Inkjet Printing of Isolation Layers for Back-Contacted Silicon-Heterojunction Solar Cells

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Abstract

For wafer based silicon solar cells, the combination of amorphous/crystalline silicon (a-Si:H/c-Si) heterojunction emitters (SHJ) [1] and back-contacted back-junction solar cell concepts (BCBJ) [2] offer a very high efficiency potential of around 24%. Stangl et al. proposed a relatively simple and therefore attractive cell concept comprising a two level metallization isolated by an insulation layer. The emitter layer consisting of doped amorphous silicon with a thickness of several nm and the emitter metallization layer comprise circular openings where the back surface field layers and the respective metallization establish contact to the absorber.

In this work the potential of inkjet printing for the deposition of the isolation layer with photoresists or other polymeric fluids is evaluated. Challenges are the required placement precision and the feature size. In order to produce circular openings of the order 10 µm, the drop formation has to be optimized, and the ink spreading on both surfaces - on the aluminum emitter and on the silicon wafer substrate - have to be controlled.

Introduction

For wafer based silicon solar cells, the combination of amorphous/crystalline silicon (a-Si:H/c-Si) heterojunction emitters (SHJ) [1] and back-contacted back-junction solar cell concepts (BCBJ) [2] offer a very high efficiency potential of around 24% [3] due to the high V_{oc} values enabled by silicon heterojunctions in conjunction with the excellent short circuit current of BCBJ solar cells. In addition, one-sided a-Si:H/c-Si hetero contact systems can be relevant in crystalline thin-film Si photovoltaics if the bulk carrier lifetime in the thin film absorber material is high enough, such that the cell benefits from the reduced surface recombination at the heterojunction.

Figure 1 displays schematic cross sections of the solar cell investigated in this approach as proposed by Stangl et al (Point Rear Contacted Amorphous-crystalline Silicon Heterojunction). The front side is coated with an anti-reflection coating which also serves as passivation layer. The crystalline silicon substrate (here n-type, polarities are interchangeable) is textured with random pyramids on the front side in order to further enhance the absorption of the incoming light. The emitter layer consists of (p/n)-doped amorphous silicon with a thickness of several nm. Amorphous silicon layers provide an excellent surface passivation of the crystal and a good selectivity regarding charge carrier collection, enabling the aforementioned high V_{oc} values. The emitter is contacted with a first metal layer. Emitter and metallization layer comprise circle openings where the back surface field layer, consisting of n-doped amorphous silicon and the respective metallization establish contact to the absorber (see horizontal cross section on the left of Figure 1). Thus the two polarities must be isolated in order to avoid parasitic current paths from the emitter metallization to the BSF metallization, which significantly decrease the solar cell performance.

The fabrication process is shown schematically in Figure 2. After a single sided texturization, realized by masking one side against the wet-chemical texturization bath consisting of potassium hydroxide and isopropanole the front side is coated with a SiN_x antireflection coating for passivation and antireflection purposes.

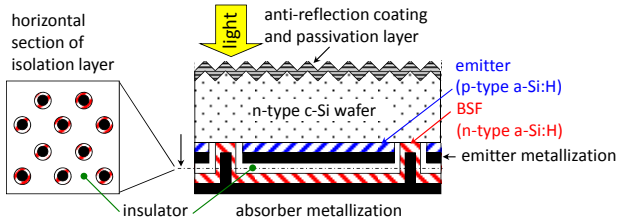

Figure 1: Cell architecture of PRECASH solar cell concept. The emitter (blue) and back-surface field (red) is formed by amorphous silicon layers of a thickness in the range of 10nm. The emitter is contacted with a first layer of metal. The emitter layer and its metallization comprise circle openings where the back-surface field layer and its metallization contact the absorber. Between the first metal layer and the amorphous BSF-layer an isolation layer is required.

After a cleaning step the amorphous emitter layer is deposited on the rear side by plasma enhanced chemical vapour deposition (PECVD). Subsequently the emitter is metalized with aluminium by physical vapour deposition (PVD). The layer stack is masked by photolithography and etched such that circle openings are created. The first metal layer is then covered with an isolation layer and the amorphous silicon back-surface field layer is deposited by PECVD at around 200°C. The last step comprises the physical vapour deposition of the second metal layer for BSF metallization.

