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Towards ink-jet printed fine line front side metallization of crystalline silicon solar cells

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ABSTRACT

An ink-jet method for fabrication of fine and smooth front side highly conductive silver lines on crystalline Silicon substrate is described. The fabricated conductive silver lines on different substrates are characterized by means optical microscope, optical profilometers, scanning electron microscope (SEM), and electrical measurements. The *coffee-ring effect* is controlled by increasing the solid loading of the ink from 20 W% to 40 W% and printing at optimum substrate temperature (90–100 °C) and optimum printing parameters. Smooth printed conductive silver lines, with line thickness ranges from $0.8 \sim 0.9\ \mu m$ for single pass, are obtained. When increased substrate temperature, a significant reduction of spreading of ink was observed. And conductive silver lines obtained at optimum substrate temperature (90–100 °C), free of periodic wrinkles and line bleeding, are produced. The influence of annealing temperature on line resistance, the morphology and functionality of the printed conductive silver lines is optically and electrically analyzed. To deposit thicker lines multiple passes of ink-jet printing were done on polished single crystalline silicon (sc-Si) and standard alkaline (NaOH) textured n^+/p single crystalline silicon (n^+/p sc-Si). Moreover, the printed conductive silver lines are characterized optically and electrically. And, promising results in terms of printed line thickness and electrical property are achieved.

1. Introduction

Photovoltaic solar cells require a collector grid pattern on the front and rear sides of the processed silicon wafers. Thus, in the photovoltaic technology, fabrication of conductive lines is vital and inevitable. Screen printing has been the very successfully and the most commonly applied technique in industrial cell fabrication for the front side metallization of silicon solar cells. It is rather inexpensive, atmospheric printing technique and highly flexible as far as ink is concerned. However, in order to keep screen printing technique as the best available industrial fabrication tool for crystalline silicon solar cells front contact, as it has been almost for decades, it has to ensure the possibility to satisfy the fast growing interest of improving the efficiency of the solar cells at a low unit price. Otherwise, screen printing technique has to hand over its place to other emerging printing techniques, leaving behind its legacy.

The main starting point, among others, to increase the efficiency of the solar cells at a low unit price are both open circuit voltage V_{oc} and short circuit current density J_{sc} needed to be improved without a complexity and without any additional structuring processes. This may, for instance, be achieved by employing high sheet resistance emitters ($\rho_s \approx 100\ \Omega/sq$). Which then lowered the total series resistance (R_s) of the cell increased the fill factor. Currently, commercial screen-printed cells are fabricated on 35–50 Ω/sq emitters because it is difficult to achieve good screen-printed ohmic contacts on high sheet-resistance emitters [1–3]. So, high throughput is realized at the expense of fill factor (FF) and cell performance. As a consequence such high doping results lower short-circuit current or blue–response due to heavy-doping effects in the emitter, and poor front-surface passivation or higher emitter saturation current density (j_{oe}). Even on 30–45 Ω/sq emitters, the FFs are only approximately 0.75 in commercial screen-printed cells due to high series-resistance and/or junction shunting. One of the most technological efforts is to form a low-ohmic contact on lightly

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doped emitters (with a sheet resistance of $\geq 70\,\Omega/\text{sq}$) since lightly doped emitters are more transparent, which can lead to higher blue-response with good surface-passivation and reduced j_{oe}. Many different processes are being developed to achieve this goal, among the others, like firing optimization involving rapid firing at $\sim 800\,^{\circ}\text{C}$–$840\,^{\circ}\text{C}$ temperatures resulted in high FFs of ≥ 0.775 on a $100\,\Omega/\text{sq}$ emitters [4],use of selective emitter designs using a phosphorus source in the paste to achieve better particle dispersion in the region below the screen printed contacts during firing [5]. Moreover, by laser drilled opening and by modification of the screen printing process, maximum cell efficiency upto 16.1% are reached for mc-si metal wrap through solar cells (cell area: $125 \times 125\,\text{mm}^2$ and emitter sheet resistance: $65\,\Omega/\text{sq}$) [6]. Recently, a two-layer process: aerosol printed fine line followed by light-induced plating (LIP) to contact solar cells with an emitter sheet resistance as high as $130\,\Omega/\text{sq}$ with the resulted solar cell efficiency of 20.6% has been reported [7].

