Journal of the Korean Nuclear Society
Volume 7, Number 2, June 1975

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Comparative Study on Current-Voltage Characteristics and Efficiencies of Ion-Implanted and Dopant-Diffused Silicon Solar Cells

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(Received January 13, 1975)

Abstract

A comparative study has been carried out on three silicon solar cell samples through their current-voltage (I-V) characteristics and their efficiencies. One sample is an ion-implanted cell made by our laboratory, and the other two samples are the dopant-diffused cells made by a foreign maker. The experiments have shown that both the properties of junction formation and the efficiency of each sample depend highly on the I-V characteristic of each p-n junction. The cause of incomplete properties in the ion-implanted sample has been clarified through this comparative study to be due to the various reasons such as slightly deficient surface impurity concentrations, defects induced by both the radiation and the foreign impurities, and insufficient ohmic contacts at the electrodes. The conversion efficiency of the ion-implanted sample can be figured out to be 4.2% whereas those of the other samples to be 14.3% and 8.3%, respectively.

요 약

3개 태양전지 견본의 전류 전압특성과 효율에 관한 비교 연구를 수행하였다. 견본 하나는 우리 연구실에서 만든 이온주입식의 것이며, 나머지 두개는 외국의 한 메이커가 만든 열확산식의 것이다. 실험에 의하면 각 견본의 접합형성의 특성과 그 효율은 각 p-n 접합의 전류 전압 특성에 크게 의존된다는 것을 알 수 있었다. 이온 주입식 견본의 불완전한 특성의 원인은 약간 부족한 불순물의 표면농도, 이온 충격과 잡불순물에 의한 격자 결함, 전극에 있어서의 불충분한 Ohm 접촉등의 원인에 기인된다는 것을 본 비교 연구를 통해서 명백히 알 수 있었다. 변환효율에 있어서는 열확산으로 된 두 견본의 것은 각각 14.3%와 9.3%인데 비해서 이온주입으로 된 견본의 것은 4.2%였다.

1. Introduction

It is known that the p-n junction for silicon solar cell has the following special features such as the highest possible impurity concentrations in the surface layer, steeply graded impurity concentrations, extremely shallow junction depth, and so on. Such a particular doping has been done so far by controlling the conditions of thermal diffusion.

Recently, the p-n junction for silicon

solar cell has been attempted to form by a new doping method of ion-implantation which will replace the former method in near future although such a high density doping by the implanting method is now under the developing stage at present time. We have recently made a silicon solar cell by a new method of ion-implantation.

The purpose of this paper is to appreciate the present status of our ion-implanted sample by comparing with two dopant-diffused silicon solar cell samples through their current-voltage characteristics and their efficiencies.

The efficiency of a semiconductor solar cell sample is commonly defined as the ratio of electrical power output into a matched load to the incident power per active area. This efficiency depends highly on the I-V characteristic of the p-n junction. Generally, the higher the forward voltage necessary to pass a given forward current density, the higher will be the open-circuit voltage developed by the same current density of photon-created carriers reaching the junction, and reverse characteristic curve should be a soft form with a relevant reverse voltage.

The I-V characteristic of a semiconductor solar cell is greatly related with various factors such as minority carrier life-times, density of recombination centers, degree of radiative recombination[1], junction depth, gradient of impurity concentrations, state of carrier concentrations, surface recombination velocity, and so on.

Although the efficiency of our cell is not adequate for the comparison with a commercial grade solar cell formed by thermal diffusion, it might have a meaning to understand the present status of such a new development in this field.

2. Principle

The best possible I-V characteristic of a silicon solar cell will be obtained if there is only radiative recombination of the holes and electrons created by the incident photons. Under such conditions the forward characteristic of the cell without illumination is given by the ideal diode equation:

$$I=I_0[\exp(eV/kT)-1] \cdots\cdots\cdots\cdots\cdots (1)$$

where I is the junction current, I_o the minimum reverse saturation current, V the voltage applied to the junction, e the electronic charge, k the Boltzmann's constant, and T the absolute temperature. Generally, I_o can be dominated by both concentrations of the majority carriers and the minority carriers in the regions of both sides of the p-n junction.