This work aims at finding means of replacing the photolithographic step for generating the circular openings as well as depositing the isolation layer. The deposit should - after appropriate baking - provide electrical isolation of the first metal layer and BSF-layer and the second metal layer as well as vacuum stability (no outgassing at temperatures lower than 200°C to avoid contamination of PECVD-chambers).

Inkjet printing offers a variety of benefits as well as challenges due to its purely additive nature. The benefits present themselves in the ability to dispense a variety of materials from the liquid phase with a negligible amount of waste as well as fully digital material

mask&wet chemistry	single sided texturisation
PECVD	SiN_x anti-reflection coating & front side passivation
PECVD	a-Si:H(p/n) emitter deposition
PVD	metal depostion
mask & wet chemistry	patterning of emitter and emitter metallization
inkjetting mask	deposition of isolation layer
PECVD	deposition of a-Si:H(n/p) back-surface field layer
PVD	metal depostion

Figure 2: Schematic process flow (simplified). In the left column the technologies used for the process steps on the right are indicated.

deposition within the resolution of the process. The challenges are typically found in the amount of the functional material present in the inks, due to the viscosity limits of drop-on-demand (DoD) inkjet, the drying characteristics in the printhead as well as spreading and drying nature of the deposit on the substrate.

Liquid phase materials for the generation of insulation layers are abundant in the filed of photolithography and spin coating, where it is essential to evaporate the carrier solvent of the material quickly in order to generate homogeneous thin films. Applying such materials using DOD inkjet technology is typically complicated by the drying of these materials, resulting in either a change in the acoustic impedance at the nozzle or the physical blockage of the channel, calling for elaborate maintenance of the printhead and, therefore, downtime. Alternatives can be found in the area of graphic arts, where solvent inks formulations as well as UV-curable ink systems have been applied for many years. These two ink systems with insulating properties in the cured state are evaluated here for the application in the generation of insulating layers for back-contacted silicon heterojunction solar cells. The paper discusses their properties with respect to their compatibility with the DoD technology, their latency behavior and jetting characteristics.

Experimental

A solvent-based fluid *AZ520D* (Micro Chemicals, Germany) as well as a UV curable resist, *InkEpo* (Micro Resist Technology, Germany) were used in the study. Viscosity adaptation was carried out using PGMEA and butyl-l-lactate (Sigma Aldrich, Germany). Shear and temperature dependent rheology of the fluids was assessed using a plate-cone rheometer (CSL2-100, TA Instruments, USA).

Jetting experiments were conducted using a Xaar126 printhead with a nominal droplet volume of 50 pL. Droplet formation was studied using an in-house developed stroboscopic tool using sub-microsecond length light pulses from a triggered red high power LED. Temperature of the fluid was measured using the built-in temperature sensor of the printhead and controlled using a Peltier element. The meniscus pressure was set to -8 mbar.

Rheology

Typical viscosities of the solvent-based were found to be in the range of 50 mPas at room temperature, while typical viscosities jetted from Xaar-type printheads are in the range of 8-12 mPas in order to reduce the viscosity-induced damping of the acoustic energy in the channel and enable acoustic firing. While elevated temperatures may be utilized to reduce the viscosity, the fluid under consideration was highly volatile. Therefore, elevating the temperature of the fluid will increase its vapor pressure and, hence, increase the possibility of nozzle clogging [4].

The issue was, therefore, approached by adding appropriate solvents with high boiling points. This decreased the viscosity at room temperature at the expense of depositing a reduced amount of functional material at a given drop volume-DPI combination.

Figure 3 shows the depletion of the viscosity of *AZ520D* as the weight percentage of the added solvent increases. One can clearly discern the more rapid reduction using PGMEA than with butyl-l-lactate, due to its low viscosity nature. Additions of approx. 15 wt% PGMEA show viscosities optimal for Xaar-type DoD printheads. However, its boiling point is too low and, therefore, butyl-l-lactate appeared a more viable option for omitting deviations induced by latency, which is refers to the time to allow the printhead to idle with effortless subsequent start-up. Figure 3 also shows the behavior *AZ520D* with butyl-l-lactate as added solvent. The reduction of the room temperature viscosity is less pronounced, due to the characteristic viscosity of the solvent. The trend indicates that jetable values will be reached at 45 to 50 wt% additional solvent.

