Influence of Different Metals Back Surface Field on BSF Silicon Solar Cell Performance Deposited by Thermal Evaporation Method

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Abstract This paper presents comparison of thermal evaporation method based passivation and BSF formation with different materials (Au, Al, and Cu). Silicon solar cells with different rear surface contact using these materials were fabricated. A comprehensive comparison of the samples have been carried out to find better back surface contact regarding the efficiency by investigating I-V characteristics, fill factor, external quantum efficiency and carrier diffusion length and lifetime, etc. Experimental data revealed that Cu based back surface contact has maximum output efficiency of about 13.73%, whereas Au shows maximum external quantum efficiency of about 86%. Moreover, use of Al shows the maximum carrier diffusion length 97.2 μ m and highest carrier lifetime of 3.5 μ s with overall cell efficiency of 12.90% indicating that Al is a promising material for back contact for n⁺-p-p⁺ back surface field silicon solar cell.

Keywords Back Surface Field (BSF), External Quantum Efficiency, Gold, Aluminum, Copper

1. Introduction

Commercial wafer based silicon solar cell production involves the use of expensive aluminum (Al) paste as screen printed back contact that contributes towards a moderate

level of Back Surface Field (BSF). As BSF plays a significant role in improving the cell performance as well as minimizing the cost of production, therefore introducing new methods and materials for BSF is still under consideration.

Crystalline silicon photovoltaic (PV) cells are still the most widely used technology for commercial solar cell production [1, 3]. Increasing the efficiency of solar cells with lower fabrication cost is a major challenge in photovoltaic research. However, the efficiency of a solar cell is restricted by the main three loss mechanisms: absorption loss, electrical loss and minority carrier surface recombination loss [3-5]. All these three types of losses are associated with rare surface contact (back contact) where metals are commonly used to form metal-semiconductor contact. In addition to that, metallization cost is the second most expensive step in the photovoltaic cell production [6]. Moreover, back contact can act as a reflector which plays a crucial role in improving light-trapping properties and improving the cell efficiency. At the same time, improved back reflectivity reduces photon absorption that leads to higher quantum efficiency. Furthermore, less resistive ohmic back contact results in less joule heating enhancing electrical efficiency [3] [7]. Thus, materials used in back contact and methodology of back contact formation is an important factor for improving the cell efficiency and reducing the production cost.

Figure 1. Different solar cell fabrication technology annual production [1]

Figure 2. Back-side passivation to reduce recombination [2]

Figure 3. (a) $n^+ - p - p^+$ BSF solar cell schematic diagram (b) band diagram of an $n^+ - p - p^+$ solar cell

One of the major factors of degradation of cell performance is minority carrier surface recombination, lowering open circuit voltage (V_{OC}) and short circuit current (I_{SC}) of the cell [4]. To minimize the surface recombination loss at the back-surface of photovoltaic cells, instead of primarily invented n^+p solar cell, n^+-p-p^+ and p^+-p-n^+ type solar cell also known as low-high or back surface field (BSF) solar cell has been already introduced in industrial production [7-11]. The highly doped p^+ region with the lightly doped p-type semiconductor result in an electric field commonly known as Back Surface Field (BSF) [9]. BSF at p^+/p region repels the minority carrier to enter the back surface reducing surface recombination rate hence increasing minority carrier diffusion length and carrier collection efficiency [5][7][12]. Fig-3 shows the, n^+-p-p^+ solar cell schematic diagram.

Silver (Ag) and aluminum (Al) pastes in screen print technique is still the main metallization technology for the PV-industry to form the back contact [13] [14]. But in this method, a large amount of expensive paste is wasted with moderate passivation reducing surface reduction velocity [15-16]. Hence, several types of materials, methodology and geometrical structure have been introduced to form the back surface in order to improve the cell efficiency by researchers over the years [20-23]. In recent years, another potential cheaper contact-forming technique, deposition by evaporation, has been attempted that can replace fired silver/aluminum paste screen printed deposition forming the required thickness of back surface contact within very short time having advantages of good ohmic contact [6][17][24-25]. However, the impact of other materials as BSF with different metals having different work-functions by thermal evaporation method is yet to be studied thoroughly.

In this research, at first a single crystal silicon solar cell fabricated on p-type wafer without back contact is cut down to produce a number of identical small samples. Afterwards, aluminum, copper, and gold were deposited on the back surface by thermal evaporation method on the different samples. Afterwards, the samples were sent to Rapid Thermal Annealing Process (RTP) that leads to the formation of highly doped p^+ region establishing BSF [18]. Next, several experiments had been conducted including incident photon-to-current efficiency (IPCE), surface photo voltage (SPV) measurement, I-V characteristics and fill factor to compare the impact of different evaporation based back contact materials on silicon solar cells. Finally, electrical efficiency, external quantum efficiency as well as minority carrier diffusion length and lifetime, and fill factor are estimated from the experimental data to compare with one another in search of better back contact.

