longer be a region of uncertainty near the centre of the cable.

Further improvements are still possible. Cooling a photodiode or decreasing its physical size reduces the leakage current and thus permits a higher bias voltage. This has two important consequences. Firstly, it increases the detection probability almost to the quantum efficiency of the diode, and secondly, it eases optical alignment problems by increasing the useful area of the device.

The number of photons counted before advancing the sampling interval is being investigated. It is expected that there is an optimum number (possibly differing from the present 16) which will maximise the range of the apparatus and the speed of the observation but minimise the uncertainty in the location.

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OPTIMISATION OF p^+ DOPING LEVEL OF n^+-p-p^+ BIFACIAL B.S.F. SOLAR CELLS BY ION IMPLANTATION

Indexing terms: Doping, Solar cells, Ion implantation

High-low junctions of n^+-p-p^+ bifacial back surface field solar cells have been fabricated by B^{11+} implantation. After an isothermal annealing step at 900°C for 10 min, an optimum surface concentration of 5×10^{19} cm^{-3} is observed. Its origin is found to lie in the partial electrical activation of the implanted impurities.

Introduction: Ion implantation is a well known technology for the preparation of advanced solar cell structures. Recently several new configurations in which a high-low junction is present in the illuminated surface have been proposed: double sided surface field,[1] front surface field,[2] and high-low emitter.[3] In these cases the thickness and the doping level of the highly doped layer must be optimised for a good reflection of minority carriers and minimum light losses. This letter deals with the determination of an optimum doping level for the p^+ layer of n^+-p-p^+ bifacial b.s.f. solar cells made by ion implantation.

Experiments and results: p-type Czochralski-grown ⟨100⟩ 7 Ωcm Si wafers with both sides chemically polished were thermally oxidised and phosphorus diffused on one face (front face in our nomenclature) at 875°C for 40 min. B^{11+} was implanted at room temperature in the opposite face (back face) through the thermal oxide. The implantation energy, ranging from 105 to 240 keV, was selected to obtain impurity profiles with the peak at the Si-SiO_2 interface. Doses were controlled from $9{\cdot}1 \times 10^{13}$ to $1{\cdot}14 \times 10^{16}$ cm^{-2} to obtain peak concentrations from 5×10^{18} up to 5×10^{20} cm^{-3}. (The p^+ layer thickness, calculated following the l.s.s. range statistics,[4] varied from 0·3 to 0·5 μm). To avoid channelling effects, all substrates were tilted 7° from the incident beam. All samples were annealed at 900°C for 10 min in forming gas. The sheet resistance of the implanted base was measured by the four point probe method. Standard Ti-Pd-Ag contacts were sputtered and lift-off delineated on both faces. Measurements under illumination were done at 25°C with an AM1 solar simulator calibrated at 100 mW cm^{-2}.

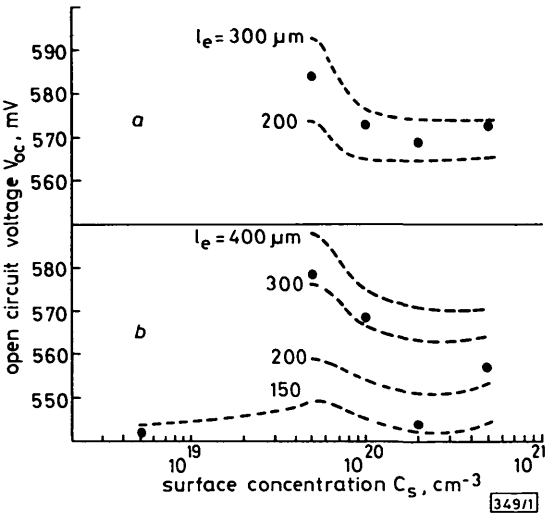

Fig. 1 *Open circuit voltage under front illumination (AM1, 25°C) versus surface concentration C_s*
● Measured ------- Theoretical
for different minority diffusion lengths in base
a Cells 220 μm thick
b Cells 80 μm thick

On Figs. 1*a* and 1*b* dots represent the maximum open circuit voltage (V_{oc}) under front illumination versus surface concentration for two cell thicknesses, namely 80 and 220 μm. An optimum surface concentration appears at 5×10^{19} cm^{-3}. Cells with this concentration have presented the highest efficiencies within this work. Intrinsic efficiencies without a.r. coating of 12·2%, 9·2% and 10·7% under front, back and bifacial illumination, respectively, have been obtained.

Discussion: Several physical mechanisms are of paramount importance on the behaviour of heavily doped layers: bandgap narrowing, s.r.h., Auger and surface recombination etc. In addition to these, electrical nonactivation of implanted impurities must be considered. To distinguish which mechanism determines our cell performance, we first analysed the degree of electrical activation. The ratio between theoretical and measured sheet resistances as a function of surface concentra-

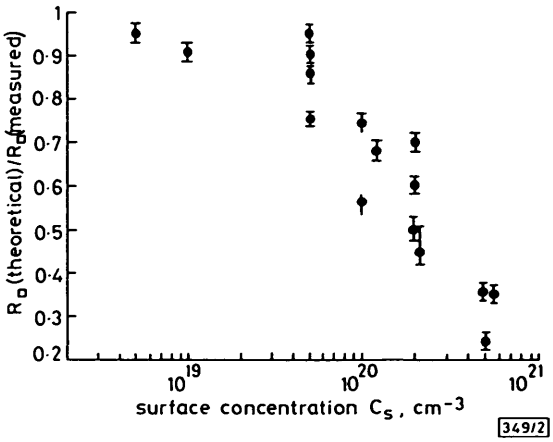

Fig. 2 *Ratio between theoretical and measured sheet resistance of implanted layer as a function of surface concentration C_s*

tion is plotted in Fig. 2. For the theoretical calculation the original implanted gaussian profile has been assumed, taking as the projected straggling the arithmetic mean for B in SiO_2 and Si. In this Figure it is clearly seen how the electrical activation of the implanted impurities decreases drastically when the concentration increases over several times 10^{19} cm^{-3}. We recalculated the sheet resistances after truncating the Gaussian profile as shown in Fig. 3. The best fit with the measured sheet resistances is obtained when the truncation is done at 6×10^{19} cm^{-3}. This value has also been found by Ryssel *et al.* who studied the annealing of implanted B at the same temperature.[5]