The forward behavior is usually described [2-3] by a relation of the type of equation (1) with an empirical factor A introduced to account for the experimental data when

$$I=I_o'[\exp(eV/AkT)-1] \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

where I_o' is also the reverse saturation current but has only the empirical meaning. Values for A between 1 and 2 can be explained on the basis of carrier recombination and generation in the space charge layer[4]. Generally, the A-value changes from 1 at low forward bias to 2 at high forward bias. The experiments typically yield A-value of 3 or even higher. Such values could still be interpreted as arising from recombination centers.[5-6]

It now appears certain that, in principle, high values of A are undesirable for solar cell operation. Although high A-values mean a slower exponential increase of forward current with the voltage, the absolute values of the current for a given voltage are higher than those predicted by the equation (1).

Empirically, it is found[7] that with increasing A-value the parameter I_s' of equation(2) also increase, generally in such a way that higher currents are obtained. Regardless of the specific physical interpretation it can be said that high A-values are an indication of unwanted excess current in the p-n junction that lower solar cell efficiency.

From the foregoing, it is evident that there is a potential for improvement of solar cells by improving junction characteristics. An understanding of the high A-values should eventually lead to methods of reducing the forward current, resulting in higher energy conversion efficiencies.

Now, it is necessary to consider the state of carrier movement through p-n junction. Figure 1 shows the energy band diagram of a silicon p-n junction with the illustration of carrier distribution in equilibrium state.

The symbols in Fig. 1 can be explained as follows,

N_h : density of holes in p region,
N_{ho}: density of holes (minority carriers) in n region,
N_e : density of electrons in n region,
N_{eo}: density of electrons (minority carriers) in p region,
d: thickness of depletion layer,
V_d: diffusion potential in p-n junction,
L_h: diffusion length for holes,
L_e: diffusion length for electrons.

In equilibrium state shown in Fig. 1, the density of holes in n region can be represented as

$$N_{ho}=N_h \exp(-eV_d/kT) \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

When the forward bias V is applied to the junction, the density of holes at x=0 can be represented as

$$N_h(O)=N_{ho} \exp(eV/kT) \cdots\cdots\cdots\cdots\cdots (4)$$

That is, the density of holes at x=0 becomes the $\exp(eV/kT)$ times of the equilibrium value. This means that a hole injection is taken place from the p region toward the n region.

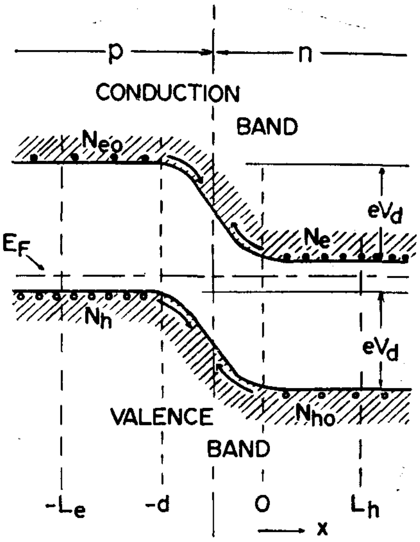

Fig. 1. **Energy band diagram of a silicon p-n junction showing the carrier distribution in equilibrium state**

At a distant point (x>0) from x=0, the density of injected holes is to be decreased in proportion as the increase of distance x, since the holes can be decreased by recombination. The excess hole density is to be exponentially decreased in proportion as the increase of the distance x, and at $x=L_h$ it becomes to 1/e times.

By the similar way as in equation (4), the density of injected electrons at x=−d under the forward bias V can be represented as

$$N_e(-d)=N_{eo} \exp(eV/kT) \cdots\cdots\cdots\cdots\cdots (5)$$

When the p-n junction is irradiated by sunlight in case of solar cell, the moving direction of minority carriers is opposite from the case of forward current in the junction, *i.e.*, the holes (minority carriers) can be moved from L_h to −d whereas the electrons (minority carriers) can be moved from $-L_e$

to O, and can create hole-electron pairs across the junction. In this case, the density of collected holes (minority carriers) at $x=-d$ can be represented as

$$N_h(-d)=N_{h_0}\exp(eV/kT), \cdots\cdots\cdots\cdots(6)$$

and the density of collected electrons (minority carriers) at $x=0$ can be represented as

$$N_e(O)=N_{e_0}\exp(eV/kT). \cdots\cdots\cdots\cdots\cdots(7)$$

Such a movement of minority carriers should be influenced by the drift field $-dE/dx$ if the impurity concentrations are graded within the diffusion area of each minority carrier.

