JOURNAL OF SEMICONDUCTOR TECHNOLOGY AND SCIENCE, VOL.15, NO.1, FEBRUARY, 2015 http://dx.doi.org/10.5573/JSTS.2015.15.1.035

Enhanced Photo Current in n-ZnO/p-Si Diode Via Embedded Ag Nanoparticles for the Solar Cell Application

Young-Uk Ko, Ho-Jin Yun, Kwang-Seok Jeong, Yu-Mi Kim, Seung-Dong Yang, Seong-Hyeon Kim, Jin-Sup Kim, Jin-Un An, Ki-Yun Eom, Hi-Deok Lee, and Ga-Won Lee*

Abstract—**In this study, an n-ZnO/p-Si heterojunction diode with embedded Ag nanoparticles was fabricated to investigate the possible improvement of light trapping via the surface plasmon resonance effect for solar cell applications. The Ag nanoparticles were fabricated by the physical sputtering method. The acquired current-voltage curves and optical absorption spectra demonstrated that the application of Ag nanoparticles in the n-ZnO/p-Si interface increased the photo current, particularly in specific wavelength regions. The results indicate that the enhancement of the photo current was caused by the surface plasmon resonance effect generated by the Ag nanoparticles. In addition, minority carrier lifetime measurements showed that the recombination losses caused by the Ag nanoparticles were negligible. These results suggest that the embedding of Ag nanoparticles is a powerful method to improve the performance of n-ZnO/p-Si heterojunction solar cells.**

Index Terms—**Surface plasmon resonance effect, Ag nanoparticles, optical absorption, photo current, minority carrier lifetime**

I. INTRODUCTION

Recently, n-ZnO/p-Si heterojunction solar cells have attracted a significant amount of interest because of their various advantages, such as a simple process flow and a low temperature process [1]. The Zinc oxide (ZnO) film can be used as the n-type layer of the heterojunction device because it is easy to have n-type conductivity due to the excess Zn [2]. For the n-ZnO/p-Si heterojunction solar cells, the solar light can be efficiently collected owing to the wide band gap of ZnO (Eg=3.3 eV). That is, high energy photons can be absorbed in the ZnO region, while low energy photons that are transmitted through the ZnO layer can be absorbed in the depletion region of p-Si [3]. In addition, ZnO film has good electrical and optical properties with low price and non-toxicity [4]. Although n-ZnO/p-Si heterojunction solar cells have many advantages, they require improvements in terms of efficiency. Among the various approaches for increasing the efficiency in solar cells, the excitation of surface plasmon resonances by metal nanoparticles (NPs) has been studied to a great extent [5, 6]. When metal NPs are illuminated, the free electrons in the metal NPs oscillate owing to the electric field of the light. The oscillation can be maintained when the frequency of the light is equal to that of the oscillation of the free electrons. This phenomenon is called localized surface plasmon resonance. This resonance between the metal NPs and the incoming light enhances the electric field of the light and the optical transition rates. The improved optical transition increases the light absorption near the metal NPs, which is well known to have the potential for application in photoelectronic devices, such as light emitting diodes, photodetectors, and solar cells [7].

In this study, we have applied this concept to n-ZnO/p-Si heterojunction devices by inserting Ag NPs to achieve increased optical absorption and energy conversion

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Manuscript received Aug. 25, 2014; accepted Dec. 22, 2014
A part of this work was presented in Asia-Pacific Workshop on Fundamental and Applications of Advanced Semiconductor Devices, Kanazawa, Japan, July. 2014

Dep. EE., Chungnam National University, Daejeon, Korea
E-mail : gawon@cnu.ac.kr

efficiency. It was found that the presence of Ag NPs at the interface enhanced the electrical properties of the device.

II. EXPERIMENTAL DETAILS

In this study, a p-type single crystal silicon (p-Si) with a thickness of 700 µm and a resistivity of 10 Ω・cm was used. Before the deposition of the ZnO film and Ag NPs, the p-Si substrate was cleaned using the SPM, RCA cleaning process. The native oxide on the surface of the p-Si substrate was removed with a diluted hydrofluoric (HF) 1% solution. To fabricate the Ag NPs, we first deposited Ag films of different thickness by an RF magnetron sputtering system. After the annealing process, the Ag film formed an agglomeration of Ag NPs [8]. Among the various methods of preparation for metal NPs, the physical sputtering method was employed. The method presents many advantages, such as low cost and easy fabrication with uniformly distributed metal NPs. Subsequently, a thin ZnO film was deposited on the Ag NPs/p-Si sample with the sputtering system. For the ohmic contacts, Al and Ti electrodes were used for the p-Si and n-ZnO, respectively.

