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Advanced Silicon Solar Cell Structures for Space Applications

S. H. Lee and D. S. Kim

Electronic Materials Lab, Samsung Advanced Institute of Technology,
P. O. Box 111, Suwon 440-600, Korea

Abstract

This paper reviews the advanced solar cell structures used in space. These are the structures which incorporate the back surface field and reflectors with very shallow and lightly doped emitters. Their use in space has shown that the thinner cells are more resistive to radiation damage than the thicker ones. It has been found that the charged particles affect both the surface and bulk of the cells used in space. This causes degradation in the output power, which in effect, can be explained by the degrading diffusion length of the cells. The PERL cells showed higher BOL (beginning of life) efficiency and almost the same EOL (end of life) efficiency as structures with wrap-around contact configuration fabricated on 10 Ωcm resistivity substrates. This observation lead to a conclusion that, the space cells do not necessarily need to have very high BOL efficiency except in specific missions which require such.

Introduction

The use of solar cells in space has aided the utilization of the available sunlight in space to remove the need to carry on-board fuels into orbit. It has also increased the active life of storage batteries, which can be recharged by the solar cell array. Silicon solar cells have successfully provided electric power for spacecraft for over 35 years with very good reliability.

There are several space missions which require a different set of operating conditions. But in general, a space cell must have high efficiency, because spacecraft real estate is expensive and limited. It must have high radiation resistance in orbits containing trapped charged particles and moderate loss of power at elevated operating temperatures.

Thus the spacecraft power designer must select the cell designs that best suit their mission requirements. This requires a detailed specification that is closely monitored to ensure that the cell design is compatible with the mission requirements to the highest level of reliability. Every solar cell design intended for use in orbit must undergo a considerable testing and validation to ascertain its suitability.

Despite the rigorous testing and validation requirement for cell design there has been continuing evolution of many different cell materials, cell designs and processing techniques. Every solar cell structure must necessarily meet the space operating conditions which are quite different from the terrestrial applications, most especially, the radiation damage which is an important issue for missions in the mid-altitude orbit (MAO) and geostationary orbit (GEO)[4]. The solar array efficiency at EOL (efficiency after a stipulated period of time in space which can span up to seven years) after radiation damage has to supply enough energy for spacecraft. Hence, the cell efficiency at the end of its life is more important than that at BOL.

Since the radiation levels are different for different orbits of the spacecraft, different radiation resistance is required for the cells to meet different missions. It is, therefore, important to know the cell performance after exposure to different radiation levels. This will also help to understand the mechanisms of the radiation damage to the cells.

There has been various silicon solar cell structures that have been used in space since its inception. In this paper only the advanced silicon solar cell structures would be reviewed with respect to radiation damage.

Space Operating Conditions

The selection of a solar cell design for a particular mission in space is determined by the operating conditions which include: solar radiation, charged particle radiation and temperature.

The spectral distribution near the earth, but outside its gaseous atmosphere is called air-mass zero (AMO), and the total intensity for the wavelength range from 0.25 to 2.5 μm is 135.3 mW/cm^2. Absorption in the earth's atmosphere results in the AM1.5 spectrum. The same cell tested under the two spectra will deliver more power under AMO illumination, but AMO efficiency is 0.85-0.9 of the AM1.5 efficiency.

The major difference between space and terrestrial operating conditions is the possibility of exposure to charged particle radiation (electrons and protons). Solar cells are usually placed on the outer surface of satellites, and they are directly to radiation transparent shields (cover glasses) that are used to reduce cell temperature can minimize degradation from the low-energy particles, but this shielding is less effective for energetic particles.

Heat is generated from the excess solar energy that is not converted to electrical energy. Photons with wavelengths($\approx$1.5 μm for Si) are not converted to electron hole pairs, and if these long wavelengths are directed out of the cell the operating temperature can be reduced. In the space (vacuum), heat cannot be transferred by conduction or convection, thus radiation is the only means for heat loss from spacecraft. The equilibrium temperature of a spacecraft is therefore determined by the balance between the absorbed solar energy and the emission of generated heat.

