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Solar cells with 20 % efficiency and lifetime evaluation of epitaxial wafers

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Abstract

We present n-type epitaxially grown wafers deposited in a reactor that allows a process transfer to inline high-throughput reactors. Those wafers exhibit an effective lifetime of up to 1720 µs locally for a phosphorous concentration of $2{\cdot}10^{15}$ cm^{-3} and a wafer thickness of about 100 µm. The most detrimental defects in those wafers are stacking faults with polycrystalline silicon inclusions. Comparing two samples with a difference in the density of those stacking faults of one order of magnitude revealed a difference in the average effective minority carrier lifetime of also one order of magnitude (reduction from more than 1500 µs to 111 µs for the defective sample).
A solar cell fabricated with 200 µm thick epitaxial wafer with a low stacking fault density and a phosphorous concentration of $3{\cdot}10^{16}$ cm^{-3} reaches an independently confirmed efficiency of 20 %, an open circuit voltage of up to 658 mV, a short circuit current density of up to 39.6 mA/cm^2 and a fill factor of up to 76.9 %. Differences of this cell to FZ references can be attributed to a reduced bulk lifetime caused by the high doping concentration and most probably to additional recombination due to the polycrystalline silicon inclusions in the still but with low density existing stacking faults. A second solar cell made of an epitaxial wafer with a high stacking fault density exhibits an efficiency reduction of 0.5 % absolute compared to the cell made of the high quality epitaxial wafer. This result underlines the importance of minimizing the stacking fault density in epitaxial wafers, particularly the density of those with polysilicon inclusions.

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Keywords: porous silicon, epitaxy, n-type, silicon foils, solar cells

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1. Motivation

The preparation of epitaxial silicon foils and wafers (EpiWafers) using porous silicon as a detachment layer between substrate and the epitaxially grown silicon layer is demonstrated to reach high quality [1,2]. One advantage of this process sequence is the easy adaption of wafer properties like thickness and doping to the desired solar cell design. Manufacturing and providing free-standing wafers would require least adaptions of existing cell fabrication lines. However, only few publications focus on free-standing epitaxial wafers prepared in an industrial environment. E. Kobayashi et al. [3] recently published a confirmed efficiency of 23.0 % for cells made out of epitaxial wafers thus showing the high potential. The aim of this work is to demonstrate high quality epitaxial wafers deposited in a reactor that allows for a process transfer to inline high-throughput reactors like the ProConCVD reactor [4]. The high EpiWafer quality that can be reached in our reactor is confirmed by calculating a lower limit of the bulk lifetime and showing cell results obtained with a clean room process. Additionally, the influence of highly defective stacking faults on the effective minority carrier lifetime and on cell results is shown. Those are the defects of currently fabricated EpiWafers in our reactor.

2. Fabrication of epitaxial wafers, lifetime samples and solar cells

Highly doped Cz wafers with a porous silicon layer stack were purchased from IMS (Institut für Mikroelektronik Stuttgart). The porous silicon stack consists of three layers, a low porosity layer on top of two high porosity layers with slightly different porosities. After the removal of the native oxide with 1% HF(aq) for 1 min the samples were loaded in a lab-type atmospheric pressure chemical vapor deposition (APCVD) reactor [5]. The reorganization of the porous silicon layers was performed at 1150 °C in hydrogen atmosphere for 30 min. Epitaxial growth took place directly after reorganization at the same temperature. Afterwards the area to be detached was defined by laser scribing and lift off was done mechanically. About 4 µm of silicon were removed with a chemical polish solution on both sides including the residual porous silicon layer on the rear side. All samples were phosphorous gettered (diffusion of a phosphorous emitter and subsequent etching in a chemical polish solution removing approx. 4 µm per side).

For investigation of the EpiWafer quality the epitaxial growth process was adopted to reduce the influence of lifetime limitations and local variations beside defects in the layers. Therefore, the phosphorus density was set to $2 \cdot 10^{15}$ cm^{-3} to reduce Auger recombination and depositions were done in a semi-stationary mode for 100 – 135 min to reduce thickness variations (mean thickness 115 – 200 µm). After gettering the 5x5 cm^2 EpiWafers were passivated with 20 nm Al_2O_3 on both sides. Additional lifetime samples with the properties of the material used for solar cell fabrication as described in the following were prepared.