Another equally important solution to improve V_{oc} and J_{sc} is reducing power losses in the front side collecting grids. The power loss in front side collecting grids ultimately comes from optical losses (shading losses) and electrical losses. The first is due to reflection of incident light on the conducting metal grid, and the later is due to the line resistance and the metal-semiconductor contact resistance. As the result of which the total series resistance (R_S) of the cell rises, causing the fill factor to decline. Given that the value of resistance will depend on the area of the solar cell, when dealing with the series resistance of solar cells which may have different areas, a common unit for resistance is in $\Omega\,\text{cm}^2$ (which is the area-normalized resistance results from replacing current with current density in Ohm's law). The total series resistance (R_S) is the cumulative sum of different series resistances, which are: (i) the series resistance due to the bulk and the back contact (R_{BB}); (ii) the series resistance due to the sheet resistivity of the emitter (R_E); (iii) the series resistance due to the metal fingers (R_M); and (iv) the series resistance due to the specific contact resistance of the metal and the silicon emitter (R_C). The main impact of series resistance is to reduce the fill factor, although excessively high values may also reduce the short-circuit current. For conventional silicon based solar cells, processed by screen printed front-contact metallization and on 30–$45\,\Omega/\text{sq}$ emitters, the R_S, depending on the geometry of the solar cell, ranges between $0.5\,\Omega\,\text{cm}^2$ for laboratory type solar cells and up to $1.3\,\Omega\,\text{cm}^2$ for commercial solar cells. The contribution of R_C is in the order of $5 \times 10^{-3}\,\Omega\,\text{cm}^2$, and the front side resistance of the conventional cell of $120\,\mu\text{m}$ screen printed conductive line width is between 0.5–$0.6\,\Omega\,\text{cm}^2$ [8].

As the industrial size of processed cells becomes larger, (from $100 \times 100\,\text{mm}^2$ a few years ago to currently $\approx 156 \times 156\,\text{mm}^2$) the current increases. And in order to keep the resistivity losses due to the increased length of collecting grids low and insignificant, fine lines with a high aspect ratio (Height/Width) and high cross sectional area of the grid perpendicular to current flow have to be deposited. Depositing fine lines with a high aspect ratio could also, beyond keeping shadowing losses at a minimum, open up an opportunity to reduce the grid line separation distance to collect charge careers as efficient as possible. The conventional way of depositing front side grids by screen printing is, however, being operated at the maximum of what it is possible. For example, the lateral resolution (that is, width of the conductive grid $= W_l$) of a typical industrial screen printed front side grids is limited to the range of 110–$150\,\mu\text{m}$, which severely restraint reducing the grid line separation distance as it increases the shadowing losses proportionally.

Therefore, in order to bring up the efficiency of industrially produced silicon solar cells close to the efficiencies obtained in the laboratory, there is an increasing market demand for the development of convenient front side metallization techniques with high throughput and/or low overall cost.

Ink-jet printing technology, among the other printing techniques, is rapidly becoming as one of the most promising and the best alternative deposition techniques in comparison to screen printing [9,10]. The opportunities and the potential payoff, here are significant: - low cost with high throughput, mask less, fine line resolution, reduction in process complexity due to direct ink-jet printing patterning, reduced material wastage due to selective deposition of materials, avoidance of degradation of the p-n junction by firing at a low temperature, scalability to large area manufacturing and an off-contact technique [11,12]. These also make it suitable for processing fragile and thin film wafers. The printing speed of ink-jet printing is lower compare to other printing techniques such as screen printing. However, this disadvantage can be outweighed by its flexibility, rapid prototyping quality, and/or overall cost.

Nevertheless, despite the abovementioned opportunities and potential payoff, the practical use of ink-jet printing as a fabrication tool for highly efficient fine lines front side metallization of Si solar cells face overarching technological challenges. The critical issues that needed to be addressed and have great effect on the electrical and morphological properties of the printed pattern are:

I) Viable ink chemistry and formulation: - inks must be formulated to fit the physical and rheological requirements of fluid flow during the printing processes which in turn are functions of the viscosity, surface tension, solid loading, wettability, dispersion stability and volatility of the ink [13,14]. Ink chemistry and formulations, in addition to determining the jet-ability of the ink and compatibility with the print head system, they also have a determinant factor on the quality and functionality of the printed pattern.

II) Jetting/printing conditions: ink-jet printing depends critically on the behaviour of ejected printed drops after the jetting action. In fact, the behaviour of these ejected drops are mainly influenced by fluid properties (ink formulation); but they also are affected by several factors, including printer driving parameters (jetting conditions) and properties of the ambient medium. Printer driving parameters play a great role and should be tailored to adjust and to compensate a slight variation in fluid properties to ensure ink-jet printability, repeatability and reliability.

III) As-printed and post-printed treatment: as-printed and post-printed treatments, such as, sintering, firing, electrochemical treatment and, etc., have a great role on optimizing the functionality (in our case, the conductivity and mechanical strength) of the printed pattern. Therefore, these parameters have to be investigated to find the optimum condition of sintering, firing or further treatment of the printed patterns.

Consequently, detail study of the challenges and examine how one can select a suitable choice of inks and maximize processes that can realize ink-jet printed fine line front side metallization of solar cells is highly demanded. Solutions to these scientific challenges will not only allow metallization of solar cells but will also contribute to the issue of printing organic and inorganic active layers on a flexible substrate in solar cells technology and thinfilm electronics. This is the overall goal of our research project carried out by IM2NP research laboratory and IMPIKA private company.

One approach to deal with the above-mentioned ink-jet printing challenges is to tailor parameters of various operating conditions with regard to jetting, the rate of solvent evaporation versus hydrodynamic outward flow, and as-printed and post-printed treatment. Therefore, this work will present representative results, which we have obtained to date, on the effect of processing parameters such as substrate temperature (T_s), solid loading (W%), annealing temperature (T_A) and