Fig. 1 and Fig. 2 show a schematic cross section of the n-ZnO/Ag NPs/p-Si diode and the process flow of the fabrication, respectively. Scanning electron microscopy (SEM) was performed to determine the morphology of the Ag NPs. Additionally, we confirmed the structure of the ZnO/Ag NPs/p-Si heterojunction by transmission electron microscopy (TEM). To examine the light absorption of the Ag NPs, the absorption spectrum was measured from the UV to the visible region with an UV-VIS spectrometer. Current-voltage (I-V) measurements were performed with an Agilent 4155C semiconductor parameter analyzer to investigate the electrical properties of the n-ZnO/Ag NPs/p-Si diode. Finally, the minority carrier lifetime, which is a key parameter in solar cell efficiency, was measured with the quasi-steady-state photoconductance (QSSPC) method using Sinton WCT-120.

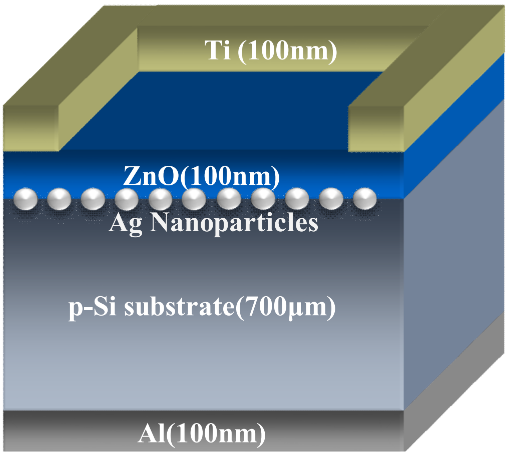

Fig. 1. A schematic diagram of the n-ZnO/Ag NPs/p-Si diode structure.

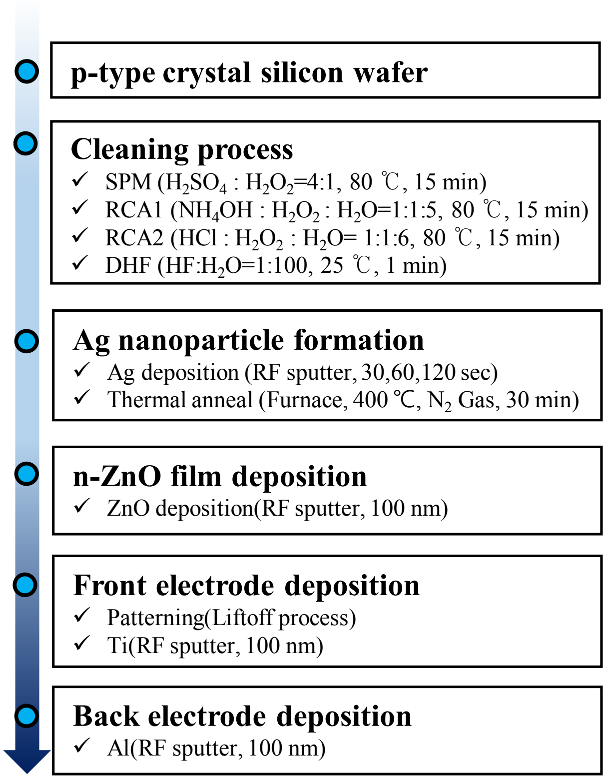

Fig. 2. Process flow diagram of the n-ZnO/Ag NPs/p-Si diode fabrication.

III. RESULT AND DISCUSSION

The Ag NPs were prepared with the RF sputtering system using various deposition times to control the size of the NPs. Since the shape, size, and distribution of the NPs have a strong influence on the absorption coefficient, we compared the optical absorption of the Ag NPs according to the sputtering times. The Ag films were sputtered on glass for 30 s, 60 s, and 120 s. Then, the films were treated by a thermal anneal process at 400 ℃ under N_2 atmosphere for 30 min. The surface tension caused the Ag films to agglomerate, forming Ag NPs at

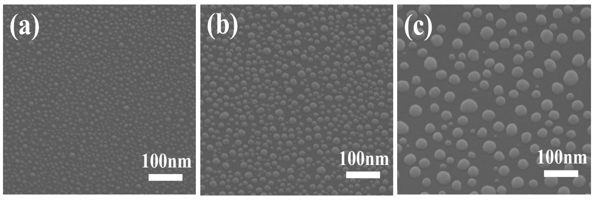

Fig. 3. SEM image of Ag NPs on glass for the sputtering times of (a) 8 nm, (b) 15 nm, (c) 35 nm.

high temperatures. Fig. 3 shows SEM images of Ag NPs with various sizes. As the deposition times increased, the Ag NPs were enlarged. The mean diameters of the Ag NPs in Figs. 3(a), (b) and (c) were 8 nm, 15 nm, and 35 nm, respectively.

