Challenges and advances in back-side metallization

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ABSTRACT

In today's market, crystalline silicon wafer technology dominates industrial solar cell production. Common devices feature opposing electrodes that are situated at the front and rear surface of the wafer and subsequent front-to-rear interconnection is used for module assembly. This paper reflects the functions which have to be fulfilled for the back-side contact of the solar cell as well as challenges and advances for the two basic classes: full-area and local rear contact formation. While full-area contacting has proven to be a reliable technology for industrial production, local contacting through dielectric layers has yet to be put through its paces in industrial implementation.

Introduction

The classical front-to-rear interconnection of crystalline silicon solar cells holds more than 80% of the market share of all PV technologies. Within the crystalline silicon world, Sunpower's rear-to-rear interconnected cell is the only mass produced exception.

The classical approach involves the rear contact being formed by depositing metal-containing paste to the full rear side of the cell and alloying during a subsequent high temperature process step. Most of the rear surface is covered by a paste that uses aluminium to enable high doping below the contact. Only the areas where the interconnector ribbons have to be soldered are covered by paste, which is mainly comprised of silver. In contrast, in the high efficiency world, the application of local contacting through a passivating layer has been the dominating approach for more than 20 years. The two approaches are compared in Fig. 1.

After reviewing the basic functions of the rear contact, the progress of some promising technological approaches is discussed in more detail in this paper. The discussion focuses on issues of cell structure and the relevant technologies; more detailed information on specific process sequences is given in the literature, partly covered by the references.

Challenges for the rear contact

For maximum solar cell efficiency the rear contact should show negligible power losses due to recombination, electrical resistance, transmission and absorption of the long wave length range of the spectrum, which does not lead to the generation of carriers.

Recombination

It is quite difficult to give even relative loss values resulting from recombination at the rear contact since this effect strongly correlates to several other device parameters, most importantly to the recombination in the volume of the base. Assuming a typical minority carrier diffusion length that is several times larger than the base thickness, the rear surface recombination velocity becomes very important. If the rather lowly doped base comes into contact with a metal layer, the recombination velocity at the surface reaches its upper physical limit of ~10^7cm/s. In principal, there are two major approaches for the passivation of the rear surface.

The first option is high doping near the surface with the aim of reducing the density of the minority carriers and therefore the probability of recombination at the surface. This approach is used in most p-type cells by doping with aluminium and/or boron and is frequently called 'back surface field (BSF) since the gradient in the doping level is frequently interpreted as giving rise to an electric field that shields the minority carriers from reaching the metallic surface.

With the second option, the passivation of the rear surface is applied not within the base but on top of it by adding a passivation layer or a stack of several layers. Such passivation layers utilize two physical mechanisms:

- The density of interface states at the surface is reduced. This is reached by use of several measures, including saturation of dangling (unsatisfied) silicon bonds at the surface, the use of layers that resemble the silicon lattice in order to

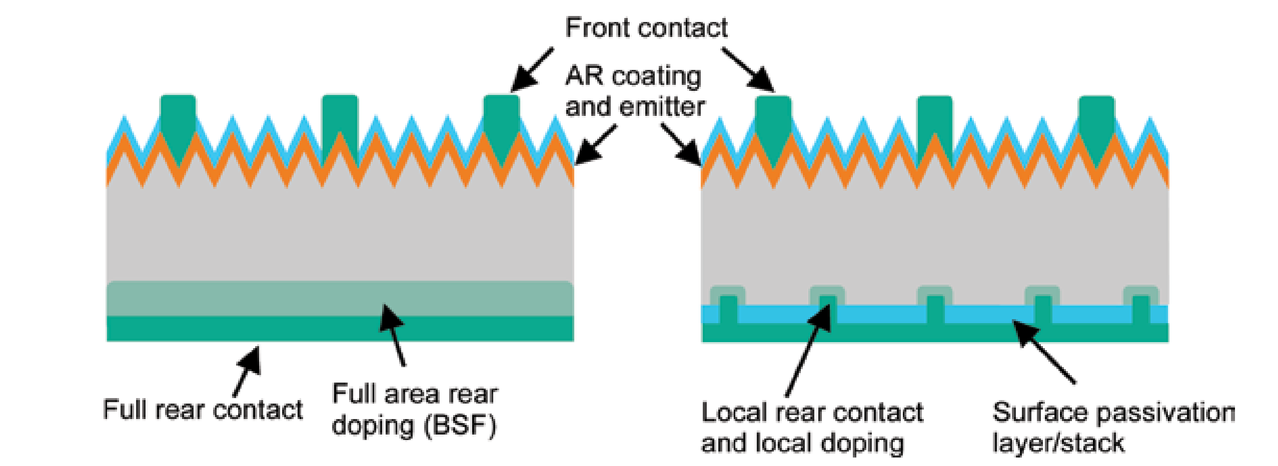

Figure 1. Two basic approaches to rear contact formation: homogeneous and local contact.

reduce structural deviations, and stress effects at the interface.

- Permanent immobile charges within a dielectric layer or at the interface induce an increased density of the opposite charge carriers near the surface, producing similar reactions to those seen in the case of high doping within the near-surface region.

