# 2D-MODELING AND DEVELOPMENT OF INTERDIGITATED BACK CONTACT SOLAR CELLS ON LOW-COST SUBSTRATES

**D. S. Kim , V. Meemongkolkiat, A. Ebong, B. Rounsaville, V. Upadhyaya, A. Das and A. Rohatgi**

University Center of Excellence for Photovoltaics Research and Education, School of Electrical and Computer Engineering, Georgia Institute of Technology, 777 Atlantic Drive, Atlanta, GA 30332-0250

## ABSTRACT

Two-dimensional numerical simulations were performed to derive design rules for low-cost, high-efficiency interdigitated back contact (IBC) solar cells on a low-cost substrate. The IBC solar cells were designed to be fabricated using either the conventional screen printing or photolithography metallization processes. Bulk lifetime, bulk resistivity, contact spacing (pitch), contact opening width, recombination in the gap between the $p^+$ BSF and $n^+$ emitter, and the ratio of emitter width to pitch have been used as key variables in the simulations. It is found that short circuit current density ($J_{sc}$) is not only a strong function of the bulk lifetime but also the emitter coverage of the rear surface. Fill factor (FF) decreases as the emitter coverage increases because the majority carriers need to travel a longer distance through the substrate for longer emitter width. The simulated IBC results were compared with those for conventional screen printed solar cells. It was found that the IBC solar cell outperforms the screen printed (SP) solar cell when the bulk lifetime is above 50 μs due to higher $V_{oc}$ and $J_{sc}$, which suggests that higher performance can be realized on low-cost substrates with the IBC structure.

## INTRODUCTION

Recently, interest in the interdigitated back contact (IBC) cell for application at one sun has increased due to its several advantages over the conventional screen printed solar cells although the original structure was published for a concentrator system 30 years ago [1]. The performance of the IBC cell has increased and high-efficiency cells of 24% [2] at 63 suns and 20.5% [3] at one sun have been reported recently. Placing both negative and positive contacts on the back side of the solar cell has a lot of advantages in a cell performance and applications over the conventional structures. Eliminating the front contact provides not only a potential to improve short circuit current but also the aesthetics of the module. In IBC cells, the metal contacts on the rear need no trade-off between shading and series resistance. Since the junctions are on the rear side, they can be optimized for electrical performance while the front surface is designed for optimum optical performance. Furthermore, IBC cells can be interconnected in an easier and simpler way with a higher packing density during the module fabrication. IBC cells are expected to be realized with low cost processes since it has the simplest contact structure among back contact solar cells such as the EWT (Emitter Wrap Through) cell, MWT (Metallized Wrap Through) cell, point contact cell, polka dot solar cell, and back OECO (Oblique Evaporation of Contact) cell.

In spite of the numerous advantages of back contact cells, there are several prerequisites for high-efficiency IBC solar cells. High-quality front surface passivation is needed since most of carriers are generated near the front surface while the collection junctions are on the rear side. Rear junctions need to be isolated to prevent shunting between two adjacent grid lines via the inversion layer or tunneling through the junction. A long diffusion length is required since the minority carriers in back contact solar cells have to travel a longer distance than those in the conventional screen printed solar cells before they are collected.

The quality of PV grade silicon materials and the surface passivation by dielectric layers have been improved since the IBC structure was published in 1975. Furthermore, silicon substrates exhibit a significant enhancement in lifetime during cell fabrication due to impurity gettering and hydrogenation [4]. Several multi-dimensional computer device simulations have been reported to optimize the structure of IBC cells [5, 6, 7]. In this paper, we investigated the effects of physical cell parameters on the cell performance to implement the IBC structure into low-cost substrates. We also studied the potentials of the PV grade silicon materials for IBC cells by calculating the lifetime range at which the IBC cell outperforms the conventional SP cell.

