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Antonio Luque, J. Eguren, J. del Alamo

Institutions: Technical University of Madrid

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INTERNAL QUANTUM EFFICIENCY OF BACK ILLUMINATED n^+pp^+ SOLAR CELLS

A. LUQUE, J. EGUREN and J. DEL ALAMO

Laboratorio de Semiconductores, Escuela Superior de Telecomunicación,
Universidad Politécnica de Madrid. Madrid-3, Spain

Résumé. — Une analyse théorique de l'efficience quantique interne (I.Q.E.), prenant en considération la génération à la couche p^+ quand on illumine de ce côté la cellule solaire n^+ pp^+, a été effectuée et le résultat comparé avec cette structure illuminée de façon conventionnelle. Dans certaines cellules expérimentales cette couche p^+ a été faite par implantation ionique et par aléation Al-Si. Les cellules très minces, présentées ici, offrent d'excellentes valeurs, plus de 90 %, de la relation des efficiences quantiques internes illuminant la couche p^+ et la n^+.

Abstract. — A theoretical analysis of the Internal Quantum Efficiency (I.Q.E.), taking into account the generation in the p^+ layer of the back illuminated n^+ pp^+ solar cells has been carried out, and compared to that of the structure illuminated in the conventional way. Experimental cells have been made both by ion implantation and by alloying Al-Si to form the p^+ layer. Very thin cells, here reported, present excellent values up to 90 % for the back illuminated to front illuminated I.Q.E. ratio.

1. **Introduction.** — High intensity silicon solar cells, illuminated on the surface opposite to where the p-n junction has been formed : Interdigitated Back Contact (I.B.C.) cells [1], have recently stirred new interest. Double Side Illuminated (D.S.I.) cells have also been described [2, 3, 4] and their usefullness for static concentration has been stressed [2].

The formation of the high-low junction under the surface opposite to the n^+ p junction can greatly reduce the Surface Recombination Velocity (S.R.V.) there. Hence I.B.C. cells with *high-low* junction at the illuminated surface could be made and this technology would permit the preparation of texturised, high absorbing surfaces with a low S.R.V.

D.S.I. cells could also be made, as we have suggested elsewhere [5], by using a n^+ pp^+ structure with a metallic grid at both faces at a much lower cost than that of present D.S.I. cells.

The purpose of this paper is to investigate the internal quantum efficiency (I.Q.E.) of a n^+ pp^+ structure when the face p^+ is illuminated. Therefore, a theoretical analysis of the quantum efficiency of such a back illuminated structure has been carried out and compared with that of the structure illuminated in the conventional way. The theoretical analysis is based on the classical model, as studied by M. Wolf [6]. The present analysis differs from other Back Surface Field (B.S.F.) structure analysis [7, 8] in the fact that it takes into account the generation in the p^+ layer, so that, a negative value of the S.R.V. at the *high-low* interface can usually be obtained.

2. **Mathematical model.** — On the basis of Wolf's calculations, the shortcircuit current density reaching a junction placed before, or after a neutral region where the minority carriers are generated, can be shown by

$$J_L = qN_j\,\varphi(\alpha L, d/L, sL/D) \quad (1)$$

or

$$J_L = qN_j\,\varphi(\alpha L, -d/L, -sL/D) \quad (2)$$

respectively, where N_j is the flux of the monochromatic photons reaching the junction, and α, d, L, D and S are : the light absorption constant, the neutral region thickness, diffusion length, diffusion constant, and the surface recombination velocity at the plane that limits the neutral region, opposite to the junction. (The minority carriers are electrons.)

$$\varphi(b, y, a) = \frac{b}{b+1}\left[1 + \frac{1}{b-1} \times \frac{\exp(-y) - b\exp(-by) - a\{\exp(-y) - \exp(by)\}}{\cosh(y) + a\sinh(y)}\right]. \quad (3)$$

