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Lift-off Contact Separation Method for Rear Contact Solar Cells

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Abstract. *A method for isolating interdigitated metal contacts for rear contact solar cells using aerosol-printed polymer masking lines which can "lift off" overlying metal during a sonication step is described. Aluminum lift-off is demonstrated with masking lines formed by aerosol-printed novolac resin and polyacrylic acid. By printing novolac resin lines that are* ∼*10* μ*m high, lift-off of evaporated aluminum in an ultrasonic bath reliably resulted in 100 to 170* μ*m isolation gaps being formed between n-type and p-type rear contacts on different wafer surfaces. Performing this lift-off process using water-soluble polyacrylic acid lines may be advantageous due to the less expensive recovery of lift-off metal from the sonication bath. © 2012 Society for Imaging Science and Technology.*
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INTRODUCTION

Rear contact solar cells have metal contacts for both the n-type and p-type semiconductor regions on the rear surface of the cell. This feature enables the optical performance of solar cells to be decoupled from their electrical performance,[1] thus potentially simplifying solar cell designs. Furthermore, having both polarities of metal contacts on the rear surface can simplify cell interconnection in modules and hence reduce module fabrication costs. However, the existence of interdigitated metal contacts on a single surface necessitates a method that can robustly isolate the n-type and p-type contacts in a metal layer. Self-aligned approaches which achieve this isolation using a single layer of metal, such as aluminum, include the use of a titanium[1] or silicon dioxide capping layer[2] on a two-level structure and then selectively removing the aluminum at the flank where the aluminum is not protected by the capping layer using a wet chemical etching step. The disadvantages of these approaches are that (i) they require a two-level structure and (ii) the metal finger width is limited by the width of the groove.

Another possible contact separation approach is to form isolation lines under a thin metal layer and then lift off the metal overlying the isolation lines by immersion in a solvent for the material used to form the lines. The thin metal layer can then be thickened by metal plating. Lift-off is widely used in microelectronics and in the fabrication of high-efficiency solar cells in association with photolithography for metal structuring. To minimize the fabrication cost, lift-off approaches that do not rely on the use of photolithography have been developed. Mingirulli et al.[3] and Granek[4] used inkjet-printed hot-melt wax and screen-printed resist, respectively, to form isolation lines. However, the hot-melt wax is sensitive to the thermal impact of the metal deposition process, which results in restrictions on the evaporation rate and metal layer thickness. For the screen-printed resist method, the dissolution/stripping step can be slow, with Granek reporting the need to form small holes in the metal layer to assist the dissolution of the resist and subsequent metal lift-off.

In this article, we report on a rear metal contact isolation method which involves aerosol printing of masking polymer lines which can subsequently be used to "lift off" the overlying metal. The masking lines can be formed by aerosol printing of either a water-soluble or acetone-soluble polymer. An aluminum layer can be deposited (e.g., by sputtering, thermal evaporation or spraying) over the entire rear surface of the solar cell, and then isolation regions can be formed in this layer by sonicating the cell in a solvent for the printed polymer. The sonication results in the metal which lies above the printed polymer being lifted off, leaving isolation lines clear of both polymer and metal. This process is depicted in Figure 1.

The printing of masking lines, comprising (i) an acetone-soluble novolac resin and (ii) water-soluble polyacrylic acid (PAA), was performed using Optomec's aerosol jet printer (AJP). Novolac resin is a resist material that is commonly used in photolithographic patterning because photo-activated chemicals can be added to control the resin's solubility and hence enable it to be patterned by light exposure and used as an acid-resistant resist material. Since the masking polymer does not need to be patterned by light or be resistant to etchants, polymers other than resist materials can be used. For this reason we also report the use of PAA to form the masking lines. Since PAA is a water-soluble polymer, sonication can be performed using inexpensive aqueous solutions, and there is the potential to more easily separate and recycle aluminum waste in the sonication liquid. We show that isolation lines can be formed in 1–2 μm thick evaporated aluminum layers after sonication in an ultrasonic bath for ∼10 min. The advantage of this lift-off approach is that a two-level structure is not required for isolation, thus making the method also suitable for thin film devices. Furthermore, unlike the previously described methods which are sensitive to etching time, the

