

MODELLING OF THE PERC STRUCTURE WITH STRIPE AND DOT BACK CONTACTS

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ABSTRACT: The PERC cell design offers the possibility of significantly improved performance over conventional commercial cell designs with only a small increase in process complexity. Optimisation of the PERC structure to date has been aimed at high efficiency cells. This paper reports the results of comprehensive modelling to determine what advantage the PERC structure with dot or stripe contacts has over conventional screen printed rear cells for lower quality substrate wafers. The efficiency trade-offs of contact spacing and contact area are investigated as a function of wafer resistivity, diffusion length and wafer thickness, taking into account recombination elsewhere in the device. The efficiency for a PERC cell and a cell with a silver screen printed rear are compared for different wafer resistivities.

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1. INTRODUCTION

The PERC (passivated emitter and rear cell) structure was developed by one of the authors in 1988 [1] and produced record efficiency silicon cells for that time. It has a lightly doped emitter with heavier diffusions under the front contacts, a SiO_2 passivating layer and antireflection coating, and inverted pyramids on the top surface (figure 1). Rear contact is made directly to the substrate via contact holes through the rear oxide, without the use of a boron diffusion. The spacing of the holes is large compared to the cell thickness in order to minimise contact recombination. The substrate of the record efficiency cell was reasonably heavily doped ($0.2\text{--}0.5\Omega\text{cm}$) in order to reduce series resistance due to the widely spaced contacts and to allow low resistance contact to be made with aluminium to the substrate.

The PERC cell design offers the possibility of significantly improved performance over conventional commercial cell designs with only a small increase in process complexity. For example, a high quality bifacial commercial multicrystalline cell could be made simply by phosphorus diffusing the top surface, depositing silicon nitride on both surfaces, screen printing aluminium on the rear and silver on the front and firing through the nitride. For a monofacial cell, stripes could be cut in the silicon nitride with a laser or dicing saw, followed by plasma-spraying aluminium through a shadow mask. A dot contact cell could be made by cutting dots in the silicon nitride with a laser before plasma-spraying, or by locally damaging the nitride with a set of “pins”. The stripe structure has the advantage of a potentially simpler manufacturing process

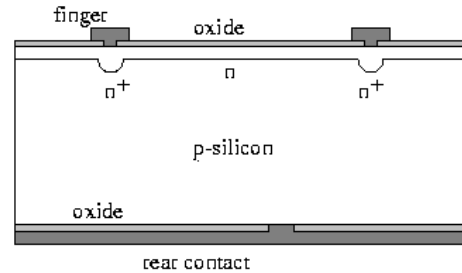


Figure 1: The PERC cell structure. The surface texturing is not shown.

and the possibility of bifacial illumination. These processes avoid all high temperature steps post-diffusion, which allows the large gettered lifetimes to be preserved. Oxidations and boron diffusions after the gettering step tend to degrade the minority carrier lifetime.

The small metallisation fraction of the PERC cell means that recombination at the rear is significantly reduced compared to a cell with 100% rear metallisation. The current increase that goes along with a V_{oc} increase means that overall cell efficiency improvement can be substantial, provided that the diffusion length is larger than the wafer thickness, even neglecting the benefits of the bifacial design.

Spreading resistance losses for majority carriers in the base are proportional to wafer resistivity. High efficiency PERC cells have small contact areas (1%) and large contact spacings (around 2mm) to minimise recombination. This requires relatively low wafer

resistivities (0.2–0.5 Ωcm) to keep spreading resistance losses low. The modelling shows that high efficiencies can also be achieved with 1 Ωcm material. This allows advantage to be taken of the higher lifetimes achievable with 1 Ωcm silicon, which is important for industrial quality multicrystalline material. A broad optimum in the efficiency with back contact fraction and back contact spacing gives flexibility in cell design and manufacturing processes.

2. OTHER STUDIES OF PERC CELLS

Optimisations of the PERC structure have been previously reported in the literature. These papers are aimed at high efficiency cells, and so only consider a narrow range of wafer resistivities and material qualities. Aberle *et.al.* [2] solve the fully coupled set of semiconductor differential equations in two (cartesian) dimensions. Aberle *et.al.* analysed one resistivity (0.5 Ωcm), one wafer thickness (280 μm), a fixed rear metallisation fraction of 1.5% and only large diffusion lengths. Spacings were restricted to less than 1.4mm because the main emphasis of the modelling was on cells with locally diffused rear contacts.

Sterk *et.al.* [3] used a 3D simplified model which requires the use of assumptions in the calculation of the fill factor. One wafer thickness (200 μm), one resistivity (0.5 Ωcm) and one diffusion length (500 μm) were modelled. Rear metallisation fractions of 0.5% and 4% and contact spacings from 0.02mm to 6mm were used.