The dark shortcircuit current traversing the junction when a concentration n_0 is present in the junction edge, can be shown in the following expression

$$J_d = -qn_0\frac{D}{L}F(d/L, sL/D) \quad (4)$$

or

$$J_d = -qn_0\frac{D}{L}F(-d/L, -sL/D) \quad (5)$$

for a junction placed respectively before, or after the neutral region mentioned above, being

$$F(y, a) = \frac{a + \tanh(y)}{1 + a\tanh(y)}. \quad (6)$$

The I.Q.E. of a solar cell is defined by :

$$\sigma = J_{sc}/qN_0 \quad (7)$$

where J_{sc} is the cell shortcircuit current and N_0 is the flux of photons entering the semiconductor. For a $n^+ pp^+$ cell illuminated on its front, on the n^+ face, the I.Q.E. for a monochromatic illumination is :

$$\sigma = \exp(-\alpha W_e)\left[\varphi\left(\alpha L, \frac{W}{L}, \frac{S_{eff} L}{D}\right) - \varphi\left(\alpha L_e, -\frac{W_e}{L_e}, \frac{-S_f L_e}{D_e}\right)\right] \quad (8)$$

where the parameters without subindex refer to the p type cell base, the parameters with the subindex « e » refer to the n^+ layer, S_f to the S.R.V. on its surface, and S_{eff} is the equivalent S.R.V. of a pp^+ junction [6] and is given by

$$S_{eff} = \frac{N_A}{N_A^+}\frac{D^+}{L^+}F\left(\frac{W^+}{L^+}, \frac{SL^+}{D^+}\right). \quad (9)$$

Here, the parameters with the superscript + refer to the p^+ layer, being S, the S.R.V. at its surface. N_A and N_A^+ are the majority carrier concentration of the base and the p^+ layer respectively.

The calculation of the spectral I.Q.E. of the $n^+ pp^+$ cell illuminated on its back, on the p^+ face, needs to integrate the differential equation regulating the concentration of minority carriers in the p and the p^+ regions. This is a linear differential equation of the second order, non homogeneous due to the light generation term. The boundary conditions are

$$Sn^+(-W^+) = D^+ \left.\frac{dn^+}{dx}\right|_{-W^-} \quad (10)$$

at the p^+ surface and

$$n(W) = 0 \quad (11)$$

at the pn^+ junction. (It has been assumed that the thermal equilibrium concentration of electrons is negligible.)

At the pp^+ interface, it can be stated that

$$N_A^+ n^+(0) = N_A n(0) \quad (12)$$

and

$$J_0 = J_0^+ \quad (13)$$

where J_0 and J_0^+ represent the electron current density in the p and p^+ sides, of the pp^+ junction, respectively. This condition assumes that there is not a sheet of high recombination velocity in the pp^+ interface, however, this is not always the case.

The concentration profiles $n(x)$ and $n^+(x)$ of electrons in the p and p^+ regions can be considered as the superposition of the solutions of the homogeneous equation (dark profile) and of the non-homogeneous equation (illuminated profile) shown in figure 1.

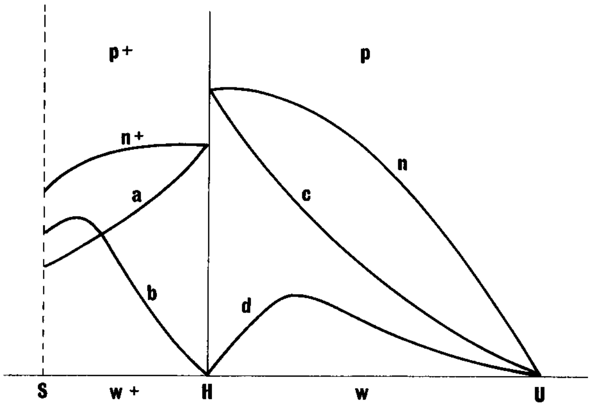

FIG. 1. — Minority carrier profiles in the p and p^+ regions, composed by superposition of illuminated (a, c) and dark (b, d) profiles in each region.

