Chapter 2

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2.1 Introduction:

After the fabrication of the first silicon p-n junction solar cell [1], tremendous amount of research and development work have been done to improve the efficiency of the solar cell [2-6]. Over the years many new designs of silicon solar cells were developed. Schottky-barrier solar cell (SBSC) is one of such devices, which has been investigated by various researchers. 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 calculations of maximum conversion efficiency of SBSC have been performed by Pulfrey and McOuat [7-8] and they concluded that due to the simplicity of the fabrication process of these devices, would make them attractive as solar energy converter. Drift-field Schottky-barrier solar cells were considered by Munoz & Ferrarons [9] and considering inhomogeneous doping profile numerical simulation of the device was done. Analytical work on the Schottky-barrier solar cells was carried out by Dubey and Paranjape [10] 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[11] and by Bhaumik and Sharan[12]. A detailed review of the metal-semiconductor contacts was undertaken and a comparison between Schottky diodes and p-n junctions was done by Rhoderick[13]. 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 [14]. A detailed study on the properties of Electron-Sensitive detectors with Schottky Barrier has given by V.A.
Skryshevskii, S.V. Litvinenko and V.I. Strikha [15]. Schottky barrier UV photodetectors based on zinc-selinide was studied by V.P. Makhnii [16]. A photovoltaic device structure based on internal electron emission, have been studied by E.W. McFarland and J. Tang [17].

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. We also investigated the effect of the back surface recombination velocity on the minority carrier distribution and the spectral response of a SBSC and a new design for the SBSC structure has been suggested. In analogy with the back surface field \( n^+ p^+ \) silicon solar cells, the new SBSC yields much improved performance than the conventional SBSC.

2.2 Analysis:

The schematic diagram of a metal n-type Si Schottky-barrier solar cell (SBSC) is shown in Figure1. The expression for excess carrier concentration and the photocurrent of the cell, has been obtained from the method described by Hovel [18],

![Figure 1. A Schottky – barrier Si solar cell](image)

When light of wave-length \( \lambda \) is incident on the surface of the SBSC, the generation rate of electron-hole pairs as a function of distance \( x \) is
\[ G(\lambda) = \alpha(\lambda)F(\lambda)T(\lambda)\exp[-\alpha(\lambda)x] \]  

(1)

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

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

\[ G = \frac{p_n - p_{n0}}{\tau_p} - \frac{1}{q} \frac{dJ_p}{dx} = 0 \]  

(2)

where, \( p_{n0} \) is the concentration of holes at thermal equilibrium and \( \tau_p \) 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,

\[ J_p = -qD_p \frac{dp_n}{dx} \]  

(3)

where, \( D_p \) is the diffusion coefficient.

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

\[ D_p \frac{d^2(p_n - p_{n0})}{dx^2} + \alpha FT \exp(-\alpha x) - \frac{p_n - p_{n0}}{\tau_p} = 0 \]  

(4)

The general solution of this equation can be written as

\[ (p_n - p_{n0}) = A \cosh \left( \frac{x}{L_p} \right) + B \sinh \left( \frac{x}{L_p} \right) - \frac{\alpha FT \tau_p}{(\alpha^2 L_p^2 - 1)} \exp(-\alpha x) \]  

(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 [18].

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

(6)

and
\[ S(p_n - p_{n0}) = -D_p \frac{d(p_n - p_{n0})}{dx} \quad \text{at} \quad [x = H] \] (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 carrier holes may be written as

\[ (p_n - p_{n0}) = \left[ \frac{\alpha FT\tau_p}{(\alpha^2 L_p^2 - 1)} \right] \exp(-\alpha W) \]

\[ \times \left[ \cosh\left( \frac{x - W}{L_p} \right) - \exp(-\alpha(x - W)) \right] \]

\[ - \left( \frac{SL_p}{D_p} \right) \left[ \cosh\left( \frac{H'}{L_p} \right) - \exp(-\alpha H') \right] + \sinh\left( \frac{H'}{L_p} \right) + \alpha L_p \exp(-\alpha H') \]

\[ \times \sinh\left( \frac{x - W}{L_p} \right) \] (8)

where, \( H' = H - W \)

