A NOVEL APPROACH TO COST-EFFECTIVE HIGH EFFICIENCY SOLAR CELLS

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ABSTRACT: To make photovoltaics an economical large-scale source of energy, very high efficiencies have to be achieved by low-cost processing suitable for mass production. As an innovative approach towards this goal, the ART (Abrased-Ridge-Top) solar cell concept is introduced and first results for silicon are reported.

The fabrication process includes a novel technique for mechanical surface structuring by parallel wires (wire grooving), low-temperature surface passivation by plasma silicon nitride, local removal of the passivation layer and self-aligned metal grid formation. The concept is discussed for diffused p-n cells as well as for inversion-layer solar cells, whereby in both cases bifacial sensitivity is included. With the potential for efficiencies above 20% on silicon a significant reduction of the present costs per Watt of solar electricity is expected.

1. INTRODUCTION

The high costs are presently the main obstacle for a world-wide increased utilization of electric power provided by photovoltaic solar cells. Mass production could indeed drastically reduce the price of solar cells, however, it´s not sufficient to reach the cost level required to become fully competitive with the conventional energy sources. New concepts have to be introduced, combining very high cell efficiencies with simple short-time processing, including cost-effective materials. By increasing the efficiency, all area-dependent costs are reduced.

Together with an optimized coupling of the light into the cells by proper surface structuring, antireflection layers and contact design, excellent surface passivation and a low metal-semiconductor contact area are the main prerequisites for the achievement of very high efficiencies. Record laboratory efficiencies of 24 % could be obtained for single crystalline silicon solar cells with diffused p-n junctions [1]. However, extremely complex processing was applied, including surface structuring - inverted pyramids - by photolithography and etching, high temperature passivation by thermal oxidation, whereby the contact system has to be defined by photolithography. It is evident that the fabrication process is not suitable for a cost-effective mass production of solar cells. An innovative concept has already been introduced, by which highly efficient solar cells should be attainable by high-temperature as well as low-temperature processing and including simple large-area fabrication methods. The concept is applicable for single- and polycrystalline semiconductors, particularly for ribbon-grown material and for solar cells with diffused and induced p-n junctions. The basic principle of this approach is as follows:

(i) Formation of specific elevations on the semiconductor surface. (ii) Excellent surface passivation by high- or low-temperature films after the junction has been fabricated. (iii) For contact window opening removal of the passivation layer and possibly some semiconductor material from the tips of the elevations, and (iv) Selective metal deposition upon the elevated regions.

As a first example, pyramids on monocrystalline silicon have been chosen as elevations, resulting in a novel point-contact device, the so-called "truncated pyramid" solar cell [2].

In the following, novel line-contact solar cells based on the above mentioned concept are introduced, with the ridges of parallel grooves serving as elevations. Since step (iii) is the most characteristic feature, this cell type is designated by us as "Abrased-Ridge-Top (ART) solar cell. The fabrication process is outlined both for diffused p-n junction solar cells as well as for inversion-layer solar cells. The main technological procedures are discussed and first results are presented. In this context, a completely new way of mechanical surface grooving by a set of parallel wires is introduced.

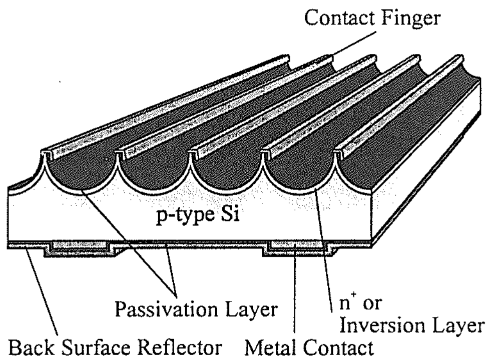

Figure 1: Schematic diagram of the wire-grooved ART solar cell for one-sided and bifacial operation. In this approach, high-efficiency features are combined with simple technology.