It is well known that the size of the NPs has a significant effect on the optical absorption and Ag NPs have a specific absorption peak in the visible region due to the surface plasmon resonance [9].

An UV-VIS spectrometer was employed to determine the optical absorption according to the Ag NPs size. The absorption spectra of Ag NPs with various sizes are shown in Fig. 4. The maximum absorption peaks are located at the wavelengths of 447, 469, and 512 nm when the average diameters of the Ag NPs are 8, 15, and 35 nm, respectively. Moreover, as the size increases, the absorption peak exhibits a red shift, which is caused by the surface plasmon resonance effect [10].

Based on the observation that the highest absorption peak was achieved for 15 nm Ag NPs, as shown in Fig. 4, 15 nm NPs were inserted in the interface between n-ZnO and p-Si to improve the photo current of the heterojunction diode. The TEM image displayed in Fig. 5 clearly shows that the Ag NPs (dark spherical regions) had sizes between 10 nm and 20 nm.

Next, we studied the effect of surface plasmon resonance on the electrical properties. Fig. 6 shows the measurement results of I-V characteristics of the n-ZnO/p-Si diodes with and without Ag NPs. The I-V properties in reverse bias region are important because the solar cell efficiency is associated with reverse saturation current [11]. Both the dark current and the photo current under a 532 nm light source with an intensity of 200 mW/cm^2 are increased after applying the Ag NPs. The dark-reverse current can be increased by the easier carrier injection due to the modified interface by Ag NPs [12]. It is evident that the photo current of the n-ZnO/Ag NPs/p-Si diode is remarkably enhanced compared to the photo current of n-Zno/p-Si diode. At a bias of 0 V, the measured photo current values were 8.17 mA/cm^2 and 1.02 mA/cm^2 for the n-ZnO/15 nm Ag NPs/p-Si diode and the n-ZnO/p-Si diode, respectively. These results show that the photo current were largely increased after inserting the 15 nm Ag NPs. In case of the photo current, it is thought that the primary reason for the large increase is the enhanced light scattering and absorption at specific wavelengths induced by the Ag NPs.

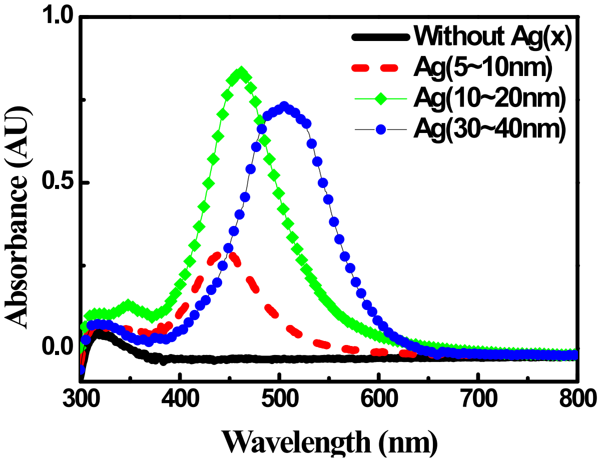

Fig. 4. Optical absorption spectrum of Ag NPs according to Ag NPs sizes.

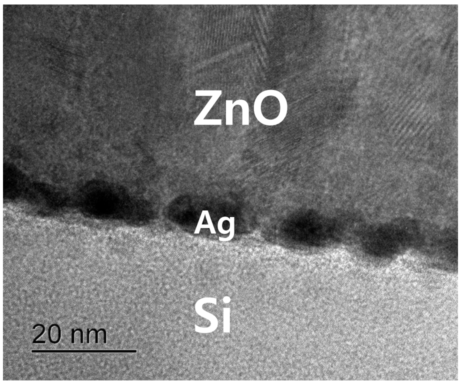

Fig. 5. TEM image of cross section view of ZnO/Ag NPs/p-Si structure.

