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**Antireflective Nanocomposite Based Coating on Crystalline Silicon Solar Cells for Building-Integrated Photovoltaic Systems**

[1] **Mr.SHYAMALENDU KHUNTIA**, [2] **Mrs.MITALI MOHAPATRA**
*[1*] Asst. Professor, Dept. Of Electrical Engineering, NIT BBSR,*
*Asst. Professor DEPT. of Electrical Engineering, NIT BBSR,*
[1*] shyamalendukhuntia@thenalanda.com, , mitalimohapatra@thenalanda.com,

**ABSTRACT**

**Building integrated photovoltaic (BIPV) systems is an interesting alternative approach to increase the area available for electricity production and potentially reduce the cost of solar energy. In BIPV systems, the visual impression of the solar module, including its color, becomes important. However, the range of solar cells and shapes currently available to architects and designers of BIPV systems is still very limited and this prevents the widespread use of solar cells as a building material. The color of the solar module is determined by the color of the cells in the module, which is provided with the anti-reflective coating (ARC). However, the availability of efficient but different colored solar cells is important for the further development of BIPV systems. In this paper, we used a diamond-like nano composite layer as an anti-reflection nano composite-based (ARNAB) coating material for a crystalline silicon solar cell, and the effect of ARC color change on the optical properties and efficiency of the solar cell. is investigated. . . In addition to comparing the optical properties of such solar cells, the effect of using colored ARCs on solar cell efficiency is measured using the PC1D solar cell modeling tool**

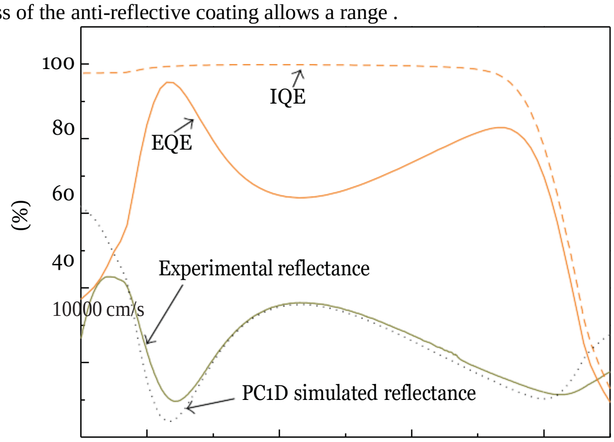
## 1. Introduction

A building-integrated solar energy system is a combination of aesthetic considerations, carbon-free power generation and weather protection that makes glass-glass solar modules so attractive for building facades and roofs. Solar panels are an environmentally friendly alternative to granite, marble and other building materials and create inspiring, functional solutions. It is for good reason that more and more builders, architects, engineers and designers are embracing this technology.

In addition, the BIPV system represents an interesting alternative approach to electricity production and can further reduce the cost of solar energy [1]. However, the total market share is not at all important at the moment. One factor is that BIPV elements are partially hindered by the limited range of aesthetic variations of the . An architectural study (approx. 85%) found that aesthetic concerns would allow installing solar energy systems with reduced efficiency [2]. The use of PV modules in architectural applications is now well established and there are large glass-to-glass modules produced specifically for the BIPV market. However, the range of solar cells and shapes currently available to architects and designers of BIPV systems is still very limited and this prevents the widespread use of solar cells as a building material. In principle, color filters could be used to change the appearance of solar cells or modules. However, this would increase the complexity and cost of the production process, and it would also prevent a significant part of the incoming radiation from reaching the cell surface. A more efficient and cost-effective approach is to use the thin film interference effect in the anti-reflective coating responsible for the familiar dark blue color when optimized for AM1.5 minimum reflectance. Adjusting the thickness of the anti-reflective coating allows a range .

