LIST OF RESEARCH PAPERS OF SRI MANORANJAN BERA,
ALREADY PUBLISHED OR AWAITING PUBLICATION,
WHICH ARE INCORPORATED IN THE THESIS

1. 'Heavy Doping Effects on Open Circuit Voltage Decay in an
   Co-authors: De, S.S., Ghosh, A.K., Hajra, A.K. and
   Haldar, J.C.

2. 'Studies on Surface Recombination Velocity in a Heavily
Doped Abrupt $n^+-p$ Junction', Phys. stat. sol.(a) 146
(1994), K5.
   Co-authors: De, S.S., Ghosh, A.K., Sinha, P.K.,
   Sil, D. and Haldar, J.C.

3. 'Effect of Surface Recombination on the Transit-Time in
Heavily Doped $n^+-p$ Junction Silicon Solar Cell', Solid-St.
   Co-authors: De, S.S., Ghosh, A.K., Sil, D. and Sinha,
   P.K.

4. 'Influence of Built-in Potential on the Effective Surface
Recombination Velocity for a Heavily Doped High-Low
Junction', — in course of publication.
   Co-authors: De, S.S., Ghosh, A.K., Hajra, A.K.
   and Haldar, J.C.

5. 'Studies on Potential Profiles in a Heavily Doped
Semiconductor Heterojunction in Equilibrium', phys.
stat. sol.(a) 130 (1992), K49.
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12. 'On Some Physical Characteristics of GaAs-(Ga,Al)As Quantum Well Photoluminescence' — in course of publication.
    Co-authors: De, S.S. and Ghosh, A.K.

13. 'Studies on Refractive Index and Stark Effect in Asymmetrical Quantum Well with an Applied Electric Field' — in course of publication.
    Co-authors: De, S.S. and Ghosh, A.K.
NOTE

HEAVY DOPING EFFECTS ON OPEN CIRCUIT VOLTAGE DECAY IN AN ABRUPT $p^+\!-\!n$ JUNCTION

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1. INTRODUCTION

Open circuit voltage decay is used as a technique for determining minority carrier lifetime in semiconductor devices[1-5]. Open circuit voltage decay measurement provides information about the effective back-surface recombination velocity and the minority carrier lifetime. Carrier mobility of semiconductors is one of the important parameters for designing devices and integrated circuits. The characteristic curve of open circuit voltage decay is useful for designing silicon devices. The mobilities of holes and electrons depend on impurity ion nature and density. The dependence of carrier mobilities of heavily doped silicon on other parameters has been presented in a comprehensive manner by Arora et al.[6]. There are numerous silicon devices[7-9] with doping levels of the order of $10^{18}$ cm$^{-3}$, based on the injection of minority carriers. Earlier workers considered the effects of heavy doping[10-12] on energy gap, minority carrier diffusion constant and minority carrier diffusion length. Heavy doping produces high emitter efficiencies in bipolar transistors and high open circuit voltage in silicon solar cells. In a heavily doped region, the recombination process reduces the dimension of the doped region and yields higher power conversion efficiency. Consequently, the role of minority carriers in the heavily doped region becomes important. The influences of heavy doping are now often considered for different device fabrications.

In this note, an attempt has been made to investigate the influence of heavy doping on open circuit voltage decay in an abrupt $p^+\!-\!n$ junction silicon semiconductor diode. Bandgap narrowing and carrier degeneracy are taken into consideration as heavy doping effects. The analysis also includes the contribution to the decay characteristic of the holes and electrons that come from the junction space charge region. The results of numerical computations are used to study the open circuit voltage decay characteristic. The variation of open circuit voltage with time, normalised by minority carrier lifetime, is also studied for the situation when the minority carrier concentration exceeds the equilibrium majority carrier concentration. In the design of heavily doped semiconductor devices, such an analysis may be useful.

2. MATHEMATICAL FORMULATION

The excess minority carrier densities at the abrupt $p^+\!-\!n$ junction under heavy doping condition are related to each other by:

$$P_m(t) = \frac{\rho_m(t)}{\rho_m^0} = \frac{n_m(t)}{n_m^0}$$  (1)

where:

- $\rho_m(t)$ = hole density at $n$-region
- $n_m(t)$ = electron density at $p^+$-region
- $\rho_m^0$ = hole density at $n$-region
- $n_m^0$ = electron density at $p^+$-region
- $\Delta E_g$ = band gap narrowing
- $A$ = asymmetry factor
- $E_r$ = intrinsic Fermi energy

Open circuit voltage decay, incorporating the contribution to the decay characteristic of the holes and electrons that come from the junction space charge region, may be written as:

$$V(t) = V(0) - \frac{K T}{q \tau_m}$$  (2)

where $V(t)$ is the instantaneous junction voltage, $q$ is the electronic charge and $\tau_m$ is the effective decay time which is given by:

$$\tau_m = \frac{\tau_e \tau_h}{\tau_e + \tau_h}$$  (3)

$\tau_e$ and $\tau_h$ are the electron lifetime at $p^+$-region and hole lifetime at $n$-region respectively. Minority carrier lifetime in heavily doped semiconductor empirically modelled as:

$$\tau_m = \frac{1}{C \Lambda N^2}$$  (4)

where $\Lambda$ is the minority carrier lifetime ($\Lambda = n$ or $\Lambda = p$ would denote electrons or holes), $N$ is the net doping density (cm$^{-3}$) and $C$ is a constant (cm$^2$s$^{-1}$):

- $n_m$ = effective intrinsic carrier density
- $D_m$ = diffusion coefficient
- $\mu$ = mobility
Substituting the expressions of effective carrier density and of mobility into eqn (4), one can get:

$$\begin{align*}
\tau_r &= \frac{K T}{q} n_i^3 \left[ F_{10}^{(1)}(\eta_s) F_{10}^{(2)}(\eta_s) \exp \frac{E_{10}^{(2)}(\eta_s)}{K T} \right] \times \left[ 54.3 T_s^{-0.57} + \frac{1.36 \times 10^4 T_s^{-12.3}}{1 + [N/(2.35 \times 10^{17} T_s^{24})] 0.88 T_s^{3.146}} \right] \\
\tau_s &= \frac{K T}{q} n_i^3 \left[ F_{10}^{(1)}(\eta_s) F_{10}^{(2)}(\eta_s) \exp \frac{E_{10}^{(2)}(\eta_s)}{K T} \right] \times \left[ 88 T_s^{-0.57} + \frac{7.4 \times 10^4 T_s^{-12.3}}{1 + [N/(1.26 \times 10^{17} T_s^{24})] 0.88 T_s^{3.146}} \right]
\end{align*}$$

From eqns (2), (3), (5) and (6), one obtains the expression of open circuit voltage decay as:

$$V(t) = V(0) - \frac{2 C^2 N^2}{n_i} \left[ \exp(\eta_s) \exp\left(\frac{2 \Delta E_s}{K T}\exp\left(\frac{E_{10}^{(2)}(\eta_s)}{K T}\right)\right) \right] + \frac{1.36 \times 10^4 T_s^{-12.3}}{1 + [N/(2.35 \times 10^{17} T_s^{24})] 0.88 T_s^{3.146}}$$

$$\times F_{10}^{(1)}(\eta_s) \left[ \exp(\eta_s) \exp\left(\frac{\Delta E_s}{K T}\exp\left(\frac{E_{10}^{(2)}(\eta_s)}{K T}\right)\right) \right]^{-1}$$

