Heavily Doped Polysilicon-Contact Solar Cells

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Abstract—**We report the first use of a (silicon)/(heavily doped polysilicon)/(metal) structure to replace the conventional high-low junction or back-surface-field (BSF) structure, of silicon solar cells. Compared with BSF and back-ohmic-contact (BOC) control samples, the polysilicon-back solar cells show improvements in red spectral response (RSR) and open-circuit voltage. Measurement reveals that a decrease in effective surface recombination velocity *S* is responsible for this improvement. Decreased *S* results for n-type (Si:As) polysilicon, consistent with past findings for bipolar transistors, and for p-type (Si:B) polysilicon, reported here for the first time. Though the present polysilicon-back solar cells are far from optimal, the results suggest a new class of designs for high efficiency silicon solar cells. Detailed technical reasons are advanced to support this view.**

I. INTRODUCTION

HIGHLY CONDUCTING polysilicon contacts to crystalline silicon are widely used in bipolar integrated circuits [1]. Among other properties, these heterojunctions reduce recombination current by forming quasi-blocking contacts [2].

Our purpose is to describe experimental results and their implications deriving from the first use of such contacts in silicon solar cells. Specifically, in this letter we report the results of introducing such contacts at the back surface. The resulting solar cells show large improvements in red spectral response (RSR) and moderate improvements in open-circuit voltage V_{oc} when compared with control cells made with the conventional back-surface-field (BSF) structure or with back-ohmic contact (BOC) structures. To assess the origin of these improvements, we measure the effective recombination velocity S of minority carriers in the monocrystalline silicon as they enter the polysilicon layer. This determines that S (polysilicon back) $< S$ (BSF controls), and we interpret this lowering of the recombination velocity to be the mechanism responsible for the improvement in V_{oc} and RSR. The solar cells and controls described here have n-type and p-type base regions; the decrease in S resulting from p-type polysilicon (Si:B) is reported here for the first time.

II. FABRICATION

The substrate resistivity was $2 \pm 0.5\ \Omega\cdot$cm for both the p-type and n-type samples. The p-type substrates were chemically polished on the back side; the n-type substrates were polished chemically-mechanically. About 2000-Å-thick layers of n^+ and p^+ polysilicon were deposited (*in situ* doped) at 670°C in an atmospheric pressure CVD reactor. The n^+-emitter (Si:P) was diffused at 875°C for about 12 min, and the p^+-emitter (Si:B) was diffused at 900°C for 30 min. During the polysilicon deposition and the emitter diffusion, CVD-SiO_2 protected the other side of the sample. Outdiffusion from the doped polysilicon into the base occurring during the emitter diffusion creates a crystalline low-high junction of thickness <200 Å [2]. The thinness of the resulting n^+ (or p^+) layer at the back suggests that negligible recombination occurs in its volume.

The conventional Al-paste alloying technique formed the BSF region to a depth of about 3 to 5 μm for the p-base BSF controls. Phosphorous diffusion formed a 1-μm-thick BSF region for the n-base BSF controls. These n-base controls and back-ohmic-contact controls had an ohmic contact (Ti + Pd + Ag) deposited and then annealed on the back surface. The p-base samples had a thin layer of Al under the Ti + Pd + Ag, and the heating was below the Al-alloy temperature (~400°C).

III. MEASUREMENTS AND EXPERIMENTAL DATA

We made measurements to compare the merit of the polysilicon-back-contact structure to that of the BSF and BOC controls. Our main object was to explore the influence of the back surface recombination velocity, which enters the boundary-value problem describing the solar cells.

To obtain the boundary-value problem, we follow Shockley in thinking of the device as comprising two quasi-neutral regions separated by a junction space-charge region [3]. We focus on recombination in the volume and at the surface of the quasi-neutral base. If we define the surface as the interface between the silicon and the polysilicon contact, characterized by S, we get a simple model in which the polysilicon recombination and transport mechanisms are imbedded in S. For a BSF cell, we define the surface as that plane where the low-high (p/p+ or n/n+) crystalline junction begins. Then S characterizes recombination occurring in the transition and heavily doped regions. (The usual carrier density and voltage relations together with the continuity equation for minority carriers, completes the boundary-value problem.)

Using an AMO spectrum, we measured the solar-cell parameters. Of these the one most closely linked to S is the RSR, ($\lambda > 6000$ Å). The data appear in Table I. For a p-*type base*, the cells having a polysilicon contact show significant increases in V_{oc} and RSR over those having an

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TABLE I
SUMMARY OF MEASURED PARAMETERS AT 28°C, (NO AR COATING)

Cell	Base type	Back contact	V_{oc} (mV)	$I_{SCR}(\lambda>0.6\mu m)$ (mA)	L (μm)	S (cm/s)
1P	p	ohmic	573	63	310-350	
2P	p	BSF	574	64	310-350	4.2×10^4-5×10^4
5P	p	poly-Si BSF	583	67.7	310-350	1100-1500
1N	n	ohmic	566	62.7	190-250	
2N	n	BSF	565	65.2	190-250	700-1000
5N	n	poly-Si BSF	591	65.5	190-250	100-160

Note: The cells have area $A = 4$ cm^2 and thickness of about 210 ± 10 μm except for cell 2*N* which was 330 μm thick. The results are the average values from 10–20 cells.

ohmic back contact or an aluminum-alloy back surface field. Note, however, that the alloy BSF controls showed no improvement compared with the BOC controls in V_{oc} and only a slight increase in RSR. This indicates that the alloy process failed to yield an effective back-surface field. It is common experience that the alloy process does not consistently yield good BSF regions for ρ as low as 2 Ω·cm, although it is reliable for higher base resistivities. For the cells having an n-*type base*, both the polysilicon devices and the BSF controls, formed by P-diffusion, showed significant and similar increases in RSR when compared with the response of the BOC controls.

