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Abstract

The back contact can detract from solar cell performance by a number of means: high recombination, barrier, photovoltage, minority carrier collection, resistance. These effects may act in a non-uniform fashion over the cell area, and complicate the analysis of photovoltaic performance aimed at a better understanding of the effects of device geometry and material and/or processing parameters.

The back contact can be tested by reproducing it on both sides of a substrate. The dark current-voltage characteristic should obey Ohm's law calculated using the resistivity of the substrate. Sintered aluminum on p-type silicon substrates of moderate and low resistivity behaves in this way, and so may be used as a reference against which other back contact technologies are measured.

The objective is to find a back contact which performs well as a back contact, can be applied cheaply to large area solar cells, fits well into a practical process sequence, does not introduce structural damage or undesirable impurities into the silicon substrate, is compatible with an effective front contact technology, permits low temperature solder contacting, adheres well to silicon, and is reliable.

1. HIGH RECOMBINATION
2. MINORITY CARRIER COLLECTION
3. RESISTANCE
    - LINEAR
    - NON-LINEAR
4. BARRIER
5. PHOTOVOLTAGE

BACK CONTACT PROBLEMS

TABLE 1

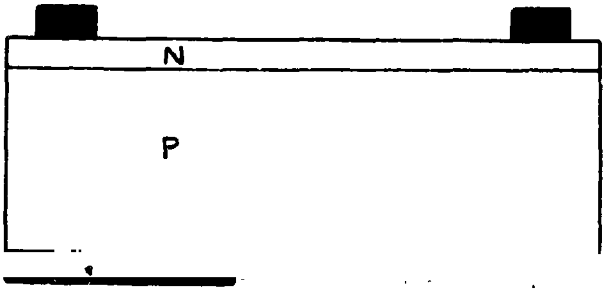

FIGURE 1. Simple solar cell section.

Introduction

Reduction of the cost of solar cell metallization is necessary if the projected low prices for modules are to be realized. Towards this goal, various new technologies are under investigation.[1,2,3] Back contact problems have been seen with some material systems, as - fabricated[3] or after stress ageing.[4] Back contact problems that can occur are listed in Table 1.

A Model for Back Contact Studies

Figure 1 shows a simple solar cell cross section. The back contact can degrade performance of the structure in two ways:

1. by removing carriers (through recombination or collection) which would otherwise contribute to photocurrent at the P-N junction, or by generating carriers that increase the diffusion component of dark current, and
2. by introducing resistances or barriers that reduce terminal voltage.

Barrier effects on overall solar cell performance may be modified by photovoltage generation due to light reaching the back contact region.

If we ascribe back-surface minority carrier effects on the P-N junction to photocurrent losses in the photogenerator and dark diffusion current increases in the n=1 diode, the rest of the back surface problems (3,4 and 5 in Table 1) may be removed into a separate 2-port network section, as shown in Figure 2. The top 2-port section is the active one, with J_{ph} reduced by minority carrier recombination and collection at the back contact, and the n=1 diode having its dark current influenced by minority carrier generation or injection at the back contact. The n diode contains all the n>1 components. The shunt conductance Z_{sh} may be non-linear.

In the 2-port section at the bottom of Figure 2, barriers of either polarity, with photocurrents J_{ph_B} and $J^{I}_{ph_B}$ are indicated as possible parasitics. The V-I characteristics of these barriers are generally much more conductive than those of a p-n junction because they are often low grade Schottky barriers and, particularly for large area devices, shunted in a non-uniform fashion. The shunt impedance Z_{SB} may be nonlinear if the ohmic solar cell current traverses grain regions; this can be particularly prominent if the back contact region is segmented so lateral ohmic current in the base is appreciable.

