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Short Communication

Applying Dielectrophoresis on Silver Nanowires Alignment and Assembly to Enhance the Efficiency of Plasmonic Silicon Solar Cells

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The enhancement effects for solar cell are examined on the plasmonic properties of Ag nanowires (AgNWs) arrays, which fabricated by dielectrophoresis techniques. AgNWs in 100 nm diameters with aspect ratio (AR) of 100 were assembled into an array between the micrometer spaced electrodes by applying an AC electric field. The simulating results show that the array AgNWs can enhance the localized surface electric field on the silicon surface efficiently. Since, the incident lights can be scattered and trapped in the silicon layers which improves the enhancement of the external quantum efficiency. The optimized result of alignment of AgNWs average angle are 89.17 degree to the electrode edges and 21.98 degree of standard deviation under 100 Vpp, 250 kHz. In addition, the reflectance is 18.4% lower than those without AgNWs ones. The optimized plasmonic solar cells increase efficiency from 7.78% to 8.72%.

Keywords: Dielectrophoresis, Silver nanowires, Alignment, Plasmonic, Solar cell

1. INTRODUCTION

Photovoltaic cell is the promising technology to replace traditional thermal power plants for electricity generation. However, high reflectivity in the range of solar wavelength is disadvantageous to the utilization of silicon-based solar cell, which results in large waste of useful sunlight by reflecting them back into free space. Take metal nanoparticles (NPs) as components to increase the amount of incoming light is the appropriate method without damage on surface of photovoltaic device [1-4]. The enhanced field strength resulting from metal NPs depends on the particle material, size, shape and surrounding medium [5]. From the simulated calculations, the results indicated the prisms, rods and spheroids with similar size dimension show similar enhancement which is significantly higher than sphere [6-7]. Besides these considered factors, the distance between particles also determines resonances in coupled systems of metal NPs [8]. When the particles are closely spaced, the plasmonic oscillations in each particle are affected due to the neighbouring particle oscillations. The positional distribution of the metal NPs must be taking into account. Typically, the distributions of these NPs on the photovoltaic cell are randomness. It should be kept in mind that the metal NPs do also introduce losses through absorption or shading of light. Therefore, the manipulation of the distributions of metal NPs is important for improved solar cell applications.

For the metal NPs, the alignment and assembling are simply completed by several approaches [9-10]. However, to control over metal nanowires (NWs) spatial position, various envisaged applications of NWs demand control over their collective orientation in suspension and also after deposition at the substrate. Among various approaches [11-13] of one-dimension NPs manipulation, dielectrophoretic force has become increasingly popular due to the ability to fast depositing anisotropic NWs precisely on a substrate, allowing integration with conventional top-down semiconductor processing [14].

In this work, we employ the dielectrophoretic method to manipulate the agreement of AgNWs on the solar cell. Using the different space of electrodes and applied AC voltages, AgNWs can be assembled into an array effectively. We also simulate the different geometric parameters of AgNWs and compare their localized surface electric fields. The results show that the alignment AgNWs have better enhancement than the random distributions. The optimized result of alignment of AgNWs average angle are 89.17 degree to the electrode edges and 21.98 degree of standard deviation under 100 Vpp at 250 kHz on electrode gap of 50 μm by using AgNWs 100 nm in diameter and 10 μm in length. In addition, the reflectance is 18.4% lower and the transmittance is 11.2% higher than those without AgNWs ones. Furthermore, the experiments demonstrate that AgNWs in 100 nm diameters with AR of 100 can improve the conversion efficiency of the solar cell from 7.78% to 8.72% under applied 100 Vpp.

