

## PROCESS DEVELOPMENT OF COLOURED LGBC SOLAR CELLS FOR BIPV APPLICATIONS

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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 on offer to architects and BIPV system designers is still very limited and this is a barrier to the widespread use of PV modules as a constructional “material”. 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 was 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 across the 149.6 cm<sup>2</sup> area of the cell in all cases. The efficiency of trial cells fabricated on non-textured Cz silicon wafers ranged from 16% for a standard dark blue ARC to 13.3% for a green ARC, with purple, yellow and light blue cells all having efficiencies over 15%.

**Keywords:** antireflection coating, building integration, buried contacts, 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 on offer to architects and BIPV system designers is still very limited and this is a barrier to the widespread use of PV modules as a constructional “material”. 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 reflection 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 relatively low manufacturing yield resulting from inadequate process control in the silicon nitride deposition and subsequent process steps, which leads to an unacceptable degree of colour variation both across an individual cell and from cell-to-cell and batch-to-batch. The present work is aimed at understanding the processes that affect the thickness of the silicon nitride ARC and hence controlling the colour of LGBC solar cells.

### 2 THEORY

The intensity and spectral distribution of light reflected from a silicon nitride coated silicon surface is determined by the reflections at the air / silicon nitride and silicon nitride / silicon interfaces and the resulting interference effects within the silicon nitride layer. The overall reflection as a function of wavelength is expressed by Fresnel’s formula [5]:

$$R = \frac{r_1^2 + r_2^2 - 2r_1 r_2 \cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 \cos 2\theta}$$

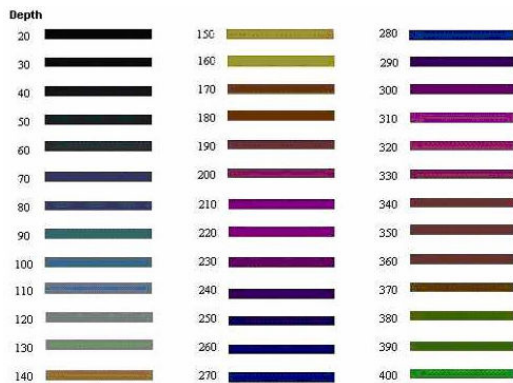
where:-

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}$$

$$r_2 = \frac{n_1 - n_2}{n_1 + n_2}$$

$$\theta = \frac{2\pi n_1 d_1}{\lambda}$$

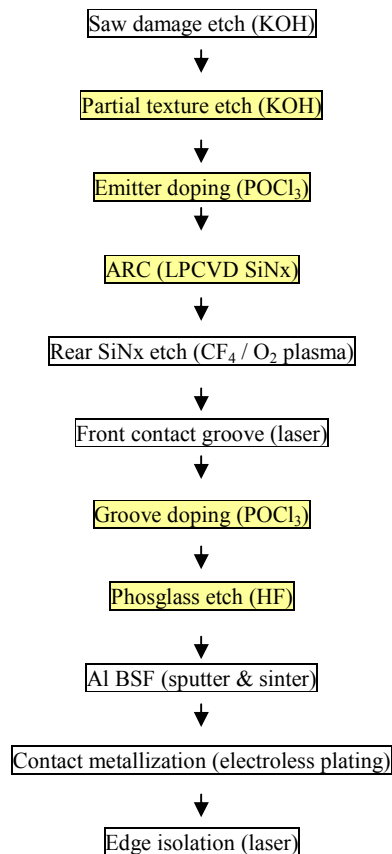
$n_1$ ,  $n_2$  and  $n_3$  are the refractive indices of the air, silicon nitride and silicon respectively,  $d_1$  is the thickness of the silicon nitride and  $\lambda$  is the wavelength of the incident light. Assuming AM1.5 illumination at normal incidence to a flat surface, solving Fresnel’s equation for any chosen silicon nitride thickness allows the reflected spectrum, and hence colour, to be predicted. Figure 1 shows the range of colours generated in this way, for silicon nitride thicknesses between 20 nm and 400 nm.



**Figure 1:** Interference colour versus thickness of silicon nitride coating (prediction using Fresnel's equation)

### 3 COLOURED LGBC CELL FABRICATION

The main process steps in the LGBC cell fabrication process are shown in Figure 2.



**Figure 2:** Main steps of the LGBC process sequence.

The process steps that determine the colour of the finished cell are shaded yellow in Figure 2. 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 multicrystalline 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 2 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 (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 3.



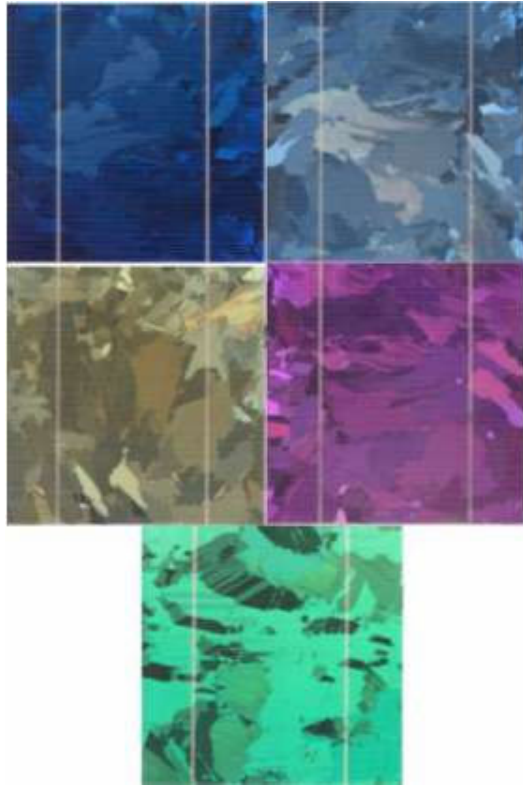
**Figure 3:** Interference colours in a silicon nitride layer of varying thickness on a non-textured monocrystalline silicon surface

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 PLCVD 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 colours were fabricated on both monocrystalline (Cz) wafers and block-cast multicrystalline wafers.

