at the temperature of 150°C for 2, 7, and 10 days, respectively.

After the heating process, morphologies of FGLNAs were characterized by scanning electron microscopy (SEM; JSM-7000FK, JEOL Ltd., Akishima, Tokyo, Japan), energy-dispersive X-ray (EDX), and X-ray diffraction (XRD).

**Results and discussion**

Figure 1 shows SEM images of (a) Cu₂O grass-like nanoarchitectures, (b) ZnO flower-like nanoarchitectures, and (c) Al nanowires grown on Cu, Zn, and Al powder samples at 150°C under 55% to 75% humidity for 2, 7, and 10 days, respectively. The size of Cu₂O grass-like nanoarchitectures is 10 to 15 μm, and the width of their petals is 350 to 900 nm. The size of ZnO flower-like nanoarchitectures is 9 to 17 μm, and the width of their petals is 450 to 950 nm. The length of Al nanowires is approximately 120 μm, and the mean diameter is 10 μm approximately. It has been confirmed experimentally that there was no FGLNA growth when the experimental conditions were changed to vacuum environment, without catalyst or under the humidity lower than 55% or higher than 75%, respectively. Therefore, it is thought that besides temperature, oxygen atmosphere, catalyst, and humidity were three essential conditions for the growth of FGLNAs.

Figure 2 shows the EDX results of Cu₂O grass-like nanoarchitectures. It indicates that the grass-like nanoarchitectures are mainly composed of Cu element (30.95%) and oxygen element (68.30%). We also obtained similar EDX results for the other samples. As shown in the XRD spectrum in Figure 3, orientations 111, 200, 311, etc. of Cu₂O indicate that the FGLNAs are composed of Cu₂O. As shown in the XRD spectrum, Ni was not oxidized. The reason is that oxidation temperature of Ni is above 400°C. Figure 4 shows EDX analysis of the flower-like nanoarchitectures grown on the Zn powder sample heated at 150°C for 10 days. It indicates that the architectures are mainly composed of Zn element (58.26%) and oxygen element (41.74%). As shown in the XRD spectrum in Figure 5, orientations 002, 101, 201, etc. of ZnO indicate that the FGLNAs are composed of ZnO. As shown in the XRD spectrum, Ni was not oxidized. We also obtained the EDX results of Al nanowires grown on the Al powder sample, as shown in Figure 6. The EDX result indicates that the nanowires grown on the Al powder sample are Al nanowires instead of Al₂O₃ nanowires.

The growth mechanism is similar with that described in our previous study of Cu foil/film samples [22]. An oxide layer formed on the surface of the metal powders when the samples were heated in air. Taking the Cu powder sample as an example, as shown in Figure 7, stress occurred in the oxide shell due to the oxide volume extension. Stress in the oxide shell can be determined by the Pilling-Bedworth ratio (PBR), which is defined as [26]

\[
PBR = \frac{\text{Volume of oxide}}{\text{Volume of metal}}
\]

Here, the volume of metal expresses the consumed metal volume during the formation of oxide shell in the oxidation process. When PBR >1, a compressive stress develops in the oxide shell, while a tensile stress develops in the shell with PBR <1. The larger the difference of PBR from 1, the larger the stress will be. In this

**Figure 1 SEM images.** (a) Cu₂O grass-like nanoarchitectures, (b) ZnO flower-like nanoarchitectures, and (c) Al nanowires grown on Cu, Zn, and Al powders at 150°C under 55% to 75% humidity for 2, 7, and 10 days, respectively.
experiment, due to volume extension of the Cu$_2$O and ZnO oxide shell, the PBR of Cu$_2$O and ZnO is larger than 1. Therefore, the Cu$_2$O shell suffers tangential compressive stress (TCS) from the core, as illustrated in Figure 7. The same situation happens in the ZnO shell.

