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Forming aluminum electrodes by screen printing and electron-beam evaporation for high performance interdigitated back contact solar cells

Yizhan Chen [a,b,c], Yang Yang [b], Xueling Zhang [b], Guanchao Xu [b], Jason K. Marmon [d], Zhonglan Li [b], Zhiqiang Feng [a,b], Pierre J. Verlinden [a,b], Hui Shen [a,b,*]

[a] Institute for Solar Energy Systems, Sun Yat-sen University, Guangdong, China
[b] State Key Laboratory of PV Science and Technology, Trina Solar Limited Company, Jiangsu, China
[c] School of Applied Physics and Materials, Wuyi University, Guangdong, China
[d] Nanoscale Science Ph.D. Program, University of North Carolina at Charlotte, Charlotte, NC 28223, USA

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ABSTRACT

Interdigitated back contact (IBC) solar cell is one of the most efficient silicon solar cells commercially available to date. This paper studies the application of aluminum electrodes, deposited by electron-beam evaporation, instead of commonly used silver paste. Furthermore, screen printing instead of optical lithography method was used to generate etching masks. Together, we develop a low-cost technology for production. The specific contact resistivity of Al was found to be even lower than that of traditionally used Ag paste. The specific contact resistivity (ρ_c) and the recombination parameter (J_o) were found to be dependent on the doping level. Therefore, there is a design trade-off between a low J_o obtained with a low surface doping concentration, and a low ρ_c obtained with a high surface doping concentration. This process produced an IBC solar cell with a size of 4 cm^2, an open circuit voltage of 680 mV, a conversion efficiency (η) of 22.72%, a fill factor of 0.80, and a short circuit current density of 41.69 mA/cm^2. The optimal design for the Al contact IBC cell was found by comparing the 3D Quokka© simulations of the Al contact and Ag paste contact IBC cells. The simulation indicated that further decrease in the Al contact size and spacing using screen printing and optimize the doping level could result in η up to 23.4% in production, comparable to the performance achieved in small cells using optical lithography.

1. Introduction

The photovoltaic industry is always in search of high-efficiency solar cell technologies and ways to reduce the cost of photovoltaic module. The interdigitated back contact (IBC) solar cell has several advantages including no front emitter, no shading loss from a front metal grid, allowing for an independent optimization of surface passivation and optics at the front, and a large metal coverage to minimize series resistance at the back. Long bulk lifetime in the silicon substrate and low surface recombination velocity at the front surface are required to achieve significant efficiencies. The IBC solar cell was first investigated by Schwartz and Lammert for concentration application [1]. Swanson [2] further improved the design with a small contact and emitter coverage fraction, a design called Point Contact (PC) solar cell, mostly for high-concentration applications. IBC solar cells have been commercially available from 1991 for concentrator applications, and from 1993 for one-sun high-value applications, like solar race cars and solar airplanes. Since 2003, IBC solar cells became commercially available for flat-plate PV modules. In 2013, a group at Australian National University (ANU) [3] demonstrated an IBC solar cell (4 cm^2) with an aperture efficiency of 24.6%, using photolithography and vacuum evaporation for aluminum metallization. In 2014, Interuniversity Microelectronics Centre (IMEC) developed a photolithography free process to finish IBC solar cell with an aperture efficiency of 22.7% [4]. ANU developed a laser ablation process to fabricate IBC solar cell with an aperture efficiency of 23.5% [5]. SunPower announced a large-area IBC solar cell with an aperture efficiency of 25% [6].

Silver (Ag) and aluminum (Al) pastes are widely used in industrial solar cell contacting [7], but they have inferior performance compared to PVD-deposited Al contact that can form a good ohmic contact with n-type and p-type silicon [8]. Al has a

* Corresponding author at: Institute for Solar Energy Systems, Sun Yat-sen University, Guangdong, China. Tel.: +86 13825024856; fax: +86 2039332866.
E-mail address: shenhui1956@163.com (H. Shen).

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high work function of (4.28 eV), is cheaper than Ag, it can be deposited by sputtering or e-beam evaporation at a fast speed, and can potentially be cheaper than screen printed Ag contacts [9]. High-rate e-beam deposition of an Al contact was used in rear interdigitated single evaporation emitter wrap through (RISE EWT) solar cells [10]. The specific contact resistivity (ρ_c) of Al contact is smaller than Ag paste, which mainly depends on the doping level [11]. The recombination parameter (J_o) is also influenced by the doping level, a decrease in J_o with increasing sheet resistance (R_s) was found [12]. Our goal is to develop a low-cost approach using Al contact for high performance IBC cells.

Besides the contact resistance, the contact size also obviously influences the cell performance, such as conversion efficiency (η) and fill factor (FF) [13]. In this paper, 3D Quokka© [14] was used to stimulate the efficiency of the IBC cell, more specifically, the power loss in the solar cell caused by contact resistance. The optimal doping level was also simulated for this Al contact IBC solar cell. The simulation predicts the feasibility of reaching 23.4% efficiency in production by further reducing the Al contact size and optimizing the doping level.