Schöfthaler *et.al.*[4] use a 3D model based on Fourier decomposition of the minority carrier diffusion equation. This model also requires extra assumptions for the calculation of the fill factor and again only one wafer thickness, diffusion length and wafer resistivity were modelled. Metallisation fractions of 0.4–16% and contact spacings of 100 μm to 10mm were used.

3. MODELLING OF PERC CELLS

The aim of the modelling is to optimise the cell design for stripe and dot back contact structures and determine what advantage the PERC structure has over conventional screen printed rear cells. The modelling package Dessis [5] is used which solves the fully coupled set of semiconductor differential equations. The efficiency trade-offs of contact spacing and contact area are investigated as a function of wafer resistivity, diffusion length and wafer thickness, taking into account recombination elsewhere in the device.

The stripe structure was modelled in two dimensions using cartesian coordinates. The dot structure was modelled using cylindrical coordinates. For dots in a hexagonal pattern, the PERC structure can be modelled with a hexagonal prism as the unit cell. This was replaced with a cylinder to allow the use of cylindrical coordinates. The error introduced by this assumption is expected to be small. Dessis can also

be used to solve the semiconductor equations in three dimensions without the need for the assumption of cylindrical symmetry, but such an approach is very computationally intensive, especially for large contact spacings.

A perfectly passivated emitter with negligible sheet resistance was used in order to focus attention on the bulk and rear surface. This was modelled with a 100% front contact and a very heavily doped emitter (2 Ω/\square) to make the minority carrier diffusion length in the emitter so low that recombination at the front contact is negligible. Band gap narrowing was turned off to avoid lowering the open circuit voltage through Auger recombination in the emitter. The light was made to appear close to the junction in order to avoid the loss of short wavelength light in the heavily doped emitter. This results in a structure with essentially no recombination at the front surface.

The light intensity was adjusted to give short circuit currents in agreement with the one-dimensional modelling package PC1D [6] when diffusions at the rear contacts were added to reduce recombination. Monofacial illumination was used and excellent light trapping was assumed. Shading by metal fingers was not taken into account.

Wafer resistivities of 0.2 Ωcm and 1 Ωcm were used, with the corresponding contact resistivities for aluminium of $4 \times 10^{-4}\Omega\text{cm}^2$ and $1 \times 10^{-3}\Omega\text{cm}^2$ respectively [7]. Surface recombination velocities of 10cm/s for 1 Ωcm material and 100cm/s for 0.2 Ωcm material were used. These values have been achieved in the laboratory with silicon nitride on p-type silicon and it is expected that this will soon be repeated in an industrial setting. Back contact spacings were varied from 100 μm to 7000 μm and back contact fractions from 0.2% to 100%. The wafer thickness was varied in the range 100–400 μm . Two bulk minority carrier lifetimes were used for each wafer resistivity, corresponding to industrial quality and state-of-the-art multicrystalline wafers. For 1 Ωcm silicon these were 50 μs and 400 μs , and for 0.2 Ωcm they were 5 μs and 25 μs .

4. RESULTS

There is a broad optimum for back contact spacings and back contact fraction. This optimum broadens further for low wafer resistivities and higher contact fractions. For the dot structure with high quality 1 Ωcm material there is less than 0.2% (absolute) difference in efficiency in the back contact spacing range 800–2400 μm for a back contact fractions of 1%, as shown in figure 2. For a dot structure with high quality 0.2 Ωcm material with a contact fraction of 10% the range for constant efficiency is 1600–8000 μm .

The stripe structure shows a broader optimum for back contact spacings than the dot structure. For 0.2 Ωcm material with a stripe structure and a back contact fraction of 1% there is less than 0.2% (absolute) difference in efficiency in the range 1200–7200 μm whereas for a dot structure with the same contact fraction the range is 800–3600 μm . This is due to the lower

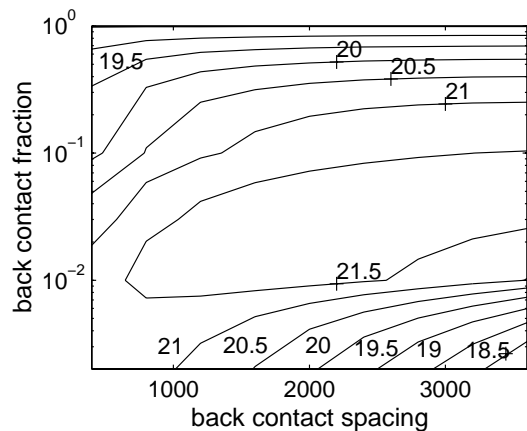


Figure 2: A contour plot of efficiency showing the broad optimum with back contact spacing and back contact fraction for a $400\mu\text{m}$ thick high quality ($\tau = 400\mu\text{s}$) $1\Omega\text{cm}$ wafer with a dot contact structure.

spreading resistance of the stripe structure.

