Revista Mexicana de Física **41**, *No. 4 (1995) 556–562*

A simple analysis of buried contact silicon solar cells

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Recibido el 8 de agosto de 1994; aceptado el 22 de marzo de 1995

ABSTRACT. One of the most promising structures for solar cells is the buried contact solar cell (BCSC), because it offers the possibility of production at low cost, at the same time that allows the combination of several high efficiency concepts, without any design compromise as occurs in conventional cells. Therefore, there is a growing interest for such kind of solar cells. Unfortunately, this structure poses new problems for its design since the buried contact will cause 2–dimensional carrier flow effects under both light and dark current conditions. However, as we describe in this paper, it is possible to make a simple analysis of the conversion efficiency as a function of the buried contact depth in the BCSC cell. In this article we show that the efficiency is minimum for depths in the range between 50 μm and 70 μm when the assumed parameters are typical for silicon solar cells. In addition, we show that in order to have good performance for these cells, the buried contact depth should be either very small (below 5 μm), or very large (bigger than 150 μm), but not in-between these values, in order to avoid any efficiency degradation caused by the buried contacts. Finally, we show that the efficiency can be better than for conventional cells only when the buried contacts have a large depth, whenever they are designed properly in such a way that they allow an additional collection of charge carriers generated by sunlight.

RESUMEN. Una de las estructuras más promisorias en celdas solares de silicio cristalino es la celda solar con contactos enterrados (BCSC), porque ofrece la posibilidad de bajo costo de producción al mismo tiempo que permite combinar varios conceptos de diseño de alta eficiencia, sin los compromisos típicos que hay en celdas solares convencionales. Es por eso que hay un interés cada vez mayor en celdas tipo BCSC. Desafortunadamente, la estructura BCSC presenta nuevos problemas para su diseño, puesto que los contactos enterrados causarán flujos de portadores en dos dimensiones tanto en obscuridad como bajo iluminación. Sin embargo, como mostraremos en este trabajo, es posible hacer un análisis simple de la eficiencia de conversión como función de la profundidad de los contactos enterrados en este tipo de celdas. En el presente artículo, mostraremos que la eficiencia tiene un mínimo para profundidades en el intervalo entre 50 μm y 70 μm cuando se asumen parámetros típicos en celdas solares de silicio. Mostraremos también que para obtener un buen funcionamiento de estas celdas, la profundidad de los contactos deberá ser pequeña (menor que 5 μm) o, por el contrario, muy grande (mayor que 150 μm), para evitar la degradación de su funcionmiento como consecuencia de las uniones enterradas en el volumen del dispositivo. Finalmente, mostraremos que la eficiencia de celdas BCSC podría ser mayor que en celdas convencionales sólo cuando los contactos enterrados tengan gran profundidad y se diseñen de manera que permitan una mayor colección de los portadores de carga generados por la luz.

PACS: 84.60.J

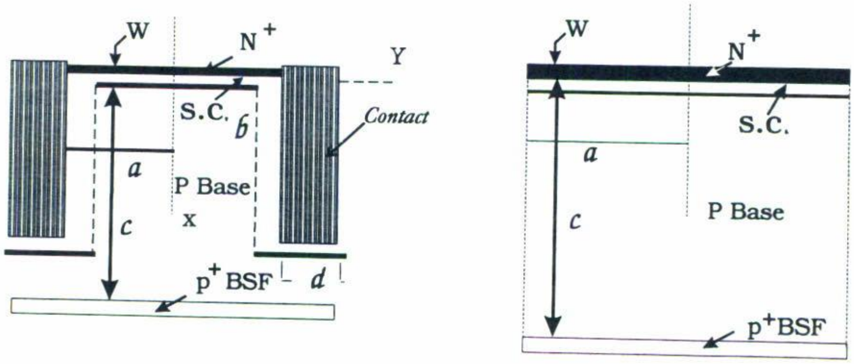

FIGURE 1. (A) Schematic of the buried contact solar cell structure. The separation between contacts is a, the contact depth is b, the base thickness is c, and d is the contact width. (B) Schematic of the "ideal" reference cell. This structure is assumed to have minimum reflection and shadowing with a low emitter surface recombination such that $J_L^i = .40\ \mathrm{A/cm^2}$, $J_o^i = 8 \times 10^{-14}\ \mathrm{A/cm^2}$, and $V_{oc}^i = 700$ mV at 300 K.

