CHARACTERISATION OF SILICON EPITAXIAL LAYERS FOR SOLAR CELL APPLICATIONS

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ABSTRACT: The growth and detachment of epitaxial layers of semiconductor material on a suitable substrate, with subsequent re-use of the substrate, is of interest due to its potential for significant reductions in the cost of the epitaxial material, and therefore in the cost of solar cells fabricated on epitaxial layers. Recently the epilift technique was introduced which allows the fabrication of single crystalline layers of silicon of arbitrary size and shape by liquid phase epitaxy (LPE) on single crystal silicon substrates which have been patterned with a suitable masking layer material such as SiO₂. Detachment of the layers proceeds by etching through the regions where the epitaxial layer is attached to the substrate. The substrate can be re-used many times. The quality of the epitaxial layers was investigated by SEM following defect etching and the lifetimes of several samples were measured by microwave photoconductive decay after detachment from the substrate. The light trapping for the epilift structure was modelled for a just-closed epilayer as double-sided inverted pyramids with zero layer thickness at the tips of the pyramids. It was found that the light trapping is as good as for double-sided inverted pyramids whose height is small compared with the layer thickness. We show that the quality of epitaxial layers and the texturing inherent in the epilift technique allows fabrication of high quality, single crystal silicon films which are particularly suitable for the production of high efficiency solar cells.

Keywords: c-Si - 1: Characterisation - 2: Thin Film - 3

1 INTRODUCTION

Much of the current work in crystalline silicon photovoltaics focuses on the production of thin silicon films, of thickness around 50 μm. Such films should allow the fabrication of cells of medium to high efficiency at significantly lower cost than current silicon cells. Recently we developed an approach, termed the epilift technique, which leads to the production of single crystal silicon films, suitable for the fabrication of high efficiency solar cells, through the utilisation of re-useable single crystal silicon substrates [1]. This paper presents progress on the development of the epilift technique.

2 THE EPILIFT TECHNIQUE

Figure 1 illustrates one version of the epilift technique. First, a masking layer is deposited and patterned on top of a (100) oriented single crystal silicon substrate, so that the substrate is only exposed along lines (typically 2-10 μm wide) which form a mesh pattern and run along the (110) directions of silicon. The masking layer prevents nucleation of silicon anywhere except along these lines. An epitaxial layer is then grown on the wafer by LPE. Silicon nucleates out of the lines and forms a continuous mesh. Due to the particular stability of the Si {111} planes, faces with near {111} orientation develop. As a result, the epilayer displays a diamond shape in cross section, illustrated in figure 1. The initial part of the epilayer is grown heavily doped while the subsequent epilayer is more lightly doped. Growth is terminated before the holes in the epilayer have closed up.

To detach the layer from the substrate, the wafer is immersed in an etchant which etches heavily doped silicon faster than lightly doped silicon, such as a solution of 1:3:8 HF:HNO₃:CH₃COOH [2]. The initial part of the
Figure 1: An example of the epitaxial lift-off process. (a) The structure following deposition of the epitaxial layer on a (100) oriented single crystal substrate, (b) Cross section through the epitaxial layer.

Figure 2: A p/p⁺ epilayer grown on a p⁺ substrate with the junction in the epilayer delineated with Yang’s etch. This shows that most of the lateral growth out of the seeding windows occurs during the first part of the growth of the epilayer.

The epitaxial lift-off process extracts the epitaxial layer from a substrate. The image shows a cross-section of the process, illustrating the epitaxial layer (top) and the substrate (bottom). The layer is grown heavily doped. Figure 2 shows that most of the lateral growth occurs early in the growth of the epilayer, leaving p⁺ silicon exposed to be attacked by the etchant. Due to the narrowness of the attachment regions the etchant rapidly detaches the layer from the substrate, leaving the substrate ready for the growth of another layer. Films with a thickness of 50-100 μm can easily be produced by the above method.

The epitaxial lift-off technique can make use of a wide range of selective silicon etchants for the separation of the epilayer from the substrate, including various electrochemical etches which can display selectivities in excess of 1000:1 [3]. While electrochemical etching results in a loss of some of the substrate because the technique invariably results in etching of the layer to which electrical contact is made, it has a much higher selectivity than 1:3:8 HF:HNO₃:CH₃COOH. Figure 3 shows an epitaxial layer lifted off the substrate using electrochemical etching.