2. SOLAR CELL STRUCTURE

In Figure 1, a schematic respresentation of the novel line-contact solar cell is shown. The surface is characterized by a set of parallel rounded grooves, which are covered by a passivation layer. Either a n+ emitter (p-n junction cell) or an inversion-layer induced by positive charges present in the passivating film (inversion-layer cell) is located at the semiconductor surface. From the groove tops the passivation layer is removed for contact opening, and the contact metal is deposited by a self-aligned process, both on top and along the flanks. It´s important to note that the horizontal metal-semiconductor contact area should be as small as possible, whereas for a high metal cross section the main part of the metal fingers running along the steep flanks upon the passivation layer may be more extended.

For the rear side various configurations can be chosen. We selected a simple design recently introduced by us for bifacially sensitive solar cells [3,4.] As an outstanding feature, low-temperature back surface passivation is achieved by deposition of plasma silicon nitride <u>after</u> the ohmic metal grid has been formed, so that in contrast to the generally used much more complex procedures [1] no openings in the passivation film are required. In addition to its simplicity low surface recombination velocities are achievable, as outlined below. Thus, without extra cost, light impinging on the rear side can also be utilized with high efficiencies. A back surface reflector (BSR) for increased light trapping can easily be obtained by covering the rear side with a reflecting metal layer.

The novel concept provides the following features required for very high efficiencies :

(i) Optimization of surface passivation, either by high temperature or low temperature steps, can be performed before the contact preparation.

(ii) Very small metal-semiconductor contact areas, since the main part of the grid finger is running upon the passivation layer. Groove top dimensions down to 1 μm are homogeneously achievable on large wafer areas.

(iii) Large finger width combined with low effective shadowing, since the metal fingers are running along the steep flanks of the grooves. Reflection of light occurs from the metal into the opposite face of the grooves.

(iv) Low surface reflectance, increased optical absorption and light trapping.

(v) Enhanced carrier collection due to the generation of charge carriers close to the p-n junction.

(vi) The semiconductor substrate can be made relatively thin due to the mechanical support by the ridges. Perpendicular grooving of the rear side is also possible.

(vii) The concept is equally well suited for mono- and polycrystalline semiconductors as well as for ribbon material.

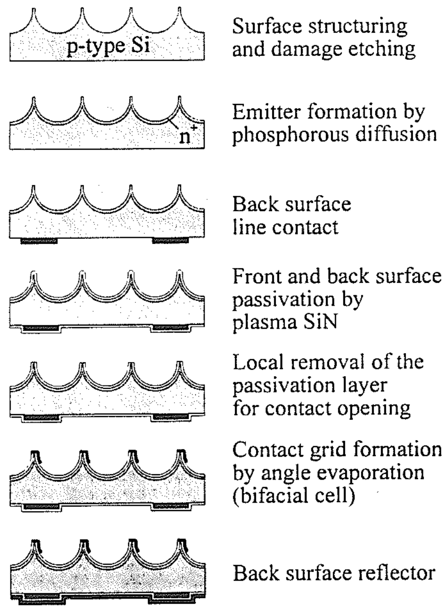

Figure 2: Processing sequence for high-efficiency p-n junction silicon solar cells (mono- and bifacial) of the ART type.

3. CELL FABRICATION PROCESS

3.1. Solar cells with diffused p-n junctions

As a first example, one possible version of a p-n junction solar cell of the ART-type will be discussed.

The fabrication process is outlined in Figure 2. On a p-type silicon wafer a surface structure consisting of parallel grooves and narrow ridges is mechanically fabricated, followed by a damage etch. The n^+-emitter is introduced at the front side, preferably by phosphorous diffusion, and a metal grid (aluminum) is deposited at the rear side. Both, front and rear side are then covered with a plasma silicon nitride passivation layer. In order to save costs this can be done simultaneously for front and back, so that only one fabrication step is required. For contact opening, the passivation layer and, if necessary, also some silicon is selectively removed from the narrow horizontal ridges on top and optionally at the edges and in the upper part of one or both flanks. As a final step, the metal grid is formed simultaneously both on the horizontal contact region and on the steep flanks by the self-aligned process of low-angle vacuum evaporation. In this way a bifacially sensitive version of the novel solar cell concept is completed. A back surface reflector can easily be added by simply covering the rear side with a suitable metal, such as Al or Ag.

