

Fabrication of Crystalline Silicon Solar Cell in Bangladesh: Limitations and Remedies

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Abstract-- For the first time in 2015, single crystalline solar cell was fabricated in Bangladesh and the fabricated mono-crystalline silicon solar cell efficiency is near 6.89%. This paper discuss about the reasons and limitations of achieving 6.89% efficient solar cell and also remedies to achieve to high efficiency crystalline solar cell. Clean room class 100-1000 was not achieved during solar cell fabrication. Moreover Czochralski (CZ) silicon wafer, which contains higher impurity was used instead of Float Zone (FZ) silicon wafer. Inefficient technique like edge isolation barrier paste was used to isolate the edges of solar cell, instead of stacking the wafers on top of each other and using CF_4 , O_2 and generating plasma with microwave frequency 2.45 GHz. While achieving good surface passivation requires thermal oxidation technique which requires temperature set at $900^\circ C - 1200^\circ C$, could not be achieved due to Rapid Thermal Annealing furnace whose maximum temperature is around $1000^\circ C$. Moreover shunt resistance and minority carrier diffusion length ($88 \mu m$) was found low. High series resistance was found ($6.197 \Omega.cm^2$). Though line resistance of a tabbing wire is typically 20 times better than that of a screen printed busbar, no tabbing wire was soldered on top of each busbar. Remedies to improve efficiency of mono crystalline solar cell is to use TiO_2 or ZnO layer as anti-reflecting coating, as no anti-reflecting was used during solar cell fabrication process. Also for $12.5 \times 12.5 cm^2$ silicon wafer, it is suggested to use 3 bus bars in front contact metallization process because applying 3 busbar layout design improves current collection because of lower electric resistance. As for back contact metallization, not covering the back fully covered with Ferro FX53-038 aluminum paste, it is proposed to use discontinuous busbars (2 strips with 3 gaps or 3 strips with 3 gaps) on the back side made with Ferro CN33-462 silver paste.

Keywords: Crystalline silicon solar cell; Float Zone (FZ); Edge isolation; ARC layer; Busbars; Thermal Oxidation; RTA furnace; Shunt resistance; Series resistance

1. INTRODUCTION

The demand for energy is everlasting and it is increasing day by day. Oil is not found everywhere [1], Coal is still abundant and cheap but polluting [2], natural gas is scarce and nuclear energy production is costly and risky. Seeing that oil, coal, gas, nuclear power is not green energy, not abundant and will not last forever the only option is to turn to renewable energy. By looking at the current technical, environmental and economic aspect solar cell is the best option for utilizing renewable energy. But by looking the solar cell efficiency table (version 46) [3], it is seen that on an average solar cell efficiency is not more than 20%. So making the solar cell highly efficient is a challenging task, and necessary because the sources of conventional energy is depleted day by day, resorting to alternative sources of energy like solar and making solar cell highly efficient has become essential of the hour. So, for the first time in 2015, single crystalline solar cell was fabricated in Bangladesh and the fabricated mono-crystalline silicon solar cell efficiency is near 6.89%. [4, 5].

Due to vast demand of solar panel and as solar cell, thus solar panel are not made locally in Bangladesh, the main goal is to fabricate high efficiency solar cell in Bangladesh. Because the efficiency of the fabricated solar cell for the first time in Bangladesh, is too low for commercialization, this paper discuss about what are the reasons for achieving such low efficiency and also the possible remedies to improve the efficiency of solar cell in Bangladesh.

Limitations like ISO-8 class clean room, lack of FZ wafer, use of edge isolation paste, high series resistance low shunt resistance and rapid thermal annealing equipment (max temperature around $1000^\circ C$) etc. which are the causes for of achieving 6.89% efficient solar cell are discussed in this paper. In the old approach (The solar cell which was fabricated in Bangladesh) did not use any kind of anti-reflecting coating or discontinues busbars, whereas in the new approach it is proposed to use of ZnO (Zinc Oxide) or TiO_2 (Titanium Oxide) anti-reflecting coating, discontinues busbars (2 strips with 3 gaps or 3 strips with 3 gaps), use of tabbing wire, clean room, FZ wafer, Microwave plasma system for edge isolation, thermal oxidation at $1200^\circ C$ with O_2 gas and different texturing methods to achieve to high efficiency crystalline solar cell.