A full-area BSF with direct metallic contact intrinsically cannot reach the same low effective surface recombination velocity (SRV) level as one that is based on dielectric passivation, even if contacts have to be formed through the passivating layer to allow for efficient majority carrier transport to the contacts.

> "The resistance within the semiconductor base depends largely on the contacted area fraction, the contact geometry and the conductivity of the semiconductor."

Electrical resistance

To reduce the electrical resistance of the device, at least three contributors have to be considered (see Fig. 2): the resistance within the semiconductor for majorities flowing to the rear contact (R_{base}); the contact resistance between the semiconductor and the metal ($R_{contact}$); and the lateral resistance within the metallic layer to the points of interconnection ($R_{lateral}$). Introducing global area normalized resistance parameters, a useful rule of thumb holds for most relevant cases: the relative efficiency loss $\Delta P/P$ relates well to $5 \times R_{series}/\Omega cm^2$ [1] and helps to determine the relevant contributors to the resistive losses and their magnitude.

The resistance within the semiconductor base depends largely on the contacted area fraction, the contact geometry and the conductivity of the semiconductor. The set-up most applicable to the case of the solar cell is that which involves illuminated conditions, i.e. where the carriers are generated with a homogeneous lateral distribution and mostly near the front side. Thus for a fully-contacted rear surface, the area normalized base resistance is described by the expression $R_{base} = \rho_{base}\, t_{base}$, where ρ_{base}, t_{base} are the base resistivity and thickness, respectively. If a BSF is applied, this highly doped layer is typically thin compared to the base thickness. The resistance in this highly-doped region is much lower than for the rest of the base, thus the contribution of the back surface field can be neglected. For typical values t_{base} of 200µm and ρ_{base} of 1Ωcm, the respective R_{base} is 0.02Ωcm^2, which corresponds to a relative power loss of 0.1%.

In the case of local contacting, exact values can only be calculated numerically. Nevertheless, several analytical approximations have been derived to calculate the contribution of the spreading semiconductor resistance around the contacts depending on different geometrical conditions [2-4]. For most cases of local rear contacts, this spreading resistance is the dominating contributor. Typical conditions feature a point-like contact grid with a contact radius of approximately 50µm and 200 contacts per cm^2, which means that the resistance for one individual contact is 40Ω for a base resistivity of ρ = 1Ωcm [5]. This results in a series resistance contribution of 0.2Ωcm^2 and a relative power loss of 1%, both values being a factor of 10 higher than for the full contact case. This result already implies that a high base conductivity is favourable for the case of locally contacted cells. For given contact geometry, a higher base resistivity requires an increased contact area fraction, which leads to an increased recombination rate due to the much higher SRV of the metallized surface compared to that of the passivated area.

In most practical cases, the lateral carrier transport to the interconnector is dominated by the current flow through the metallic layer and the corresponding resistance loss is relatively low. For the rather standard case whereby the current flows through a metallic layer, the resistance depends mainly on the geometrical layout, the layer thickness and the resistivity. For metallic aluminium, even a few µm layers of thickness are sufficient to yield a very low lateral resistance loss. Nevertheless it must be considered that with today's pastes, the rear contact does not form a homogeneous Al layer after firing, but a sinter body with sinter necks that contribute significantly to the current transport. Thus the resistivity strongly depends on the microstructure of the paste after contact firing.

Optical performance of the rear surface

In an ideal scenario, the rear surface should exhibit 100% internal reflection if the absorption length equals or exceeds the wafer thickness. For a silicon wafer with a thickness of 200µm, this occurs for incoming photons with a wavelength above 1000nm and moves to shorter wavelengths if the thickness is reduced. Regardless, it should be taken into account that for textured surfaces the effective thickness of the wafer is increased and the incidence on the rear surface is oblique. Due to the interaction of the radiation with the free carriers within a metal layer, the reflectance of a metal layer directly situated on top of the silicon is strongly limited.

In the case of an intermediate transparent dielectric layer, the reflection increases substantially if the thickness is sufficient to prevent absorption of the evanescent wave and supports constructive interference for the reflected wave. The experimentally derived value for the angle-weighted long wavelength rear reflectance of a fully Al-covered rear surface is given in the range from 65-80%, including parasitic absorption in the highly doped layer. For a single layer system using around 100nm of silicon oxide, local contacts with a low area fraction of around 1% and aluminium as cover layer, this weighted reflectance is in the range of 95%. This difference in reflectance yields a carrier generation benefit in the range of 2 to 3% for moderate thicknesses and further increases if thinner wafers are applied [6].