3. RESULTS

Numerical analyses of eqn (7) have been made to study the influence of heavy doping on open circuit voltage decay in a heavily doped abrupt $p^+--n$ junction silicon semiconductor diode. Computation has been carried out for $n_i = 1.5 \times 10^{20} \text{cm}^{-3}$, $\Delta E_s(N) = 3.4 \times 10^{-3} \text{mV}$, $E_s = 1.21 \text{mV}$, $K T/q = 0.025 \text{eV}$, $C = 1.72 \times 10^{-2} \text{cm}^{-2} \cdot \text{s}^{-1}$, $I_{in} = 7300$, $T = 300 \text{K}$, $n_i$ and the corresponding values of $F_{10}^{(1)}(\eta_s)$, $F_{10}^{(2)}(\eta_s)$ are chosen from Blakemore[13] for a fixed value of $N = 10^{19} \text{cm}^{-3}$. The results so obtained are shown graphically. Figure 1 depicts the open circuit voltage characteristic of a heavily doped abrupt $p^+--n$ junction. It reveals that the decay rate is nearly $5.2 \times 10^5 \text{V/s}$. This rapid decay rate is due to heavy doping effects on the junction. Figure 2 shows the variation of open circuit voltage with $t/t_{in}$ for a heavily doped $p^+--n$ junction of silicon.
Introduction

In semiconductor devices like LEDs, photodetectors, solar cells minority carriers recombine at the free surfaces. In the models of these minority carrier controlled devices, the phenomenon of surface recombination is recognised by the parameter $S$, the surface recombination velocity. The value of $S$ depends on the physical and chemical states of the surface, viz., free, oxidised, metallised, etc. [1 to 3]. Recombination is assumed to take place [1, 4 to 9] via deep traps either at or close to the surface. These traps may direct the Fermi level at the free surface [6].

It is assumed that under heavy doping conditions, the surface recombination is a combination of the Shockley-Read-Hall (S.R.H.) process through surface states in the band gap and the band-to-band Auger recombination process, due to which the recombination rate [10] depends on the density of surface states, the distribution of band bending, etc. Thus $S$ is not a constant parameter during the change of the physical and chemical states of the surface.

On the stated physical background, an attempt has been made in this note to study the variation of $S$ with doping density for a heavily doped abrupt $n^+ - p$ junction, considering band gap narrowing and carrier degeneracy as heavy doping effects. The results obtained by numerical computations are presented and compared graphically with an earlier work [11].

Mathematical formulation

The surface recombination rate due to the Shockley-Read-Hall (S.R.H.) process [12] is given by

$$R(x) = \frac{n(x) p(x) - n_i^2}{\tau_e(p(x) + p_i) + \tau_p(n(x) + n_i)}$$

and the net Auger recombination can be written as

$$R_{Aug} = \gamma \frac{n(x) p(x) - n_i^2}{n_i^2} (n + p),$$

where $n(x)$ and $p(x)$ are the electron concentration in conduction band and the hole concentration in the valence band, respectively; $n_i$ is the intrinsic carrier concentration; $\tau_e$ and $\tau_p$ are the electron and hole minority carrier lifetimes, and $\gamma$ is the Auger recombination rate.
coefficient. $n_i$ and $p_i$ are the Shockley-Read-Hall parameters, given by

$$n_i = n_i \exp \left( \frac{E_i - E_i}{k_B T} \right), \quad p_i = n_i \exp \left( \frac{E_i - E_i}{k_B T} \right),$$

where $E_i$ is the effective energy of the trapping level; $E_i$ the intrinsic Fermi energy; $k_B$ the Boltzmann constant, and $T$ the absolute temperature.

In the presence of band gap narrowing and carrier degeneracy due to heavy doping, the expressions for electron and hole concentrations can be written as

$$n(x) = n_i F_{1/2}(\eta_n) \exp (-\eta_n) \exp \left( \frac{A \Delta E_x}{k_B T} \right) \exp \left( \frac{E_{fa} - E_i}{k_B T} \right),$$

$$p(x) = n_i F_{1/2}(\eta_p) \exp (-\eta_p) \exp \left( \frac{(1 - A) \Delta E_x}{k_B T} \right) \exp \left( \frac{E_i - E_{fa}}{k_B T} \right),$$

where $F_{1/2}(\eta)$ is the Fermi-Dirac integral of order $1/2$; $\eta$ the reduced Fermi energy; $A$ the asymmetry factor; $\Delta E_x$ the band gap narrowing; $E_{fa}$ the quasi-Fermi energy for electrons, and $E_{fa}$ the quasi-Fermi energy for holes. At equilibrium, $E_{fn} = E_{fp}$. The expression for the surface recombination velocity $S$ can be written as

$$S = \frac{J_s}{q \Delta n},$$

where $q$ is the electronic charge, $\Delta n$ the injected carrier density, and $J_s$ the surface recombination current density.

Moreover,

$$J_s = q[R(x) + R_{Aug}].$$

Thus

$$\frac{S}{\Delta n} = \frac{R(x) + R_{Aug}}{\Delta n} = \frac{np - n_i^2}{\Delta n} \left[ \frac{1}{\tau_p (p + n_i) + \tau_n (n + n_i)} + \frac{\gamma (n + p)}{n_i^2} \right].$$

Incorporating (3) in (6), the expression for the surface recombination velocity can be derived as

$$S = \frac{n_i}{\Delta n} \left[ \tau_p \left\{ F_{1/2}(\eta_p) \exp (-\eta_p) \exp \left( \frac{A \Delta E_x}{k_B T} \right) \exp \left( \frac{E_{fa} - E_i}{k_B T} \right) + 1 \right\} \right.$$

$$+ \tau_n \left\{ F_{1/2}(\eta_n) \exp (-\eta_n) \exp \left( \frac{A \Delta E_x}{k_B T} \right) \exp \left( \frac{E_{fa} - E_i}{k_B T} \right) + 1 \right\} \right]^{-1}$$

$$+ \gamma \left\{ F_{1/2}(\eta_n) \exp (-\eta_n) \exp \left( \frac{A \Delta E_x}{k_B T} \right) \exp \left( \frac{E_{fa} - E_i}{k_B T} \right) \right\}$$

$$+ F_{1/2}(\eta_p) \exp (-\eta_p) \exp \left( \frac{(1 - A) \Delta E_x}{k_B T} \right) \exp \left( \frac{E_i - E_{fa}}{k_B T} \right)$$

$$\times \left[ F_{1/2}(\eta_n) F_{1/2}(\eta_p) \exp \left( \frac{\Delta E_x}{k_B T} \right) \exp \left( -\eta_n + \eta_p \right) - 1 \right].$$
Results  From (7), numerical analyses are carried out to study the variation of the surface recombination velocity with dopant density in a heavily doped abrupt n⁺–p junction. The results are shown in Fig. 1. Curve a represents the results of the numerical analysis of the present model, whereas curve b represents the results of an earlier work [11]. Numerical analyses of (7) have been carried out considering 

\[ \Delta E_p = 10.23 \left( N/10^{18} \right)^{1/3} + 13.12 \left( N/10^{18} \right)^{1/4} + 2.93 \left( N/10^{18} \right)^{1/2} \text{meV}, \]

\[ n = 1.5 \times 10^{16} \text{cm}^{-3}, \quad T = 300 \text{K}, \quad E_g = 1.21 \text{eV}. \]

The values of \( \eta_p, \eta_n, F_{1/2}(\eta_p), \) and \( F_{1/2}(\eta_n) \) are chosen suitably [14] for the specified dopant densities. In the numerical analysis, the values of \( \tau_p \) for the variation of majority carrier concentration in the range \( 10^{19} \) to \( 10^{21} \text{cm}^{-3} \) have been chosen within \( 10^{-8} \) to \( 3 \times 10^{-9} \) s; while in the minority carrier concentration range between \( (3 \times 9) \times 10^{16} \text{cm}^{-3} \), the values of \( \tau_n \) are taken within \( 10^{-10} \) to \( 10^{-12} \) s. Several effects decrease the minority carrier lifetime with increasing doping level, because many recombination mechanisms may compete with each other. Moreover, the change of minority carrier lifetime with doping concentration is not uniform. It is inversely proportional to the concentration at lower values and inversely proportional to the square of the concentration at higher values. The nonuniform change of minority carrier lifetime with concentration is also considered in the computation of the present analysis. It is also assumed that the injected carrier density is always small compared to the majority carrier density.