For solar cells the phosphine flow was adjusted to reach a doping density of $3 \cdot 10^{16}$ cm^{-3} as no lower doping densities were technically possible at the time of the depositions. Samples were deposited in stationary mode for 88 min resulting in a thickness of about 200 µm in the area of the demonstrated 2x2 cm^2 solar cells. The front side of the cells corresponds to the rear side of the EpiWafer during epitaxial growth (border to porous silicon). In the final cells this side exhibits random pyramids, a shallow 90 Ω/sq boron doped emitter, Al_2O_3 and Si_xN_y as passivation and antireflection layers and evaporated Ag contacts on top of Ti/Pd/Ag seed layers. The rear side features an n-TOPCon contact [6]. As references 200 µm thick, 1 Ωcm n-type FZ wafers were added to the cell process.

3. Quality of epitaxial wafers

The property of wafers most important for accessible solar cell parameters is the electrical quality expressed e.g. in minority carrier lifetime. This property depends on the crystal quality and the presence of impurities. The amount of metal impurities in our samples after epitaxial growth is assumed to be equal in all samples. However, the efficiency of the phosphorous gettering step for metal impurities has proven in other studies to depend on the amount of defects in the crystal [7]. In our samples the most important crystal defects are stacking fault tetrahedra originating at the interface between porous and epitaxially deposited silicon. They appear in two different ways. Either a single silicon crystal is surrounded by four triangular two-dimensional stacking faults lying in {111}-planes

(SF) or within the same borders a highly defective polycrystalline area is existent (polySF). The polySFs are the most detrimental defects in our samples. They might be caused by silicon particles on the substrate surface [8]. Their impact on the minority carrier lifetime is investigated in the following.

Two 5x5 cm^2 EpiWafers ($2 \cdot 10^{15}$ P-atoms/cm^3) were prepared with a difference in the polySF density (*polySFD*) of one order of magnitude, the low quality sample and the high quality sample have 16 polySF/cm^2 and 1.8 polySF/cm^2, respectively. Photographs and space resolved effective lifetimes determined by microwave photoconductive decay (MWPCD) measurements are shown in Figure 1; the properties of the two EpiWafers are summarized in Table 1.

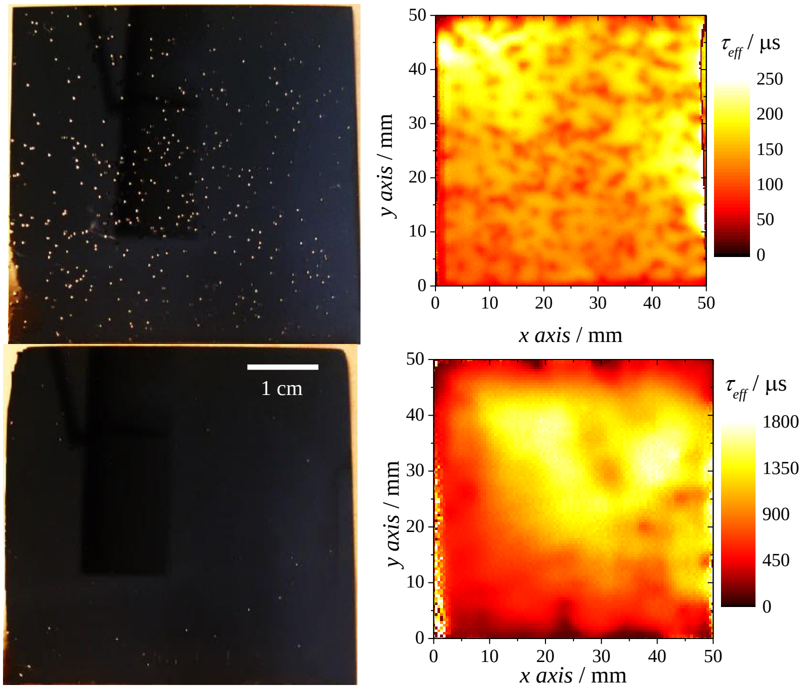

Figure 1: Photographs (left) and lifetime mappings measured by MWPCD (right) of samples with a high and a low *polySFD* in upper and lower row, respectively.