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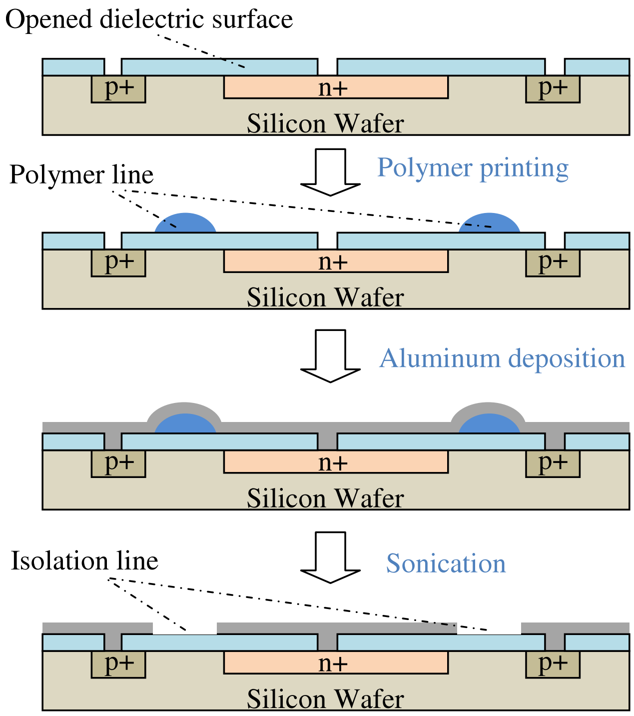


Figure 1. A schematic showing the steps involved in the lift-off process.

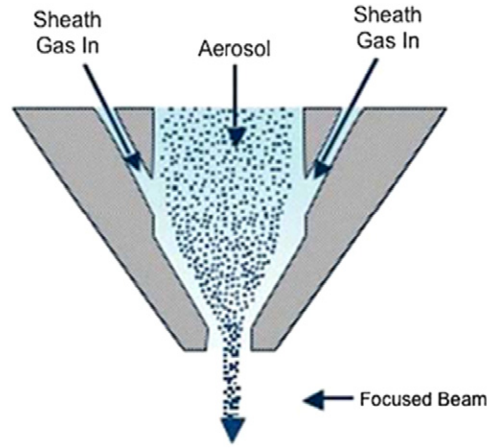


Figure 2. A schematic of atomized material flow and the sheath gas flow in the deposition head of an AJP (reproduced with permission from Optomec Inc.).

process is robust to variations in printed polymer height and sonication time, and therefore are amenable to a production environment. This method can potentially be used for contact isolation of metal electrodes on rear contact cells in which openings to rear p+ and n+ regions have been achieved using dielectric patterning approaches, such as the direct etching method.[5–7]

EXPERIMENTAL

The lift-off performance was assessed for different surface morphologies with experiments being performed using polished, planar, alkaline-textured and acidic-textured silicon wafer surfaces. For the planar surfaces, the effects of sawing damage were removed from the planar wafers by etching in 30% (w/v) NaOH for 20 min at a temperature of 80°C. All wafer surfaces were coated with a 75 nm silicon nitride layer, deposited using either direct or indirect plasma-enhanced chemical vapor deposition (PECVD). Silicon nitride is a commonly used dielectric layer for silicon solar cells, being employed both as a front surface antireflection coating and a rear passivation layer. For the alkaline-textured surfaces, the pyramid height was less than 4 μm, and, for the acidic-textured surface, the maximum surface height variation was 2.5 μm.

The novolac resin and the PAA were both printed using an Optomec AJP. Atomization of the print material for aerosol jet printing can be achieved using either an ultrasonic or pneumatic atomizer to form a fine mist of the material. A nitrogen carrier gas then transports this mist to the deposition head, where a focusing sheath gas is directed down the edges of the deposition head, as shown in Figure 2, to focus the aerosol stream on the substrate.

