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PHYSICS OF SEMICONDUCTOR DEVICES

A New Type of High-Efficiency Bifacial Silicon Solar Cell with External Busbars and a Current-Collecting Wire Grid

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Abstract—Results regarding bifacial silicon solar cells with external busbars are presented. The cells consist of [$n^+p(n)p^+$] *Cz*-Si structures with a current-collecting system of new design: a laminated grid of wire external busbars (LGWEB). A LGWEB consists of a transparent conducting oxide film deposited onto a Si structure, busbars adjacent to the Si structure, and a contact wire grid attached simultaneously to the oxide and busbars using the low-temperature lamination method. Bifacial LGWEB solar cells demonstrate record high efficiency for similar devices: 17.7%(*n*-Si)/17.3%(*p*-Si) with 74–82% bifaciality for the smooth back surface and 16.3%(*n*-Si)/16.4%(*p*-Si) with 89% bifaciality for the textured back surface. It is shown that the LGWEB technology can provide an efficiency exceeding 21%. *© 2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

The development of new techniques for the formation of electric contacts to solar cells is one of the key directions when solving the principal tasks of semiconductor solar photovoltaics.

In order to make solar photovoltaics competitive with present-day energy sources (fossil fuel, nuclear power, other types of renewable energy sources), the cost per peak watt (W_p) of installed power of the solar systems should be lowered by at least by half from its present-day value of \$6/W_p to below \$3/W_p, and the production volume (700 MW_p in 2003) should be raised by approximately a factor of 1000 within 30–50 years [1, 2]. Reasoning from the trend in the development of solar photovoltaics, which steadily demonstrated an annual 25–30% rise in output volume and 5–6% reduction of the W_p cost [1] in the period from 1979 to 2003, these goals seem to be attainable. Accordingly, a historic surmounting of the cost threshold is planned for the year 2013. However, what technical problems are to be resolved in order to achieve this goal?

At present, flat-panel crystalline silicon modules constitute more than 90% of the total manufacture of photovoltaic devices [2]. No alternative to silicon is anticipated in medium-range forecasts [3]. The European Photovoltaics Industrial Association is relying on the flat-panel approach and is planning, among other things [4]:

(i) to raise solar-cell efficiency from the present-day 12–16% to 20%, for which purpose, it is considered necessary, in particular, to develop high-efficiency contacts, preferentially situated on the back surface (back-contact solar cell (BCSC)), in order to reduce the cost of module assembly;

(ii) to reduce the consumption of silicon from 16 g/W_p (now) to 8 g/W_p, because the cost of Si wafers makes up about half of the module cost [5, 6]; therefore, the cell thickness must be reduced from 300 to ~120 μm.

It is necessary to note that the development of bifacial [7] and concentrator [8, 9] cells are also regarded as efficient ways to reduce the W_p cost.

Thus, the need to reduce the W_p cost determines the main lines of research in silicon photovoltaics: solar cells must have a high efficiency, be thin (flat-panel approach), and, desirably, be bifacial with back contacts or of a concentrator type (the concentrator approach is under development now).

Discussing the present-day situation concerning the efficiency of silicon solar cells, it is necessary to note that an efficiency exceeding 20% has already been reached in laboratory devices (the absolute record for silicon cells is 24.7%) [10], but the efficiency of commercially available cells is much lower (12–16%). The main factor limiting the efficiency of commercial cells is the technology of formation of the electric contacts.

Electric contacts define the photocell “face,” both in a literal and metaphorical sense. At present, screen-printing (SP) technology involving the baking-in of metal-containing pastes dominates in the industry: it is used in the fabrication of 90% of silicon solar cells. However, the simple and economical SP technology has serious disadvantages, which make it inapplicable for the production of thin solar cells and restrict the efficiency of commercial cells [11]. In turn, all the record-high values of efficiency have been obtained using the technology of evaporated contacts (ECOs) deposited in vacuum, with the pattern formed by photolithography. However, the ECO technology is not used in wide-scale production because of its high cost.

