

# >21% Efficient Silicon Heterojunction Solar Cells on n- and p-Type Wafers Compared

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**Abstract**—The properties and high-efficiency potential of front- and rear-emitter silicon heterojunction solar cells on n- and p-type wafers were experimentally investigated. In the low-carrier-injection range, cells on p-type wafers suffer from reduced minority carrier lifetime, mainly due to the asymmetry in interface defect capture cross sections. This leads to slightly lower fill factors than for n-type cells. By using high-quality passivation layers, however, these losses can be minimized. High open-circuit voltages ( $V_{oc}$ s) were obtained on both types of float zone (FZ) wafers: up to 735 mV on n-type and 726 mV on p-type. The best  $V_{oc}$  measured on Czochralski (CZ) p-type wafers was only 692 mV, whereas it reached 732 mV on CZ n-type. The highest aperture-area certified efficiencies obtained on 4 cm<sup>2</sup> cells were 22.14% ( $V_{oc} = 727$  mV, FF = 78.4%) and 21.38% ( $V_{oc} = 722$  mV, FF = 77.1%) on n- and p-type FZ wafers, respectively, proving that heterojunction schemes can perform almost as well on high-quality p-type as on n-type wafers. To our knowledge, this is the highest efficiency ever reported for a full silicon heterojunction solar cell on a p-type wafer, and the highest  $V_{oc}$  on any p-type crystalline silicon device with reasonable FF.

**Index Terms**—Amorphous silicon, crystalline silicon, heterojunctions, photovoltaic cells.

## I. INTRODUCTION

SILICON heterojunction solar cells are interesting candidates for low-cost high-efficiency solar cells. Conversion efficiencies above 23% have indeed already been demonstrated by Sanyo [1], and the production costs of such devices are potentially low. No high-temperature or photolithographic processes are required, since passivation of the crystalline silicon (c-Si) wafer surfaces and formation of the emitter and back surface field are all performed with thin intrinsic and doped hydrogenated amorphous silicon (a-Si:H) layers, usually deposited by plasma-enhanced chemical vapor deposition (PECVD). PECVD fabrication steps are presently well controlled at the industrial scale, benefiting from the knowledge gained in the past decades in the fabrication of large-area thin-film devices.

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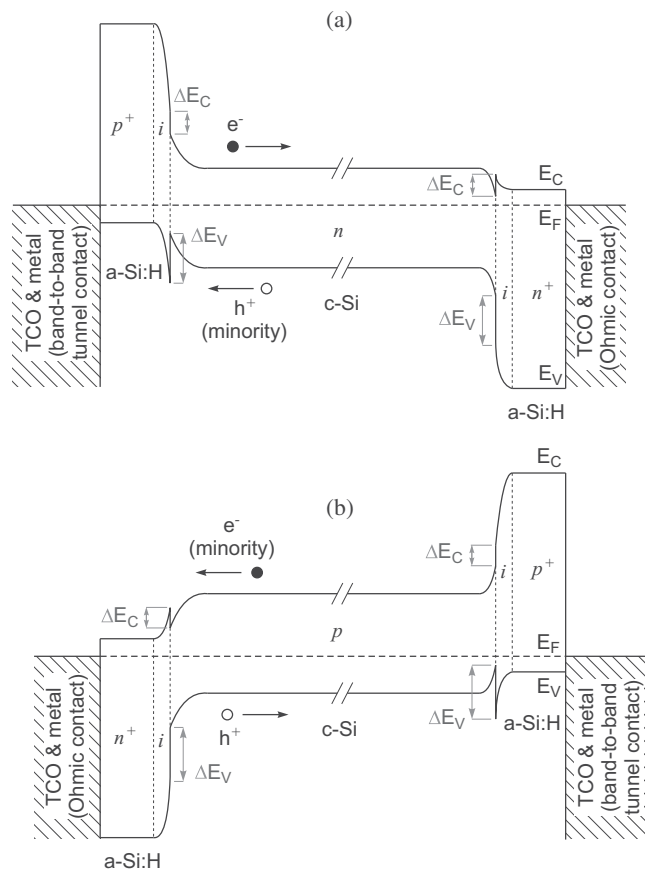


Fig. 1. Schematic band diagram of a silicon heterojunction cell based on (a) n-type c-Si wafer and (b) p-type c-Si wafer.  $E_C$  denotes the conduction band edge,  $E_V$  the valence band edge,  $E_F$  the Fermi level,  $e^-$  electrons, and  $h^+$  holes. The thin intrinsic a-Si:H layers provide a drastic improvement in c-Si surface passivation. Band offsets ( $\Delta E_C$ ,  $\Delta E_V$ ) are present at each a-Si:H/c-Si interface, in both bands, and band bending is likely induced at the a-Si:H/TCO interface as well (not drawn, for simplicity). Most of the electron-hole pairs are generated close to the illuminated side. For front-emitter cells, light is incident from the left; for rear-emitter cells, from the right.