A 17% (w/v) solution of novolac resin in sulfolane was deposited using the pneumatic atomizer of the AJP. The optimization of the printing process for the lift-off process involved varying (i) the nozzle size, (ii) the sheath gas flow rate (SFR), (iii) the atomizer flow rate (AFR), (iv) the impact exhaust (IE), (v) the process speed, (vi) the platen temperature, and (vii) the number of deposited layers.

A solution of 1% (w/v) PAA was printed using the ultrasonic atomizer of the AJP. In addition to the above-mentioned advantages of using PAA as the masking polymer, material consumption is minimized by use of the ultrasonic atomizer, since there is no exhausting of generated excess aerosol as there is for the pneumatic atomizer. Approximately 1 mL of the 1% (w/v) PAA solution was added to the ultrasonic atomizer vial, and the atomizer voltage was set to 45 V to initiate aerosolization. After ∼20 min, the generated aerosol density inside the vial stabilized. For all experiments, the platen temperature was maintained at 50°C, and the temperature of the cooling bath was 25°C.

To evaluate the dependence of the lift-off performance on printed polymer line height and width, polymer lines were printed using different printing conditions. The heights and widths of the printed polymer lines were measured using a Dektak II profiler and an optical microscope, respectively.

Before thermal evaporation of the aluminum layer, wafers were cleaned by immersing in 1% (w/v) hydrofluoric acid (HF) for 1 min and then rinsed for 10 min in deionized (DI) water before being dried using a nitrogen gun. Approximately 24 6N-purity aluminum pellets were loaded into two tungsten evaporation boats, and aluminum layers having a thickness ranging from 0.5 μm to 2.5 μm were evaporated at a pressure of approximately 2×10^{-5} Torr to determine the influence of aluminum thickness on the lift-off performance.

Sonication (for lift-off) was performed inside a 40 kHz ultrasonic cleaner, as shown in Figure 3. Wafers were supported by a pair of tweezers in a beaker of solvent with the aluminum surface facing downward, as shown in Fig. 3. The water level outside the beaker was ∼1.5 cm, whereas

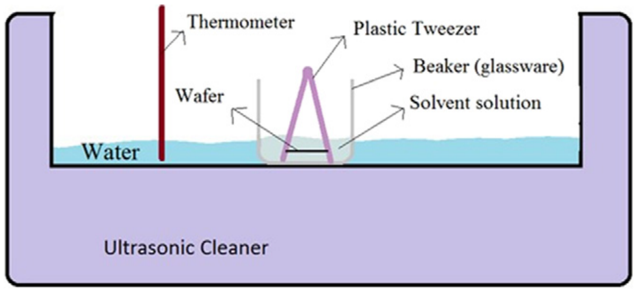


Figure 3. Schematic diagram showing the set up for the sonication process.

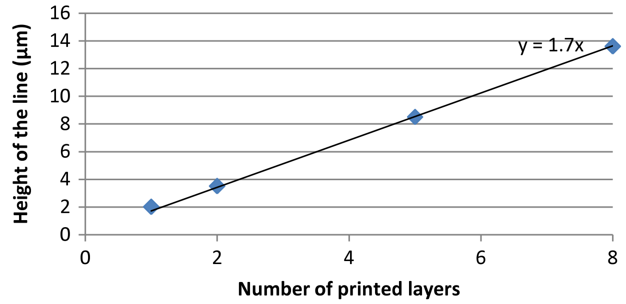


Figure 5. The relationship between the number of printed layers and the resulting height of a printed novolac line when the processing velocity was 5 mm/s on a silicon nitride surface of an alkaline-textured monocrystalline silicon wafer. Other printing parameters were (i) SFR = 30 sccm, (ii) AFR = 1930 sccm, (iii) IE = 1900 sccm, and (iv) 200 μm nozzle.

the solvent level inside the beaker was 1.5–2 cm. It was found that, if the wafer contacted the bottom of the beaker, its effective minority carrier lifetime was decreased. The temperature of the bath was controlled by water circulation. The heating function of the ultrasonic cleaner was used to maintain a constant temperature; however, for low sonication temperatures it was necessary to add ice to the recycling water bath.

