Colour and Shape in Laser Grooved Buried Contact Solar Cells for Applications in the Built Environment

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ABSTRACT: The use of photovoltaic modules in architectural applications is now firmly established and large modules of glass-glass construction produced specifically for the BIPV market are available. However, the range of solar cell colours and shapes currently offered by suppliers is still very limited and this is a barrier to the widespread use of PV modules as constructional components. Initial investigations of the colour and efficiency of Laser Grooved Buried Contact (LGBC) solar cells as a function of the thickness of the LPCVD silicon nitride antireflection coating were reported in the late 1990s, but the subsequent commercialisation of coloured cell products has been limited in part by the difficulty in controlling the uniformity and reproducibility of colour in large scale cell production. The aim of the present work is to understand and control the processes that affect the thickness and hence colour of the silicon nitride ARC. Process conditions were optimised to enable the formation of antireflection coatings with thicknesses in the range 90 nm to 400 nm. LGBC solar cells were fabricated in 5 colours on both non-textured Cz and partially textured multicrystalline wafers. Good uniformity of colour was achieved both across individual cells and throughout whole process runs. Investigations into defining colours was developed using RGB component analysis and laser scribing was used to produce cells in a range of shapes which, in conjunction with the choice of colours, demonstrates the potential for novel BIPV applications.

Keywords: antireflection coating, building integration, colour

1 INTRODUCTION

The use of photovoltaic modules in architectural applications is now firmly established and large modules of glass-glass construction produced specifically for the BIPV market are available. However, the range of solar cell colours and shapes currently offered by suppliers is still very limited and this is a barrier to the widespread use of PV modules as architectural components. In principle, coloured filters could be used to change the appearance of solar cells or modules. However, this would add complexity and cost to the manufacturing process in addition to preventing a significant portion of the incident radiation from reaching the surface of the cell. A more efficient and cost effective approach is to use the thin film interference effect in the antireflection coating, which is responsible for the familiar dark blue colour when optimised for minimum power loss under AM1.5. Adjusting the thickness of the antireflection coating enables a range of colours to be produced, albeit with some loss of energy conversion efficiency. An initial investigation of the colour and efficiency of Laser Grooved Buried Contact (LGBC) solar cells as a function of the thickness of the LPCVD (Low Pressure Chemical Vapour Deposition) silicon nitride antireflection coating was reported by Mason et al [1] in 1995. In the European BIMODE project in the late 1990s, coloured cells fabricated using this technique were used to produce a number of demonstration modules of various shapes, with module efficiencies in the range 6.3% to 12.1% [2, 3, 4]. Subsequent commercialisation of coloured cell products has been limited in part by the difficulty of achieving acceptable visual quality and high yield. This is a result of the tighter tolerances required in the silicon nitride deposition and subsequent process steps in order to achieve uniformity and reproducibility in colours other than the standard dark blue. Work at NaREC is aimed at understanding the processes that affect the thickness of the silicon nitride ARC and hence controlling the colour of LGBC solar cells. The theoretical background and results of preliminary experiments were reported by Roberts et al [5]. In the present paper, further experimental results on coloured multicrystalline LGBC cells are reported, including a study of the colour uniformity obtainable in large production runs. Examples of cells of novel shape, produced by laser cutting, are also presented.

2 COLOURED LGBC CELL FABRICATION

The main process steps in the LGBC cell fabrication process are shown in Figure 1. The process steps that determine the colour of the finished cell are shaded yellow in Figure 1. The first of these is the texturisation, which affects the overall reflectivity of the surface. For the purpose of producing visually attractive coloured cells, the focus of the work was on block-cast multicryatalline wafers. A KOH-based texture etch (as used conventionally for Cz wafers) was used to partially texture the surface and accentuate the grain pattern in order to enhance the appearance of the cell. Cells were also fabricated on non-textured Cz wafers in order to evaluate the effect of colour on cell efficiency without the random influence of grain orientation. Highly textured silicon surfaces, such as random pyramid textured monocrystalline and acid isotextured multicrystalline wafers, are less interesting for BIPV applications as the low intensity of reflected light means that the colours are relatively dull. (Textured coloured cells are of potential interest for camouflaged PV power installations for military applications, but this is not the subject of this paper).