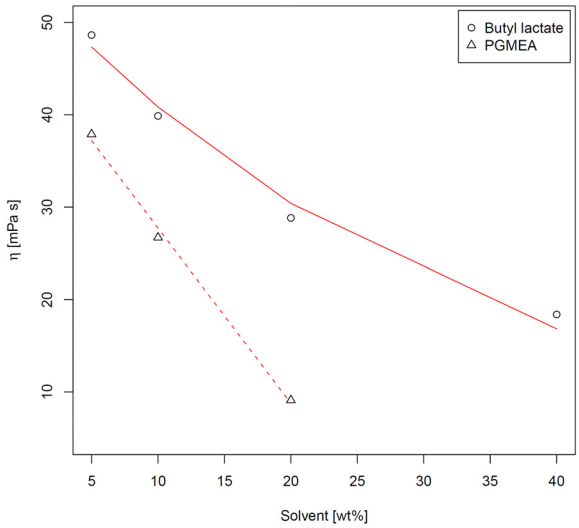

Figure 3: Viscosity vs. amount of added solvent for AZ520D at room temperature [shear stress constant at 1500 s^{-1}, 6 cm diameter, 1 degree]

Figure 4 shows the temperature response of the UV-curable system *InkEpo*. In contrast to the fluid discussed above a modification of the ink is not necessary, as these monomer-based systems exhibit rather low volatility and lend themselves to viscosity adjustment via temperature.

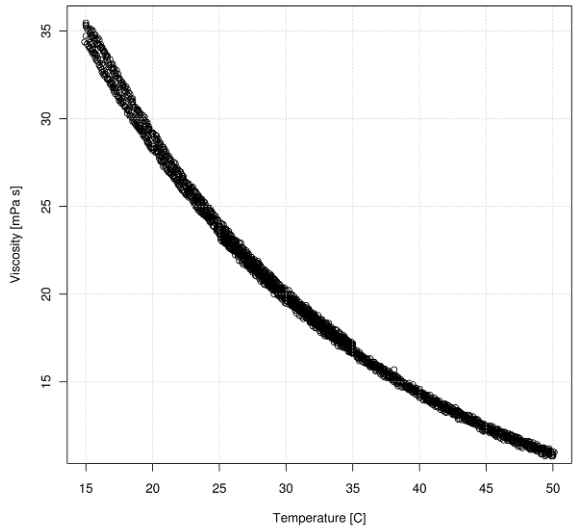

Figure 4: Temperature viscosity characteristic for InkEpo [shear stress constant at 1500 s^{-1}, 6 cm diameter, 1 degree]

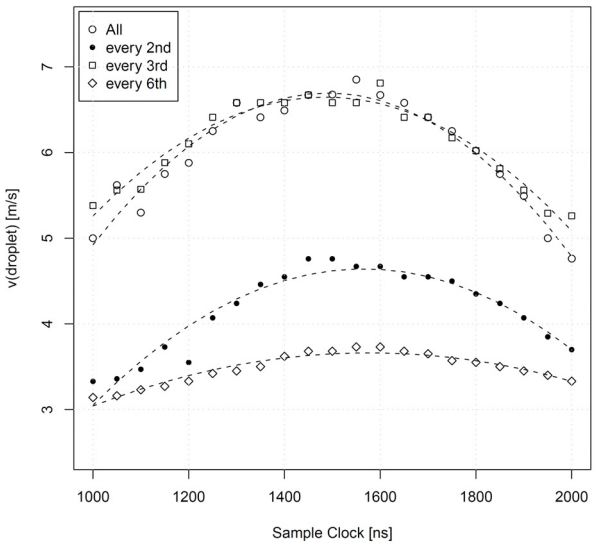

Figure 5: Response curves a mixture of 60 wt% AZ520D and 40 wt% Butyl-l-lactate

This system exhibits an additional advantage as a consequence of its higher viscosity at room temperature. Due to its high surface area to volume ratio, the droplet cools down during its trajectory from the nozzle to substrate. This increases the viscosity and, therefore, results in a higher amount of kinetic energy dissipated in viscous friction and, hence, allows for finer features. It has been shown in the literature, that evaporation may be used to reduce the feature size with solvent-based systems [5], however, at the expense of higher throw distances, which may reduce placement accuracy due to enhanced Stokes friction as well as increased influence from intrinsic angle deviations.