2. REASONS FOR ACHIEVING 6.89% EFFICIENT SOLAR CELL

2.1 Clean Room

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Modern solar cell manufacturing is performed in a sophisticated facility known as a clean room. A clean room is a facility that is isolated from outside environment and free from pollutants such as particles, metals, organic molecules, electrostatic discharge (ESD) and chemical vapors [6]. A typical room in urban environment contains 35,200,000 particles per cubic meter (Size range of 0.5 μm and larger in diameter) and known as ISO 9 cleanroom, where as an ISO 1 cleanroom has no particles in that size range and only 2 particles per cubic meter of 0.2 μm and smaller [7]. U.S. General Service Administration's standards (known as FS209E) class 100 to 1000 equivalent to International Standards Organization (ISO) ISO 5 – ISO 6 class requirement was not meet during the solar cell fabrication in Bangladesh. By using met one a2400 laser particle counter it is seen that ISO class is in between ISO 7 and ISO 8.

2.2. Wafer Selection

The first step of making silicon solar cell is choosing the p type silicon wafer. For single crystalline silicon solar cell there are two ways that p type silicon wafer can be manufactured. They are of Czochralski (CZ) method and Float Zone (FZ) method and the wafers are called CZ silicon wafers and FZ silicon wafer. It is seen that in FZ silicon wafer, oxygen is less than 10^{16} atom/cm³ where as in Grade A type CZ wafer it is 9×10^{17} atom/cm³. Also carbon concentration is less than below 10^{16} atom/cm³ in FZ where as in CZ, it is 1×10^{17} atom/cm³ [8]. These oxygen and carbon are the main impurities of solar cell processing and the precipitation of oxygen and carbon occurs during crystal growth [9]. Moreover oxygen defects reduces the lifetime of the bulk. Since the melt does not come into contact with a quartz crucible, and no hot graphite container is used during FZ crystal growth, FZ wafer has lower oxygen and carbon concentration compared to CZ silicon [10]. In fact FZ wafer is superior over CZ wafer is based on low impurity, minority carrier bulk lifetime and low resistivity variation. Still fabricating solar cell in Bangladesh, CZ wafer was used instead of FZ wafer.

2.3. Edge Isolation

Edge isolation is a process that removes the phosphorous diffused area around the p-type wafer, so that the front emitter (N-type layer) is isolated from the rear (P-type layer) [11]. The removal diffused layer around the edge of the solar cell is absolutely necessary because the diffused layer acts as short for p-n junction of the solar cell and

thus reduces the efficiency of solar cell. Here in Bangladesh for the edge isolation process, edge isolation paste was used before phosphorous diffusion. Little is known about the edge isolation paste which was bought from the market and it is assumed as one kind of flux rosin. Using edge isolation paste is one of the main reason for achieving low efficiency solar cell in Bangladesh. But for better performance in the edge isolation process it is proposed to use Microwave Plasma System [27]. Where edge isolation is done by stacking the wafers on top of each other and using, and generating plasma with microwave frequency 2.45 GHz and having an etching environment consists of combination of fluorinated gas (CF_4) and oxidant gas (O_2).

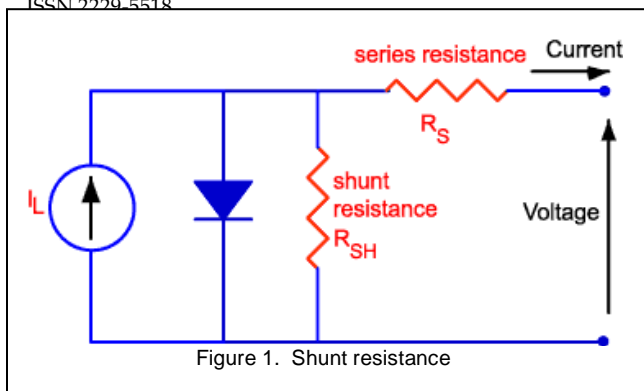
2.4. Thermal Oxidation

One of the reason that the efficiency in silicon solar cells continues to be limited is, by the recombination of photo-excited electron-hole pairs that takes places at surfaces and interfaces. The process for producing semiconductor surface with very low recombination rate is called surface passivation [12]. To achieve high surface passivation, thermal oxidation technique is used and the temperature most appropriate for thermal oxidation is 900°C - 1200°C [13]. Rapid thermal annealing (RTA) furnace was used for thermal oxidation technique but the required temperature 900°C - 1200°C could not be achieve because the RTA furnace maximum temperature is around 1000°C . Moreover no oxygen (O_2) and nitrogen (N_2) gas was used as the furnace provide no option to utilize these gases.