As to the metal contacts at the front side, a n^{++}-diffusion can be included in the process to suppress carrier recombination. However, a higher doping concentration is present in the contact region even without this additional step, since in the narrow ridge tops the diffusion profiles originating from both flanks are overlapping. The contact properties can be further improved and possible shunting to the base avoided if a tunnel oxide of about 1.5 nm thickness is grown on the diffused contact region at low temperatures [2].

3.2. MIS inversion layer solar cells

The first-generation of MIS inversion layer solar cells as developed in our laboratory using a simple time- and energy-saving low temperature fabrication process could be successfully transferred to an industrial pilot production line for 10 x 10 cm^2 cells [4]. Since spring of 1994, these cells encapsulated in novel large-area modules are installed in many places, only to mention the German-Spanish PV demonstration plant in Toledo with an output power of more than 400 kW [5]. They are reported to work without any problems up to now [6]. Efficiencies of 15.3% on large-area cells fabricated on CZ silicon wafers could be achieved. However, because of the poor front surface passivation applied for these first-generation MIS-IL cells, improvement of the efficiency above 16% is rather difficult. The poor passivation properties are due to the fact that the silicon nitride passivation film is deposited after the metal grid formation at the relatively low temperature of 250°C in order not to degrade the tunnel contact. With the new cell concept this problem can easily be overcome. The silicon nitride passivation films can now be prepared before the contact metallization at the more favourable temperatures lying in the range 400-500°C, where strongly improved passivation properties are demonstrated [3, 7]. Thus, a drastic increase in efficiency can be predicted for these second-generation MIS inversion layer solar cells, without complicating or perhaps even further simplifying the fabrication process [8] (see also chapter 4.2.). Two-dimensional numerical modelling reveals that inversion layer cells can principally achieve the same high efficiencies (> 23%) as p-n junction cells [7].

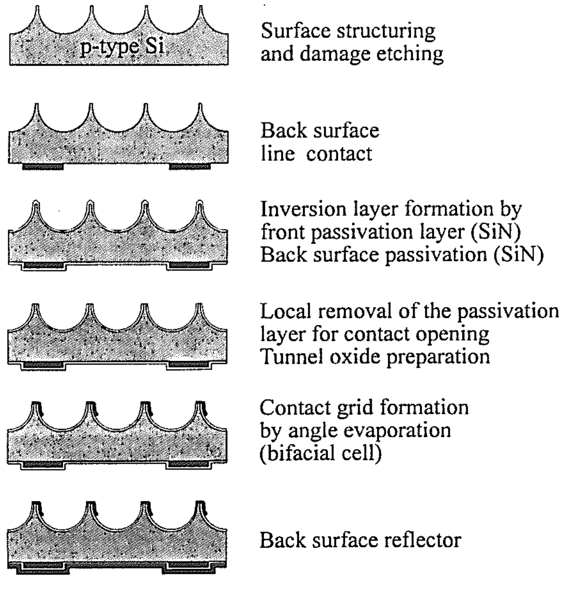

Figure 3: Processing sequence for high-efficiency MIS-inversion layer solar cells (mono- and bifacial) of the ART type.

According to the fabrication process outlined in Figure 3, after surface grooving and damage etch of the p-type silicon wafer a metal grid is formed at the rear side. Both sides of the wafer are covered with plasma silicon nitride as passivation and antireflection layer. At the silicon/silicon nitride interface a high density of positive charges is present, inducing an extremely thin (about 20 nm) inversion layer made up of electrons. In order to lower inversion layer sheet resistance, the positive charge density can be drastically increased by the introduction of cesium via a simple room temperature dipping process [4]. As the next step, the passivation layer and possibly some silicon is removed from the horizontal groove tops and optionally from the upper parts of the steep flanks. A tunnel oxide of 1.4 - 1.5 nm in thickness is grown in the contact region at about 500° C, followed by the maskless formation of the front metal grid by low-angle vacuum evaporation. A back surface reflector can easily be added.