## DESIGN OF IBC CELL FOR SIMULATION

Numerical simulations were performed with DESSIS™ (ISE TCAD Release 10.0), a software package from Integrated Systems Engineering, Inc. The material constants in the DESSIS program were adjusted to match the I-V curve with that of PC1D for one-dimensional test structures. The schematic diagrams of the conventional IBC cell and the SP cell used for the simulation are shown in Fig.1. The front structures of both the IBC and SP cell are textured with random pyramids, diffused with phosphorus, and passivated with SiNx. The sheet resistances of the emitters were 45 Ω/sq and 100 Ω/sq for SP and IBC cells, respectively. A gap of 80 μm between $p^+$ BSF and $n^+$ emitter for the IBC cell was assumed in order to eliminate the possibility of shunting. The front surface recombination velocity (FSRV) and the back surface recombination velocity (BSRV) on $n^+$ emitter and $p^+$ BSF were fixed to 1000 cm/sec for the IBC cell, which is achievable by SiNx or $SiO_2$ passivation [8]. The key parameters used for the modeling were the minority carrier lifetime, distance between negative and positive grid fingers (pitch; P), coverage of carrier-collecting emitter (E/P), contact opening width (2xC), and surface recombination velocity (SRV) of the gap (G). The SRV of the gap was varied from 10 to 1000 cm/sec. The effect of contact opening width on the cell performance was investigated. The device parameters used in the modeling were summarized in Table1. The series resistances related to the specific contact resistance were not included in either IBC or SP solar cells since the values are quite dependent on the process conditions. But the series resistance component due to the grid finger and bus bar was accounted for in the SP solar cell. Note that the series resistance due to the grid finger in the IBC cell was neglected since the cross sectional area of the rear metal contacts can be increased widely without hurting the shadowing loss. Therefore, the fill factor values obtained by the simulation could be higher than actual values.

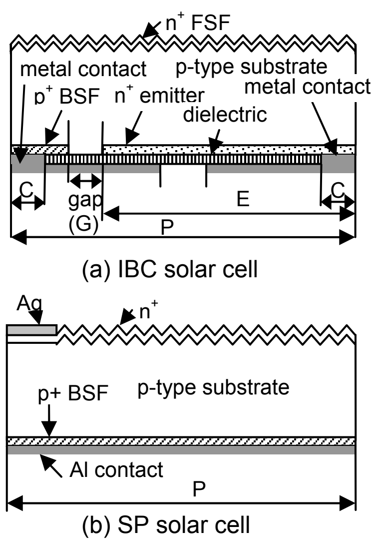



Fig. 1. Schematic diagrams used for the simulation of the IBC and conventional SP solar cell. P, E and C are the pitch, the width of emitter and half of contact opening width, respectively.

## THE EFFECT OF SRV IN THE GAP

The area diffused with boron or phosphorus was passivated with dielectric layers and the SRV was assumed to be 1000 cm/sec which corresponds to the emitter saturation current density of 35.6 fA/cm$^2$ and the effective surface recombination velocity ($S_{eff}$) of 16 cm/s at the junction edge on the base side for the doping profile used in the modeling. The resistivity and the bulk lifetime of the substrate were assumed to be 2 Ωcm and 1 ms, respectively. Fig. 2 shows the relationship between the SRV in the space between $n^+$ and $p^+$ regions and the cell performance for a gap width of 80 μm. As the pitch increases from 600 μm to 1200 μm, the impact of SRV on the cell efficiency decreases because the surface area fraction of the 80 μm wide gap decreases. Note that the small gap of 80 μm can significantly degrade cell performance if it is not well passivated. The SRV in the gap was fixed at 50 cm/sec for the remainder of calculations in this study.

Table1. Physical device parameters used in the modeling.

| Cell parameters | SP cell | IBC cell |
|---|---|---|
| Pitch (μm) | 1000 | 600-2000 |
| Substrate thickness (μm) | 200 | 200 |
| Substrate resistivity (Ωcm) | 2 | 0.5-10 |
| Texturing | Yes | Yes |
| AR coating (nm) | 75 | 75 |
| Contact opening (μm) | 170 | 10-170 |
| Front surface passivation | Dielectric | Floating |
| FSRV (cm/sec) | 60000 | 1000 |
| BSRV (cm/sec) | 1000000 | 1000 |
| BSF thickness (μm) | 8 | 1 |
| Peak doping in BSF | $1.79x10^{18}$ | $2.98x10^{19}$ |
| Gap between $n^+$ and $p^+$ (μm) | NA | 80 |
| Lifetime (μs) | 10-1000 | 10-1000 |
| Emitter sheet resistance (Ω/sq) | 45 | 100 |
| Peak doping in emitter | $4.26x10^{19}$ | $2.98x10^{19}$ |
| Contact resistance | Neglected | Neglected |
| Series resistance due to grid resistance (Ωcm$^2$) | 0.31[9] | Neglected |
| Internal front reflectance | 0.92 | 0.92 |
| Internal back reflectance | 0.7 | 0.95-0.98 |

