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Realization of the Welding of Individual TiO$_2$ Semiconductor Nanoobjects by Using Novel 1D Au$_{80}$Sn$_{20}$ Nanosolder

Ke Qu,$^2$ Hong Zhang,$^2$ Qianqian Lan,$^2$ Xia Deng,$^2$ Xinlong Ma,$^2$ Yuanqing Huang,$^2$ Junwei Zhang,$^2$ Hongbin Ma,$^2$ Beverley J Inkson,$^3$ Desheng Xue$^a$ and Yong Peng$^{*a}$

Individual semiconductor nanowires (NWs) TiO$_2$ were successfully welded together by using novel one-dimensional (1D) Au$_{80}$Sn$_{20}$ (mass ratio) nanosolders at the nano scale for the first time. The nanosolders were electrodeposited into nanoporous templates to form 1D structure, and their morphology, crystal structure, chemistry and elemental electronic states were systematically characterized. Individual Au$_{80}$Sn$_{20}$ nanowires were proved to consist of mixed crystal phases, including Au5Sn phase with trigonal structure, AuSn phase with hexagonal structure and little SnO$_2$ phase produced by oxidation of the surface portion. Chemical analysis indicates that the composition is Au$_{80}$Sn$_{20}$. The testing of welding capability either in situ TEM or in situ SEM by nanomanipulators and Infiltration experiment reveal a good wet ability and diffusion ability between the Au$_{80}$Sn$_{20}$ nanosolder and TiO$_2$ nanowire. It is believed that our work contribute a special nanosolders for future nanoscale welding techniques, which also make the bondings of titanium-based semiconductor oxide nanomaterials at the nanoscale a reality.

1. INTRODUCTION

Welding techniques at the nano scale is crucial to the development of nanoscience and nanotechnology because the full utilization of the novel physical and chemical properties of individual nanoobjects is requested to bond them together into nano-electronics, nano-sensors and nano-devices.$^5-3$ Several nanowelding techniques, including thermal heating$^4$, ion beam deposition$^5-6$, laser heating$^7$, ultrasonic welding$^8$, electrical welding technique$^9$, high-energy electron beam irradiation$^{10}$, and Joule heating$^{11-13}$, has been invented to joint nanostructures, nanowires, nanobelts, or nanotubes together at the nanoscale so far. For example, the electrical welding technique was used to weld individual Au NWs into nanocircuits and nanopatterns.$^9$ The high-energy electron beam irradiation (EBI) welding technique was used to bond carbon nanotubes together,$^{14}$ or metallic NWs (Au, Ag, Ni) with a Si NW which forms metal-semiconductor nanojoints.$^{10}$ However, current nanowelding body materials are dominated to be metallic nanowires and carbon nanotubes. The welding of semiconductor oxide nanoobjects is surprisingly sparse.

Semiconductor oxide nanomaterials have many novel and unique electrical, optical, chemical and biological properties,$^{15}$ which lead to a great interest for their usage in the fabrication of the next generation nanocircuits, nanotools, nanowires lasers, photon tunneling devices, near-field photo-waveguide devices, etc.$^{16}$ Titanium dioxide (TiO$_2$) NWs as one member of the semiconductor oxide nanomaterial family are considered to have a wide application into photoelectric conversion and energy saving fields based on their optical, photocatalytic, photohydrophilic properties.$^{17,18}$ Bonding individual TiO$_2$ nano-objects together or with electrode pads to form secure, functional and long-lasting nanoscale systems is significant and urgent for the quick realisation of their practical applications. There are two attempts on the welding of TiO$_2$ NWs onto electrode pads.$^{19,20}$ But, individual TiO$_2$ NWs have not been welded together so far as far as we know. It is believed to be due to the high melting point and good chemical stability of TiO$_2$, which is not conductive to bond them together directly. Alike traditional welding method, using a proper solder media to bond the TiO$_2$ nanoobjects should be an effective way, which also have the opportunity to specifically tailor the weld properties of these joints such as chemistry, strength, and conductivity.