The lift-off performance was assessed by defining the lift-off percentage as the fraction of line length over which complete lift-off occurred to the total length of the line. The objective of the optimization was therefore to minimize the sonication time required to achieve 100% lift-off.

RESULTS

Novolac resin masking lines

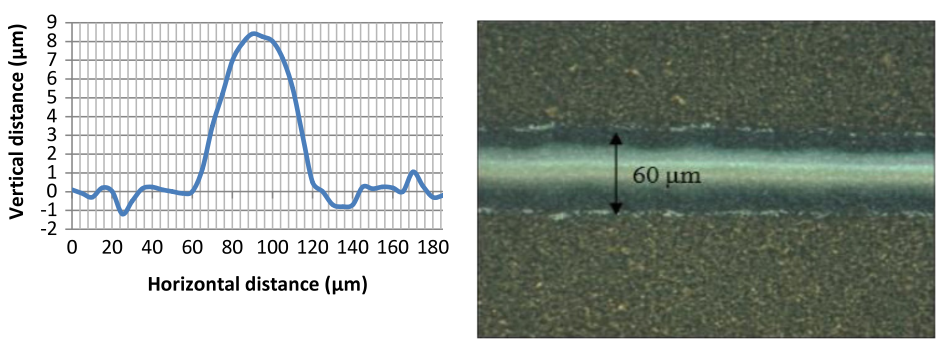
Initial experiments indicated that, as the platen temperature was increased, the morphology of the printed polymer lines improved and the discontinuities of printed polymer that were observed at lower temperatures were eliminated. Thus, in order to maintain the parabolic shape of the printed line, it was found that the platen temperature should be greater than 120°C. A cross-sectional profile, recorded by a Dektak II Profiler, of a printed novolac resin line when the platen temperature was 150°C is shown in Figure 4(a). An optical microscope image of that printed line is shown in Fig. 4(b).

The height of printed novolac resin masking lines can be increased by either printing more layers or using a lower AJP process velocity. However, if the process velocity is too low, resulting in too much aerosol being deposited, then, instead of increasing the line height, the excess material spreads laterally. If the process velocity exceeded 5 mm/s, then the height of the line increased linearly (1.7 μm/layer) as the number of printed layers increased (as shown in Figure 5).

The material flow rate exiting the nozzle is determined by the difference between the AFR and IE. Consequently, having a high AFR and IE only results in more wasted (exhausted) material. The optimal AFR and IE flow rates were found to be 830 and 800 sccm, respectively. Furthermore, it was found that use of a 200 μm diameter nozzle resulted in wider lines and decreased the possibility of the tip becoming clogged. The final optimized AJP settings for the printing of the novolac resin using the pneumatic atomizer were (i) 200 μm nozzle, (ii) SFR of 30 sccm, (iii) AFR of 830 sccm, (iv) IE of 800 sccm, (v) 8 mm/s printing speed, and (vi) 150°C platen temperature. This resulted in ∼1.2 μm height gains in the masking line per printed layer, and the width of the resulting polymer lines was ∼110 μm.

PAA masking lines

As observed in previous reports involving inkjet printing of dilute polymer solutions, the printed PAA line had a “humped” cross-sectional profile [see Figure 6(a)]. This



(a) (b)

Figure 4. (a) Dektak profile and (b) optical image of a novolac resin line that was formed by printing four layers of 17% (w/v) solution of novolac resin in sulfolane on a silicon nitride surface of an alkaline-textured monocrystalline silicon wafer. A 200 μm diameter nozzle was used for the printing and the AJP settings used were (i) SFR = 30 sccm, (ii) AFR = 1930 sccm, (iii) IE = 1900 sccm, and (iv) 1 mm/s process speed.