2. Experimental details

Fig. 1a shows a diagram of an e-beam evaporated Al contact in an IBC solar cell structure. Device construction requires total over 30 steps, the most pertinent ones are outlined in Fig. 2, which will be discussed subsequently. The dashed lines in Fig. 1b represent the metallization pattern of the solar cell, while the circles represent the local contacts. Blue and yellow circles correspond to the n- and p-bus bars respectively, the p^+ and n^+ contact positions are opposite. The interdigitated fingers connect to bus bars on two of the solar cell edges, where one edge is the n-bus bar and the other is the p-bus bar.

The primary fabrication steps, from Fig. 2, include:

(1) A long lifetime, 200 μm thick, monocrystalline Cz n-type silicon wafer undergoing wafer polishing and the RCA clean processes.
(2) Boron diffusion to create the p^+ emitter on the silicon wafer's back side. Boron tribromide (BBr_3) was introduced at the upstream argon (Ar) carrier gas inlet and was streamed through a chemical vapor deposition (CVD) setup at 200 sccm at 950 °C for 30 min [15]. A borosilicate glass (BSG) layer acted as a barrier on the doped regions produced by the oxidation process.
(3) An HF-based etching paste was screen printed onto the back surface using a predetermined pattern. The result was opening the back-surface field (BSF) holes through the BSG layer.
(4) Liquid phosphorus trichloride ($POCl_3$) was used to create the n^+ BSF, and was accomplished by introducing the precursor upstream in the Ar carrier gas at a rate of 600 sccm for 20 min at 830 °C [16].
(5) The front surface was textured with a KOH solution to make pyramid structures before front surface field (FSF) diffusion [17], with a R_s of 180 Ω/□.
(6) Silicon nitride (SiN_x)and Al_2O_3/SiN_x stack layer were deposited on the front side and back side of the substrate respectively, the SiN_x and Al_2O_3 refractive indices are 2.01 and 1.60 respectively. They were deposited using plasma-enhanced CVD and sintered at 700 °C. Step (3) was repeated to open contact holes at the p^+ emitter and n^+ BSF.
(7) An Al metal layer was evaporated onto the structure using an e-beam evaporation instrument, thereby filling the contact holes. This method could potentially result in lower cost, as it is more cost effective [6], and has a higher production yield than screen printing Ag paste. A resist mask was screen printed onto the device instead of the previous optical lithography deposition procedure with a printing accuracy of 5 μm.
(8) A 16:1:2:1 mixture of phosphoric and acetic acids, water and **n**itric acid (PAWN) was used to etch back the Al film before the resist mask was removed. Al is highly reactive and suffers from a spiking and shorting [18]. Methods for avoiding reactivity issues are to sinter the cell at a low temperature for a short time, or to use an aluminum layer that is pre-saturated with silicon for a given sintering temperature, the thickness of the

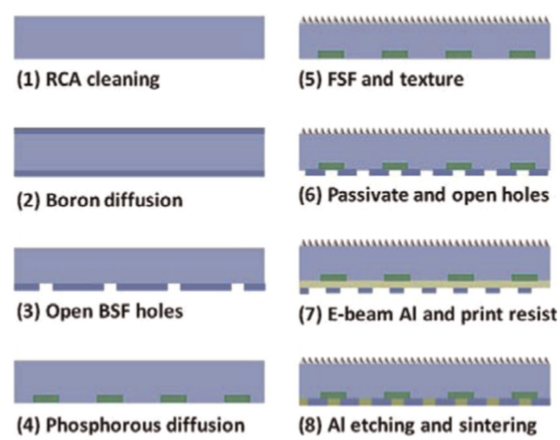

Fig. 2. Fabrication schematic for e-beam evaporated Al contact IBC solar cell.

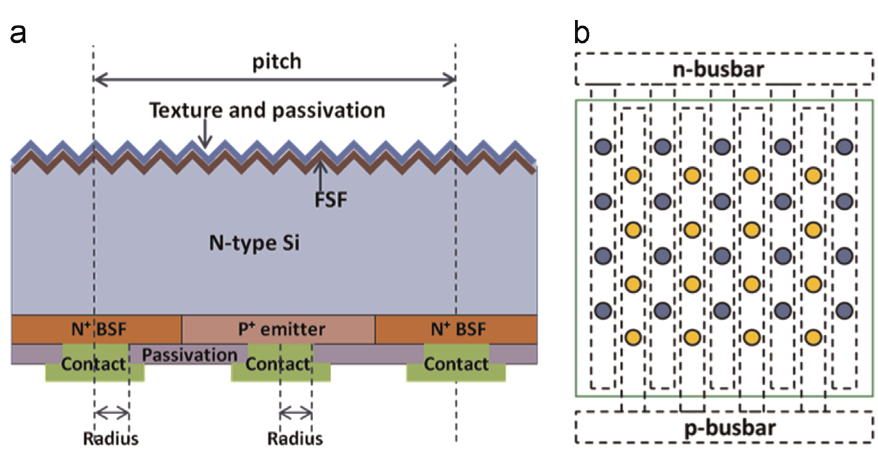

Fig. 1. (a) Structure of e-beam evaporated Al contact IBC solar cell. (b) Illustration of metallization (dotted line), and local contacts (circles). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)