References


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NOTE

EFFECT OF SURFACE RECOMBINATION ON THE TRANSIT-TIME
IN HEAVILY DOPED $n^+-p$ JUNCTION SILICON
SOLAR CELL

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1. INTRODUCTION

There are numerous semiconductor devices, viz., bipolar transistors, solar cell, LED, etc., where carrier flow is controlled by injection and diffusion of minority carriers, contain active regions with doping levels above \(10^{18} \text{ cm}^{-3}\). The recombination effects in these situations play an important role in the behaviour of certain characteristics of the devices[1-4]. In the modelling of minority carrier controlled devices, surface recombination velocity \(S\) acts as a parameter which characterizes surface recombination. It is established that surface recombination is a Shockley-Read-Hall (SRH) process through surface states in the bandgap[5]. Surface recombination velocity \(S\) depends on the physical and chemical states of the surface[6,7], viz., free, oxidized, metallized, damaged, etc. Surface recombination is highly affected owing to the influence of heavy doping, particularly through bandgap narrowing. Moreover, surface recombination velocity depends on injection of carriers. Thus, \(S\) changes under different physical conditions.

In the performance of semiconductor devices using heavily doped semiconductor junctions, surface recombination velocity plays a very important role. The junction leakage current with variation of injection level of a high-low junction has been modeled by the effective surface recombination velocity \(S\) depends on the bandgap narrowing and carrier degeneracy as heavy doping effects. The results so obtained by numerical computations are presented and compared graphically with an earlier experimental work[10].

In this article, a model has been developed to investigate the variation of the charge control transit-time, required for minority carriers to cross the emitter region of a heavily doped \(n^+-p\) junction silicon solar cell, with surface recombination velocity of the minority carriers taking into account the bandgap narrowing and carrier degeneracy as heavy doping effects. The results so obtained by numerical computations are presented and compared graphically with an earlier experimental work[10].

2. MATHEMATICAL FORMULATION

The expression for the charge control transit-time[10] required for minority carrier to cross the emitter region is:

\[
\tau_e = \frac{W_e}{2D} + \frac{W_e}{S},
\]

where \(D\) is the average minority carrier diffusivity in the emitter region, whose width is \(W_e\), and \(S\) is the surface recombination velocity.

Again, the surface recombination velocity is defined as:

\[
S = \frac{J_e}{q\Delta n},
\]

Moreover:

\[
J_e = q[R(x) + R_{Aug}].
\]

where \(R(x)\) is the surface recombination due to Shockley-Read-Hall (SRH) process[11,12] and \(R_{Aug}\) is the net Auger recombination.

Now:

\[
R(x) = \frac{n(x)p(x) - n_i^2}{\tau_e p(x) + \tau_i n(x) + n_i},
\]

and

\[
R_{Aug} = \frac{n(x)p(x) - n_i^2}{n_i^2(n + p)}.
\]

where \(\tau_e\) and \(\tau_i\) are the electron and hole lifetimes, respectively; \(n_i\) the intrinsic carrier density and \(r\) is the Auger recombination coefficient. The electron concentration \(n(x)\) and hole concentration \(p(x)\) under heavy doping condition are defined as[13]:

\[
n(x) = n_i F_{10}(\eta_i) \exp(-\eta_i) \exp\left[\frac{A\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right]
\]

\[
p(x) = n_i F_{10}(\eta_i) \exp(-\eta_i) \exp\left(\frac{(1 - A)\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right)
\]

where \(F_{10}(\eta_i)\) is the Fermi-Dirac integral of order 1/2; \(\eta_i\) the reduced Fermi energy; \(A\), the asymmetry factor; \(\Delta E_s\) the bandgap narrowing; \(\kappa\), the Boltzmann constant; \(T\), the absolute temperature; \(E_{in}\) and \(E_{ex}\), the quasi Fermi energies of electron and hole respectively, and \(E_i\) is the intrinsic Fermi energy. At equilibrium \(E_{in} = E_{ex}\).

Thus from eqns (2-6), one obtains:

\[
S = \frac{n_i}{\Delta n} \left[ \tau_e \left\{ F_{10}(\eta_i) \exp(-\eta_i) \exp\left(\frac{(1 - A)\Delta E_s}{kT}\right) \right\} + \tau_i \left\{ F_{10}(\eta_i) \exp(-\eta_i) \exp\left(\frac{A\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) + 1\right\}^{-1} \right.
\]

\[
\left. + r \left\{ F_{10}(\eta_i) \exp(-\eta_i) \exp\left(\frac{A\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) \right\} \right]^{-1}
\]

\[
\times \left[ F_{10}(\eta_i) \exp\left(\frac{(1 - A)\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) \right]
\]

\[
\times \left[ F_{10}(\eta_i) \exp\left(\frac{A\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) \right]
\]

\[
+ F_{10}(\eta_i) \exp(-\eta_i) \exp\left(\frac{A\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) \right]
\]

\[
\times \left[ F_{10}(\eta_i) \exp\left(\frac{(1 - A)\Delta E_s}{kT} \exp\left(\frac{E_i - E_i}{kT}\right)\right) \right]^{-1}
\]
To arrive at the expression of transit-time, the minority carrier diffusion-mobility relation will be made useful, which is given by:

$$D_p = \frac{kT}{q \mu_p}, \tag{8}$$

where $\mu_p$ is the hole mobility. Assuming the minority and majority carrier mobilities to have the similar functional form[14,15], e.g.:

$$\mu_\tau = \frac{54.37 \times 10^7}{T^2} \times \left[1 + \left[1 + \left(\frac{1}{2.35 \times 10^7 T^2}\right)^{0.872} \times \frac{S}{10^{17}} \right]^{1.36} \right], \tag{9}$$

where $T = T/300$ and $N_a$ is the acceptor density.

Using eqns (1),(7)–(9), the expression of $\tau_\tau$ has been derived as:

$$\tau_\tau = \frac{q}{2kT} \left[54.37 \times 10^7 \right] \times \left[1 + \left(\frac{1}{2.35 \times 10^7 T^2}\right)^{0.872} \times \frac{S}{10^{17}} \right]^{-1} \times \left[1 + \left[\frac{1}{2.35 \times 10^7 T^2}\right]^{0.872} \times \frac{S}{10^{17}} \right]^{1.36} \times \exp\left[\frac{E_\tau - E}{kT}\right]$$

$$+ \exp\left[\frac{E_\tau - E}{kT}\right] + \left\{\frac{F_{11}(\eta_\tau)}{\eta_\tau} \exp\left(-\eta_\tau\right) \frac{(1 - \Delta) \Delta E}{kT} \right\}^{1/2} \times \exp\left[\frac{E_\tau - E}{kT}\right]$$

$$+ \frac{\Delta W_s}{\eta_\tau} \times \exp\left[\frac{E_\tau - E}{kT}\right] + \left\{\frac{F_{11}(\eta_\tau)}{\eta_\tau} \exp\left(-\eta_\tau\right) \exp\left[\frac{E_\tau - E}{kT}\right] + 1\right\}^{-1} \times \exp\left[\frac{E_\tau - E}{kT}\right]$$

$$+ r \left\{\frac{F_{11}(\eta_\tau)}{\eta_\tau} \exp\left(-\eta_\tau\right) \exp\left[\frac{E_\tau - E}{kT}\right] + 1\right\}^{-1} \times \exp\left[\frac{E_\tau - E}{kT}\right]$$

$$+ F_{11}(\eta_\tau) \exp\left(-\eta_\tau\right) \exp\left[\frac{E_\tau - E}{kT}\right]$$

This model also reveals that the efficiency of the solar cell can be increased by the photogenerated minority carriers. Moreover, cell performance would be improved if the minority carrier diffusion length in the base region exceeds the base thickness. The emitter collection efficiency under transparent approximation at carrier generating spike at $x = x_a$ may be written as:

$$\eta_e(x_a) = 1 - \frac{\int_0^{\Delta x} dx / D_p \mu_p}{\int_0^{\Delta x} dx / D_p \mu_p}$$

$$= 1 - \frac{S \rho_p(W) q}{K T} \int_0^{\Delta x} dx / \mu_p \rho_p(p - \Delta p)$$

where $W$ is the separation width between surface and depletion region boundary, $E_\tau(W)$, equilibrium hole concentration at the surface and $\Delta P$ is the excess hole carrier density. Since, $S$ is a dopant density dependent parameter, it is obvious that for certain range of values of dopant densities, the efficiency of the cell will be improved. Conversion efficiency may be increased by reducing recombination losses through proper chemical processing of the surface. Also, appropriate dopant density in the diffused region would produce drift field that should counteract minority carrier diffusion, thereby the cell performance may be improved.

**Fig. 1.** Variations of charge-control transit-time ($\tau_\tau$) with surface recombination velocity ($S_\tau$) of minority carrier for an $n^+ - p$ silicon solar cell with a transparent emitter. The curve (a) depicts the results of the present analysis, whereas the curve (b) represents that of an earlier work[10].

3. DISCUSSION

The results of numerical computations of eqn (10) are presented graphically in Fig. 1. It depicts the variation of charge-control transit-time of minority carrier ($\tau_\tau$) with its surface recombination velocity ($S_\tau$) for a heavily doped $n^+ - p$ silicon solar cell with a transparent emitter at 300 K. The cell emitter is transparent, because, for higher value of $S$, eqn (1) reveals that charge-control transit-time is very low ($\sim 10^{-10}$s), which is significantly smaller than hole recombination lifetime ($\sim 10^{-7}$s). Curve (a) represents the results of the numerical analysis of the present model, whereas the curve (b) is due to an earlier work[10].

Numerical analyses of (10) have been carried out considering $\Delta E_g = 3.4 \times 10^{-4}$ ($n^{10} + p^{10}$) eV, $\eta_e = 1.5 \times 10^{10}$ cm$^{-3}$, $T = 300 K$. $E_\tau = 1.21$ eV. The values of $\eta_e$, $\eta_l$, $F_{11}(\eta_l)$ and $F_{11}(\eta_l)$ are chosen suitably[16] for the specified dopant densities. Variation of carrier lifetime with dopant densities is also incorporated in the numerical analysis. The values of $\tau_\tau$ for the variation of majority carrier concentration in the range $10^{19}$-$10^{21}$ cm$^{-3}$ have been chosen within $10^{-3}$-$3 \times 10^{-8}$s; while in the minority carrier concentration range between $(3-9) \times 10^{16}$ cm$^{-3}$, the values of $\tau_\tau$ are taken within $10^{-7}$-$10^{-9}$s.

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REFERENCES

Introduction

Several approaches have been made to analyse various compositionally nonuniform semiconductor devices since the last three decades /1 to 6/. Based on depletion approximations, earlier workers offered approximate solutions in case of abrupt graded junctions /7, 8/. Modified techniques are adopted to study heavy doping effects in heterojunctions /9 to 12/. Earlier workers /11 to 13/ derived transport equations in terms of a nonuniform band structure using approximate methods. These methods are developed to model heavily doped silicon devices /12, 13/.

In this note, a new model has been developed to investigate the potential distribution of a heavily doped semiconductor heterojunction in equilibrium, considering the various heavy doping effects, viz., band-gap narrowing, carrier degeneracy, many-body effects, and non-ideal behaviours of electrons at junction interface. The results so obtained by numerical computations are presented graphically.

Mathematical formulation

In this case of a heterojunction, it is assumed that the right side is a highly doped n-type semiconductor in comparison with the left side, p-type semiconductor and the system is in equilibrium. Poisson’s equation for the stated condition can be written as

\[
\frac{d^2 \phi}{dx^2} = \frac{q}{\varepsilon \varepsilon_0} (p - n + N_D - N_A),
\]

where donors and acceptors \((N_D, N_A)\) are completely ionised, \(\phi\) is the electrostatic potential. In equilibrium, the carrier concentrations \(p\) and \(n\) are related to the electrostatic potential by

\[
p = n_i \exp(U), \quad U = q\phi/kT = (E_p - E_F)/kT, \]

\[
n = n_i \exp(-U);
\]

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4 physica (a)
The energy band diagram of a heterostructure with continuity of the vacuum level at \( x = 0 \) is shown in Fig. 1 which depicts the conventional discontinuity in the conduction band and in the valence band. In the figure, the quantity \( \delta_p \) is the distance from the valence band \( E_v \) to the Fermi level \( E_F \) on the p-side and \( \delta_n \) is the distance from \( E_F \) to the conduction band \( E_C \) on the n-side. The conduction band discontinuity and the valence band discontinuity in terms of \( \chi_p \) and \( \chi_n \), the electron affinity on p-side and n-sides, respectively, can be expressed as

\[
\Delta E_C = \chi_p - \chi_n, \quad \Delta E_V = (E_{Gn} - E_{Gp}) - (\chi_p - \chi_n),
\]

where \( E_{Gn} \) and \( E_{Gp} \) are the n-type energy gap and the p-type energy gap, respectively. These are known as affinity rules. Similarly, the discontinuity in the intrinsic level \( \Delta E_i \) is given by \( \Delta E_i = E_i - E_V \). The positions of \( E_V \) and \( E_i \) on each side of the junction are located in Fig. 1 with respect to the uniform Fermi level.
The electron affinities accommodate the two vacuum levels \( E_{\text{vac}} \) in which the energy difference between the levels is the diffusion potential \( V_D \), given by \( V_D = V_{D_p} + V_{D_n} \). \( V_{D_p} \) is the diffusion or barrier potential yielding the band bending on the p-side, and \( V_{D_n} \) is the corresponding parameter for the n-side.