In determining the importance of long wavelength radiation, free carrier absorption (FCA) in highly doped regions of the cell has to be considered, as it limits the optical path length in the cell even if the surfaces are perfect mirrors. The main contribution to FCA is introduced by the high carrier density regions of the diffused

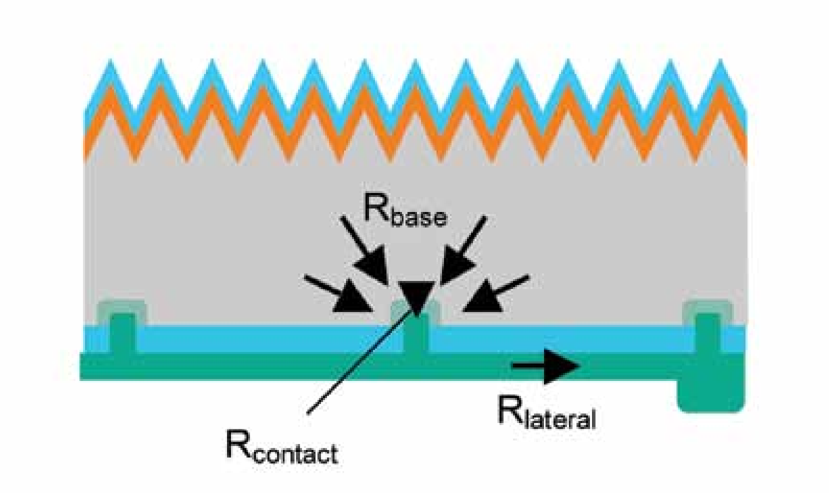

Figure 2. Dominating resistive loss mechanisms that must be considered for the rear contact of a solar cell.

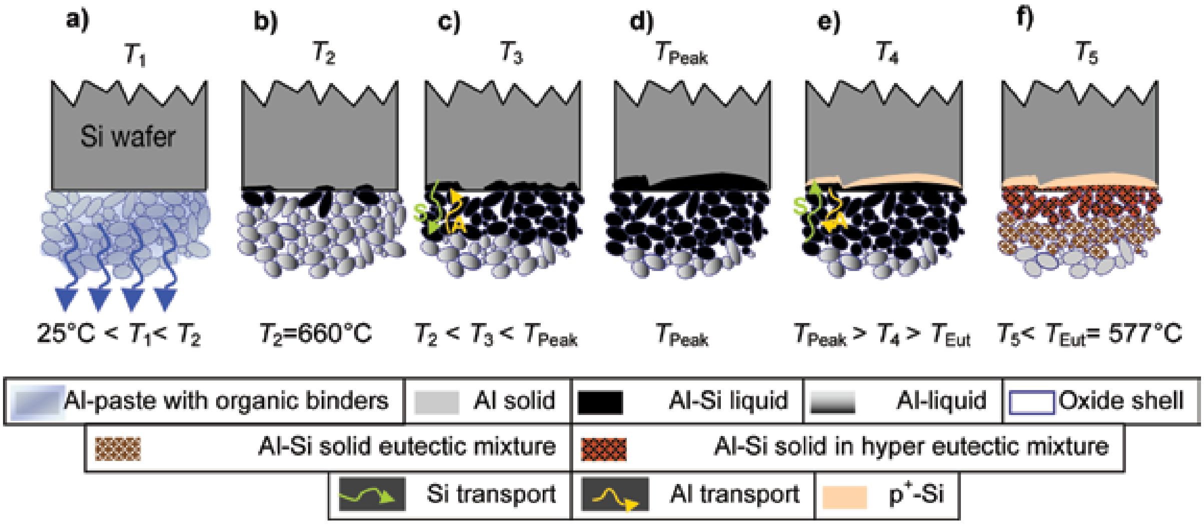

Figure 3. Current model for the formation of the rear Al-BSF (based on [9]).
a) Organic components are burned during the first stage of firing.
b) Oxide shells of the particles are enhanced due to increased temperature under oxidizing atmosphere. Al liquidizes, local contact areas between particles and wafer surface develop, start of alloying process.
c) Si is transported over the contact areas to the particles and Al is transported to the wafer surface, Si/Al concentration ratio rises as long as temperature increases.
d) At the peak temperature the maximum concentration of silicon in the liquid phase is reached. For thick Al layers and short heating times the aluminium is not fully saturated by silicon.
e) For decreasing temperature, silicon grows epitaxial from the liquid phase on the solid silicon wafer with an aluminium doping concentration determined by the liquidus curve. The transport process from c) is reversed.
f) As the eutectic temperature is reached, the remaining liquid alloy solidifies quickly. It can become hypereutectic if active and intense cooling is applied.
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emitter and back-surface field. Not only is the range between 1000 and 1200nm of interest, but also longer wavelength photons, since efficient back reflection of sub-band gap photons can result in lower cell temperature and thus higher open circuit voltage.

Solderability

In addition to all of its technical functions in reaching high cell efficiencies, the rear contact has to allow easy and durable interconnection. This is a delicate issue with aluminium as the contact material, which is well known for its tendency towards oxidation. Silver is used as the contact material to allow for reliable solder contact formation for standard Al-BSF cells. Many soldering contact pastes contain a small amount of aluminium to allow for improved electrical contact to the underlying silicon. Limiting the concentration of aluminium to a few atomic percent prevents the formation of a homogeneous layer of aluminium oxide at the surface, which would complicate the soldering process. However, silver pastes without any aluminium are also successfully applied to this process.