Jetting Experiments

Droplet formation was observed using a special waveform. As the acoustics of the channel are connected to the efficiency of ejection, as well as the propagation of perturbations causing the disintegration of the emerging jet, changing the overall length of the driving signal by means of the sample clock timing is expected to influence droplet speed and satellite formation.

The response of the actuator to these changes using a mixture of 60 wt% *AZ520D* and 40 wt% butyl-l-lactate is shown in Figure 5. The parabolic nature of the velocity profile as a function of sample clock timing clearly illustrates the optimization of the driving signal to the acoustics of the channel. The depiction, furthermore, illustrates crosstalk phenomena, where the droplet velocity increases when firing channels simultaneously and the velocity reduces when applying firing pulses to adjacent phases or distant nozzles of the same phase [6], resulting in a deviating landing position. Depending on the substrate velocity applied in the process this phenomenon has to be minimized in order to have highly reliable placement accuracies. The slight misalignment in the maxima originates from insufficient cooling of the actuator during 100% firing experiments. The drop in viscosity resulted in a reduced compliance of the actuator, which lowers the effective speed of sound in the channel [7].

Figure 6 shows the jetting performance of the mixture at different sample clock timings, when the applied voltage to the piezoelectric walls was tuned to give 6 m/s. As can be seen, shorter timings not only give reduced droplet velocities, but also reduce the number of satellites, which is highly desirable. With better matching between the electrical driving signal and the acoustics of the channel, longer ligaments are observed, which disintegrate erratically due to perturbation and the superimposed residual energy.

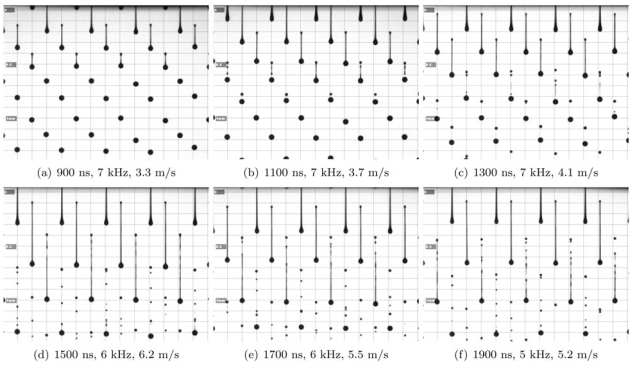

Figure 6: Jetting photographs of a mixture of 60 wt% AZ520D and 40 wt% Butyl-l-lactate at different sample clock timings [room temperature]

Figure 7 illustrates the stability of droplet formation at 7, 6 and 5 kHz, which relates to the maximum frequency of the waveform-sample clock timing constellation. Again, low sample clock timings enable a stable ejection when firing 100% patterns. The transition phase towards higher droplet velocities is characterized by occasional loss of channels, which makes sample clock timings of 1100 ns and 1300 ns unfavorable for printing of functional layers. Higher sample clock timings show stable behavior at the highest possible frequency, but exhibit an erratic jitter, which may lead to grouping of droplets or discontinuity in line features.

Interestingly, the longest timing at its full frequency shows stable behavior, indicated by the sharp projection of the leading drop, but preserves the disadvantageous characteristic of a high satellites density.

The UV-curable fluid, *InkEpo*, was subjected to similar iterations as discussed above. However, no optimal settings could be found using the developed waveform (cf. Figure 8 (a)). Therefore, a waveform generating a special time-dependent pressure profile was developed for the fluid, based on the assessed optimal sample clock timing of 1300 ns. Figure 8 (b) shows the result of the waveform optimization, exhibiting well-defined, satellite-free droplets with a high velocity of 4.5 m/s. Even though satellite droplets could be omitted by thorough waveform optimization, misting, i.e. the formation of sub-picoliter droplets with low momentum, prevailed. These may be critical as the resulting topography during etching will obstruct pinhole-free thin film formation of subsequent layers.