Experimental observations of the parasitic dark characteristics of the back contact are instructive in determining their cause and helping with their elimination. Figure 3(a) shows a section of a solar cell. Leaving off the p-n junction and making ohmic contact to top and bottom, Figure 3(b), would place two of the lower (parasitic) 2-ports in series. If the top-to-bottom V-I characteristic of the structure in Figure 3(b) obeys Ohm's Law for the substrate material, there are no prominent back contact parasitics. Otherwise, it will be necessary to use a known ohmic structure. Figure 3(c), with p^+ contacts, can be entirely ohmic, e.g. for a 0.25 Ω - cm substrate 250 μM thick, top-to-bottom conductance is 160 mhos/cm^2 (resistance = 6.25 mΩ - cm^2). At 36 ma/cm^2, the parasitic bulk drop is less than ½ mV. For a 100 cm^2 cell, conductance = 16000 mhos (series resistance = .06 mΩ). This p$^+$ contact then becomes a standard against which other technologies are measured. The structure in Figure 3(d) can be used to measure the ohmic character of the experimental contact formed on the top side.

Solar cells are sometimes made with segmented back contacts, Figure 4. In this type of geometry, there is a considerable amount of lateral current flow. By omitting the P-N junction, back contact parasitics can be tested for photogeneration. However, the bulk series resistance will be larger, and more susceptible to grain boundary effects. Quantitatively, consider a solar cell 250μM thick with 5 equispaced contact lines/cm top and bottom, and a substrate resistivity of 0.25 Ω-cm. Conductance between top and bottom contact sets will be approximately 20 mhos, assuming the average photocurrent induced majority carrier path length is 0.05cm., half the contact spacing, and no grain boundary impedance. For a 100 cm^2 cell, g=2000 mhos, or series resistance is 0.5 mΩ. This resistance is about an order of magnitude larger than that of a similar cell with full back-surface metallization, but still small enough to serve as an effective shunt for an otherwise severe back surface barrier (e.g. an npn structure with a network of p$^+$ back contacts penetrating to the p-type substrate).

Some Examples

Examples of how parasitic back-surface elements can degrade the V-I characteristic of an otherwise good cell are constructed by adding voltages of the 2-port sections at common currents. The upper 2-port V-I characteristic for a theoretical resistance-free base-dominated thick diode is shown in Figure 5. Parameters chosen are n=1, p=1.5x10^{17}/cm^3, L_n=100μM, μ_n=624 cm^2/V sec ($J_o \sim 10^{-10}$ mA/cm^2). Under 1-sun illumination, assuming 36 mA/cm^2, the V-I characteristic is shifted downward as shown in Figure 6.

Figure 7 shows the effect on a 1 cm^2 cell of a series resistance of 1 Ω; this would be obtained on a structure as given in the example illustrated in Figure 4 if the base resistivity were 5 Ω-cm.

Figure 8 shows the effect of a diode with a polarity opposing the P-N junction. The diode V-I characteristic is sketched on the left side of the current axis; when added to the theoretical diode curve the resultant form is S-shaped. This diode is on the left side of the bottom 2-port in Figure 2. If this diode has a photocurrent J_{ph_B} of 2 ma/cm^2, the resultant solar cell V-I characteristic is as sketched in Figure 9.

If the back-surface barrier is directed in the same sense as the P-N junction, the main photocurrent will drive it in the reverse-bias direction. Figure 10 indicates the effect of a very leaky "reverse" barrier, and Figure 11 shows that for a J_{ph_B} of 10 mA/cm^2, Voc is increased although the peak power region is degraded. For this polarity of barrier to provide a net increase in cell power, its photocurrent must be very nearly as large as that of the main P-N junction; a thin cell made on high resistivity, high lifetime material (i.e. a BSF cell) would be of this type.

Total Back Contact Requirements

The back contact must be relatively free from the problems listed in Table 1, i.e., it must be capable of good optoelectronic performance. In addition, it must have the rest of the characteristics listed in Table 2 if it is to contribute to meeting the DOE long range cost/performance goals.

References

1. MOD Silver Metallization for Photovoltaics, G. M. Vest and R. W. Vest, Quarterly Technical Report, December 1, 1983-February 29, 1984, DOE Contract No. NAS-7-100-956679.

2. Development of Metallization Process, Alexander Garcia III, Quarterly Technical Progress Report, December 31, 1983, JPL Contract 956205.

3. Development of an All-Metal Thick Film Cost Effective Metallization System for Solar Cells, Bernd Ross and Joseph Parker, Final Report, December 1983, DOE Contract No. NAS-7-100-955688.