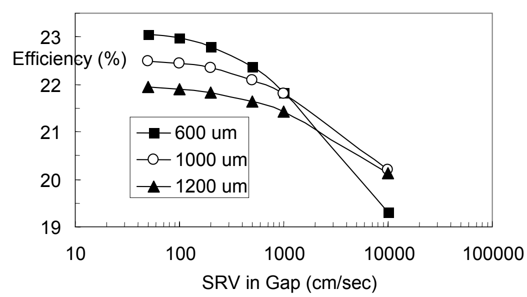
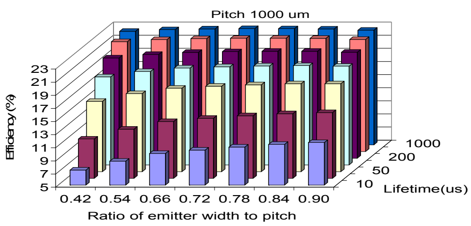


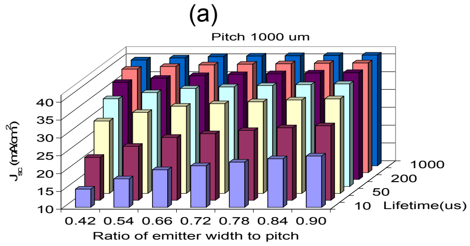

Fig. 2. The effects of surface recombination velocity in the gap between $p^+$ BSF and $n^+$ emitter on the cell efficiency for a pitch of 600 μm, 1000 μm, and 1200 μm.

## THE INFLUENCE OF EMITTER FRACTION AND THE BULK LIFETIME

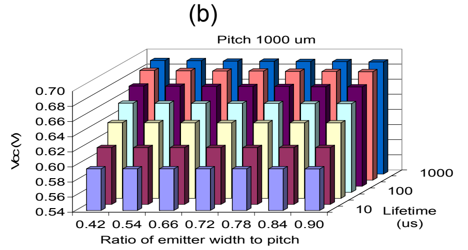
The emitter fraction is critical for IBC cell performance and its effect was studied by Nakamura for a fixed bulk lifetime [10]. Fig. 3 illustrates the cell performance as a function of the emitter fraction for lifetimes in the range of 10-1000 μs. The bulk resistivity and the pitch were fixed to 2 Ωcm and 1000 μm, respectively. The results in Fig. 3(a) show that efficiency increases with the emitter ratio (E/P) regardless of lifetime. This suggests that maximizing the emitter fraction is a prerequisite for raising the performance of the IBC cell on low-lifetime substrates. $J_{sc}$ increases with the emitter ratio since the recombination of minority carriers decreases due to the reduction in the average travel length through the bulk. On the contrary, FF decreases with the increase in the emitter fraction since the travel length of the majority carriers increases resulting in high series resistance. $V_{oc}$ is a strong function of lifetime but was nearly independent of the emitter ratio for the current design. This is because the surface recombination velocity of the BSF and the emitter were nearly equal and low. In case of low quality materials, the emitter fraction becomes an important design parameter since the enhancement of $J_{sc}$ can surpass the FF loss at higher emitter fraction.



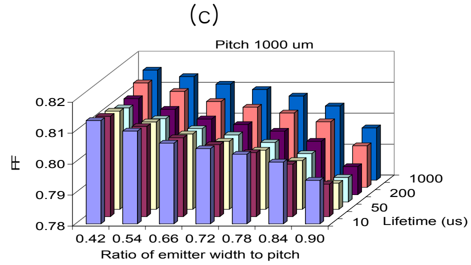

(a)




(b)




(c)



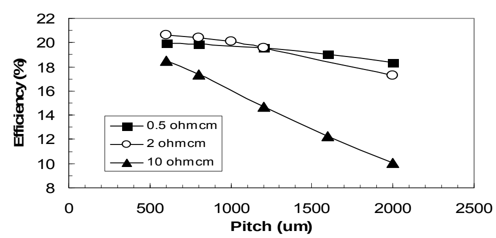

(d)

Fig. 3. Effect of lifetime and emitter fraction on (a) IBC cell efficiency, (b) $J_{sc}$, (c) $V_{oc}$, and (d) FF.