2. EXPERIMENTAL

In this experiment, we use dielectrophoresis to make a spaced alignment of AgNWs to avoid too close packing, which will increase the reflection of substrate and result in negative effect on conversion efficiency of solar cells. In addition to spaced alignment of AgNWs, dielectrophoresis force possesses advantages of rapid alignment as well. Therefore, by utilizing high aspect ratio AgNWs [15] to fabricate plasmonic structure *via* dielectrophoresis force is considered as a quite convenient, fast, and effective method to increase the efficiency of solar cells. The basic device structure of Si-based p-n junction solar cell employed in this work is shown in Fig. 1. To form the shallow p-n junctions, phosphorous was implanted into the wafers by low energy of 10 keV and dense concentration of doping elements of 1×10^{15} ions/cm^2. After implantation, the substrates were treated by annealing process of 900 °C and 30 seconds to eliminate the damage of materials during implantation. Various electrodes was designed and deposited upon the device by thermal evaporation to align AgNWs. Before utilizing AgNWs arrays on solar cell, preliminary experiment was designed to investigate the effect of voltage, frequency, and material dimension on AgNWs alignment. Under these results, we applied these concepts on solar cell as component to enhance the conversion efficiency.

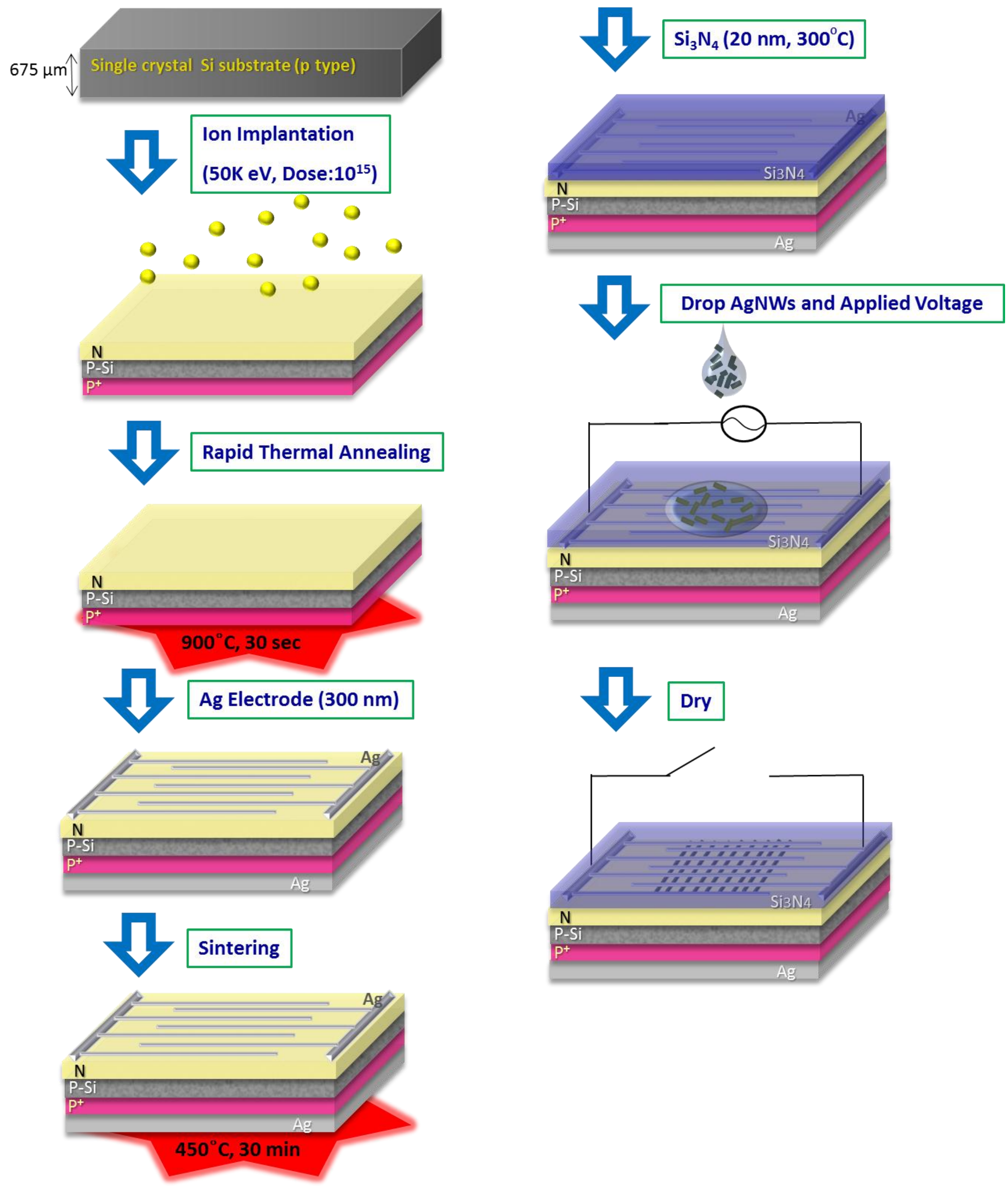


Figure 1. The manufacturing processes of plasmonic crystalline silicon photovoltaic cells.

After accomplishing electrodes for alignment, AgNWs are aligned between electrodes. A sinusoidal AC voltage is applied to silver electrodes using a function generator (30 MHz, 33522A) and an amplifier. The frequencies of 250 kHz, 10 MHz, 30 MHz and the peak-to-peak voltages of 10 Vpp, 20 Vpp, 40 Vpp, 80 Vpp, 120 Vpp, 160 Vpp, 200 Vpp, are applied to estimate the optimal results on various types of electrodes. In the one pair interdigital electrode, the DEP force method is useful to keep aligning silver nanowires. In addition to the one pair interdigital electrode, the substrates will be larger for further application on solar cells. In order to save the usage amount of silver nanowires solution and let AgNWs cover all of interdigital electrodes, we add isopropanol to our AgNWs solution. Since isopropanol is hydrophobic on silicon substrates, the contact angles of isopropanol are bigger than the contact angles of water on silicon substrates. We put 1.7 µl drops containing silver nanowires and isopropanol on the substrate. Therefore, the substrate is completely covered by silver nanowires solution.

3. RESULTS AND DISCUSSION

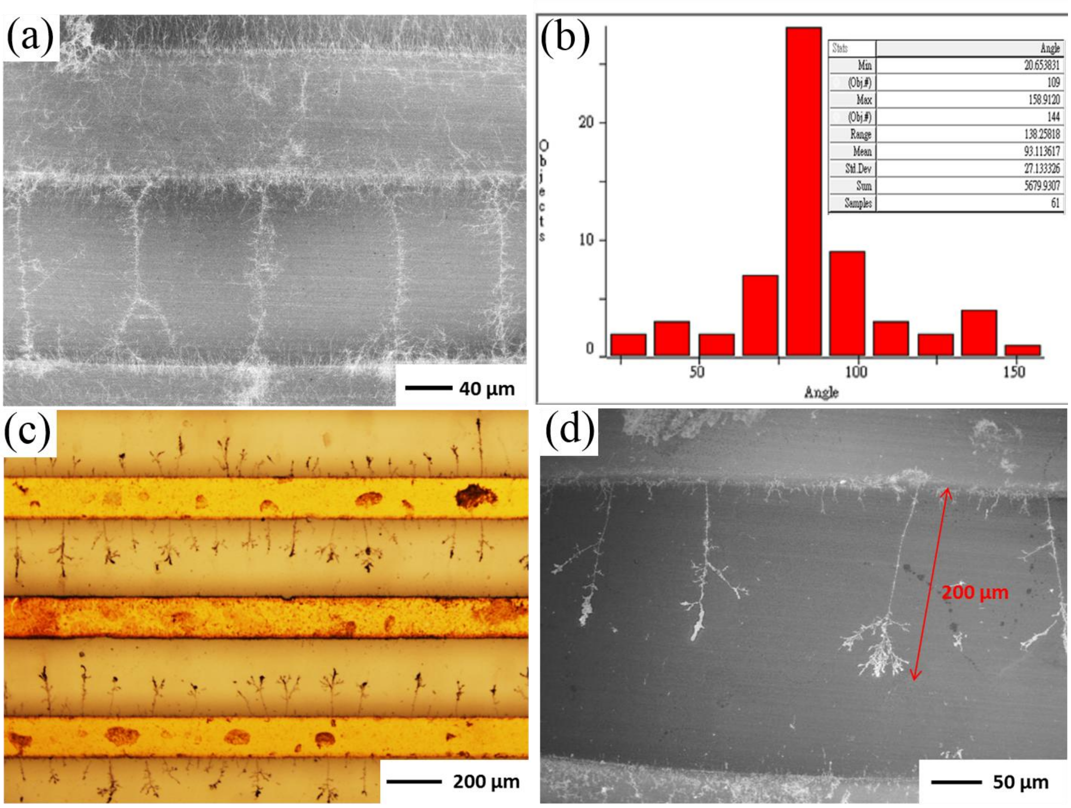
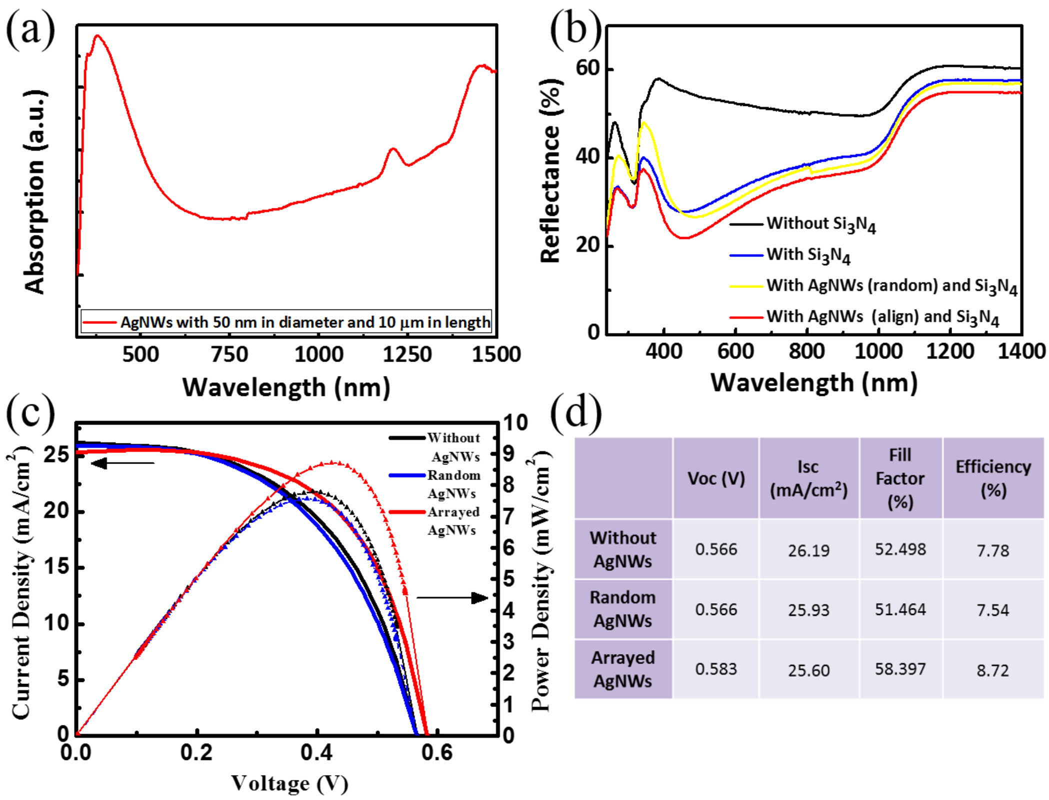


Figure 2. (a) The SEM images of assembled AgNWs with 50 nm in diameter in a 200-µm-widthgap under applying voltage of 80 Vpp, frequency of 250 kHz. (b) The result of histograms indicates the angular distribution of silver nanowires. (c) The OM image shows assembled silver nanowires with 50 nm in diameter and 10 µm in length on a 400-µm-width gap under applied the voltage of 200 Vpp and the frequency of 250 kHz. (d) The SEM image shows the localized shape of AgNWs.

From the above-mentioned experiments, the effect of voltage on alignment was investigated. As it is shown in Fig. 2(a), AgNWs suspensions are dropped on the 200 µm electrode spacing under the voltage of 80 Vpp and frequency of 250 kHZ. AgNWs were deposited predominantly within the space between two electrodes near the electrode edges. For parallel plane electrodes, the electric field as well as the field gradient was large near the electrodes. Apart from bridging between the gaps, AgNWs were attracted more inside the gap. In addition to the dense attraction of AgNWs, the improvement of AgNWs alignment also observed when the applied voltages increased [16-17]. The increase of applied voltages led to large magnitude and gradient of electric field, which contribute to large dielectrophoresis force. Besides, the increase of electric field was also contributed to large torque motion [18]. Therefore, accumulated AgNWs tended to aligned in uniform orientation parallel with the direction of electric field. To bridge the wider electrode gap, the shorter AgNWs should be replaced with longer one. AgNWs would undergo the large force under the same exerted voltage that on the smaller dimension.



	Voc (V)	Isc (mA/cm²)	Fill Factor (%)	Efficiency (%)
Without AgNWs	0.566	26.19	52.498	7.78
Random AgNWs	0.566	25.93	51.464	7.54
Arrayed AgNWs	0.583	25.60	58.397	8.72

Figure 3. (a) UV-visible absorption spectra of AgNWs suspensions. (b) The result compares with the reflectance of various conditions on the same solar cell. (c) J-V curves and power density of the same solar cell under different conditions. (d) Photovoltaic performance of open circuit voltage, short current and fill factor and efficiency corresponding in different conditions.

According to aforementioned experiment, we investigated that we can move small AgNWs with small voltage although dielectrophoresis force induced by AgNWs with small diameter is minor; which is enough to shift light-weight AgNWs. AgNWs are easier bridging between smaller gap width than larger gap width. Interestingly, AgNWs align as arborescent or reticular form when they align between larger gap width. Fig. 2(c) shows the large area distribution of AgNWs array and we can see the localized shape of AgNWs on the SEM image Fig. 2(d). In this situation, the longest chain length of AgNWs is 200 μm and the density of AgNWs is larger than others. Under 200 Vpp on 400 μm electrode gap, we gather the mean angle and standard deviation, which are 93^{o} and 27^{o}, respectively in Fig. 2(b). The percentage of 80^{o}~100^{o} AgNWs is 49%. We apply various voltages on electrode pads with electrode spacing of 400 μm. From the experimental results, we obviously see the density of AgNWs that is larger under applying larger voltage. The result is the same as foregoing experiments that the rising strength of the electric field can attract more AgNWs [19-20]. According to statistics, when we apply 200 Vpp, the result of the mean angle, standard deviation and percentage are all better than others that we apply a smaller voltage on the same electrode spacing [21].

Fig. 3 (a) shows the measured absorption spectra of AgNWs suspensions. As the foregoing mentioned, there are not only one peak in absorption spectra because there are two axes of wire to resonance in different wavelengths. The wavelength of 378 nm is the first peak corresponding to the short axis of 50 nm and the wavelength of 1466 nm is the second peak corresponding to the long axis. Consequently, AgNWs have two main SPR band wavelengths. In addition, there are some small SPR band between 378 nm and 1466 nm because parts of AgNWs with the certain length of the long axis induce SPR at the wavelength. Moreover, there are coupling between two SPR bands of AgNWs. Therefore, AgNWs have characteristics to enhance at broadband wavelength.

In the next section, we discuss different experiment conditions and AgNWs affecting reflectance. From Fig. 3(b), the black line stands for the solar cell without silicon nitride and the blue line stands for the solar cell deposit silicon nitride of 20 μm. The reflectance obviously reduces with silicon nitride, even though it only has 20 μm which is not the best antireflective layer of 70 μm. AgNWs suspensions are dropped on the same solar cell with silicon nitride of 20 μm and evaporate at room temperature without applying voltage. We observe that the reflectance of the yellow line is higher than the solar cell without random AgNWs at wavelength below 450 nm and lower than the solar cell without random AgNWs above 450 nm. Then, we clean away random AgNWs on the solar cell. AgNWs suspensions are dropped on the same solar cell and then electrode pads are applied extra voltage. Subsequently, after AgNWs suspensions dry, AgNWs arrays are aligned on the solar cell by dielectrophoresis force under applyied voltage. Reflectance of the red line is lower than other reflectance on wavelength of 240 nm to 1400 nm. Average reflectance of the black, blue, yellow, and red line is 53.72%, 41.91%, 41.96%, and 35.39%, respectively. The AgNWs array can decrease the reflectance by trapping light more efficiently into the solar cell [22]. Fig. 3(b) uses the same solar cell under different conditions and we prove the efficiency of the solar cell increase afterward. Therefore, we can obviate different characteristics of the solar cell and investigate the effect of incident light absorbency by AgNWs arrays.

We discuss different conditions causing the efficiency of solar cells. A figure measures by the same solar cell in order to obviate different characteristics of the solar cell. From Fig. 3(c), the black line is the solar cell with interdigital electrodes and silicon nitride of 20 μm. After we measure efficiency, AgNWs suspensions are dropped on the solar cell and dry at room temperature (the blue line). Subsequently, the random AgNWs are removed. Then AgNWs suspensions are dropped on the same solar cell and apply a voltage on electrode pads (the red line). Fig. 3(d) shows photovoltaic performance of open circuit voltage, short current and fill factor as well efficiency corresponding to different conditions from Fig.3(c). Voc slightly increases from 0.566 V to 0.583 V and ISC little decreases from 26.19 mA to 25.6 mA. The fill factor rises from 52.498% to 58.397%. At last, the efficiency of solar cell with AgNWs arrays increases 12% than without AgNWs array. Therefore, electrons are absorbed efficiently due to aligned AgNWs array on the edge of electrodes that has strong electric field by SPR and waveguide [23].

It is necessary for the substrates to be larger for further application in solar cells. In order to save the amount of AgNWs usage, we put several individual 1.7 μl drops containing AgNWs in 100 nm diameters with AR of 100. Next, we used a hydrophobic sheet to cover and pull with shearing direction leading complete coverage of AgNWs solution and achievement of alignment. After applied of these conditions, we examined the effect of AgNWs array under different electrode gap width and array. For the finger width of 1 μm, the smaller gap gives the better performance than larger one. Because the smaller gap provides well aligning effect to AgNWs. Comparing the same gap with different finger widths, the wider width of the finger produces stable dielectrophoresis force to align AgNWs array, thus the efficiency is little better than the narrower finger. In addition, the AgNWs array is also to evaluate under the same geometric condition of finger and gap. The experiments show that the aligned AgNWs has the preferable conversion efficiency contrast to the random dispersed AgNWs. The similar results are reported in references [6-7]. In a word, it is found out that indeed increase of conversion efficiency with different degree under AgNWs and AgNWs array. The conversion efficiency of solar cell could be improved through light trapping by using plasmonic structure [24-25].

It is worth mentioning that the shading light effect and enhancement form AgNWs must be compromise. For the lower surface coverage, AgNWs can trap light into the solar cell effectively [26-28]. But the shading light would reduce the enhancement when the surface coverage of AgNWs is dense. Besides, the absorption due to itself leads to heat dissipation is another deliberate issue in solar cell applications. However, plasmonic nanomaterials offer a unique way to circumvent the inherent trade-off between absorption and carrier collection in the design of solar cells electrode. Therefore, it would enhance more and more appropriate solar cell design.

4. CONCLUSIONS

In this study, we have demonstrated the aligned silver nanowires arrays on single silicon solar cells by dielectrophoresis force. There are many factors influencing dielectrophoresis force and the result of alignment. We modulate factors such as electrodes with different gap width, voltage, frequency of sinusoidal current, length of AgNWs, diameter of AgNWs, material of substrates and the permittivity of the medium sequentially. The average angle of optimized AgNWs alignment are 89.17 degree to the electrode edges and 21.98 degree of standard deviation under 100 Vpp, 250 kHz on electrode gap of 50 μm by using AgNWs 100 nm in diameter and 10 μm in length. Moreover, the reflectance of solar cell reduces from 41.91% without AgNWs to 35.39% with AgNWs arrays. The optimized plasmonic solar cells increase efficiency from from 7.78% to 8.72%. From the result of the experiment, we confirm that aligning AgNWs on single-crystalline silicon solar cells by using dielectrophoresis force enhance efficiency obviously. In the future, we can use AgNWs arrays as optical film. As well, we can use AgNWs arrays on thin film solar cells to make incident light trap inside the photovoltaic device and reflect multiple times to increase light path. Therefore, we could overcome the thin film solar cell by its natural physical thickness limitation to utilize incident light more efficiently.

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