Therefore, the key long-standing problem in photovoltaics is to reduce the breach between the efficiencies of industrial and laboratory solar cells; thus, new simple and economical technologies must be developed. This problem is particularly important for technologies used in the fabrication of high-efficiency contacts, which should not include photolithographic and masking operations.

Promising designs of solar cells with an efficiency above 20% are being considered, in particular, the HIT structure (heterojunction with an intrinsic thin layer) developed by the Sanyo Electric Co. [12], the point-contact solar cell from Sun Power [13], and the OECO design (oblique evaporated contacts) developed at ISFH [14]. This report presents the results obtained for bifacial silicon solar cells with a wire contact grid and external busbars fabricated by a newly developed low-temperature LGWEB (laminated grid of wire external busbars) technology [15].

2. THE DESIGN OF LGWEB SOLAR CELL

The solar cell (Fig. 1) consists of a [$n^+p(n)p^+$]-Si structure (*1*) and two (facial and back surface) current-collecting systems. Each current-collecting system includes: (i) a transparent conducting oxide (TCO) layer deposited on the surface of a structure, which also serves as an antireflection coating; (ii) electric busbars, facial *2* and back surface *3*, located near structure *1* and a contact grid (facial *4*) produced from a copper wire coated with contact composition and fixed, using the low-temperature lamination method, simultaneously with the facial TCO layer and facial busbars (and similarly on the back surface); (iii) a lamination film (*5*) attached to the TCO surface and fixing the wire contact grid.

3. THE TECHNOLOGY OF LGWEB SOLAR CELL FABRICATION

Solar cells were produced from structures based on *n*- and *p*-type Czochralski-grown silicon (*Cz*-Si). For the *n*-Si structures, the resistivity of silicon was ρ = 4.5 Ω cm and the thickness was 390 µm; for *p*-Si, the corresponding values were 40 Ω cm and 290 µm, respectively. The [n^+np^+]-Si and [n^+pp^+]-Si structures were produced at Kvark (Krasnodar, Russia) by diffusion of phosphorus and boron from deposited P- and B-containing glass using the standard technological equipment. The used wafers were either textured on both sides or had their back surface smoothed by alkaline etching. After removal of the glass, the structures could be etched in a solution of nitric and hydrofluoric acids [16].

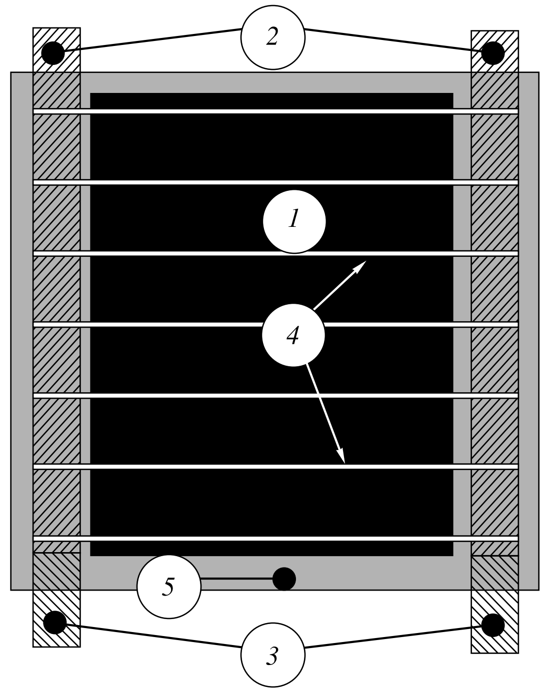


Fig. 1. Design of LGWEB solar cell (the front and back view are identical). (*1*) [$n^+p(n)p^+$]-Si structure with layers of transparent conducting oxide deposited on both sides; (*2*) frontal busbars; (*3*) back-surface busbars; (*4*) wire contact strips; and (*5*) lamination film.