Many studies have shown that there exists good diffusion between titanium and gold.$^{21,22}$ In the previous report,$^{22}$ Ti was verified to sufficiently diffuse through 260 nm Au thin film at temperatures ranging between 200 and 400 °C, and the surficial oxidation of Ti can enhance the diffusion. Therefore, it is feasible to utilize gold-rich nanosolders with a moderate melting point to weld titanium-based semiconductor nanometarils at the nano scale. It is worthy to note that the electronic industry banned the lead to use as an elemental composition of solders on 1 July 2006 due to its high toxicity and environmental pollution. The exploitation and studies of Au-Sn solders become more important and necessary, especially, when the nanoscale welding techniques have turned into practical ways to connect nanoscale building...
blocks in the future nano industry. Au_{80}Sn_{20} alloy solder composed of 80 wt% gold and 20 wt% tin could be a good candidate, which is at the eutectic point with a relatively low melting point of 278 °C on Au-Sn binary phase diagram. As an important industrial solder, Au_{80}Sn_{20} solder is typically used in the welding of opto/microelectronic packaging areas, and semiconductor materials. In comparison with the conventional solders, Au_{80}Sn_{20} solder has many excellent properties, such as high strength, good corrosion resistance, high thermal conductivity, good electrical properties, free-flux, and so on, which make it an ideal solder. However, nanoscale Au_{80}Sn_{20} alloy and its application into individual nanoscale building blocks of semiconductor or other materials in nano space have not been reported so far.

In this work, we present a preparation of 1D Au_{80}Sn_{20} alloy nanosolders by using electrodeposition into nanoporous templates. The morphological, structural and chemical characterizations of 1D Au_{80}Sn_{20} alloy nanosolders have been systematically investigated. Furthermore, the Au_{80}Sn_{20} nanosolders have been used to weld individual TiO$_2$ NWs together. It is believed that our work not only contributes an important nanosolder for the nanowelding techniques, but also takes the first step to realize the welding of semiconductor oxide nanomaterials, which is critical and significant for the transformation of semiconductor nanomaterials into nano-electronics, nano-sensors or nano-devices.

2. EXPERIMENTAL SECTION

2.1. Preparation of 1D Au$_{80}$Sn$_{20}$ alloy nanosolders.

1D Au$_{80}$Sn$_{20}$ alloy nanosolders were prepared by DC electrodeposition into anodic aluminum oxide (AAO) templates or polycarbonate (PC, Anodisc, Whatman Inc., Florham Park, NJ, USA) templates with 50 nm diameter pores. The AAO templates were prepared in-house, of which detailed procedures were described in our previous report. One side of the non-barrier-layered AAO/PC templates was sputtered by thermally evaporating a 50 nm Ag thin film, serving as the working electrode. The electrodeposition was achieved in a three-electrode electrolytic cell at room temperature on a CHI630B electrochemical workstation, in which the reference electrode was a saturated calomel electrode (SCE) and the counter-electrode was a graphite sheet. The electrodeposition electrolyte is composed of 0.016 M HAuCl$_4$•4H$_2$O, 0.007 M SnCl$_2$•2H$_2$O, 0.125 M ammonium citrate, 0.059 M Na$_2$SO$_3$ and 0.01 M L-ascorbic acid. HauCl$_4$•4H$_2$O and SnCl$_2$•2H$_2$O are the main salts to provide Au$^{3+}$ and Sn$^{4+}$. Na$_2$SO$_3$ is a complexing agent for Au$^{3+}$. Ammonium citrate is a complexing agent for Sn$^{4+}$, and also an auxiliary complexing agent for Au$^{3+}$. L-ascorbic acid is an antioxidant. The pH value of the electrodeposition electrolyte was 5.5-6.0. Voltammetric experiments were completed to determine the optimal electrodeposition potentials for the co-electrodeposition AuSn alloy. In this work, a -1.4 V potential is applied to obtain Au$_{80}$Sn$_{20}$ eutectic alloy nanosolders, of which typical curve of the time dependence of the observed current during the growth of AuSn alloy nanowires in AAO/PC templates is shown in Fig. S1. The chemical composition of AuSn alloy nanosolders is strongly dependent on electrodeposition potential. According to XPS analysis, a -1.3 V potential obtained a Au$_{80}$Sn$_{20}$ composition. The typical deposition time for PC templates is set up to 30 mins, and for AAO templates is 120 mins, which determine the length of nanowires (Fig. S2). The electrodeposition electrolyte was continuously agitated throughout by a magnetic stirrer.