The broad optimum in the back contact fraction for both the dot and stripe structures is due to a decrease in recombination offset by an increase in spreading resistance as the contact fraction is decreased. This means it is not necessary to use small dots or thin stripes to achieve high efficiencies. Contacts can also be very widely spaced without significant loss in efficiency.

The difference in efficiency between the stripe structure and the dot structure is small for optimised back contact spacings, as shown in figure 3. It was found that for both $0.2\Omega\text{cm}$ and $1\Omega\text{cm}$ material with contact fractions of 1% and 10%, the efficiency of the stripe contact structure and the dot structure was the same within the uncertainty of the modelling (0.1% absolute). The optimised back contact spacings for the stripe structure were 3.2mm for a 1% contact fraction and $4\text{--}4.8\text{mm}$ for a 10% contact fraction. For the dot structure the optimised back contact spacings were 1.2mm for a 1% contact fraction and 3.6mm for a 10% contact fraction. The choice of dot or stripe structure will therefore be decided by manufacturability issues. A 1% dot contact with a spacing of 1.2mm corresponds to a dot diameter of $120\mu\text{m}$, while a 1% stripe contact with a spacing of 3.2mm will be $32\mu\text{m}$ wide. Such narrow contacts could present manufacturing difficulties. A larger contact fraction is likely to be tolerable because of the broad optimum in efficiency with contact fraction. The stripe structure may be favoured because it could be formed with a dicing saw rather than requiring a laser and because it lends itself well to a bifacial design.

The results for both dot and stripe contacts show a broad maximum in efficiency as the ratio of diffusion length to wafer thickness (L/W) is varied, provided that $L/W > 1$. For high quality $0.2\Omega\text{cm}$ and $1\Omega\text{cm}$ wafers, and industrial quality $1\Omega\text{cm}$ wafers, wafer thickness has little effect on cell performance in

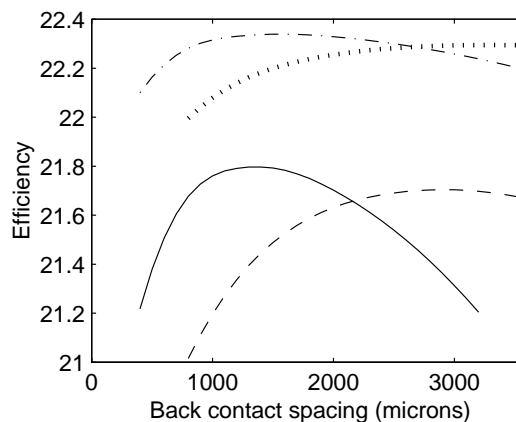


Figure 3: The efficiency of stripe and dot contact cells as a function of back contact spacing, for a contact fraction of 1%. From top to bottom the curves are: $0.2\Omega\text{cm}$ dot (dash-dot), $0.2\Omega\text{cm}$ stripe (dotted), $1\Omega\text{cm}$ dot (solid), $1\Omega\text{cm}$ stripe (dashes).

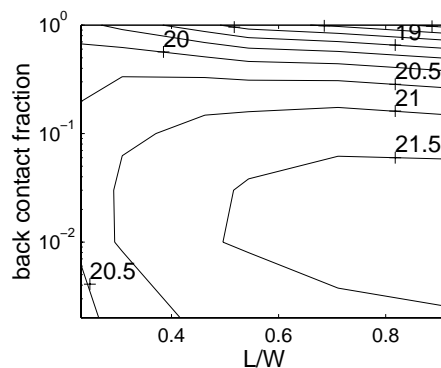


Figure 4: A contour plot of efficiency vs. L/W and back contact fraction for an industrial quality ($\tau = 5\mu\text{s}$) $0.2\Omega\text{cm}$ wafer with a dot contact structure and a back contact spacing of 1.6mm .

the range $100\text{--}400\mu\text{m}$ because L/W is always greater than 1 in this range. For industrial quality $0.2\Omega\text{cm}$ material L/W varies from about 0.3 to 0.9 as the wafer thickness is decreased from $400\mu\text{m}$ to $100\mu\text{m}$. The best results with this material using a PERC structure can be obtained with thin (around $100\mu\text{m}$) wafers eg. multicrystalline wafers manufactured by ribbon processes. In this case the use of a thin wafer can increase achievable efficiencies by about 1% absolute as shown in figure 4. The reason for this increase in efficiency is the reduction in bulk recombination as the wafer is made thinner. This is offset to some extent by the increase in recombination rate at the rear contacts as L/W increases and more carriers “see” the contacts.

