AN n-SIPOS: p-SIPOS* HOMOJUNCTION AND A SIPOS-Si-SIPOS DOUBLE HETEROSTRUCTURE

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For maximal performance solar cells should resemble semiconductor lasers i.e. they should be constructed in the form of a double heterostructure. This configuration is also sometimes called "minority carrier mirrors". We have found rather good performance in SIPOS-crystalline silicon-SIPOS double heterostructures as well as in a p-n homojunction made entirely of SIPOS. This sheds some light on the truly outstanding performance of the n^+-SIPOS: Si heterojunction which has a $J_0 = 10^{-14}$ Amps/cm^2.

It has been recognized for some time that the structure of an ideal solar cell should resemble that of a semiconductor laser. The solar cell should be built in the form of a double heterostructure. In this configuration, a narrow bandgap active layer is sandwiched between two wide bandgap layers of opposite doping. An example of a double heterostructure biased at a forward voltage V is shown in figure 1. The wide bandgap materials may be called "minority carrier mirrors" although this term is more frequently applied to high-low homojunctions at the rear of solar cells.

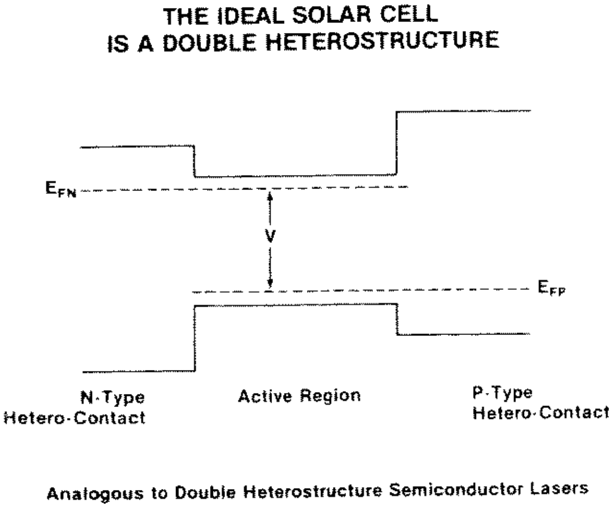

Fig. 1. An example of a double heterostructure under forward bias at a voltage V as would be the case for a solar cell under illumination.

It is usually assumed that the wide bandgap heterocontact layers must be single crystal and lattice-matched to the active layer to assure high performance. While this is a sufficient condition it is not actually necessary. The wide bandgap layers need only be of sufficient electronic quality to support the quasi-Fermi level separation of the high quality narrow-gap active layer. Due to its larger bandgap, the heterocontact material may be disordered and of poor quality and still be able to support the voltage generated in the active layer. That is the key point. The other main requirement is that interface states between the two materials be passivated.

Since crystalline silicon has no useful lattice-matched heterocontacts, it is a prime candidate for a disordered semiconductor heterojunction. Semi-insulating Polysilicon, (SIPOS) is such a candidate material. It is a poorly understood mixture of microcrystalline silicon and silicon dioxide. The interface states between SIPOS and c-Si are probably passivated equally well as the high quality interface between SiO_2 and c-Si.

The first indication of a superior quality heterojunction using SIPOS came in the pioneering work (1) at Sony. Matsushita (1) et al showed that SIPOS heterojunction emitters incorporated as part of a bipolar transistor structure showed greatly enhanced current gains. A more direct measure of heterojunction quality is the forward leakage current J_0, where the forward current is given by $J = J_0 \exp[V/KT]$, where $1/J_0$ may be regarded as a figure of merit for heterojunctions. As a result of adjusting the oxygen content and the annealing sequence of the SIPOS heterojunction fabrication we now routinely produce $J_0 = 10^{-14}$ Amps/cm^2 for n-SIPOS heterocontacts on p-Si. This is about two orders of magnitude superior to a conventional homojunction. Unfortunately, we have been unable thus far to achieve an equivalent figure of merit for p-type SIPOS. Our best value of forward leakage current on p-type SIPOS is $J_0 = 8 \times 10^{-14}$ Amps/cm^2, which is nevertheless superior to that of a homojunction.