Meanwhile, tangential tensile stress (TTS), caused by the reactive force of TCS in the oxide shell, occurred in the inner part of Cu powders at the interface of Cu$_2$O (shell)/Cu (core), which leads to the generation of radial stress gradient (RSG) in the thickness direction of the powders. RSG serves as a driving force for the migration of Cu atoms from the center of Cu powders to the interface between the oxide shell and Cu core. At the beginning, the relatively low temperature (150°C) causes relatively lower surface oxidation speed. The Cu$_2$O shell which formed on the Cu powder sample is very thin, and the RSG is not large enough. Therefore, the diffused Cu atoms cannot penetrate the oxidation shell. However, sufficient bivalent oxygen ions with two chemical bonds (BOICBs) were generated from the water vapors during the process of hydrogen absorption of nickel catalyst, as indicated in Equation 2.

\[ \text{H}_2\text{O} + \text{H}_2 \rightarrow \Delta \text{Ni} \text{O} \rightarrow \text{H}_2 \]

Thus, the low-temperature oxidation was enhanced, and the thickness of the Cu$_2$O shell became larger and larger. Therefore, the TCS in the Cu$_2$O shell caused by oxide volume extension will be larger than the results without participation of catalyst and humidity, thereby creating larger RSG. On the other hand, the TCS in the oxide shell also made it difficult for Cu atoms to penetrate through the oxide layer from the weak spots on the surface. Consequently, Cu atoms kept accumulating under the oxide shell until there were enough Cu atoms to break the balance, and finally, a large number of Cu

| Element | O K | Cu K |
|---------|-----|------|
| Weight% | 35.71 | 64.29 |
| Atomic% | 68.30 | 30.95 |

Figure 2 EDX spectra of architectures on Cu powders heated at 150°C under 55% to 75% humidity for 2 days.

Figure 3 XRD spectra of architectures on Cu powders heated at 150°C under 55% to 75% humidity for 2 days.
atoms suddenly penetrated the oxide shell through the weak spots in a flash. Fewer weak spots appear due to the relatively thicker oxide shell, and a relatively large penetration force is required. A large number of Cu atoms accumulate and penetrate the Cu$_2$O shell through the same weak spots. Cu atoms burst out and get more easily oxidized. Moreover, during the formation of FGLNAs, the BOICBs served as a nuclear site. In conclusion, more migrations of Cu atoms caused by larger RSG and larger TCS caused by sufficient BOICBs are two key factors for the growth of FGLNAs.

The mechanism of RSG created in metal powder samples here is different from that in Cu film on Si substrate [10,23,24] in which the gradient stress was generated due to the thermal expansion mismatch of the materials. In this study, RSG was generated due to the TCS and reaction TTS caused by oxide volume extension. However, the experiments in this study proved that oxide volume extension degree has a decisive effect on the growth type of nanostructures. That is the reason that Cu$_2$O and ZnO FGLNA growth under a relatively low temperature was realized, instead of that CuO and ZnO nanowires grow under a relatively high temperature.

To further study the growth mechanism of nanoarchitectures, we focus on the different migration mechanisms of Cu/Zn atoms and Al atoms. It is believed that the migration of Cu/Zn atoms is OLM and the migration of Al atoms is TSM [24]. For the OLM of Cu/Zn atoms, during the growth, the old atoms were covered by the new atoms, which seem to be overlapping. As shown in Figure 8a, using Cu as an example, before penetration through the oxide shell, Cu atoms were ordered by the

| Element | O K | Zn K |
|---------|-----|------|
| Weight% | 14.92 | 85.08 |
| Atomic% | 41.74 | 58.26 |

Figure 4 EDX spectra of architectures on Zn powders heated at 150°C under 55% to 75% humidity for 7 days.

Figure 5 XRD spectra of architectures on Zn powders heated at 150°C under 55% to 75% humidity for 7 days.
Figure 6 EDX spectra of architectures on Al powders heated at 150°C under 55% to 75% humidity for 10 days.

Figure 7 Illustration of grow mechanism.
colors yellow, blue, and green from top to bottom. After the penetration, the sequence of Cu atoms changes reversely. From top to bottom, the Cu atoms are green, blue, and yellow, respectively. On the contrary, the migration of the Al atom is TSM. As shown in Figure 8b, before penetration through the oxide shell, Al atoms were ordered by the colors yellow, blue, and green from top to bottom. After the penetration, the sequence of Al atoms stays the same. In other words, during the penetration, the Al atoms keep the same sequence and the first Al atom that penetrated the oxide shell will migrate to the top of the Al nanowire, which seems like toothpaste squeezing.