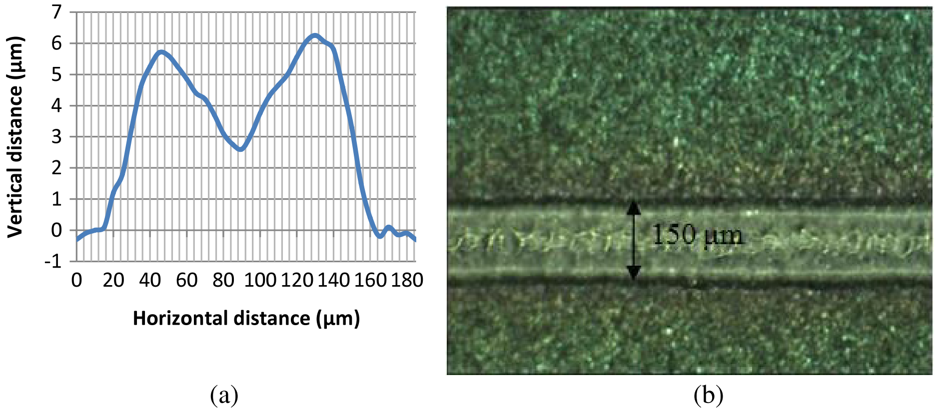


Figure 6. (a) Dektak profile and (b) optical image of a printed PAA line. The lines were achieved by printing 8 layers of 1% (w/v) PAA solution on an acidic-textured multicrystalline wafer using a 150 μm nozzle. The AJP settings used were (i) SFR = 20 sccm, (ii) AFR = 30 sccm, and (iii) 5 mm/s process velocity.

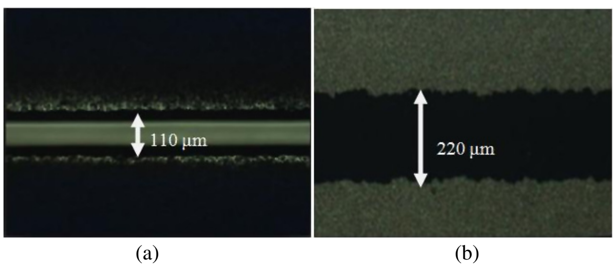


Figure 7. (a) Optical microscope image of a printed PAA line with 12.5 μm height after printing and (b) its corresponding isolation line after lift-off. The printed line in (a) was formed by printing 12 layers of 1% (w/v) PAA solution at a process velocity of 3 mm/s. Other printing parameters were (i) SFR = 20 sccm, (ii) AFR = 30 sccm, and (iii) 200 μm nozzle. The aluminum layer thickness is 1.5 μm and lift-off was performed in 30°C solution for 15 min.

shape has been attributed to the "coffee-ring" effect with inkjet-printed polymer structures.[8] Given that the PAA concentration was very low in these experiments, it is likely that the there was sufficient water retained in the deposited polymer to result in a similar effect contributing to the shape of the deposited PAA lines. If the height of the printed PAA line was greater than 15 μm (achieved by printing more than 12 layers), the cross-sectional profile became more parabolic (i.e., the "humps" were no longer evident). The "humped" profile of the printed PAA lines did not appear to significantly impact the lift-off performance using PAA masking lines.

The printing of PAA masking lines has some disadvantages compared with the printing of novolac resin lines. First, due to the low PAA concentration in the printed solution, it was difficult to achieve significant height gains per layer, as a large weight fraction of the deposited material was solvent which was removed by evaporation. Second, there was more variability between experiments in the printing of the PAA masking lines than observed with the printed novolac resin lines, suggesting more variability in the aerosolization process using the ultrasonic atomizer. Finally, the printed line spreads on contacting the wafer and the presence of small PAA particles that are deposited at the edges of the lines can result in isolation lines after lift-off [shown in Figure 7(b)] that are ∼100 μm wider than the printed PAA lines [shown in Fig. 7(a)].