1. INTRODUCTION

The search for high efficiencies in silicon solar cells has given good results as efficiencies greater than 23% at 1 sun have been reported recently [1]. Also, a record efficiency (larger than 20%) has been established for silicon cell modules [2], using cells with structures based on passivated surfaces, optimum base and emitter dopings, and minimum shadowing and reflection losses.

Among the high efficiency structures, one of the most promising is the buried contact solar cell (BCSC) because it may lead to lower production costs [3]. As seen in Fig. 1 (A), the BCSC allows for passivation of the surfaces, reduced shadowing, and optimum surface emitter doping, together with low series resistance and less involved technological processes than similar cells, like the PERL (passivated emitter, rear locally diffused) cell, for example.

However, one must be aware that light generated carriers will behave differently in this kind of structure, because of its intrinsic two dimensional geometry, as compared with conventional planar junction cells, where the flux of carriers may be considered as one dimensional.

Intuitively, one expects that the short circuit current of the cell will increase as the contact depth increases because carriers will be collected not only at the surface junction, but also at the lateral contact junctions. A two dimensional calculation made by Strollo and Vitalle [4,5] confirms that for thick cells the lateral junction current may add to the short circuit current up to 7% more, when the contact groove is relatively large (200 μm).

Then, a question arises regarding the open circuit voltage dependence as a function of the contact depth. In this case, one expects a reduction of the open circuit voltage as the depth increases for two main reasons. The first one is the lateral junction built into the volume of the cell which will increase the total dark current. Additionally, the dark current density produced at such buried junctions, in general, will be larger than that of the junction at the surface because of the high dopings under the contact junctions. In this case, Auger recombination and band gap shrinkage effects will cause large saturation current densities as established in past studies for passivated emitter solar cells [6,7].

Based on these intuitive ideas we have developed a simple analysis to study BCSC cells, in order to determine the expected efficiency as a function of the contact depth. Our analysis, which is described in the next section, indicates that for thick cells (around 300 μm), the efficiency has a minimum for contact depths in the range between 50 μm and 70 μm, when typical values for the junction parameters are assumed. In addition, for thin cells (light trapping structures with thickness less than 100 μm) these results imply that it is better to have the contact depth as low as possible (less than 5 μm) in order to achieve a good performance.

2. Analytic model

In order to have a reference cell we shall define an "ideal" cell as shown in Fig. 1 (B). We assume that such a structure has an emitter close the ideal *i.e.*, one with minimum recombination, as a consequence of low impurity concentration in the whole volume, a passivated surface and a small thickness. Since in our model for the BCSC cell we want to take into account the shadowing due to the contacts, for the "ideal" cell we shall consider the contact area as zero. The reflection losses will also be considered as minimum, because of a good anti-reflection coating and textured surface. Under such circumstances for our ideal silicon cell, the following typical parameters may be expected at 300 K:

$$J_{\mathrm{L}}^{\mathrm{i}} = .040\ \mathrm{A/cm^2},$$

$$J_{\mathrm{o}}^{\mathrm{i}} = 8 \times 10^{-14}\ \mathrm{A/cm^2},$$

$$V_{\mathrm{oc}}^{\mathrm{i}} = 700\ \mathrm{mV},$$

where $J_{\mathrm{L}}^{\mathrm{i}}$ is the light generated current density, $J_{\mathrm{o}}^{\mathrm{i}}$ is the dark saturation current density and $V_{\mathrm{oc}}^{\mathrm{i}}$ is the open circuit voltage for the "ideal" cell.

We shall assume that the fill factor changes as a function of the open circuit voltage according to the following empirical expression proposed by Green [8]:

$$FF = \frac{\nu_{\mathrm{oc}} - \ln(\nu_{\mathrm{oc}} + 0.72)}{\nu_{\mathrm{oc}} + 1}, \tag{1}$$

where ν_{oc} is the open circuit voltage V_{oc} normalized to the thermal voltage $V_T = kT/q$.