If the forward characteristic of a silicon solar cell is ideal as shown in equation (1), density of injected holes and that of injected electrons (both, minority carriers) should be ideal as shown in equations (4) and (5), respectively. In such a case, photon-created holes and the electrons are ideally collected at $x=-d$ and $x=0$ respectively as shown in both equations (6) and (7). If there are many recombination centers within each diffusion length, each density of collected holes and the electrons should be greatly decreased, hence in this case fairly high A value should be considered in both equations (6) and (7).

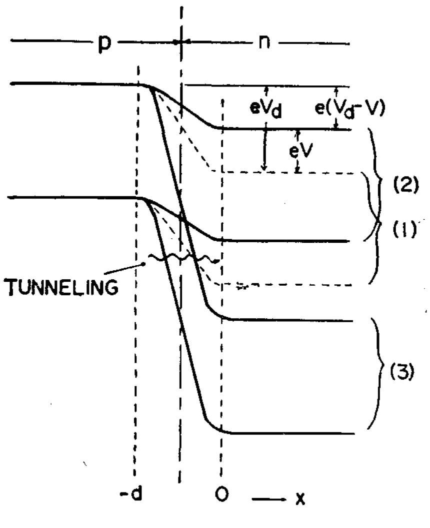

Fig. 2. Energy band structure of a silicon p-n junction showing eash barrier height of forward or reverse bias

The energy band structure in a silicon p-n junction describing each barrier height of forward or reverse bias is shown in Fig. 2. The state (1) is the equilibrium condition as shown in Fig. 1, and the state (2) is a condition of lowered barrier when forward bias is applied to the junction, and the state (3) is a condition of elevated barrier when a fairly high reverse bias is applied to the junction.

In case of reverse bias as shown in the state (3) of Fig. 2, hole current from p to n region is not so much varied, but electron current from n to p region is greatly decreased as the barrier height is suddenly elevated, and the whole reverse current can be written as

$$I_R=I_o'[\exp(-eV_R/AkT)-1] \cdots\cdots\cdots(8)$$
$$\approx I_o'$$

where V_R is the reverse bias voltage. When the A-value in equation (8) is increased, the reverse current will also be increased. As has been stated in the foregoing, high A-value is caused by dense recombination centers.

In case of the p-n junction for solar cell, extremely high or low A-values are not desirable, but a medium A-value ($2\geq A>1$) is necessary for the appearance of well-known "softness" on the reverse curve[5]. If a step-like deep junction is formed by dense impurity concentrations, high voltage reverse bias can be applied to the junction as shown in state (3) of Fig. 2. In such a case, holes and electrons under crossing through the space charge layer can be accelerated by intense drift field so as to form many hole-electron pairs, and these pairs can be suddenly multiplied in their numbers by the collisions with the lattice atoms so as to cause the avalanche breakdown. If the impurity concentration is extremely high in the state of degeneracy, electrons in the valence band can be tunneled to the conduction band through the narrow space charge layer so as to cause the Zener breakdown. Generally, the latter effect can be taken place at more lower reverse voltage than the former.

3. Experimental Results and Discussion

Experiments were performed on three different silicon solar cell samples. A couple of solar cell samples (a) and (b) were acquired from a Japanese solar cell maker (KODENSHIKOGYO CO., Ltd.), and (a) is a commercial cell whereas the (b) is non-selling second rate one. These cells were produced by a shallow thermal diffusion of boron into n-type silicon base. The sample (c) is made in our laboratory by a shallow and simultaneous implantation of boron and aluminum into n-type silicon base. We have developed a new implantation method due to argon enhanced diffusion to be introduced elsewhere.8) The I-V characteristics of the three samples were measured with the tolerable current voltage values. Especially, when the reverse characteristic of each sample is measured under an insufficient reverse current for the size of active area, "double break" is often found although the reason of this effect is not yet understood.