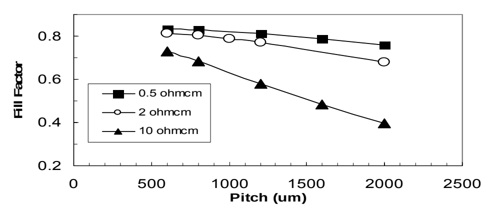
The FF is influenced by the series resistance and the open circuit voltage. Fig. 3 (d) shows that for a fixed emitter fraction, the FF exhibits minimum value at a certain lifetime. This minimum FF is the result of the competition between the series resistance and the open circuit voltage. As the bulk lifetime increases, the high $V_{oc}$ increases the FF while the high $J_{sc}$ reduces the FF due to IR drop associated with the series resistance.

## EFFECTS OF BULK RESISTIVITY AND THE PITCH ON IBC CELL PERFORMANCE

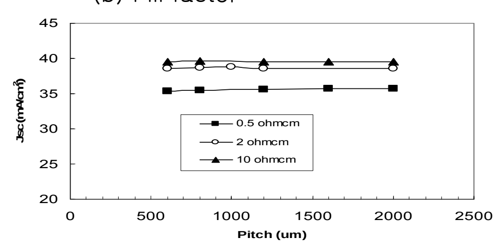
One of the important physical parameters in the design of IBC cells is the contact spacing since low-cost printing technologies require wide contact spacing. Fig. 4 shows the cell performance as a function of the contact spacing for bulk resistivities in the range of 0.5-10 Ωcm. Cell efficiency decreases as pitch increases regardless of the bulk lifetime and the bulk resistivity because the cell performance is dominated by FF. Note that the optimum resistivity changes depending on the pitch for the same bulk lifetime. For one sun applications, a bulk resistivity of about 2 Ωcm is expected to produce the best result when the pitch is lower than 1200 µm. Fig. 4 (c) shows that $J_{sc}$ decreases with base doping for a fixed pitch, because $S_{eff}$ increases with base doping.




(a) Efficiency




(b) Fill factor




(c) Short circuit current density

Fig. 4. Effect of the pitch on (a) cell efficiency, (b) FF, and (c) $J_{sc}$ for 100 µs lifetime material.

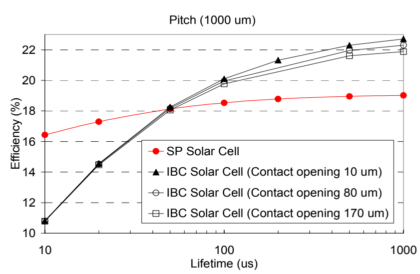
The effective surface recombination velocity at low-level injection can be expressed as

$$S_{eff} = \frac{J_o}{q n_i^2} N_b \qquad (1)$$

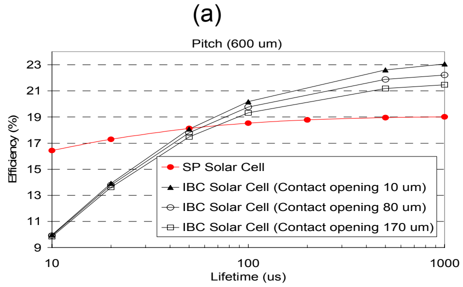
where $J_o$ is recombination saturation current density for the boron-diffused or phosphorus-diffused region and $n_i$ is intrinsic carrier concentration and $N_b$ is base doping concentration , and $S_{eff}$ is the recombination velocity at the base side of junction edge [11]. $J_o$ is constant for a fixed doping profile and surface recombination velocity. For a fixed surface recombination velocity and bulk lifetime, $S_{eff}$ increases with the base doping according to equation (1) and $J_{sc}$ is reduced by the recombination current. In the IBC cell, most of carriers are generated near the front floating emitter and average travel length of the carrier is longer than that of SP cells. Consequently, the loss of minority carriers due to $S_{eff}$ is bigger than in the conventional screen printed cell