TABLe 1: Solar cell parameters used during PCID simulation.

| Parameter | Value |
|---|---|
| Bulk silicon material thickness | 200 $\mu$m |
| Bulk doping concentration | $10^{16}$ cc |
| Emitter $n^+$ junction depth | 0.3 $\mu$m |
| Diffusion: sheet resistance/peak doping | 45 Ω/; $1 \times 10^{19}$ cc |
| Surface recombination velocity at emitter and rear surface | |
| Real $p^+$ concentration | $1 \times 10^{19}$ cc |

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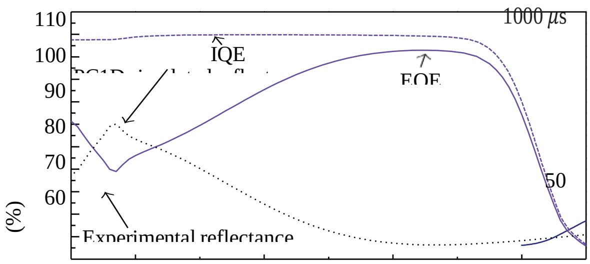

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20

0

400 600 800 1000

Wavelength (nm)

40
30
20
10
0

400 600 800 1000

Wavelength (nm)

(a)

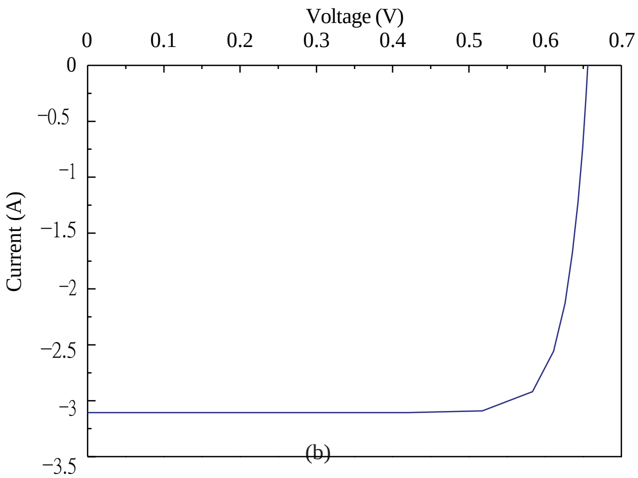
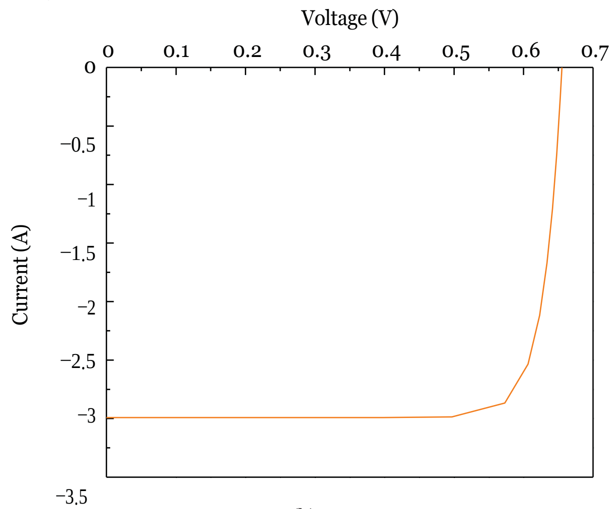



FIGURE 1: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with fed blue colour ARC. (b) Simulated illuminated *I-V* characteristic of fed blue colourmc-Si solar cell.

of colours to be produced, albeit with some loss of energy conversion efficiency.

An initial investigation of the colour and efficiency of Laser Grooved

(a)




(b)

FIGURE 2: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Yellow colour ARC. (b) Simulated illuminated *I-V* characteristic of yellow colour mc-Si solar cell.

coating was reported by Mason et al. [3] 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% [4]. Subsequent