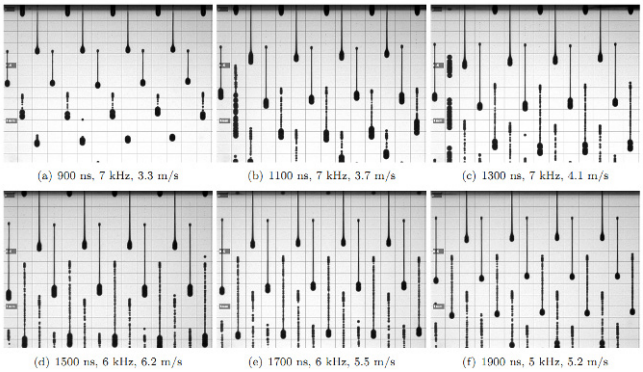

Figure 7: Stability graph of a mixture of 60 wt% AZ520D and 40 wt% Butyl-l-lactate jetting at different sample clock timings [room temperature, 100 images overlaid, frame rate 30 Hz]

Latency times were investigated by stalling the printhead for defined amounts of seconds and observing the number of lost or deviating channels on the screen. Significant channel loss was observed for the solvent-based system for stalling times greater than five seconds, making this printhead-ink combination non-applicable on industrial scale. Latency issues were not observed with UV- based ink, resulting from its low volatile compound concentrations.

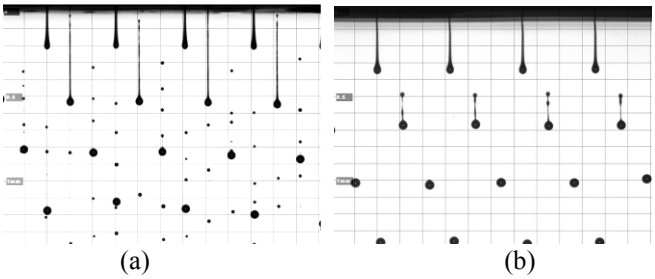

Figure 8: Jetting photographs of InkEpo with (a) the standard waveform and (b) an optimized waveform for this specific fluid [40 ºC, sample clock timing 1300]

Conclusion

The paper presented two possible routes for applying insulation layers via photoresists by inkjet technology for the application in back-contacted silicon-heterojunction solar cells was explored.

The solvent-based ink *AZ520D* was optimized for rheology by addition of PGMEA as well as butyl-l-lactate. The resulting optimized mixture of 60% resist and 40% butyl-l-lactate was jetable at room temperature and optimum jetting conditions were found to be 1900 ns. Short latency times of less than 5 seconds omit the application of the fluid on an industrial scale and calls for reformulation.

The UV-based system *InkEpo* showed no drying due to the low volatile compound concentration. However, a highly sophisticated driving waveform was necessary in order to generate satellite-free droplets at 40 ºC with a sample clock timing of 1300 ns and droplet velocities of 4.5 m/s, allowing for good drop placement at low substrate velocities.

Film and feature formation with these two systems still have to be determined on the respective layers. The systems chosen, however, offer the potential of optimization, as spreading may be controlled by the application of increased substrate temperatures in case of the solvent and by the application of appropriate pinning lamps in case of the UV-curable ink. Careful tuning of these parameters will ensure pinhole-free film formation as well as minimal feature sizes.

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Author Biography

Ingo Reinhold graduated in micromechanics-mechatronics with emphasis on print- and media technology from Chemnitz University of Technology in 2008. After joining Xaar’s Advanced Application Technology group in Järfälla, Sweden, he focused on advanced acoustic driving of piezo-type inkjet printheads alongside with pre- and post-processing of functional materials in digital fabrication. He is currently enrolled as a PhD student within the iPack VINN Excellence Center at the Royal Institute of Technology (KTH) in Stockholm, Sweden.

Nicola Mingirulli studied physics at the Universtiy of Karlsruhe in Germany until 2005. He obtained his PhD degree in 2009 from the University of Konstanz in Germany carrying out studies about silicon wafer-based back-contacted solar cells at Fraunhofer Institute for Solar Energy Systems in Freiburg, Germany . Since 2009 he works on back-contacted silicon heterojunction solar cells and related structuring technologies at Helmholtz Zentrum Berlin.