Fully-contacted rear side

Twenty years ago, in the early days of screen-printed cells, most of the industry's attention was focused on dealing with resistive losses of the rear contact, since recombination was dominated by insufficient minority carrier diffusion length of the rather thick solar-grade wafers. As a result, the rear side was contacted typically via a grid of well conducting paste. At that time, the standard conversion efficiencies of industrial solar cells were in the range of 12% for multicrystalline and 14% for monocrystalline silicon.

> "Silver is used as the contact material to allow for reliable solder contact formation for standard Al-BSF cells."

Investigations by Lölgen [7], for example, unveiled that effective surface recombination velocities down to 200cm/s can be obtained by alloying aluminium paste into the rear side of the solar cell. This work substantially contributed to the basic understanding of the alloy formation process and the adaptation of this approach to co-firing of the front and rear contacts. Further development of the contacting procedure – especially the paste formulation and firing conditions – greatly enabled the increase in efficiency to the current values with above 16% for multicrystalline silicon and above 17% for monocrystalline silicon.

Substantial progress in the understanding was obtained at the EU PVSEC in Barcelona, 2005, where Huster [8-10] published papers on his in-depth investigation of the BSF formed using an Al paste. One of the major observations of these papers was that under beneficial conditions, the BSF can be dominated by boron acting as the acceptor, which can be reached by adding boron in different forms. Furthermore, he also published a consistent model for the so-called stress-relief cooling which allows reduction of the bow being introduced by the Al-alloying process. This approach has been adapted by some of the commercially available fast-firing furnaces. Fig. 3 depicts a phase model of the formation of the pastes as introduced by Huster. Fig. 4 shows a cross-sectional scanning electron micrograph of an Al-BSF rear contact.

Locally contacted rear side

Locally rear-contacted solar cells with dielectric passivation for high efficiency solar cells were introduced more than 20 years ago by Swanson and Sinton [11] as well as Blakers and Green et al [12]. Within the past 10 years, substantial efforts and progress have been made to introduce this concept to industrial production. Compared to the dominating full Al-BSF approach, the differences in device features needed in order to successfully implement such a structure into an industrial process are quite substantial. The following section provides an overview of the different critical issues including the current status for the technological solutions to these functions as well as the main challenges that have yet to be addressed.

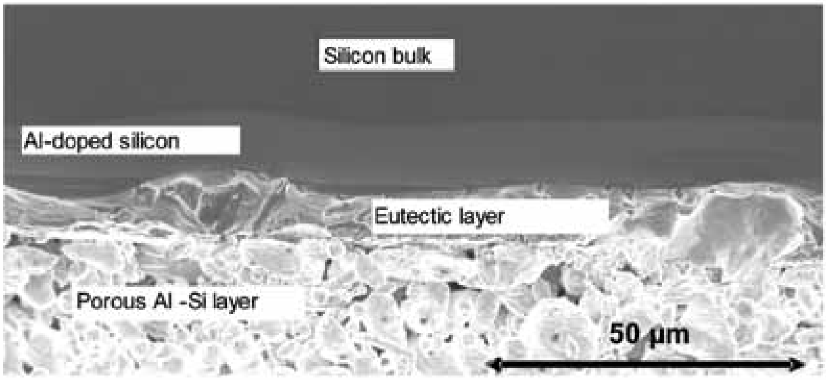

Figure 4. Scanning electron microscope image of a cross-section through the rear contact layer after Al paste deposition and firing.

High diffusion length versus cell thickness

In order to reach sufficiently low saturation current densities in the base, a ratio of at least 3 between bulk diffusion length versus base thickness should be reached. For standard boron-doped Czochralski silicon wafers at a doping level of $10^{16}cm^{-3}$ at moderate thicknesses around 200µm, this is a difficult task due to the well-known degradation effect associated with the boron and oxygen concentration.

A straightforward route is to use thinner wafers in order to reduce the volume where recombination occurs. Cells of 20% efficiency and above have been demonstrated down to thicknesses below 40µm [13] as well as efficiencies of above 18% using production and pilot production processes for less than 140µm-thin wafers [14]. The transition to thinner wafers in production will take time, since the respective developments have to take place along all individual steps of the value chain from wafer to module, and reliability of thin-celled modules have yet to be proven.

There are a number of options available to achieve a higher bulk diffusion length for boron-doped silicon, including an improved understanding of the boron-oxygen-related defect mechanism and its possible regeneration, float zone grown, magnetic and Ga-doped Cz-Si [15] as well as improvements in casted silicon.

Switching to phosphorus-doped n-type silicon makes a very high bulk diffusion length in Cz-Si easier to access. Some very high efficiencies have been obtained for the specific approaches of SunPower and Sanyo as well as passivated emitter and rear cells [16]. While a lot of progress has been made to develop simple process sequences [17], large-scale processing the latter approaches has yet to be demonstrated.

Surface conditioning

The preparation of the surface is as important as the passivation layer itself. Clean, smooth surfaces are vital features for low recombination [18]. The cleaning can be performed wet or dry. Dry etching is especially preferential in the case of plasma-deposited passivation layers since it allows integrated processing in one large vacuum system and consequently enables the substantial reduction of evacuation and handling costs. Excellent results for the preparation of the surface for subsequent passivation have been shown with both dry etch and wet chemical etch on large-scale production type equipment [19]. Nevertheless, there are waste gas treatment issues that must still be addressed.