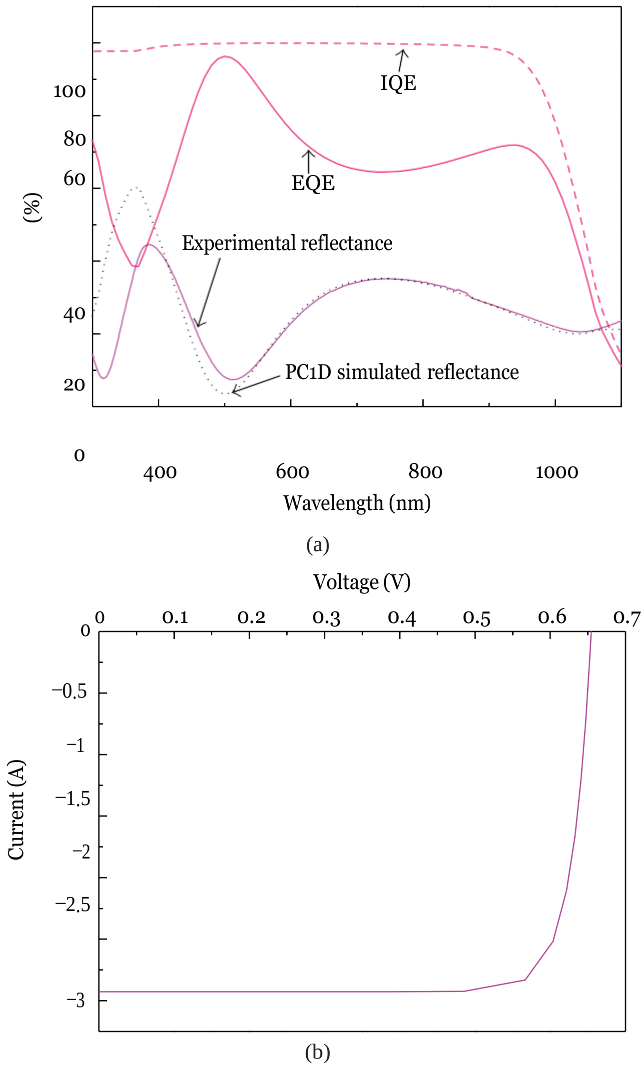



FIGURE 3: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Magenta colour ARC. (b) Simulated illuminated *I-V* characteristic of magenta colour mc-Si solar cell.

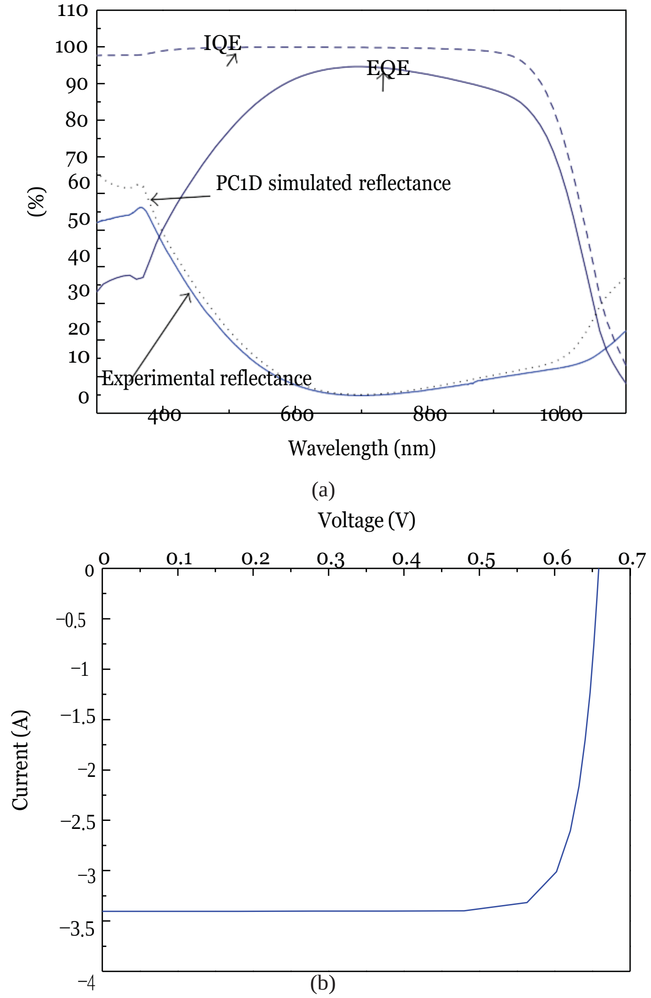



FIGURE 4: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Blue colour ARC. (b) simulated illuminated *I-V* characteristic of blue colour mc-Si solar cell.