The TCO layers were deposited onto the surfaces of a silicon wafer. For the p^+ layer, this was In_2O_3:Sn (indium tin oxide (ITO)) film, and for the n^+ layer, In_2O_3:F film was used [17]. The films were grown by spraying a solution at the substrate temperature of 400–500°C [18]. The deposition time was ~1 min. The films were ~75 nm thick and dark blue in color. The sheet resistivity of the ITO and In_2O_3:F films was ~50 and ~30 Ω/sq, respectively. After the deposition of the TCO, a sample of the desired area was cut out using a diamond scriber; no additional treatment of edges was performed. The contact grid, made of copper wire 70 µm in diameter and coated with a contact composition, was fixed onto the TCO with a 32-µm-thick lamination film at a temperature of 150°C.

4. THE MERITS OF THE LGWEB DESIGN

(i) The introduction of a TCO makes it possible to use a simple homogeneous (nonselective) emitter with a high sheet resistivity of 100 Ω/sq or higher in an LGWEB.

(ii) The combination of contact grid wire with a TCO in an LGWEB makes it possible to obtain extraordinarily low (3.2%) shadow loss and serial resistance loss [19]. Such losses are no higher than in solar cells with ECO metallization and about three times less than for SP metallization [20–22]. The width of the wire contact finger is only ~80 µm, and it can easily be

Table 1. Parameters of LGWEB solar cells

Parameter	Group 1: n^+–n–p^+				Group 2: n^+–p–p^+			
	#615		#739		#1044-2		#1043-1	
	front	back	front	back	front	back	front	back
Texture	+	+	+	–	+	+	+	–
R_{ini}, Ω cm^2	26		60		52		84	
R_{fin}, Ω cm^2	112		110		85		84	
I_{sc}, mA cm^{-2}	35.0	30.8	36.2	27.3	35.4	31.3	36.6	29.8
V_{oc}, mV	609	607	623	615	617	614	619	615
FF, %	76.5	77.4	78.3	78.5	75.2	76.6	76.2	78.0
Eff, %	16.3	14.5	17.7	13.2	16.4	14.7	17.3	14.3
Eff$_{total}$, %	30.8		30.9		31.1		31.6	
Bifaciality, %	88.9		74.6		89.6		82.7	
Area, cm^2	32.2		42		42.3		42.3	

Note: R_{ini} denotes the sheet resistivity of the emitter after diffusion; R_{fin}, the sheet resistivity of the emitter after its etching; and Eff$_{total}$, the total efficiency on the front and back surfaces. Bifaciality refers to the ratio of efficiencies for illumination of the back and front surfaces. Solar cell no. 615 was tested at the Sandia National Laboratories and further used as the reference sample.

reduced. In addition, the copper wire contact fingers have a low longitudinal resistance, ~40 mΩ/cm, which is more than 15 times lower than that obtained by the SP method. These properties are especially important for large-area solar cells and concentrator cells.

(iii) The LGWEB design is preferable to the BCSC variant because it is free of the principal disadvantage of the latter, that is, the production of a high-efficiency BCSC consumes expensive floating-zone *Fz*-Si. For example, calculations carried out by Sun Power have shown that, in order to obtain >20% efficiency in their Point Contact cells, silicon with a carrier lifetime >1 ms is necessary, i.e., *Fz*-Si [13]. Similarly, to obtain high efficiency in an OECO solar cell of 200–300 μm in thickness, the diffusion length must be no less than 500–800 μm [23]. For silicon of inferior quality, the efficiency of a BCSC sharply decreases, and this decrease is even stronger than for cells with contacts on both sides. Thus, the unique advantage of LGWEB solar cells is that their busbars lie clear of the cell but contact strips are present on both surfaces. As a result, not only is the module assembly simplified, even more than in the case of the BCSC version, but the requirements placed on Si quality do not become more stringent.

(iv) The contact fingers can be produced from wire of any cross-sectional shape, e.g., triangular, which is considered to be an efficient method to reduce shading [24].

(v) Wire contact fingers are compatible with virtually any shape of solar cell surface, not only smooth or textured, but also rough, undulated, or curved. This circumstance means that the LGWEB design offers extraordinary advantages over other techniques for ribbon silicon (EFG).

(vi) LGWEB solar cells are bifacial.

(vii) The low (<150°C) temperature of fabrication makes LGWEB technology applicable to solar cells based on amorphous materials, including the HIT structure.

