Journal of Crystal Growth 463 (2017) 54–58

Contents lists available at ScienceDirect

Journal of Crystal Growth

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

Study of magnetoconductance effect in silicon nanowires formed by chemical etching in $HF/AgNO_3$ solution: Effect of etching time

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ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form 20 January 2017
Accepted 3 February 2017
Available online 7 February 2017
Communicated by T.F. Kuech

Keywords:
Silicon nanowires
Electrical properties
Magnetic properties
Weak localization

ABSTRACT

The magneto-transport proprieties of silicon nanowires (SiNWs) for various etching time at room temperature has been studied. SiNWs were formed by metal-assisted chemical etching of crystalline silicon in $AgNO_3$-based chemical solutions. Scanning electron microscopy (SEM) shows that the SiNWs may have different structures and their lengths depending on the etching time. We found that the electrical conductance and magnetoconductance (MC) effect are extremely depended on the etching time. MC measurements at room temperature revealed a positive MC and this effect is important and it reaches up to 9% at a magnetic field of 0.5 T. The latter effect can be discussed in terms of quasi-one-dimensional (quasi-1D) weak localization (WL) theory.

1. Introduction

Silicon nanowires (SiNWs) have attracted much attention in the last decade for their electronic properties and potential applications in nanoelectronics [1,2] and optoelectronics [3,4]. Numerous methods have been used to fabricate SiNWs such as vapor liquid solid (VLS) [5], electron beam lithography (EBL) [6], focused ion beam (FIB) [7], deep reactive ion etching (DRIE) [8] and metal assisted chemical etching (MACE) of silicon [9]. Compared with the above techniques, the MACE has recently attracted tremendous interest because it is a very simple and low cost method allowing for the fabrication of high quality SiNWs with controlled dimensions and orientations [9]. The study of electrical conductance and magnetoconductance (MC) effect in SiNWs is of fundamental interest, and underlies recent developments for the improvement of magnetic recording in electronic devices. The reduction of the conductance of low dimensional and disordered systems is a result of the quantum interference effect (QIE). The contributions from QIE of these systems at room temperature have been intensively studied [10–12], and the quantum corrections to the classical conductance can be called weak localization (WL) theory [13,14]. The applied low magnetic field, leads to an increase the conductance which corresponds to a positive MC. The positive MC (negative magnetoresistance) effect has been observed in porous amorphous silicon at room temperature and this effect is attributed to the magnetic field stimulated suppression the QIE in one-dimensional (1D) system [15]. Recently, the observation of positive MC in quasi-1D silicon quantum wire at room temperature has been intensively studied and can be interpreted as a WL theory [13,16]. The MC of thin-film degenerate n-type silicon has been studied at room temperature and can be described through the use of WL theory [17]. The experimental studies on 1D SiNWs systems reveal similar characteristics. This behavior has been understood in terms of WL theory for 1D system.

In the present work, the SiNWs samples were formed by MACE method at different etching times, ranging from 10 to 60 min. As a consequence, this method should be explored to create the quasi-1D geometry of SiNWs. Here, we propose to evaluate the dependence of etching time on average SiNWs length and try to correlate it with the electrical transport properties and to see the influence of magnetic field on MC effect. The positive MC effect in SiNWs of transverse static magnetic field is observed and it is important, compared to n-type porous silicon nanostructures in our previous work [16], which is reached up to 9%. To reproduce theoretically the observed MC effect, we have used the 1D WL corrections to provide insight into the physical mechanisms of magnetic field dependent electrical transport properties and it suggests strategies for optimizing this important behavior in many applications based on SiNWs.

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http://dx.doi.org/10.1016/j.jcrysgro.2017.02.007
0022-0248/

2. Experiment details

SiNWs were fabricated by Ag assisted chemical etching method from a p-type Boron-doped Si wafer (100) with a resistivity of 0.5–3.0 Ω cm and a thickness of about 500 μm. For the cleaning steps, we immerse them in a boiling acetone for 10 min and then in ethanol for 5 min to remove organic deposits from the surface. Samples were then etched into dilute hydrofluoric acid (HF, 5%) solution for 1 min to eliminate native silicon dioxides. The electroless etching solution is a mixture of a 10 ml aqueous HF (40%) solution, 10 ml $AgNO_3$ solution (0.02 M) and 1 ml of H_2O_2 (10.00 M). Samples are etched for various durations at room temperature: 10, 20, 30, 40, 50 and 60 min. After etching, samples were rinsed with de-ionized water to remove the silver layer with the diluted HNO_3 (44%) aqueous solution for several minutes. Finally, samples were rinsed in de-ionized water during 1 min to remove the residual acids. After SiNWs fabrication, argent (Ag) layers about 2 μm thick, were deposed by serigraphic technical on the back and on the top surface of the sample, as a result we obtained this structure: Ag/Si/SiNWs/Ag. The Ag contacts on the back and on the top surface were fired at 550 °C in an infrared furnace for 10 min to ensure good diffusion of Ag in the silicon substrate. The device structure is shown in Fig. 1. The morphology of the etched Si wafers was characterized by scanning electron microscopy (SEM). The electrical characterizations of Ag/Si/SiNWs/Ag structures were measured using a Keithley 2400 Source-meter. The MC measurements at room temperature were performed by a controlled computer setup. During the MC measurements, the sample is placed in a static magnetic field H, which we varied from 0 T to 0.5 T and the direction of the magnetic field is perpendicular to the direction of the current flow. The magnetic field H is produced by two coils forming the BRUKER: MAGNET B-E 10.