2.2. Fabrication of TiO$_2$ nanowires.

TiO$_2$ nanofibers were fabricated by using a conventional electrospinning method. In a typical synthesis, 1.2 ml tetraethyl titanate was mixed with 2.2 ml acetic acid and 1.6 ml ethanol. After 10 min, 3.6 ml ethanol and 0.4 g PVP (Aldrich, Mw ≈ 1 300 000) were added, followed by magnetic stirring for about 1 h (with the solution held in a capped bottle). The mixture was immediately loaded into a plastic syringe equipped for electrospinning. The electrospinning process was performed by a dedicated electrospinning facility at 18 kV DC voltage, 15 cm spacing between needle tip and collector, and a feed rate was fixed with 0.4 ml/h. The electrospun polymer composite fibers were collected using alumina crucibles and then calcined at 500 °C for 2 h with a heating rate of 1 °C/min in air. The sample was finally allowed to cool to room temperature.

2.3. Characterization.

The morphological, crystal structural and chemical characterisation of the 1D Au$_{80}$Sn$_{20}$ nanosolder were analyzed on a nano-scale using field emission scanning electron microscopy (FESEM, Tescan Mira 3 xmu, Czech Republic), high-resolution transmission electron microscope (HRTEM, TecnaiTM G2 F30, FEI, US) equipped with energy-dispersive X-ray analysis (EDAX, AMETEK Co., LTD), high angle annular dark field and scanning transmission electron microscopy (HAADF-STEM), X-ray photoelectron spectroscopy (XPS, Kratos Axis Ultra DLD, Japan). The AAO templates or PC templates were completely dissolved in 0.1 M sodium hydroxide solution or dichloromethane for releasing nanowires, which are then rinsed with distilled water and dispersed on holey carbon coated copper grids for TEM, STEM, EDX and analysis.

2.4. Welding of TiO$_2$ nanowires in situ TEM and in situ SEM by nanomanipulators.

The testing of welding capability of 1D Au$_{80}$Sn$_{20}$ nanosolder into TiO$_2$ semiconductor oxide nanowires at the nanoscale space were carried out in-situ the HRTEM operated at 300 kV and spot size 1. Individual TiO$_2$ nanowires and Au$_{80}$Sn$_{20}$ nanosolders were successively dispersed on holey carbon coated Cu grids to obtain cross-sectioned structures. A similar quality test was also carried out by using four nanomanipulators (Kleindiek Nanotechnik, Germany) equipped with nichrome nanotips and a Keithley 6487 picoammeter in situ SEM to weld TiO$_2$ nanopatterns at the
The crystalline structures of individual 1D Au₈₀Sn₄₀ nanosolders are characterized in detail using selected-area electron diffraction (SAED) and high-resolution TEM (HRTEM). The large magnified TEM image as shown in Fig. 1c displays that individual Au₈₀Sn₄₀ nanowires consist of many crystal grains stacking along the nanowire axis, and the surface is slightly oxidized (about 3~4 nm thickness, as marked by red double lines). Its corresponding SAED pattern is shown in Fig. 1d, revealing that the individual 1D Au₈₀Sn₄₀ nanosolders is multi-crystal. The rings can be well indexed to two sets of lattice planes. The yellow one can be well indexed to the (110), (006), (116), (300) and (223) planes of the trigonal Au₅Sn phase. The red one can be well indexed to the (102), (210), (212), (114) and (205) planes of the hexagonal Au₅Sn phase. Fig. 1e and 1f show lattice-resolution images of the Au₅Sn phase and AuSn phase marked by white squares E and F in Fig. 1c. The interplanar distances are measured to be 2.247 Å and 2.546 Å for Au₅Sn phase in Fig. 1f, matching with (201) and (102) planes of the hexagonal Au₅Sn phase. The corresponding FFT patterns and crystal structure simulation of the areas ‘E’ and ‘F’ are shown in the insets of Fig. 1e and 1f. The crystal structure was further investigated by XRD technique. Figure S3 shows a typical XRD spectrum of 1D Au₈₀Sn₄₀ nanosolders embedded into PC templates with a 100 nm Cu thin film evaporated as the working electrode, which also shows a mixture of trigonal Au₅Sn crystal phase and hexagonal Au₅Sn crystal phase. It is then concluded that the as-deposited 1D Au₈₀Sn₄₀ nanosolder is comprised of trigonal Au₅Sn phase and hexagonal Au₅Sn phase, which preserve their bulk crystal structure. 