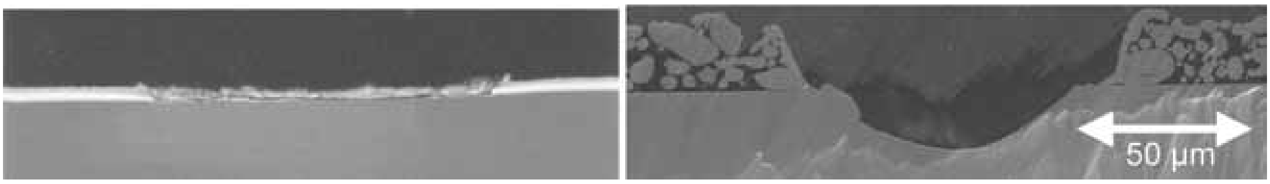

Figure 5. Scanning electron microscope image of a cross-section through a laser-fired contact on a 2µm-thin layer of evaporated aluminium (left) and a 20µm-thin layer of screen-printed aluminium (right). The depth of the LFC crater is similar to the thickness of the aluminium layer for both cases. The scale on the right side is valid for both images.

Though wet chemical single-side etching is standard for the rear emitter removal of Al-BSF cells, this can become challenging for different states within the process sequence. Process routes that allow for a low-cost etching mask on the front side are preferential. Silicon nitride, for example, can be efficiently used as a wet chemical etching and oxidation mask as has been demonstrated recently [14].

Passivation

Passivation layers can be classified into four groups that can all result in surface recombination velocities (SRV) below 10cm/s on 1Ωcm silicon. Application in PERC-like cell structures uses stacks of different layers in order to combine and produce favourable properties. In-situ or subsequent deposition of additional layers can improve internal reflectance, act as a diffusion barrier for the rear metal or even improve the passivation quality of the layer by injecting interface defect passivating hydrogen or enhancing the fixed charge density to favourable energy band conditions.

The first option for passivation is the thermal oxidation of the surface, which has been the basis for most high efficiency devices so far. It is different from all other available passivation methods in that it is a high temperature process (maximum process temperature T_{max}>800°C) and thus typically interacts more with other device structures.

An SRV below 10cm/s on p-type silicon can be reached in combination with a so-called alneal, which helps to hydrogenate the silicon-to-silicon dioxide interface and thus reduce the interface density of states D_{it}. This alneal can also be applied to recover the passivation properties after a subsequent high-temperature process as being used for firing of the contact [20]. The interface between the silicon oxide layer and the silicon is shifted inside the silicon wafer. This property has substantial advantages especially for non-uniform and increased aspect ratio surfaces as can be found in realistic process scenarios.

Substantial progress has been made in regard to the cost-effectiveness of the oxidation by preparing the transfer to wet oxides by purified steam instead of the traditional hydrogen burners. An overview of the present status of silicon oxide layers has been given recently [21].

The second group is also based on very low densities of interface traps with a low or moderate density of fixed charges, which in this case are deposited by plasma processing.

Amorphous silicon is the only representative of this group known so far. Excellent efficiencies for heterojunction and PERC-like cell structures have been reached and the use of large-area high throughput systems for the deposition has been demonstrated [22-24]. Nevertheless, the use of this approach for industrial solar cell processes yields two major drawbacks. The SRV of a passivated surface is inherently more dependent on the smoothness of the surface compared to the other passivation approaches. Secondly, amorphous silicon is very sensitive to high temperature treatments [25].

> "Excellent passivation results have been obtained by atomic layer deposited aluminium oxide, now also available as a high throughput PECVD process"

The third group is based on a deposited layer yielding a low or moderate D_{it} (well below 10^{12} $cm^{-2}eV^{-1}$) and