In this paper, we have used Diamond-like nanocompos-ite layer [5–7] as an Antireflective Nanocomposite Based (ARNAB) coating material for crystalline silicon solar cell, and the impact of varying the color of an ARC upon the optical characteristics and efficiency of a solar cell is investigated. The overall transmittance and reflectance of a set of differently colored single layer ARCs are compared with multilayered ARNAB coating, all made using DLN layer deposition by PACVD technique. In addition to a comparison of the optical characteristics of such solar cells, the effect of using colored ARCs on solar cell efficiency is quantified using the solar cell modeling tool PC1D

## 2. Experimental

Diamond-like nanocomposite films optimized for an Antire- flective Nanocomposite Based (ARNAB) coating were syn- thesized and characterized in this work. Plasma enhanced chemical vapor deposition (PECVD) is used for DLN film synthesis [6]. The synthesis procedures attempt to exclude or minimize cluster formation in the sources, in the primary plasma, in the deposition region, and during film growth. The mean free path of each particle species must exceed the distance between its source and the growing film surface. Radicals were formed via glow discharge plasma breakdown of the precursor using a quasi-closed plasmatron, and high frequency (13.56 MHz, 0.3–5.0 kV) fields were used to trans- port the radicals to the substrate. Variation of precursor, plasma, and field conditions changes the state of the basic matrix. The precursors belong to family of Silazanes, and the species selected depends on the elemental ratios and bonding states desired in the film. Deposition pressure utilized $7.0 \times 10^{-4}$ torr. The growth rate of DLN films typically varies from 1.0 to 3.0 $\mu$m/hr and depends on a number of factors. The details experimental procedure has already mentioned in the author's published paper [6, 7]. By changing

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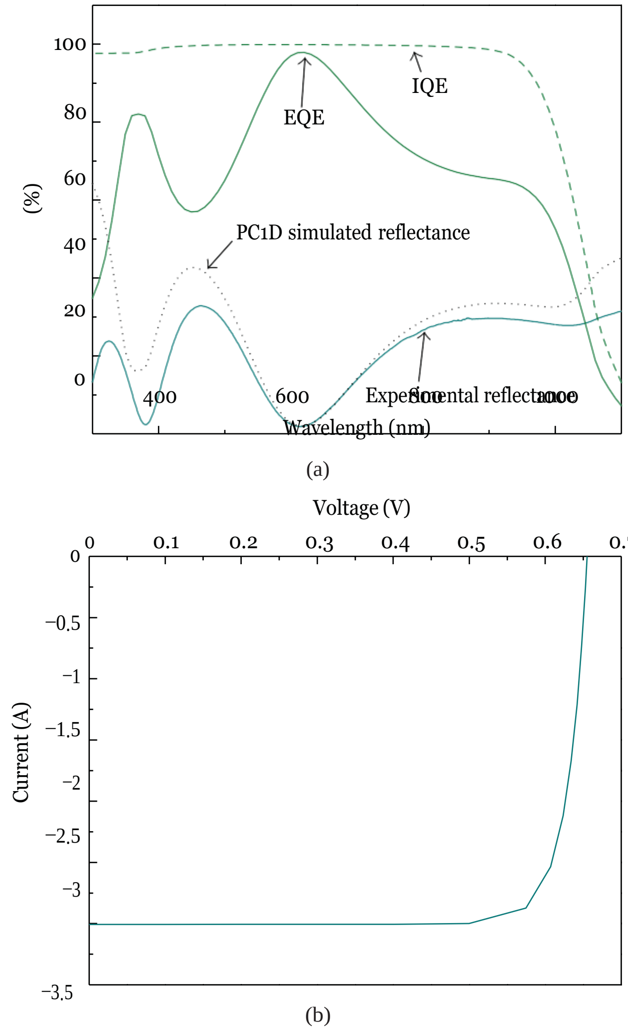


FIGURE 5: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Greenish bluecolour ARC. (b) simulated illuminated *I-V* characteristic of greenish blue colour mc-Si solar cell.