It is expected that the collection of carriers at the lateral junctions will cause an increment of the short circuit current as the contact depth increases. Then, to first order approximation, we assume that the short circuit current increases with the contact depth in a linear way. Of course, this approximation will be good whenever the diffusion length is larger than half the separation between the contacts. In the case that the diffusion length is smaller than half the separation between the lateral contacts, they will not contribute much to the collection of photo generated carriers, as confirmed by the calculations made by Strollo and Vitalle [4,5]. Therefore, assuming that the cell is designed according to the first case above, and neglecting second order nonlinear corrections, we have

$$J_{\mathrm{L}} = J_{\mathrm{L}}^{\mathrm{i}}(1+\alpha b)\left(\frac{a}{a+d}\right). \tag{2}$$

The value of α will be related to the higher carrier collection at the lateral junctions, and can be estimated from the calculations made by Strollo *et al.* [4] giving a value approximately equal to $\alpha = 5\times 10^{-4}\ \mu\mathrm{m}^{-1}$, when the diffusion length in the base is larger than half the separation between the contacts, as explained before. Notice that the shadowing caused by the contact area has been taken into account in the above equation through the factor $a/(a+d)$.

Under dark conditions the saturation current densities for each kind of junction will be different. The surface junction will have a dark saturation current density $J_{\mathrm{os}} = J_{\mathrm{o}}^{\mathrm{i}}$, but at the buried contact junctions the dark saturation current density will be $J_{\mathrm{og}} = \beta J_{\mathrm{os}} = \beta J_{\mathrm{o}}^{\mathrm{i}}$. In general, it is expected that $\beta > 1$ because of the high doping under the contacts which may cause Auger recombination and band-gap shrinkage effects [6,7].

Again, for simplicity, we shall neglect any series resistance and current distribution effects, and we shall assume that the voltage drop at the junction will be constant and equal at both space charge regions edges. Then, we will have two kinds of diodes in parallel that give a total dark current density (related to the front surface area of the cell)

$$J_{0T} = J_{\mathrm{o}}^{\mathrm{i}}\left[\left(\frac{a}{a+d}\right)+\beta\left(\frac{d+b}{a+d}\right)\right]. \tag{3}$$

Then, we can approximate the open circuit voltage as

$$V_{\mathrm{oc}} = V_{\mathrm{oc}}^{\mathrm{i}} + V_T \ln\left[\frac{1+\alpha b}{1+\beta\left(\frac{d+b}{a}\right)}\right]. \tag{4}$$

Finally, if we take into account the variation of the fill factor as given by Eq. (1), we may calculate the conversion efficiency from

$$\eta = \frac{J_{\mathrm{L}}\, V_{\mathrm{oc}}\, FF}{P_{\mathrm{inc}}}, \tag{5}$$

where P_{inc} is the normalized AM 1.5 solar radiation intensity ($0.1\ \mathrm{W/cm^2}$).

The above expressions have been used to determine the variation of the efficiency as a function of the contact depth as we shall discuss in the next section.

3. Results obtained from the model

In order to make calculations, we have taken in our simple model the following parameters as constant:

$$a = 235\ \mu\mathrm{m},\quad d = 15\ \mu\mathrm{m},\quad \alpha = 5\times 10^{-4}\ \mu\mathrm{m}^{-1},\quad \beta = 15\ \text{at},\quad T = 300\ \mathrm{K}.$$