4. Accelerated Degradation of Silicon Metallization Systems, Jay W. Lathrop, Proceedings of the Flat-Plate Solar Array Project Research Forum on Photovoltaic Metallization Systems, DOE/JPL-1012-92, November 15, 1983.

CAPABLE OF GOOD OPTOELECTRONIC PERFORMANCE
ECONOMICALLY APPLICABLE TO LARGE AREA CELLS
CONSISTENT WITH A PRACTICAL PROCESS SEQUENCE
NON-DETERIORATING OF BULK SILICON PROPERTIES
    STRUCTURAL
    IMPURITIES
COMPATIBLE WITH EFFECTIVE FRONT CONTACT TECHNOLOGY
ADHERENT
RELIABLE
SOLDERABLE

BACK CONTACT REQUIREMENTS

TABLE 2

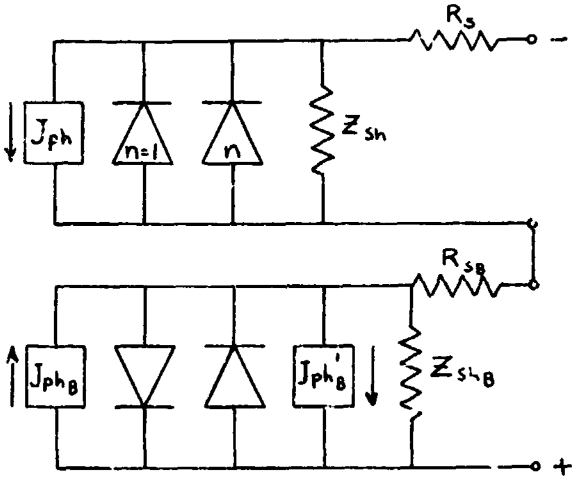

FIGURE 2. Active (top) and passive (bottom) 2-port network sections.

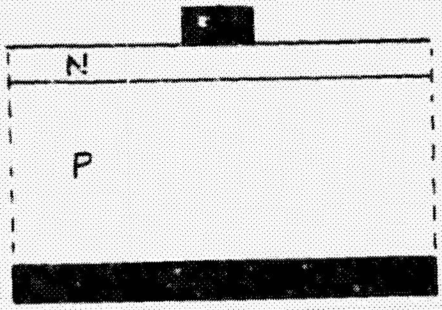

FIGURE 3(a). Simple solar cell section.

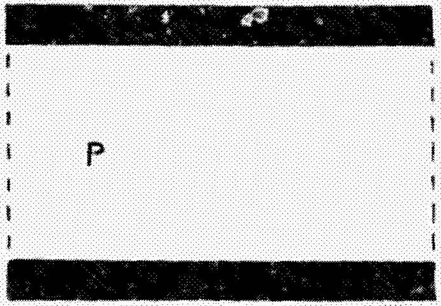

FIGURE 3(b). Bottom contact structure produced on both sides of a substrate.

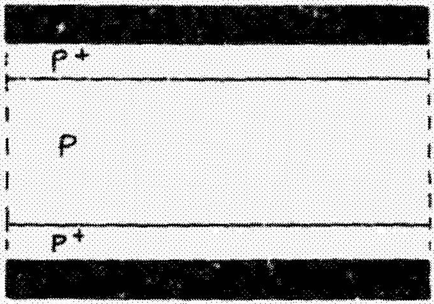

FIGURE 3(c). Ohmic contact produced on both sides of a substrate.

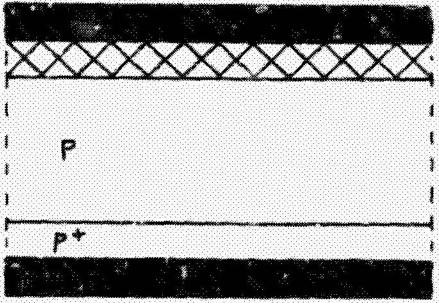

FIGURE 3(d). Geometry for measuring ohmic characteristics of experimental contact (top).