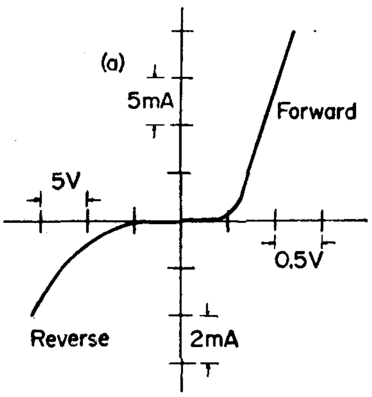

Fig. 3. I-V Characteristic of the sample (a), Forward: 5mA/D., 0.5V/D., Reverse: 2mA/D., 5V/D., Active area: 0.6cm^2

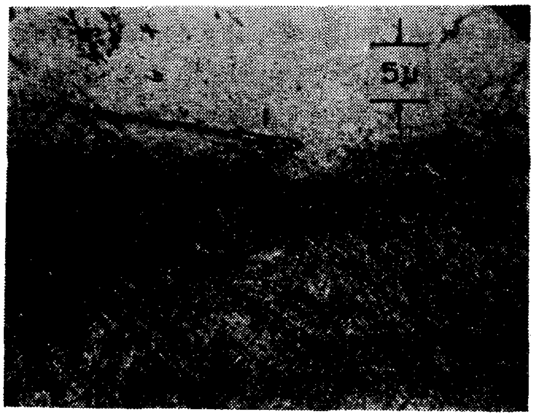

Fig. 4. Photomicrograph of the p-n Junction of the sample (a), which is delineated by copper-stain on the bevelled and lapped face with 1.5 degrees, ×2000

1) I-V Characteristics

I-V characteristic of the sample (a) is as shown in Fig. 3. Generally, this type of I-V characteristic can be observed at a commercial grade silicon solar cell having the double junctions formed by double diffusion method,9) and such a cell has its fairly low threshold voltage of less than 0.6V. In this sample, the forward voltage and the current per division are 0.5V and 5mA respectively although the current value can be varied depending upon the size of the cell. The active area of this sample is 0.6cm^2. The special feature of such a forward curve of the sample (a) is in almost straight rise except both a minor part of the exponential rise at the deflecting region and a flat part before the onset of the rise. Such a straight rise of forward characteristic can often be observed at an alloy-type silicon diode having a step-like abrupt junction with high impurity concentration in the doped layer.

Photomicrograph of the p-n junction in the sample (a) is shown in Fig. 4. The junction depth in average is calculated to be around 0.2μm. It can be seen in Fig. 4 that double junctions are formed with a step-like boundary in each junction and the lower layer is graded a little in its impurity concentration whereas the upper layer is very densely doped with no identifiable gradient. In such step-like double junctions with a minor part of a slight grading, it can be presumed that the forward current will never fully increase in accordance with the increasing rate of the probability exp(eV/kT) by the injected holes and electrons, hence in this case equations (4) and (5) in Part 2 will not fully be adapted except the exponential increase at the deflecting region. Such an exponential increase in part may follow a relation of the type of equation (2) in Part 2 with nearly medium A value. And also generally, it is known that when the thickness of doped layer is optimum, *i.e.*, neither too thick nor too thin compared with the diffusion length in the layer, the distribution of the minority carrier density can stand between the exponential distribution and the linear distribution. The Ohm's-law-like increase after the onset of the rise may be caused by above reasons.

It can be thought that the flat part of the forward characteristic of the sample (a) is caused by the minority carrier life-times and the drift mobilities in the silicon base. As a reference, the mobilities and life-times of minority carriers in two types of 10Ω cm silicon are shown in Table 1. According to Wolf,[10] the minority carrier life-times and the drift mobilities are generally dependent on the density of impurity and the density of recombination centers at a given temperature. When the density of recombination centers is negligibly small, *i.e.*, the lifetimes of minority carriers are fairly long, and the drift mobilities are fairly high, the forward current will suddenly begin to flow at the threshold voltage of a silicon diode (0.6V), hence a flat part can be observed on the forward characteristic of the sample (a).

Table 1. Mobilities and Lifetimes of Minority Carriers in Two Types of 10Ωcm Silicon at 300°K

Mobilities ($cm^2V^{-1}Sec^{-1}$)		Lifetimes (μSec)	
of Holes in n-type Si μ_h	of Electrons in p-type Si μ_n	of Holes in n-type Si τ_h	of Electrons in p-type Si τ_n
500	1200	0.1	10

When the sample (a) is heated in the atmosphere to about 200°C for a few minutes, the flat part disappears, and a slow exponential rise of the forward characteristic with a higher threshold voltage than the former state appears, and at the same time photovoltaic effect of the sample is considerably decreased. It can be supposed that the minority carrier life-times are greatly shortened by the precipitation of oxygen in the p-n region and the drift mobilities are also decreased by the recombination centers caused by the oxygen. It is known[11] that the precipitation of oxygen might cause the high A value. In such a state, sudden increase of forward current at the threshold voltage of silicon diode is impossible, and as has been stated in Part(2), a fairly high A value should be considered in the three equations (2), (6), and (7) respectively. Considering from these points of view, we can understand that the flat part of the forward characteristic is significant as the nature of p-n junction for the silicon solar cell.

The reverse characteristic of the sample (a) shown in Fig. 3 is almost representing a well-known "softness" which is especially noticeable for high efficiency solar cell, but a little "hardness" is included in the flat part of the reverse characteristic. The ideal "softness" of the reverse characteristic can be obtained by the shallow and steeply graded doped layer, *i. e.* the value of the impurity gradient —dn/dx should be large. Actually, such a doping method is very difficult, so that they employed an equivalent method of double diffusion so as to form the double junctions as mentioned in the foregoing. It can be supposed that the form of the reverse characteristic is obtained by the resultant effect due to both of the step-like upper junction and nearly step-like lower junction with a slowly graded impurity distribution. The junction state having a tolerable reverse current (2mA per division at the active area of 0.6cm^2) to a relevant reverse voltage (5V per division) is also a special feature of the silicon solar cell. The tolerable reverse current may be caused by the fairly dense impurity doping which will bring rather defects to be functioned as recombination centers in the silicon crystal lattice. Such an effect can be understood in the type of equation (8) in Part 2 with nearly medium A value.

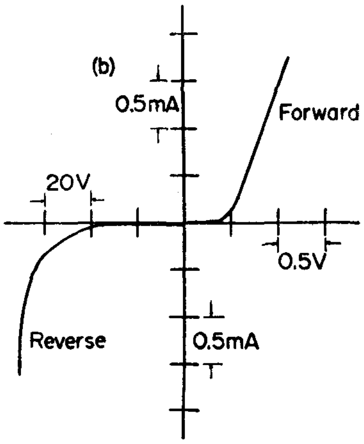

Fig. 5. I-V characteristic of the sample (b), Forward: 0.5mA/D., 0.5V/D., Reverse: 0.5mA/D., 20V/D., Active area: 0.08cm^2

Fig. 6. Photomicrograph of the p-n junction of the sample (b), which is delineated by copper-stain on the bevelled and lapped face with 1.5 degrees, ×2000

The I-V characteristic of the sample (b) is as shown in Fig. 5. The forward characteristic of the sample (b) is almost similar to that of the sample (a). The only different point is in a little lower threshold voltage than the case of sample (a). It can be thought that this state is caused by both reasons due to a little shorter minority carrier life-times and a little higher drift mobilities. The reverse characteristic of the sample (b) is representing an unusual feature of considerable "hardness" with a breakdown at the reverse bias voltage of around 75V.

Photomicrograph of the p-n junction in the sample (b) is shown in Fig. 6. The junction depth in average is calculated to be around 0.12μm. It can be seen in Fig. 6 that double junctions having both a step junction and a steeply graded junction are formed in the doped layer. Although each boundary might not be clearly observed in Fig. 6, we could directly observe the dense color of copper-stained upper layer with a distinct junction through the microscope. The heavily doped upper layer occupies the major part of the whole doped layer whereas the steeply graded lower layer is a fringe-like minor part in it.

In this case, the reverse current should follow the form of equation (8) in Part 2, and as has already been stated about the general relation between the two parameters I_s' and A, considerably large reverse current (0.5mA per division at the active area of 0.08cm^2) in this case is caused by a considerable defects due to fairly heavy doping in a shallower junction depth than the case of the sample (a). In this case the A value should be very high, but it is greatly alleviated by the fairly high drift mobilities due to the steeply graded lower doped layer, hence the A value is thought to be fairly larger than its medium. Considering from the magnitude of the reverse bias (20V per division) in Fig. 5, the barrier height in the energy band structure of such a state can be compared with the state (3) in Fig. 2. In this case, the state of upper layer in the silicon bulk is thought to be on the edge of degeneracy. Judging from both the slight "softness" of the reverse characteristic at the deflecting region and the magnitude of the reverse bias voltage, the sudden increase of the reverse current may be mainly caused by an avalanche breakdown including a partial Zener breakdown due to the tunneling of the electrons as shown in Fig. 2.

The I-V characteristic of the sample (c) is as shown in Fig. 7. The forward characteristic is risen exponentially from the origin without yielding a flat part as the case of the other samples. In this case, the forward behavior should be described by a relation of the type of equation (2) with a slightly higher A value than its medium, however the state of the junction in the sample (c) is a little different from the case of the other samples made by thermal diffusion. Judging from the form of the forward characteristic, it can be presumed that the sample (c) has both the fairly short minority carrier life-times and the tolerable drift mobilities.

Photomicrograph of the p-n junction in

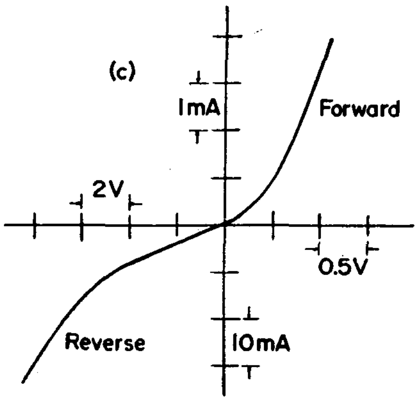

Fig. 7. I-V characteristic of the sample (c), Forward: 1mA/D., 0.5V/D., Reverse: 10mA/D., 2V/D., Active area: 3cm^2

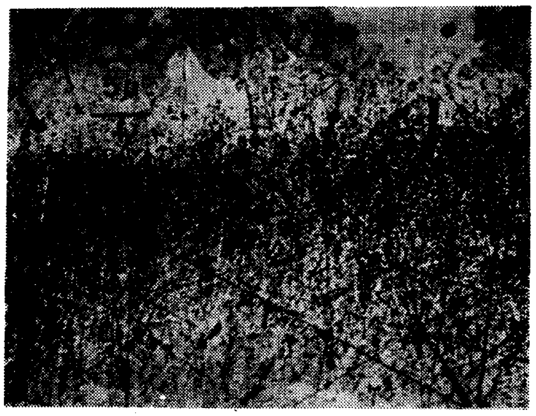

Fig. 8. Photomicrograph of the p-n junction of the sample (c), which is delineated by copper-stain on the bevelled and lapped face with 1.5 degrees, × 2000

the sample (c) is shown in Fig. 8. The junction depth in average is calculated to be around 0.26μm. This depth is a little deeper than those of the other samples. It can be seen in Fig. 8 that the doped layer has both a slowly graded impurity concentration and a graded junction at the junction boundary. Although we have implanted two kind of impurities, boron and aluminum, into silicon simultaneously, we could not observe an intermediate junction that might be formed by each difference of their diffusion constants and their activation energies. As the reference, these differences are shown in Table 2.

Table 2. Diffusion Constant D_o and Activation Energy E of the Impurities B and Al in the Host Crystal of Silicon

Impurities	B	Al
$D_o \times 10^4$ ($m^2 sec^{-1}$)	10.5	8.0
$E(eV)$	3.68	3.47

Since no intermediate step-like junction is formed in the sample (c), the effective drift mobilities of the minority carriers due to the drift field should be fairly large. On the other hand, the presence of both the radiation-induced defects and some foreign impurities will make the minority carrier lifetimes shorten. Under such a state, sudden increase of forward current at the threshold voltage in the silicon diode like the case of the other samples is almost impossible, instead of this, exponential increase of forward current is possible in this sample. Since the ion-implanted samples tend to form fairly dense radiation-induced defects, it is difficult to alleviate the density of defects to the average defect level of dopant-diffused samples by post-annealing for about ten minutes at the temperature of around 700°C. It is known that the post-annealing for several ten minutes tends to bring out-diffusion[12].

This state can be explained by both the equations (4) and (5) together with the Fig. 1 in Part 2. In the both equations, N_h and N_e should be small on account of their fairly short life-times, so that minority carrier injection at both $x=o$ and $x=-d$ will not be done suddenly at the threshold voltage of silicon diode. On the other hand, both densities of injected minority carriers $N_h(o)$ and $N_e(-d)$ will exponentially increase by the influence of fairly large drift mobilities in accordance with the increase of the forward bias voltage, hence the forward characteristic will exponentially rise from the origin. In this case, the collection of minority carriers at both $x=-d$ and $x=o$ should also be insufficient by above reasons, hence fairly high A value should be considered in the types of both equations (6) and (7) in Part 2.