So far, the highest efficiency silicon heterojunction solar cells were obtained using n-doped, rather than p-doped, c-Si wafers [2]. Fundamental issues with the band structure, such as the asymmetry between the conduction and valence band offsets (see Fig. 1), are often assumed to reduce the performance of p-type heterojunction solar cells [3], [4]. Nevertheless, n-type wafers are less readily available on the market than p-type wafers, which are widely used for the production of conventional (diffused-emitter) silicon solar cells. The possibility to produce high-efficiency heterojunction solar cells from p-type wafers is, thus, of great practical interest. Such cells have already been

demonstrated by several groups [5]–[11] but with efficiencies significantly lower than those achieved on n-type wafers.

In this study, by means of minority carrier lifetime, current-voltage, and quantum-efficiency measurements, a systematic comparison of silicon heterojunction solar cells produced on n- and p-type wafers is performed in order to investigate their potential and limitations for high efficiencies. In particular, since charge transport in the cell is one of the major differences when using n- or p-type substrates (different types of minority carriers and different band structures, as shown in Fig. 1), cells with front and rear emitters are experimentally analyzed. This way, insights into transport are provided. Finally, the best efficiencies obtained on different wafer types (doping type and material quality) are presented.

## II. HETEROJUNCTION SOLAR CELL FABRICATION

Unless otherwise stated, n- and p-doped ( $4 \Omega\cdot\text{cm}$ ) float zone (FZ) c-Si(1 0 0) wafers were used as substrates. As-cut wafers were textured in a potassium hydroxide (KOH) solution (final wafer thickness:  $230 \mu\text{m}$ ), wet-chemically cleaned, and dipped in hydrofluoric acid (HF) just before PECVD. Intrinsic and doped a-Si:H layers were deposited on the whole wafer surfaces at  $200^\circ\text{C}$  using mixtures of silane ( $\text{SiH}_4$ ), hydrogen ( $\text{H}_2$ ), phosphine ( $\text{PH}_3$ ), and trimethylboron ( $\text{B}(\text{CH}_3)_3$ ) in an automated, large-area (electrode size:  $50 \text{ cm} \times 60 \text{ cm}$ ), narrow-gap ( $13 \text{ mm}$ ), parallel-plate industrial PECVD reactor powered at very high frequency (VHF,  $40.68 \text{ MHz}$ ). The large area of this reactor allowed us to codeposit identical a-Si:H layers on several wafers in the same run, with excellent uniformity.

Transparent conductive oxide (TCO), typically indium tin oxide (ITO), was then deposited on the front and back of the wafers by dc magnetron sputtering. The size of the cell on the wafer was defined by using a shadow mask during deposition of the front and back ITO layers. The ITO properties required for the front and back layers differ from each other. At the front, the ITO refractive index and the layer thickness were chosen in order to create an antireflection coating with a minimum in reflectivity at approximately  $600 \text{ nm}$ . The carrier density is also an important parameter for the front ITO layer, since there is a tradeoff between low parasitic free-carrier absorption and low resistivity [12]. The back ITO layer was optimized for transparency alone since lateral transport is not required, as it is covered by a silver back reflector. This back reflector was deposited by sputtering immediately after the back ITO, using the same shadow mask. A front grid was screen-printed with a low-temperature silver paste, and the cell was cured at around  $200^\circ\text{C}$  for several minutes. Note that all of these fabrication steps are fully compatible with cell production at an industrial scale.

## III. RESULTS AND DISCUSSION

### A. Effect of the Wafer Doping Type and Emitter Position on Silicon Heterojunction Solar Cell Performance

Heterojunction solar cells were produced on n- and p-type wafers, with the emitter located either at the front side (front-emitter cell) or at the back side of the cell (rear-emitter cell). This

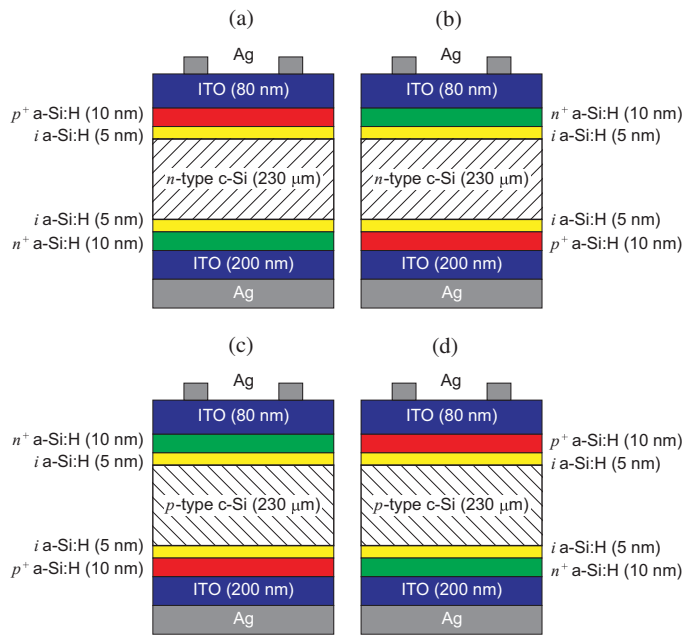


Fig. 2. Schematic drawings of the different heterojunction solar cell structures tested (not to scale). (a) n-type wafer with front emitter. (b) n-type wafer with rear emitter. (c) p-type wafer with front emitter. (d) p-type wafer with rear emitter.

way, potential differences in charge carrier transport through the wafer are highlighted. All four possible cell structures were tested and are schematically shown in Fig. 2. All wafers were batch-processed together during the wet-chemical treatments and the a-Si:H, ITO, and back Ag layer depositions. Only the screen-printed front grid was applied on one cell at a time, but consecutively, and with the same Ag paste and screen. Therefore, every individual layer can be considered as strictly identical on all cells, although each cell has its own particular structure. The size of each cell is  $2 \text{ cm} \times 2 \text{ cm}$ .

After deposition of the  $\text{in}^+$  and  $\text{ip}^+$  a-Si:H stacks by PECVD, the minority carrier lifetimes of the solar cell precursors were measured with a quasi-steady-state photoconductance system [13]. Since infrared light is used to generate carriers homogeneously in the wafer, no difference is observed when illuminating from the  $\text{in}^+$  or the  $\text{ip}^+$  side. Samples on n-type and p-type wafers exhibit different behavior, especially in the low-injection range [see Fig. 3(a)]. On the one hand, at high injection levels, the lifetime values are relatively similar:  $1.9 \text{ ms}$  on n-type and  $1.6 \text{ ms}$  on p-type at a minority carrier density of  $10^{16} \text{ cm}^{-3}$ , for example (lifetimes are limited by unavoidable Auger recombination in this range). Therefore, there is the potential for high open-circuit voltages ( $V_{\text{oc}}$ ) on both types of wafers, since these high-lifetime cells reach high injection at open circuit. The 1-sun implied  $V_{\text{oc}}$  values given in Fig. 3(a) confirm this high  $V_{\text{oc}}$  potential and show no significant difference between n- and p-type. On the other hand, a dramatic drop is observed on p-type at injection levels below  $3 \times 10^{15} \text{ cm}^{-3}$ :  $5.6 \text{ ms}$  is measured on n-type and  $2.1 \text{ ms}$  on p-type at  $10^{15} \text{ cm}^{-3}$ , for example. As with c-Si passivated by thermally grown silicon dioxide ( $\text{SiO}_2$ ) [14], the larger capture cross section of interface defects for electrons

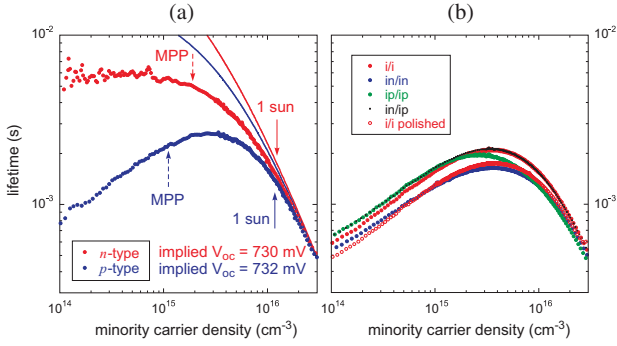


Fig. 3. (a) Minority carrier effective lifetimes of solar cell precursors (textured wafers passivated with codeposited  $\text{in}^+$  and  $\text{ip}^+$  a-Si:H stacks) on n- and p-type FZ wafers. The injection levels corresponding to 1-sun illumination are marked by solid arrows, and the corresponding implied  $V_{oc}$  values are given. The injection levels corresponding to the MPPs of the finished devices (under 1-sun illumination) are marked by the dashed arrows. Combined radiative and Auger recombination limits are shown by the solid lines [17], [18]. (b) Minority carrier effective lifetimes of textured p-type FZ wafers passivated with  $i/i$ ,  $\text{in}/\text{in}$ ,  $\text{ip}/\text{ip}$ , and  $\text{in}/\text{ip}$  a-Si:H layers, and of a polished p-type FZ wafer passivated with  $i/i$  a-Si:H layers.

than for holes explains this difference in the injection-dependent lifetimes of n- and p-doped samples. Since electrons (minority carriers in p-doped c-Si) are more easily lost at the interface than holes, p-type samples suffer more from surface defect-assisted minority carrier recombination than n-type samples, especially at low injection. Even if the asymmetry in the respective cross sections is much less pronounced for defects at the a-Si:H/c-Si interface than for defects at the  $\text{SiO}_2/\text{c-Si}$  interface [15], it is nevertheless sufficient to reduce the low-injection lifetime on p-type samples. This behavior cannot be attributed to bulk defects: High-quality FZ wafers were used here, and longer low-injection lifetimes are observed when similar wafers are passivated with the negative fixed-charge dielectric aluminum oxide ( $\text{Al}_2\text{O}_3$ ) [16]. Note that the behavior at low injection is also seen with p-doped wafers passivated with  $\text{ip}^+$  a-Si:H stacks on both sides [see Fig. 3(b)]. This suggests that the small additional field-effect passivation created by the  $\text{p}^+$ -doped layers is not sufficiently strong to screen the interface defects and avoid surface recombination at low injection levels. In addition, p-doped samples passivated with  $\text{in}^+$  a-Si:H stacks on both sides or with only  $i$  a-Si:H layers on both sides exhibit also the same behavior [see Fig. 3(b)]. Thus, the drop in lifetime at low injection is not dominated by the band bending configuration at the interface.

Since the minority carrier density changes from high to low values during an illuminated current–voltage ( $IV$ ) measurement as we move from open-circuit to short-circuit conditions, a reduced fill factor (FF) can be expected for completed solar cells when p-type wafers are used. This drop in the lifetime will indeed cause a reduction in the cell performance at the maximum power point (MPP) compared with a cell for which the lifetime stays flat for decreasing injection (n-type case). This effect can be clearly seen and quantified by calculating “implied  $IV$  curves” from the solar cell precursor lifetime data, similar to  $\text{suns}-V_{oc}$  measurements [19]. In a standard  $\text{suns}-V_{oc}$  measurement, the  $V_{oc}$  of a finished device is measured at illumination

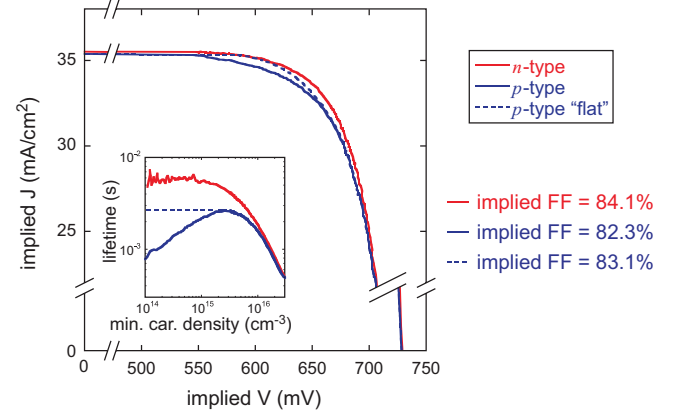


Fig. 4. Detail of the “implied  $IV$  curves” around the MPP and implied FF values calculated from the lifetime data of the n- and p-type solar cell precursors of Fig. 3(a). The calculated implied  $IV$  curve of a modified p-type case is also shown, in which we assumed a constant (“flat”) lifetime at low injection (see corresponding curves in the inset). The  $J_{sc}$  values taken for the calculations of implied  $J$  are the actual values obtained from the finished cells (see Table I).