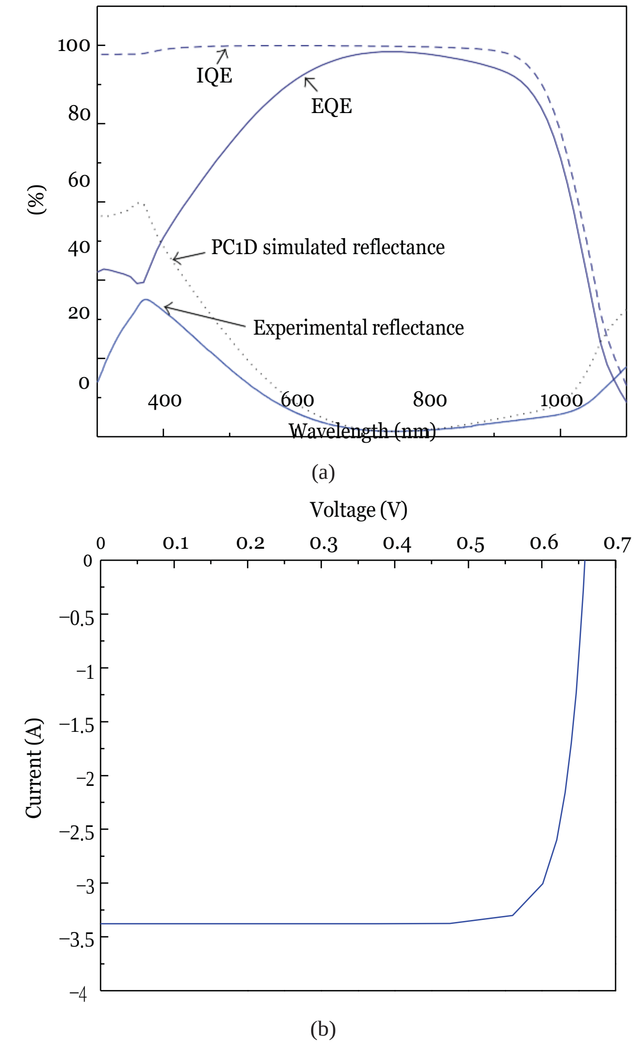


FIGURE 6: (a) Experimental and simulated spectral reflectance along with simulated IQE and EQE of mc-Si solar cell with Dark blue colour ARC. (b) Simulated Illuminated *I-V* Characteristic of Dark blue colour mc-Si Solar Cell.

deposition conditions, the optical properties of DLN film canbe varied over a wide range. The substrates used were boron doped NaOH-NaOCl polished multicrystalline silicon (mc- Si) wafers [8].

Prior to the deposition of the films of ARNAB layer,the thickness and deposition rate of the separate films were assessed by precursor flow rate, chamber working pressure and other deposition parameters respectively. The refractive index and thickness of the deposited ARNAB layers for BIPV system were estimated by ellipsometer. In addition to experimental films optical characterization, the impact of the resulting reflection variations upon the solar cell efficiency was determined by device modeling using PC1D software.

## 3. BIPV Modeling and Experimental Results

The modeling was made by using PC1D simulation software. During modeling, textured p-type crystalline silicon had taken. Above the emitter surface, AR coating layer was con- sidered. Simulation study was carried out by varying different coating thickness and refractive index and compared the datawith experimentally observed data.

Standard n-p-p$^+$ structured solar cell had taken with surface area 100 cm$^2$. The Solar cell parameters used during PC1D simulations are described in Table 1.

During simulation, each simulated solar cell reflectance curve was fitting with experimental reflectance curve. After matching the simulated reflectance spectra in each case, the expected solar cell parameters and illuminated current— voltage, IQE, and EQE characteristics—were, respectively, drawn as shown in Figures 1, 2, 3, 4, 5, and 6 and Table 2.

It was observed from Table 2 that the dark blue colour AR coated mc-Si solar cell can be able to produce the highest simulated efficiency whereas yellow colour c-Si solar cell can

TABLE 2: Simulated solar cell's parameters after curve fitting with experimental reflectance curve, refractive index, and thickness of ARNAB coating.

| Sample | ARC thickness (nm) | ARC r.i* | Broad band reflectance (%) | Isc (A) | Voc (V) | $\eta$ (%) |
|---|---|---|---|---|---|---|
| #120001B (without ARC) | — | — | — | 2.53 | 0.64 | 13.5 |
| #121006 fed blue | 125 | 1.85 | 7 | 3.10 | 0.66 | 17.02 |
| #121008A yellow | 175 | 1.85 | 1 | 2.99 | 0.65 | 16.03 |
| #121010 magenta | 205 | 1.83 | 2 | 2.92 | 0.65 | 16.09 |
| #120703B blue | 94 | 1.85 | 5 | 3.40 | 0.65 | 18.82 |
| #121006B green blue | 250 | 1.85 | 1.5 | 3.00 | 0.65 | 16.51 |
| #120706B dark blue | 100 | 1.85 | 1.2 | 3.49 | 0.65 | 19.35 |

ARC: antireflective coating; *r.i: refractive index; $\eta$: efficiency.