## EFFECTS OF METAL CONTACT AREA

It is interesting to study the effects of contact opening width (2xC) on the cell performance of the low-cost IBC cell since the width is a key parameter that limits the contact formation process. The widths of negative and positive contacts were varied simultaneously assuming the same contact formation process will be used. Fig. 4 demonstrates the performance of IBC solar cells for contact opening widths of 10 μm, 80 μm, 170 μm. Note that the opening width does not hurt the performance significantly if the bulk lifetime is less than 100 μs and the pitch longer than 1000 μm. This indicates that the low-cost printing technology can be used for the fabrication of a high-efficiency IBC cells on low-cost material. Fig. 4 also shows that the IBC solar cell outperforms the SP solar cell when the bulk lifetimes are above 50 μs, due to higher $V_{oc}$ and $J_{sc}$ (see also Fig. 3). This result suggests that higher performance in IBC solar cells can be realized on low-cost substrates.




(a)




(b)

Fig.5. Comparison of cell efficiency between IBC and SP solar cells for various contact opening widths. The pitches of the IBC cells were (a) 1000 um and (b) 600 um. The emitter fraction was 0.78 for all the IBC cells.

## CONCLUSION

Two-dimensional numerical simulations were performed to design a low-cost high-efficiency interdigitated back contact (IBC) solar cell on a low-cost substrate. The effect of key physical cell parameters on the cell performance was investigated. Short circuit current density is a strong function of the bulk lifetime and the emitter coverage of the rear surface. Fill factor decreases as the emitter coverage increases because the majority carriers need to travel a longer distance. The surface recombination in the gap between $p^+$ BSF and $n^+$ emitter significantly degrades the cell performance when the pitch becomes short. The contact opening width is not a critical factor when the pitch is longer than 1000 μm, suggesting that low-cost printing technologies can be used to fabricate IBC cells. IBC solar cells outperform the screen printed solar cell when the bulk lifetime is above 50 μs due to higher $V_{oc}$ and $J_{sc}$, which suggests that higher performance can be realized on low-cost substrates with the IBC structure.

## ACKNOWLEDGEMENTS

The authors will like to thank the support of DOE under the contract No. DE-FC36-00GO10600.

## REFERENCES

1. R.J.Schwartz and M.D.Lammbert, International Electron Devices Meeting. (Technical digest), Washington, DC, 1975
2. A.Mohr, M.Hermle, T.Roth, S.W.Glunz, 19th European Photovoltaic Solar Energy Conference, Paris, France 2004
3. K.Nakamura, T.Isaka, Y.Funakoshi, Y.Tonomura, T.Machida and K.Okamoto, 20 th European Photovoltaic Solar Energy Conference, Barcelona, 2005
4. A.Rohatgi, 15th Workshop on Crystalline Silicon Solar Cells and Modules;Materials and Processes, Vail, CO 2005.
5. O.Nichporuk, A.Kaminski, M.Lemiti, A.Fave, and V.Skryshevsky, Solar Energy Materials and Solar Cells, 86, 517-526(2005).
6. T.Nagashima, K.Hokoi, K.Okumura, and M.Yamaguchi, 20 th European Photovoltaic Solar Energy Conference, Barcelona, Spain 2005.
7. K.R.McIntosh, M.J.Cudzinovic, D.D.Smith, W.P.Muligan, and R.M.Swanson, 3rd World Conference on Photovoltaic Conversion, Osaka, Japan 2003.
8. M.J.Kerr, J.Schmidt, and A.Cuevas, J. Appl. Phys., 80, no.7, 3821-3826(2001).
9. K.Fukui, S.Goto, J.Atobe, H.Hashigami, Y.Sakai, M.Tsuchida, Y.Inomata, S.Fujii, K.Shirasawa, 31st IEEE Photovoltaic Specialist Conference, Lake buena Vista, FL 2005.
10. K.Nakamura, T.Isaka, Y.Funakoshi, Y.Fonomura, T.Machida, and K.Okamoto, 15th International Photovoltaic Science & Engineering Conference, Shanghai, China 2005
11. S.Bowden, D.S.Kim, C.Honsberg, and A.Rohatgi, 29th IEEE Photovoltaic Specialist Conference, New Orleans, LA 2002