Crystalline Si thin-film solar cells: a review

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Abstract. The present review summarizes the results of research efforts in the field of crystalline silicon thin-film solar cells on foreign substrates. The large number of competing approaches can be broadly classified according to the grain size of the crystalline Si films and the doping of the crystalline absorber. Currently, solar cells based on microcrystalline Si films on glass with an intrinsic or moderately doped absorber film achieve efficiencies around 10%, whereas thin-film cells fabricated from large-grained polycrystalline Si on high-temperature-resistant substrates have efficiencies in the range of 15%. The paper discusses the limitations of various approaches and describes recent developments in the area of thin, monocrystalline Si films that may open the way towards 20% efficient thin-film Si solar cells.

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The present review starts with a discussion of current achievements in the field of crystalline Si thin-film solar cells on foreign substrates and compares their performance with thin-film solar cells based on other materials. The fabrication of solar cells based on thin, crystalline Si films on foreign substrates appears to be one of the most attractive routes to realize cheap and efficient photovoltaic devices [1–4], as crystalline Si solar cells are well known for their high efficiencies. Combining crystalline Si with glass as the cheapest substrate material that in addition allows one to realize very efficient light-trapping [5] has stimulated a lot of research activities during the last couple of years. The limited thermal stability of glass and its amorphous nature led to the development of a great variety of techniques to deposit and crystallize device-grade crystalline Si-films [6–8] or to transfer monocrystalline Si-films onto glass or plastic substrates [9, 10]. From today's perspective, it appears that thin-film crystalline Si has not yet fulfilled its high efficiency expectations that resulted from record efficiencies of 24.4% using high-quality bulk Si wafers and complex processing [11].

A closer look at the structural properties of crystalline Si films allows one to distinguish basic types of crystalline Si films with specific electrical properties.

This overview therefore discusses the material properties of crystalline Si and the specific limitations in performance associated with these properties.

Finally, the last years have seen a number of encouraging new concepts to realize cheap and high-efficiency crystalline Si thin-film solar cells. The paper presents an outlook on the most promising routes to realize cheap and efficient thin-film solar cells.

1 The status of crystalline Si thin-film solar cells

The performance of crystalline Si thin-film solar cells shows the following trends: cell efficiencies comparable to those obtained from thick, crystalline Si wafers have, up to now, only been achieved with large-grained polycrystalline Si (poly-Si) on high-temperature-resistant substrates or with thin, monocrystalline Si (mono-Si) films.

As a general trend, cell efficiency decreases with grain size. Information on grain size given in this review is either obtained from explicit statements or from structural information such as micrographs obtained from electron microscopy provided in the respective publications. Grain sizes are, due to the statistical nature of most grain-growth processes [12], to be considered as information on the order of magnitude rather than a precise value. Figure 1 shows efficiencies η obtained from various laboratory-scale thin-film solar cells based on crystalline Si as a function of grain size g. For comparison with results obtained from other (potentially low-cost) thin-film materials, confirmed record efficiencies from thin-film solar cells made from amorphous Si, CdTe, CuInGaSe (CIGS), and photochemical (dye) cells are given. All solar cells have a device area in the range of 1–$4\,cm^2$ if not stated otherwise. Record efficiencies are continuously being compiled and updated [13].

Thin-film cells purely based on small-grained Si films ($g \leq 1\,\mu m$) on glass substrates achieve efficiencies around 10% and are thus outperformed by today's triple-junction hydrogenated amorphous Si (a-Si:H) solar cells, whereas micromorph solar cells, a combination of nanocrystalline Si (nc-Si) and a-Si:H solar cells nearly achieve the efficiency of
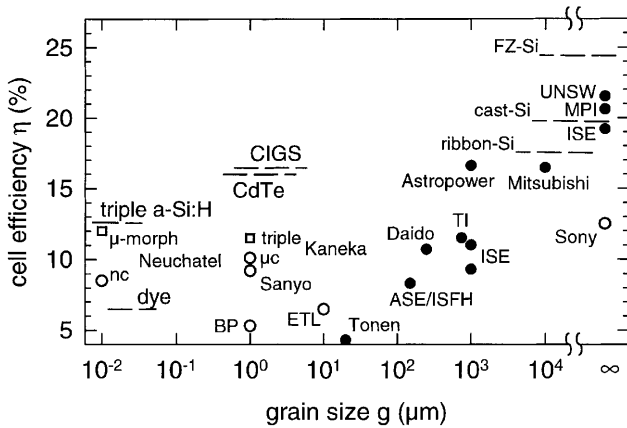
Fig. 1. Conversion efficiency η of crystalline Si thin-film solar cells as a function of grain size g. Current best value for solar cells fabricated from wafer-based float-zone (Fz) Si, cast Si, and ribbon Si given for comparison (dashed lines at $g = \infty$). Performance of crystalline Si solar cells is compared to efficiencies of thin-film cells based on other photovoltaic thin-film materials (*dashed lines* at $g \approx 10$ nm for triple a-Si:H and at $g \approx 1$ μm for CIGS and CdTe solar cells). *Open circles:* Si thin-film cells with a thickness ≤ 12 μm, *closed circles:* Si thin-film cells with a thickness of 30–100 μm, except for the results of Tonen and Daido Hoxan with a higher thickness. *Open squares:* tandem or triple cells combining crystalline and amorphous-Si films. The graph includes best values of laboratory cells with an area of 1–4 cm^2, except for the results of Neuchatel with a cell area of 0.33 cm^2, for references see text