A number of different configurations suggest themselves for combining heterojunctions with crystalline silicon. Figure 2(a) shows the most classic configuration in which the crystalline silicon is sandwiched by SIPOS on either side.

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*SIPOS ≡ Semi-insulating Polysilicon, a microscopic mixture of silicon and its oxides.

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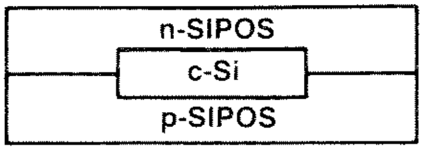
This is in full analogy with a double heterostructure semiconductor laser illustrated in reference 2. A most critical role is played by the vertex on either side where the n-SIPOS, p-SIPOS and c-Si all meet. Recombination is likely to be most severe that point since it represents the only part of the surface of the crystalline silicon which overlaps the depletion region. It may seem surprising that the n-SIPOS and p-SIPOS can be permitted to form a homojunction on either side of the crystalline silicon in figure 1(a). In fact, if the doping level of the SIPOS is too high there is a risk of leakage at that interface, which would degrade solar cell performance.

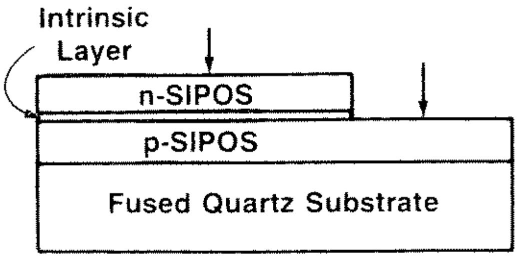


(a)

Fig. 2(a). In an ideal double heterostructure the narrow bandgap active material is surrounded by the wide bandgap material on all sides including the edges. This means that the wide bandgap material must be able to form a homojunction in its own right.

To be useful, the SIPOS homojunction should be capable of supporting a voltage without too much leakage. Indeed an all-SIPOS homojunction should be capable of solar cell action in its own right albeit very inefficiently.

To demonstrate this point we constructed the structure shown in Fig. 2(b). Successive layers of n and p type SIPOS were deposited by cold wall chemical vapor deposition on a fused quartz substrate heated to 650^{0}C by a graphite susceptor. The oxygen source was N_2O while phospine and diborane at a level of 5% of the silane concentration were the doping gases. The proportion of silicon dioxide in the SIPOS was close to 50%. There was a thin intrinsic layer between the n and p layers due to a time delay between turning off the diborane and turning on the phosphine during which SIPOS deposition continued.

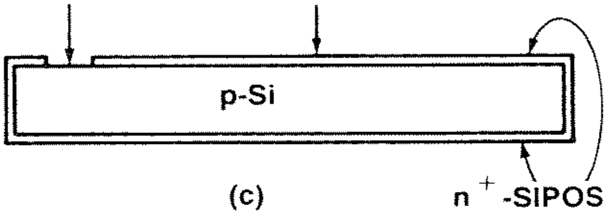


(b)

Fig. 2(b). A low quality homojunction can be constructed entirely of SIPOS

After deposition, the SIPOS was annealed at 950^{0}C in dry nitrogen gas and then removed from the furnace. A contact opening was etched into the upper n-type layer and pressure contact probes were applied at the positions of the arrows in Fig. 2(b). Upon illumination at one sun an open circuit voltage $\simeq$0.15 volts was typically measured. Then the SIPOS homojunctions were annealed in forming gas at 450^{0}C for a period of one hour. This annealing step is known to greatly improve the electronic quality of the silicon-silicon dioxide interface. Since the SIPOS is microcrystalline its electronic properties are dominated by that interfacial quality. Indeed the forming gas anneal raised the open circuit voltage to $\simeq$0.3 volts, which is surprisingly good for such a heterogeneous disordered substance. This shows that while SIPOS is far from ideal as an electronic material, it is nevertheless electronically active. This must be one of the reasons why it plays a successful role as a heterojunction material.

The main task which a heterojunction fulfills with regard to the smaller bandgap active material is to passivate its surface against recombination, while permitting only one of its two types of carriers to be conducted away. Therefore, the structure of Fig. 2(a) need not have opposite doping types on the two faces. Instead, both faces can be covered with the same type heterojunction and the opposite type heterojunction could be relegated to an edge or a corner of the active material. Such a structure is illustrated in Fig. 2(c).



(c)

Fig. 2(c). Since p-SIPOS does not share the excellent figure of merit of n-SIPOS it is necessary to design a solar cell which does not require a p heterocontact. Both faces of the silicon wafer are covered with n-SIPOS and p contact is made through a small opening at the edge.

Obviously the structure of Fig. 2(c) is very advantageous in consideration of the fact that only the n-type SIPOS has a truly outstanding forward leakage current. Since the contact opening for the p-type heterocontact is very small and located on a corner of a much larger wafer the leakage at the p-type contact is relatively unimportant. Under these circumstances, an open circuit voltage measurement can be made without benefit of any special type of p-type heterocontact at all. A simple pressure point contact was applied to the crystalline silicon substrate through the contact opening while the opposite contact was made directly to the SIPOS surface as indicated by the arrows in Fig. 2(c). The parameters of the silicon wafer were as follows:

resistivity	0.5 Ω-cm p-type
doping concentration	$2.5 \times 10^{16}/\mathrm{cm}^3$
bulk lifetime	450 μsec
minority carrier mobility	700 cm^2/volt sec
diffusion length	0.9 mm
thickness	50 μm
J_0 of n^+-SIPOS heterocontact	10^{-14} Amps/cm^2 at 27°C

Notice that the silicon wafer is much thinner than its diffusion length. This assures a uniform distribution of minority carriers throughout the thickness and demands good surface passivation on both front and rear surfaces. On the other hand a thin silicon wafer is beneficial since it reduces the bulk recombination by reducing the bulk. This comes at no expense to the short circuit current if light trapping is incorporated into the cell by texturing the surface. However, in this case both faces were plane parallel and no attempt was made to optimize the current collection.

The open circuit voltage measurement was made under a simulator at 1.3 suns. The light intensity was caliborated by two separate standard solar cells obtained from SERI. An intensity slightly above one sun was chosen in order to partially compensate for the absence of an anti-reflection coating on the silicon wafer and to simulate one sun absorbed internally. The measured open circuit voltage was 720 mV at 25°C.

This outstanding voltage is made possible both by the excellent bulk quality of the crystalline silicon and the excellent surface passivation of the SIPOS heterocontact. The forward leakage current J_0 of the SIPOS heterocontact was checked in two ways in addition to the implicit check associated with the measured open circuit voltage. One method was to fabricate bipolar transistors using SIPOS emitters and measuring the transistor characteristics. Another method was to measure the photoconductivity decay lifetime on wafers with known excellent bulk lifetime and known doping density. Especially for thin wafers, surface recombination will dominate and that can be used to determine J_0. The formula is $J_0 = n_i^2 \, S \, e/P$ where n_i is the intrinsic carrier concentration, S is the measured surface recombination velocity, e is the electronic charge and p is the majority carrier concentration. All these measurement methods agreed with a $J_0 = 10^{-14}$ Amps/cm^2 under an optimized fabrication sequence.

CONCLUSIONS

In a recent article (3) it was shown that the incorporation of light trapping in crystalline silicon raised the theoretical efficiency to the surprisingly high value of 29.8%. In addition they showed that the bulk quality of available silicon was not the limiting factor in trying to achieve the theoretical limit. Rather, the main obstacle is our ability to surface passivate the silicon, especially at the electrical contacts. The availability of SIPOS heterocontacts to solve this problem now permits us to design practical solar cells with efficiencies in the mid 20's percent range, approaching now the theoretical limit.

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