So, although it was considered advantageous to be able to perform the lift-off using aqueous solutions, due to the above reasons novolac resin was selected as the masking polymer for the subsequent experiments reported. It is possible, with further refinement of the method of printing PAA, that PAA may in the future represent a viable material for the printing of masking lines. Furthermore, other polymers which can be deposited at a higher throughput rate could also be potentially used in the future.

The effect of isolation line height and width

In general, as the cross-sectional area of the printed masking polymer line increased, it became easier to lift off the aluminum above the line. One way to increase the cross-sectional area of the polymer line is to print more layers. As the number of printed layers increased, the width of the masking lines increased. Figure 8 shows the lift-off percentage as a function of sonication time for different heights and widths of printed novolac resin lines. The resin lines were printed on an alkaline-textured monocrystalline silicon surface that had residual periodic variations in height due to the wire-sawing process, subsequently referred to as "saw lines".

On the alkaline-textured monocrystalline silicon surface (with saw lines), if 1.2 μm of aluminum was evaporated over the printed lines then the minimum height of the novolac resin required was 3 μm (width of 97 μm) to achieve 100% lift-off within 10 min sonication. However, reliable 100% lift-off is required in order to avoid shunting of the final interdigitated rear contact cells. Consequently, to ensure reliable lift-off it was decided to use masking lines that were ∼10 μm in height with a width larger than 80 μm. This required the printing of 8 layers of the novolac resin solution using the optimized AJP novolac resin printing parameters.

Another approach that can be used to increase the cross-sectional area of the polymer lines is to print multiple lines adjacent to each other to form a much wider line. Experimental results indicated that this approach could

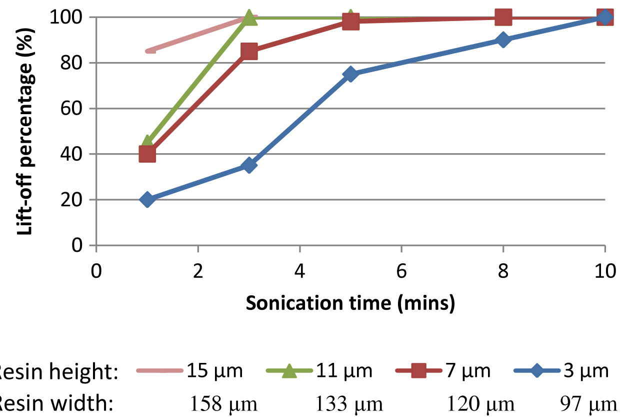


Figure 8. Lift-off percentage as a function of sonication time for different heights of the printed novolac resin lines on an alkaline-textured monocrystalline silicon surface (with saw lines). The aluminum layer thickness was 1.2 μm and the lift-off solution temperature was 20°C.

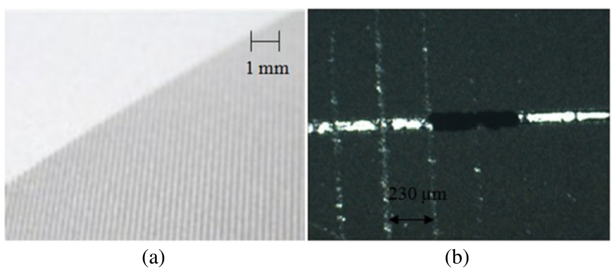


Figure 9. (a) Visible saw lines on monocrystalline wafers and (b) the negative influence of the saw lines on the lift-off process if the masking line is not sufficiently thick and wide.

enhance the lift-off to some extent. However, if using the same printing time, the lift-off performance using this approach was inferior to the approach described above, which involves the printing of a single line. In addition, wider masking lines result in wider isolation lines and hence thinner metal fingers, thus necessitating thicker metal layers to minimize series resistance in the final devices.