If a value of the electron concentration n_0 is assumed in the p region at the pp^+ interface, the current J_0 is the superposition of the currents given by formulas (1) and (4), calculated by using the p region parameters and the infinite value of surface recombination velocity, that can be formed in the shortcircuited $n^+ p$ junction. The current J_0^+ is the superposition of the currents given by formulas (2) and (5) calculated by the p^+ region parameters and the value of the S.R.V. at the back surface. By equating both currents a value of n_0 can be obtained

$$qn_0 = \frac{qN_j\,\varphi\left(\alpha L^+, -\frac{W^+}{L^+}, -\frac{SL^+}{D^+}\right) - qN_j\,\varphi\left(L, \frac{W}{L}, \infty\right)}{\frac{N_A}{N_A^+}\frac{D^+}{L^+}F\left(-\frac{W^+}{L^+}, -\frac{SL^+}{D^+}\right) - \frac{D}{L}F\left(\frac{W}{L}, \infty\right)}. \quad (14)$$

The substitution of this parameter in the expression of the current J_0 under illumination leads to an effective S.R.V. shown by

$$S_{eff} = \frac{qN_j}{qn_0}\varphi\left(\alpha L, \frac{W}{L}, \infty\right) - \frac{D}{L}F\left(\frac{W}{L}, \infty\right). \quad (15)$$

The value of the back illuminated spectral I.Q.E. can be calculated, neglecting the generation in the n^+ layer, by means of this equation :

$$\sigma_{sb} = \exp[-\alpha(W + W^+)]\,\varphi\left(\alpha L, -\frac{W}{L}, \frac{S_{eff} L}{D}\right). \quad (16)$$

The integrated I.Q.E. can be defined as

$$\sigma_i = \frac{\int N_0(\lambda)\, \sigma_s(\lambda)\, d\lambda}{\int N_0(\lambda)\, d\lambda} \tag{17}$$

where $N_0(\lambda)$ is the spectral density of photons of the solar AM1 illumination.

Using this model, four types of technologies have been studied in preparing the p^+ layer, very shallow ion implantation of Gallium, one step *P* diffusion, two steps (predeposition and drive-in) *P* diffusion, and Al alloying. The values of the parameters involved in the calculations appear in table I. The spectral I.Q.E. of the front and back illuminated cells, using the four technologies, appear in figure 2. The integrated I.Q.E. of the front and back illuminated cells for different cell thickness and base diffusion length appear in figure 3. The integrated I.Q.E. of back illuminated cells, as a function of back S.R.V. appears in figure 4,

TABLE I

Values of the parameters involved in the calculations

Layer	N(cm^{-3})	D(cm^2/sg)	L(μm)	S(cm/sg)	w(μm)
n^+	5×10^{20}	1.2	0.3	10^4	0.3
p	3.5×10^{15}	20	100	-	100
p^+ (ion implan)	10^{20}	2.2	1.6	10^5	0.0
p^+ (predep.)	5×10^{20}	2.2	0.3	10^5	0.4
p^+ (diff.)	10^{19}	8	20	10^4	0.8
p^+ (Al)	10^{19}	2.5	1	10^5	0.2

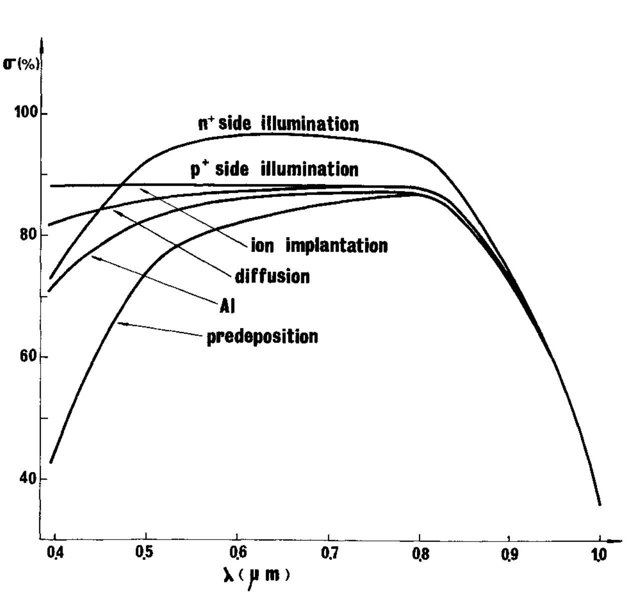

FIG. 2. — Spectral I.Q.E. of front and back illuminated cells, for the four technologies employed to make the p^+ layer.