To further examine the effect of the Ag NPs, we compared the photo current at various wavelengths. Fig. 7 shows the normalized photo-generated current of the diode with and without Ag NPs. The dark current values of the n-ZnO/15 nm Ag NPs/p-Si and the n-ZnO/p-Si diode were extracted in -1 V. Also, the photo current values of the n-ZnO/15 nm Ag NPs/p-Si and n-ZnO/p-Si diode were extracted in -1 V as a function of

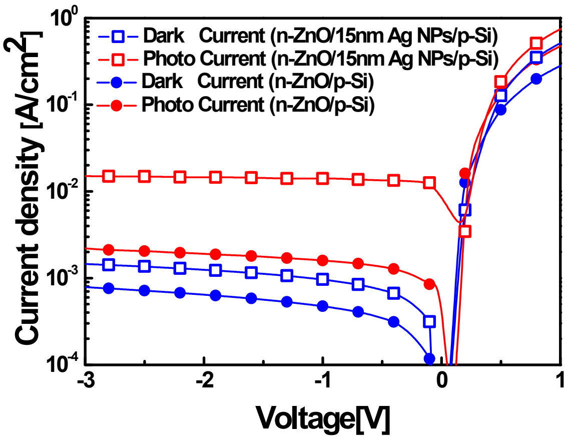

Fig. 6. Dark and photo current I-V characteristic in the n-ZnO/15 nm Ag NPs/p-Si diode and the n-ZnO/p-Si diode.

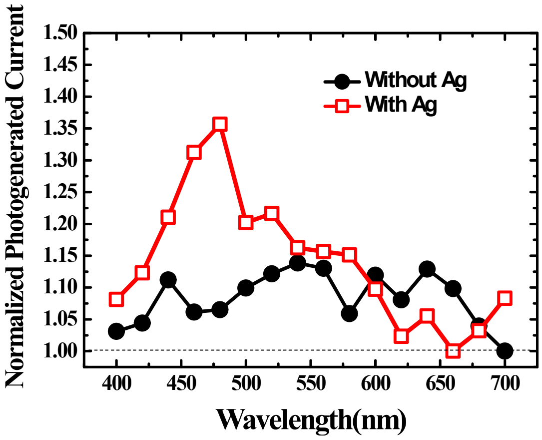

Fig. 7. Normalized photo-generated current at a bias of -1 V in n-ZnO/p-Si diode with and without Ag NPs as a function of wavelength.

wavelengths from 400 nm to 700 nm. The photo-generated current is the growth rate of photo current as compared with that of the dark current. The insertion of Ag NPs caused an increase in the maximum photo-generated current by a factor of 1.13–1.35.

For the device with the Ag NPs, this increase was particularly prominent in the wavelength region from 460 nm to 500 nm. This result agrees well with the optical absorption spectra of the Ag NPs shown in Fig. 4, indicating that the large increase in the photo-generated current is mostly due to the coupling of the Ag NPs with the surface plasmon resonance. Therefore, an improved absorption in the visible region can be expected from the addition of Ag NPs at the n-ZnO/p-Si interface.

However, the Ag NPs in the interface can increase the interface trap densities which can lower the solar cell performance [13]. Table 1 shows the minority carrier lifetime values which are measured to confirm the possible effect of Ag NPs. The structure with Ag NPs and without Ag NPs indicates 289.1 μsec and 264.24 μsec, respectively.

Table 1. Measurement results of the minority carrier lifetime from without and with Ag NPs structure

	Minority carrier lifetime
(A) Without Ag NPs	289.1 μsec
(B) With Ag NPs	264.24 μsec

When the Ag NPs were inserted, the minority carrier lifetime values were slightly reduced, but this difference is too low to estimate the efficiency reduction of the solar cell. This result shows that the effect of the Ag NPs on the recombination losses was negligible.

V. CONCLUSIONS

In this work, we investigated the effect of inserting Ag NPs in the interface of n-ZnO/p-Si heterojunction devices. In n-ZnO/Ag NPs/p-Si diode, the surface plasmon resonance peak was observed, which exhibited a red shift when the size of the Ag NPs size increased. The application of Ag NPs enhanced the I-V characteristics of the diodes and the photo-generated current was increased by a factor of 1.35. The Ag NPs appeared to produce enhanced light scattering and absorption at specific wavelengths through the surface plasmon resonance. Additionally, we found that the recombination losses due to the Ag NPs can be ignorable. Therefore, the fabrication of heterojunction solar cells with embedded Ag NPs is advantageous for obtaining the photocurrent enhancement without accelerating the recombination losses.