Based on these operating conditions a silicon solar cell is designed. Thus the next section reviews the structures used or that have been tested for radiation damage in preparation for use in space.

Advanced Silicon Solar Cell Structures

The advanced structures include the following:

- Cell structures with WA or WT (wrap-around or wrap-through) metal contact to reduce solar array assembly cost through reduction of handling [7,8] which consist of BSFR (back surface field with reflector) and BSF (back surface field) configurations. In this paper this structure would be referred to as WA or WT. The features of WA or WT are gridded back contact, wrap-through contacts, dual AR on the backside, lightly diffused emitter, dielectric layer in conjunction with a reflector to reduce absorption (for BSFR cell); thick layer of SiO_2 to isolate the n^+ contact from BSF and the p-type substrate.
- PESC (passivated emitter solar cell)[1,2]. The PESC structure consists lightly doped emitter on silicon substrate, passivating silicon dioxide layer on front surface, inverted pyramids on the

illuminated front surface (for reduced reflection as well as improved light trapping), heavy, deep diffusion underneath the front metal contact for low metal contact recombination, boron diffusion across the entire rear surface (BSF) and rear metal contact.

- NRS/LBSF (non reflecting surface/locally diffused back surface field)[5] which is basically the PERL (passivated emitter and rear locally diffused) structure [1]. The features of PERL cell are basically the same as those of the PESC except in the rear metal contacting scheme. The heavy, deep diffusion underneath the rear metal contact has enabled the PERL cell to exhibit lower metal contact recombination than PESC. The NRS/LBSF cell manufactured by Sharp Corporation is basically the PERL structure.
- Bifacial cell which is mainly the n^+pp^+ cell [6,9]. The features of the bifacial silicon solar cells reported today for space applications are a lightly diffused phosphorus emitter and heavy, deep diffusion underneath the front metal contacts, boron diffusion across the entire rear to provide the back surface field and heavy, deep boron diffusion underneath the rear metal contacts, passivation oxide layer on both surfaces, double AR coating on front surface.

Thus the distinguishing features of an advanced cell structure are the back surface field which can either be diffused to the entire rear surface or through some holes, back surface reflectors, non reflective surfaces, lightly doped emitters and front surface passivation. In the next section, the basic theory of solar cell will be revised, in particular to relate the diffusion length to radiation damage.

Basic theory of solar cell operation

A solar cell is basically a p-n junction diode operating in parallel with a constant current source, figure 1. The relationship between the current and voltage at the output terminals of the solar cell is [4]

$$I = I_s\{\exp[(q/kT)(V-IR_s)]-1\}-I_L+ (V+IR_s)/R_{sh} \qquad (1)$$

where I_s is the diode saturation current, and I_L is the light-generated current in the solar cell. The diode saturation current is given by

$$I_s = Aq[(D_p p_{no}/L_p) + (D_n n_{po}/L_n) \qquad (2)$$

q is the value of the electric charge, D_p is the diffusion coefficient for holes in the n region, D_n is the diffusion coefficient for electrons in the p region, p_{no} is the equilibrium concentration of holes in the n region, n_{po} is the equilibrium concentration of electrons in the p region, A is the total area, and L_p and L_n are the diffusions lengths of holes and electrons, respectively. The output power of the device is simply

$$P = IV = I\{[kT/q]\ln[(I+I_L)/I_s + 1] - IR_s \qquad (3)$$

Equation assumes that, the shunt esistance as low as 100 Ω have negligible effect on the output of the cell, therefore the last term of Eq.1 can be discarded. Under short circuit conditions, V=0 and Eq.1 becomes

$$I_{sc} = I_s\{\exp[(q/kT)(-I_{sc}R_s)]-1\} - I_L \qquad (4)$$

Under one sun conditions, I_{sc} is equal to I_L for low values of R_s, and Eq.4 becomes

