Electrical properties of silver nanowires prepared by nanoskiving approach

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KEYWORDS: Nano-cutting, Nanoskiving, Nanowire, Electrical property

The excellent conductivity and light transmittance of silver nanowires make them a darling in the field of flexible transparent electrodes, which greatly promotes the development of wearable flexible electronic devices. However, the existing methods for preparing ultralong silver nanowires are limited by poor controllability or high preparation costs. As a simple and effective new nanofabrication method, nanoskiving has been proven to be used for the preparation of ultralong nanowires. Herein, silver nanowires are prepared by the nanoskiving method, and their electrical properties are tested by the two-point electrical measurement method. The morphology and integrity of the nanowires are characterized by scanning electron microscopy. Polymers around silver nanowires are removed by argon plasma. The current-voltage curve of Ag nanowires is obtained by a two-point measurement method. The resistivity of silver nanowires with a height of 80 ~ 200 nm, width of 160 nm, and 208 nm is analyzed. The resistivity of nanowires is in the range of $5\sim25\times10^{-8}$ Ω·m, which is higher than that of bulk silver (1.65×10^{-8} Ω·m). The failure current of silver nanowires increases with the increase of its height, whereas the failure current density decreases. This study guides the design and preparation of microelectronic functional devices based on silver nanowires.

1. Introduction

As a kind of nanostructure with an ultra-high aspect ratio, nanowires (NWs) have shown wide application prospects due to their excellent mechanical, electrical, and optical properties [1]. The excellent conductivity and light transmittance of Ag NWs make them a darling in the field of flexible transparent electrodes, which greatly promotes the development of wearable flexible electronic devices [2, 3].

The nanoskiving method was first proposed by Whitesides in 2006 [4]. It has many advantages such as simple operation, low equipment cost, convenient control of the size of the prepared nanowires, high slice yield, and transfer to any substrate. Nanoskiving has become an indispensable micro-nano manufacturing method [5]. However, rare reports have systematically studied the electrical behavior of NWs fabricated by nanoskiving. This restricts the integration and application of NWs in novel micro-nano electrical devices. Therefore, it is necessary to test the electrical properties of Ag NWs prepared by the nanoskiving method.

In this paper, the electrical properties of Ag NWs prepared by nanoskiving method are tested. The relationship between the resistivity and failure behavior of the NWs and the cross-sectional dimension is analyzed.

2. Method

The experimental processes of preparing Ag NWs by nanoskiving are shown in Fig. 1, which mainly includes the following steps: (1) Ag film with nanometer thickness is deposited on epoxy resin. (2) The resin blocks are cut into strips. (3) The Ag film is embedded into more resins. (4) A thin slice is cut from resin blocks using an ultramicrotome machine. (5) The NW is transferred to the silicon substrate and removed from the epoxy resin.

The two-point measurement method is used to measure the electrical properties of NWs. The construction processes of the test platform are illustrated in Fig. 2. As shown in Fig. 2(a), first, a layer of photoresist is spin-coated on the substrate. Second, micro-scale feature patterns are obtained by lithography exposure. Third, unexposed negative photoresist is developed and removed. Fourth, a layer of Au film with nanometer thickness is deposited on the substrate after photolithography. Fifth, the structured Au electrode is formed after the lift-off process. Sixth, the slice with Ag NW is transferred to the Au electrode. In Figs. 2(b) and (c), post-treatment processes such as heating or plasma etching are performed to improve the contact between the resin slice and the electrode.

The width and height of NWs are determined by high-magnification scanning electron microscope (SEM; Talos, Scios2, Thermo Scientific, USA) and atomic force microscope (AFM; Dimension Icon, Bruker, USA), respectively. The electrical tests of NWs are carried out on the probe station (PW400, Shanghai Yizhun Electronic Technology Co., Ltd., China) under the monitoring of the digital source table (Keithley 6430, Tektronix, USA).

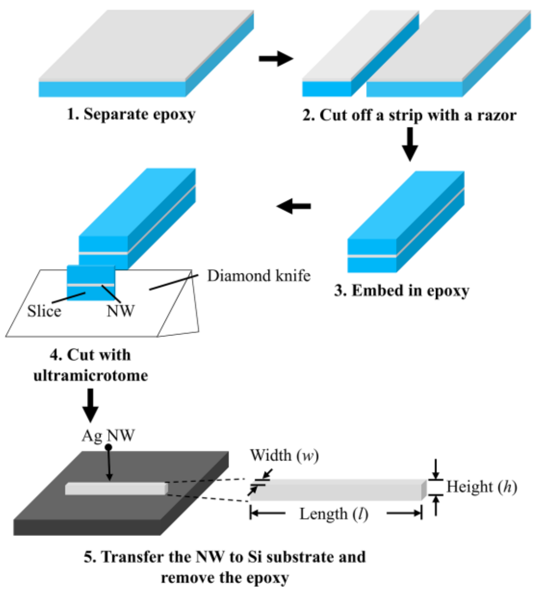

Fig. 1 Scheme diagram of nanoskiving.

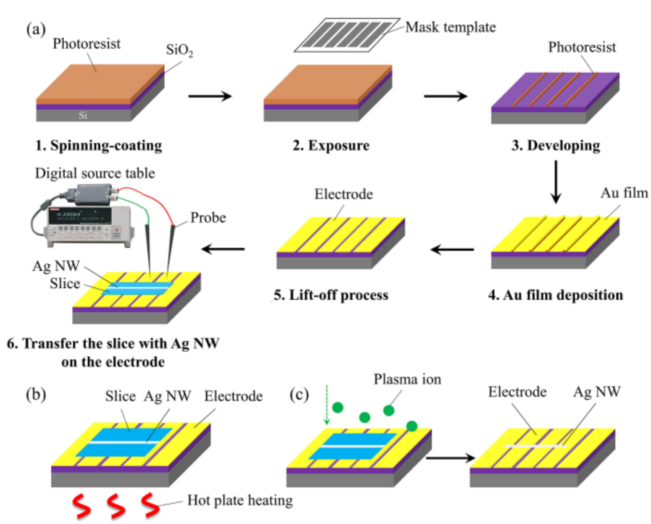

Fig. 2 (a) Experimental flow chart of NW electrical properties measurement. Post-treatment of (b) heating and (c) plasma etching treatment.

3. Results and discussion

The typical electrical test platform of Ag NW is shown in Fig. 3(a). The NWs have a width (w) of 208 nm, a height (h) of 200 nm, and an electrode spacing of 8.4 μm. The supply voltage of the digital source meter is set to -1~+1 mV, the voltage step is 0.05 mV, and the sampling time interval is 0.01 s. The current-voltage (I-V) curve of the Ag NW to be tested is shown in Fig. 3(b), and its resistance is about 43.47 Ω.

The resistivity of NWs ρ can be calculated according to the equation:

$$\rho = \frac{RS}{L} \tag{1}$$

Where R is the measured resistance of NWs, S is the theoretical cross-sectional area of NWs, and L is the span length of NWs between two adjacent Au electrodes. The calculated resistivity of the NW shown in Fig. 3 is 21.53×10^{-8} Ω·m.

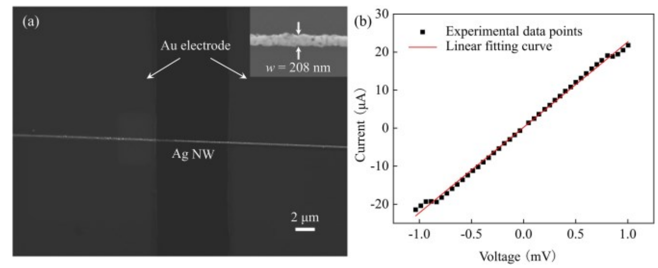

Fig. 3 (a) SEM image and (b) current-voltage curve of one NW. The inset in (a) is the locally enlarged SEM image of the Ag NW.

Fig. 4 shows the effect of NWs' height on their resistivity. The resistivity of all Ag NWs is higher than that of bulk silver, which is attributed to the size effect and quantum effect when the material is reduced to the nanometer scale. The resistivity of Ag NWs increases with the increase in height. The main reason for this phenomenon may be the effect of unreliable NW-electrode overlap.

In addition, the resistivity fluctuation of NWs at the same height and width is very large. This is mainly because the Ag NWs prepared by the nanoskiving method have a large number of microscopic defects such as randomly distributed dislocations. These defects aggravate the grain boundary scattering of electrons, the electron transport is hindered and then leads to the change in the resistivity of the NWs.

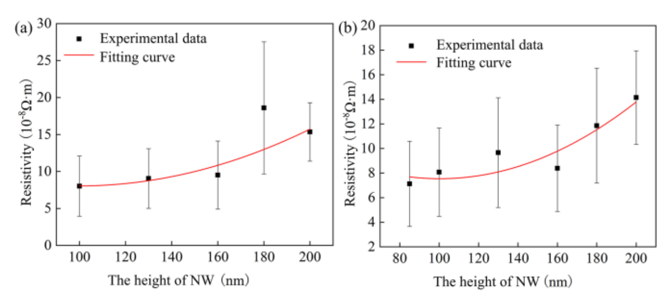

Fig. 4 The effect of NWs height on their resistivity. (a) w = 160 nm, (b) w = 208 nm.

Excessive current density aggravates the influence of harmful defects (e.g., Joule heat and electromigration) in metal NWs, and finally leads to the failure of NWs under the action of electrical stress [6].

The electronic device at both ends is prepared with Ag NWs with w = 160 nm and h = 100 nm. A voltage of 0~1 V is applied to the device, the voltage step is set to 0.025 V, and the sampling time interval is 0.01 s. The electrical failure curve of Ag NW is shown in Fig. 5(a). The SEM image of the NW after failure is shown in the inset of Fig. 5(a).

The current flowing through Ag NWs increases with the increase of voltage. Finally, when the voltage increases to 0.45 V, the NWs break and the limit current is 6.72 mA. The voltage value corresponding to the inflection point of the Ag NW failure curve is defined as the failure voltage, the corresponding current value is the failure current, and the corresponding current density value is the failure current density.

The electrical failure of Ag NW is caused by the combined action of Joule heat and electromigration. Part of the electrical energy in the pressurization process is transferred into heat energy, making the temperature of the NWs increase. When the current density in the circuit is too high, the NW is melted into nanosphere chains due to Joule heat. Electromigration comes from the momentum exchange between electrons and atoms during the flow process. When the current density in the NW is as high as 10^9~10^{10} A·m^{-2}, the Ag atom originally at the equilibrium position gradually moves to the current direction under the action of momentum exchange [1]. The migration of Ag atoms leaves vacancies at their original equilibrium position, and these vacancies combine to form larger pores. The existence of pores reduces the effective conductive area at the cross-section of NW and aggravates the scattering effect of electron boundary, thus increasing the resistance of the Ag NW, as shown in these descending segments of the failure curves in Figs. 5(a) and (b). The increase of pores exerted tensile stress on Ag NW. Tear failure in the inset of Fig. 5(a) occurs when the tensile stress exceeds the strength limit of the NW material. Fig. 5(b) is the electrical failure curve of Ag NWs at different heights. The failure voltage and failure current of Ag NWs with different heights are different.

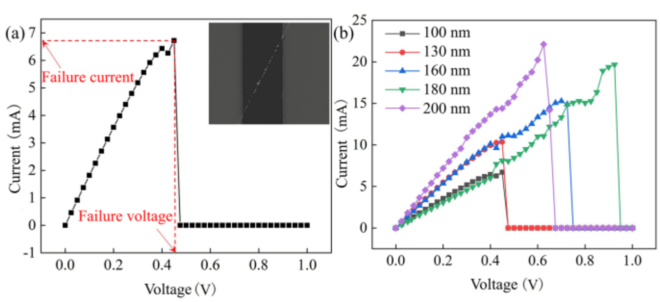

Fig. 5 Electrical failure curve of NWs. (a) Failure behavior definition diagram of the NW, (b) The failure curves of NWs at different heights.

The relationship between the failure voltage and failure current of Ag NWs and the cross-sectional dimensions of NWs is shown in Figs. 6(a) and (b). In Fig. 6(a), when the width of NWs is 160 nm, the failure voltage of Ag NWs increases with the increase of their height. When the width is 208 nm, the failure voltage of Ag NWs increases first and then decreases with the increase of NWs height, and there is an obvious inflection point when the NW height is 140 nm. In Fig. 6(b), the failure current of NWs increases with the increase of their height. The variation trend of failure voltage is different from that of failure current, which may not fully describe the failure behavior of NWs.

As shown in Fig. 6(c), the electrical failure experiments of different Ag NWs at the same dimensions are carried out. The failure voltage and current of F1 are 3.80 V and 11.97 mA, respectively. The failure voltage and current of F2 are 1.90 V and 13.18 mA, respectively. The failure voltage and current of F3 are 0.62 V and 13.79 mA, respectively. The failure voltage of NWs with large resistance is greater than that of NWs with small resistance, while the failure current is not much different. This indicates that the resistance value of the NW itself has a great influence on its failure voltage. Compared with the voltage value, the current value is a more critical factor affecting the failure of Ag NWs.

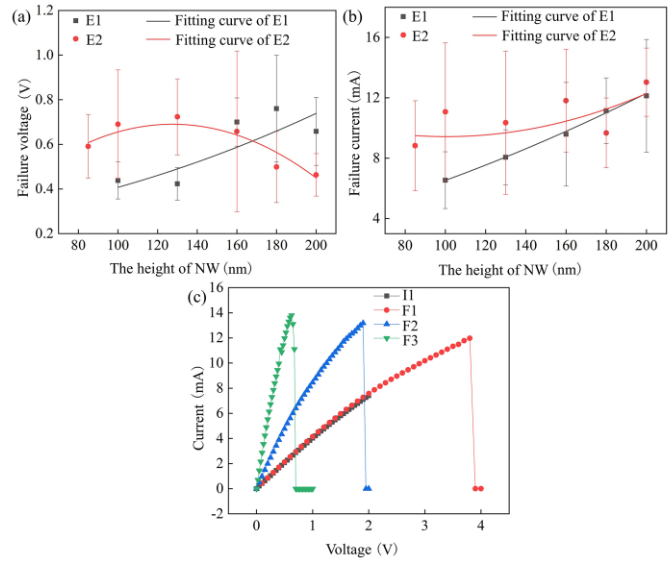

Fig. 6 Failure parameter curve of NWs. (a) failure voltage, (b) failure current, and (c) the failure curves of NWs with the same dimensions and different resistances. E1 = NWs with a width of 160 nm, E2 = NWs with a width of 208 nm, F1 = NW with w = 208 nm, h = 85nm, and R = 244.3 Ω, F2 = NW with w = 208 nm, h = 85nm, and R = 98.3 Ω, and F3= NW with w = 208 nm, h = 85nm, and R = 40.0 Ω.

The failure current density corresponding to Figs. 6(a) and (b) are shown in Fig. 7. The failure current density of Ag NWs decreases with the increase of their height at the same width, which is more obvious than that of 160 nm at the width of 208 nm. There are fewer defects such as grain boundaries and pores in small NWs, and the probability of electron grain boundary scattering and random diffusion of pore defects decreases accordingly, which eventually leads to a slight increase in the failure current density of small NWs.

The changing trend of failure current density is consistent with the results reported by Waliullah. He argued that Joule heat is the main factor in the electrical failure of Ag NWs [1].

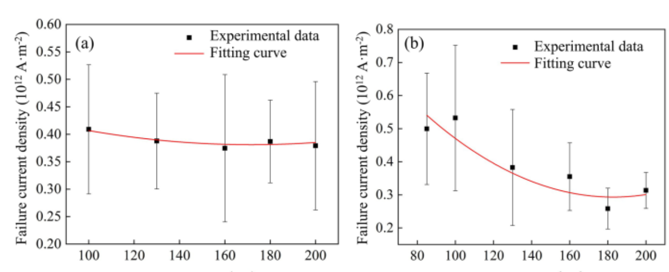

Fig. 7 The effect of NWs on the failure current density of NWs. (a) w = 160 nm and (b) w = 208 nm.

4. Conclusions

In this work, the electrical properties of Ag NWs prepared by nanoskiving method are measured. The resistivity of Ag NWs with a height of 80~200 nm, width of 160 nm, and 208 nm is analyzed. The resistivity of NWs is between 5~25×10^{-8} Ω·m, which is greater than that of bulk silver (1.65×10^{-8} Ω·m). The failure current of Ag NWs increases with the increase of their height, while the failure current density decreases gradually. The research results have guiding significance for the design and preparation of microelectronic functional devices based on Ag NWs.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial supports of the National Natural Science Foundation of China (52222512), the Natural Science Foundation of Heilongjiang Province of China (YQ2020E015), and the Fundamental Research Funds for the Central Universities (Grant No. HITBRET.2022008 and FRFCU5710050521)

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