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Full Length Article

Investigate the electrical and thermal properties of the low temperature resistant silver nanowire fabricated by two-beam laser technique

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ABSTRACT

A two-beam laser fabrication technique is introduced to fabricate the single silver nanowire (AgNW) on polyethylene terephthalate (PET) substrate. The resistivity of the AgNW is $(1.31 \pm 0.05) \times 10^{-7}\ \Omega \cdot m$, which is about 8 times of the bulk silver resistivity ($1.65 \times 10^{-8}\ \Omega \cdot m$). The AgNW electrical resistance is measured in temperature range of 10–300 K and fitted with the Bloch-Grüneisen formula. The fitting results show that the residue resistance is 153 Ω, the Debye temperature is 210 K and the electron-phonon coupling constant is $(5.72 \pm 0.24) \times 10^{-8}\ \Omega \cdot m$. Due to the surface scattering, the Debye temperature and the electron-phonon coupling constant are lower than those of bulk silver, and the residue resistance is bigger than that of bulk silver. Thermal conductivity of the single AgNW is calculated in the corresponding temperature range, which is the biggest at the temperature approaching the Debye temperature. The AgNW on PET substrate is the low temperature resistance material and is able to be operated stably at such a low temperature of 10 K.

1. Introduction

Recently, metal nanowire has attracted considerable attention due to its great potential for applications such as flexible touch screen, wearable electronics and thermal devices [1–3]. To design and optimize the metal nanowire for these applications, the electrical and thermal properties of an individual metal nanowire are critical and fundamental. The excellent electrical conductivity of the metal nanowire is desired for electronic devices. Thus, the fabrication of the metal nanowire with low electrical resistivity is a considerable issue. The exploration of electrical resistance and thermal resistivity dependence on the temperature, and the investigation of the conductive mechanism of metal nanowire are in despensible for the applications in flexible thermal electronic devices. With the development of the cryogenic science and technology, the metal nanowire is expected to be explored in micro/-nanoscale devices and systems at low temperature. Therefore, it is highly desirable to figure out an effective protocol for preparing metal nanowire and to study the electrical or thermal properties of the metal nanowire.

Many methods have been explored to fabricate the conductive metal nanowire on different flexible substrates, which prompted the application of the metal nanowire in flexible devices [4–6]. However, the experimental processes in most of studies are very complicated and the resistance is higher than the corresponding bulk metal. Thus, a simple process to fabricate metal nanowire with lower resistivity is urgently demanded for the electrical devices. Besides, the nanowires that fabricated by different methods would have different crystal structures. Consequently, the electrical and thermal conductive mechanism would be different. Some previous reports mentioned that the Debye temperature, Seebeck coefficient, Lorenz number, thermal and electrical conductivity of the silver nanowire (AgNW) are reduced compared to the bulk silver [7–9]. The temperature dependence of the resistivity of nanowire has been studied by many groups [10–12] but the universal model which is suitable to explain the electrical and thermal conductive mechanism has not been established until now. Moreover, to the best of our knowledge, the investigation of the temperature dependence on the electrical and thermal resistivity and the low temperature property of the individual metal nanowire on the flexible substrate is rarely reported.

Herein, a two-beam laser technique is used to fabricate single AgNW on the polyethylene terephthalate (PET) substrate. The

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resistance of the AgNW that fabricated by this technique is only about 8 times of the resistance of the bulk silver. The temperature dependence of the resistance of the AgNW was measured in the temperature range of 10–300 K, and fitted with the Bloch-Grüneisen formula. The AgNW residue resistance, Debye temperature, electron-phonon coupling constant have been obtained from the fitting data, respectively. The AgNW thermal conductivity is investigated and found that the maximum value of the thermal conductivity is at the temperature approaching the Debye temperature. Particularly worth mentioning is that the AgNW resistance is hardly changed while measured 100 times at the low temperature of 10 K. This study provides an effective protocol for fabricating single AgNW with excellent electrical conductivity and thermal properties on the PET substrate.

2. Experiment

The core idea of the fabrication technique is that the Ag nanoparticles are reduced from silver ion aqueous solution by the femtosecond pulse laser, and the Ag nanoparticles are aggregated to form the single AgNW on the PET substrate by the continuous wave (CW) laser [13,14]. The silver ion aqueous solution was prepared according to previous study [15]. The photoreduction of the silver ions was carried out with a mode-locked Ti–sapphire laser (Tsunami, Spectra Physics), which provided a pulse width of 120 fs, a wavelength of 780 nm as well as a repetition rate of 80 MHz. The CW laser with a wavelength of 442 nm (He-Cd laser, IK5751I-G) works as an optical tweezers and gives rise to a trapping force towards the focus [16,17]. As illustrated in Fig. 1, the pulse laser beam and the CW laser beam are overlapped together by a dichroic mirror (DM). Then the two-beam laser is focused into the sample by an oil-immersion high numerical aperture objective lens (Olympus, N.A. = 1.42, ×60). The sample is silver ion aqueous solution which was sandwiched between the glass and the PET substrate. The Ag nanoparticles were photoreduced from the silver ion aqueous solution by the pulse laser and gathered together compactly by the optical trapping force [17,18] of the CW laser (Fig. 1). The AgNW could be generated on the PET substrate while the PET substrate is moved relative to the laser focus.

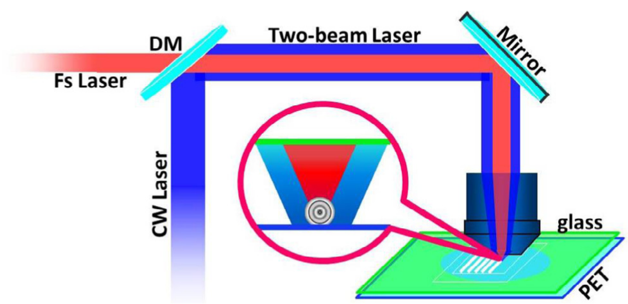

Fig. 1. Schematic diagram of the two-beam laser writing method.

3. Results and discussion

3.1. Measure the resistance of the AgNW

The electrical property of the AgNW is very important for its application in electronics, thermotics and so on. In order to investigate the electrical conductivity of the AgNW, a AgNW was fabricated on the PET substrate using two-beam laser technique. Here, the power of pulse laser and CW laser is 0.41 mW and 1.71 mW, respectively. The scanning speed of the two-beam laser focus is 3 μm/s. Two silver electrodes were deposited on both ends of the AgNW by radio frequency magnetron sputtering (Fig. 2a). The atomic force microscope (AFM) images and the corresponding cross-section of the AgNW are shown in Fig. 2b and c, respectively. The resistance of the AgNW was measured using a Keilthley 4200-SCS semiconductor system under vacuum environment condition. The measured current-voltage curve of the AgNW is shown in Fig. 2d, and the resistance of the AgNW is 180.57 Ω. The resistivity of the AgNW is calculated from the equation of $\rho = RS/L$, in which R

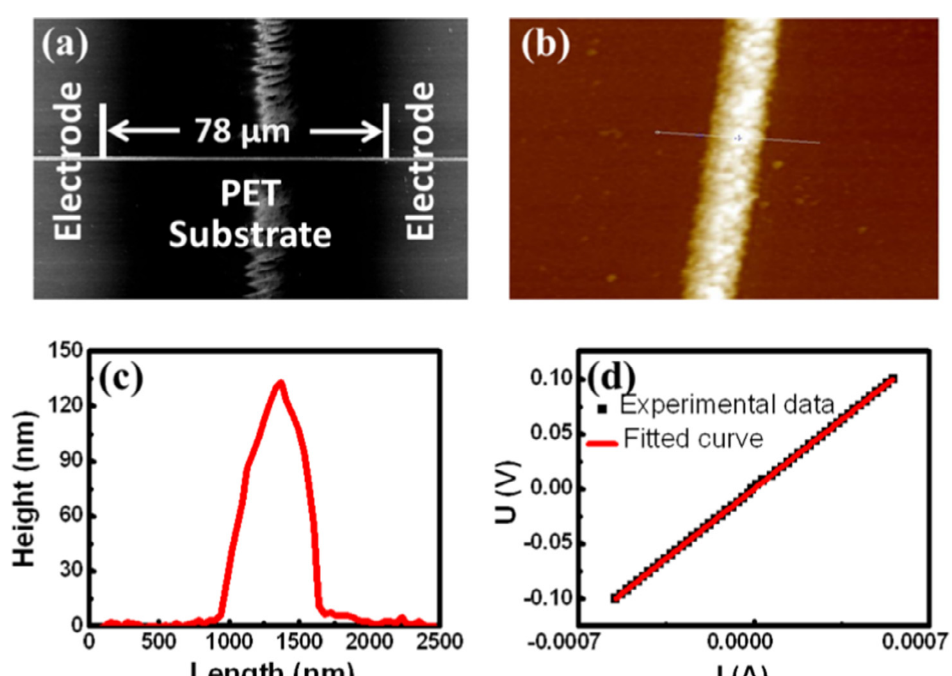

Fig. 2. Investigation of the AgNW conductivity. (a) Scanning electron microscope (SEM) image of the AgNW between two silver electrodes. (b) AFM image of the AgNW. (c) The cross-section profile of the AgNW in (b). (d) The I-V curve measured at room temperature.