2.5 Other Factors

i) Shunt Resistance

Significant power loss can be seen in solar cell due to low shunt resistance, R_{SH} . Shown in Figure 1. For an ideal cell, R_{SH} should be infinite and should not provide an alternate path for current to low, and if R_{SH} is low, the value of V_{oc} will also be low and in our fabrication process shunt resistance was found low.



Under low light conditions the shunt resistance was found 234 ohm for a 12.5X12.5 cm² wafer, whereas good solar cell has more than 1000 ohm of shunt resistance [14]. It is seen that at 850° C to 900° C the solar cell broke in the RTA furnace, if not shunt resistance was lower. A dryer oven (whose max temperature is 250° C) was used (shown in Figure 2), which improved the shunt resistance but still it was much lower than commercial solar cell's shunt resistance.

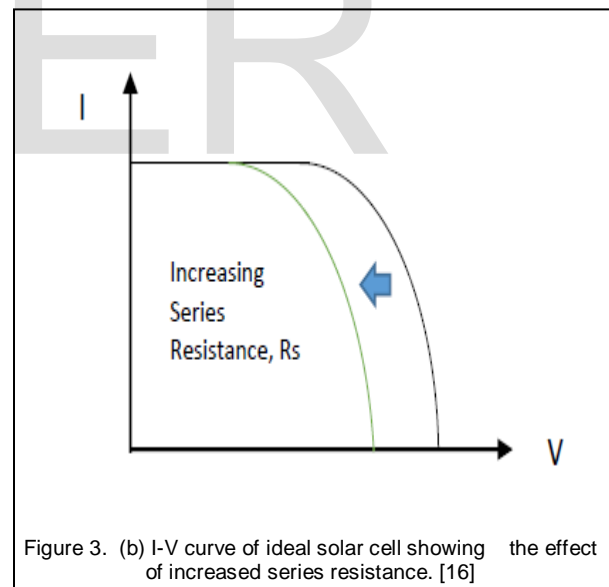
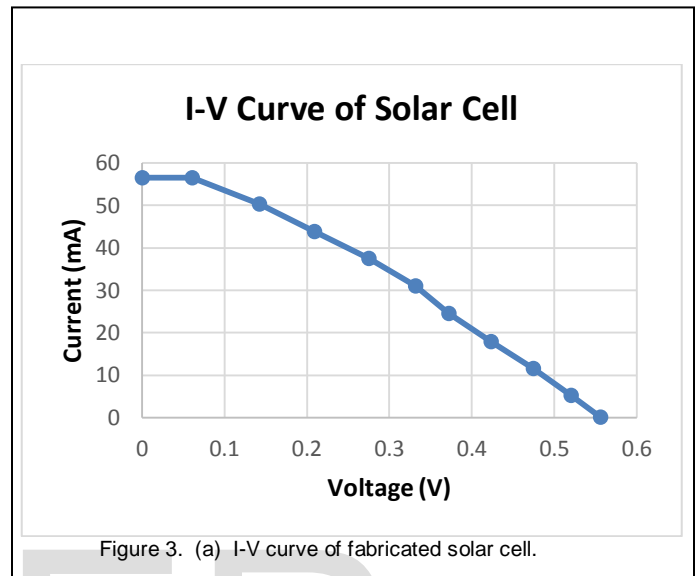


iii) Series Resistance

The light (L) intensity current (I)-voltage (V) (LIV) measurement instrument was used to measure the current and voltage of the fabricated solar cell. After obtaining the current voltage data the I-V characteristics curve was drawn, shown in the figure

3(a), and by using two-curve method [15] and the following series resistance equation the series resistance of the fabricated solar cell was determined.

$$R_S = \frac{\Delta V}{\Delta I} = \frac{V_1 - V_2}{I_2 - I_1}$$



The series resistance, R_S of the fabricated solar cell was found 6.197 $\Omega \cdot \text{cm}^2$. Which is much higher as high efficient solar cell series resistance value varies from 0.3 $\Omega \cdot \text{cm}^2$ to 1 $\Omega \cdot \text{cm}^2$ [17]. Meanwhile the high series resistance of the fabricated solar cell can also be seen from the I-V curve, as series resistance increases the I-V curve of the solar cell deviates from

the ideal I-V curve of the solar cell shown in figure 3(b).

iv) Minority carrier diffusion length & Minority carrier Life Time

Light-induced surface photo voltage (SPV) measurement system was used to measure the minority carrier diffusion length. It was seen that minority carrier diffusion length is 88 μm which lacks the required diffusion length because typical minority carrier diffusion length is 100-300 μm [18].