It may be mentioned here that in equation (8) and all other expressions to be derived in future

\[ \alpha^2 L_p^2 \neq 1 \]

The hole current can thus be found as [18]

\[ J_p = \left[ \frac{qFT\alpha L_p}{(\alpha^2 L_p^2 - 1)} \right] \exp(-\alpha W) \]

\[ \times \left[ \alpha L_p \right] \]

\[ - \left( \frac{SL_p}{D_p} \right) \left[ \cosh\left( \frac{H'}{L_p} \right) - \exp(-\alpha H') \right] + \sinh\left( \frac{H'}{L_p} \right) + \alpha L_p \exp(-\alpha H') \]

\[ \left( \frac{SL_p}{D_p} \right) \sinh\left( \frac{H'}{L_p} \right) + \cosh\left( \frac{H'}{L_p} \right) \] (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 [18].

\[ J_{dr} = qT(\lambda)F(\lambda)[1 - \exp(-aW)] \]  
(10)

where the expression for the width of the depletion region is given by Sze [19]

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

and the expression for built in potential of the SBSC is available in published literature[20].

\[ V_d = \Phi_b - \frac{1}{q}(E_C - E_F) \]  
(12)

where,

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

and \( \Phi_b \) 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

\[ SR(\lambda) = \frac{J_p(\lambda) + J_{dr}(\lambda)}{qF(\lambda)T(\lambda)} \]  
(14)
\[
SR(\lambda) = \left[ 1 - \exp(-\alpha W) \right] + \left[ \frac{\alpha L_p}{(\alpha^2 L_p^2 - 1)} \right] \left[ \exp(-\alpha W) \right] \\
\times \left[ \frac{(SL_p)}{D_p} \left[ \cosh \left( \frac{H}{L_p} \right) - \exp(-\alpha H') \right] + \sinh \left( \frac{H}{L_p} \right) + \alpha L_p \exp(-\alpha H') \right] \left[ \sinh \left( \frac{H}{L_p} \right) + \cosh \left( \frac{H}{L_p} \right) \right] \right] 
\]

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[21]:

For direct band gap semiconductor:
\[
\alpha(E) = \alpha_0 \sqrt{\frac{E - E_g}{E_g}} 
\]
(16)

For indirect band gap semiconductor:
\[
\alpha(E) = \alpha_0 \left( \frac{E - E_g}{E_g} \right)^2 
\]
(17)

The values of the doping dependent life time of the minority carrier holes were obtained using the expression given by Fossum [22]. The expression for the hole lifetime is
\[
\tau_p = \frac{\tau_{p0}}{1 + \frac{N_p}{N_{OD}}} 
\]
(18)

where, \(\tau_{p0} = 3.95 \times 10^{-4} \text{ sec}\)

and \(N_{OD} = 7.10 \times 10^{15} \text{ cm}^{-3}\)

The values of carrier mobilities as a function of doping concentration have been obtained from the published literature [23].
\[ \mu_p = \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left( \frac{N}{N_{\text{ref}}} \right) \alpha_c} + \mu_{\text{min}} \]  

(19)

where,

\[ \mu_{\text{max}} = 495 \text{ cm}^2/\text{V.s}, \]

\[ \mu_{\text{max}} = 47.7 \text{ cm}^2/\text{V.s} \]

\[ \alpha_c = 0.76 \]

\[ N_{\text{ref}} = 6.3 \times 10^{16} \text{ atoms/cm}^3 \]

The corresponding values of doping dependent diffusion coefficients have been obtained using the Einstein’s relationship [19].

\[ D_p = \left( \frac{kT}{q} \right) \mu_p \]

(20)

where, \( k \) is the Boltzmann constant, \( T \) is the temperature of the cell and \( q \) is the electronic charge.