5. PARAMETERS OF AN LGWEB SOLAR CELL

The parameters of the solar cells were determined from light current–voltage (*I–V*) characteristics: short-circuit current density J_{sc}, open-circuit voltage V_{oc}, filling factor FF, and efficiency Eff. For sample no. 615, the results were obtained at the Sandia National Laboratories (SNL); these data included spectral response and reflectance. For the other cells, J_{sc} was measured using a Telecom–STV pulse tester, and sample no. 615 was used for current calibration. It was found that, with an adequate current calibration, the Telecom–STV tester provides a correct measurement of J_{sc} with less than ±2% error, but V_{oc}, and especially FF, are underestimated, which is related to the nature of pulse measurements. The extent of underestimation increases as the effective lifetime of minority carriers in the base increases. Therefore, V_{oc}, FF, and Eff were determined from steady-state light *I–V* characteristics under illumination with a 1000 W halogen incandescent lamp on a thermostated table, in which case the temperature of the solar cell reached (25 ± 0.1)°C. In these measurements, the short-circuit current of each solar cell was set according to the value measured with the Telecom–STV tester.

The parameters of the LGWEB solar cells made of *n*-Si (group 1) and *p*-Si (group 2), for both a textured and a smooth back surface, are listed in Table 1. As can be seen from Table 1, the LGWEB technology makes it

Table 2. Parameters of LGWEB solar cells and cells produced at ISFH using different contact deposition techniques

Type of solar cell		Si (type)	Area, cm^2	ρ(Si), Ω cm	Eff, % (front)	Eff, % (back)
OECO [14, 23]	Monofacial	*Fz*(*p*)	4	0.5	21.1	–
				1.5	20.4	
			100	0.5	20.0	–
		Cz(*p*)	4	1.3	18.3	–
			100	1.3	17.9	–
	Bifacial	*Fz*(*p*)	4	0.5	19.0	17.0
	Bifacial BCSC				18.1	17.4
					19.2	16.0
ECO (front and back), bifacial [7]		*Fz*(*p*)	4	0.5	20.1	17.2
ECO (front)/SP(back), bifacial [25]		*Fz*(*p*)	4	1.5	17.4	13.4
SP (front and back), bifacial [26]		*Fz*(*p*)	2.6	1.5	14.5	12.7
		Cz(*p*)	4	6.0	13.4	11.5
LGWEB		*Cz*(*p*)	42	40	16.4	14.7*
					17.3	14.3**
		Cz(*n*)	32	4.5	16.3	14.5*
			42		17.7	13.2**

Notes: * Indicates that the front and back surfaces are textured and ** indicates that only front is surface textured.

possible to fabricate bifacial solar cells from *Cz*-Si with a facial and back surface efficiency over 17% and 14%, respectively.

6. COMPARISON OF LGWEB AND OECO SOLAR CELLS

To assess the quality of the obtained results, we compare them with data obtained by R. Hezel, a pioneer and leader in photovoltaics, at ISFH (Germany) using other contact deposition techniques and, in particular, the new high-efficiency OECO technology. The unique specific feature of OECO technology is that, for the first time, high-efficiency MTIS (metal–(tunnel insulator)-semiconductor) contacts were deposited onto a solar cell without photolithography and masking. Table 2 offers a comparison of the parameters of solar cells produced at ISFH by different metallization techniques (OECO, ECO, and SP) and using the LGWEB design developed by our team.

The choice in favor of the ISFH team for the comparison is due exclusively to the wide diversity and record-high level of their results, which make it possible to reveal the influence exerted on solar cell efficiency by such important factors as silicon (*Cz*-Si or *Fz*-Si) quality, silicon resistivity ρ, size of a solar cell, contact deposition technique (ECO or SP), and cell design (monofacial, bifacial, or with all contacts on the back surface (BCSC)).