3 QUALITY OF THE EPITAXIAL LAYERS

Growth of an oxide layer on a silicon substrate causes stress in the oxide and silicon due to differences in thermal expansion coefficients and the volume expansion during the oxidation process. When a pattern is etched in the oxide the stress is concentrated at the edges of the pattern [4]. This can result in the nucleation and subsequent multiplication of dislocations in the epilayer. Defect etching of epilayers using Yang’s etch [5] and subsequent investigation by scanning electron microscopy (SEM) has revealed a large spatial variation in the dislocation density, with some regions apparently dislocation free, while other regions have high dislocation densities.

The minority carrier lifetimes of several epilayers were measured using a microwave photoconductive decay system following detachment from the substrate. Surface passivation was achieved by a light phosphorus diffusion followed by the growth of a thin oxide around the entire layer. Figure 4 shows the results on one sample obtained for various intensities of bias light. The slow decay of the conductance signal for low intensities of bias light following photoexcitation is attributed to the detrapping of minority carriers from trapping levels in the silicon bandgap. A strong bias light was subsequently used in order to saturate these traps and remove this effect. The results of measurements of the minority carrier lifetime on 9 positions of one sample yielded values between 3.8 and 11.7 μs. The large variation of the lifetime is likely to be a result of the variation in dislocation...
density across the sample. The average lifetime of 7 μs corresponds to a minority carrier diffusion length of over 100 μm, which is more than twice the average thickness of the epilayer. Note that the above values are effective lifetimes. The actual lifetime of the bulk material is likely to be somewhat higher due to the limitations of the surface passivation method and the fact that the structure of the epilayer results in a high surface area to volume ratio. Thus, the quality of the material is sufficient for high efficiency solar cells.

Current work is aimed at improving the understanding of the mechanisms responsible for the formation and multiplication of dislocations, and an optimisation of the growth conditions. One option is to use carbon instead of silicon dioxide as a masking material for the epitaxial growth. Carbon is likely to form a weaker bond with the silicon, resulting in a reduced dislocation density and hence a higher lifetime.

4 MODELLING OF LIGHT TRAPPING

The light trapping of an epilayer grown from a square mesh structure was modelled using a modified version of Thorp’s “Tracey” program [6]. For the initial modelling the fraction of the epilayer surface covered by holes was taken to be zero, corresponding to a just-closed epilayer. Figure 5 compares the short-circuit current obtained with that from a one-sided pyramid and a one-sided lambertian texture as a function of effective thickness (defined as the volume of silicon divided by the silicon film area). It is expected that while a reduced current would be obtained from epilayers with holes, the use of a detached rear reflector could reduce that loss. These situations are currently being modelled.

6 LIFT-OFF ON ⟨110⟩ SUBSTRATES

Another option for lifting off thin, high quality silicon layers is to use ⟨110⟩ wafers. A heavily doped, p-type buffer layer is deposited on the substrate followed by the more lightly doped layer to be lifted off. An oxide is deposited and a pattern of long narrow grooves extending along the [1 -1 -2] direction is defined in the oxide as shown in figure 6. The structure is then etched with KOH. Because a ⟨110⟩ wafer is used, the {111} planes along the long axis of the grooves are perpendicular to the plane of the wafer. Thus the etching results in grooves with perpendicular sidewalls which extend through the epitaxial layer and into the buffer as illustrated in figure 7. The {111} planes along the short axis of the grooves are at an angle of 35.26° to the plane of the wafer so the grooves must be more than 2W/tan35.26° long where W is the width of the epilayer. The epilayer can then be detached using the 1/3/8 etch. Electrochemical etching can also be employed. The pattern has the advantage that a high density of slots can be made to extend through the epilayer, allowing detachment of the layer with only moderate etch selectivity. Figure 8 shows a layer lifted off using this technique.

7 CONCLUSION

In conclusion, we have presented progress on the epilift technique which allows the fabrication of single crystal silicon films of 50-100 μm thickness without incurring the cost of single crystal
silicon wafers. The lifetime and light trapping results show that the epilift technique has the potential to enable the fabrication of highly efficient, low cost solar cells. Cell processing options are currently being investigated and cell fabrication is underway.

References