$$\ln[2I_{sc}/I_s+1] = qI_{sc}R_s/kT \qquad (5)$$

The preferred structure for a space cell is a thin (<0.2 μm) n-type emitter on a thin (<100 μm) p-type base. In such a cell, the base component of short circuit current predominates for all but the longest wavelengths of the incoming solar illumination. Thus the minority-carrier electrons in the base

$$I_s = qAD_nn_{po}/L_n \text{(for p-type material)} \qquad (6)$$

where A is the cell area. Using the approximation $I_{sc} >> I_s$, Eq.5 becomes

$$\ln(1/I_s)+\ln(2I_{sc})=qI_{sc}R_s/kT \qquad (7)$$

and

$$I_{sc}=(kT/qR_s)[\ln(L_n/qD_nn_{po})+\ln(2I_{sc})] \qquad (8)$$

Eq.8 shows that the short circuit current is a slowly varying function of the particle fluence. This can be approximated to

$$I_{sc}=a\ln(L_n)+b \qquad (9)$$

where a and b are constants.

The open circuit voltage V_{oc} of a solar cell is given as

$$V_{oc} = (kT/q)\ln[I_{sc}/I_s+1] \qquad (10)$$

and using the Eq.9 this expression can be written as

$$V_{oc}=(kT/q)\ln\{[b+a\ln(L_n)]/AqD_nn_{po}/L_n\} \qquad (11)$$

Eq.11 gives the dependence of open circuit voltage on diffusion length which is more complex than the short circuit current dependence.

The maximum power out of the solar cell under illumination is given by

$$P_{max} = I_mV_m \qquad (12)$$

where I_m and V_m are the current and voltage at the maximum power point. The ratio of current and voltage at the maximum power point to I_{sc} and V_{oc} is the fill factor of a cell, FF:

$$FF = I_m V_m / I_{sc} V_{oc} \qquad (13)$$

and $$P_{max} = FF\ I_{sc} V_{oc} \qquad (14)$$

The efficiency (η) of the cell is the ratio of maximum power out to the total power in, or

$$\eta = P_{max}/P_{in} = FFI_{sc}V_{oc}/P_{in} \qquad (15)$$

Thus Eq.15 can be used to predict the performance of a solar cell as a function of diffusion length.

Effect of radiation on diffusion length of a space cell

The radiation damage affects primarily the diffusion length of the cell as seen in Eq.15. This equation can therefore predict cell behavior as a function of radiation damage. It is well known that the lifetimes of the excess electron and hole minority carriers in a solar cell, under low-level injection conditions, are inversely dependent on the density of recombination centers by creating defects in the solar cell material. Thus it can be assumed, to the first approximation, that the density of additional recombination centers at any instant during the exposure is proportional to the total accumulated fluence. The minority carrier lifetime is then given by

$$1/\tau = 1/\tau_o + c\Phi \qquad (16)$$

where τ_o is the initial lifetime, Φ is the fluence (number of particles/cm^2), and c is a constant for a given material and particle type. Since the diffusion length is defined as

$$L = (D\tau)^{1/2} \qquad (17)$$

Eq.16 may be rewritten as

$$(1/L)^2 = (1/L_o)^2 + K\Phi \qquad (18)$$

where L_o is the initial diffusion length, and $K = c/D$ is the diffusion length damage coefficient. The fluence required to reduce the output of a cell to 75% of the initial value, defined as the 'critical fluence' Φ_c, is a convenient measure of radiation tolerance [14].