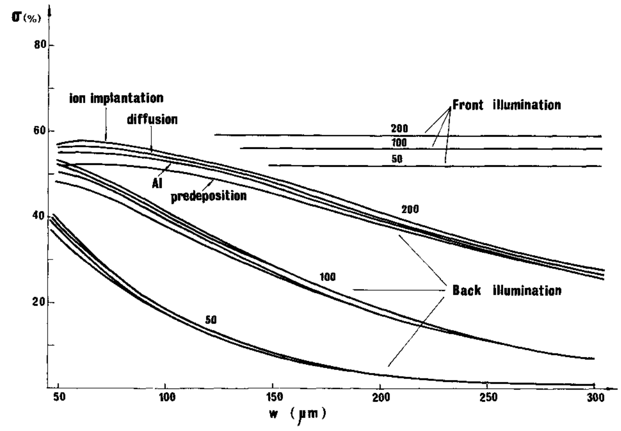

FIG. 3. — Integrated I.Q.E. of front and back illuminated cells, *vs* cell thickness, for different diffusion length.

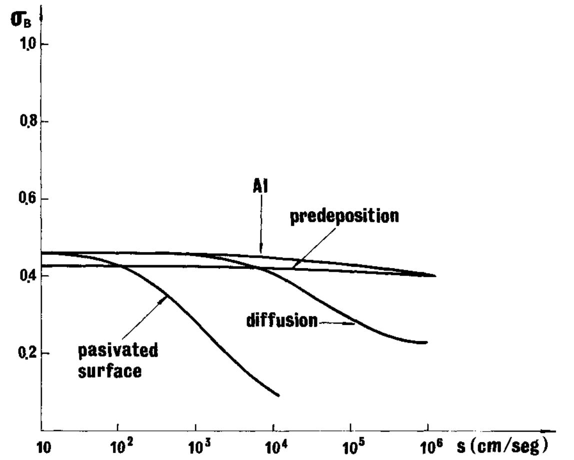

FIG. 4. — Integrated I.Q.E. of back illuminated cells as a function of back S.R.V., through the diffusion and alloy technologies and compared with a passivated back surface.

through the diffusion and alloy technologies, and is compared to the case in which only a surface passivation, without p^+p junction, exists in the back of the cell.

3. **Experimental.** — Three series of experiments have been carried out. In the first, some wafers of ⟨ 111 ⟩ orientation, 260 μm thick were *P* diffused on one side with $POCl_3$ and B ion implanted on the other. The ions were implanted at different accelerating voltages, in order to obtain squared p^+, profiles of different concentration and depth. In one case an exponential profile was implanted to avoid high concentration gradients that could induce dislocation fronts with high recombination velocity. An annealing process is needed to recover the damage made during the implantation. Data of the resulting p^+ layer appear in table II.

In a second series of experiments, ⟨ 111 ⟩ wafers 140 μm thick were *P* diffused on one side, using the same technique as before. A layer of Al was evaporated on the other side and the wafer was heated over the Al-Si eutectic temperature. After cooling, an Al-Si layer of eutectic composition was removed and a

TABLE II

Back illuminated to front illuminated integrated I.Q.E. *ratio for cells fabricated with ion implantation and* Al *alloying.*

