EPITAXIAL LAYERS ON LOW COST SILICON SUBSTRATES FOR INDUSTRIAL SCALE PRODUCTION

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ABSTRACT: Upgraded metallurgical silicon (UMG-Si), developed at Elkem Solar, was used as a low cost substrate for the growth of thin layers by liquid phase epitaxy (LPE) [1]. If such an inexpensive Si substrate is applied and the LPE melt back technique is used, no electronic grade silicon is needed at all. The intention of our present investigation is the development of an LPE technology which can be scaled up to a large number of layers per run. Therefore up to 6 substrates were simultaneously dipped into an indium growth solution resulting in mirroring bright epitaxial layers of 30µm thickness. Improved solar cells of η=10.0% on a research scale area of 2cm^2 have been achieved on this material.
Keywords: Silicon -1: LPE -2; Metallurgical Grade -3

1. INTRODUCTION

The growth of silicon layers by liquid phase epitaxy (LPE) requires in general lower temperatures than the chemical vapour deposition (CVD) technique. In addition the yield of electronic grade silicon is close to 100% which is 2-3 times higher as achieved by the deposition from the vapour phase so far. If an inexpensive Si substrate is applied and the LPE melt back technique is used even no electronic grade silicon is needed at all. The major task of our present investigations is the development of an LPE technology which can be scaled up to a few hundred layers per run. The standard sliding boat approach contains several disadvantages such as problems of solvent removal, limited wafer size capability and the necessity of changing the solvent after each epitaxial growth sequence. Therefore in prior investigations we reported on a horizontal steady state LPE method for fast subsequent layer growth using an solvent of large quantity. In this work the LPE apparatus was expanded for the growth of up to 6 layers per run.

In order to obtain thin p-conductive layers with carrier concentrations suited for PV applications (p = 5×10^{16}cm^{-3} - 10^{17}cm^{-3}) the composition of the growth solution was optimised using several mechanical and electrical characterisation methods [2].

2. EXPERIMENTAL APPROACH

Upgraded metallurgical silicon (UMG-Si), developed at Elkem Solar, was used as a low cost substrate. The cast ingots have been fabricated by directional solidification in a furnace specially adapted for the use of UMG-Si [1]. The wafering of the blocks was carried out in a wire sawing machine with conventional performance as for electronic grade silicon (EG-Si) based ingots. These substrate wafers were heavily p-typ doped due to the high boron content of the UMG-Si material. As most impurities segregated on the surface of the melt during the directional solidification the wafers contained only a low concentration of metallic impurities of less than 1ppm.

P-type LPE layers were grown from an indium solution with a small fraction of gallium content for doping. In prior investigations we reported on the development of a horizontal LPE apparatus [3] for fast subsequent layer growth, where the substrate wafers were placed onto the surface of the solvent. Fast growth rates of more than 2 µm/min have been achieved so far. However for industrial production a batch of several wafers would be favourable. Therefore in the present investigation up to 6 wafers 50×25mm^2 were fully dipped into the melt during growth. Deposition took place on both the upper and the lower side of the substrates. While the surfaces on the lower side were as rough as the layers obtained in the prior investigations, the surfaces of the upper epi-layers were very smooth causing the In solvent draining off the wafer after epitaxial growth. The grown layers were closed even at the grain boundaries (see Fig. 1 after SECCO etching) and showed a similar overall thickness of about 30µm sufficient for photovoltaic applications. In order to avoid an unintentional growth on both sides, the lower side was coated by a suitable barrier in some cases prior to LPE growth.

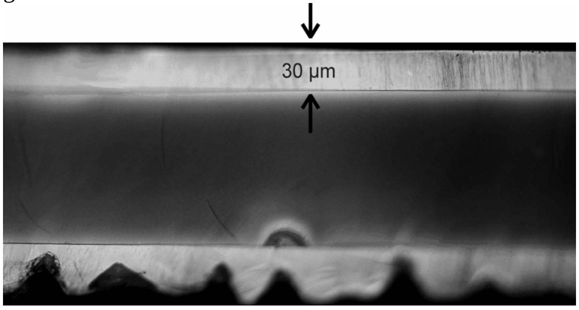

Figure 1: *Cross section of a UMG-Si substrate coated with two LPE layers, after SECCO etching.*

The LPE was carried out at starting temperatures around 990°C cooling down to 890°C. After each growth cycle the solvent temperature was increased again to its starting value of 990°C. The next wafers were loaded and the solvent was saturated with Si from the substrate itself, which means that the substrates were etched in liquid indium, resulting in a bright mirror like surface. This procedure might replace the alkaline saw damage etch of wafers normally practiced in silicon solar sell production.