The effect of surface morphology

Many monocrystalline wafers exhibit visible saw lines [shown in Figure 9(a)]. The variation in surface height can be as much as 4 μm on the saw line regions. If the masking line is printed across the saw lines and the deposited masking line is not thick and wide enough to cover the top of the saw lines properly, the lift-off process may be impeded, as shown in Fig. 9(b). The novolac resin line in Fig. 9(b) was 4 μm high and 60 μm wide. This result demonstrated the dependence of the lift-off process on the surface morphology. The lift-off percentage versus sonication time for five kinds of surface is shown in Figure 10. The novolac resin lines were all ∼7 μm high and ∼130 μm wide.

As shown above, the best lift-off performance was achieved from the alkaline-textured surface with saw lines. This indicated that, if the masking novolac resin lines are thick and wide enough, a rougher surface can enhance the lift-off. Both the acidic-textured and the alkaline-textured

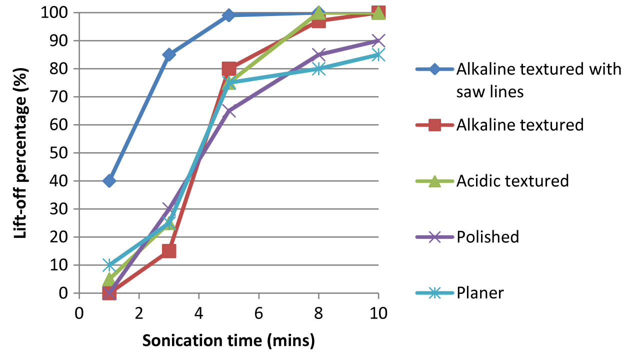


Figure 10. Lift-off percentage versus sonication time for five different silicon nitride coated surfaces with the same masking line height and width. The aluminum layer thickness was 1.2 μm and the lift-off solution temperature was 20°C.

Table I. The lift-off percentage after 15 min sonication at temperatures of 20°C and 50°C for different novolac resin line heights and widths.

	Masking novolac resin line height and width:			
	Height: 3 μm Width: 30 μm	Height: 3 μm Width: 60 μm	Height: 6 μm Width: 35 μm	Height: 6 μm Width: 65 μm
20°C	93%	100%	96%	100%
50°C	0%	0%	0%	40%

surfaces (without the saw lines) resulted in 100% lift-off within 10 min. However, for the polished and planar surfaces, 100% lift-off cannot be achieved within 10 min. Complete lift-off can occur for these surfaces if the masking lines are higher than 10 μm; however, under these conditions some aluminum regions which are not masked by the resin are occasionally removed.

To conclude, as long as the masking novolac resin is sufficiently thick and wide, rougher surfaces reduce the required sonication time necessary to achieve 100% lift-off. This is because (i) rougher surfaces can enhance the dissolution of the solvent and also possibly enhance the transport of the suspended aluminum layer away from the surface, and (ii) rougher surfaces may improve the adhesion of the aluminum to the non-polymer coated regions.

This is a promising result for commercial photovoltaic applications, because it means that the lift-off contact separation method described in this article can be applied to commercially textured wafers which have defects such as the wire saw marks. Furthermore, the process does not require that the rear surface of a textured wafer be planarized to achieve contact separation.

The effect of sonication temperature on lift-off

The effect of sonication temperature on lift-off was determined by comparing the lift-off performance at sonication temperatures of 20°C and 50°C (see Table I). It was concluded that, by using a lower solvent temperature, 100% lift-off can be achieved in a shorter time. Improved temperature control of the sonication bath will enable the optimum lift-off temperature to be determined.