intensities  $I_L$  between 0 and  $>1$  sun. A “pseudo  $IV$  curve” is then obtained by plotting pseudo current density ( $pJ$ ) against the measured illumination-dependent  $V_{oc}(I_L)$ . This pseudo current density is defined by  $pJ(I_L) = J_{sc} \cdot (1 - I_L)$ , where  $J_{sc}$  is the short-circuit current density of the finished device measured in a standard  $IV$  measurement (at 1 sun), and  $I_L$  is expressed in number of suns. In our implied  $IV$  measurements, however, the device is not finished (the emitter is present but without terminals), and  $V_{oc}(I_L)$  is, thus, replaced by the implied voltage determined from the excess minority carrier densities [13], which is also measured at different illumination intensities during an injection-dependent lifetime measurement. The implied current density is calculated in the same way as  $pJ$  in a  $\text{suns}-V_{oc}$  measurement, namely  $\text{implied } J(I_L) = J_{sc} \cdot (1 - I_L)$ . Since both pseudo  $IV$  and implied  $IV$  measurements are performed at open circuit, the pseudo fill factor (pFF) and implied FF values that are obtained from these curves exclude series resistance and possible issues related to transport and extraction of carriers through the contacts. Fig. 4 shows the implied  $IV$  curves of the two solar cell precursors of Fig. 3(a), and also of a virtual p-type sample with a constant lifetime at low injection and the same behavior at high injection as the actual p-type sample. Implied FF values obtained from these curves show clearly that an absolute loss of around 1% in the real FF of the finished device can be attributed to the drop in lifetime at low injection for the p-type sample, compared with the virtual flat-lifetime case (“p-type” curve compared with “p-type flat” curve). A total absolute loss of around 2% in real FF is estimated compared with the n-type sample, due solely to this difference in lifetime at low injection (“p-type” curve compared with “n-type” curve). From this, we conclude that high  $V_{oc}$  values are not a sufficient criterion to obtain high FF values and, despite comparable  $V_{oc}$ s, cells on p-type wafers are expected to be less efficient than those on n-type wafers. High voltage at maximum power point ( $V_{MPP}$ ) is of greater importance. As the lifetime at MPP is determined here by surface recombination, FF depends thus fundamentally

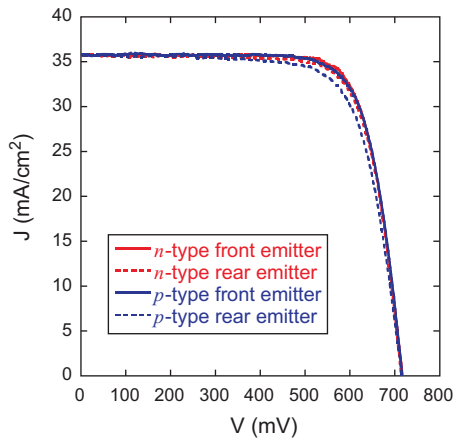


Fig. 5. Illuminated  $IV$  curves of  $2\text{ cm} \times 2\text{ cm}$  cells with screen-printed contacts measured under standard test conditions (in-house measurements).

TABLE I  
IV PARAMETERS OF  $2\text{ cm} \times 2\text{ cm}$  CELLS (AVERAGE OF SIX CELLS)

Wafer type	Emitter position	$V_{oc}$ (mV)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF (%)	pFF (%)	Efficiency (%)
n-type	front	718	35.6	76.5	83.2	19.6
n-type	rear	713	35.6	75.0	80.7	19.0
p-type	front	718	35.7	75.5	81.6	19.4
p-type	rear	716	35.6	71.8	77.5	18.3

on the a-Si:H/c-Si interface properties. Note that in p-type multicrystalline silicon solar cells, *bulk* defects (rather than *surface* defects) create also a strong injection-level dependence of the lifetime, resulting similarly in a limitation of FF values [20].

The illuminated  $IV$  curves of the finished cells are shown in Fig. 5, and the detailed cell parameters are given in Table I. The cells were measured under standard test conditions ( $25^\circ\text{C}$ , AM 1.5 G) with a shadow mask that has an opening that is the same size as the cells (defined by the front ITO layer and back metallization). pFF values obtained from standard suns- $V_{oc}$  measurements performed with the same shadow mask are also given in Table I.

For standard front-emitter cells, similar  $V_{oc}$  values are obtained on n- and p-type wafers, as expected from the carrier lifetime measurements (see Figs. 3(a) and 4), whereas FF and pFF are slightly lower on p-type. Measured FF and pFF values are consistent with implied FF values that are predicted in Fig. 4, showing an absolute loss of between 1% and 2% on p-type compared with n-type. pFF is consistently slightly lower than implied FF, likely due to additional passivation losses induced by the processes required to finish the cells (ITO and Ag sputtering, front grid screen-printing, and curing). The  $J_{sc}$  values are very similar on both types of wafers because light absorption in the cells is comparable. The wafer thicknesses and front ITO layers are identical, and our n- and p-doped a-Si:H layers have similar optical absorption properties [12] and thicknesses.