triple-junction cells made from a-Si:H. Cells based on large-grained polycrystalline Si (poly-Si) films achieve efficiencies around 17% and have thus essentially the same performance as CdTe and CIGS-based thin-film solar cells. It should be emphasized, that CdTe and CIGS-based modules are fabricated using soda-lime glass substrates [14] and monolithic cell integration [15], whereas large-grained poly-Si films are currently deposited on comparatively small-sized high-temperature-resistant substrates. The competitiveness of any thin-film approaches will finally depend on cost issues [16]. The most prominent approaches for the fabrication of crystalline Si thin-film cells are now discussed in detail.

1.1 Thin-film solar cell approaches compatible with glass substrates

At the Institute of Microtechnology at the University of Neuchâtel, very high-frequency plasma-enhanced chemical vapor deposition (VHF-PE-CVD) serves to deposit nc-Si on glass at a temperature of 220 °C. The material consists of small grains with a diameter of around 10 nm [17]. Solar cells based on nc-Si with a film thickness of a few μm using a *pin* structure for charge separation currently achieve a maximum cell efficiency of 8.5% [18], the cell area is 0.33 cm^2 [7]. Similar results have recently been obtained at the Research Center Jülich, Germany, with the fabrication of a 7.5% efficient nc-Si thin-film solar cell with an active area of 0.7 cm^2 [19]. So-called micromorph solar cells fabricated by the group in Neuchâtel consist of a combination of amorphous and nc-Si films (the latter is often also named microcrystalline Si) and achieve a stabilized conversion efficiency of 12% [20].

Recent investigations in the field of nc-Si concentrate on the enhancement of the deposition rate [21]. Raising the deposition rate from 12 to 65 nm/min still results in a cell

efficiency of 5.2% [22]. Hot wire CVD (HW-CVD) may be used to deposit device-grade nc-Si and achieves a deposition rate close to 100 nm/min at substrate temperatures below 500 °C [23]. First solar cells have an efficiency of 3.15% [24]. A combination of HW-CVD and VHF-PECVD has recently allowed the deposition of powder-free nc-Si at a deposition rate of 156 nm/min [18], however, no device results have been reported so far.

Low-temperature cell processes for nc-Si are quite similar to amorphous Si technology, however they are more sensitive towards contaminants [25]. The micromorph cell approach will most probably offer a substitute for a-SiGe:H in triple-junction a-Si:H solar cells, and is expected to be capable of providing efficiencies around 13% [18].

Micro-(μc-Si) or poly-Si films can be formed on glass at temperatures around 500–650 °C for example by laser- or solid-phase crystallization. Kaneka Corp. utilized laser crystallization of a highly doped contact layer followed by the deposition of an intrinsic absorber film at an earlier stage of their investigations [26]. Nowadays, laser crystallization seems to be abandoned from the process, however, the description of the deposition process is very rudimentary. The so-called STAR structure [6] realizes efficient light-trapping in a 2-μm-thin μc-Si film by a surface texture that develops during the deposition process, the absorber film itself is deposited on a textured multilayer back side reflector. A thin-film cell with an area of 1.2 cm^2 achieves a conversion efficiency of 10.1%. In view of module production, Kaneka Corp. aims to increase the deposition rate of the μc-Si absorber from around 50 nm/min to at least 150 nm/min [27]. Similar to the approach of the Neuchatel group, Kaneka Corp. also develops thin-film solar cells that consist of a combination of μc and amorphous Si. A triple stack of a-Si:H/μc-Si/μc-Si achieves a stabilized efficiency of 11.5% with a cell area of 0.5 cm^2 [28].

Sanyo Corp. used solid-phase crystallization (SPC) to fabricate μc-Si films for thin-film solar cells. An undoped, amorphous Si-film on top of a highly phosphorous-doped, amorphous Si-film deposited on a metal substrate, is crystallized at a temperature around 550–600 °C for more than 10 h. The cell with a heteroemitter consisting of amorphous Si achieves a conversion efficiency of 9.2% [29]. Due to the long crystallization times involved in the SPC process, the approach is not actively investigated any more by Sanyo.

Apart from the technologies described above, the Center for Photovoltaic Devices and Systems at the University of New South Wales [30] and Pacific Solar Corp. [31], both located in Sydney, Australia, are exploring the so-called multijunction solar cell concept. Multijunction solar cells on heavily doped monocrystalline Si achieve an efficiency of 17.6% [32]. The potential benefit of the approach critically depends on junction design [33] and surface recombination [34]. However, no device results are yet reported using μc- or poly-Si films on glass.

At the Institute of Physical Electronics, we explore high-throughput technologies based on HW-CVD [35] and rapid epitaxy by ion-assisted deposition of Si [36] on laser-crystallized seeding Si films on glass substrates [37, 38]. Presently, laser crystallization appears to be the only approach that is capable of forming crystalline Si films with a grain size substantially larger than 1 μm on commercially available glass substrates [39, 40].

1.2 Thin-film solar cell approaches for high-temperature resistant substrates

Conversion efficiencies in the range of 15% are currently only realized with Si deposited on high-temperature resistant substrates. Recently, Astropower Corp. announced the first commercially available crystalline Si thin-film modules based on a high-temperature process [41]. Laboratory cells achieve a conversion efficiency of 16.6%. Unfortunately, only a few details of the process have been disclosed so far. As important process steps, impurity gettering and hydrogen passivation serve to boost the minority carrier diffusion length from 25–40 μm in as-grown Si films to values exceeding 150 μm [42]. Latest results demonstrate a monolithically integrated module with an aperture area of 321.3 cm^2 and a conversion efficiency of 9.79%. Short-term forecasts of module efficiencies based on this technology amount to 13%, whereas in the long term, even 19% module efficiency is expected [43].

Most groups working on crystalline Si films prepared by high-temperature processes crystallize Si at its melting point at $T_{\text{melt}} \approx 1400\,°C$ by (zone) melting processes in order to obtain grains as large as possible. Oxidized Si substrates [44], graphite [45], or ceramic materials [46] have been used as a substrate. Mitsubishi Corp. reported a solar cell efficiency of 16.5% with a Si film epitaxially deposited on a zone-recrystallized Si film on oxidized Si wafers [47]. Fraunhofer ISE quotes efficiencies of 11% for thin-film solar cells on graphite and 9.3% for cells on SiSiC ceramics using a zone-melting process [46]. A similar process using a graphite substrate results in a cell efficiency of 8.3% at ASE Corp. [48]. The results quoted above have been achieved with Si films of a thickness ranging from 30–100 μm.

Daido Hoxan and Tonen Corp. used plasma spraying to deposit Si films with a thickness of 500 μm and an efficiency of 10.7% [49], and a thickness of 330 μm and an efficiency of 4.3% [50], respectively. An approach, that does not fit into the conventional picture of thin-film deposition, is the *spheral solar cell* approach developed by Texas Instruments Corp. Solar cells are fabricated from purified metallurgical-grade Si spheres with a diameter of 750 μm embedded in an aluminum foil. A mini-module with an area of 10 cm^2 achieves an efficiency of 11.5% [51]. Modules with an area of 3931 cm^2 were fabricated with an efficiency of 10.3% [13, 52]. However, there are no more reports on developments of this and the former two approaches found in the literature during the last years.