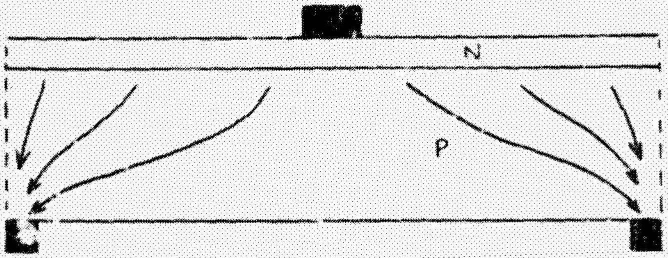

FIGURE 4. Segmented back contact structure.

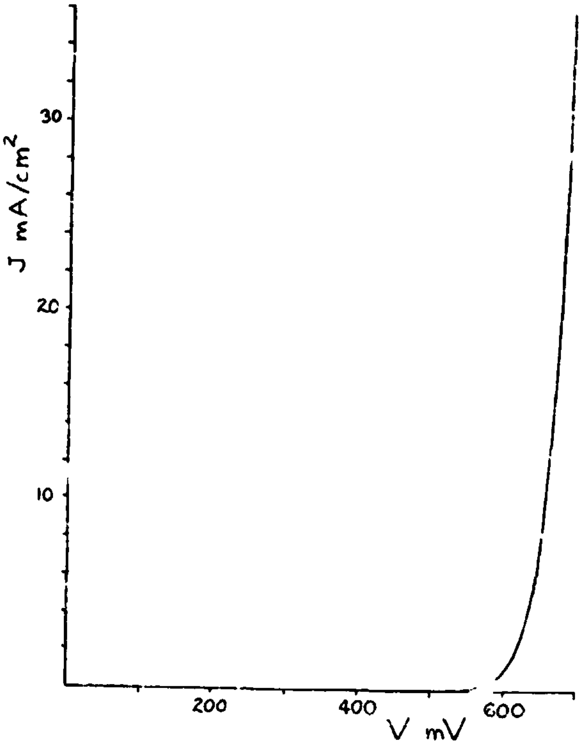

FIGURE 5. Dark V-I characteristic calculated for selected diode.

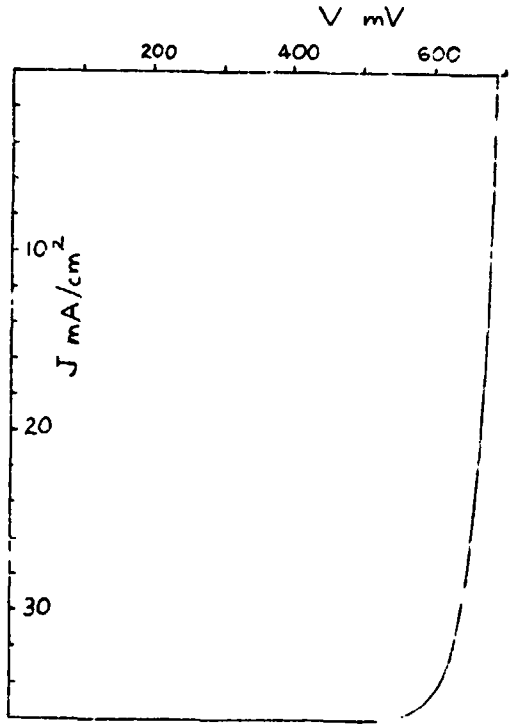

FIGURE 6. Illuminated V-I characteristic calculated with J_{sc} = 36 mA/cm^2.