Analysis of the data in Table 2 shows that the record efficiency for OECO technology (21.1%) was obtained for a monofacial solar cell of 4 cm^2 in area made from *p*-*Fz*-Si with ρ = 0.5 Ω cm. However, the efficiency of OECO cells decreases on passing (i) from *Fz*-Si to *Cz*-Si by 2.1–2.8%, (ii) from monofacial to bifacial design by ~2.1%, (iii) from monofacial to bifacial design with back surface contacts by 1.9–3%, and (iv) from the size of 4 cm^2 to 100 cm^2 by 0.4–1%.

A correct comparison of OECO and LGWEB cells demands data for solar cells with comparable parameters, which are, regretfully, absent. However, the efficiency of a bifacial OECO cell made of *Cz*-Si, with back surface contacts of 4 cm^2 in area, can be estimated as 15.3–16.4% on the front side and 13.2–14.6% on the back surface, which is no higher than the efficiency of an LGWEB solar cell (~1% less on the front side).

7. LGWEB SOLAR CELL AS COMPARED WITH A CELL WITH SCREEN PRINTING METALLIZATION

The data listed in Table 2 can also be used for tracing how the efficiency of a bifacial solar cell based on *Fz*-Si decreases when ECO contacts are replaced by SP ones. For example, when ECO metallization is used on both sides, the front–back efficiencies are fairly high: 20.1 and 17.2%, respectively. When ECO contacts are replaced by SP ones only on the back surface,

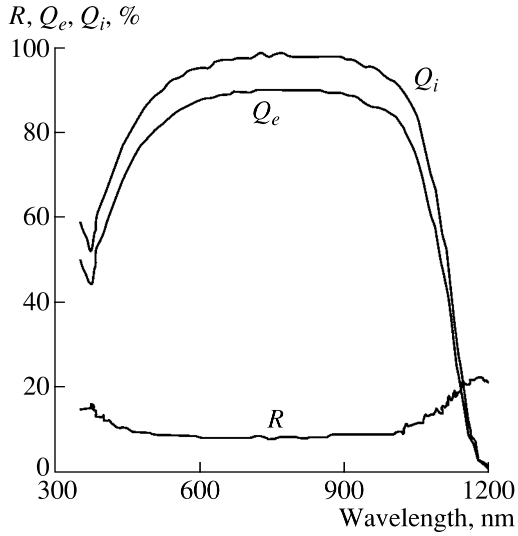
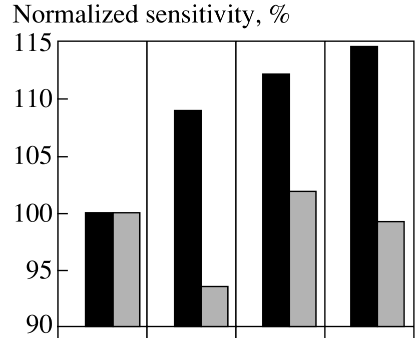


Fig. 2. The reflectance R and internal Q_i and external Q_e quantum yield of charge separation for solar cell no. 615.



	#615	#1044–2	#739	#1043–1
R_{ini}, Ω/sq	26	52	60	84
■ 350–540 nm	100	109	112	115
□ 920–1200 nm	100	94	102	99

Fig. 3. Comparison of spectral sensitivities of LGWEB solar cells in the blue-green (350–540 nm) and IR (920–1200 nm) spectral ranges under frontal illumination normalized to the sensitivity of solar cell no. 615.

the efficiency falls to 17.4 and 13.4%, and, for a cell with SP contacts on both sides, the efficiency falls to the exceedingly low values of 14.5 and 12.7%. This example clearly demonstrates the drawbacks of SP technology.

8. PROSPECTS FOR RAISING THE EFFICIENCY OF LGWEB SOLAR CELLS

The efficiency of LGWEB solar cells can be raised by more than 4.5% and, correspondingly, exceed 21% by applying the measures considered below.

Reflection. First of all, we stress that our LGWEB solar cell is already laminated, which means that its measured efficiency approaches that in a module. Currently, we use a lamination film with high refractive index ($n \approx 1.56$) which leads to high reflection (~4.8%). Figure 2 shows the reflectance R and external Q_e and internal Q_i quantum yield for solar cell no. 615. It can be seen that, in the range 450–1000 nm, $R \approx 8$–9%, of which ~4.8% and 3.2% are accounted for by the lamination film and wire grid, respectively. Therefore, the efficiency can be raised by ~0.5% by reducing n to 1.3.