Some other results should be mentioned, although the device area of the cells reported is very small or there is very little information on the process. Although the open-circuit voltages may be taken with some confidence, a meaningful comparison of efficiencies with other solar cells should be taken with care. A group at the Electrotechnical Laboratory in Tsukuba, Japan, achieved a 6.5% efficient thin-film cell by Ar-laser crystallization of a 4.2-μm-thick Si film on an alumina ceramic substrate with a cell area of only 0.01 cm^2 [53]. A group at BP Corp. in collaboration with South Bank University in London demonstrated a 5.3% efficient thin-film cell with 10–15 μm in thickness by direct deposition of μc-Si from plasma-assisted CVD at a temperature of 800 $°C$ on a carbon substrate. The grain size of the film is reported to be $\leq 1\,\mu$m and the cell area is 0.17 cm^2 [54]. Global Photovoltaic Specialists Inc. reported on the formation of thin-film solar cells by electrodeposition of 50 μm thick crystalline Si films. Cell efficiencies between 8% and 8.4% are obtained on metalized substrates such as polyester, ceramic, and clay tile. However, the investigators do not reveal any details on the Si film properties [55]. Several other deposition approaches, which have not yet led to device results are summarized in [4].

For the high-temperature processes described above, Fig. 1 demonstrates a clear trend of an efficiency increase with grain size g. Best thin-film solar cells based on large-grained poly-Si currently have a performance comparable to ribbon-based Si solar cells: Evergreen Corp. achieved a conversion efficiency of 15.2% [56] and Georgia Tech manufactures 17.3% efficient cells [57], both using 100 μm thin Si ribbons. High-temperature-deposition processes currently suffer from the availability of cheap and sufficiently pure substrates and recrystallization processes are fairly slow.

Thin-film solar cells based on CdTe and CIGS achieve efficiencies in the 16% range, see also Fig. 1, therefore poly-Si-based thin-film solar cells on foreign substrates currently fight an up-hill battle against other technologies with a yet unpredictable outcome. As efficiencies obtained from different materials are no more significantly different, this competition will be only based on the cost of mass production of modules from the various materials, until in the far future, material constraints may limit the use of non-Si-based thin-film photovoltaics at a very large scale [58].

1.3 Thin-film solar cells based on monocrystalline Si

Latest developments in the area of thin monocrystalline Si films obtained from transfer techniques raise new hope for cheap and high-efficiency crystalline thin-film photovoltaics. Recently, Sony Corp. presented the first solar cell result based on a 12 μm thin, monocrystalline Si film with an efficiency of 12.5% [10]. Although this efficiency is not yet competitive with thin-film cells based on large-grained poly-Si, the open-circuit voltage of 623 mV of this cell is higher than that obtained from other crystalline Si thin-films on foreign substrates and thus demonstrates the superior material quality. High conversion efficiencies may therefore be expected once light-trapping and cell design are improved.

Efficiencies above 19% are currently only obtained by techniques that are not suited for low-cost production such as wafer thinning employed at the Max-Planck Institute for Solid State Research (MPI) in Stuttgart, Germany [59] and at the University of New South Wales (UNSW) in Sydney, Australia [60] or the use of epitaxial films on SIMOX substrates by the Fraunhofer Institute for Solar Energy Research (ISE) in Freiburg, Germany [61].

2 Classification of crystalline Si thin films on foreign substrates

A basic classification of the properties of crystalline Si films may be performed according to the grain size of the films. In most cases, the grain size is intimately related to the processing temperature used to create the films. In addition, the grain size also determines the choice of the electrical design

of the solar cell. Cells based on nc or μc-Si films use an intrinsic or moderately doped absorber and therefore employ a *pin* junction with a built-in drift field. Large-grained poly-Si cells use absorbers with a higher doping level and thus employ *pn* junctions based on minority carrier diffusion for charge carrier separation. Crystalline Si solar cells based on *pn* junctions can, in principle, deliver higher open-circuit voltages, as has been demonstrated for example by simple modeling of appropriate solar cell structures using PC-1D [38]. However, voltage limitations predicted by device modeling based on the parameters of crystalline Si are not necessarily valid for thin-film cells fabricated from nc-Si [18], as this material consists of a mixture of nc and amorphous Si.

Figure 2 shows open-circuit voltages V_{oc} of the thin-film cell results reported in Fig. 1 as function of grain size g. For poly-Si-based *pn*-junction solar cells with $g > 1\,\mu m$, the open-circuit voltage V_{oc} strongly decreases with decreasing grain size g. This decrease is much more severe than predicted by the performance dependence on grain size as determined from cast Si reported by Imaizumi, see [62]. In the area of small-grained Si with $g \leq 1\,\mu m$, two cases may be distinguished: (i) For nc-Si based cells ($g \approx 10$ nm), an open-circuit voltage V_{oc} of 531 mV is observed for cells with a maximum conversion efficiency of 8.5%. Cells with higher open-circuit voltage suffer from a severely degraded fill factor [18]. (ii) For μc-Si films ($g \approx 1\,\mu m$), there seems to be an optimum doping level in the range of 10^{15}–10^{16} cm^{-3} that results in V_{oc} of 539 mV for the cell of Kaneka Corp. [27] and 553 mV for the cell of Sanyo Corp. [29]. In contrast to the voltages achieved with nc-Si-based cells, the latter two voltages are in good agreement with PC-1D modeling based on the parameters of crystalline Si [38].