ACKNOWLEDGMENTS

This work was supported by the New & Renewable Energy Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea. (No. 20123010010120) and a grant from the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2012R1A1A3018050).

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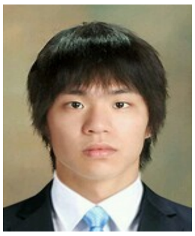
Young-Uk Ko received the B.S. degree in Electrical Engineering from Chungnam National University, Daejeon, Korea in 2013. He is currently working toward the M.S. degree in the Dept. of Advanced Circuit Substrate Engineering from the Chungnam National University, Daejeon, Korea. His research fields are heterojunction solar cell including fabrication, electrical analysis and flicker noise analysis.



Ho-Jin Yun received a B.S. and M.S. degree in Electronics Engineering from the Chungnam National University, Daejeon, Korea in 2009 and 2011, respectively. He is currently working toward a Ph.D. degree in the Department of Electronics Engineering, Chungnam National University, Daejeon, Korea. His research interests include TFTs such as organic TFTs, and oxide-based TFTs.

Kwang-Seok Jeong received a B.S. and M.S. degree in Electronics Engineering from the Chungnam National University, Daejeon, Korea in 2007 and 2011, respectively. He is currently working toward a Ph.D. degree in the Department of Electronics Engineering, Chungnam National University, Daejeon, Korea. His research interests include TFTs such as LTPS TFTs, organic TFTs, and oxide-based TFTs, and high efficient silicon solar cells.

Yu-Mi Kim received a B.S. and M.S. degree in Electronics Engineering from the Chungnam National University, Daejeon, Korea in 2009 and 2011, respectively. He is currently working toward a Ph.D. degree in the Department of Electronics Engineering, Chungnam National University, Daejeon, Korea. His research interests include LTPS TFTs and TCAD simulation.

Seung-Dong Yang received a B.S. and M.S. degree in Electronics Engineering from the Chungnam National University, Daejeon, Korea in 2010 and 2012, respectively. He is currently working toward a Ph.D. degree in the Department of Electronics Engineering, Chungnam National University, Daejeon, Korea. His research interests include SONOS flash memory and TCAD simulation.

Seong-Hyeon Kim received the B.S. degree in Electronics Engineering, in 2013, and is currently working toward the M.S. degree in the Dept. of Electronics Engineering from the Chungnam National University, Daejeon, Korea. His research interests include SONOS flash memory and TFTs.

Jin-Sup Kim received the B.S. degree in Electronics Engineering, in 2013, and is currently working toward the M.S. degree in the Dept. of Electronics Engineering from the Chungnam National University, Daejeon, Korea. His research interests include spintronics and TFTs.

Jin-Un An received the B.S. degree in Electronics Engineering, in 2013, and is currently working toward the M.S. degree in the Dept. of Electronics Engineering from the Chungnam National University, Daejeon, Korea. His research interests include TCO and LED.

Ki-Yun Eom received the B.S. degree in Electronics Engineering, in 2014, and is currently working toward the M.S. degree in the Dept. of Electronics Engineering from the Chungnam National University, Daejeon, Korea. His research interests include TFTs with SICN materials.

Hi-Deok Lee received a B.S., M.S., and Ph.D. degrees in Electrical Engineering from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1990, 1992, and 1996, respectively. In 1993, he joined the LG Semicon Company, Ltd. (currently SK Hynix Semiconductor Ltd.), Chongju, Choongbuk, Korea. His research interests are in nanoscale CMOS technology and its reliability physics, silicide technology, and Test Element Group design. His research interests also include development of high performance analog and high voltage MOSFETs, and high efficient silicon solar cells.

Ga-Won Lee received a B.S., M.S., and Ph.D. degrees in Electrical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1994, 1996, and 1999, respectively. In 1999, she joined Hynix Semiconductor Ltd. (currently SK Hynix Semiconductor Ltd.) as a senior research engineer, where she was involved in the development of 0.115-μm, 0.09-μm DDRII DRAM technologies. Since 2005, she has been at Chungnam National University, Daejeon, Korea, as an Associate Professor with the Department of Electronics Engineering. Her main research fields are flash memory, flexible display technology including fabrication, electrical analysis, and modeling.