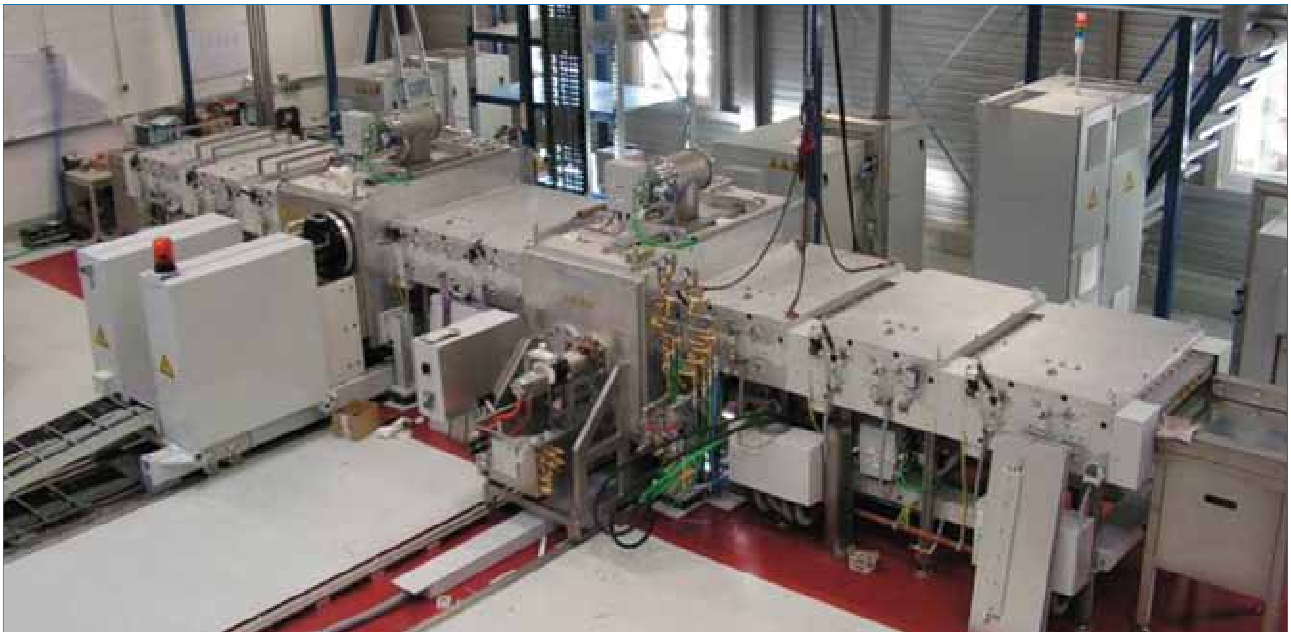

Figure 6. Pilot-line evaporation system from Applied Materials for high throughput physical vapour deposition metallization. Deposition rates for thermal evaporation are in the range of up to 500nm/s while maintaining high cell quality; up to 21.0% efficiency has been demonstrated (performed at Fraunhofer ISE).

high densities of fixed positive charges Q_f (above $10^{12}cm^{-2}$). This group holds hydrogenated layers of amorphous silicon nitride, oxide and carbide as well as metamorphic versions as siliconoxynitride [26]. The high Q_f can be maintained or even achieved by a high temperature treatment that could replace the conventional contact firing. These layers have been used to successfully passivate the surfaces of p-type wafers. But, for p-type PERC-type cells, a substantial gap of up to 1% absolute for high efficiency solar cells has not yet been overcome using these layers, which is attributed to the inversion layer induced by the positive charges in combination with non-ideal junctions of the local contacts [27]. Though this so-called inversion layer shunting has been known for several years, it seems technologically difficult to overcome this problem by production-feasible means. For n-type silicon, this group of passivation forms an accumulation layer and seems to present an adequate solution for contacted surfaces, as can also be taken from the successful surface silicon nitride passivation of phosphorous-doped emitters.

Due to the aforementioned drawbacks of passivation layers like silicon nitride, much attention has been drawn of late to negatively-charged layers which produce accumulation layers in p-type silicon. Excellent passivation results have been obtained by atomic layer deposited aluminium oxide, which so far remains a rather low-throughput deposition process [28]. Just recently we were able to demonstrate very low surface recombination velocities using a large-area PECVD system [29].

Overall, it can be concluded that wet chemical etching plus oxidation and dry etching in combination with plasma-deposited aluminium oxide are industrially viable approaches for excellent passivation of the rear surface of p-type wafers at competitive costs.

Rear contact formation

Locally defined contacts need at least two steps consisting of the application of the full-area metal layer and the local structuring process itself. Until several years ago, all rear surface passivated solar cells had been contacted by means of evaporation. i.e. physical vapour deposited (PVD) aluminium layers. Photo-lithographical removal of the passivation layer used to be the standard for structural purposes. This process can be substantially simplified using a laser to locally ablate the passivation layer [30]. After structuring, the metal layer can be deposited. Very high efficiency cells feature a local back-surface field (LBSF) below the contacts, originally applying additional photolithographic structuring. Following the introduction 10 years ago of the local laser firing of contacts (LFC), the structuring process has now been moved to after the metal layer deposition, forming a local back-surface field of medium quality compared to the diffused boron LBSF reference.

High temperature contact formation has not been feasible for aluminium deposited on silicon dioxide or amorphous silicon passivation. This is a result of the chemical reduction of the oxide in the first case and crystallization or even alloying of the underlying layer in the second case. The use of silicon nitride diffusion barriers in combination with local laser opening and the application of aluminium paste has been successfully demonstrated by Agostinelli [31]. A similar approach has been introduced by using laser-fired contacts in combination with a screen-printed and fired aluminium paste layer [32]. Applying this sequence in combination with printed front contacts has resulted in a 20.5% efficient cell, the highest efficiency reported so far for all printed contacts (2cm x $2cm^2$ cell on p-type Fz-Si) (see Fig. 5) [5].

Recent progress has shown how to overcome the throughput limitation of conventional systems for physical vapour deposition. In order to reach sufficient lateral conductivity for a back-side coating, a thickness of at least 2µm of aluminium is needed. In order to meet the resulting demand for a throughput of several thousand wafers/hour, a high-rate evaporation system was introduced in 2009 (see Fig. 6). Results from this deposition system have shown excellent static deposition rates of 500nm/s and a very good uniformity of better than 2% on the whole carrier. Equivalent cell results on a level of 21% have also been shown on high-efficiency solar cells in direct comparison to lab-type e-gun deposition [33].

