Analytical Study of the Minority Carrier Distribution and Photocurrent of a Schottky-Barrier Silicon Solar Cell

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Abstract- Schottky-barrier solar cells have been studied previously by various research workers. In this paper, the excess minority carrier distribution and the photocurrent of Schottky-barrier solar cell have been studied analytically and their dependence of doping concentration and back surface recombination velocity has been reported. An attempt has been made to give an interpretation of the results obtained from theoretical considerations.

Keywords- Schottky-barrier, solar cells, spectral response.

1. Introduction

Solar cells have been studied extensively by researchers during the last few decades [1-5]. A Schottky-barrier solar cell is a metal-semiconductor contact in which light falls on the front surface. The advantage of Schottky-barrier solar cells over the conventional p-n junction solar cells is due to their simple and economical fabrication process. Also these cells have good short wavelength response. Theoretical studies on Schottky-barrier solar cells were carried out by Pulfrey & McOuat [6-7]. Drift-field Schottky-barrier solar cells were considered by Munoz & Ferrarons [8] in which an inhomogeneous doping profile was considered and a numerical simulation of the device was done. Analytical work on the Schottky-barrier solar cells was carried out by Dubey and Paranjape [9] in which an expression for the open circuit voltage was obtained using appropriate boundary conditions. Temperature effects in Schottky–barrier solar cells were studied by Vemon and Anderson [10] and by Bhaumik and Sharan [11]. A detailed review of the metal-semiconductor contacts was undertaken and a comparison between Schottky diodes and p-n junctions was done by Rhoderick [12]. Recently, studies on atomistic simulation of doping effects on growth and charge transport in Si/Ag interface in high-performance solar cells have been done [13]. A photovoltaic device structure based on internal electron emission, have been studied by E.W. McFarland and J. Tang [14]. In our present work, we have studied the variation of photo-generated excess minority carrier concentrations as a function of distance from the metal surface in the semiconductor, for different values of absorption coefficient of the material. The variation of the spectral response with doping concentration of the minority of the material for different values of surface recombination velocities has also been studied.

2. Analysis

The schematic diagram of a metal n-type Si Schottky-barrier solar cell (SBSC) is shown in Fig.1. To obtain the expression for excess carrier concentration and the photocurrent of the cell, the method described by Hovel [15] is followed,

When light of wave-length λ is incident on the surface of the SBSC, the generation rate of electron-hole pairs as a function of distance x is

$$G(\lambda) = \alpha(\lambda) F(\lambda) T(\lambda) \exp[-\alpha(\lambda) x] \quad (1)$$

Where $F(\lambda)$ is the incident photon flux, $T(\lambda)$ is the transmission of light through the metal and α is the absorption coefficient.

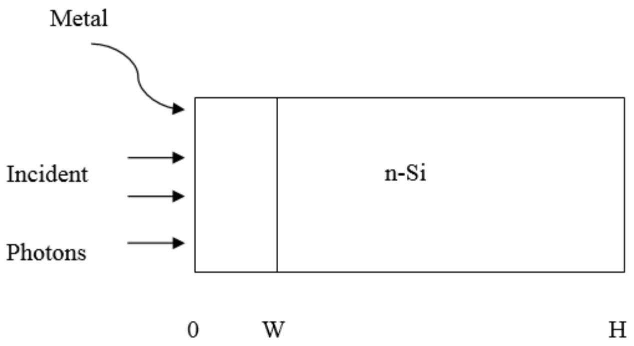

Fig.1. A Schottky – barrier Si solar cell

Assuming low–level injection, the continuity equation for holes in the n-type semiconductor is

$$G-\frac{p_n-p_{no}}{\tau_p}-\frac{1}{q}\frac{dJ_p}{dx}=0 \qquad (2)$$

Where, p_{no} is the thermal equilibrium concentration of holes and τ_p is the lifetime of holes.