For the right side of the configuration, as shown in Fig. 1, in presence of heavy doping effects viz., band-gap narrowing, effective density of states, carrier degeneracy, and non-ideal behaviour of electron and many-body influence, the relationship between carrier concentrations \( p \) and \( n \), under equilibrium condition, and electrostatic potential may be given by

\[
p = n_i \exp\left[\frac{-\Phi - (\gamma - 1)\Delta_G}{kT}\right],
\]

\[
n = n_i \exp\left[\frac{q\Phi + \gamma \Delta_G}{kT}\right],
\]

where

\[
\gamma = \left[\chi(x) - \chi(0)\right] + kT \ln \left(\frac{N_c(x)}{N_c(0)}\right) + kT \ln \left(\frac{F_{1/2}(\eta_c(x))}{\exp(\eta_c(x))}\right)
\]

\[
- kT \ln \left(\frac{F_{1/2}(\eta_n(0))}{\exp(\eta_n(0))}\right) + kT \ln \left(\frac{\zeta_c(x)}{\zeta_n(0)}\right) \Delta_G,
\]

and effective band gap shrinkage,

\[
\Delta_G = \left[\frac{kT \ln \left(\frac{N_c(x)N_v(x)}{N(v(0))N_c(0)}\right) + kT \ln \left(\frac{F_{1/2}(\eta_c(x))F_{1/2}(\eta_v(x))}{\exp(\eta_c(x))\exp(\eta_v(x))}\right)}{2} + \frac{E_G(x) - E_G(0)}{2}\right] + \frac{\zeta_c(x)}{\zeta_n(0)} \frac{\exp(\eta_v(0))}{\exp(\eta_c(x))}
\]

\[
- kT \ln \left(\frac{N_c(0)N_v(x)}{N(v(0))N_c(0)}\right) + \frac{2\Delta}{4\pi^2}\left[\frac{m^e_{\text{con}}}{h^2} + \frac{2\Delta}{3}\left(\frac{m^e_{\text{val}}}{m^v_{\text{con}}}\right)^{1/2}\right] + \frac{2\Delta}{3}\left(\frac{m^e_{\text{con}}}{m^e_{\text{val}}}\right)^{1/2}.
\]

where \( \chi \) is the electron affinity, \( N_c, N_v \) are the effective density states in conduction and valence bands, respectively, \( F_{1/2} \) is the Fermi-Dirac integral of order one-half with \( \eta_c = (E_F - E_c)/kT \), \( \zeta \) is the degeneracy factor, \( \Lambda = 0.35 \) accounts for the anisotropic electron effective mass, \( r_s \) is the dimensionless density parameter, \( m^e_{\text{con}} \) is the conductivity effective mass of holes, \( m^e_{\text{val}} \) is the effective mass of electron.

Using (2) and (3), Poisson's equation (1) can be written as

\[
\frac{d^2\phi}{dx^2} = - \frac{\Delta}{\varepsilon r_o} \left[\frac{n_i \exp\left[\frac{-q\Phi - (\gamma - 1)\Delta_G}{kT}\right]}{n_i \exp\left[\frac{q\Phi + \gamma \Delta_G}{kT}\right] + (N_D - N_A)}\right].
\]
Equation (6) yields the equilibrium electrostatic potential and is applicable to the GaAs side of a heterojunction with nonuniform band structure. The following relations are used to simplify (8):

\[ U_G = \frac{A_G}{kT} , \]

\[ D = \frac{N_D - N_A}{2\eta} , \]

\[ \rho = \frac{K}{L_D} , \]

\[ R = \frac{e}{\varepsilon_o} , \]

where \( L_D = \left[ \frac{\varepsilon_o kT}{2q^2 n_i} \right]^{1/2} \) is the intrinsic Debye length in GaAs.

The normalized Poisson equation reads

\[
\begin{align*}
\frac{\partial^2 U}{\partial x^2} &= \frac{1}{2R} \left[ \exp(U_G/2) \left[ \exp\left(-U + \left(\gamma - \frac{1}{2}\right)U_G\right) \right. \right. \\
&\quad - \exp\left[U + \left(\gamma - \frac{1}{2}\right)U_G\right] + \frac{N_D - N_A}{n_L} \left. \right] \\
&= \frac{1}{2R} \left[ \exp(U_G/2) \left[ \cosh\left[U + \left(\gamma - \frac{1}{2}\right)U_G\right] - \frac{N_D - N_A}{n_L} \right] \right] \\
&= R^{-1} \left[ \exp(U_G/2) \sinh\left[U + \left(\gamma - \frac{1}{2}\right)U_G\right] - D \right] .
\end{align*}
\]

In the stated configuration, shown in Fig. 1, let the junction be located at \( x = 0 \) and the contacts of the device be chosen at \( x = -W_L \) and \( x = W_R \).

For \( x > 0 \), (8) is suitable to obtain the potential. Integrating (8),

\[
\frac{dU}{dx} = \left[ \frac{2}{R} \left[ \exp(U_G/2) \cosh\left[U + \left(\gamma - \frac{1}{2}\right)U_G\right] - DU \right] + \frac{2C}{R} \right]^{1/2} ,
\]

where \( C \) is the integrating constant, to be determined through the use of the boundary condition, \( dU/dx = 0 \), at the ohmic contact \( (x = W_R) \). It yields
Thus equation (9) becomes

$$dr = \frac{dU}{2R \exp(U_G/2) \cosh \left( U + \left( \gamma - \frac{1}{2} \right) U_G \right) - \frac{2D}{R} U + \frac{2C}{R}}^{1/2}$$

or,

$$r = \frac{X}{I_D}$$

$$= \frac{U}{\sqrt{2R}} \left[ \frac{2R}{\exp(U_G/2) \cosh \left( U + \left( \gamma - \frac{1}{2} \right) U_G \right) - \frac{2D}{R} U + \frac{2C}{R}} \right]^{-1/2} dU \ . \ (11)$$

Results. Equation (11) has been used for numerical computations to study the variation of the normalised potential with dopant densities (Fig. 2). With increased value of the density, the variation of the normalised potential changes more sharply than at lower concentration. This is in agreement with the nature of variation as presented in an earlier work /14/.

For the left side, the relatively lightly doped side of the heterojunction, the present derivation is not applicable to study the potential distribution through this solution. The potential distribution in this region is to be carried out for non-degenerate semiconductors through the expression

$$r = \frac{U}{\sqrt{2}} \left[ \frac{2 \cosh(U) - D' U + C'}{2} \right]^{-1/2} dU \ ,$$

where $C' = D' U(0) - \cosh(U(0))$, $D'$ is the value of $D$ in the left side i.e., the lightly doped side of the stated heterojunction.
References


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A model for studying the characteristics of heavily doped n⁺-GaAs/n-Ge heterojunction structures is developed through the use of a Poisson-Boltzmann integral equation. The equation is used to investigate the nature of variation of conduction band/Fermi level separation with depth. The changes of carrier concentration with depth are also computed.

1. Introduction

The measurement of C/V doping profiles in semiconductor structures is an essential tool in choosing device materials specially for the devices which have dependence on electrical transport properties (viz., FETs, solar cells, etc.). There are several approaches to deal with compositionally non-uniform semiconductor devices [1 to 5]. Utilising the depletion approximation, earlier workers offered an approximate solution of the Poisson-Boltzmann equation in case of a graded junction [6, 7]. Earlier workers adopted different techniques to study heavy doping effects in heterojunctions [8 to 10] and derived transport equations in terms of a non-uniform band structure using approximate methods [8, 9, 11].

In this presentation, a new model has been developed to investigate some characteristics of heavily doped n⁺-GaAs/n-Ge heterojunction structures through a Poisson-Boltzmann integral equation. The equation is utilised to study the variation of conduction band/Fermi level separation and carrier concentration distribution with depth for the stated structures. The numerical analyses have been presented graphically.

2. Mathematical Derivation

Poisson's equation for the curvature of the conduction band edge at any point for the n⁺-GaAs/n-Ge heterojunction can be written as [12]

\[
\frac{d}{dx} \left[ e(x) \frac{d}{dx} \left( \frac{E_F - E_C}{KT/q} \right) \right] = \frac{q^2(n - N_D^+/N_D)}{KT},
\]

(1)

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where $E_C$ is the conduction band energy, $E_F$ the Fermi level energy, $n$ the electron density in the conduction band, $N_D^+$ the ionised donor density, $K$ the Boltzmann constant, $T$ the absolute temperature, $\varepsilon$ the dielectric constant, $q$ the electronic charge, and $x$ the distance.

Equation (1) can be represented as

$$\frac{\partial^2 \varphi}{\partial x^2} + \left( \frac{\partial}{\partial x} \ln \varepsilon \right) \frac{\partial \varphi}{\partial x} = \frac{q}{\varepsilon} \left( n - N_D^+ \right),$$  

where

$$\varphi = E_F - E_C.$$

The permittivity $\varepsilon$ varies in the $x$-direction in the $n^+\text{-GaAs}/n\text{-Ge}$ heterojunction under consideration. To incorporate this variation across the heterojunction, an equivalent position variable $\chi$ may be defined as

$$\chi = \varepsilon_0 \int_0^x \frac{dy}{\varepsilon(y)},$$

where $\varepsilon_0$ is a uniform dielectric permittivity of some value.

Relation (3) implies

$$\frac{d\chi}{dx} = \frac{dx}{\varepsilon(x)}.$$  

Similarly, an equivalent doping distribution can be written as

$$\varepsilon_0 n(x) = \varepsilon(x) \frac{N_D^+(x)}{N_D^+}.$$

and an equivalent effective density of states distribution would yield

$$\varepsilon_0 \eta_C(\chi) = \varepsilon(x) \frac{N_C(x)}{N_C}.$$

$N_C$ is the effective density of states.

Hence, an equivalent total electron distribution and an equivalent intrinsic concentration yield, respectively,

$$\varepsilon_0 \eta(\chi) = \varepsilon(x) n(x)$$

and

$$\varepsilon_0 \eta(\chi) = \varepsilon(x) n_i(x).$$

Incorporating (2) to (8) in (1), one can get

$$\frac{d^2 \varphi(x)}{dx^2} = \frac{q}{\varepsilon_0} \{ \eta(x) - \mu(\chi) \}. $$

In a heavily doped region, bandgap, electron affinity and density of states change due to impurity band widening, band tailing, electron–electron interaction, and screening effects. These mechanisms introduce unequal shifts from the intrinsic conduction band and valence band edges owing to their unequal influences on electrons and holes. Under heavily doped conditions, Ge and GaAs behave in many respects like metals and the
standard band structure, for rigid band approximation, may be assumed to be parabolic. Thus, for a degenerate semiconductor, using Fermi-Dirac statistics for the impurity concentrations \[14\] in terms of the equivalent intrinsic concentration \(n(x)\), the expressions for \(\eta(x)\) and \(\mu(x)\) are given by

\[
\eta(x) = \eta(x) \frac{F_{1/2}(\eta_n)}{\exp(\eta_n)} \exp\frac{\Delta E_g}{KT} \exp q\left(\frac{E_F - E_C + E_g/2\phi}{KT}\right)
\]

and

\[
\mu(x) = \eta(x) \exp q\left\{(E_{FB} - E_{B})/KT\right\} \left\{1 + g \exp q\left(\frac{E_F - E_C + \phi_D}{KT}\right)\right\}^{-1}
\]

\[
= \eta(x) \exp (U_B) \left\{1 + g \exp q\left(\frac{E_F - E_C + \phi_D}{KT}\right)\right\}^{-1},
\]

where \(\Delta E_g\) is the total bandgap narrowing, \(A\) the asymmetry factor, \(F_{1/2}(\eta_n)\) the Fermi-Dirac integral of order 1/2 for the reduced electron energy, \(g\) the donor level degeneracy, \(U_B = g(E_{FB} - E_{B})/KT\) the normalised bulk potential, \(E_{FB}, E_{B}\) the conduction band energy and Fermi level energy of the bulk, and \(\phi_D\) the donor depth. Here, \(\eta_n = (E_{FB} - E_C)/KT\), where \(E_{FB}\) is the quasi-Fermi energy of electrons. Due to heavy doping, there will be some deviation from the condition of thermal equilibrium. For this, \(E_F\) is replaced by the quasi-Fermi level, \(E_{FB}\).

It is obvious that at \(x = 0\), \(d\phi/dx \neq 0\), hence the charge neutrality condition is not satisfied at \(x = 0\) in the n⁺-GaAs layer, since \(d^2\phi/dx^2 \neq 0\). According to Maxwell’s equations, the displacement vector \(D = eE\) is assumed to be continuous across the interface where the state density can be considered to be negligible, which is a good approximation for bulk material. It facilitates different theoretical investigations. Thus, assuming the charge neutrality condition and considering that the bandgap narrowing in the n-type heavily doped semiconductor would arise mainly from impurity band widening \((A \approx 1)\) and choosing \(g = 2\) as the donor level degeneracy \([12, 15]\), Poisson’s equation becomes

\[
\frac{d^2}{dx^2} \frac{q(E_F - E_C)}{KT} = \frac{q^2}{KT \epsilon_n} \left[\eta(x) \frac{F_{1/2}(\eta_n)}{\exp(\eta_n)} \exp\frac{\Delta E_g}{KT} \exp q\left(\frac{E_F - E_C + E_g/2\phi}{KT}\right)\right]
\]

\[
-\eta(x) \exp (U_B) \left\{1 + 2 \exp q\left(\frac{E_F - E_C + \phi_D}{KT}\right)\right\}^{-1}.
\]

This yields

\[
\frac{d^2U}{dx^2} = \frac{1}{2L_D^2} \left[\gamma_n \exp E_g + 2\Delta E_g \exp (U) - \exp (U_B) \left\{1 + 2 \exp (U + \phi')\right\}^{-1}\right]
\]

\[
= \frac{1}{2L_D^2} \left[\gamma_n \exp E_g + 2\Delta E_g \exp (U) - \exp (U_B) \left\{1 - 2 \exp (U + \phi')\right\}\right],
\]

(11)
where
\[ U = \frac{q(E_F - E_C)}{KT}; \quad \{1 + 2 \exp (U + \varphi')\}^{-1} = 1 - 2 \exp (U + \varphi'), \]
for higher negative values of \( U \),
\[ \gamma_n = \frac{F_{1/2}(\eta_n)}{\exp (\eta_n)}, \]
\[ L_{Di} = (e_n KT/2q^2 \eta_n)^{1/2} \quad (\text{the intrinsic Debye length}), \]
\[ \varphi' = q\varphi_D/KT. \]

As the surface charge is never absent, using boundary conditions \( U \to U_B \) and \( dU/dx \to 0 \) as \( x \to \infty \) (bulk) and assuming \( U \) to be maximum at the interface and minimum at the \( n^-\text{-GaAs} \) surface, whereas for the \( n^-\text{-Ge} \) side \( U \) is maximum at the surface and minimum at the interface, (11) yields
\[ \frac{dU}{dx} \int_0^U \left( \frac{\partial U}{\partial x} \right) dU = \frac{1}{2L_{Di}^2} \int_{U_b}^U \gamma_n \exp \left( \frac{E_e + 2 \Delta E_e}{2KT} \right) \exp (U) \]
\[ \quad - \exp (U_B) \{1 - 2 \exp (U + \varphi')\} dU. \quad (12) \]

Thus,
\[ \frac{dU}{dx} = \frac{1}{L_{Di}^2} \left[ \gamma_n \exp \left( \frac{E_e + 2 \Delta E_e}{2KT} \right) \{\exp (U) - \exp (U_B)\} \right. \]
\[ \quad - \left. (U - U_B) \exp (U_B) + 2 \exp (U_B + \varphi') \{\exp (U) - \exp (U_B)\}\right]^{1/2} \quad (13) \]

Incorporating the relation
\[ \frac{X}{L_{Di}(\cosh U_B)^{1/2}} = \frac{X}{L_{Di}} \]
one obtains the equation for the normalised position in terms of the extrinsic Debye length \( L_D \) as
\[ \frac{X}{L_D} = 2^{-1/2} \int_{U_S}^U \left[ \exp (U_B) + \exp (-U_B)\right]^{1/2} \]
\[ \times \left[ \gamma_n \exp \left( \frac{E_e + 2 \Delta E_e}{2KT} \right) \{\exp (U) - \exp (U_B)\} - (U - U_B) \exp (U_B) \right. \]
\[ \quad + \left. 2 \exp (U_B + \varphi') \{\exp (U) - \exp (U_B)\}\right]^{-1/2} dU, \quad (14) \]
where \( U_S \) is the normalised surface potential.

For large values of \( U_B \), \( \exp (-U_B) \) can be neglected. Under this physical situation, (14) reduces to
Some Characteristics of $n^+\text{-GaAs}/n\text{-Ge}$ Heterojunction Structures

\[ \frac{X}{L_D} = 2^{-1/2} \int_0^U \left[ \gamma_n \exp \frac{E_g + 2\Delta E_g}{2KT} \{ \exp (U - U_B) - 1 \} - (U - U_B) \right. \]
\[ + 2 \exp (U_B + \phi') \{ \exp (U - U_B) - 1 \} \left. \right]^{-1/2} dU \]
\[ = 2^{-1/2} \int_0^U \left[ \left\{ \gamma_n \exp \frac{E_g + 2\Delta E_g}{2KT} + 2 \exp (U_B + \phi') \right\} \right. \]
\[ \times \left\{ \exp (U - U_B) - 1 \} - (U - U_B) \left. \right]^{-1/2} dU. \tag{15} \]

Substituting
\[ \gamma_n \exp \frac{E_g + 2\Delta E_g}{2KT} + 2 \exp (U_B + \phi') = A, \]
\[ U_B - A = B, \quad \text{and} \quad \frac{A}{\exp (U_B)} = C, \]

one can get from (15)
\[ \frac{X}{L_D} = \int_0^U \left[ B + C \exp (U) - U \right]^{-1/2} dU. \tag{16} \]

3. Discussion

Computational analyses of (16) have been carried out for some arbitrarily chosen values of different parameters involved in the stated equation. Fig. 1 shows the variation of conduction band/Fermi level separation with depth for $n^+\text{-GaAs}/n\text{-Ge}$ heterojunction structures. This curve has been

Fig. 1. Variation of $(E_F - E_C)/KT$ with depth for the $n^+\text{-GaAs} (1 \times 10^{17} \text{cm}^{-3})/n\text{-Ge} (4 \times 10^{15} \text{cm}^{-3})$ heterojunction structures.
Fig. 2. Variation of carrier concentration with depth for the $n^+$-GaAs $(1 \times 10^{17}$ cm$^{-3})/n$-Ge $(4 \times 10^{15}$ cm$^{-3}$) heterojunction structures.

drawn using the following parameter values: $N_D = 1 \times 10^{17}$ cm$^{-3}$, $n_i = 1.79 \times 10^6$ cm$^{-3}$, $E_g = 1.42$ eV, $L_D = 0.013$ μm, and $N_C = 4.7 \times 10^{17}$ cm$^{-3}$ for the $n^+$-GaAs side and for the n-Ge side, $N_D = 4 \times 10^{15}$ cm$^{-3}$, $n_i = 2.4 \times 10^{13}$ cm$^{-3}$, $E_g = 0.66$ eV, $L_D = 0.065$ μm, and $N_C = 1.04 \times 10^{19}$ cm$^{-3}$. Also the spatial variation of $L_D$ with $N_D$ has been considered for both sides. Equation (16') is suitable for the highly doped ($n^+$-GaAs) side. Thus, for the lightly doped (n-Ge) side, the computation neglects the terms involved due to heavy doping effects. From the conduction band/Fermi level separation, the curvature of the conduction band edge at any point may be determined. The thickness of the $n^+$-GaAs layer is depicted as 0.07 μm.

Equation (16) may also be used to investigate the variation of carrier concentration with depth for the heterojunction structure. The expression of carrier concentration $n$ is expressed as $n \approx N_C A(1 + 0.15A)$, where $A = \ln[1 + \exp(U)]$ and $N_C$ is the effective density of states at the conduction band edge [16]. Fig. 2 is drawn taking the same values as chosen for Fig. 1. The thickness for the $n^+$-GaAs layer also yields the same value, i.e., 0.07 μm. In the numerical analyses of these two situations, according to the spatial variation of concentration, the values of $U_B$, $U_S$, and $U$ have been incorporated. In the analysis, there are some assumptions which are not superfluous, but are true under specific circumstances considered in this model.

References

Some Characteristics of \textit{n}+-GaAs/\textit{n}-Ge Heterojunction Structures

I—V CHARACTERISTICS AND THEIR TEMPERATURE DEPENDENCE IN In$_{0.53}$Ga$_{0.47}$As AND GaAs COLLECTOR REGIONS OF HEAVILY DOPED HBTs

S.S. De et al.

A modified expression of the collector leakage current is derived through which the common-emitter I-V characteristics of In$_{0.53}$Ga$_{0.47}$As and GaAs collector regions of heavily doped Al$_{0.48}$Ga$_{0.52}$As/In$_{0.53}$Ga$_{0.47}$As and Al$_{0.3}$Ga$_{0.7}$As/GaAs HBT structures are studied at 25°C and 125°C. The influence of heavy doping, viz band-gap narrowing, carrier degeneracy, non-ideal behaviour of electrons and holes, modified density of states have been taken into account. The obtained results are compared with an earlier work.

Keywords: I-V characteristics of HBTs

1 INTRODUCTION

Heterojunction bipolar transistors (HBTs) have attracted considerable interest in the fabrication of devices for mm-wave amplification, high-speed digital and microwave integrated circuits [1]-[3]. There are numerous papers giving different aspects of the HBT performance. Asbeck et al [4] have given a detailed discussion on the applications of GaAlAs/GaAs HBTs. The characteristics of AlInAs/InGaAs HBTs are very attractive for different applications. The properties of III-V HBTs have already been explored in terms of their breakdown voltage, output conductance, band-gap and also in connection with their operations at higher temperatures. Different characteristics and the common-emitter collector breakdown voltage for In$_{0.53}$Ga$_{0.47}$As collector transistor are generally studied through collector leakage currents of the HBTs. Similar investigations in InGaP/GaAs materials are made for HBT by other workers [5]-[8].