In order to elucidate different types of crystalline Si films on foreign substrates, Fig. 3 gives a schematic representation of four basic material systems: (a) nc-Si films are deposited on (metal-coated) glass substrates at temperatures well below 450 °C, (b) μc- or fine-grained poly-Si is deposited or crystallized on soda-lime, borosilicate [63], or alumina silicate glass [64, 65], or metal films [29] at medium tempera-
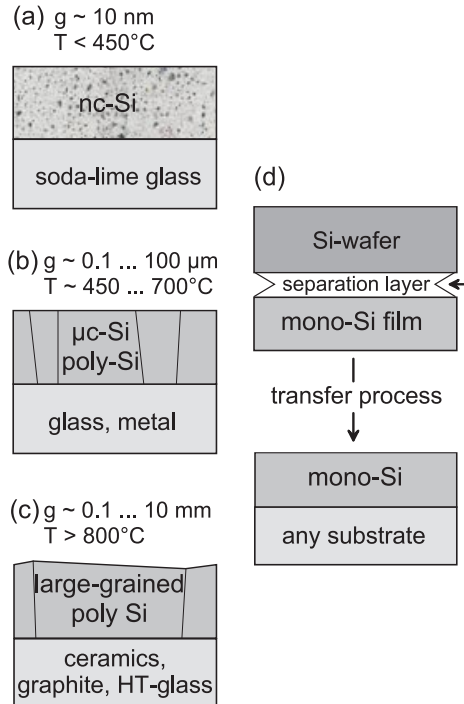

Fig. 3a–d. Classification of crystalline Si films on foreign substrates according to grain size. **a** nc-Si films are deposited at temperatures below 450 °C on soda-lime glass. **b** μc- or poly-Si films with a grain size in the range of 0.1–100 μm form by direct deposition and/or solid-phase crystallization at temperatures around 450–700 °C or by laser crystallization. Substrates such as metal foils or glass may be used, depending on the thermal budget of the process. **c** Large-grained Si films with mm or larger sized grains are obtained from (zone) melting processes at high temperatures $T > 800$ °C mainly on ceramic substrates and graphite or on high-temperature glass. **d** Monocrystalline-Si films on foreign substrates are formed on Si wafers and are subsequently transferred to a suitable substrate
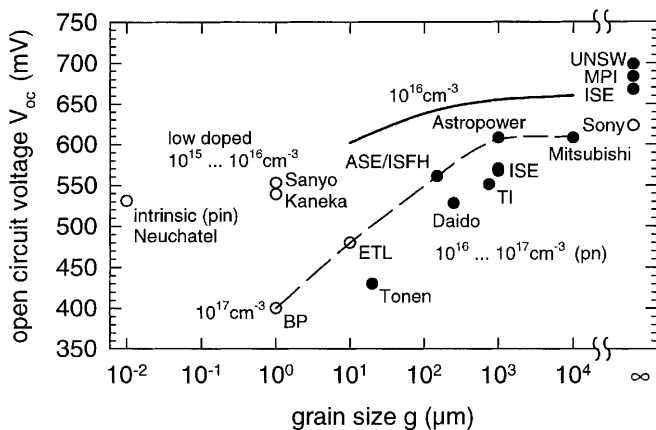
tures in the range of 450–700 °C, (c) large-grained poly-Si is formed and processed by (zone) melting processes on high-temperature-resistant substrates such as graphite, ceramics [46], or high-temperature glass [66] at temperatures well above 800 °C. (d) The formation of monocrystalline Si films requires a process that transfers a monocrystalline Si film grown on a monocrystalline Si-substrate to a foreign substrate, which can in principle be of arbitrary nature.

2.1 Nanocrystalline Si

Electronic transport in nc-Si is considerably different from transport in poly-Si [67] and is not yet understood in detail [68]. Recent experimental investigations, assisted by two-dimensional transport simulations, indicate that there is no significant band bending at grain boundaries of grains with 10–20 nm diameter. The Debye screening length in Si is within the range of 100 nm and thus much higher than the average grain size [69]. The carrier transport in nc-Si is therefore dominated by trapping and recombination and not by potential barriers at grain boundaries. A comparison of simulated and calculated I–V curves of *pin* junctions indicates that amorphous regions within the material are randomly distributed rather than located at the grain boundaries of the crystallites [69]. Majority carrier mobility is of the order of

Fig. 2. Open-circuit voltages V_{oc} of the crystalline-Si thin-film solar cells included in Fig. 1 as a function of grain size g. For poly-Si based, *pn* junction thin-film cells, V_{oc} rapidly decreases with grain size. Experimentally observed decrease (*dashed line*) is much stronger than the open-circuit dependence on grain size as predicted from a fit of diffusion length data based on cast Si (*solid line*). There is no such trend for nc- or μc-Si based *pin*-junction devices

a few cm^2/Vs [68] and the minority carrier diffusion length is generally well below 1 μm [70]. Minority carrier devices are realized using *pin* structures in order to benefit from drift fields for carrier extraction. However, the evaluation of the relative contributions of drift and diffusion to carrier transport [71] and the inhomogeneous nature of the charge transport [72] need further investigation.

2.2 Fine-grained polycrystalline Si

Carrier transport in μc- or poly-Si films is governed by potential barriers at grain boundaries [67]. The height of these potential barriers depends on the trap density N_T at the grain boundary, the intra-grain doping density N_G, and the grain size g and has its maximum around a critical intra-grain doping of $N_G^* = N_T/g$. Both the majority carrier mobility as well as the minority carrier recombination velocity at the grain boundary exponentially depend on the height of the potential barrier [73]. In order to reduce the barrier height and thus charge carrier recombination, one has to reduce the doping of the absorber layer and/or the trap density at the grain boundary. In the case of μc-Si-based solar cells, a *pin*-junction structure should therefore be employed. In large-grained Si the spacing of grain boundaries is so large, that potential barriers no longer dominate recombination and a *pn* junction with its higher open-circuit voltage potential may be used.

Material quality can, in some cases to a great extent, be improved by hydrogen passivation [74, 75]. The majority carrier mobility of these films may approach that of monocrystalline Si. However, very few studies are concerned with measurements on minority carrier diffusion length in fine-grained poly-Si [76]. Minority carrier diffusion lengths are usually in the range of only a few μm even for monocrystalline Si films deposited at temperatures around 600 °C [38]. The analysis of minority carrier properties of poly-Si films is intrinsically complicated by its inhomogeneous nature that results from the broad grain-size distribution [77, 78] and potential fluctuations within individual grain boundaries [79]. Due to the wide distribution of grain sizes and, as a consequence, also of the minority carrier diffusion length, the open-circuit voltage of a poly-Si thin-film cell cannot be accurately predicted from diffusion lengths obtained, for example from internal quantum efficiency measurements. The current obtained from a solar cell represents an average of the diffusion length distribution, whereas the open-circuit voltage of the cell strongly decreases as an effect of even a small fraction of grains with a diffusion length that is small compared to the rest of the material [80].

2.3 Large-grained polycrystalline Si

Material properties of large-grained Si films come close to those of monocrystalline Si as far as majority and minority carrier properties are concerned. However, even here effects of polycrystallinity cannot be neglected. Recent investigations have shown, that the minority carrier diffusion length distribution in large-grained cast-Si is bimodal and the cell performance is significantly decreased by the influence of

areas with low diffusion length [81]. As a result of the investigations on the structure of poly-Si presented in this and the preceding paragraph, it appears obvious that the performance of solar cells based on poly-Si will remain significantly below that of cells based on monocrystalline Si simply as a consequence of the inhomogeneous nature of the material.

3 Monocrystalline Si thin-films for photovoltaics

Monocrystalline Si films appear to be ideally suited for thin-film solar cells. However, cost issues have up to now, in contrast to applications in the area of microelectronics [82], inhibited the use of monocrystalline Si films in photovoltaics. Recently, several innovative concepts for the fabrication of monocrystalline Si films were reported which will be described here.

Figure 4 shows a schematic compilation of structures recently introduced to realize thin-film solar cells based on monocrystalline Si films. The approaches are: (a) The formation of a net-like monocrystalline Si structure by the so-called Epi-lift technique [83], (b) the formation of thin, monocrystalline Si-waffles using the so-called Ψ-process [84], (c) epitaxial growth of monocrystalline Si films on crystallized porous Si introduced by Sony Corp. [10], and (d) the formation of so-called quasi-monocrystalline Si films with internal light-trapping introduced at the Institute of Physical Electronics in Stuttgart [85, 86].

3.1 Epi-lift

The Epi-lift technique is based on the formation of (111)-oriented crystal planes [87] during near-equilibrium growth of Si using liquid phase epitaxy. An oxidized, (100)-oriented Si wafer with oxide-free seed lines oriented close to two orthogonal [110] directions on the wafer surface serves as a substrate for Si epitaxial growth from a liquid-metal solution [88]. Due to the surface energy minimum of the (111)-oriented Si surface, a Si net enclosed by (111) planes develops as shown in Fig. 4a. The process aims at fabricating a solar cell from the monocrystalline Si-net and to detach it from the wafer by use of a suitable etch. The starting Si-wafer is then supposed to be reused for further growth sequences. Up to now, no information on the reusability of the wafer or solar cell results are reported. Monocrystalline Si-nets were separated from the starting wafer and an effective minority carrier lifetime of over 100 μm was determined [89].

3.2 Ψ-process

The Ψ-process starts with a textured (100)-oriented Si wafer with a porous Si film that serves as an epitaxial seed for the growth of an approximately 10 μm thick monocrystalline Si film. Epitaxial growth serves to conformaly coat the surface of porous Si, thus a waffle-like structure enclosed by (111) planes forms, see Fig. 4b. This waffle has very good light-trapping properties and is, due to the mechanical weakness of the sacrificial porous film, easily detached from the Si starting wafer [9]. Up to now, no information is available
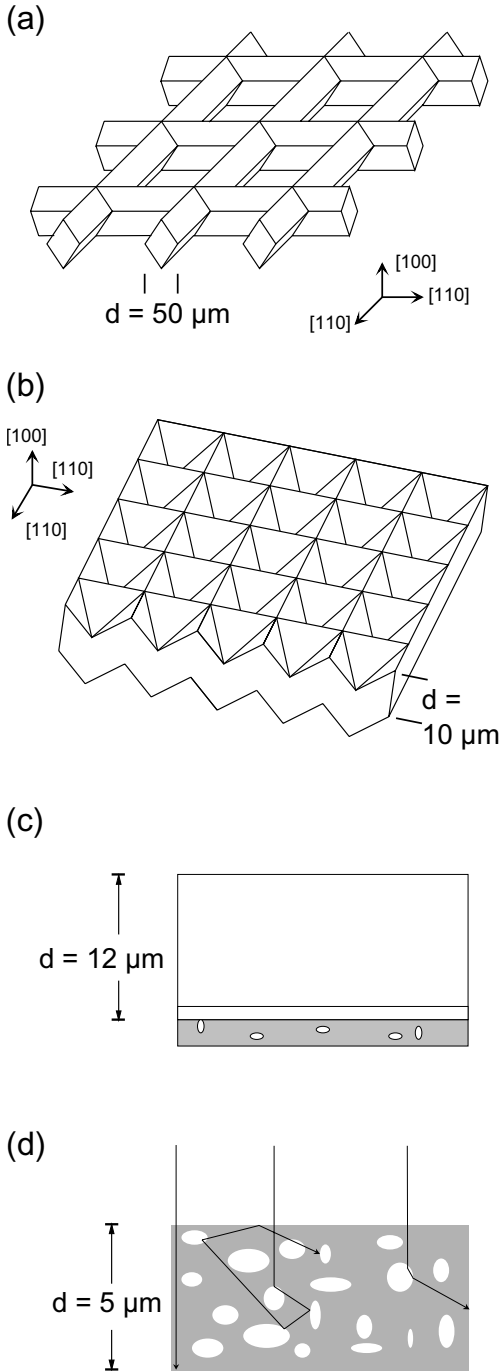
(a)

[100]

[110]

[110]

d = 50 μm

(b)

[100]

[110]

[110]

d =
10 μm

(c)

d = 12 μm

(d)

d = 5 μm

Fig. 4a–d. Approaches recently published for the creation of monocrystalline Si films. **a** The Epi-lift process creates a Si net with surfaces formed by (111) planes. The net is separated from a partially oxidized Si substrate that is to be reused. **b** The Ψ process forms a waffle-like Si film by epitaxial growth on a (111) texture etched Si wafer with a porous Si surface. The porous Si serves as a separation layer while the wafer is to be reused. **c** Sony Corp. uses epitaxial growth of Si on thermally crystallized porous Si films, that serves as a separation layer. Again the process aims to reuse the wafer. **d** Quasi-monocrystalline Si films obtained from thermal crystallization of porous Si is separated from a reusable Si wafer. Voids embedded in the Si film create internal light-trapping

neither on the reusability of the starting wafer nor on solar cell efficiencies. However, two-dimensional device simulation shows, that an efficiency up to 19.3% is attainable using realistic simulation parameters [90].

3.3 High-temperature epitaxy on crystallized porous Si

Due to the porous nature of the crystallographic template used for epitaxial growth in the Ψ-process, growth temperatures are limited to around 800 °C at maximum. This boundary condition limits the quality and rate of epitaxial growth. Sony Corp. developed a process that creates a porous double layer with a buried film of high porosity. Upon thermal annealing at temperatures around 1100 °C, the film with a lower porosity at the top of the double layer forms a monocrystalline film that withstands high-temperature epitaxy using standard trichlorosilane-based epitaxial growth, while the buried layer forms a separation layer that enables one to detach the epitaxial film from the starting wafer, see Fig. 4c. Using a 12 μm thick epitaxial film that is detached from the substrate, Sony reported a conversion efficiency of 12.5% on 4 cm^2 area [10].

3.4 Quasi-monocrystalline Si

Independently from the work of Sony, we developed a process that realizes the formation of monocrystalline Si films by thermal annealing of porous Si. The crystallization of a several-μm-thick film of low porosity on a thin film with high porosity forms a so-called quasi-monocrystalline Si film [85] on a separation layer. Films are termed quasi-monocrystalline, because the crystallization of several-μm-thick Si films results in the formation of a monocrystalline structure that contains voids with a size up to 1 μm. These voids lead to an internal light-trapping effect within the crystalline film. Films with a thickness of 4 μm have transmission losses of only 10% without any additional means of optical confinement. The material therefore offers an elegant way to realize cheap and efficient thin-film solar cells. Quasi-monocrystalline Si films are easily detached from the substrate before or after further processing. Up to 30 porous Si films have been produced by us from one Si wafer up to now, clearly demonstrating the reusability of the Si starting wafer. Solar cell processing suitable for quasi-monocrystalline Si films is currently being developed at our institute.

4 Conclusions and outlook

The field of thin-film crystalline Si solar cells has seen remarkable developments during the last years. Most encouraging results have been presented by Astropower Corp. with a large-grained poly-Si thin-film solar cell with an efficiency of 16.6% on a high-temperature-resistant substrate and by Kaneka Corp. with a μc-Si thin-film solar cell with 10.1% efficiency on glass. Thin-film solar cell technologies based on nc- and μc-Si aim at a combination with a-Si:H solar cell technology in a tandem or triple-cell configuration. Efficiencies around 13% are expected for this material combination.

However, presently emerging thin-film technologies based on crystalline Si on foreign substrates are entering an uphill battle against other thin-film materials such as CdTe or CIGS with efficiencies in the range of 17%. Within the crystalline-Si-based technologies, large-grained Si films on foreign substrates have to compete with ribbon-based crystalline Si technology that currently achieves slightly higher efficiencies with apparently less complex processing.

Large-grained poly-Si presently has efficiencies in the range of 15%–17%, and is expected to improve to around 18% [42]. In the case of monocrystalline Si thin-films, maximum performance may be limited by the complexity of the process rather than material constraints and efficiencies in the range of 20% appear feasible.

The estimates stated above are not based on "first principles". In contrast to maximum efficiency calculations as a function of the band gap which are based on fundamental processes [91, 92], calculations of maximum efficiencies in polycrystalline material will have to rely on material-specific parameters such as the recombination at grain boundaries [93–95]. Here, a sufficiently deep understanding is still lacking.

Although efficiencies obtained from crystalline Si on glass are presently low compared to those from other techniques, the combination of crystalline Si and glass as a substrate still appears to be the commercially most attractive approach for large-area monolithically integrated modules. If module efficiencies based on crystalline Si on glass cannot be increased substantially beyond those of amorphous-Si modules, thin monocrystalline-Si films transferred to glass may provide an alternative route to low-cost, high-efficiency thin-film solar cells.

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