If a uniform doping is assumed on the semiconductor, there will be no field outside the depletion region and the hole current density equation may be written as ,

$$J_p=-qD_p\frac{dp_n}{dx} \qquad (3)$$

Combining equations (1), (2) and (3) we obtain

$$D_p\frac{d^2(p_n-p_{no})}{dx^2}+\alpha FT\exp(-\alpha x)-\frac{(p_n-p_{no})}{\tau_p}=0 \qquad (4)$$

The general solution of this equation may be written as

$$(p_n-p_{no})=A\cosh\left(\frac{x}{L_p}\right)+B\sinh\left(\frac{x}{L_p}\right)-\frac{\alpha FT\tau_p}{(\alpha^2L_p^2-1)}\exp(-\alpha x) \qquad (5)$$

where, $L_p=\sqrt{D_p\tau_p}$ is the diffusion length for holes . A and B are constants, which can be evaluated using the boundary conditions [15].

$$(p_n-p_{n0})=0 \qquad \text{at } [x=W] \qquad (6)$$

and

$$S(p_n-p_{n0})=-D_p\frac{d(p_n-p_{no})}{dx} \qquad \text{at } [x=H] \qquad (7)$$

where S is the back surface recombination velocity. Substituting the values of the constants thus obtained into equation (5) an expression for the excess minority carriers holes may be written as

$$(p_n-p_{n0})=\left[\frac{\alpha FT\tau_p}{(\alpha^2L_p^2-1)}\right][\exp(-\alpha W)]\times$$
$$\left[\cosh\left(\frac{x-W}{L_p}\right)-\exp(-\alpha(x-W))-\frac{\left(\frac{SL_p}{D_p}\right)\left[\cosh\left(\frac{H'}{L_p}\right)-\exp(-\alpha H')\right]+\sinh\left(\frac{H'}{L_p}\right)+\alpha L_p\exp(-\alpha H')}{\left(\frac{SL_p}{D_p}\right)\sinh\left(\frac{H'}{L_p}\right)+\cosh\left(\frac{H'}{L_p}\right)}\times\right.$$
$$\left.\sinh\left(\frac{x-W}{L_p}\right)\right] \qquad (8)$$

where $H'=H-W$

The hole current can thus be found as [15]

$$J_p=\left[\frac{qFT\alpha L_p}{(\alpha^2L_p^2-1)}\right][\exp(-\alpha W)] \quad \times$$
$$\left[\alpha L_p-\frac{\left(\frac{SL_p}{D_p}\right)\left[\cosh\left(\frac{H'}{L_p}\right)-\exp(-\alpha H')\right]+\sinh\left(\frac{H'}{L_p}\right)+\alpha L_p\exp(-\alpha H')}{\left(\frac{SL_p}{D_p}\right)\sinh\left(\frac{H'}{L_p}\right)+\cosh\left(\frac{H'}{L_p}\right)}\right]$$
(9)

Another contribution to the photocurrent of the cell comes from the depletion region. The high field in the depletion region sweeps the minority carriers giving rise to the photocurrent [15].

$$J_{dr}=qT(\lambda)F(\lambda)[1-\exp(-\alpha W)] \qquad (10)$$

where the expression for the width of the depletion region is given by Sze [16]

$$W=\sqrt{\left[\frac{2\epsilon_s}{qN_d}\left(V_d-\left(\frac{kT}{q}\right)\right)\right]} \qquad (11)$$

and the expression for built in potential of the SBSC is available in published literature[17].

$$V_d=\Phi_b-\frac{1}{q}(E_C-E_F) \qquad (12)$$

where,

$$E_C-E_F=\frac{kT}{q}\ln\left(\frac{N_c}{N_d}\right) \qquad (13)$$

and Φ_b is the Schottky barrier height. For Si, $N_c=2.726\times10^{19}$ cm^{-3} and N_d is the doping concentration of the n-type base.

The spectral response of the Schottky-barrier solar cell is then given by [15]

$$SR(\lambda)=\frac{J_p(\lambda)+J_{dr}(\lambda)}{qF(\lambda)T(\lambda)} \qquad (14)$$

$$SR(\lambda)=\quad[1-\exp(-\alpha W)]+\left[\frac{\alpha L_p}{(\alpha^2L_p^2-1)}\right][\exp(-\alpha W)]\times$$
$$\left[\alpha L_p-\frac{\left(\frac{SL_p}{D_p}\right)\left[\cosh\left(\frac{H'}{L_p}\right)-\exp(-\alpha H')\right]+\sinh\left(\frac{H'}{L_p}\right)+\alpha L_p\exp(-\alpha H')}{\left(\frac{SL_p}{D_p}\right)\sinh\left(\frac{H'}{L_p}\right)+\cosh\left(\frac{H'}{L_p}\right)}\right] \qquad (15)$$

Electrons in the valence band of a semiconductor can absorb photons whose energy are higher than the bandgap energy, E_g and jump to the conduction band. The absorption coefficient $\alpha(E)$ for an energy E higher than the bandgap energy is given by E. Fred Schubert [18]

