PASTE DEVELOPMENT FOR LOW COST HIGH EFFICIENCY SILICON SOLAR CELLS

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ABSTRACT

Increasing cell efficiency and lowering the manufacturing cost is a continuous challenge in solar cell industries. Higher efficiency concepts like interdigitated back contact (IBC), emitter wrap through (EWT), and bifacial cells are ways to reduce the total solar cell manufacturing cost by increasing the solar cell efficiency. Typically the high efficiency concepts require costly extra processing steps. Developing the proper paste for printing application of high efficiency concepts could make these designs cost effective and reduce the manufacturing cost by using screen-printing technology. This paper describes newly developed low cost phosphorous, boron, and diffusion barrier pastes. It shows the characterization of the newly developed phosphorous paste (99-038), boron paste (99-033), and diffusion barrier paste (99-001). These low cost pastes can easily be printed using typical low cost screen-printing or ink jet printing methods. Another way to reduce solar cell manufacturing cost is to use thinner silicon wafers. Currently manufacturers are trying to use less than 200 μm thick silicon wafers. Newly developed aluminum boron (Al/B) paste is introduced as a low-bow lead-free replacement for typical Aluminum (Al) paste for 150 to 200 μm thick silicon wafers with less than 1.5 mm bowing.

INTRODUCTION

Silicon solar cell manufacturers want to reduce manufacturing cost by using thinner silicon wafers (less than 200 μm) and high efficiency solar cell concepts. A major problem with Silicon wafers below 200 um is bowing after Al back surface field (BSF) formation. A printable boron or Al/B paste that can form BSF at typical processing temperature is an ideal solution to wafer bowing. Boron paste makes it possible to use both p-type and n-type wafers in typical solar cell manufacturing. It also makes it possible to fabricate a bifacial solar cell by simultaneous diffusion of phosphorous and boron paste in a single diffusion step. Other high efficiency concepts like IBC cells and EWT cells need n^+ diffusion (phosphorous paste), p^+ diffusion (boron, Al, Al/B or Ag/Al paste) and a diffusion barrier paste to isolate the n^+ regions from the p^+ regions during contact formation. Diffusion barrier paste can easily be applied as the mask to isolate n^+ areas from the p^+ areas. The newly developed low-bow lead-free Al/B paste, phosphorous paste, boron and diffusion barrier paste by Ferro can pave the way for the next generation of low cost high efficiency solar cells.

EXPERIMENTAL

The phosphorous diffusion paste 99-038, Boron diffusion paste 99-033, and diffusion barrier paste 99-001 were developed and screen printed on 100 cm^2 CZ wafers with thickness of 300 μm and resistivity of 1 to 2 Ω-cm to investigate diffusion properties. All the pastes were screen-printed using a 200-mesh screen with emulsion thickness of 0.5 to 0.7 mils. Measured deposited weights are about 1 to 2 mg/cm^2 for all diffusion pastes that are dried at

200° C for 2 to 5 minutes. All the pastes were fired at different temperatures in air ambient using an infrared belt furnace. The resulting emitters were characterized by four-point probe. Depth profiles were measured using spreading resistance analysis.

Low-bow lead-free Al/B paste formulation involves finding an optimum in Al powder size, morphology, frit chemistry, organic and inorganic additives to make up the paste. Varieties of environmentally friendly organic and inorganic compounds were tested to improve sintering without increasing the bowing of silicon solar cells. An optimum paste formulation was engineered from the combination of all the additives and compounds. Adding boron to Al paste will make it possible to achieve higher concentration of p^+-doping in BSF with lower amount of Al paste. New Al/B paste can control BSF profile thickness and maximum doping concentration. The amount of paste deposited on silicon wafers determines the thickness of BSF layer and the alloying temperature controls the doping concentration from 3E18 to 9E19 cm^{-3}.

RESULTS

Phosphorous Paste

Figure 1 shows measured sheet resistance for phosphorous paste as a function of diffusion temperature for different phosphorous concentration. Measured minority carrier lifetime was improved after diffusion from 10 µsec to 25 µsec. Figure 2 shows the measured junction depth and surface concentration. Regions with higher phosphorous concentration had emitter depth of 0.4 µm and surface concentration greater than 10^{20} cm^{-3}. Regions with lower phosphorous concentration show shallower emitter depth of 0.15 um and surface concentration of 10^{19} cm^{-3}. This allows for selective emitter diffusion concept to be controlled by changing the phosphorous concentration and keeping the temperature constant.

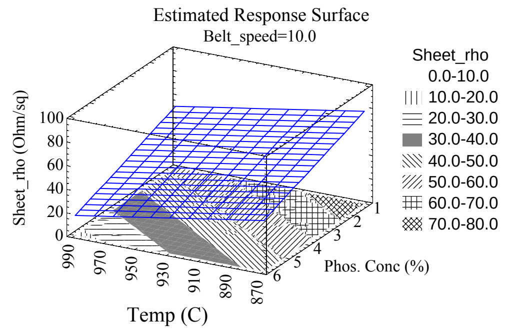

Fig. 1. phosphorus sheet resistance as a function of phosphorus concentration and diffusion temperature.