Wafer #	p^+ tech.	w (μm)	w_{p+} (μm)	N_A^+ (cm^{-3})	ρ (Ω.cm)	L (μm)	σ_B/σ_F (%) (4 cells)
3	implant	260	0.16	6.3×10^{19}	10	210	65 63 63 59
2	implant	260	0.3	4×10^{19}	10	190	58 56 48 46
1	implant	260	0.3	9×10^{18}	10	150	36 - - -
5	implant	260	0.5	1.7×10^{18}	10	160	47 44 42 42
7	implant	220	exponential		5	200	59 58 56 54
11	Al alloy	-	0.1	0.7×10^{18}	5	-	43 - - -
12	Al alloy	136	0.1	2.5×10^{18}	5	100	53 - - -
13	Al alloy	50	0.2	1.0×10^{19}	5	60	83 76 76 67
14	Al alloy	50	0.2	1.0×10^{19}	5	45	70 63 60 54
15	Al alloy	60	0.1	1.0×10^{18}	14	100	90 82 - -

recristalysed layer of Si, doped with Al at the limit solubility, remained to form a p^+ layer. Data of concentration and thickness of this layer also appear in table II.

Finally, a third series of ⟨ 100 ⟩ wafers were decreased in thickness to 50 μm by using a 30 % aqueous solution of NaOH [9], heated at 100 °C. The same process, already mentioned in the second series of experiments, was then followed. It is worthwhile to mention that such very thin wafers can easily be handled since they are very flexible.

The shortcircuit currents of the cells illuminated on the front (n^+) and the back (p^+) sides were then measured. The back to the front shortcircuit current ratio was assumed to be equal to the integrated I.Q.E. ratio. This assumption implied that the reflectivity of both sides would be the same. The results are also presented in table II.

4. **Discussion of results.** — A general conclusion that can be obtained from this mathematical model, and which is deduced from figure 3, is that the back integrated I.Q.E. is greatly affected by the cell thickness and the diffusion length. It can be stated with a fair degree of accuracy that the I.Q.E. depends on the diffusion length to cell thickness ratio, as can be observed in figure 5. Very thin (50 μm) cells present, in agreement with this theory, excellent values up to 90 % for the back to the front integrated I.Q.E. ratio.

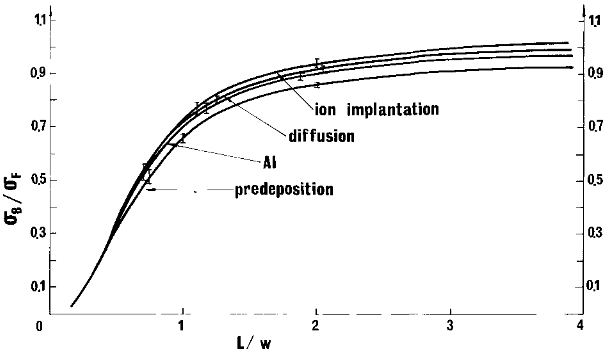

FIG. 5. — Back illuminated to front illuminated integrated I.Q.E. ratio as a function of diffusion length to cell thickness ratio.

The selected technology for the p^+ layer has some influence on the back illuminated cells, in particular for cells with high diffusion length to thickness ratio. The best technology is that which produces thinner p^+ layers, as in the Gallium ion implant. If such a shallow region cannot be produced, the lower the concentration, the higher the short wavelength response of the back illuminated cell (see Fig. 2). This effect is due to the fact that low doped p^+ layers have a structural perfection and behaves as generation zones and not as dead layers. As a result, the relatively thick two step diffusion p^+ layers present quite high I.Q.E.

This effect is also observed in the experimental results obtained with the wafers 3, 2, 1 and 5. The highest value of the back to the front integrated I.Q.E. is obtained with very shallow ion implanted layers, but good results are also obtained with thick ion implanted lightly doped layers.

In figure 3 it can be observed that for higher doping of the p^+ layer, the influence of the S.R.V. is lower in the back surface.

5. **Conclusions.** — The possibility of efficient n^+pp^+ cells illuminated on both sides has been shown both theoretically and experimentally with cells, using a simpler process, than in previous double sided cells.

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