The chemical composition of individual Au₈₀Sn₄₀ alloy nanosolder is analyzed by EDX spectrum (in Fig. 2a), of which detected area come from the region A marked by blue circle in Fig. 1a. The Au and Sn peaks come from the 1D Au₈₀Sn₄₀ alloy nanosolders. The O peak originates from the thin oxide layer covered on the surfaces of the 1D nanosolders as observed in Fig. 1c, which is deduced to their exposure in the air after released from the templates. The C and Cu peaks are believed to derive from the holey carbon coated copper grid, which was confirmed by the measurement of an EDX baseline of an empty holey carbon coated copper grid. Quantitative analysis of this spectrum reveals that the chemical composition of individual 1D Au₈₀Sn₄₀ nanosolders is a 80:1:19.9 weight ratio of Au:Sn, referring a Au₈₀Sn₄₀ chemical phase. The chemical elemental distributions of 1D Au₈₀Sn₄₀ nanosolders were further studied by EDX elemental mapping analysis techniques (Fig. 2b-d). Fig. 2b shows a representative HADDF-STEM image of two 1D Au₈₀Sn₄₀ nanosolders. Fig. 2c and 2d display the EDX elemental mappings of Au-La (9.71 keV) and Sn-La (3.44 keV), respectively. The elements of Au and Sn are evenly distributed.

Fig. 1. (a) HADDF-STEM image of 1D Au₈₀Sn₄₀ nanosolders dissolved from PC template. (b) TEM image of single 1D Au₈₀Sn₄₀ nanosolder fabricated by AAO template. (c) The large magnified TEM image of individual 1D Au₈₀Sn₄₀ nanosolders. (d) SEAD image of individual 1D Au₈₀Sn₄₀ nanosolders. Yellow for Au₅Sn phase and red for Au₅Sn phase. (e) and (f) Lattice-resolution HRTEM image of Au₅Sn phase and Au₅Sn phase form the white squares in (c). Insets, the corresponding FFT patterns and crystal structure simulation.
throughout the whole nanosolder, indicating a uniform \(\text{Au}_{80}\text{Sn}_{20}\) chemical phase.

In order to accurately determine the electronic states, the as-grown \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders were further examined by XPS while they were still in situ embedded in the PC templates. The Ar ion beam sputtering was employed to realize the analysis of layer by layer. The templates were cross-sectioned from the top surface of the PC template, which was parallel to the \(\text{Au}_{80}\text{Sn}_{20}\) nanosolder length axes. Fig. 2e shows the relevant XPS spectra of Au 4f and Sn 3d after Ar ion sputtering for 0 s, 30 s, 60 s, 100 s, 140 s, 190 s and 240 s, respectively. The binding energies were calibrated by using the C 1s peak of 285 eV as a standard. It is seen that the Au 4f 7/2 peaking at 84.0 eV bonding energy in Fig. 2e can be attributed to AuSn (binding energy is 84.20 eV) or Au$_5$Sn (binding energy is 84.14 eV), but it cannot be distinguished from XPS because its resolution is about 0.3 eV. There is no peak shift before and after Ar ion beam sputtering, indicating a stability of Au chemical phase along with nanowire length. The Sn 3d 5/2 spectra consist of two peaks located at 484.3 eV and 486.4 eV (marked by two double white lines), indicating a formation of metallic Sn and SnO$_x$ respectively. This result indicates that the top ends of the \(\text{Au}_{80}\text{Sn}_{20}\) alloy solders which are exposed to air have been partly oxidized. After sputtering 240 s, the quantitative analysis of XPS wide spectrum reveals that the \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders reach a stable 80.17:19.83 mass ratio of Au:Sn, and have not been detected any oxygen peak. Therefore, the chemical composition of the \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders in this work is inferred to be \(\text{Au}_{80}\text{Sn}_{20}\).

### 3.2. Welding individual TiO$_2$ nanowires together by using \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders in situ TEM.

Individual \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders have been used in the application of welding nanopatterns at the nanoscale to test their quality as nanosolder. Fig. 3 shows the whole process of welding two TiO$_2$ nanowires by using \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders via a high-energy electron beam irradiation nanowelding technique in situ HRTEM. The crossed structure (Fig. 3a) was achieved by successively dispersing the electrospun TiO$_2$ nanowires (see supplementary Fig. S4 for their structural and chemical characterization) and the \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders on the holey carbon coated Cu grids. After the electron beam irradiated, the \(\text{Au}_{80}\text{Sn}_{20}\) nanosolders gradually melted (Fig. 3b), diffused into TiO$_2$ nanowires (Fig. 3c) and eventually welded the two TiO$_2$ nanowires together (Fig. 3d). TiO$_2$ nanowires always remained their morphologies and structure during the whole welding process, which is due to their high melting point (the melting point of bulk TiO$_2$ is approximately 1800 °C). However, Fig. 3d only intuitively displays a connection of the two TiO$_2$ nanowires. Solid evidence is required.