The reason is believed to include two aspects. The first is the different atom densities of Cu$_2$O, ZnO, and Al$_2$O$_3$.

$$\rho_{\text{Cu}_2\text{O}} = \frac{m}{V} = 6.00 \text{ g/cm}^3$$

(3)

$$\rho_{\text{Cu}_2\text{O} \text{ molecular}} = \frac{m}{V \cdot M} = 0.0416 \text{ mol/cm}^3$$

(4)

$$\rho_{\text{Cu}_2\text{O} \text{ atoms}} = \frac{n \cdot m}{V \cdot M} = 3\rho_{\text{Cu}_2\text{O} \text{ molecular}} = 0.125 \text{ mol/cm}^3$$

(5)

Figure 8 Illustration of metal atom migration mechanism. (a) Overlapping migration (OLM) of Cu atoms. (b) Toothpaste squeezing migration (TSM) of Al atoms.
Here, \( m \) is the mass of Cu\(_2\)O, \( M \) is the molar mass of Cu\(_2\)O, \( n \) is the number of atoms in a single molecule (for Cu\(_2\)O, it is 3), \( \rho_{\text{Cu}_2\text{O}} \) is the density of Cu\(_2\)O, \( \rho_{\text{Cu}_2\text{O m ol ecular}} \) is the Cu\(_2\)O molecular density, and \( \rho_{\text{Cu}_2\text{O atoms}} \) is the Cu\(_2\)O atom density. As we know, the density of the Cu\(_2\)O material is 6.00 g/cm\(^3\), as shown in Equation 3. Cu\(_2\)O molecular density can be calculated to be 0.0416 mol/cm\(^3\), as shown in Equation 4. Cu\(_2\)O atom density was calculated to be 0.125 mol/cm\(^3\), as shown in Equation 5. Using the same method, the ZnO and Al\(_2\)O\(_3\) atom densities are calculated to be 0.138 and 0.194 mol/cm\(^3\), respectively.

ZnO and Cu\(_2\)O atoms have much lower atom density than Al\(_2\)O\(_3\) atoms. Taking Cu\(_2\)O as an example, the lower atom density of the Cu\(_2\)O oxide surface layer on FGLNA leaves makes Cu atoms easily penetrate the oxide surface layer and get oxidized. Afterwards, a new oxide layer forms on the top surface layer of FGLNA leaves. As shown in Figure 8a, the yellow Cu atoms are the first Cu atoms to penetrate the oxide surface layer, and after oxidation, the Cu\(_2\)O atoms generated by the yellow Cu atoms would be laying on the bottom layer of Cu\(_2\)O FGLNAs. Due to the sparse Cu\(_2\)O FGLNA oxide surface layer, new blue Cu atoms penetrated the surface layer of FGLNA leaves and get oxidized. As shown in Figure 8a, the yellow dotted line arrow indicates the direction of blue Cu atoms migrating and penetrating the oxide surface layer of FGLNA leaves formed by yellow Cu atoms. Green Cu atoms keep this penetration and oxidation cycle. At last, the layer generated by green Cu atoms lie above the one generated by the blue Cu atoms. Due to this cycle, the leaves of Cu\(_2\)O FGLNAs grow bigger and bigger. For the Al powder case, when the Al powder sample was heated in the air, dense thin oxide layers formed on the surface of Al powders, which prevent atoms from getting further oxidation. As has been calculated above, the Al\(_2\)O\(_3\) atom density is much higher than Cu\(_2\)O and ZnO atom densities, and this dense oxide shell on the surface of the Al powder makes it difficult for the Al atoms to penetrate through it. Thus, Al atoms keep the same sequence and migrate in a straight line during migration. Therefore, Al nanowires were generated on the surface of the oxide shell. Afterwards, due to the high density of the surface oxide layer on Al nanowires, Al atoms migrate straight and cannot penetrate the surface layer of Al nanowires. Therefore, the present TOS method is unavailable to generate Al\(_2\)O\(_3\) FGLNAs due to the unique oxidation properties and higher atom density of Al\(_2\)O\(_3\).

Secondly, according to the previous study, the PBR of Al\(_2\)O\(_3\) is 1.28 which is much smaller than those of Cu\(_2\)O and ZnO [27]. Higher PBR of Cu\(_2\)O and ZnO means bigger oxide volume extension during oxidation. Therefore, higher TCS and TTS were generated, which results in higher RSG. Higher driving force of RSG leads to more Cu and Zn atoms migrating from the metal core to the interface of the oxide shell. More Cu and Zn atoms accumulate and erupt from the weak spots on the surface of metal powder to form FGLNAs.