The 4 remaining shaded process steps in Figure 1 are those which determine the final thickness of the ARC and hence the colour of the cell. The residual phosglass layer from the emitter doping is left in place as a surface passivation and to remove the need for an additional etching step. This layer therefore contributes to the total optical thickness of the ARC and influences the colour. The phosphorus doping level under the front contact grid is increased by performing a second diffusion step

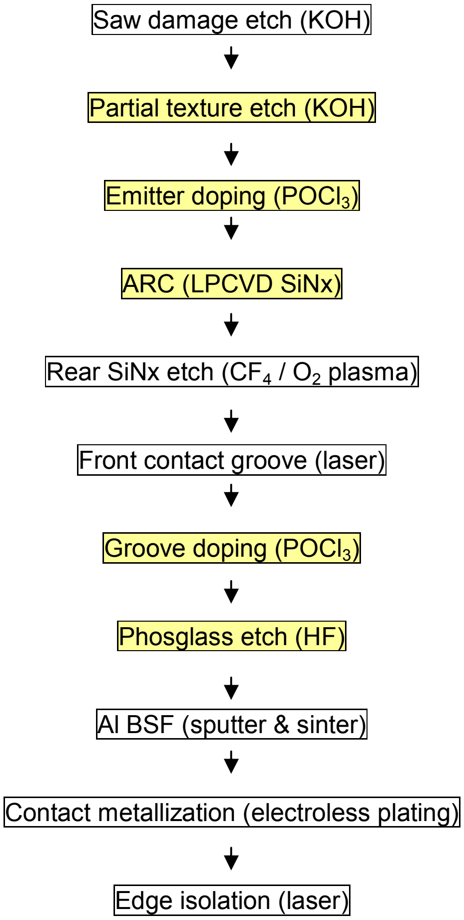

Figure 1 Main steps of the LGBC process sequence.

(groove doping) after laser grooving the wafer to define the front contact pattern. During this process step the silicon nitride ARC acts as a mask which prevents further doping of the emitter away from the front contact regions. However, the silicon nitride itself becomes doped with phosphorus, to a depth dependent upon the process conditions. The phosphorus-doped nitride is etched rapidly in dilute HF during the phosglass removal step which follows groove doping. The thickness of the silicon nitride layer deposited must be adjusted to take the above effects into consideration, such that the ARC on the finished cell has the correct optical thickness.

The range of colours achievable in practice was investigated by depositing a silicon nitride film of varying thickness onto a silicon surface. This was accomplished by placing 2 silicon wafers in close proximity in the LPCVD furnace, with a small angle between the wafer faces in order to achieve a varying degree of shading from the deposition process. The resulting spectrum of colours is shown in Figure 2.

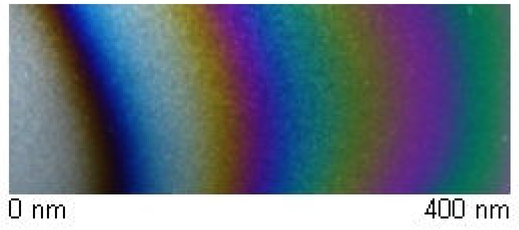

Figure 2: Interference colours in a silicon nitride layer of varying thickness on a non-textured monocrystalline silicon surface

Process trials were conducted to determine the process conditions for the fabrication of cells in 5 colours: dark blue (i.e. standard process), light blue, yellow, purple and green. The sequence of interference colours is repeated as the thickness of the silicon nitride layer is increased; ideally the “first order” colour would be selected in order to minimize the LPCVD process time and the stress in the silicon nitride layer. However, the degree of thickness control required to produce any chosen colour is not constant for all orders. In practice it was found that while good colour uniformity across the wafer was achievable in the first order for dark blue, light blue, yellow and purple, for green it was necessary to go to the second order and this required a relatively thick silicon nitride layer to be deposited (~ 400 nm). Once the process conditions were established, LGBC cells in each of the chosen coulours were fabricated on both monocrystalline (Cz) wafers and block-cast multicrystalline wafers.

3 CELL COLOUR AND EFFICIENCY

Examples of multicrystalline LGBC cells in the 5 colours are shown in Figure 4. Excellent uniformity of colour across the cell was achieved in all cases.

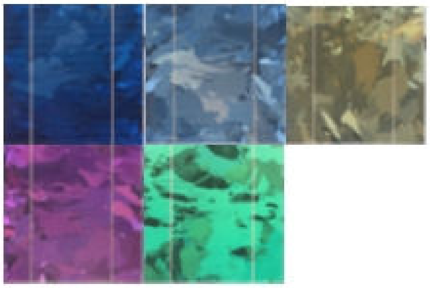

Figure 3: Coloured LGBC cells on multicrystalline silicon wafers.