Measurement of minority carrier life time was also done using the following equation.

$$L = \sqrt{D\tau}$$

Where L is the diffusion length in meters, D is the diffusivity in m^2/s and τ is the lifetime in seconds. Diffusivity is considered as 27 cm^2/s and from the equation it was found that the minority carrier life time is 2.8681 μsec , which is much below 10 μsec .

3. REMEDIES

Apart from having clean room class 100 -1000, using FZ wafer, thermal oxidation at 900° C - 1200° C and microwave plasma system for edge isolation there are several other options also to improve the efficiency of single crystalline solar cell in Bangladesh. They are described below.

3.1 Anti-reflecting coating

Antireflection coating (ARC) is a layer on the surface of solar cell (On n-type layer) to reduce the reflection of sunlight. But no anti-reflection coating was used in fabricating solar cell in Bangladesh. Spin Coater ACE-200 can be used to deposit TiO_2 (Titanium Oxide) layer on emitter as anti-reflection coating. ZnO (Zinc oxide) layer can also be used as ARC as the transmittance of ZnO layer is more than 85% [19] at wavelength range of 600nm-900nm. Though silicon nitride (SiN_x) layer is the most widely used materials as ARC, cannot be applied on emitter of solar cell in Bangladesh because of insufficient equipment.

3.2 Front and Back Contact Metallization

Metallic top contacts are essential for collecting the current generated by a solar cell. The metallic top contacts which is of wide strips and vertical in arrangement is called busbars shown in Figure -4(a). The

narrow lines of metallization perpendicular to the busbars are called fingers shown in figure -4 (a). "Busbars" are connected directly to the external interconnection, while "fingers" collect current and deliver to the busbars [20]. The solar which was fabricated in Bangladesh has two busbars, but as 12.5X 12.5 cm^2 solar cell is quite big [21] it is assumed that using of 3 busbars instead of 2 busbars in front contact metallization process will increase the efficiency of solar cell.

Applying 3 busbar layout design will improve current collection because of lower electric resistance. Also for front contact metallization process no tabbing wire was used and it is suggested to use tabbing wire, which will be soldered on top of each busbar. These tabbing wires serve mainly two functions. The first is to provide electrical interconnection to other cells in a module. The second function is to provide extra conductivity for the busbar. The line resistance of a tab is typically 20 times better than that of a screen printed busbar [22].

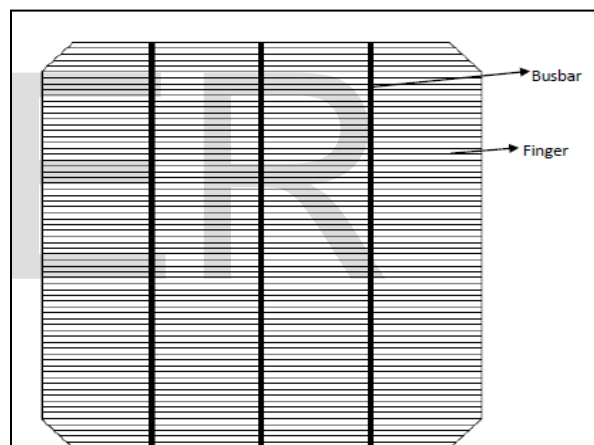


Figure 4. (a) Busbars and Fingers.

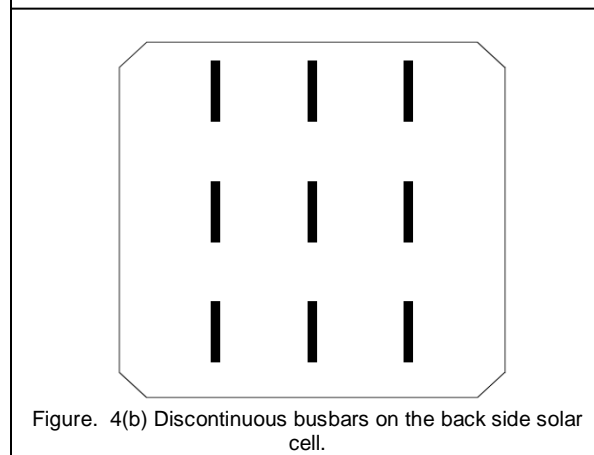


Figure. 4(b) Discontinuous busbars on the back side solar cell.