In addition to the asymmetry in capture cross sections described before, the different band offset configurations in n-

and p-type cells are believed to affect carrier recombination and transport at the heterointerface, and hence  $V_{oc}$  and FF [3], [4]. Detailed analysis of band offsets at the a-Si:H/c-Si interface by photoelectron spectroscopy and surface photovoltage measurements showed that the conduction band offset  $\Delta E_C$  and the valence band offset  $\Delta E_V$  are independent of both substrate and film doping, being in all cases roughly equal to 0.15 and 0.45 eV, respectively [3], [21]. More recent data showed also that  $\Delta E_V$  further increases when the hydrogen content in a-Si:H is increased, whereas  $\Delta E_C$  remains constant [22]. This asymmetry between  $\Delta E_C$  and  $\Delta E_V$  (see Fig. 1) is, in principle, more favorable to n-type heterojunction solar cells than p-type ones. Indeed, recombination is reduced if the concentration of recombining carriers at the interface is kept low. A large band offset in the minority carrier band provides precisely such a condition. Since holes are the minority carriers in n-type c-Si and since  $\Delta E_V > \Delta E_C$ ,  $V_{oc}$  of n-type cells may be higher than that of p-type cells [3], [4]. In the p-type case, electrons (minority carriers) may recombine more easily at the interface due to a lower  $\Delta E_C$  barrier. According to our cell results, however, this effect seems to be negligible under the open-circuit condition: the  $V_{oc}$  values of n- and p-type front-emitter cells are identical, because lifetime is limited by Auger recombination rather than by surface recombination at this injection level.

With regard to carrier transport, it was shown by both experiment and simulation that band offsets influence the transport mechanisms at low bias, where tunneling of carriers through band offsets can take place [23]–[25]. This will result in a different carrier transport in n- and p-type heterojunction solar cells due to the different band structure seen by minority carriers [24], [25]. Under device-operating conditions (similar to a high-bias regime), however, the a-Si:H/c-Si interface defect density was shown to be the limiting factor for solar cell performance [3], [23]–[26]. Suppressing the defect states at the interfaces is indeed the key to efficient transport and high  $V_{oc}$  and FF values, whereas band structures may play only a minor role [25]. Therefore, the slightly lower FF of p-type cells is probably not caused only by pure transport problems that are linked to band offsets, e.g., band offset tunneling. The asymmetry in capture cross sections is rather the dominant effect which is responsible for the lower FF of p-type cells, as discussed previously. When transport across the ITO/doped a-Si:H interface is considered, however, efficient tunneling *does* seem to be critical to achieve high efficiency and influences strongly FF [24]. Here, carriers have to tunnel from band to band rather than through band offsets. Band bending at the ITO/a-Si:H interface plays an important role in this context.

When the emitter is put at the back of the cell, losses in FF and pFF are observed on both types of wafers, especially in the p-type case. The pFF values indicate that the FF ranking of the different cells is not dictated only by series resistance losses, but also by something intrinsically related to the cell structure (pFF excludes series resistance).  $V_{oc}$  values are slightly reduced as well, but to a lesser extent. This reduction in performance of rear-emitter cells may result from the decreased illumination of the a-Si:H layers at the emitter side. The properties of the emitter and the transport through the a-Si:H layers may improve under



increased illumination, resulting in higher FF for front-emitter devices. The relatively similar  $J_{sc}$  values of the four different kinds of cells are again explained by comparable absorption coefficients and thicknesses of the n- and p-doped a-Si:H layers. Overall, despite these slight differences, the performance of rear-emitter cells is not dramatically lower than that of front-emitter cells, underlining the potential to fabricate high-efficiency back-contacted heterojunction solar cells.

Briefly, we remark here that for rear-emitter cells, Desrues *et al.* observed that replacing the rear intrinsic passivating layer by a slightly doped layer (less doped than the emitter itself) can lead to a further increase in the FF but simultaneously to a reduction in  $V_{oc}$  [27]. FF values close to 80% were also reported by Bivour *et al.* on n- and p-type wafers with the use of a diffused front surface field and a heterojunction rear emitter [28], but again the  $V_{oc}$  values were lower than those obtained with both sides passivated with intrinsic a-Si:H layers. After specific optimization of the a-Si:H layers thicknesses for rear-emitter cells and with the use of a high mobility front TCO (hydrogen-doped indium oxide [29]), the best FF that we obtained on an n-type wafer was 78.1% (82.8% pFF), and the best efficiency was 20.3%. Whereas the previously cited authors optimized the series resistance of their devices, our focus has been on increasing  $V_{MPP}$ , leading to better diode ideality factors. Combining both approaches may lead to FF values above 80% for rear-emitter heterojunction solar cells.

Notably, the device geometry of rear-emitter cells can impact FF values and external quantum efficiency (EQE) measurements, possibly leading to measurement artifacts. If the wafer rear side is fully covered by the emitter, ITO layer, and metalization (asymmetry between the front and the back collection areas), the total collected current of the EQE measurement is unexpectedly small and does not correspond to the  $J_{sc}$  value of the illuminated *IV* measurement. In this configuration, one measures the dark saturation current density ( $J_0$ ) of an emitter that is the size of the entire wafer and not just 4 cm<sup>2</sup>, resulting in an underestimated FF value and EQE current. It was experimentally found that rear-emitter cells on p-type wafers are more prone to this effect than cells on n-type wafers. In order to obtain a correct EQE measurement, one has to take care that the collection area at the rear of the cell matches exactly that at the front, as is the case for all cells presented in this paper. As shown in Fig. 6, no significant difference is observed in spectral response (EQE, reflection R, and internal quantum efficiency IQE) between n- and p-type cells and between front- and rear-emitter cells. This is in good agreement with the similar  $J_{sc}$  values that are obtained from illuminated *IV* measurements (see Table I).

### B. Best Efficiencies Obtained on n- and p-Type Wafers

Finally, we present in this section the results of optimized front-emitter heterojunction solar cells produced on different types of wafers [n- or p-doped, FZ or Czochralski (CZ)] and of different sizes (4, 100, and 149 cm<sup>2</sup>, aperture areas). It should be noted that more optimization has been done on 4 cm<sup>2</sup> cells. All wafers have the same resistivity (4 Ω·cm). Specific optimization has been done differently for n- and p-type wafer-based cells.

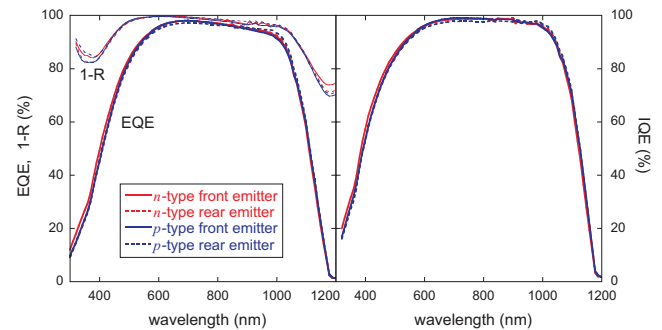


Fig. 6. EQE, 1-reflection, and IQE measurements of front- and rear-emitter n- and p-type 2 cm × 2 cm cells.

TABLE II  
IV PARAMETERS OF THE BEST HETEROJUNCTION SOLAR CELLS (ALL CELLS HAVE SCREEN-PRINTED CONTACTS)

Wafer type	Cell area (cm <sup>2</sup> )	$V_{oc}$ (mV)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF (%)	Efficiency (%)
FZ n-type	4	727	38.9	78.4	22.14(*)
FZ n-type	100	727	36.5	78.9	20.95
FZ n-type	149	732	36.3	75.2	19.95
CZ n-type	4	731	36.9	77.1	20.80
CZ n-type	100	730	36.5	77.7	20.71
CZ n-type	149	728	35.0	73.4	18.74
FZ p-type	4	722	38.4	77.1	21.38(*)
CZ p-type	4	679	36.2	70.6	17.33
CZ p-type	100	692	35.1	70.1	17.04
CZ p-type	149	689	36.3	67.7	16.92

(\*) certified by Fraunhofer ISE CalLab.

Since parasitic light absorption in the front stack of layers is of particular importance for heterojunction solar cells [12], the properties and thicknesses of the n- and p-doped a-Si:H layers and TCO layers have been adjusted differently according to the cell structure, aiming for high transparency at the front. This optimization explains the higher efficiencies obtained compared with the cells described in the previous section, where simple codepositions of standard layers were done. The electrical properties of these optimized cells are given in Table II.