On the low quality sample a strong correlation between the local lifetime and the presence of polySFs is visible. The photograph shows an almost homogeneous distribution of polySFs with a slight increase in the lower left area. The effective lifetime is clearly reduced to about 100 µs at the position of a polySF. In the regions between the polySFs lifetime values up to 250 µs are measured. Additionally, the lifetime between the polySFs is reduced in the lower left area where the *polySFD* is increased. This might be explained by an increased diffusion of holes to the recombination active polySFs as the diffusion length of holes can be more than 500 µm assuming an effective lifetime of 250 µs and a realistic surface recombination velocity (*SRV*) of 3 cm/s [9]. An average lifetime of this sample was measured by quasi-steady-state photo conductance to be 111 µs at an injection level of 10^{15} cm^{-3}.

On the high quality EpiWafer a maximum lifetime above 1700 µs is measured in the upper right area. Assuming a very good *SRV* of 1 cm/s for the Al_2O_3 passivated surfaces leads to a lower limit for the bulk lifetime in this sample of above 2500 µs. This is high enough for the fabrication of high efficiency solar cells although the theoretical maximum bulk lifetime for the given doping density of $2 \cdot 10^{15}$ cm^{-3} is 32 ms [10]. The mean effective lifetime measured by QSSPC is with 1583 µs close to the local maximum (see Table 1). On this EpiWafer only a slight correlation between the local lifetime and the presence of polySF is visible, other effects seem to dominate. The reduced lifetime close to the edges is visible on reference FZ samples and results most probably from issues related to chemical polishing; this effect was already shown in [11]. Another surface effect is assumed to be the appearance of spots with reduced lifetime visible best in the high lifetime region. FZ wafers cleaned and passivated in the same batch show similar spots with the same reduction of the local lifetime of approx. 500 µs compared to the surrounding area. The reason for the reduced lifetime in the lower left region is not clear up to now. Possible reasons might be a further reduced crystal quality (SFs and/or dislocations), the presence of impurities still in the sample after gettering or surface issues. Nevertheless, this sample demonstrates the high quality that is possible for an EpiWafer.

Table 1: Properties of EpiWafers with two different qualities.

EpiWafer quality	*polySFD* /cm^{-2}	$\tau_{eff,\,mean}$ / µs	$\tau_{eff,\,max}$ / µs
Low	16	111	250
High	1.8	1583	1720

For the solar cells presented in the next section 200 µm thick EpiWafers with a phosphorous concentration of $3{\cdot}10^{16}$ cm^{-3} were used. On this samples average lifetimes up to 120 µs were measured by QSSPC on EpiWafers with polySFD lying between 2 cm^{-2} and 16 cm^{-2}. Assuming a realistic SRV of 3 cm/s [9] and a thickness of 100 µm this corresponds to a bulk lifetime of 130 µs and a diffusion length of above 360 µm, which is approx. twice the thickness of the EpiWafers used to fabricate solar cells.

4. Solar cell results

In the following mainly the effect of polySFs on the cell parameters is exemplarily investigated. For a detailed investigation of cell results and an elaborate loss analysis see [12]. Here, two cells are chosen, one made of a high quality EpiWafer (*polySFD* of approx. 2.5 cm^{-2}) and one made of an EpiWafer with an increased amount of polySF. In this case the polySF are not homogeneously distributed but mainly located in the middle (see Figure 2). Due to overlapping the *polySFD* could not reliably be determined in this region. The cause of the increased *polySFD* is most probably a scratch on the porous silicon layer prior to reorganization and epitaxial growth.

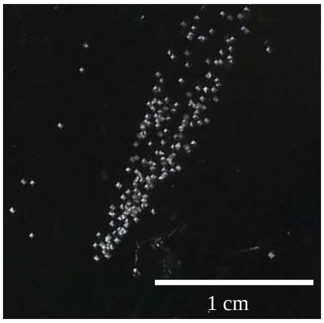

Figure 2: Picture of the front side of the low quality EpiWafer used for solar cell fabrication, this side corresponds to the rear side of the cell.