2. Methodology

P-type Cz-Si wafers with base resistivity of 1-2 Ω cm were used in this experiment. At first, saw-damage removal and surface texturing were carried out in order to increase the optical absorption of the incident light [26]. Applying alkaline solutions (KOH), anisotropic texturing, a process of formation of random pyramids on the silicon surface, was created [27]. Afterwards, the wafers were cut down into pieces of 2x2cm before metallization of front and back surface to make different samples. Then, thermal evaporation process was applied at an air pressure of 1.6×10^{-5} torr by a thermal evaporator (Min-coater, Tectra, Germany). Initially, the front surface was deposited by silver for all the samples. Then all the samples back surface were deposited by different metals (Au, Cu, and Al). Next, rapid thermal annealing process, where samples pass through a moving belt was applied with the temperature profile of 500°C, 600°C, and 800°C, respectively.

The characterization of the individual samples were performed by K3100EQX Spectral IPCE Measurement System, from which the external quantum efficiency (EQE) was measured by incident photon-to-current efficiency (IPCE) method in the spectral range of 360-1100 nm wavelength. Followed by LIV measurement to measure the cell efficiency and fill factor using a standard AM 1.5 calibrated DC LIV Solar Cell Characterization System. Finally, the surface photo voltage (SPV) of the samples had been measured for the wavelength ranging from 400 nm to 1000 nm. Minority carrier diffusion length had been estimated by Goodman (1961) method; and then carrier lifetime measurement carried out by the formula $L_n = \sqrt{D\tau_n}$; where L_n , the diffusion length for electron, D is the diffusivity, and τ_n is the minority carrier lifetime [19].

3. Results and Discussion

The external quantum efficiency measurement is done to measure the photon to electron conversion efficiency with the different BSF materials used. The fig.-4 shows the EQE measurement of silicon solar cell with different BSF layers deposited by thermal evaporation process. Among the samples, the EQE response for gold deposited sample was around 86% in the spectrum of 400–800nm wavelengths. On the other hand, copper, and aluminum showed the EQE response of about 85% and 83%, respectively. The difference in EQE appeared due to the different work function of the metals as gold having a work function of ($\Phi = 5.1$) provided the highest EQE followed by copper and aluminum having work function of, $\Phi = 4.7$ and $\Phi = 4.1$, respectively.

Figure 4. EQE of silicon solar cells with different back contact materials (Al, Cu, and Au) deposited by thermal evaporation process

Figure 5. I-V curves with different metals (Al, Cu, and Au) deposited on back surface of silicon solar cells

The performance of a solar cell depends mainly on three factors which are electron-hole pair (EHP) generation, charge separation due to the built in potential (V_{bi}) and collection of electrons and holes through the respective front and back contacts. The first two phenomena depend on the quality of p-n junction whereas collection of electron and hole relies on the quality of the front and back contacts, respectively. The electron can move easily through the front contact but collection of holes is difficult and depends on the work-function (Φ) of the back contact materials. Therefore, Fig. 5 illustrates the I-V curves of Si solar cells deposited with different metals on the rear surface using the thermal evaporation process. The short circuit currents measured are 0.46A, 0.45A, and 0.43A for gold, copper, and aluminum, respectively. From the I-V graph it is evident that although gold has the highest short circuit current but the fill factor is comparatively low than the other two metals used and had an

efficiency of 12.88%. On the other hand, copper with the highest fill factor obtained the highest efficiency of 13.73% and the efficiency of 12.90% was achieved with aluminum as the back contact having, I_{sc} of 0.43A and FF of 0.60, respectively.

Fig. 6 demonstrates the carrier diffusion length and the carrier diffusion lifetime versus the solar cell fabricated with different back contacts. From the figure it is clear that aluminum shows the highest carrier diffusion length of 97.15 μ m and highest carrier life time of 3.5 μ s, followed by gold having carrier diffusion length of 78.78 μ m and carrier life time 2.3 μ s. The silicon solar cells prepared using copper as the back contact showed short carrier lifetime compared to aluminum and gold. Hence, from the figure below it can be said that aluminum can be used as a back contact materials for silicon solar cells. In addition to that, because of small carrier life time, use of gold and copper are not suggested as a back contact materials for silicon solar cells.

Figure 6. Carrier diffusion length and carrier diffusion lifetime with different back contacts of silicon solar cell

4. Conclusions

Metals (Al, Cu, and Au) of different work-functions have been deposited by thermal evaporation method to passivate the back surface of silicon solar cells. The effects of different passivation are observed in terms of external quantum efficiency, electrical efficiency, fill factor, and carrier diffusion length and lifetime with the different back contact materials. Copper passivated back surface cell exhibits maximum output efficiency of 13.73%. On the other hand, gold exhibits maximum external quantum efficiency 86%, and aluminum showed better performance with the maximum carrier diffusion length of 97.2 μ m and highest carrier diffusion lifetime of 3.5 μ s. The external quantum efficiency of 83% and overall cell efficiency of 12.90% with aluminum based back contact revealed that aluminum is the best material to be used as the back contact of silicon solar cells compared to other metals used in this study.

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