#### 4 RESULTS

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.



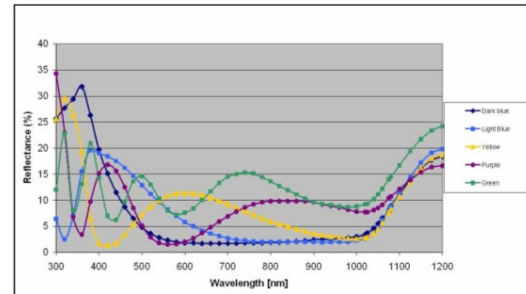
**Figure 4:** Coloured LGBC cells on multicrystalline silicon wafers

The thickness and refractive index of the silicon nitride was measured by ellipsometry on polished wafers processed alongside the cells of each colour. This data, together with the silicon nitride deposition time in the LPCVD process is shown in Table 1.

**Table 1:** ARC properties corresponding to the 5 colours

Colour	Dep. Time (min)	Thickness (nm)	Refractive index
Dark blue	33	86	2.03
Light blue	41	109	2.03
Yellow	54	148	2.03
Purple	72	211	2.03
Green	125	385	2.03

In order to eliminate the effects of random grain orientation on the reflectivity, the effect of changing the ARC thickness on the cell efficiency was investigated using non-textured (saw damage etched only) Cz wafers. Reflectance curves from these cells are shown in Figure 5 and typical cell parameters are shown in Table 2. The final cell area after laser edge isolation was 149.6 cm<sup>2</sup>.

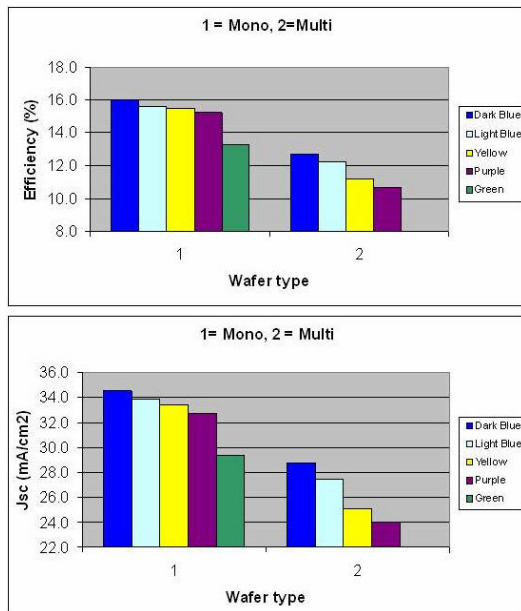


**Figure 5:** Reflectance curves from coloured ARC on non-textured monocrystalline silicon

**Table 2:** Light-IV parameters of coloured cells on non-textured Cz wafers

Colour	Jsc (mA.cm <sup>-2</sup> )	Voc (mV)	FF (%)	η (%)
Dark blue	34.5	611	75.9	16.0
Light blue	33.8	608	76.0	15.6
Yellow	33.4	609	76.1	15.5
Purple	32.7	606	76.5	15.2
Green	29.4	583	77.5	13.3

The efficiencies of the coloured cells fabricated on multicrystalline silicon wafers were substantially lower than those on Cz wafers and were lower than expected from earlier LGBC process trials on multicrystalline silicon with standard ARC thickness. The quality of the wafers used in the present work is thought to be a contributory factor, as the extended time at high temperature in the LGBC process can lead to significant bulk lifetime degradation in some multicrystalline material.



**Figure 5:** Cell efficiency (top) and short circuit current density (bottom) of coloured cells on multicrystalline and monocrystalline silicon.

## 5 CONCLUSIONS

Process conditions were controlled 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: dark blue, light blue, yellow, purple and green. Good brightness and uniformity of colour was achieved across the 149.6 cm<sup>2</sup> area of the cell in all cases. The efficiency of trial cells fabricated on non-textured Cz silicon wafers ranged from 16% for the standard dark blue ARC to 13.3% for a green ARC. Purple, yellow and light blue cells all had efficiencies over 15%. The efficiencies of cells fabricated on partially textured multicrystalline silicon were significantly lower than expected. Wafer quality is believed to be a contributory factor to this result.

The ability to achieve good cell efficiency and colour uniformity has been confirmed in small scale trials. For the commercial production of coloured LGBC cells for the BIPV market, the reproducibility of cell colour in large scale production runs is an important consideration and this still needs to be demonstrated.

## 6 ACKNOWLEDGEMENTS

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## 7 REFERENCES

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