Dielectrophoresis 방법으로 제작한 Si 나노선과 ZnO 나노입자 필름 기반 p-n 이종접합 다이오드

논 문
60-1-16

A p-n Heterojunction Diode Constructed with A p-Si Nanowire and An n-ZnO Nanoparticle Thin-Film by Dielectrophoresis

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Abstract - Newly-developed fabrication of a p-n heterojunction diode constructed with a p-Si nanowire (NW) and an n-ZnO nanoparticle (NP) thin-film by the dielectrophoresis (DEP) technique is demonstrated in this study. With the bias of 20 Vp-p at the input frequency of 1 MHz, the most efficient assembly of the n-ZnO NPs is shown for the fabrication of the p-n heterojunction diode with a p-Si NW. The p-n heterojunction diode fabricated in this study represents current rectifying characteristics with the turn on voltage of 1.1 V. The diode can be applied to the fabrication of optoelectrical devices such as photodetectors, light-emitting diodes (LEDs), or solar cells based on the high conductivity of the NW and the high surface to volume ratio of the NP thin film.

Key Words : P-n heterojunction, Si, ZnO, Nanowire, Nanoparticle, Dielectrophoresis

1. Introduction

The recent trend to manufacture the optoelectronic devices using hybrid materials has been promoted due to the merits of the combination of hetero-dimensional materials [1-2]. Specially, the combination of 1-dimensional nanowires (NWs) and 0-dimensional nanoparticles (NPs) enhances the optoelectrical characteristics of the devices owing to the high conductivity of NWs and the high surface to volume ratio of NPs [3].

One interesting combination is the combination of a p-Si nanowire (NW) and an n-ZnO nanoparticle (NP) thin-film which has not been reported yet. One of the motivations for our study on this combination is the promising optoelectronic properties of the n-ZnO NP thin-film, such as direct wide band-gap (3.24 eV), large exciton binding energy (60 meV), and efficient radiative recombination [4].

For the fabrication of the p-n heterojunction diodes constructed with n-type and p-type nanomaterials, the technique for orderly arrays of the materials is necessary. Dielectrophoresis (DEP) is the force on the polarizable particles in the medium under the AC electric field and is the easy and cost-efficient approach for assembly of nanomaterials [5].

In this paper, newly-developed fabrication process of a p-n heterojunction diode constructed with a p-Si NW and an n-ZnO NP thin-film is demonstrated and its electrical characteristics are investigated. The n-ZnO NPs are assembled by the DEP technique to form the hybrid p-n diode with a p-Si NW.

2. Experimental procedures

2.1 Size distribution of the n-ZnO NPs

N-ZnO NPs with an average diameter of about 90 nm methanol solution. For the assembly of the n-ZnO NPs

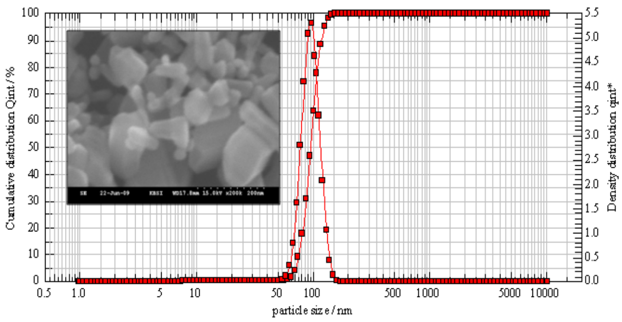

Fig. 1 DLS analysis of the n-ZnO NPs. The inset shows the SEM image of the NPs

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(purchased from Sigma-Aldrich Inc.) were dispersed in by the DEP method, the density of the n-ZnO NP solution was controlled by adding the more amount of the ZnO NPs into 100 ml of methanol. As a result, 0.01 g of the ZnO NPs was the ideal quantity for the DEP assembly.

The dynamic light scattering (DLS) study of the n-ZnO NPs for the analysis of the distribution range of the NPs in methanol solution represented in Fig. 1. DLS analysis is suited to obtain the information on the distribution of particles whose diameters are smaller than 1 μm. The average size of the n-ZnO NPs obtained from the qint(volume/%) plot is about 90 nm and the size distribution is in the range of 60 nm-130 nm. It is known that the DLS technique averages out the dimensions in the form of an equivalent sphere [6]. The inset shows the SEM image of the n-ZnO NPs used in this study, which shows the size of the NPs.