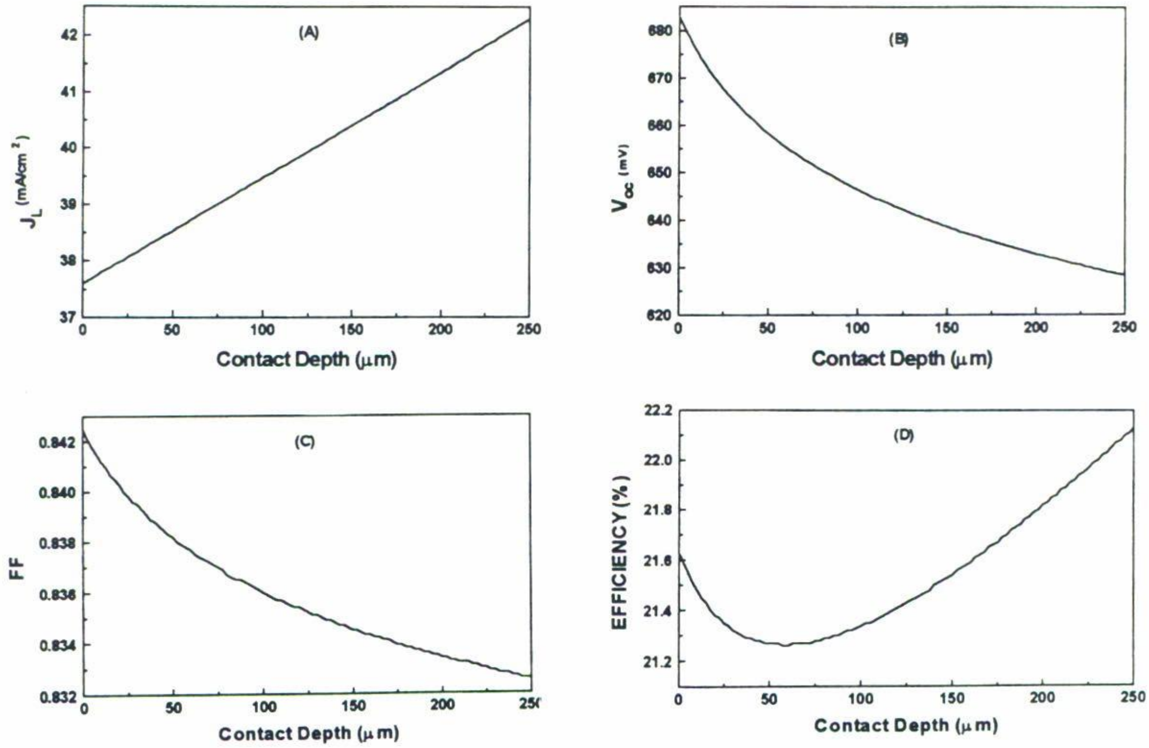

FIGURE 2. (A) Light current density, (B) open circuit voltage, (C) fill factor, and (D) efficiency, respectively, as functions of the contact depth (b) with $a = 235$ μm, $d = 15$ μm, $\beta = 15$, and other parameters as given in the text.

In this case, the shadowing factor, determined by a and d, is around 6%, and it can be easily achieved by photolithography. The value of β is such that the saturation current density at the contact junctions is typical for a non-passivated emitter with high surface dopant concentration [6]. If all the surface in the cell were covered with such an emitter, the open circuit voltage would be around 630 mV as compared with the 700 mV to be obtained from the "ideal" cell.

In Figs. 2 (A), (B), (C) and (D) we show the results obtained with the model for the short circuit current density (J_L), the open circuit voltage (V_{oc}), the fill factor (FF) and the efficiency (η), respectively, as a function of the contact depth. Notice the reduction of both the open circuit voltage and fill factor as the junction depth increases, contrary to the behavior of the short circuit current. Then, the net result is that the efficiency has a minimum for a groove depth around 60 μm.

The above results suggest that a good cell would be one which has a large contact depth. For thick cells (300 μm) it would be advisable to have groove depths larger than 150 μm, but this could be difficult to achieve technologically and would impose a very careful handing of these cells making them not appropriate for industrialization. In addition, currently the tendency is to make thin cells by means of trapping light structures, in order to reduce production costs. Therefore, the appropriate contact depth would be the minimum value possible in accordance to the technological processes.