In summary, two high-throughput rear-surface metallization concepts are available to form the rear aluminium layer of such cells. Metallization based on screen-printed aluminium paste is well proven and is low in investment. It can yield good BSF conditions after alloying and allows easy integration into existing lines as well as application of current interconnection technology. Evaporated aluminium layers show excellent lateral conductivity even in the as-deposited state, thus allowing a substantial reduction in the amount of aluminium used, and removing the need for firing of the deposited layer.

While the investment and running costs for the equipment are higher, the costs for consumed materials can be substantially lower compared to the screen-printed Al paste approach. An alternative option with substantial cost-reduction potential is the use of aluminium foil, which, while it has demonstrated very promising results combined with local laser firing, is still in an early stage of development [34].

> "Metallization based on screen-printed aluminium paste is well proven and is low in investment."

Structuring of the contacts in combination with the formation of local laser alloying by use of LFC seems to be the most flexible approach, while local patterning and subsequent Al paste deposition and firing allows use of conditions similar to the standard Al-BSF formation. Local printing of paste with subsequent firing through the passivation layer is a third option, but has not yet yielded any outstanding results.

Other cell designs

In principle, it is possible to form a hybrid of the two basic approaches (BSF and dielectric passivation). This idea has been formulated to address the problem of high resistive losses that ensue from manufacturing high efficiency solar cells on lowly doped silicon with local contacts. In this approach, a highly conductive area is formed at the rear surface, which helps to substantially improve the lateral conductivity within the semiconductor. Nevertheless, the surface is still passivated with a dielectric layer, which also ensures high performance. Technologically this area

Function	Approach	Status	Main challenges
Surface conditioning	Wet chemical etching	• Inline single side etching is available • Simplified RCA-clean was demonstrated to work well on pilot wet bench	• Further simplification/reduction of chemical consumption • Improved single sidedness, homogeneity of process • Polishing of surfaces.
	Dry etching	• Very low surface recombination velocity (S_{eff}<10cm/s on 1Ωcm p-type Si) after dry etching on large area plasma etching system demonstrated	• Waste gas treatment • Improved single sidedness and homogeneity of processes • Polishing of surfaces
Passivation	Wet Thermal Oxidation, thick	• Excellent and firing stable passivation, if combined with alneal at the end of process • High throughput demonstrated, substantial cost reduction by the introduction of wet oxides using purified steam	• Integration of high temperature process and double sided growth of oxide in total process flow • Development of low-cost high quality inline oxidation
	Firing stable vacuum-deposited stacks of silicon oxide/nitride/ carbide	• Very low S_{eff} on high throughput systems demonstrated, based on large positive fixed charge density	• High positive fixed charge density ($Q_f > 10^{12}$ cm^{-2}) of layers led to substantial efficiency losses for locally contacted cells on p-type silicon, well suited for n-type Si
	Amorphous silicon	• Very low S_{eff} on high throughput system demonstrated	• Relatively low Q_f, so far very smooth surface required, still most sensitive to high temperatures • Firing stability on cell level
	Firing stable vacuum deposited stacks of aluminium oxide	• Very low Seff for atomic layer deposition (very dense and homogeneous) and PECVD (high throughput system) demonstrated • High negative Q_f of layers allows beneficial carrier accumulation on p-type silicon	• So far only little experience in cell processing
Point like local contact formation	Laser-fired Contacts	• High efficiencies and high throughput demonstrated for a variety of approaches	• Further improvement of local back surface field quality • Up-scaling to industrial application
	Laser ablation	• High efficiencies demonstrated for screen printed cells	• Local back surface field formation depends on subsequent firing step
	Screen printing	• Simple approach, frequently tested	• High efficiency to be demonstrated
Metallization rear	2-3µm Al-PVD-layer	• LFC has proven to be a high throughput process, high throughput Al-PVD-deposition system set-up with excellent results under development	• Interconnection demands for additional contact layer
	10-30µm screen printed and fired Al layer	• High throughput for LFC process • Easy implementation module inter-connection using screen printing of pads	• Simple introduction of firing stable rear stack
	15-30µm thin Al foil	• Good cell results demonstrated	• Very early stage of development
Annealing	Forming gas anneal	• Tube furnace process is a standard for high efficiency cells	• First forming gas inline furnace for PV cells to be investigated

Table 1. Overview of the most critical process functions to implement a solar cell with passivated rear and local contacts, including the most promising approaches, their status and the main challenges for a process transfer to industrial scale.

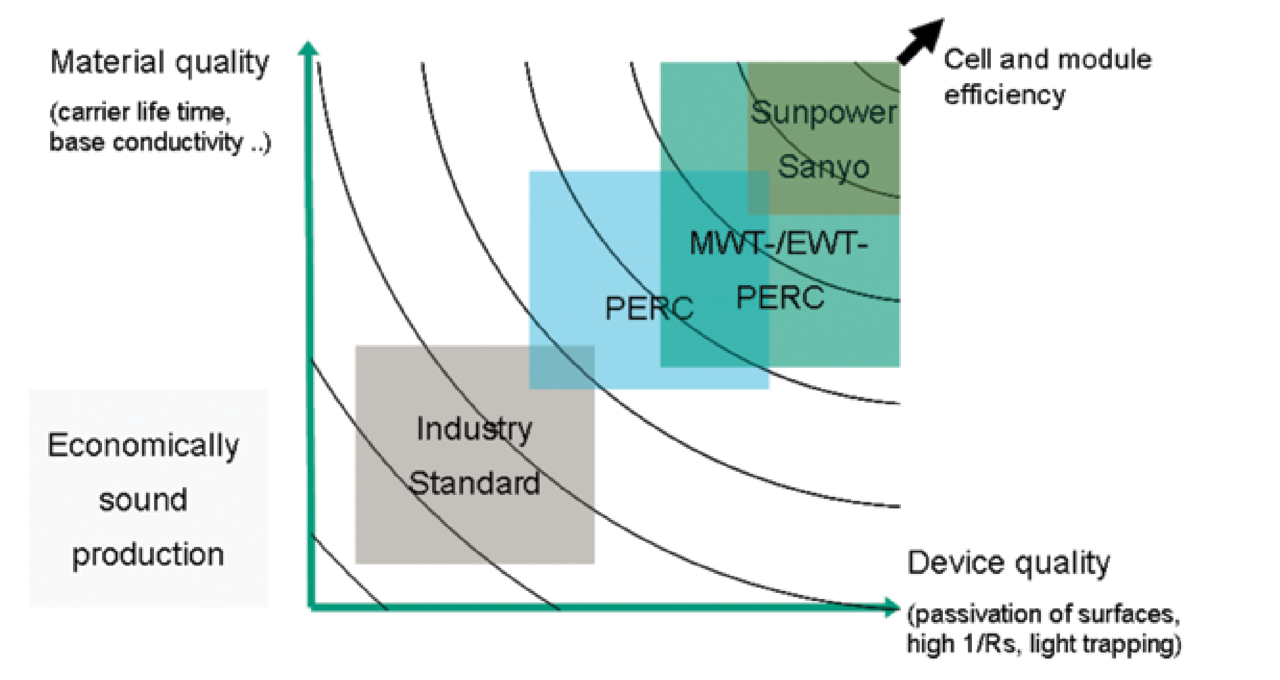

Figure 7. Portfolio for economically sound production of passivated solar cells. Combination of high quality material and device structure will enable filling of the gap between today's standard screen-printed cells and the premium cells of Sanyo and SunPower.

can be prepared like a BSF. Zhao et al. have taken the so-called passivated emitter and rear totally diffused (PERT) cell approach, which has resulted in efficiencies up to 24.5% [35].

Adaptations of the two basic approaches are necessary for rear contact formation if both polarities are placed on the rear side as is the case with Metal Wrap Through (MWT), Emitter Wrap Through (EWT) and Rear Junction Back Contact (RJ-BC) cells. In each of these approaches, the junction area is situated more or less directly at the surface. High quality junction passivation is vital

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to reach high efficiencies. For RJ-BC cells like SunPower's A320, the use of dielectric passivation in the junction areas is mandatory [36].

EWT cells have been produced without a dielectric passivation of the junction areas, but the difference in efficiency is substantial, and junction passivation also seems to be essential and can lead to efficiencies of up to 18.8% for screen-printed solar cells [37]. Most MWT cells are based on an Al-BSF, and junction passivation is less important since the junction area at the rear is about one order of magnitude smaller than for EWT and RJ-BC cells. But recent results have shown that the dielectric passivation of the p-n junction area is also very helpful to reach higher efficiencies [38].

In summary, it can be said that for all rear-contacted cells, dielectric passivation of the rear surface is even more important than for the classical cell architecture itself.

Summary and outlook

The boundary conditions for the back contact of crystalline silicon solar cells are well known. Screen-printed Al-BSF technology has advanced substantially over the years and represents a very widespread and robust technology. Nevertheless, achieving further efficiency increases on this route is a challenge. In particular, the implementation of an increased internal reflection requires new approaches. Substantial further reduction of the wafer thickness relies on the use of dielectrically passivated layers to yield mechanical and efficiency benefits.

The solar cells with the highest efficiencies feature local rear contacts. In the field of local contacts through dielectric layers, a lot of progress has been made during the last three years in terms of industrial feasibility. The first silicon solar cell-dedicated PVD equipment has proven its high throughput and efficiency potential. Similarly, screen-printed contact formation and dielectric passivation, which have been regarded as a contradiction for a long time, have shown to harmonize very well.

The respective approaches allow an introduction of passivated rear-side cell design to industrial processing of boron-doped silicon wafers, with the first implementations expected this year. Application of high diffusion length material and other enhancing techniques such as fine line contacts and selective emitters will result in industrial solar cells featuring efficiencies above 20%. Further combination with rear-contact approaches like MWT or EWT is expected to then fill the gap between the upper limit of standard screen-printed and the premium but complex cells of Sunpower and Sanyo (see Fig. 7).

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