3. Results and discussion

3.1. Analysis of the electrical conductance

The samples morphology was analyzed using a scanning electron microscope (SEM) in order to study the structural quality of the SiNWs. Fig. 2 shows a SEM image of SiNWs, with etching time of 10 min, 20 min, 30 min, 40 min, 50 min and 60 min. The SEM images were used to evaluate the length of SiNWs. From Fig. 2, we conclude that the length of SiNWs depends on etching time. Hence, we plot in Fig. 3 the variation of the SiNWs length (L) vs. etching time. Lengths of different samples were determined from their cross-sectional SEM images. We remark that the length varies from only 8 μm to 18 μm for 10 min to 60 min, respectively. The extended error of these measurements is estimated to 2%. In Fig. 4, we represent the current-voltage (I-V) measurements of Ag/Si/SiNWs/Ag structure which were observed for different etching times from 0 V to 3 V. The electrical conductance measurements are achieved in the dark I-V characteristics. The experimental results of the conductance (G = 1/R, where R is the resistance (V/I) at room temperature) are measured for various etching times. Fig. 5 shows the experimental electrical conductance in SiNWs at various voltages 1 V, 1.5 V, 2 V, 2.5 V and 3 V.

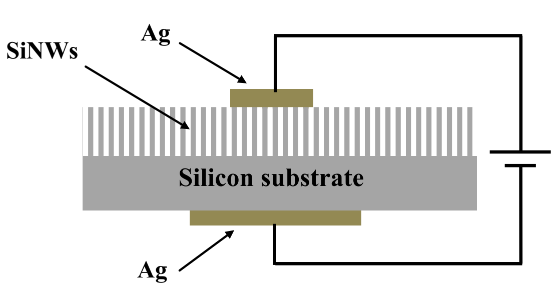

Fig. 1. Schematic representation of Ag/Si/SiNWs/Ag structure.

The dark I–V characteristics of the Ag/Si/SiNWs/Ag structure measured in this work were found nonlinear (Fig. 4). In the preparation of Ag/Si/SiNWs/Ag structure, Schottky contact was formed between metal and semiconductors (Ag/SiNWs and Ag/Si). I-V measurements are performed on a MIS (Metal–Insulator–Semicon ductor) structures formed on SiNWs films (Ag/Si/SiNWs/Ag). The electronic transport in Ag/Si/SiNWs/Ag structure may be governed by either Ag/SiNWs interface or Ag/Si interface, or both of them. From Fig. 5, we remark that the measured electrical conductance in Ag/Si/SiNWs/Ag structure decreases as a function of etching time. For this, we assumed that the total current in the devices was governed by the carrier transport in the high resistivity SiNWs layers. From Fig. 4, we note that the I-V profiles have approximately the same shape of that one performed on the MIS diode. The potential barrier between metal and semiconductors may significantly contribute to the measured of electrical conductance. However, the investigation of the electrical conductance for our samples depends on etching time. It is necessary to ensure that the current in the structure is controlled by the SiNWs. As a consequence, we assume that the electrical transport properties of the Ag/Si/SiNWs/Ag structure are governed by the contribution of SiNWs. We note from Fig. 3 that the length of SiNWs increases with increasing etching time. The total thickness of the Ag/Si/SiNWs/Ag structure was kept constant in experiments, and thus the thickness of Si substrate decreased with the length of SiNWs increasing, which can also lead to the reduction of total electrical conductance. Since we assumed that the total conductance in Ag/Si/SiNWs/Ag structure roughly equal to the conductance of SiNWs, the reduction of the conductance is assumed to be due to the increase of SiNWs length. It is a possibility that increasing the etching time will reduce the number N of SiNWs contributes to the conduction; this will reduce the conductance of SiNWs not only due to the increase of SiNWs length but also due to the variation of their number N. We think this approximation can significantly affect the analysis of experimental data. The SiNWs is considered to be a disordered electronic system. This consideration can be attributed that the Boron atoms randomly substitute silicon atoms to form an intrinsically disordered medium [17]. Another most important point regarding the reduction of the conductance of low dimensional and disordered systems, we assumed that the WL correction might be playing some part to the reduction of the conductance in SiNWs.

3.2. Transverse magnetoconductance effect

Fig. 6 shows the MC effect of SiNWs at room temperature for different etching times 20 min, 30 min, 40 min and 60 min for an applied transverse low magnetic field up to 0.5 T at 3 V. The experimental results indicate a positive MC (MC = G(H) − G(H = 0), where G(H) is the conductance (I/V) at magnetic field H) which depends heavily on the etching time. From Fig. 6, we remark that the MC effect increases with the increase of the magnetic field in the sweep direction 0 T → 0.5 T. We report in Fig. 7 the relative MC (RMC) effect (RMC (%) = (G(H) − G(H = 0))/G(H = 0)) × 100) for different etching times 20 min, 30 min, 40 min and 60 min. We observed that the RMC effect is important which attains a maximum of 8.5%, 4%, 9% and 6.5% at 0.5 T for etching times 20 min, 30 min, 40 min and 60 min respectively at 3 V.

The positive MC is often observed in semiconductor nanowires in the WL regime. However, in such cases are usually observed at low temperatures [18,19]. Recently, the positive MC has been observed in thin films at low temperatures [20–22]. On the other