The reverse characteristic of the sample (c) shown in Fig. 7 is slightly over-softened compared with the ideal "softness" of the silicon solar cell. Generally, when the doped layer having both the insufficient impurity concentration on the surface layer and slowly graded impurity concentration is formed such a reverse characteristic tends to be yielded. The surface impurity concentration of the sample (c) was determined to be 1.5×10^{19} atoms per cubic centimeter by measuring the sheet resistivity. This concentration is a little lower than that of a commercial grade silicon solar cell. The carrier concentration of the sample (c) is not measured as the apparatus is not available. In this case, the barrier height should be far lower than the state (3) in Fig. 2, and the reverse current will be described by a relation of the equation

(8) with the fairly high values of I'_0 and A. As has been stated in Part 2, these values can be proportionally increased each other. In such an ion-implanted sample, A value tends to be increased by a fairly dense formation of radiation-induced defects which are generally higher than those of the diffusion-induced defects, and moreover many recombination centers caused by the undesirable foreign impurities will also play a role of increasing the A value. In this case, it can be thought that the above effects to increase the A value are greatly alleviated by the fairly high drift mobilities. The tolerably large reverse current (10mA per division at the active area of 3cm^2) may be caused by the resultant A value which is slightly higher than the case of the sample (a), but the improper I-V characteristic of this sample may be brought by both the different type of considerably high defects and the slightly insufficient surface impurity concentrations.

2) Efficiencies

Two fundamental phenomena arising on the solar cell behavior are as follows, (i) excess carriers are to be created by the absorption of photons under thermal non-equilibrium, (ii) collection of carriers is to be efficiently done across the *p—n* junction. Therefore, in order to improve the conversion efficiency these two processes should be optimized.

Wolf[13] has classified the powerlosses which are related to the conversion efficiency. These are the following factors such as (a) reflection loss, (b) non-generative photon losses, (c) incomplete utilization of photon energy, (d) incomplete utilization of minority carriers, (f) shunt and series resistance losses, and so on. Among these factors, the factors from (a) to (d) are mainly dependent on the light absorption characteristic of the semiconductor material, which prescribes the short circuit current of a solar cell, and directly related to the over-all collection efficiency. The factor (e) is directly related to the I-V characteristic of the *p—n* junction, corresponding to the following items such as voltage factor relating to the open circuit voltage, the product of short circuit current by open circuit voltage, curve factor relating to the maximum deliverable power output, and conduction mechanism of forward current in *p—n* juction in case of low impurity concentrations. The factor (f) is directly related to both the shunt leakage current and the series resistance due to both the bulk resistivity and the contact resistance.

If the measures for the utilization of sunlight are appropriate, the major part of the powerlosses in a silicon solar cell can be governed by the both factors (e) and (f). As has been discussed pertaining to the I-V characteristics of three samples in Part 3-(1), the I-V characteristic of a silicon solar cell is a barometer of distinguishing the state of junction characteristic in the cell, hence the conversion efficiency is greatly related to the nature of the I-V characteristic of a silicon solar cell.

By analyzing the nature of I-V characteristic of a silicon solar cell, Prince[14] has derived a relation to calculate the rough estimation of the maximum expected power density as given below

$$P_A = 0.8\, I_{SC}\, V_{OC} \text{ Watts/cm}^2 \cdots\cdots\cdots\cdots (9)$$

where I_{sc} is the short circuit current, V_{oc} the open circuit voltage. This relation is derived on the basis of his precise calculation in his previous work[15]. This relation is thought to be nearly correct at the conversion efficiency

Table 3. Estimation of the Maximum Expected Power Density of Each Sample due to the Measured Data under the Irradiation of Sun-Light

Samples	V_{oc} (mV)	I_{sc} (mA/cm^2)	$V_{oc}\cdot I_{sc}$ (mW/cm^2)	$0.8V_{oc}\cdot I_{sc}$ (mW/cm^2)	Conversion Efficiency at the Solar Radient Power Density of 60mW/cm^2
(a)	0.54	20	10.8	8.6	14.3%
(b)	0.46	13.7	6.3	5.0	8.3%
(c)	0.41	7.5	3.1	2.5	4.2%

of higher than 10.7%. We have roughly estimated the maximum expected power density of each sample by adopting the relation (9), and the results are shown in Table 3.