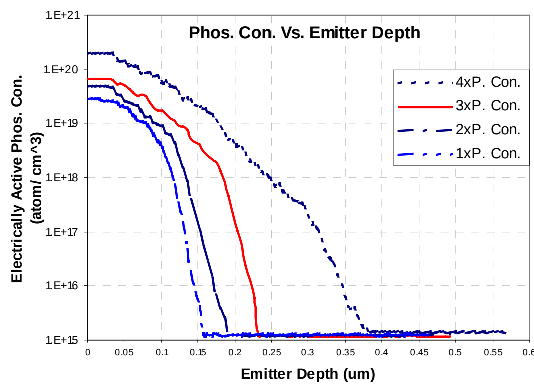

Fig. 2. Measured phosphorous concentration and emitter depth using spreading resistance technique.

Boron Paste

Figure 3 shows the measured sheet resistance and a linear model to describe the relationship between boron diffusion temperature and measured boron sheet resistance with 95% confidence limits. Figure 4 shows the measured junction depth and surface concentration. Boron paste and phosphorous paste can be printed and dried and co-diffused at the same time to get an emitter and a BSF. This is an inexpensive way to make bifacial solar cells.

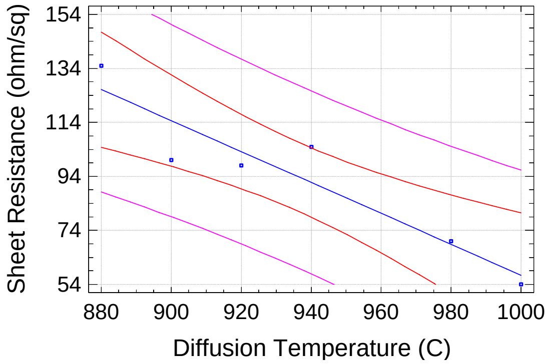

Fig. 3. Measured boron sheet resistance at different temperatures and a fitted linear

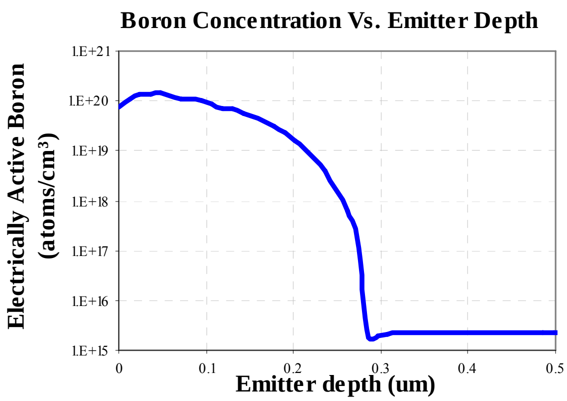

Fig. 4. Measured boron concentration and emitter depth using the spreading resistance technique.

Diffusion Barrier

99-001 developed diffusion barrier paste forms a TiO_2 layer after curing at 450 to 500°C. Silicon wafers were printed with diffusion barrier paste and after curing the diffusion barrier paste the wafers were screen printed with phosphorous paste. Then samples were heat treated at 980 °C for 5 minutes. Figure 5 shows spreading resistance measured after diffusion under the diffusion barrier layer. This shows that diffusion barrier 99-001 can easily be used to block phosphorous diffusion. 99-001 can lower the manufacturing cost of IBC type solar cells.

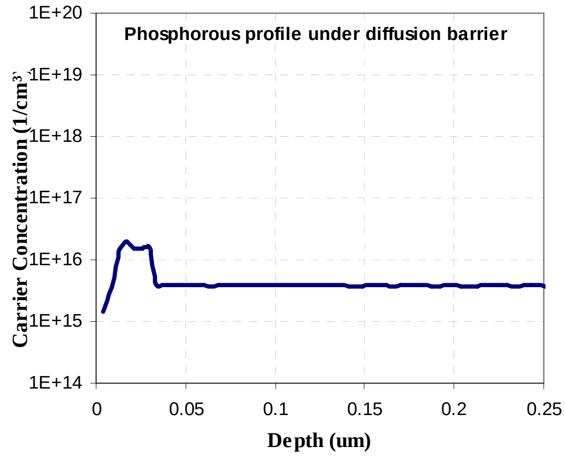

Fig. 5. Measured phosphorus concentration through diffusion barrier paste.

Low-Bow Lead-Free Al/B Paste

The screen printed alloyed aluminum BSF is the standard rear passivation and contact for more than 85% of industrial silicon solar cell production. Most manufacturers like to use thinner silicon wafers to reduce the production cost. In an industrial silicon solar cell process, a thick layer of about 30 to 60 µm of Al paste is screen printed onto the backside of Si wafer and fired at 750 to 850ºC for a few seconds to alloy Al and form p+-doping in silicon. The wafer bowing is caused by thick aluminum paste deposit and different thermal coefficients (CTE) of expansion of aluminum and silicon. Ferro Al/B paste is designed to reduce bowing by engineering the paste ingredients to minimize the CTE effect and be able to deposit less paste without losing rear surface passivation. Figure 6 shows modeling results for reducing effective surface recombination velocity by increasing the BSF doping. The new Al/B paste is formulated with a boron source that can provide higher concentration of p+ dopant during the Al alloying process. Al alloying process without boron is limited to solid solubility of Al in silicon. This results in doping concentration of 2 to 3E18 cm^{-3} at typical firing temperatures and belt speeds. Figure 7 shows the measured doping profile using the spreading resistance technique for Al/B paste. It shows that Al/B paste can yield a BSF layer with carrier concentration of one order of magnitude higher than Al doping profiles.

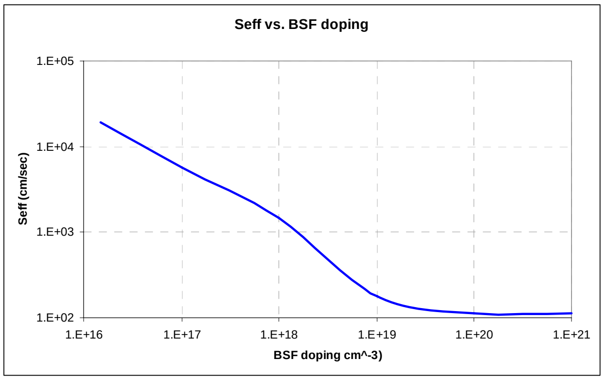

Fig. 6. PC1D modeling of effective surface recombination velocity vs. BSF doping

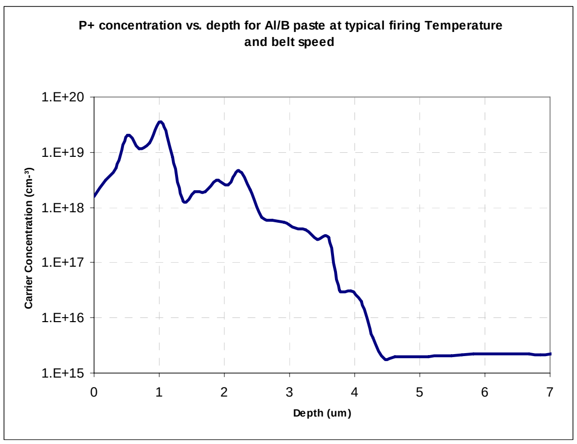

Fig. 7. Measured carrier concentration vs. BSF depth using spreading resistance method.

We have printed the newly developed Al/B paste on 6-inch square and 160 μm thick multi-crystalline wafers using a 200-mesh screen. The initial wet deposited weight is about 6.9 mg/cm^2 and after firing the deposited weight is about 4.9 mg/cm^2. The wafer is then co-fired at typical firing temperature at 120 IPM belt speed. The following table shows average measured electrical parameters for these cells:

Paste	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	Eff (%)
Al/B	603.4	32.9	76.1	15.1

The averaged bowing of these wafers ranges from 0.5 to 1.2 mm.

SUMMARY

Ferro has introduced the following diffusion related pastes: phosphorous paste 99-038, boron paste 99-033, and diffusion barrier paste 99-001. These new high quality diffusion pastes and diffusion barrier pastes can reduce manufacturing costs and make it possible to use less than 180 μm thick silicon wafers for selective emitter solar cells, IBC cells, emitter-wrap-through (EWT) cell design, and bifacial solar cell application. Also we have reported on the development of a new low-bow lead-free Al/B paste (53-120) for 150 to 200 μm thick silicon wafers.

REFERENCES

[1] J. Salami et al., "Self-aligned Locally Diffused Emitter (SALDE) Silicon Solar Cell" Solar Energy Materials and Solar Cells 48 (1997) 159-165
[2] R.A. Sinton et al, "Quasi-Steady State Photoconductance, a New Method for Solar Cell Materials and Device Characterization" Proc. 25th IEEE Photovoltaic Specialist Conference, Washington, pp. 457-460, 1996.
[3] J. Salami et al., "Characterization of Screen Printed Phosphorus Diffusion Paste for Silicon Solar Cells" Technical Digest of the International PVSEC-14, Bangkok, Thailand, 2004.
[4] G. Bueno et al., Proc. EPSEC-20, Barcelona 2005.
[5] H. Kerp et al, Proc. "Comparison of Two Different Methods to Construct Phosphorus Screen-printed Selective Emitters for Silicon Solar Cells" Proc. PVSEC-15, Shanghai 2005.
[6] P. Hacke et al, "Application of a Boron Source Diffusion Barrier for the Fabrication of Back Contact Solar Cells" proc. 31st IEEE PVSC, Florida 2005
[7] P. Lolgen et al., "Boron doping of silicon using coalloying with aluminum", Appl. Phys. Lett, Vol 65, No. 22, 28, P. 2792, November 1994.