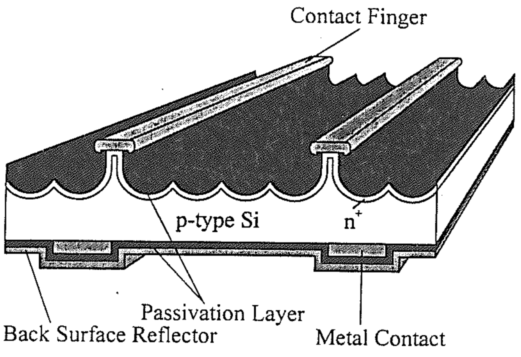

Figure 4: p-n junction ART solar cell with a wire-grooved surface and protruding contact ridges.

3.3. Alternative cell structure

Another example of a line contact solar cell structure of the ART-type is shown in Fig. 4. With this device, particularly tailored for diffused p-n junctions, very simple self-aligned non-vacuum metallization techniques can be used.

Among the many parallel grooves with narrow ridges in some larger distance broader ridges are protruding, on which the contacts are placed. This surface structure can be fabricated by the novel method of parallel wires simply by omitting a few wires at the location of the contact ridges and grooving somewhat deeper. Local removal of the passivation layer is easily performed by large-area mechanical or chemical-mechanical means. Self-aligned techniques such as roller printing or electroplating are suitable for the deposition of the contact metal onto the protruding ridges. It should be mentioned that the groove structure with elevated contact regions described above for the front side can, with some alterations, also be applied for the rear side of (bifacial) solar cells.

4. FABRICATION TECHNIQUES

4.1. Surface structuring

The surface structure of the novel devices has to serve several purposes. The main task is to allow simple preparation of small-area metal contacts upon the narrow ridges with low obscuration and high conductance. Coupling as much light as possible into the cells is also very important for high-efficiency solar cells. As our goal, by cost-effective surface structuring at least the low reflectance known from randomly oriented pyramids should be reached, with the further advantage that no restriction to single crystaline semiconductor material exists. For this purpose, mechanical surface grooving which can be performed by various techniques is a promising way.

Conventional dicing saws normally used in microelectronics for chip separation have already been successfully applied for the improvement of multicrystalline silicon surfaces with respect to their antireflection behaviour [9,10]. Ultrathin self-supporting bifacial solar cells on single- and multicrystalline silicon were fabricated by mechanical structuring, whereby the silicon base thickness could be reduced to 20 µm [11,12]. In all cases, thin dicing blades consisting of diamond particles (1-5 µm in size) embedded in a Ni matrix were used. This technique is well suited for preparing the surface structure required for our new solar cells, particularly if multiblade dicing wheels for higher throughput are available.

In this paper, however, a completely new technique of mechanical surface structuring, the so-called wire-grooving, will be introduced, which causes less surface damage and may be more cost-effective due to the large area available for grooving. It's based on the wire-sawing technique, well known in photovoltaics for cutting the silicon rods into thin wafers. A commercial wire saw had to be modified for its application to mechanical surface grooving. A conventional steel wire of about 180 µm in diameter and 120 km in length is guided by four grooved rollers to form a homogeneous web with a certain wire distance (Fig. 5). The wafer's surface is pressed against the wire web, whereby a slurry consisting e.g. of a suspension of SiC and oil is added. The wire speed is about 4 m/s.

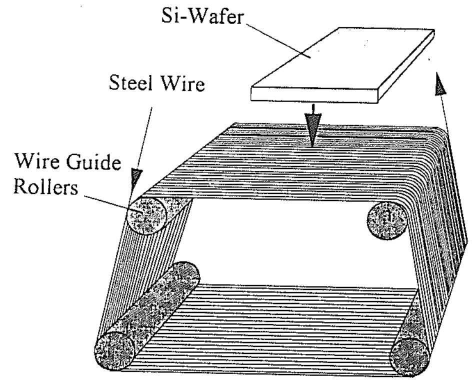

Figure 5: Essential features of the wire-grooving technique.