2.2 Formation of p-Si NWs

Inverted-triangular-shaped p-Si NWs were formed from a 6 inch (100)-oriented Si wafer with a boron dopant concentration of ~10^{18} cm^{-3} by etching process. The active regions were patterned on the Si wafer by photolithography (Fig. 2(a)), and the trenches were then formed by inductively coupled plasma (ICP) (Fig. 2(b)). Subsequently, the trenches were underwent with crystallographic wet etching process in order to shape inverted-triangular-shaped p-Si NWs (Fig. 2(c)). The formation of the inverted p-Si NWs was attributed to the differential etching ratio of the (111) to (110)-oriented surfaces of the Si wafer. The SEM image of an inverted-triangular- shaped p-Si NW is shown in Fig. 2(d).

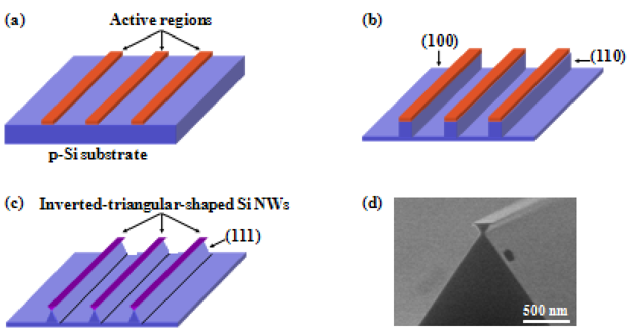

Fig. 2 Formation of p-Si NWs. (a) Deposition of active regions by photolithography, (b) formation of trenches by ICP, (c) formation of inverted-triangular- shaped p-Si NWs. and (d) SEM image of an inverted-triangular-shaped p-Si NW

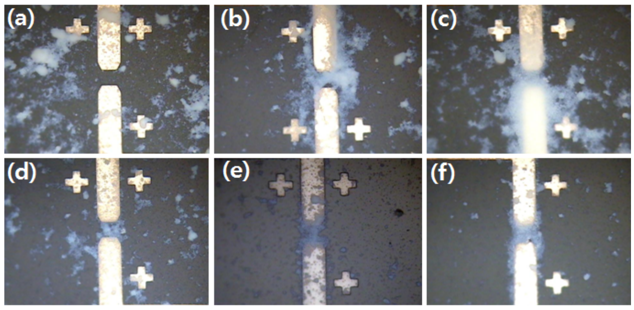

Fig. 3 The assembly of the n-ZnO NPs by the DEP technique between the electrodes at frequencies of (a) 10 Hz, (b) 100 Hz, (c) 1 kHz, (d) 10 kHz, (e) 100 khz, and (f) 1 MHz

3. Results and discussions

3.1 Assembly of the n-ZnO NPs by the DEP technique

The DEP force on a polarizable particles in an AC electric field can be expressed by [7-9]

$$F_{DEP} = 4\pi v \epsilon_m K(\omega) \nabla E_{RMS}^2 \quad (1)$$

where ϵ_m is the permittivity of the suspending medium, v is the volume of the particles, E_{RMS} is the RMS value of the electric field, and $K(\omega)$ is the Clausius-Mosotti factor which is expressed by

$$K(\omega) = Re\left[\frac{\epsilon_n^* - \epsilon_m^*}{\epsilon_m^*}\right] \quad (2)$$

where ϵ_n^* and ϵ_m^* indicate the complex permittivities of the NPs and medium, respectively. Note that these complex permittivities are decided by the input frequency.

Figure 3 shows the frequency dependance of the DEP assembly of the ZnO NPs. The assembly of the n-ZnO NPs are performed at frequencies of 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz under the bias of 20 V_{p-p} (Figs. 3(a)-(f)). Consequently, the most effective assembly of the ZnO NPs is carried out at 1 MHz as shown in Fig. 3(f).