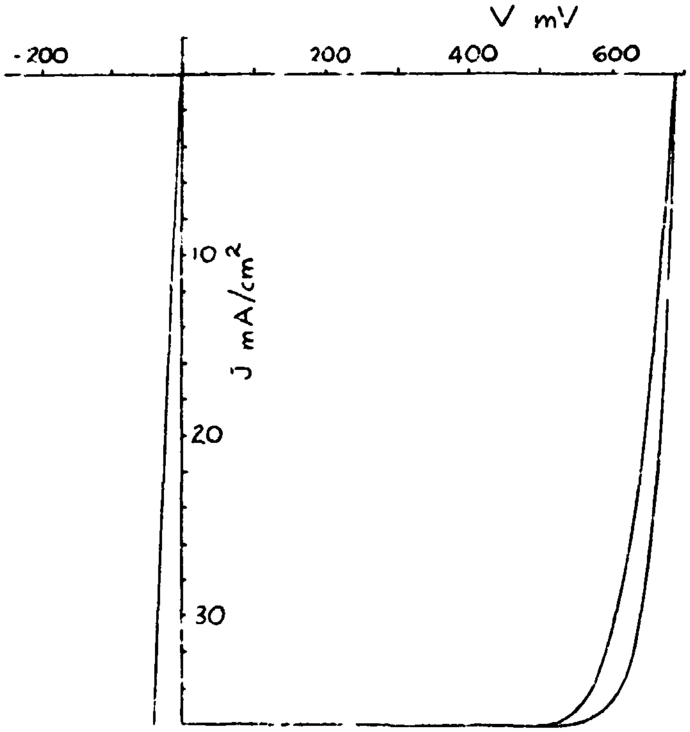

FIGURE 7. Series resistance = 1 Ω for 1 cm^2.

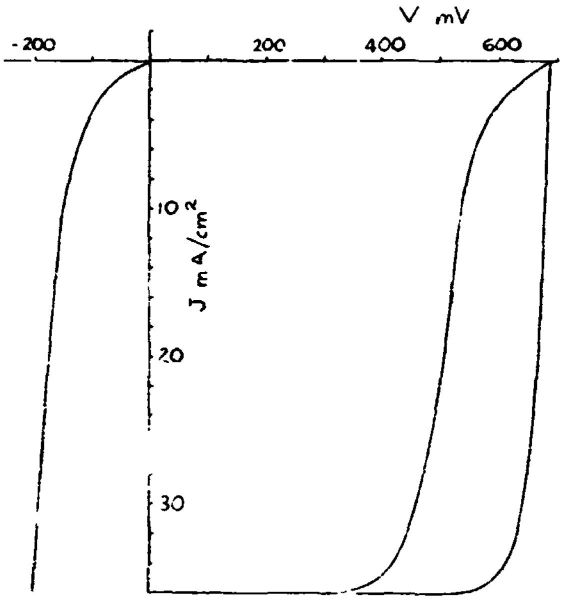

FIGURE 8. Series "forward" diode.

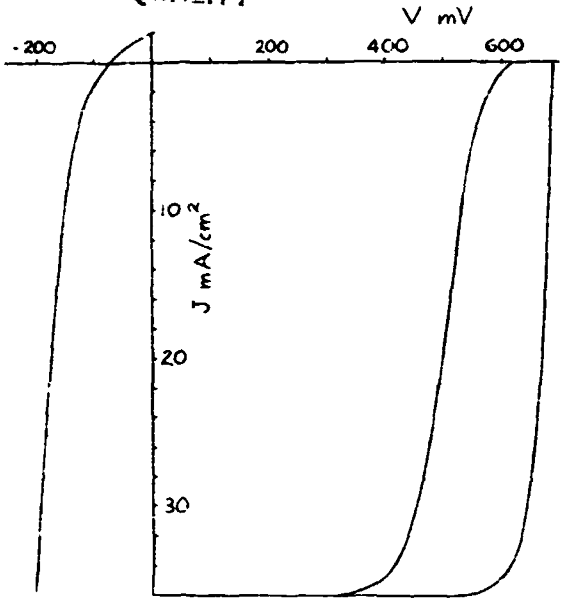

FIGURE 9. Series "forward" diode with photocurrent.

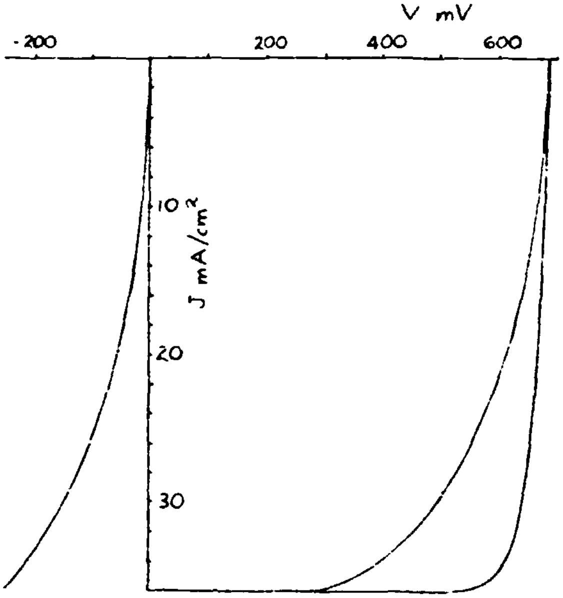

FIGURE 10. Effect of a "reverse" barrier.