Thanks to well-controlled wafer cleaning and to high-quality passivating a-Si:H layers [30], [31],  $V_{oc}$ s on n-type wafers are similar on FZ and CZ materials. Values as high as 733 and 732 mV were obtained on FZ and CZ materials, respectively (160 μm thick wafers). The slightly lower value for the best 4 cm<sup>2</sup> cell on FZ is due to a greater wafer thickness (230 μm). It is well known that  $V_{oc}$  of a cell increases when the wafer thickness is reduced, provided that the passivation level is sufficiently high [1], [32]. Indeed, if the surface recombination velocity is close to zero, bulk recombination linearly decreases with thickness.  $J_0$  will then decrease, producing a higher  $V_{oc}$ . In this study, the highest  $V_{oc}$  value was obtained using a 110-μm-thick FZ n-type wafer, yielding 735 mV (20.8% cell efficiency, limited by  $J_{sc}$ ). Differences in wafer thickness also explain the higher  $J_{sc}$  of the 4 cm<sup>2</sup> cell on FZ, as more light is absorbed in the thicker wafer. Although cell performance slightly decreases when cell

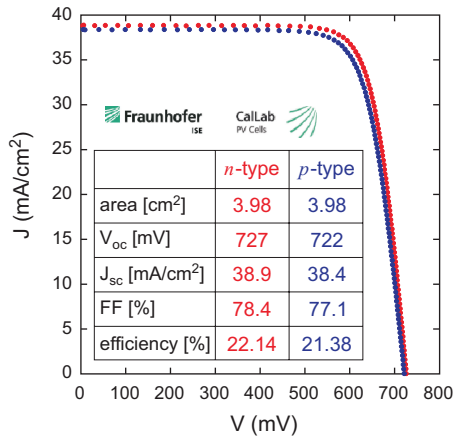


Fig. 7. Illuminated IV curves of the best 2 cm × 2 cm cells on n- and p-type FZ wafers (certified by the Fraunhofer ISE CalLab).

area increases (mainly due to some inhomogeneities, slightly increased shadow losses, and electrical losses in the front grid), efficiencies well above 20% can be maintained on 100 cm<sup>2</sup> cells, and close to 20% on full-5-in cells. The highest aperture-area efficiencies obtained on CZ and FZ n-type materials are 20.8% and 22.1%, respectively.

Conversely, on the p-type wafers used in this study, a difference of more than 30 mV in  $V_{oc}$  is clearly visible between FZ and CZ materials. This large difference is likely due to the relatively low quality of the CZ p-type wafers used in this study (numerous *bulk* defects with large electron capture cross section). Wang *et al.* showed that a loss of less than 10 mV can be maintained when changing from FZ to CZ p-type wafers [5], using CZ p-type material that was probably of better quality than that used here. The low FF values of the CZ p-type cells are also attributed in part to the lifetime dependence at low injection described previously, which become even more critical if the implied  $V_{oc}$  is reduced (MPP is at an even lower injection level, and therefore,  $V_{MPP}$  is strongly reduced). It should also be noted that, contrary to n-type c-Si, CZ p-type material additionally suffers from severe light-induced degradation caused by the boron–oxygen complex (nondegraded cells presented here) [33]. Thus, the use of thinner wafers should be especially beneficial in the p-type case. Then, light-induced degradation is reduced, and the minority carrier density is increased at MPP, leading to higher FF values.

As discussed earlier, the FF and  $V_{oc}$  values are generally lower on p-type than on n-type wafers, limiting cell performance. Nevertheless, a cell with  $V_{oc}$  of 722 mV, an FF of 77.1%, and an efficiency of 21.38% has been produced on FZ p-doped material, and the highest  $V_{oc}$  measured on a p-type cell reached 726 mV (230- $\mu$ m-thick wafers). To our knowledge, these are the first  $V_{oc}$ s significantly above 700 mV and the highest efficiency ever reported for a full silicon heterojunction solar cell on a p-type wafer. Silicon heterojunction solar cells can, thus, perform almost as well on high-quality p-type as on n-type wafers, with efficiencies over 21% demonstrated for both doping types (see Fig. 7).

#### IV. CONCLUSION AND OUTLOOK

Mainly due to the asymmetry in interface defect capture cross sections but also due to the band structure seen by minority carriers, silicon heterojunction solar cells generally perform better on n-type than on p-type wafers. A major difference is observed in the minority carrier lifetime, especially at low injection, leading to reduced FF values for p-type cells. Nevertheless, devices with efficiencies above 21% and  $V_{oc}$  values above 720 mV have been demonstrated on both types of FZ wafers. This key feature of heterojunction solar cells is, thus, preserved independent of the wafer-doping type, proving that high efficiencies are also possible on p-type material. However, for mass scale production, the use of CZ material is obviously the only possible option due to economic considerations. In this case, n-type wafers are probably preferable, as we achieved comparable efficiencies on n-type FZ and CZ materials. Nevertheless, if the quality of commercially available p-type CZ material is improved or if the wafer thickness is sufficiently reduced, the use of p-type CZ wafers could be a possible alternative for the industrial production of silicon heterojunction solar cells.

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