Base resistivity. The optimization of the base resistivity ρ offers a significant reserve for increasing LGWEB solar cell efficiency. It is necessary to note that, in the record cells, the base material is usually heavily doped, to $\sim 3 \times 10^{16}$ cm^{-3} ($\rho \approx 0.5$ Ω cm), which improves the efficiency by diminishing the bulk recombination current, series resistance, and negative effect of a high injection level. The influence of ρ in the range ρ = 0.08–1.4 Ω cm on the efficiency of OECO solar cells was studied in detail in [23]. It was shown that, as ρ increases from the optimal value of 0.4 to 1.4 Ω cm, the efficiency decreases from 21.1 to 20.4%, i.e. by 0.7%. At the same time, our LGWEB solar cells are produced from silicon with a nonoptimal doping level, which is 30–100 times lower than that conventionally used in high-efficiency solar cells. Therefore, we believe that optimization of ρ will raise the efficiency of LGWEB cells by more than 1%.

Diffusion layers. The diffusion layers in LGWEB solar cells are not yet optimized. The short-wavelength sensitivity of solar cell no. 615 is low [20], and we attribute this fact to the heavy initial doping of the emitter (26 Ω/sq). It was found, however, that the short-wavelength sensitivity increases as the initial (i.e., immediately after the diffusion) sheet resistivity R_{ini} of the emitter increases (Fig. 3). Moreover, increasing R_{ini} not only makes the short-wavelength sensitivity higher but also improves the other parameters of solar cells (Table 1). It is noteworthy that the long-wavelength sensitivity of the samples with a smooth back surface is higher than that for samples with a textured back surface, which, evidently, is related to enhanced reflection of long-wavelength light from the smooth surface. In addition, the long-wavelength sensitivity of the solar cells based on n-Si is, in general, higher than for p-Si cells, possibly because their thickness is 100 μm larger.

The edges. The edges of the LGWEB solar cells were not specially treated, so they are a source of losses. The experimental data presented in Fig. 4 show that increasing the area of LGWEB cells results in an increase in their efficiency. This result contrasts strongly with the case of OECO cells, where the opposite effect was observed. Therefore, resolution of the edge problem will allow the efficiency to be increased by ~0.5%.

The quality of silicon. As can be seen from Table 2, the use of high-quality Fz-Si can enhance the efficiency of LGWEB solar cells by ~2.5%.

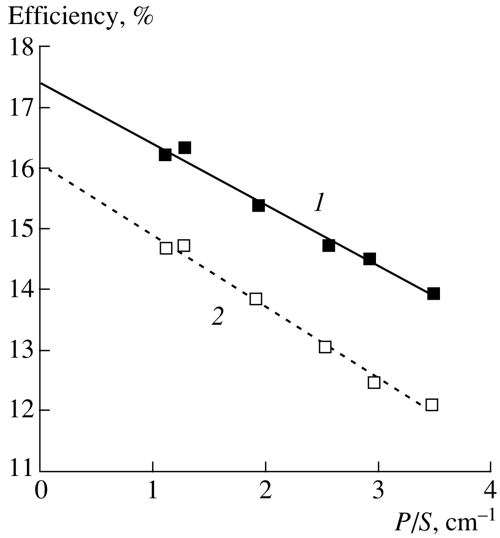


Fig. 4. Efficiency of an LGWEB solar cell vs the ratio between its perimeter and area, *P/S*. Curve *1* shows frontal illumination and curve *2*, back surface illumination.

9. CONCLUSION

Thus, solar cells with a new design and technology for the fabrication of the current collecting system, LGWEB, demonstrate record-high efficiency for their class of solar cells (bifacial, back-contact, and *Cz*-Si). The analysis shows that a wide field of action is open for the optimization of LGWEB solar cells and improvement of their efficiency, which can potentially exceed 21%.

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