To assess whether one can attribute these results to smaller *S*, we measured *S* and diffusion length *L* using an MOS-switch version of the method of [4]. In these experiments, the silicon–polysilicon junction was shown to provide a blocking contact that is markedly superior to the low–high junction of the BSF controls (Table I).

IV. DISCUSSION AND EXTENSIONS

The most important columns in Table I pertain to the red spectral response and to *S*, which emphasize the improvements deriving from the polysilicon/silicon back contact. The improvement in V_{oc} is less striking, partly because V_{oc} depends not only on *S* but also on the collective effects of *L*, shunt conductance, and recombination current in the junction space-charge region and in the quasi-neutral emitter.

The polysilicon/silicon junction is also superior in other respects. Process control for BSF devices is critical for good performance. This is particularly true for the Al alloy process commonly used to fabricate a p-type BSF region. As noted, this process does not reliably form good BSF regions for $\rho \leqslant 2$ Ω·cm. For BSF regions formed by solid-state diffusion, the high temperatures required may degrade lifetime and the low–high junction may be shifted by subsequent thermal processing such as that used to form the p/n junction. Both diffusion and alloy processing consumes part of the substrate, which may pose difficulties for thin solar cells. In contrast the polysilicon-back structure derives from a noncritical deposition process at low temperature [2]; the post-deposition heat treatment also is not critical [2]. Polysilicon back processing consumes essentially none of the substrate. It can be controlled precisely and, is reliable, as employment in bipolar integrated-circuit technology has shown.

Consider now extensions of the present design. First, consider low-ρ substrates (0.5 Ω·cm $< \rho <$ 0.1·cm, corresponding to doping concentrations $\sim 10^{17}$ cm^{-3}), which reduce base-region volume recombination, thus tending to increase V_{oc} and efficiency η. However, effective BSF regions on low-ρ substrates have never been made. In BSF solar cells, $S \propto \rho^{-1}$ for low-injection conditions [5] and for $\rho > 0.5$ Ω·cm approximately. For $\rho < 0.5$ Ω·cm, the potential barrier V (BSF) between the low- ($\sim 10^{17}$ cm^{-3}) and high-doped sides of the BSF junction becomes ineffective: V (BSF) $\simeq (kT/e) \ln [N_{eff}/N \text{ (low)}] \leq 2.3\ (kT/e)$ where N (low) is the doping concentration on the low-doped side and $N_{eff} \sim 10^{18}$ cm^{-3} is the *effective* doping concentration on the high-doped side, corrected for band-gap shrinkage ΔE_G. Thus from [5], $S = (D/L)[N_{eff}/N \text{ (low) (high)}] \rightarrow D/L = S_{max}$, where the minority-carrier diffusivity D and diffusion length L pertain to the highly doped side. For a polysilicon-contacted solar cell, recent experiments [2] show that S_{max} (poly junction) $\ll S_{max}$ (BSF). The mechanisms underlying the relatively low value of S_{max} (poly junction) are still debated in the literature. The polysilicon of [2] and that for our devices of Table I was deposited without an intentional interfacial oxide, and [2] advances the view that the low value of S_{max} derives from extremely low values of D in the highly disordered interfacial region.

Thus we anticipate that polysilicon deposition can give low-*S* contacts on base regions having low resistivities (~ 0.1 Ω·cm). From the results of [2], we anticipate $S <$ 1000 cm/s.

Attaining high efficiency (η) depends on reducing *S* at the front surface as well. Thermal oxides have proved effective over the surface, exclusive of that portion where ohmic contacts exist. Even though ohmic contacts constitute only 5 percent or less of the front surface, one should note that the increase in emitter recombination current caused by areal inhomogeneity greatly exceeds that calculated by consideration of the areal ratio of low-*S* to high-*S* regions [6], [7]. To avoid the resultant drop in η, Green *et al.* [8] have used thin tunneling oxides between the silicon and the metal. Substitution of heavily doped polysilicon for the tunneling oxides

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may provide a better contacting structure with higher yield and longer life.

Sah has recently proposed detailed practical designs for controlling the recombination losses at the front, or emitter, surface [9]–[10]. He has proposed using thin and doped polysilicon layers between the metal and the heavily doped silicon surface of the emitter while using a thermal oxide over the emitter area not shadowed by metal. Employing the data of [2], he has calculated a practical maximum efficiency of above 23 percent provided by the low recombination losses at the front and back surfaces and assumed volume recombination only by Auger and radiative processes.

Thus, we suggest elements of the following new class of silicon solar cell designs: 1) use thin (≤ 150 μm) base regions of resistivity ~ 0.1 $\Omega \cdot$cm contacted on the back by heavily doped polysilicon; 2) interleave the front surface with oxide and a polysilicon/metal system; and 3) use either n-type or p-type silicon for the base region.

As suggested by the work of Sah quoted above, we expect that these solar cells could have very high conversion efficiencies. The present work, together with the somewhat related efforts using SIPOS junctions to reduce surface combination [11], constitute recent significant departures from conventional silicon solar cell designs.

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