The characteristics of the two EpiWafer cells and the FZ references are summarized in Table 2. The cell made of the high quality EpiWafer is with an independently confirmed efficiency of η = 20 % one of the best EpiWafer cells fabricated at Fraunhofer ISE so far. Nevertheless, this cell has a lower efficiency compared to the FZ references and to what is possible with the applied cell design. Also the efficiency of the FZ references in this batch is reduced (21.8 % in average). This can partly be explained by a shallow emitter with a low thermal budget used in this cell process. Additionally, the recombination on the front side in the metal contacted areas seems to be increased.

Table 2. Results of IV-measurements of n-type solar cells on FZ (ref) and EpiWafers.

Material	V_{OC} / mV	J_{SC} / mA/cm^2	FF / %	PFF / %	η / %
Ref (14 cells)	669 ± 2	40.9 ± 0.1	79.8 ± 0.2	83.6 ± 0.5	21.8 ± 0.1
Low quality EpiWafer	653*	39.0*	76.6*	78.9	19.5*
High quality EpiWafer	658*	39.6*	76.9*	78.6	20.0*

*independently confirmed at Fraunhofer ISE CalLab

Besides those issues the high quality EpiWafer has additional losses leading to a further reduction of all cell parameters (open circuit voltage V_{OC}, short circuit current J_{SC} and fill factor FF). A reduced bulk lifetime caused by the high phosphorous doping concentration ($3{\cdot}10^{16}$ cm^{-3} instead of $5{\cdot}10^{15}$ cm^{-3} in the FZ references) cannot solely explain this loss. Although the amount of polySFs is comparably low in this sample it leads to additional losses due to recombination in the bulk and at the rear side where each polySF covers an area of 0.08 mm^2. A reduction of the pseudo fill factor (*PFF*) as obtained for this cell was also explained by the presence of SF in literature [13].

Looking at the results of the low quality EpiWafer cell further losses are mainly visible in V_{OC}, J_{SC} and *FF* resulting in an efficiency drop of 0.5 % absolute. This can be explained by the reduced bulk lifetime caused by the stacking faults. Measurements of the external quantum efficiency show an increasing loss compared to the high quality EpiWafer cell with increasing wavelength. This points to a reduction of the wafer quality from front to rear as expected for the influence of stacking faults whose volume increases from front to rear (the rear of the cells corresponds to the front side during epitaxial growth).

In conclusion a low *polySFD* is important for reaching cells with high efficiencies. The processes for reorganization of porous silicon and epitaxial growth have to be further optimized for this. Additionally, the doping concentration of the EpiWafer has to be adjusted to reduce the lifetime reduction mainly by Auger recombination.

5. Summary

In this paper properties of phosphorous doped free-standing wafers that were fabricated by a lift-off process using porous silicon as detachment layer and epitaxial growth of the final wafer are shown. The quality of such epitaxial wafers deposited in our lab-type CVD reactor is mainly limited and determined by stacking faults with polycrystalline inclusions. On a passivated high quality 5x5 cm^2 epitaxial wafer with a low amount of these stacking faults (<2 cm^{-2}) an average effective lifetime of 1583 µs with local values up to 1720 µs is measured. An increase of the stacking fault density by one order of magnitude leads to a reduction of the average lifetime of also approx. one order of magnitude to 111 µs.

To investigate the influence of stacking faults with polycrystalline silicon inclusions on solar cell parameters two solar cells made of epitaxial wafers with a phosphorous concentration of $3{\cdot}10^{16}$ cm^{-3} and different amounts of such defects are compared. The high quality wafer led to an independently confirmed efficiency of 20 %. This is a very promising result for the first batch of cells with epitaxial wafers ever fabricated at Fraunhofer ISE. The cell made of the low quality epitaxial wafer results in a reduced efficiency by 0.5 % absolute. Additionally, both cells suffer from losses caused by the high doping density and even the cell with the high quality epitaxial wafer is limited by the crystal defects to some extend as a comparison to FZ references shows. This demonstrates the importance of achieving low densities of stacking faults with polycrystalline inclusions in epitaxial wafers for the fabrication of high efficiency solar cells.

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