3.2 Fabrication procedure of a p-n heterojunction diode

The entire fabrication process of a p-n heterojunction diode composed of a p-Si NW and an n-ZnO NP thin-film by the DEP technique is depicted in Fig. 4. The p-Si NWs formed by the ething processes were transferred onto a plastic substrate by imprinting method (Fig. 4(a)), and the Ni/Au electrodes were deposited at the ends of a p-Si NW chosen from the transferred Si

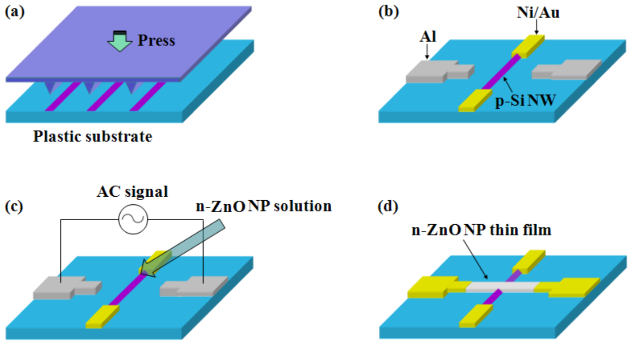

Fig. 4 Fabrication process of a p-n heterojunction diode constructed with a p-Si NW and n-ZnO NP thin-film by the DEP technique. (a) Transfer of the p-Si NWs, (b) deposition of the electrodes, (c) formation of the ZnO NP thin film by the DEP method, and (d) formation of a p-n heterojunction diode

NWs. Then, Al electrodes with the 20 μm distance were deposited at the positions for the assembly of the n-ZnO NPs (Fig. 4(b)). With the voltage of 20 V_{p-p} at the frequency of 1 MHz, the n-ZnO NP-dispersed solution was dropped into the gap of Al electrodes (Fig. 4(c)), and the p-n heterojunction diode composed of a p-Si NW and an n-ZnO NP thin-film was constructed (Fig. 4(d)). The p-n heterojunction diode was then annealed at 150 °C for 10 minutes for better formation of the ZnO NP thin-film and for better contact between the NW and the NP thin-film [10].

3.3 Electrical characteristics of the p-n heterojunction diode

The current-rectifying characteristics of the p-n heterojunction diode is shown in Fig. 5, which exhibits the diode characteristics with the turn-on voltage of 1.1 V and the ohmic contact properties of the p-Si NW and the n-ZnO NP thin-film with the electrodes.

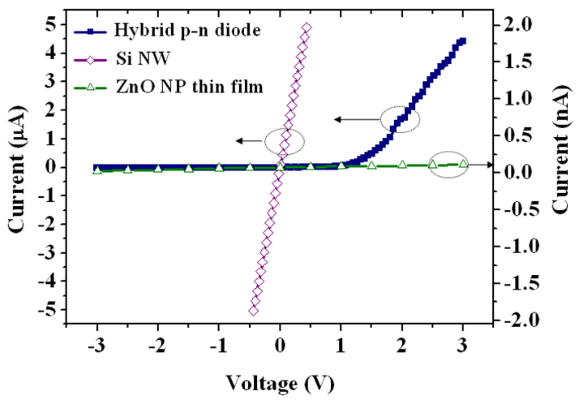

Fig. 5 Electrical characteristics of the p-n heterojunction diode composed of a p-Si NW and an n-ZnO NP thin-film

4. Conclusions

In conclusion, unconventional fabrication process of the p-n heterojunction diode constructed with a p-Si NW and an n-ZnO NP thin-film by the DEP technique is demonstrated and its electrical characteristics are investigated. The p-n heterojunction diode exhibits current rectifying characteristics with the turn-on voltage of 1.1 V. This device can be applied to the fabrication of the optoelectrical devices such as photodetectors, light-emitting diodes (LEDs), or solar cells based on the high conductivity of the NW and the high surface to volume ratio of the NW thin film.

Acknowledgments

This work was partly supported by the IT R&D program of MKE/KEIT[10030559, Development of next generation high performance organic/nano materials and printing process technology], the Nano R&D Program (M10703000980-08M0300-98010), and the World Class University (WCU, R32-2008-000-10082-0) Project of the Ministry of Education, Science and Technology (Korea Science and Engineering Foundation).

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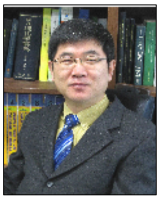

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