The efficiency improvement achievable through the use of a PERC structure rather than a 100% back contact is significant, as shown in figure 5. The efficiency difference is 3% absolute for $400\mu\text{s}$ $1\Omega\text{cm}$ silicon, from 18.5% to 21.5%. For $125\mu\text{s}$ $1\Omega\text{cm}$ silicon the improvement is 1.5% absolute from 18.5% to

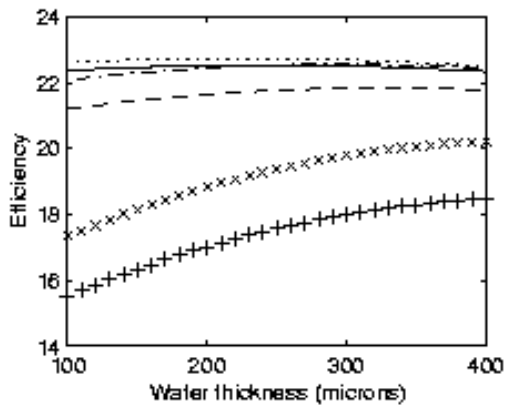


Figure 5: The efficiency for PERC, PERL and 100% back contact cells as a function of wafer thickness, for a contact fraction of 1% and a back contact spacing of $1600\mu\text{m}$ for the PERC and PERL cells. From top to bottom the curves are: $0.2\Omega\text{cm}$ PERL (dotted), $0.2\Omega\text{cm}$ PERC (solid), $1\Omega\text{cm}$ PERL (dash-dot), $1\Omega\text{cm}$ PERC (dashes), $0.2\Omega\text{cm}$ 100% contact (x), $1\Omega\text{cm}$ 100% contact (+).

20%. As expected the influence of the back surface is smaller for lower bulk lifetimes. Significant front surface recombination will also reduce the advantage of the PERC structure. The figure also shows that the loss in efficiency with the use of a PERC structure rather than locally diffused rear contacts is small for a contact fraction of 1%.

5. CONTACT RESISTANCE IN PERC CELLS

Contact resistance and spreading resistance in the PERC structure were compared. Contact resistance is given by $R_c = \rho_c/A$ where ρ_c is the contact resistivity and A is the area of the contact. The largest value of contact resistivity between metal and p-type silicon where the contact remains ohmic is about $10^{-3}\Omega\text{cm}^2$ for evaporated contacts [7]. The spreading resistance between a circular contact of radius a and a plane contact at a distance W is given by $R_{sp} = \rho_b/(4a)$, where ρ_b is the bulk resistivity of the material, with the requirement that $a \ll W$. This expression provides a lower bound for the spreading resistance due to the back contacts of a PERC structure. (There is also a lateral resistance component due to the transport of carriers to the neighbourhood of the rear contact. The expression given above is for a plane contact in which the carriers travel through the plane contact with no loss.)

The above expressions are for a single dot contact. To account for dots with a contact spacing s the resistances must be multiplied by the number of dots per square centimetre which for a hexagonal contact pattern is $(\sqrt{3}/2)s^2$.

In general, contact resistance is much smaller than spreading resistance for contact spacings typically

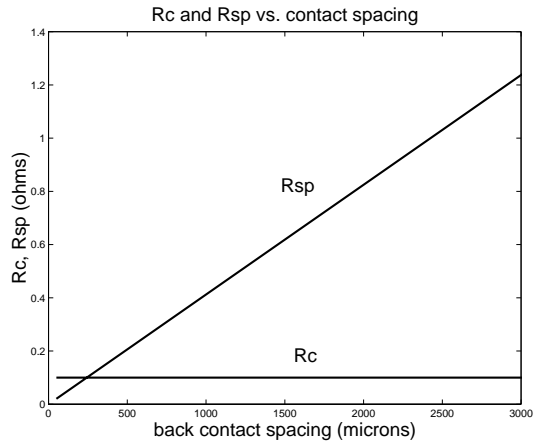


Figure 6: A comparison of R_c and R_{sp} for a 1% contact fraction with $\rho_b = 1\Omega\text{cm}$ and $\rho_c = 10^{-3}\Omega\text{cm}^2$ which is the contact resistivity of Al to $1\Omega\text{cm}$ p-type silicon. The wafer thickness is $280\mu\text{m}$.

used with the PERC structure. This is illustrated in figure 6 for a 1% contact fraction. Since the optimum efficiency occurs at spacings greater than $800\mu\text{m}$, R_c is less than R_{sp} for all cases of interest. Therefore the exact value of the contact resistance does not need to be known, although the contact must be ohmic.

6. CONCLUSIONS

The PERC structure has significant efficiency advantages for industrial multicrystalline cells over the 100% back contact structure. There is little difference between a stripe structure and a dot structure of the same contact fraction provided the back contact spacing is optimised. Contact resistance is negligible in PERC cells compared to spreading resistance for optimised back contact spacings.

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