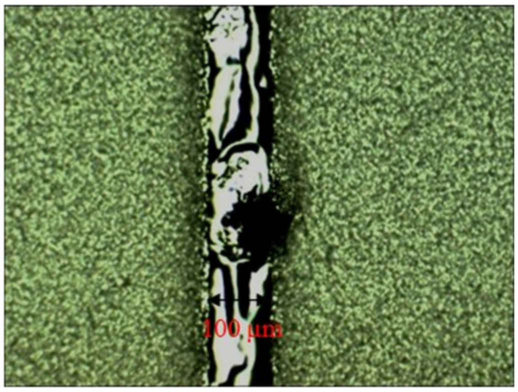


Figure 11. Optical microscope image of a resin line with a height of 10 μm covered by aluminum after 5 s sonication. On the creation of a crack in the metal, the exposed masking polymer begins to dissolve.

Microscopic mechanism

In the first few seconds of sonication, it is proposed that some small cracks in the aluminum surface are induced by the sonication process. These cracks occur where the stress in the aluminum layer is greatest (i.e., where the aluminum covers the masking line or on the border of the aluminum, polymer and textured silicon surface), as shown in Figure 11. The solvent then permeates through these cracks and dissolves the printed polymer inside near the crack, further weakening the aluminum covering the polymer lines. Once the aluminum over the sides of the polymer lines is removed, the metal is easily lifted from the surface and transported away from the surface. Once the lift-off is initiated at isolated spots, the dissolution of the polymer (with subsequent aluminum lift-off) can proceed along the lines.

CONCLUSION

A lift-off method which can be used to separate electrodes of different polarity for interdigitated rear contact solar cells was described. Compared to other contact separation methods for rear contact cells, the method involves fewer steps, consumes small quantities of chemicals, and is more tolerant of process variation. Results presented in this article demonstrate that the method can be used to form reliable isolation lines with a width of 80–160 μm on different kinds of surface. Although the contact angle of the printed novolac resin lines is less than 90° and the lines are totally covered by the evaporated metal, 100% lift-off of the overlying aluminum can be reliably achieved in less than 10 min for all wafer surfaces trialed by adjusting the polymer height and sonication time.

Two kinds of masking polymer were studied, although superior lift-off performance was observed by printing novolac resin isolation lines. However, future use of the water-soluble PAA may have benefits with respect to waste management and recovery of aluminum which remains in the sonication bath after the lift-off process. Future work is required to (i) identify alternative masking polymers that could be used to increase the throughput, (ii) evaluate the lift-off performance on different types of dielectric layer, and (iii) apply this technique to rear contact solar cells.

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REFERENCES

[1] R. A. Sinton and R. M. Swanson, "Simplified backside-contact solar cells," IEEE Trans. Electron Devices **37**, 348–352 (1990).

[2] P. Engelhart, N.-P. Harder, R. Grischke, A. Merkle, R. Meyer, and R. Brendel, "Laser structuring for back junction silicon solar cells," Prog. Photovolt.: Res. Appl. **15**, 237–243 (2007).

[3] N. Mingirulli, R. Keding, J. Specht, A. Fallisch, D. Stuwe, and D. Biro, "Hot-melt inkjet as masking technology for back-contacted cells," *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*, vol., no., pp. 001064–001068 (2009).

[4] F. Granek, *High-Efficiency Back-Contact Back-Junction Silicon Solar Cells*, München: Verlag Dr. Hut, 2010, 206 pp.

[5] A. J. Lennon, A. W. Y Ho-Baillie, and S. R. Wenham, "Direct patterned etching of silicon dioxide and silicon nitride dielectric layers by inkjet printing," Sol. Energy Mater. Sol. Cells **93**, 1865–1874 (2009).

[6] J. Rodriguez, "Direct etching - targeting commercial photovoltaic applications," *Proc. NIP27 and Digital Fabrication 2011* (IS&T, Springfield, VA, 2011).

[7] J. Rodriguez, A. J. Lennon, M. Luo, Z. Li, Y. Yao, P. H. Lu, C. Chan, and S. R. Wenham, "Dielectric patterning using aerosol jet printing," J. Imaging Sci. Technol. **56**, 040502-1–040502-7 (2012).

[8] D. Soltman and V. Subramanian, "Inkjet-printed line morphologies and temperature control of the coffee ring effect," Langmuir **24**, 2224–2231 (2008).