3. RESULTS AND DISCUSSION

Although the melt back procedure of the UMG-Si wafers was repeated about 50 times, the boron did not accumulate significantly in the indium solvent. It is expected, that the boron is transported by the protective gas hydrogen to the exhaust. The carrier concentration of the epi-layers remained still below p = 10^{17} cm^{-3} in comparison to p > 10^{18} cm^{-3} of the UMG-Si substrate.

Solar cells have been fabricated based on emitter diffusion by screen printing and firing of a phosphorous dopant paste. The cells were finished by industrial processes like PECVD SiN_x deposition and screen printed contacts, leading to η=9% [3]. Recently, after implementation of the batch process, improved epi-layers and solar cells have been achieved. As the layers were bright as a mirror, an evaporated frond grid was used in this case. The solar cells resulted in an efficiency of up to η=10.0% on 30µm thick layers of 3cm². Thicker layers of 40µm with an additional alkaline surface texturing resulted in an increase of the short circuit current, but the fill factor was low. The results are summarised in Table I. All solar cell parameters have been measured under standard conditions (100mW/cm², AM1.5, 25°C). The values of V_{OC}=597mV and FF=76% confirm the high quality of the epitaxial layers on UMG-Si substrates.

Table I: Best cell results obtained on LPE layers grown on the multicrystalline UMG-Si substrate wafers. The cell area is 3cm².

d (µm)	Voc (mV)	Isc (mA/cm²)	FF (%)	η (%)
30	597	22	76	10.0
40 + text	588	26	63	9.6

As the short circuit current of these cells is insufficiently low and represents the mean limiting factor in efficiency, LBIC (light been induced current) scans at different penetration depths and IQE (internal quantum efficiency) measurements have been investigated on the 30µm thick cell. From LBIC a relatively homogenous signal was obtained over a wide range of different oriented grains as illustrated in Fig. 2. Fig. 3 shows the corresponding average internal quantum efficiency. The IQE is low in the short wavelength range due to a dead layer most likely resulting from the phosphorous paste emitter diffusion.

4. CONCLUSION

Metallurgical silicon is an important candidate to replace the shortcoming EG-Si feedstock for the production of thin film solar cells. The UMG-Si feedstock is developed at pilot scale and can be produced in large quantity for the need of the PV-uses. LPE was used to provide a thin silicon layer onto the UMG-Si wafer in a batch type system. The solar cell parameters demonstrate the high quality of the LPE layers on the UMG-Si substrate. Further improvement of the solar cell performance is expected by the implementation of $POCl_3$ emitter diffusion and more effective optical confinement.

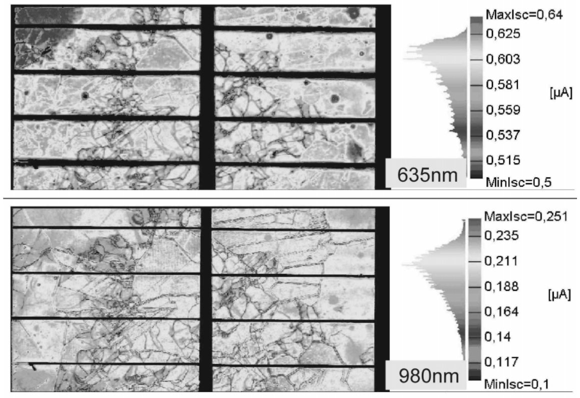

Figure 2: LBIC measurements from surface (λ=635nm) and bulk (λ=980nm) of the LPE layers. The scan clearly shows that the low current is not due to areas or gains which are not electronically active.

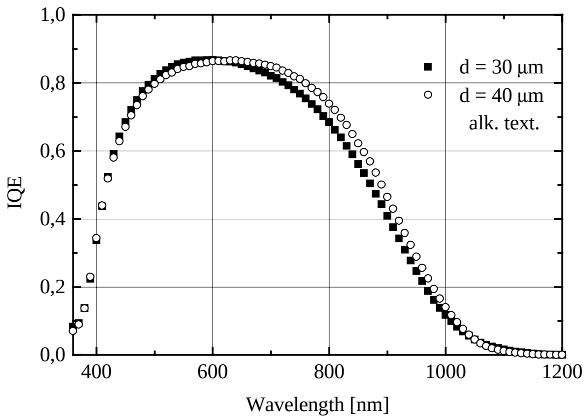

Figure 3: Internal quantum efficiency (IQE) of a 30µm thick solar cell in comparison to the IQE of a 40µm thick alkaline textured layer. The IQE is low in the short wavelength range due to a dead layer resulting from the phosphorous paste emitter diffusion.

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