Notice that the above suggestion does not imply that the depth should be zero as

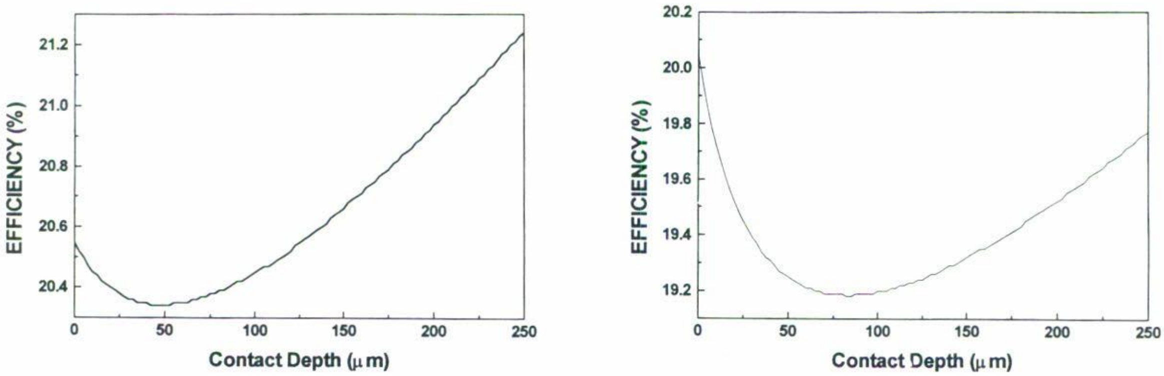

FIGURE 3. (A) Efficiency as a function of contact depth with $d = 25$ μm, and all the other parameters as in Fig. 2 (D), and (B) efficiency as a function of contact depth with $\beta = 150$ and all other parameters as in Fig. 2 (D).

the BCSC structure has been proposed because it allows the combination of several high efficiency concepts without having the design compromises that appear in conventional structures. For example, the passivated (surface) emitter can be made with a low surface impurity concentration (as required for high efficiency) but without having a high contact resistance problem. Also, it is expected that the diffusion process for the buried contacts can be made in such a way that the surface emitter can be improved by "gettering effects". In other words, our results mean that the buried contacts should be small enough, so that there is no efficiency degradation as a consequence of the increased dark current density for this kind of cells.

In Fig. 3 (A), we show the case where the shadowing factor is increased to approximately 10%. As expected, the efficiency is appreciably reduced in the whole range of contact depths because of the bigger contact area. The minimum in this case would be at 50 μm. In general, it can be obtained that the higher the shadowing factor, the lower would be the value of the contact depth for obtaining the minimum efficiency.

A very bad junction done at the grooves for the buried contacts could make β be larger than 150. In such a case, the efficiency would also become smaller, but with the same kind of dependence from the contact depth, as shown in Fig. 3 (B). In this case, the minimum occurs for a depth around 85 μm.

From the above analysis we can conclude that in order to have a good BCSC cell design, half the separation between the contacts should be smaller than the minority carrier diffusion length in the base, together with a minimum contact width, so that the shadowing factor remains small. In the case of thick cells the depth could be made larger than 150 μm, but for thin cells the depth should be as small as possible.

The above results are a consequence of the increase of the total short circuit current and the dark saturation current as the contact depth is increased. The latter dominates for contact depths up to 60 μm (or larger when the recombination in the grooved junction is high). For depths larger than this, the short circuit current gain would dominate and the efficiency would increase monotonously. Therefore, it is advisable to make very shallow grooves, or either buried contacts with depths larger than 150 μm if this was possible.

4. Conclusions

We have shown that it is possible to make a simple analysis of buried contact solar cells from which we can obtain some design rules. The model is based on the expected behavior of the short circuit and the dark saturation currents as a function of the contact depth. Our model results imply that the increase of the dark current will dominate up to a certain value of contact depth after which the light current increase begins to dominate causing a further monotonous increase of efficiency. In other words, it is expected that for this kind of structure the best would be to have thick cells together with very large buried contacts. Since these thick deep buried contact cells may not be possible for technological reasons, our model shows that it is better to maintain the depth as shallow as possible without loosing the potentiality of this structure for achieving high efficiency at low cost.

Although our model is completely phenomenological, we expect on the physical basis established here that the above results will not be greatly modified by more exact calculations that include a more detailed two dimensional flow of carriers and the distributed resistance and potential effects. Perhaps a more exact model will give better values for the contact depths at which the efficiency minimum occurs, but it will not change the design rules and the qualitative behavior established with our present model.

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