The short circuit current of Eq.9 can be rewritten by substituting for L_n,

$$I_{sc} = b - (a/2\ln)\ (K\Phi + 1/L_o^2) \qquad (19)$$

which predicts that the short circuit current is expected to vary as the natural logarithm of the total fluence. Similarly, the dark saturation current in Eq.6 becomes

$$I_s = qD_n n_{po} A[K\Phi + (1/L_o)^2]^{1/2} \qquad (20)$$

Therefore the open circuit voltage can be expressed as

$$V_{oc} = (kT/q)\ln\{[b - (a/2)\ln(K\Phi + 1/L_o^2] /qD_n n_{po} [K\Phi + (1/L_o)^2]^{1/2}\} \qquad (21)$$

Since the logarithm of the fluence (numerator in eq.21) is a more slowly varying function than the fluence itself, the variation of V_{oc} as a function of fluence can be written as

$$V_{oc} = \text{const .} - (kT/2q)\ln\{qD_n n_{po}[K\Phi + (1/L_o)^2]\} \qquad (22)$$

and

$$P_{max} = \text{const.} - g\ln[K\Phi + (1/L_o)^2] \qquad (23)$$

where g is a constant to a good approximation and neglecting the square of the logarithm compared with the first power.

In general, there are two fundamental interactions between the incoming electrons or protons and the atomic constituents of the semiconductor material: inelastic interactions with the bound atomic electrons in the solid, or elastic collisions with the atoms of the solid [4]. The first interaction, which results in ionization, is transient in nature and constitutes the primary energy loss mechanism for the incoming particles; the second can result in atomic displacement in the solid, provided the incoming particle energies are above a threshold value that is characteristic for each semiconductor type. It is the second interaction that affects the performance of solar cells, since the defects created by atomic displacement may become recombination centers for the light-induced minority carriers, reducing their lifetime and lowering cell output [4]. As noted with Eq.15, the cell parameter most important in determining the output of a solar cell as a function of radiation damage is the diffusion length.

Radiation effects on various cell structures

The experimental result of radiation damage for each cell structure have been assessed on the basis of the following parameters

- cell structure
- substrate thickness
- substrate resistivity
- emitter depth
- material growth technology (FZ or CZ) and
- surface topography (inverted or upright pyramid)

as summarized in table 1. The table also indicate the BOL and EOL efficiencies of each structure.

Discussion

Table 1 summarizes the effect of radiation damage on different solar cell structures. On the basis of structure, the PERL structure has been widely investigated for space use. It is one of the advanced structures recently scheduled for a space mission as reported by Katsu et al[5]. Comparing the PERL cells made on the same resistivity substrates i.e. cells 2 and 7 on 0.5 Ωcm and cells 3 and 5 on 2 Ω cm. The two sets of PERL cells; set 1 (2 and 3) and set 2 (5 and 7) are different from each other in the emitter depth, cell thickness and wafer growth technique. Thus the difference in the BOL efficiencies is quite obvious. But the EOL efficiencies for set 2 CZ cells are higher than the set 1 FZ cells, which may be partly attributed to the deep emitter (set 1) and the difference in substrate quality i.e. the growth technique (CZ or FZ).

The differences in FZ and CZ grown material have been noticed and correlated with the relatively high oxygen (O) and carbon (C) concentrations in the CZ material. Although the FZ material produces higher initial efficiency, the critical fluence (Φ_c) for CZ material is larger [11]. The FZ material experiences "photon degradation" after a short period (24 hours) of exposure to light following irradiation (irradiation in the dark appears to make the Si susceptible to a process that is completed by the action of light and causes the lifetime to be reduced) [10]. Addition of O and C to FZ material [11] appear to alleviate the effect of these photo-induced changes in the defect complexes.

The PESC structure has not been receiving much attention in the recent times. However, its BOL and EOL efficiencies are lower than the PERL structures fabricated on the same substrate resistivity.

The WA structures are similar to PERL cells except in the incorporation of the wrap-around contacts to provide a ready made contact for array fabrication. These cells have been commercially produced by ASEC (Applied Solar Energy Corporation) [8] in 1990. Even though their BOL efficiencies are lower than the PERL cells made on the same resistivity substrates, their EOL efficiencies are much the same with only 0.2 difference. The reason for this slight difference may be due to the cell areas which is 4 cm^2 (PERL) and 59.8 cm^2 (WA). Also, the nature of front surface topography influences the cells degradation as noted by Katsu et al [5]. Thus the inverted pyramid front surface will cause less radiation degradation than the upright pyramid surfaces.