In the Table 3, both of V_{oc} and I_{sc} were measured under the direct irradiation of sun-light. Since the solar radiant power density is 100mW per square centimeter at sea level on a bright clear day with the sun at the zenith, reestimation of this value should be done, depending on the season and the latitude. The conversion efficiencies of the three samples were figured out by estimating the solar radiant power to be 60mW per square centimeter at winter time in Seoul. Since the conversion efficiency of present commercial solar cell is generally 14.3% at the p-on-n type 1Ωcm silicon solar cell, our estimation in Table 3 may be almost reasonable.

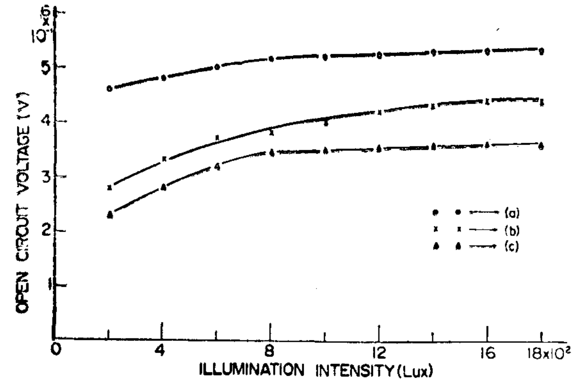

Fig. 9. Open circuit voltage *vs.* illumination intensity of each sample due to incandescent lamp

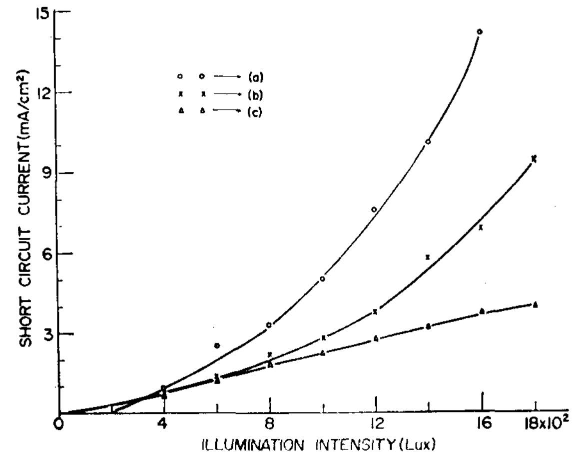

Fig. 10. Short circuit current *vs.* illumination intensity of each sample due to incandescent lamp

The state of variation on each of V_{oc} and I_{sc} of the three samples per unit area were measured by varying the illumination intensity on each obverse face under an incandescent lamp, and the results are shown in Fig. 9 and Fig. 10. Observing each of V_{oc} and I_{sc} in both Figures, the sample (a) is fairly excellent and the sample (b) is middle, whereas the sample (c) is a little poor. It is worthy to note that such differences of the photovoltaic effect are mainly caused by the state of each *p*—*n* junction which is analyzed through each I-V characteristic as stated in Part 3-(1).

The maximum deliverable power output of each sample through each matching load is not measured, since the series resistance of the sample (c) is fairly high on account of its incomplete ohmic contact at the both electrodes. The electrodes of the sample (c) are made of Al-Au alloy on the *p*-type side and Cu-Au alloy on the *n*-type side. We should change these electrodes to nickel by the plating at the further research. Nickel is known to be an effective getter to the adsorbed gas and to preserve carrier life-times$^{16)}$.

4. Conclusion

The following conclusion can be drawn through the present research.

1) The state of *p-n* junction in an ion-implanted sample could be easily analyzed by comparing with two dopant-diffused samples through the comparative study in their I-V characteristics and their efficiencies.
2) The I-V characteristic of a silicon solar cell is a barometer to analyze the state of *p*—*n* junction, and is directly related to its conversion efficiency.
3) By observing the form of I-V characteristic of a silicon solar cell, the following states can be analyzed such as impurity concentrations, carrier concentrations, step-junction, graded junction, double junctions, minority carrier life-times, drift mobilities, presence of foreign substances, shunt and series resistances, and so on.
4) Since the forming technique of *p*—*n* junction for silicon solar cell by ion-implantation is now under the developing stage at present time an ion-implanted sample (sample (c)) having a little lower efficiency than the dopant-diffused samples is not to be depreciated in their comparison. Since a new implanting technique has been firmly settled, the efficiency of the ion-implanted silicon solar cell should be greatly improved by using the semiconductor grade doping materials in the further research.

Acknowledments

The authors would like to express their gratitude to Messrs. Chang Bae Moon, Sae Woo Jun, and Soo Heon Kang for their helpful assistance throughout this research.

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