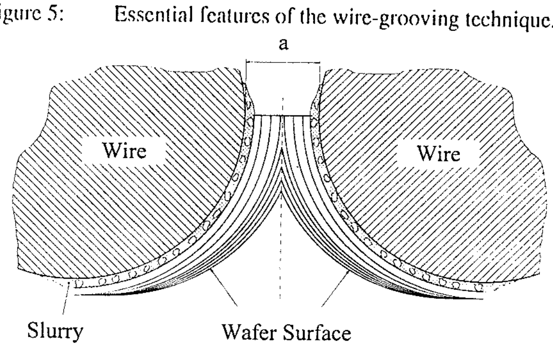

Figure 6: Principle of the surface grooving technique by parallel wires ("wire-grooving").

The principle of surface grooving by parallel wires is schematically depicted in Fig. 6. By variation of the wire distance, either broad or narrow groove ridges can be obtained. By optimizing the parameters wire speed, particle size and concentration, etching treatment etc., perfectly grooved silicon surfaces can routinely be manufactured, as is demonstrated by the SEM-picture in Fig. 7. Extremely narrow ridges with top dimensions in the submicron range are resulting (Fig. 8, left). In the right picture of Fig. 8 it is shown that very small metal-silicon contact areas, comparable in size to those obtained by complex photolithographic procedures [1] can be prepared homogeneously over large wafer areas by ridge-top abrasion. It should finally be mentioned that the application of a diamond-coated wire could be another choice for surface grooving, however, surface damage may possibly be more pronounced.

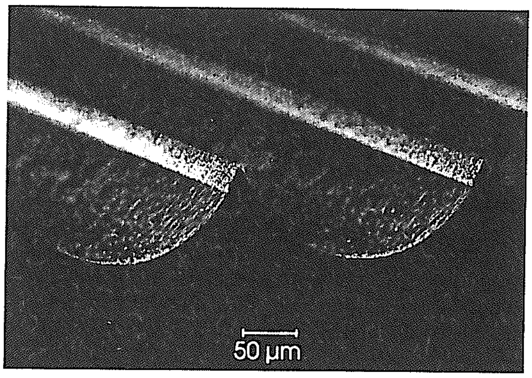

Figure 7: SEM-picture of a wire-grooved silicon surface with angle-evaporated line contacts.

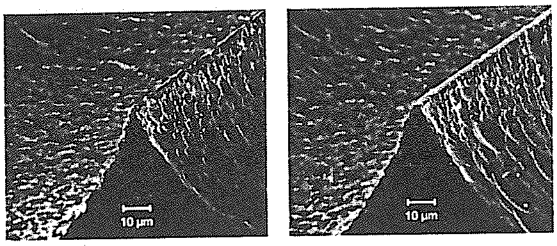

Figure 8: Extremely narrow ridges for contact preparation by the wire-grooving technique on silicon. Left SEM-picture: as fabricated ridge. Right picture: after ridge-top abrasion.

4.2. Silicon surface passivation by plasma silicon nitride

For the achievement of high efficiencies, excellent passivation of front- and rear sides of the solar cell is required. Up to now high quality thermal oxide was the only passivation layer for high-efficiency silicon solar cells. It would be well suited for the novel cell concept presented here, however high temperatures as well as energy- and time-consuming processes should be avoided. Therefore we are concentrating on low-temperature silicon surface passivation by plasma silicon nitride. This layer is deposited by the reaction of silane and ammonia in a glow discharge. The lowest values of surface state density and surface recombination velocity are achievable at deposition temperatures of about 400°C, and a further reduction occurs by post deposition annealing at 500°C [3]. Surface recombination velocities as low as 15 cm/s could be obtained by us, exceeding even the best values hitherto reported for thermal oxide on non-diffused silicon. These are very good conditions for highest efficiencies attainable with the novel cells by the application of cost-effective low-temperature passivation.