EDX elemental mapping technique was employed to check the quality of nanoweld. The inset of Fig. 3e shows a HADDF-STEM image of welded area.

![Diagram of diffusion of Ti into \(\text{Au}_{80}\text{Sn}_{20}\) nanosolder by grain boundaries diffusion mechanisms.](image)
STEM image of the welded junction, where the large white spot indicates a rich accumulation of gold and uniform chemical phase. Fig. 3e to 3h show the corresponding EDX elemental mappings of Au-Lα (9.71 keV), Sn-Lα (3.44 keV), Ti-Kα (4.51 keV) and O-Kα (0.52 keV), respectively. The elements of Au and Sn are evenly distributed throughout the welded junction, indicating the even Au$_{80}$Sn$_{20}$ chemical phase preserves after the welding and consistent with the HADDF-STEM observation. The elements of Ti and oxygen are also distributed throughout the welded junction. As the Sn is easy to be oxidized, it is deduced that the oxygen element of the welded junction mainly comes from the tin oxidation during the welding process. The Ti mapping reveals that the Ti element has diffused into the nanosolder residue after the welding of electron beam irradiation. Grain boundaries diffusion mechanism$^{31,32}$ is speculated to cause the Ti diffusion into the Au$_{80}$Sn$_{20}$ nanosolder residue. As measured by above HRTEM and SEAD in Fig. 1c-1f, the individual 1D Au$_{80}$Sn$_{20}$ nanosolders is polycrystal, which is beneficial to the diffusion of Ti atoms into the grain boundaries of Au-based alloys according to the previous reports.$^{23}$

During the irradiation of electron beam, the Ti atoms diffused from the surface of TiO$_2$ nanowires into the grain boundaries of Au$_{80}$Sn$_{20}$ nanosolder. Then Ti atoms eventually left it and continued their diffusion in the lattice regions adjacent to the boundary, which thus gave rise to a volume diffusion zone around the boundary. Fig. 4 principally illustrates the schematic diagrams of the diffusion process. The continuous distribution of Ti element ranging from the welding bodies TiO$_2$ nanowires to the welded junction indicates a formation of integrally reliable bonding, showing that the welded junction should be electrically conductive and mechanically strong. This result also proves that the prepared Au$_{80}$Sn$_{20}$ nanosolder in this work should be suitable in the applications of welding other titanium-based nanomaterials.

The welding test was also performed by nanomanipulators in situ SEM. Figure 5 illustrates the whole process, which is the same as our previous reports.$^{9,26}$ Two TiO$_2$ nanowires with 110 nm diameter were mechanically manipulated and assembled into a simple nano-pattern like Chinese word “人” on a SiO$_2$ (100nm)/Si wafer (Fig. 5a), and then a sacrificial 1D Au$_{80}$Sn$_{20}$ nanosolder with 130 nm diameter and 1.3 um length used as nanosolder was placed onto the assembled “人” nanopattern at the weld point as shown in Figure 5b. Prior to welding, a moderate current (about 80% maximum current density of a single 130 nm 1D Au$_{80}$Sn$_{20}$ nanosolder) was applied to soften the Au$_{80}$Sn$_{20}$ nanosolder for 1 ∼ 2 minutes, which was for inducing the first join to the pattern (Fig. 5c). The softening of the sacrificial nanosolder is due to Joule-heating and can greatly improve the controllability and reliability of the nanowelding procedure. A linear pulse signal of 1.5 V and 300 ms width was then run through the solder to form the weld utterly. The short voltage pulse causes significant Joule heating and associated rapid material diffusion of the 1D nanosolder onto the chosen junction (Figure 5d). During the whole welding process, the 1D Au$_{80}$Sn$_{20}$ nanosolder showed a good mechanical strength, controllability, reliability and wettability with the TiO$_2$ semiconductor nanowires. The mechanical strength of the Au$_{80}$Sn$_{20}$ solder nanojoint was strong enough to enable welded structures to be directly lifted up by a SEM nanomanipulator. This result further proves that the 1D Au$_{80}$Sn$_{20}$ nanosolder is a reliable
and high performance nanosolder material for welding titanium-based materials in the nanoscale space.