Three bifacial cells were fabricated on 50-180 μm thick wafers and it has been observed that the thinner the cell thickness the lower its BOL efficiency but the higher the EOL efficiency because at the highest fluence level, the thin cell retains more than 65% of its short circuit current. Comparing the bifacial cell (50 μm) with the PERL structure fabricated on 10 Ω cm resistivity substrates, their BOL efficiencies are the same. However their EOL efficiencies are different by only 0.6 which may be accounted for by the difference in the substrate growth technique.

Conclusion

In general, the advanced silicon solar cell structures should be designed with the following specifications;

- emitter depth ~ 0.1 μm
- use of thin substrate (50-100 μm)
- use of high resistivity substrate (2-10 Ω-cm)
- use of DARL (double anti-reflection coating layer)
- CZ substrates

The shallow emitter will ensure the collection of carriers despite the short diffusion lengths. The thin substrates would be useful in reducing the distance the electron-hole pairs must travel before they recombine. It will also be useful in reducing the weight of the space craft. The relatively high resistivity substrate will provide better lifetime, even after the exposure and DARL enhances the current collection. CZ substrates should be used because it has a larger critical fluence than the FZ wafers i.e. cells made on CZ substrates would possess higher radiation resistance. With these design specifications, the cell EOL would be improved.

The PERL structure, therefore, is most applicable structure for space use because it has been designed to give very high BOL efficiency (>20% AMO) which would be useful for low earth orbit (LEO) missions. The LEO missions require cells with high BOL efficiency because this environment is relatively radiation free. It has also been designed to give high EOL efficiency (>12% after $1x10^{15}$ e/cm^2 fluence). These cells are very useful in the MAO (mid-altitude orbits) and GEO (geostationary orbit) where radiation damage is an important factor. The bifacial cells also have the same trend to meet all the space missions.

As seen with the PERL and WA cells made on 10 Ωcm, the high BOL efficiency of the PERL cell degraded to almost the same EOL efficiency value of WA cell. It can therefore be conclude that, except for LEO missions which require cells with high BOL efficiency, missions in the MAO and GEO do not necessarily need cells with high BOL efficiency.

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Table 1: Radiation performance of advanced silicon solar cell structure: AMO efficiency (η) after 1×10^{15} e/cm^2 of 1MeV electrons.

No	Cell Structure	Front Surface topograhy	Substrate resistivity (Ωcm)	Wafer thickness (μm)	Growth technique	Emitter depth(μm)	AMO Efficiency (η) (%)	
							BOL	EOL after 1x 10^{15}e/cm^2
1	PESC	Upp[a]	2	250	FZ	0.3	17.5	9.8 [7,8]
2	PERL	Invp[b]	0.5	200	FZ	0.7	20.2	9.8 [1,3]
3	PERL	Invp[b]	2	200	FZ	0.7	19.0	9.6 [1,3]
4	PERL	Invp[b]	100	200	FZ	0.7	17.6	9.4 [1,3]
5	PERL	Invp[b]	2	100	CZ	0.15	17.8	12.2 [12,13]
6	PERL	Invp[b]	10	100	CZ	0.15	17.0	11.5 [12,13]
7	PERL	Invp[b]	0.5	100	CZ	0.1	18.0	12.2 [5]
8	PERL	Invp[b]	5	100	CZ	0.1	17.8	12.1 [5]
9	WA	Upp[a]	10	69	CZ	0.15	14.1	11.3 [8]
10	WA	Upp[a]	10	69	CZ	0.15	13.7	11.0 [8]
11	n^+pp^+	Planar	10	180	FZ	0.3	17.8	11.2 [5]
12	Bifacial		10	100	FZ	0.3	17.4	11.5 [5]
13	cell		10	50	FZ	0.3	17.0	12.1 [5]