Cell parameters for initial process runs and subsequent improved process runs on partially textured multicrystalline wafers are shown in Table I. The final cell area after laser edge isolation was 151.29 cm^2. Subsequent runs have shown significant improvement in cell parameters. This has been achieved through optimization of cell processing techniques. Greater control of rear SiNx etch using CF_4/O_2 plasma has allowed full area cells to be produced. Cell efficiency increases have also been realized by fabricating trial cells on wafers with improved bulk wafer properties.

Colour	Jsc (mA. cm-^{2})	Voc (mV)	FF (%)	η (%)
Dark blue	28.75	588	75.2	12.71
Improved dark blue	32.59	599	76.8	15.00
Light blue	27.44	589	75.7	12.23
Yellow	25.06	588	76.0	11.20
Improved yellow	28.34	594	76.7	12.92
Purple	24.06	585	75.7	10.65
Improved purple	27.30	573	76.3	11.95
Green	24.78	562	74.6	10.39

Table I: Initial and improved Light-IV parameters of coloured cells on partially-textured multicrystalline wafers

The efficiencies obtained on non-textured Cz wafers and partially textured multicrystalline wafers are compared in Figure 4. The improvements obtained to date for the dark blue, yellow and purple colours over initial process runs are evident as 'hashed' extensions to the bars.

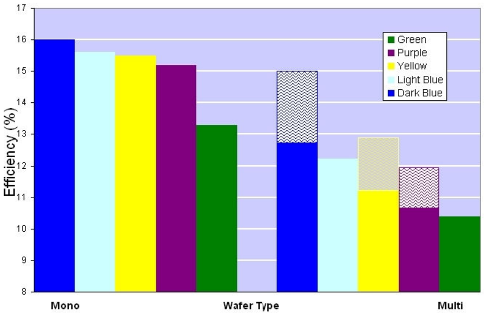

Figure 4: Cell efficiency of initial and improved coloured cells on multi and monocrystalline silicon.

3 CONTROL OF COLOUR UNIFORMITY

After optimising the process conditions (temperature profile, gas flow and pressure) in the LPCVD process, the uniformity of silicon nitride colour as a function of position in the process tube was evaluated. This was accomplished by placing trial wafers at selected positions in all 5 quartz boats in the process tube, while the remaining positions were occupied by "dummy" wafers in order to simulate a full furnace load. (Dummy wafers are wafers that are used repeatedly in the same process step, so as not to waste new bare wafers. It has been previously demonstrated that the use of dummy wafers in LPCVD nitride deposition accurately replicates the deposition conditions for a full load of bare wafers).

On the bare wafers, a slight variation in colour across each wafer is evident, Roberts et al [5], but this non-uniformity is removed by lamination. It is concluded that acceptable colour uniformity and reproducibility is achievable on at least 240 wafers out of the total furnace capacity of 250 wafers.

RGB component analysis, performed using ImageJ 1.40g software, was used in order to quantitatively define the colours of the finshed cells. Mean values of the red, green and blue colour components were obtained. Analysis in this way removes the subjective nature of the 'as seen' colours and can be used as a quality control and cell grading tool.

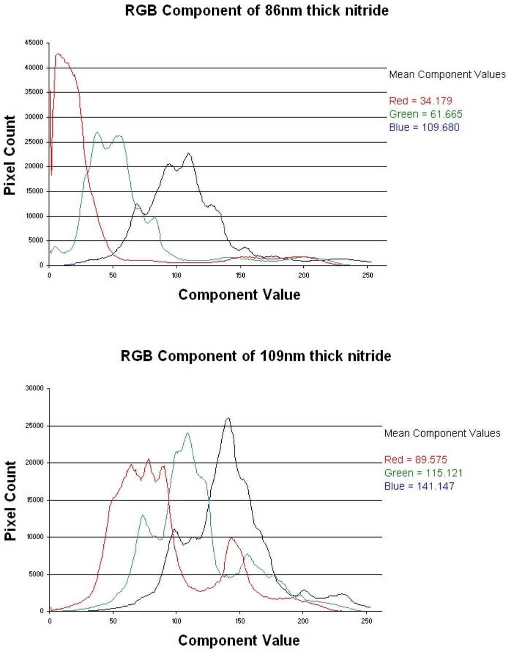

Figure 5: Results of RGB component analysis on dark blue and light blue cells.

4 NOVEL CELL SHAPES

The final stage of the standard LGBC cell fabrication process is edge isolation to remove metal which is plated around the periphery of the wafer. This is accomplished by laser scribing the back surface of the cell close to each edge and cleaving along the scribe lines. A wide range of geometrical cell shapes, including curves, can therefore be produced at the edge isolation stage by appropriate programming of the laser. Some examples are shown in Figure 6.

Figure 6: Examples of trial shapes investigated.

5 ACKNOWLEDGMENTS

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