On the other hand, the heating time for the first appearance of Cu\(_2\)O, ZnO FGLNAs, and Al nanowires was also observed for the samples of Cu, Zn, and Al powders. As shown in Figure 9, the heating time for the samples of Cu, Zn, and Al powders is 2, 7, and 10 days, respectively. Ranking of PBR from big to small is Cu\(_2\)O, ZnO, and Al\(_2\)O\(_3\), respectively. Higher PBR leads to higher RSG. Higher RSG promotes the diffusion of Cu atoms, thereby speeding up the growth of FGLNAs. In addition, it is believed that during oxidation, the BOICBs serve as a bridge to connect metal atoms. In the unit cell of Cu\(_2\)O, ZnO, and Al\(_2\)O\(_3\), BOICBs connect with two Cu atoms, four Zn atoms, and three Al atoms, respectively. Due to the two chemical bonds of BOICBs, it is believed that the combination with two Cu atoms is the easiest. Next is that with four Zn atoms, and the most difficult is that with three Al atoms. Thus, the time required for the first appearance of Cu\(_2\)O, ZnO, and Al nanoarchitectures increases orderly. Moreover, with the same length and width of Ni cuboid, the thickness of the Ni catalyst can also affect the growth time of Cu\(_2\)O FGLNAs, but not their morphology and size. Thinner thickness of the Ni catalyst would lead to longer time for the growth of FGLNAs.

**Conclusions**

Cu\(_2\)O and ZnO FGLNAs were successfully fabricated using the TOS method based on catalyst assistance under moderate humid atmosphere. Higher atom density and large oxide volume extension of Cu\(_2\)O and ZnO lead to OLM of Cu and Zn atoms, respectively. On the contrary, smaller atom density and oxide volume extension of Al\(_2\)O\(_3\) result in TSM of Al atoms. Higher PBR
promotes the diffusion of metal atoms, thereby speeding up the growth of FGLNAs. Compared with other methods to fabricate FGLNAs, the TOS method featured remarkable simplicity and cheapness.

Abbreviations
BOKCl: bivalent oxygen ions with two chemical bonds; FGLNAs: flower-like nanoarchitectures; OLM: overlapping migration; RSG: radial stress gradient; TCS: tangential compressive stress; TOS: thermal oxidation stress-induced; TSM: toothpaste squeezing migration; TTS: tangential tensile stress.

Competing interests
The authors declare that they have no competing interests.

Authors’ contributions
LJH designed and performed all the experiments, analyzed the data, and wrote the main manuscript text. YJ designed and conducted the whole study. AH helped in the XRD characterization experiments. All authors read and approved the final manuscript.