[a]Upp = upright pyramid; [b]Invp = inverted pyramid

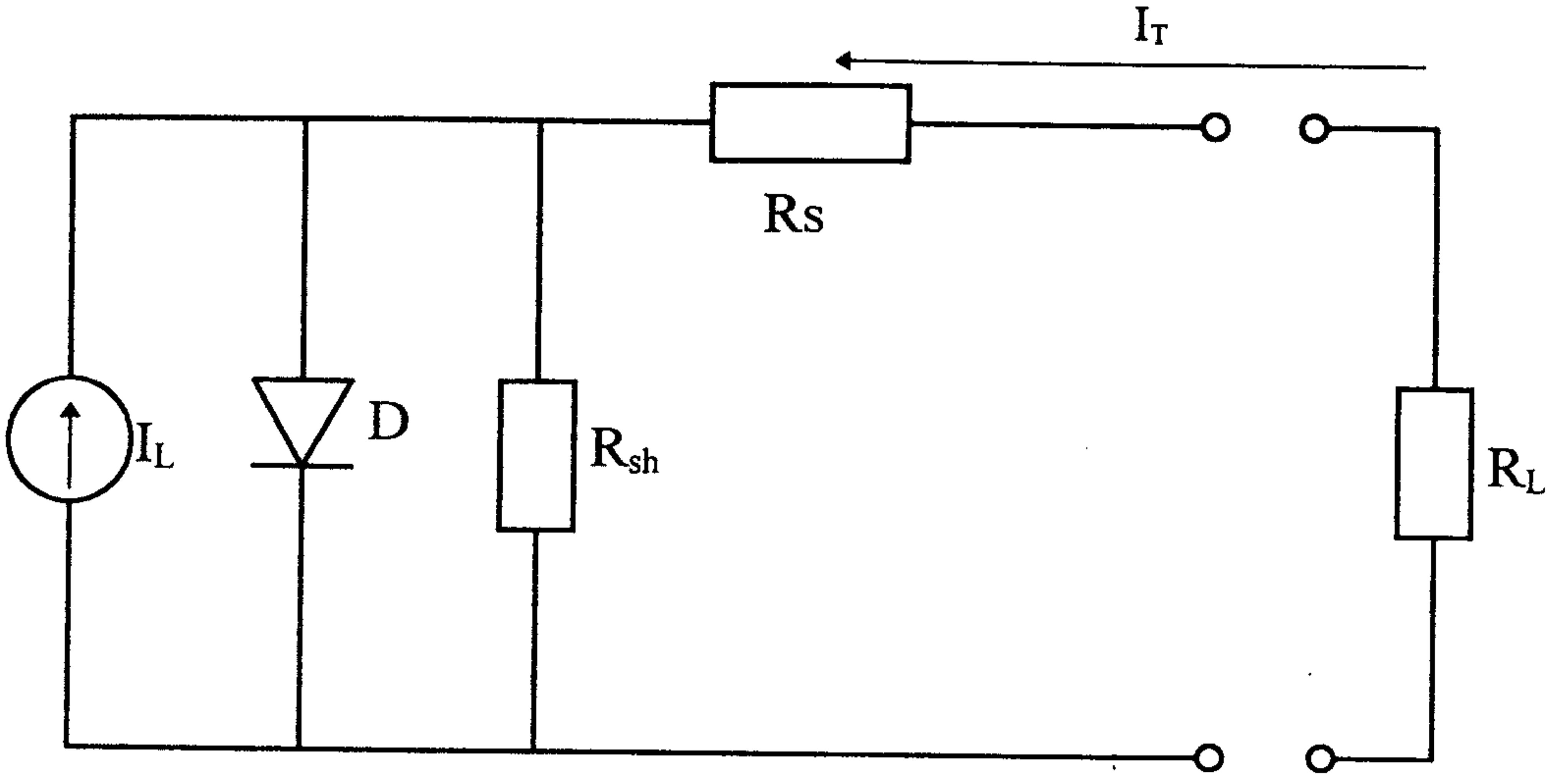

Fig. 1. Equivalent circuit of a solar cell

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