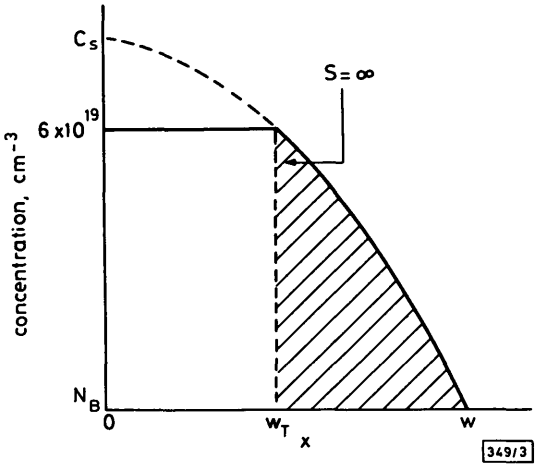

Fig. 3 *Impurities exceeding 6×10^{19} cm^{-3} are not electrically active, giving rise to an infinite recombination layer*

Once we have established that the majority carrier concentration in the p^+ layer is not higher than 6×10^{19} cm^{-3}, the bandgap narrowing effect can be considered through actual measured data, available up to this doping level, fitted by Lanyon and Tuft.[6] From the point of view of recombination of minority carriers we have distinguished two regions within the p^+ implanted layer. In the region in which the doping level is higher than 6×10^{19} cm^{-3} a great number of impurity atoms are not located in the crystal lattice positions. They are very active recombination centres, and hence this region behaves as a dead layer. The region in which all the impurities are electrically active is narrow and doped low enough to be considered, in a first approximation, as transparent, i.e. the recombination within this region can be neglected, either by Auger or s.r.h. mechanisms. The outer surface recombination velocity (S_b) is only important for profiles without a dead layer.

To quantify the influence of these physical mechanisms we characterise the high-low junction through its effective surface recombination velocity (S_{eff}). It has been shown[7] that when the highly doped side of a high-low junction is transparent, S_{eff} follows the formula

$$S_{eff} = N_B \Big/ \left\{ \int_0^W \frac{N_{Aeff}(x)}{D(x)}\,dx + \frac{N_{Aeff}(0)}{S_b} \right\} \qquad (1)$$

where N_B is the base concentration, w is the thickness of the p^+ layer, N_{Aeff} is the effective doping concentration (affected by bandgap narrowing), and D is the minority carrier diffusion coefficient. With this formula we have calculated the S_{eff} of totally transparent profiles ($C_s < 6 \times 10^{19}$). S_b has been taken as 10^6 cm s^{-1}. Although this number is rather high with respect to the usually accepted one for bare silicon, in this case the nearly infinite surface recombination velocity of the ohmic contacts has been taken into account to calculate a virtual S_b.

The profiles with a dead layer ($C_s > 6 \times 10^{19}$) are modelled through an infinite surface recombination velocity located at the truncation depth W_T (see Fig. 3). S_{eff} is now

$$S_{eff} = N_B \Big/ \int_{W_T}^{W} \frac{N_{Aeff}(x)}{D(x)}\,dx \qquad (2)$$

Calculated S_{eff} have been plotted on Fig. 4; the mobility data was taken from Plunkett *et al.*[8] An abrupt increase of S_{eff} is observed when the surface concentration increases over 6×10^{19} cm^{-3}. This behaviour is explained by the appearance of the infinitely recombining dead layer.

These calculated values of S_{eff} together with diffusion lengths typical of 7 Ωcm p-type substrates give numerical values of V_{oc}, superimposed in broken lines in Figs. 1*a* and 1*b*, in good agreement with the experimental results.

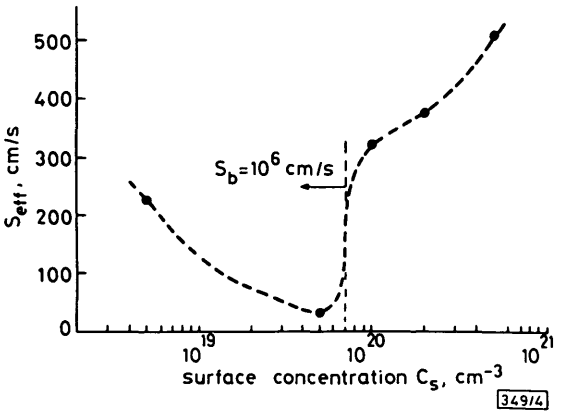

Fig. 4 *Effective surface recombination velocity S_{eff} of high-low junction versus surface concentration C_s*

Conclusions: An electrical impurity activation limit of 6×10^{19} cm^{-3} has been found after an isothermal annealing at 900°C, for 10 min, of boron implanted layers. When these implantations are done in the base of a n^+-p cell, and the S_{eff} of the high-low junction so formed is calculated, the resulting theoretical open circuit voltages are in good agreement with the experimental results. These calculations assume that the implanted region with a doping level higher than 6×10^{19} cm^3 behaves as infinitely recombining. Maximum open circuit voltages of 583 mV and bifacial intrinsic efficiencies without a.r. coating of 10·7% have been obtained.

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