3.3. Infiltration experiment.

Infiltration experiment was further carried out to verify the solderability between TiO$_2$ nanowires and Au$_{80}$Sn$_{20}$ nanosolders. Fig. 6 shows the SEM images of individual 1D Au$_{80}$Sn$_{20}$ nanosolders after sintered on TiO$_2$ substrate and SiO$_2$ substrate, revealing that the wire-shaped Au$_{80}$Sn$_{20}$ nanosolders have been melted into spherical particles (about 1 µm in diameter). The choice of SiO$_2$ substrate is only for a comparison. In order to observe the internal bonding features between the nanosolder particles and substrates, in-situ SEM nanomanipulators equipped with nichrome nanoprobes/nanotips were used to mechanically push away the formed nanosolder particles (Fig. 6a and 6d), which reveals whether there is inter-diffusion between the nanosolder and substrates. The contact angle was obtained by rotating sample stage to 90°, as shown in Fig. 6c and 6f. In the case of TiO$_2$ substrate, it is seen that the contact angle is smaller than 90°, revealing that the Au$_{80}$Sn$_{20}$ nanosolders well spread on the surface of TiO$_2$ substrate. This result proves that the Au$_{80}$Sn$_{20}$ nanosolders can infiltrate with TiO$_2$. In addition, it is also seen that the contrast of left mark is quite bright, revealing a large amount of Au$_{80}$Sn$_{20}$ nanosolder residue left. This result indicates that a solid connection between the TiO$_2$ and Au$_{80}$Sn$_{20}$ nanosolder was formed, which is consistent with above welding experiment as shown in Fig. 3 and Fig. 5.

![Image](image_url)

Fig. 6. The result of infiltration experiment for Au$_{80}$Sn$_{20}$ nanosolders with TiO$_2$ and SiO$_2$ substrates: (a) Nanoprobe approaching the sintered nanosolder on TiO$_2$ substrate. (b) The bonding trace left after the nanosolder was pushed away by the nanoprobe on TiO$_2$ substrate. (c) The lateral profile of a melted nanosolder on TiO$_2$ substrate. (d) Nanoprobe approaching the sintered nanosolder on SiO$_2$ substrate. (e) The non-bonding trace left after the nanosolder was pushed away by the nanoprobe on SiO$_2$ substrate. (f) The lateral profile of a melted nanosolder on SiO$_2$ substrate.

In comparison with the case of SiO$_2$ substrate (Fig. 6d - 6f), an opposite result is observed. After the melted Au$_{80}$Sn$_{20}$ nanosolder particle on the SiO$_2$ substrate was pushed away by the nichrome nanoprobe (Fig. 6e), the left trace is hard to be observed (the original position marked by red arrow). From Fig. 6f, it is seen that the contact angle is bigger than 90° and the Au$_{80}$Sn$_{20}$ nanosolders do not infiltrate with SiO$_2$. That is, SiO$_2$ is not solderable by the Au$_{80}$Sn$_{20}$ nanosolders. The result was also verified by the welding of SiO$_2$ nanowires using 1D Au$_{80}$Sn$_{20}$ nanosolders in TEM as shown in Fig. 5S. In addition, it is also seen in Fig. 6d and 6f that the melted Au$_{80}$Sn$_{20}$ nanosolder has an ideal spherical shape, revealing that the surfacial oxidization of individual 1D Au$_{80}$Sn$_{20}$ nanosolders as observed above (Fig. 1c) nearly does not influence their solderability and wettability. The comparative infiltration experiments further prove that the 1D Au$_{80}$Sn$_{20}$ nanosolders have a good solderability and wettability to TiO$_2$ semiconductor.

4. Conclusions

In summary, we have demonstrated a fabrication of 1D Au$_{80}$Sn$_{20}$ nanosolders and applied them into the welding of individual TiO$_2$ semiconductor nanowires at the nano scale for the first time. The analysis of crystal structures prove that the individual Au$_{80}$Sn$_{20}$ alloy nanosolders contain two eutectic phases, including Au5Sn and AuSn phases. Chemical analysis confirm that the mass ratio of Au:Sn is 80:20. The experimental results also reveal that the Ti element has diffused into the nanosolder residue during the welding of electron beam irradiation, which is further confirmed by the infiltration experiments. The good solderability and wettability between the 1D Au$_{80}$Sn$_{20}$ nanosolders and TiO$_2$ materials indicate that the Au$_{80}$Sn$_{20}$ nanosolder should be also suitable in the applications of welding other titanium-based nanomaterials. Our work is believed to contribute a special nanosolder for future nanoindustry, which can realize the bonding of tin-based semiconductor oxide nanomaterials at the nanoscale.

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Notes and references

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