There are two reasons for the excellent passivation properties of plasma silicon nitride. (i) The highly reactive hydrogen species released during the reaction of SiH_4 and NH_3 saturates dangling bonds, thus reducing the density of interface states. (ii) Charge-induced passivation occurs due to the high density of positive charges present at the SiN/Si-interface ($> 10^{12}$ cm^{-2}).The hole density at the surface of p-type silicon is drastically reduced, resulting in very low recombination, despite a relatively high surface state density ($\sim 10^{11}$ cm^{-2} eV^{-1}) is present [3].

The high positive insulator charges, which can even be further increased by the introduction of cesium, are the main reason why plasma silicon nitride is excellently suited for inversion-layer solar cells on p-type silicon [4].

4.3. Local removal of the passivation layer

Local removal of the passivation layer and, optionally, of semiconductor material from the narrow ridges is a characteristic feature of the novel cell concept. Mechanical or combined chemical-mechanical methods choosing proper abrasives are suitable for homogeneous abrasion over large wafer areas. As shown in Fig. 8, depending on the removal depth,line-contact widths in the 1-3 µm range could be achieved homogeneously.

4.4. Metallization by angle evaporation

Due to the shading effect of the ridges, the self-aligning technique of angle evaporation is a very simple and reliable method of metallization. Without any mask or alignment it is possible to deposit a relatively thick metal finger along one flank, whereas simultaneously a thin layer is formed on the truncated top contact region. The width of the finger can be adjusted by variation of the evaporation angle. The finger width can be increased to a certain extent without significantly affecting light obscuration and metal-silicon contact area. Hence, metal thickness and thus the amount of metal is reduced. A large conductor cross section is possible which makes the cells suitable for high concentration levels. As to the economy of the angle evaporation technique, the throughput of wafers is drastically increased (by a factor of 10 to 20), compared to conventional vacuum evaporation. The wafers can be arranged closely spaced on a rotating cylinder. As another big advantage of the angle evaporation, nearly all the metal evaporated is deposited for the metal grid only, so that even more expensive high-quality metal combinations like TiPdAg may come into consideration for mass production of cost-effective high efficiency solar cells. With conventional vacuum evaporation, more than 90% of the metal is lost, and additional processing is required to remove this surplus metal either from shadow masks or from the wafer itself.

5. CONCLUSION

The fabrication of silicon laboratory solar cells with efficiencies above 18% is characterized by a high number of complex steps known from integrated circuit technology. It seems to be very difficult to tailor this sophisticated process for cost-effective mass production. However, to become competitive with the conventional energy sources, very high efficiencies have to be achieved using low-cost high-volume processing.

In the present work, a possible approach towards this goal was introduced. Almost the same high precision and reproducibility as obtained with expensive microelectronic procedures for small areas should be attainable with simple cost-effective processing on large industrial wafer areas. In this respect, the high potential of the novel solar cell concept could already be demonstrated, fabricating line contacts with 1-3 µm in width homogeneously for a wafer size of 10 x 10 cm^2.

Only a small number of processing steps are required by the novel approach for high-efficiency p-n junction as well as for inversion layer solar cells. Bifacial sensitivity is included in the cells without extra cost, so that an increase in power output of up to 50% can be achieved by proper positioning of the modules.

Now all our effort has to be focussed on combining these optimized simple fabrication steps to obtain a highly efficient and reliable device. With respect to a rapid transfer to industrial production, lab work should include economic aspects more than ever before.

Acknowledgement:

The author is grateful to R. Auer, M. Freischmidt, A. Metz, R. Meyer, S. Steckemetz and M. Verbeek of the ISFH for their valuable contributions. Financial support of the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) of the FRG is gratefully acknowledged.

The ISFH is a member of the "Forschungsverbund Sonnenenergie", Germany.

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