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Study of electronic transport in gamma ray exposed nanowires

Devender Gehlawat *, R.P. Chauhan

Department of Physics, National Institute of Technology, Kurukshetra 136119, India

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ABSTRACT

One dimensional nanostructures provide the most restricted and narrow channel for the transport of charge carriers and therefore 1D structures preserve their significance from the viewpoint of electronic devices. The net radiation effect on nanomaterials is expected to be more (due to their increased reactivity and lesser bulk volume) than their bulk counterparts. Radiation often modifies the structure and simultaneously the other physical properties of materials. In this manner, the irradiation phenomenon could be counted as a strong criterion to induce changes in the structural and electrical properties of nanowires. We have studied the effect of gamma rays on the electronic flow through Cu and Cd nanowires by plotting their *I–V* characteristics (IVC). The IVC of gamma ray exposed nanowires was found to be a combination of the linear and nonlinear regions and a decreasing pattern in the electrical conductivity (calculated from the linear portion of IVC) was observed as we increased the dose of gamma rays.

1. Introduction

The unique properties of nanomaterials have aroused greater interest of the scientific community in the field of materials science. A more practical reason of exploration of nanomaterials has been the ever-present ambitious drive of electronic industry to further reduce the size of electronic structures in integrated circuits. In the quest of ideal system, a numerous attempts have been made in previous two/three decades to investigate the nanoscale. Out of 2D, 1D and zero dimensional materials, one dimensional (1D) nanostructures maintains their domination in the realization of future integrated-circuit interconnects. The electrical conductivity is so ingredient a part of the electrical properties that cannot be neglected especially in case of metal nanowires. Metal nanowires show a decrease in the electrical conductivity with a reduction in their diameter [1] and variation of the electrical conductivity also affects their other physical properties [2]. Reduction in the electrical conductivity of metal nanowires is one of the huge obstacles to the realization of nanoscale electronic devices. To achieve a reasonable electrical conductivity at nanoscale is always a challenging task. Understanding the physics and the mechanism of conduction in nanowires have been a matter of research for years. A great deal of effort has been devoted by the scientific community to study the electrical conductivity of metal nanowires [3–10].

Nanoscale contributes many interesting physical properties in the materials science. Combining the field of nano-science with radiations may add further opportunities to the field of nano-science. A survey of Radiation Materials Science indicates that a comprehensive study (adequate to prepare an experimental database) of bulk materials was done since 1940s while the endeavour to analyse the effect of radiation on nanomaterials were proved to be too short. Among these limited trials, a greater part goes in favour of either the nanofilms or CNT's [11,12]. However, some cases of radiations evaluation on nanowires were found that covers modifications in electron transport, optical and structural properties of semiconductor nanowires [13,14] and surface modifications in metal nanowires [15]. Even the peculiar radiation effects on the electrical characteristics of nano-crystal memory cells and arrays have been found [16]. As a fact, radiation when passes through the matter deposits a part of its energy in it and this deposited energy plays central role to modify the material properties. However, different kind of radiations may have different limits of effects, but radiation could change the properties of materials that are constituents of electronic devices [17] and thus cause undesirable errors in the output of electronic devices.

In the present work, an attempt has been made to study the electronic transport through gamma-ray photons (high dose/fluence) exposed Cu nanowires as an extension of our previous (low dose/fluence) work [18]. On the account of completely dissimilar behaviour at high dose (as compared to low dose/fluence) of the gamma-ray photons, we choose another material (Cd) to cross-check the effects observed in IVC. As far as Cu is concerned, it remains the best chosen material for interconnects in terms of its availability, cost and the electrical conductivity and is

* Corresponding author. Fax: +91 1744 238050.
E-mail address: gehlawatd@yahoo.com (D. Gehlawat).

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thus one of the potential candidates for conduction through 1D nanostructures. Therefore, the radiation induced resistance in the channel of electronic signals is expected to be minimal in the case of Cu. Whereas, the study of radiation effects on the Cd have significance for its application in nuclear reactors [19]. As the cadmium absorbs low energy (thermal) neutrons readily and therefore Cd rods are used to control the nuclear fission rate. Therefore, as a replacement of its bulk counterpart, Cd nanowires may be proved more useful to be used as thermal neutron dosimeters via measurement of their electrical conductivity. The radioactive environment in nuclear reactors contains secondary gamma radiations in addition to the neutrons and fission fragments. In the present work, the point of concentration is the electronic transport. In fact, the flow of both the heat as well as the current involve free electrons of the metal and also according to the Wiedemann–Franz law, the ratio of electrical and thermal conductivity at a particular temperature is constant. Therefore, a decrease in the electrical conductivity of nanowires (as we have observed) would also reduce their thermal conductivity. Both the aspects are visible here. On one side, when it might be of interest to use one dimensional Cd structures (instead of bulk as at present) in nuclear reactors, because their large surface area would probably increase the aggregate cross-section for neutron absorption. While on the other side, observed electronic transport supports the degradation of electronic transport in photons (secondary gamma rays, if used in nuclear reactors) affected Cd nanowires. Reduction in their thermal conductivity would increase the fissionable probability of Cd nanowires. However, more constructive trials in this direction are required that may be proved useful to define the sharp limits on the use of radiation exposed materials.