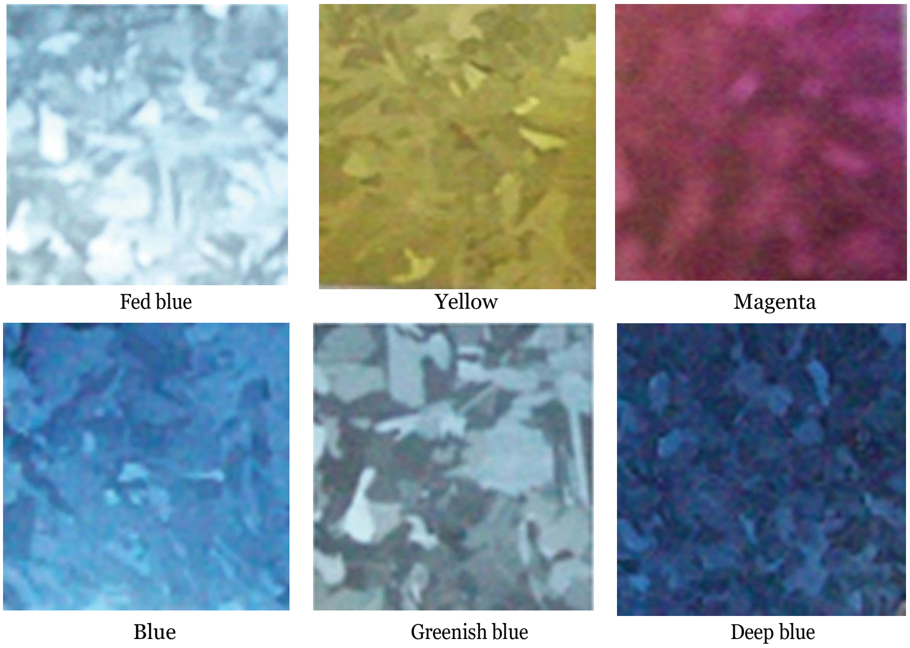


FIGURE 7: Photographs of colour mc-Si samples fabricated by ARNAB layer deposition using PACVD technique.

give the lowest solar cell simulated efficiency. Other coloursmc-Si solar cell (i.e, blue, fed blue, greenish blue and magenta solar cells) efficiencies were in-between deep blue and yellow respectively. Moreover, it was observed that the efficiency of simulated solar cell without AR coating is around 13.5%. Therefore, the lowest efficiency 16.3% with yellow colour was also reasonably high compared with the efficiency of uncoated mc-Si solar cell. Photographs of fabricated colour ARNAB layer coated multicrystalline silicon samples are shown in Figure 7.

In order to investigate the potential of ARNAB layer deposition techniques for fabrication of coloured antireflec-tion coatings, a selection of target colours were made. Opti-mization with respect to thickness and possible adjustments in target reflectance spectra during simulation may givefurther improvements in efficiency.

## 4. Conclusion

We have shown that the ARNAB coating of crystalline silicon solar cells can be adapted to produce visible colors while maintaining high efficiency. Five different colored (i.e., fed blue, yellow, magenta, blue, cyan, and deep blue) mc-Si wafers were fabricated with different thicknesses of ARNAB coating. The simulated efficiency of the Mc-S solar cells ranged from 19.35% for the standard dark blue ARC to 16.03% for the yellow ARC. The efficiency of fed blue, magenta, blue and green-blue cells was more than 16%. This approach represents a very simple AR coating process for polycrystalline silicon solar cells and may be a viable short-term way to produce multi-colored solar cells/modules for use in BIPV systems and other applications where aesthetic concerns are important.

**Acknowledgments**

This paper is dedicated to the memory of ARNAB, the one and only son of U. Gangopadhyay and Lekha Gangopadhyay. The authors would like to thank Meghnad Saha Institute of Technology, TIG for providing the infrastructural support to carry out research activity in this area. The authors also gratefully acknowledge the DST, Government of India, for financial support for carrying out solar cell related research activity.

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