For back contact metallization, the fabricated solar cell was fully covered with Ferro FX53-038 aluminum paste. Remedy includes not covering the back fully with Ferro FX53-038 aluminum paste but to have discontinuous busbar on the back side. Discontinuities should be 2 strips with 3 gaps on each busbar, or 3 strips with 3 gaps on each busbar on the back side. Shown in figure 4(b). On all discontinues busbars Ferro CN33-462 silver paste should be used instead of Ferro FX53-038 aluminum paste. The reason for using silver paste instead of aluminum paste in the back contact is that, silver has lower resistivity $1.59 \times 10^{-8} \Omega\text{-m}$ and higher conductivity $6.29 \times 10^7 \text{ S/m}$ whereas aluminum has higher resistivity $2.65 \times 10^{-8} \Omega\text{-m}$ and lower conductivity $3.77 \times 10^7 \text{ S/m}$ at 20°C . [23]. Also same kind of tabbing wire can be used for front and back contact metallization. Suggested front contact metallization for 3 busbars specification is, Fingers Spacing: 0.1831 cm, Fingers Width: 0.0182 cm, Bus Bar Width: 0.1419 cm. and Bus Bar Gap: 3.125 cm. For back contact metallization with discontinuous 3 busbars, and 3 gaps in each busbar the specification is, Bus Bar Width: 0.1419 cm, Bus Bar Gap: 3.125 cm, Vertical Gap Distance: 2.1224 cm.

3.3 Saw damage removal and Texturing

Today's high efficiency PERL (Passivated Emitter, Rear Locally-diffused) solar cell uses inverted pyramid structure which could not be achieved due to lack of lithography equipment. Wet chemicals were used for saw damage removal and texturing process. The recipe used for saw damage removal was NaOH solution and DI water and for texturing, KOH-IPA solution. Piranha or RCA solution should also be used for saw damage removal process. Various timing, concentration or different solution should also be tried to achieve better texturing which will increase the efficiency of solar cell.

4. CONCLUSION

In this paper various reasons for achieving solar cell efficiency 6.89% is discussed. Using of edge isolation barrier paste is one of the main reason for achieving low efficiency. Moreover, Rapid thermal annealing (RTA) furnace with maximum temperature around 1000°C alongside not using oxygen (O_2) and nitrogen (N_2) gas are the reasons for not having proper thermal oxidation and having high series resistance and low shunt resistance. Lagging of FZ wafer, ISO 5- ISO 6 class clean room and Microwave Plasma System for edge isolation, reduced the efficiency of solar cell and

the efficiency of solar cell can be improved by using these resources. Remedies like discontinuous busbars with silver paste on the back contact metallization process and using of tabbing wire are proposed to improve the efficiency of solar cell. Last but not the least, as no anti-reflecting coating was used for fabricating solar cell in Bangladesh, TiO_2 (Titanium Oxide), ZnO (Zinc oxide) or silicon nitride (SiN_x) layer should be used as anti-reflection coating to improve the efficiency of solar cell. Despite the lack of some fabrication equipment and characterization equipment for the first time in Bangladesh solar cell was fabricated. Though the efficiency is still 6.89% it is believed that the efficiency will be improved after observing the limitations and taking the proposed suggestions discussed in this paper.

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6. REFERENCES

- [1] John Lorie, "Atradius Oil Market Outlook", Atradius Group, 2013
- [2] Coal polluting, The Columbus Dispatch, [Online] Available: <http://www.dispatch.com/content/stories/business/2015/11/26/world-dilemma-coal-might-be-dirty-but-its-still-abundant-and-cheap.html>
- [3] Martin A. Green, Keith Emery, Yoshihiro Hishikawa, Wilhelm Warta and Ewan D. Dunlop, "Solar cell efficiency tables (version 46)", Progress in Photovoltaics: Research and Applications, vol. 23, pp. 805–812, 2015
- [4] M. K. Basher and K. M. Shorowordi, "Fabrication of Monocrystalline Silicon Solar Cell using Phosphorous Diffusion Technique", International Journal of Scientific and Research Publications, Vol. 5, Issue 3, pp. 1-7, 2015
- [5] Md. Abdur Rafiq Akand, Mohammad Khairul Basher, Md. Asrafusjaman, Nusrat Chowdhuyi, Atia Abedin, and Mahbulul Hoq, "Study and Fabrication of Crystalline Silicon Solar Cell in Bangladesh; Using Thermal Diffusion Technique", International Journal of Innovation and Scientific Research, Vol. 18 No. 2, pp. 417-426, 2015
- [6] Michael Quirk and Julian Serda (2001), "Semiconductor Manufacturing Technology", (Prentice Hall).
- [7] Terra Universal.com, ISO Cleanroom Standards, [Online] Available:

<http://www.terrauniversal.com/cleanrooms/iso-classification-cleanroom-standards.php>

- [8] M.-A. Trauwaert, J. Vanhellefont, H.E. Maes, A.-M. Van Bavel, G. Langouche, A. Stesmans and P. Clauws, "Influence of oxygen and carbon on the generation and annihilation of radiation defects in silicon" *Materials Science and Engineering: B*, Elsevier, Vol. 36, Issues 1, pp.196-199,1996.
- [9] Lukáš Válek and Jan Šik, (2012), "Defect Engineering During Czochralski Crystal Growth and Silicon Wafer Manufacturing", (Publisher – Intec).
- [10] Microchemicals GmbH, CZ and FZ, [Online]. Available: http://www.microchemicals.com/products/wafers/silicon_ingot_production.html
- [11] A.J. Nijdam and Arend Jasper, "Anisotropic Wet-Chemical Etching of Silicon Pits, Peaks, Principles, Pyramids and Particles", Ph.D. thesis, University of Twente, Enschede, Netherlands, 2001.
- [12] Paul Mak, "Piranha Clean Procedure", Revision 01, Boston University Photonics Center, pp. 1-3, 2010.
- [13] Jose Nestor Ximello Quiebras, "Wet Chemical Textures for Crystalline Silicon Solar Cells" Ph.D. thesis, Faculty of Sciences, Department of Physics, University of Konstanz, Germany 2013.
- [14] Daniel S. H. Chan and Jacob C. H. Phang, "A method for direct Measurement of Solar Cell Shunt Resistance." *IEEE Transactions on Electron Devices*, Vol. ED-31, No.3, 1984.
- [15] Joseph A. Carson, (2008) "Solar Cell Research Progress", Nova Science Publishers, Inc. U.S.A.
- [16] National Instruments, Photovoltaic Cell I-V Characterization Theory and LabVIEW Analysis Code, [Online]. Available: <http://www.ni.com/white-paper/7230/en/>
- [17] Martin Wolf and Hans Rauschenbach, "Series resistance effects on Solar Cell measurements", *Advance Energy Conversion*, Vol. 3, pp-455-479, 1963.
- [18] PVEDUCATION.org, Diffusion Length, [Online]. Available: <http://www.pveducation.org/pvcdrom/pn-junction/diffusion-length>
- [19] Ezenwa I.A., "Synthesis and Optical Characterization of Zinc Oxide Thin Film", *Research Journal of Chemical Sciences*, Vol. 2, no. 3, pp. 26-30, 2012,
- [20] Richard Corkish, Martin A Green, Muriel E Watt, and Stuart R Wenham, (2007), "Applied Photovoltaics" 2nd edition, (ARC Centre for Advance silicon Photovoltaics and Photonics, U.S.A.)
- [21] b.Solar, Monocrystalline Silicon Solar Cell TG18.5 BR D200 datasheet, [Online]. Available: <http://www.b-solar.com/Products.aspx>
- [22] Antonius Radboud Burgers, "New Metallisation Patterns and Analysis of Light Trapping for Silicon Solar Cells", Ph.D. Thesis, Utrecht University, Netherlands, 2005
- [23] Hyper Physics, Table of resistivity, [Online]. Available: <http://hyperphysics.phy-astr.gsu.edu/hbase/tables/rstiv.html>
- [24] Topsil, "Topsil Application note, "PV-FZ silicon wafers for high efficiency solar cell", Accessed: Jan, 2014. [Online], Available: <http://www.topsil.com/en/silicon-products/silicon-wafer-products/pv-fz%E2%84%A2.aspx>
- [25] Chan, D.S.H. and Phang, J.C.H., "A method for the direct measurement of solar cell shunt resistance", *Electron Devices, IEEE*, pp. 381-383, 1984

- [26] M.R.I. Ramadan, "Effect of minority carrier lifetime in solar cells", *Solar & Wind Technology*, Elsevier, Vol. 6, Issue 5, pp. 615-618, 1989.
- [27] PVATePla, Microwave Plasma System for edge isolation, Available: <http://www.pvateplaamerica.com/400solar.php>