For direct bandgap semiconductor:

$$\alpha(E)=\alpha_0\sqrt{\frac{E-E_g}{E_g}} \qquad (16)$$

For indirect band gap semiconductor:

$$\alpha(E)=\alpha_0\left(\frac{E-E_g}{E_g}\right)^2 \qquad (17)$$

3. Results and discussions

Calculations were performed based on the analytical expressions derived above. The values of the doping dependent life time of minority carrier holes were obtained using the expression given by Fossum [19] and the values of carrier mobilities as a function of doping concentration were found from the published literature [20]. The corresponding values of doping dependent diffusion coefficients were obtained using the Einstein's relationship [16]. The value of static dielectric constant ε_s for Silicon is taken as 1.053×10^{-12}F cm^{-1}. The total width of the solar cell is taken as 300μm. The values of Φ_b has been taken as 0.79 for Au, n-Si junctions [17].

Fig.2. shows the variation of excess minority carrier concentration as a function of distance corresponding to four different values of absorption coefficient α. It is observed that there is a fall in minority carrier concentration near the depletion region formed at the Schottky barrier junction. This is due to the Schottky-barrier junction. This is due to the fact that most of the carriers generated here are swept away by the high field that exists at this junction. Again, the excess minority carrier concentration falls near the back contact of the cell. This is because there is a large recombination loss at the back ohmic contact. Since the absorption coefficient α is dependent on the wavelength λ, the four curves shown here correspond to four different wavelengths incident on the cell, which explains the difference in the magnitude of excess minority carrier concentration for each case.

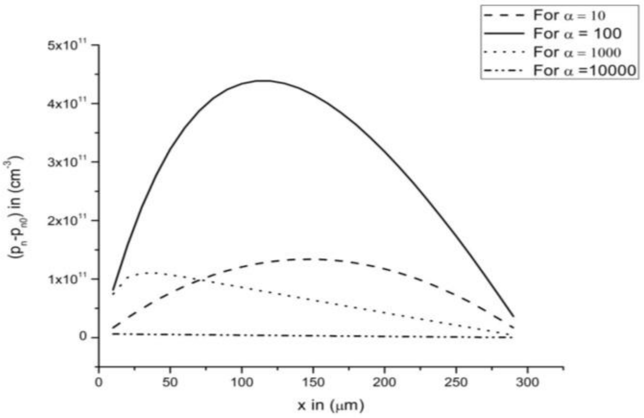

Fig. 2. Variation of the excess carrier concentration with distance from the depletion region inside the Si base.

Next, using Eq.(15), the variation of the spectral response with doping concentration has been plotted in Fig.3. for different values of surface recombination velocity. It is observed that there is a fall in the value of photocurrent as the doping concentration increases. This may be interpreted from the fact that at higher doping concentration, the lifetime of minority carrier decreases, leading to more recombination losses and fall in the photocurrent. It is also observed from Fig.3. that the magnitude of photocurrent decreases for larger values of back surface recombination velocity S. This may be interpreted by following the argument that more and more excess minority carriers are lost at the back surface due to high recombination velocity. These carriers are not available for photocurrent contri-bution, leading to lower values of spectral response corresponding to higher values of S.

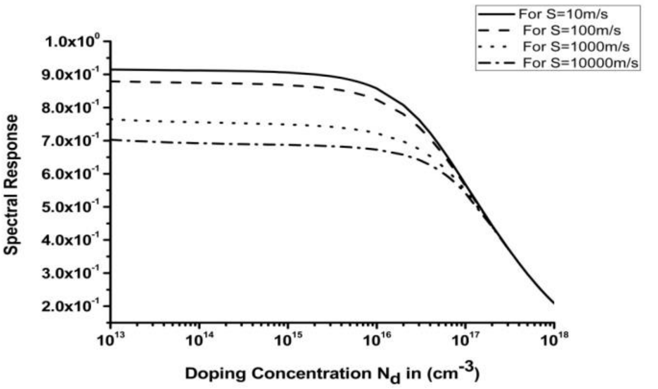

Fig. 3. Variation of spectral response with doping concentration

4. Conclusion

In this paper the light generated excess minority carrier distributions and photocurrent of a Schottky-barrier silicon solar cell has been studied analytically. It has been observed that there is a fall in the spectral response for higher values of doping concentration and also for larger back surface recombination velocity. An explanation has been given for this behavior, from theoretical considerations.

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