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References
1. Xiong YJ, Li ZQ, Zhang R, Xie Y, Yang J, Wu CZ: From complex chains to 1D metal oxides: a novel strategy to Cu2O nanowires. J Phys Chem B 2003, 107:3697–3702.
2. Briskman RN: A study of electrodeposited cuprous oxide photovoltaic cells. Sol Energy Mater Solar Cells 1992, 27:361.
3. Ho JY, Huang MH: Synthesis of submicrometer-sized Cu2O crystals with morphological evolution from cubic to hexapod structures and their comparative photocatalytic activity. J Phys Chem C 2009, 113:41159.
4. Pozor P, Laruelle S, Gurgeon S, Dupont L, Tarascon JM: Nano-sized transition-metal oxides as negative-electrode materials for lithium-ion batteries. Nature 2004, 427:496.
5. Wei HM, Gong HB, Wang YZ, Hu XL, Chen L, Xu HY, Liu P, Gao BQ: Three kinds of Cu2O/ZnO heterostructure solar cells fabricated with electrochemical deposition and their structure-related photovoltaic properties. CrysTallogrComm 2011, 13:605–6070.
6. Isaki M, Shiragawa T, Mizuno KT, Ida Y, Inaba M, Tasaka A: Electrochemically constructed p-Cu2O/n-ZnO heterojunction diode for photovoltaic device. J Phys D Appl Phys 2007, 40:3326–3329.
7. Fay S, Steinhauser J, Nicolay S, Balfic C: Polycrystalline ZnO: B grown by LPCVD as TCO for thin film silicon solar cells. Thin Solid Films 2010, 518:2961–2966.
8. Ozturk S, Kilinc N, Ozturk ZZ: Fabrication of ZnO nanorods for NOx sensor applications: effect of dimensions and electrode position. J Alloy Compd 2013, 581:196–201.
9. Yu Y, Du P, Ma LL, Li JL, Zhuang YQ, Qi XH: Synthesis of Cu2O nanowhiskers with CTAB as a template in water-in-oil microemulsion system. RARE METALS 2005, 24:283.
10. Luo YS, Li SQ, Ren QF, Liu JP, Xing LL, Wang Y, Yu Y, Ja ZL, Li JL: Facile synthesis of flowerlike Cu2O nanoarchitectures by a solution phase route. Cryst Growth Des 2007, 7:827–832.
11. Wu YJ, Liu YS, Hsieh CY, Lee PM, Wei YS, Chang YH, Lai KY, Liu CY: Light extraction enhancement of vertical LED by growing ZnO nano-rods on tips of pyramids. IEEE Photonics Tech L 2013, 25:1774–1777.
12. Fang B, Zhang CH, Zhang W, Wang GF: A novel hydrazine electrochemical sensor based on a carbon nanotube-wired ZnO nanoflower-modified electrode. Electrochim Acta 2009, 54:178–182.
13. Prabakar K, Son M, Kim WY, Kim H: TiO2 thin film encapsulated ZnO nanorod and nanoflower dye sensitized solar cells. Mater Chem Phys 2011, 125:12–14.
14. Yue YM, Chen MJ, Ju Y, Zhang L: Stress-induced growth of well-aligned Cu2O nanowire arrays and their photovoltaic effect. Scripta Mater 2012, 66:81–84.
15. Tan YW, Yue XY, Peng Q, Zhao H, Wang TH, Li YD: Controllable fabrication and electrical performance of single crystalline Cu2O nanowires with high aspect ratios. Nano Lett 2007, 7:5723.
16. Zhao X, Saka M: Growth of copper microflowers assisted by electromigration under a low current density and subsequent stress-induced migration. Mater Lett 2012, 79:270–272.
17. Gu YE, Su X, Du YL, Wang CM: Preparation of flower-like Cu2O nanoparticles by pulse electrodeposition and their electrocatalytic application. Appl Surf Sci 2010, 256:5862–5866.
18. Ma LL, Li JL, Sun HZ, Qiu MQ, Wang JB, Chen JY, Yu Y: Self-assembled Cu2O flowerlike architecture: poloy synthesis, photocatalytic activity and stability under simulated solar light. Mater Res Bull 2010, 45:961–968.
19. Liang ZH, Zhu YJ: Synthesis of uniformly sized Cu2O crystals with star-like and flower-like morphologies. Mater Lett 2005, 59:2423–2425.
20. Kim YJ, Yoo J, Kwon BH, Hong YJ, Lee CH, Yi GC: Position-controlled ZnO nanoflower arrays grown on glass substrates for electron emitter application. Nanotechnology 2008, 19:153022.
21. Jiang CY, Sun XM, Lu GQ, Kwong DL, Wang JX: Improved dye-sensitized solar cells with a ZnO-nanoflower photoanode. Appl Phys Lett 2007, 90:263501.
22. Hu LJ, Ju Y, Hosi A, Tang YP: The surface condition effect of Cu2O flower-like nanoarchitectures grown on Cu foil and Cu film. Nanoscale Res Lett 2013, 8:645.
23. Saka M, Yamaya F, Tohmyoh H: Rapid and mass growth of stress-induced nanowhiskers on the surfaces of evaporated polycrystalline Cu films. Scripta Mater 2007, 56:1031–1034.
24. Chen MJ, Yue YM, Ju Y: Growth of metal and metal oxide nanowires driven by the stress-induced migration. J Appl Phys 2012, 111:104305.
25. Chao LC, Tsai SY, Lin CN, Liau CC, Ye CC: Vertically aligned ZnO nanowires prepared by thermal oxidation of RF magnetron sputtered metallic zinc films. Mat Sci Semicon Proc 2013, 16:1316–1320.
26. Pilling NB, Bedworth RE: The oxidation of metals at high temperatures. J Clim Appl Meteorol 1929, 25:529–582.
27. Yuan L, Wang YQ, Mema R, Zhou GW: Driving force and growth mechanism for spontaneous oxide nanowire formation during the thermal oxidation of metals. Acta Mater 2011, 59:2491–2500.

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