**2.3 Results and discussions:**

Calculations were performed based on the analytical expressions derived above. The value of static dielectric constant \( \varepsilon_r \) for Silicon is taken as \( 1.053 \times 10^{12} \text{F/cm} \). The total width of the solar cell is taken as 300\( \mu \text{m} \).

Figure 2 shows the variation of excess minority carrier concentration as a function of distance corresponding to four different values of absorption coefficient \( \alpha \). 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 \( \alpha \) is dependent on the wavelength \( \lambda \), 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.

![Graph](image)

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

Figure 3 shows the variation of excess hole concentration as a function of position in the solar cell for different values of back surface recombination velocities.

It is observed that there is a large concentration of holes near the back surface, for smaller values of S, as compared to the case when high back surface recombination of carriers exists. For these higher values of S, there is large recombination of holes near the back surface, leading to smaller values of hole concentration there. Also, for these large values of S, there is steep gradient of minority carrier profile near the back surface, which gives rise to smaller values of photocurrent for these values of S.
Figure 3. Excess minority carrier distribution in semiconductor layer, as a function of the back surface recombination velocity $S$.

Next using equation (15), the variation of the spectral response with doping concentration has been plotted in Figure 4, 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 Figure 4 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 minority excess are lost at the back surface due to recombination velocity is high. These carriers are not available for photocurrent contribution, leading to lower values of spectral response corresponding to higher values of $S$. 

Figure 4. Variation of Spectral Response with Doping Concentration

In Figure 5, the variation of spectral response with base layer thickness is shown, for different values of back surface recombination velocity S. The results are consistent with the argument given in the discussion of Figure 3, that the photocurrent and hence spectral response in this case increases for smaller values of S. For larger thickness of base region, more light photons are absorbed and more photocurrent is obtained.
Figure 5. Spectral response of the SBSC as a function of thickness of the base region for different values of back surface recombination velocity S.

The plot of spectral response as a function of wavelength of incident light is shown in Figure 6, corresponding to different values of back surface recombination velocity S.
Figure 6. Spectral response of the SBSC as a function of wavelength for different values of back surface recombination velocity $S$.

As expected from the results discussed in the previous graph, the spectral response increases significantly for smaller values of $S$. Also, the effect of $S$ on the spectral response is more visible for larger values of wavelength $\lambda$. This is because larger wavelengths are mostly absorbed near the back of the cell and the effect of back surface recombination on the photocurrent is pronounced for these larger wavelengths.
2.4 Suggestion for a new design of the SBSC for improved performance:

Results obtained show that the photocurrent of a SBSC is strongly dependent on the back surface recombination velocity S. The magnitude of photocurrent increases significantly for lower values of S.

It may be mentioned here that in the development of conventional n⁺p junction solar cells, it was observed that incorporation of a highly doped p⁺ layer at the back of the cell gave an n⁺pp⁺ structure, which had much improved photocurrent and open circuit voltage than that of the conventional structure [24]. The low-high (pp⁺) junction at the back of the cell gave rise to a back surface field, which effectively reduced the back surface recombination velocity of such cells [25]. These cells were called back-surface-field (BSF) solar cells.

Since it is observed here that the photocurrent of the SBSC increases significantly for lower values of S, taking a clue from the BSF n⁺pp⁺ solar cells, we now suggest a new design of the SBSC with a back surface field, as shown in Figure 7. The width of the p⁺ layer may be about 5μm, and doping concentration may be kept at \(10^{17} \text{cm}^{-3}\).

![Diagram of the proposed Schottky-barrier solar cell with a back-surface-field](image-url)

**Figure 7.** The proposed Schottky-barrier solar cell with a back-surface-field
It is expected that this proposed new structure would give much improved photocurrent over the conventional SBSC. This is already evident from Figure 4, 5 and 6, which shows much improved spectral response for smaller values of back surface recombination velocity.

2.5 Conclusion:

In this chapter 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. Based on these results, a new design of a SBSC structure with a back surface field has been suggested, which is expected to give better performance.

References:


