Current Applied Physics 15 (2015) 642–647

Contents lists available at ScienceDirect

Current Applied Physics

journal homepage: www.elsevier.com/locate/cap

MeV carbon ion irradiation-induced changes in the electrical conductivity of silver nanowire networks

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ARTICLE INFO

Article history:
Received 22 December 2014
Received in revised form
4 February 2015
Accepted 23 February 2015
Available online 2 March 2015

Keywords:
Ag nanowires
C^+ ion irradiation
Nano-welding
Electrical conductivity

ABSTRACT

MeV carbon ion irradiation-induced changes in the electrical conductivity of Silver nanowire (Ag-NW) networks is demonstrated systematically at different C^+ ion fluences ranging from 1×10^{12} to 1×10^{16} ions/cm^2 at room temperature. At low C^+ ion fluences, the electrical conductivity of Ag-NWs decreases and subsequently increases with increase fluence. Finally, at high C^+ ion fluences, conductivity again decreases. The variation in the electrical conductivity of Ag NW network is discussed after analysis using scanning electron microscopy (SEM) and X-ray diffraction (XRD) techniques. The observed increase in electrical conductivity is thought to be due to ion induced coalescence of Ag-NWs at contact position, which causes reduction of wire–wire contact resistance, while the decrease in electrical conductivity may be due to defect production by C^+ ions into Ag-NWs. Ion beam technology is therefore a very promising technology that is capable of fabricating highly conductive Ag-NW networks for transparent electrodes. Moreover, a method for thinning, slicing and cutting of Ag-NWs using ion beam technology is also reported.

1. Introduction

Strongly conductive nanowire networks for the flow of charge carriers are vital in many novel technologies today [1]. Silver nanowires appeared to be a strong contender in the transparent electrode industry in 2008, when P. Peumans et al. [2] demonstrated Ag NWs mesh transparent electrodes, and according to the nanomarket's recent estimation, by 2019 revenue from Ag-NW electrodes will exceed $255 million. A metal nanowire provides a good percolation path for electron flow due to its intrinsic metallic nature but the nanowire–nanowire junction is found to be the main resistance point and needs a nano-welding treatment [3]. Different successful welding approaches done by different researchers include room-temperature plasma treatment [4], pulse laser processing [5], thermal sintering at sub melting temperature [2,6], cold welding [7], Joule heating [8], or incorporation of nanowires in some conducting media as conducting polymer or metal oxide nanoparticles [9–11]. Another very important tool for scalable nano-welding of junctions is ion beam irradiation that could be applied to a wide range of materials [13,14].

Structural damage to the nanostructure on exposure to high energy ion beams has been the general understanding but recent research has shown it to be also a tool for tailoring electronic [12,13], optical [14], and magnetic [15] properties and changing the structure [16] of nanomaterials in a controllable way. Different junction welding approaches done in carbon nanotubes (CNTs) using ion beams have resulted in enhanced conductivity [13–15].

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http://dx.doi.org/10.1016/j.cap.2015.02.023
1567-1739/

This study is an attempt to explore the possibility of enhancing the conductivity of Ag-NW networks by junction welding through ion beam irradiation. In this work, Ag-NW networks were formed by spray coating, being an economical method providing uniform distribution of nanowires, followed by "heavy" ion beam such as C^+ ions induced welding to enhance electrical conductivity. Heavy ion refer to a chemical element which has atomic mass greater than H, He, sometime Li element.

2. Experimental

The Silver nanowires used in this work were purchased from ACS material and had a diameter of 120 nm and were 20 μm long. They were dispersed in isopropanol with concentration 20 mg/ml which was diluted down to 0.1 mg/ml. The solution was spray coated on glass substrate placed on a hot plate at 180 °C for rapid evaporation of isopropanol. No post-heating treatment was applied. Highly transparent networks were formed on glass substrate as shown in Fig. 1(a). The prepared Ag NWs network on glass substrate was then cut into small pieces for irradiation. The prepared Ag-NWs were irradiated with a C^+ ion beam at different doses ranging from 1×10^{12} to 1×10^{16} ions/cm^2 at room temperature using a Tandem accelerator. High energy heavy C^+ ion beam was selected in such a way that heavy ions with high energy produced ion beam heating and probably produced least defects in nanostructure materials [24]. Such type of effects of heavy ions may be a useful to get perfect welded network of nanowires with least damage crystal structure as we desired. The vacuum of the target chamber was kept at 10^{-7} Pa and the ion beam energy was 5 MeV. TRIM code [17] was utilized to ensure that no ions get implanted into the nanowires. The morphology of un-irradiated and irradiated Ag-NW networks was characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). The conductivity was measured by a four-point probe. . In the four-point probe setup, the voltage potential V adjacent to a probe carrying current can be given by:

$$V = I/2\pi SG$$

where G is the surface conductivity of Ag NWs network, I is the current in the probe, and S is the distance between the voltage measurement and the current probe.

3. Results and discussion

Fig. 1(a) shows as-grown randomly arranged Ag-NWs on glass substrate indicating that the network consists of self-assembled Ag-NWs by van der Waals forces. When the Ag-NW network was subjected to a 5 MeV C^+ ion beam irradiation at low ion fluence of 1×10^{13} ions/cm^2, no ion induced coalescence at contact position was observed as shown in Fig. 1(b). At a dose of 5×10^{14} ions/cm^2, coalescence of Ag-NWs became visible due to ion beam induced local heating [18], as shown in Fig. 2. Fig. 2 shows clearly the starting of parallel and cross junction formations upon C^+ ion

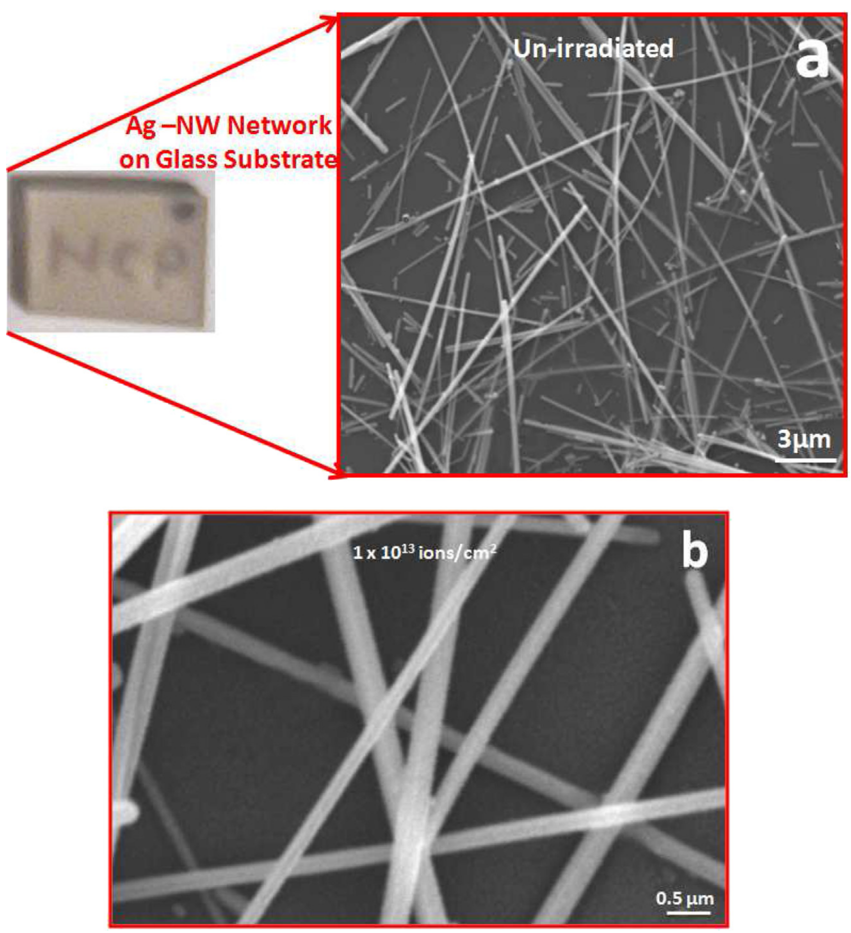

Fig. 1. SEM image of silver nanowire network on glass substrate (a) as-grown before irradiation (b) irradiation at the dose of 1×10^{13} ions/cm^2.