2. Experimental details

A number of techniques are available for synthesis of the nanowires. However, we followed a simple and cost effective template based technique [20,21] to synthesize the Cu and Cd nanowires. We used Whatman polycarbonate track etched membranes (TEMs) of thickness 10 μm as templates. The diameter of each pore was 100 nm and the pore density in membrane is 10^6 pores/cm^2. By employing the process of electro-deposition, cylindrical pores present in the membrane were filled with the Cu and Cd atoms through reduction of Cu^{2+} and Cd^{2+} ions at the cathode of two electrode electro-chemical cell. The electrolyte used for Cd nanowires was consisted of $CdCl_2$, Na_2EDTA, NaCl and NH_4Cl [22] and was buffered at pH 8.5 using NH_4OH while for the Cu nanowires [18] it was 1 M $CuSO_4$ at a pH of 2.8 (adjusted using conc. H_2SO_4). We first optimized the parameters: potential applied between the electrodes and the time of its application from the current vs. time plot. The rapid increase in current during the electro-deposition indicates slight over deposition of Cu/Cd on the template surface after complete filling of the pores [23]. The optimized parameters that ensure the filling of pores in the membrane in case of the Cu nanowires were 0.4 V for 10 min and for the Cd nanowires were 1.2 V for 20 min.

The nanowires of Cu and Cd (embedded in the pores of membrane) were exposed to the different fluence of gamma-ray photons (Table 1) from Co-60 source at Inter University Accelerator Centre (IUAC), New Delhi, India. The *I*–*V* characteristics of pristine as well as of the gamma-ray exposed in situ nanowires were drawn using a 2-probe system via Keithley 2400 series source meter. The problem of contacts was eliminated by using the silver paste for making contacts between nanowires and the probe. The XRD spectrum in each case was also recorded. The XRD spectra provide information about the structural properties of synthesized nanowires. Surface morphology of the pristine nanowires was observed by the scanning electron microscope (SEM).

Table 1
Parameters for the gamma-ray exposure on Cu and Cd nanowires.

S. no.	Radiation	Energy (MeV)	Dose (kGy)
1	γ-Photon	1.173, 1.332	10
2	γ-Photon	1.173, 1.332	40
3	γ-Photon	1.173, 1.332	60
4	γ-Photon	1.173, 1.332	80
5	γ-Photon	1.173, 1.332	100

3. Results and discussion

The synthesized nanowires of Cu and Cd were tested for their surface morphology by SEM. For the evaluation of surface morphology, we placed the substrate containing nanowires (embedded into the pores of polycarbonate membrane) into di-chloro-methane to dissolve the template (or membrane). The process was followed by washing and cleaning of the nanowires with ethanol and de-ionized (DI) water. The SEM images reveal the cylindrical shape of the nanowires (Figs. 1 and 2). However, some of the synthesized wires were found to be broken during the washing and cleaning process.

The *I*–*V* characteristics of pristine and gamma-ray exposed nanowires were drawn using a two probe set-up and the Keithley source-meter. For the measurements of *I*–*V* characteristics (IVC), the Cu foil as substrate acted as one of the electrodes while a steel tip was used as another electrode. The *I*–*V* measurement in each case was made before the dissolution the template in di-chloro-methane because the template acts as a support for the vertically aligned nanowires otherwise it could be possible that the wires may fall into bunches (in the absence of template). It may also be possible that the wires may bend and touch each other under the pressure of steel tip placed on top of them during *I*–*V* measurement, if template was removed before measuring the IVC. It was ensured that the area falls under the tip and selected for the measurement of IVC did not have any over-deposited material (Cu/Cd). The diameter of steel tip was such that it could cover simultaneously about 300 cylindrical pores containing nanowires in the parallel. The IVC of polycarbonate membrane was also checked separately which shows almost zero conductivity as expected from its noise like shape of IVC (Fig. 3). So the *I*–*V* graphs shown in the entire manuscript are assumed to be the result of fully grown 300 parallel nanowires of diameter 100 nm each. And from here on, the electrical conductivity was further calculated for one nanowire.

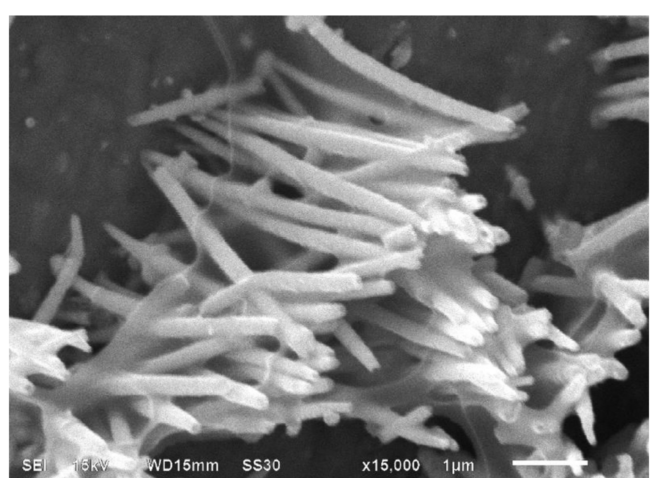

Fig. 1. SEM micrograph of the pristine Cu nanowires.