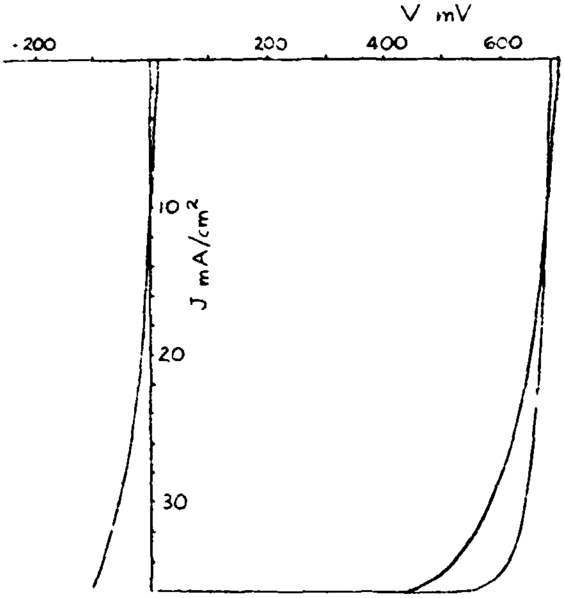

FIGURE 11. Effect of a "reverse" barrier with 10 mA/cm^2 photocurrent.

DISCUSSION

CAMPBELL: Your discussion of the gridded back contacts: as I understand it, the requirement for a gridded back-contact system is more stringent than for the front contact in terms of coverage and so forth?

LESK: I didn't mean to imply that it was tighter coverage problem. If you want to measure a system that looks good, you can put full coverage metal in the front or the back, the same metal or the same contact system, and it looks ohmic and you've got no resistance problems. You could still be doing some other things wrong; you could be putting impurities in the silicon, changing the structure, and so on, so you want to look also any photoeffects you might have in the back contact.

CAMPBELL: I have a specific reference. You mentioned 10 lines per centimeter as being optimum for the back grid.

LESK: No, I didn't say optimum. I did the calculation for that; in fact, that was five of each, five on the front and five on the back, and if you do that, and if you have a quarter of a centimeter of material, by going to that geometry where your current is flowing laterally over most of its path, its resistance is still very small.

ILES: Here is a quick one. Do you have any views about the doubling the efficiency by using bifacial cells, talking about back contacts?

LESK: Bifacial cells? Well, there is a lot written on that. I really don't know. If you want to make n-p-n-like structure and pick up the base contact in the middle and pick up two junctions -- is that what you are talking about?

ILES: It seems a pity to spend a lot of time on the back contact and then not use it for generating additional current, in a sense, but it may be rather complicated, perhaps.

LESK: All the schemes I've seen are much more complex because you've got to get the current out somehow, so you are faced perhaps with a double grid structure and a back, one ohmic and one p-n junction, and you've got to match your currents coming out of the top and the bottom, and that isn't the simplest. I have seen some results printed that are pretty good, but to my knowledge nobody has this in production.

BICKLER: Arnie, I want to ask a question about this back surface you described, which would have a diode in the same direction as the main junction. I guess it relates to what Peter just said: where do you get the second cathode?

LESK: Like an n-p-n structure?

BICKLER: Well, if you have the end top cathode and bulk is the anode p what do you do beneath that? You could put another p as a p^+ but what do you do for a cathode for that back layer?

LESK: Well, no, that's it, if you had -- let's say -- high resistivity and put a metal on there, you could form a Schottky barrier between the metal and the bulk. That would be the barrier on the back surface facing in the same direction as the p-n junction. The back-surface field junction tends to be in that direction.

QUESTION: Could you tell us a little more about that good cell you've shown, having V_{oc} of 690 volts?

LESK: A very good cell that's calculated from a lot of the numbers I've seen in the literature; n = 1. It wasn't made; it's calculated, just to show if you had that in terms of the front, how you can ruin it by what you do in the back. These numbers are not far from the numbers you were talking about as state-of-the-art.