Several important works have been reported in connection with the studies of some of the heavy doping effects in the performance of heterojunctions [9]-[14].

In this presentation, the common-emitter I-V characteristics of In$_{0.53}$Ga$_{0.47}$As and GaAs collector regions of heavily doped Al$_{0.48}$Ga$_{0.52}$As/In$_{0.53}$Ga$_{0.47}$As and Al$_{0.3}$Ga$_{0.7}$As/GaAs HBT structures are studied at 25°C and 125°C. The influence of band-gap narrowing, carrier degeneracy, non-ideal behaviour of electrons and holes, and the modified density of states have been considered in the analyses. A modified expression of the collector leakage current is derived through which the I-V characteristics are obtained. The results are compared with an earlier work.

Under reversed-biased condition, for n-p-n HBT, the collector current due to recombination of holes and electrons in the base regions is given by

$$I_c = \int_0^w qU \, dz,$$  (1)

where $U$ is the recombination rate given by

$$U = \frac{n_i}{\sqrt{\tau_{p0}\tau_{n0}}} \cdot \sinh \frac{q}{2kT} (\phi_p - \phi_n) \cdot \left\{ \cosh \left[ \frac{q}{kT} (\phi - \phi_n + \phi_n) + \ln \frac{\tau_{p0}}{\tau_{n0}} \right] + \exp \left[ -\frac{q}{2kT}(\phi_p - \phi_n) \right] \right\}^{-1},$$  (2)

where $n_i$ is the intrinsic carrier density, $q$ the electronic charge, $E_t$ the trap energy level, $k$ the Boltzmann constant, $T$ the absolute temperature, $\tau_{p0}$ the lifetime for holes injected into highly n-type specimen, $\tau_{n0}$ the lifetime for electrons injected into highly p-type specimen, $E_i$ the intrinsic Fermi-level, $\phi_p$ the
quasi-Fermi electrostatic potential for holes, $\phi_h$ the quasi-Fermi electrostatic potential for electrons and $\phi$ is the electrostatic potential.

The integration of (1) is complicated due to the fact that the hole and electron densities vary from point to point within the base region. However, it is possible to find the effect of recombination by assuming that the hole and electron densities remain constant within the transition region. As the second term in the denominator (2) is large compared to the first term for large reverse-bias, the recombination rate can be considered as constant over the entire base region.

Under this circumstance, the expression for $U$ is reduced to

$$-U = n_i \left[ 2 \sqrt{r_0 \tau_0} \cosh \left( \frac{E_i - E_1}{kT} \right) + \frac{1}{2} \ln \frac{r_0}{\tau_0} \right]^{-1} \tag{3}$$

Thus (1) yields

$$I_c = \int q[U|dz = q[U|W = \frac{qW}{\tau}, \tag{4}$$

where $n$ is the injected electron concentration in the base region, $\tau$ is the effective generation-recombination lifetime and $W$ is the depletion width in the base-collector junction. Incorporating heavy doping effects, viz band-gap narrowing, effective density of states, carrier degeneracy and non-ideal behaviour of electron, the electrons concentration $n$ can be expressed as [15]

$$n = n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \left( \frac{A \Delta E_G}{kT} \right) \exp \left( -\eta_n \right) \exp \left( \frac{E_{fn} - E_1}{kT} \right), \tag{5}$$

where $F_{1/2}$ is the Fermi-Dirac integral of order 1/2, $\eta_n$ the reduced Fermi energy of electrons, $A$ is the asymmetry factor and $E_{fn}$ is the quasi-Fermi energy of electron.

The expression of effective band-gap narrowing is chosen as

$$\Delta E_G = \left[ kT \ln \frac{N_c(x)N_v(x)}{N_v(0)N_c(0)} \right] + kT \ln \frac{F_{1/2}(\eta_n(x))F_{1/2}(\eta_v(x))}{\exp(\eta_n(x))\exp(\eta_v(x))}$$

$$- kT \ln \frac{F_{1/2}(\eta_v(0))F_{1/2}(\eta_n(0))}{\exp(\eta_v(0))\exp(\eta_n(0))}$$

$$+ kT \ln \frac{K_n(\eta_v(0))K_v(\eta_n(0))}{F_{1/2}(\eta_n(0))F_{1/2}(\eta_v(0))}$$

$$- kT \ln \frac{F_{1/2}(\eta_v(0))F_{1/2}(\eta_n(0))}{\exp(\eta_v(0))\exp(\eta_n(0))}$$

$$+ \frac{E_G(x) - E_G(0)}{2} - \frac{kT}{2} \ln \left( \frac{N_c(0)N_v(x)}{N_v(0)N_c(x)} \right), \tag{6}$$

where $N_c$ and $N_v$ are the effective densities of states in conduction and valence bands, respectively, $\eta_n = (E_F - E_G)/kT$; $E_F$ the Fermi energy, $E_G$ the conduction band energy, $E_v$ the band gap, and $K_n$ is the band integral.

Using (4)-(6), one obtains the collector current as

$$I_c = \frac{qW}{\tau} n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \left( \frac{A \Delta E_G}{kT} \right) \exp \left( -\eta_n \right) \exp \left( \frac{E_{fn} - E_1}{kT} \right). \tag{7}$$

The collector leakage current is given by

$$I_{le} = \frac{qW}{\tau} n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \left( \frac{A \Delta E_G}{kT} \right) \exp \left( -\eta_n \right) \exp \left( \frac{E_{fn} - E_1}{kT} \right), \tag{8}$$

where $\alpha$ is the overall base transport factor.

**2 NUMERICAL ANALYSIS AND DISCUSSION**

Equation (8) has been used for numerical computations to study the variation of the collector leakage current $I_{le}$ with collector-base voltage $V_{cb}$ at 25°C and 125°C for GaAs and In$_{0.53}$Ga$_{0.47}$As collector HBTs. The results are shown graphically.
Figure 1 depicts the collector leakage current variation with a reverse-biased potential for GaAs collector region of Al_{0.48}Ga_{0.52}As/GaAs HBT at 25°C and 125°C with emitter concentration as $5 \times 10^{17}$cm\(^{-3}\). The solid curves (a) and (c) represent the result of the present analysis, while the dotted curves (b) and (d) are due to an earlier work [16]. For GaAs, the numerical data have been chosen as $n_i = 1.7 \times 10^{16}$cm\(^{-3}\), $W = 0.12$µm, $r = 0.27 \times 10^{-6}$s. The variations of the collector leakage current with the reverse-biased collector-base voltage for In$_{0.53}$Ga$_{0.47}$As collector region of Al$_{0.3}$Ga$_{0.7}$As/GaAs HBT at 25°C and 125°C with base concentration of $5 \times 10^{18}$cm\(^{-3}\) are shown by the solid curves (a) and (c) in Fig. 2 along with the results of an earlier work [16] shown by the dotted curves (b) and (d). Here the physical data have been considered: $n_i = 1.7 \times 10^{11}$cm\(^{-3}\), $W = 0.29$µm and $r = 0.27 \times 10^{-6}$s. In the numerical analysis for the two regions, the values of $n_0$ and $F_{1/2}(n_0)$ are chosen suitably [17] for the specified dopant densities. The junction area has been considered as $10^{-4}$cm\(^2\).

In the present analysis, the magnitudes of $I_{cb}$ for the two HBTs depicted in Fig. 1 and Fig. 2, are much different. This is in agreement with the ratio of the intrinsic carrier densities of the two semiconductors.

This model deals with a fixed depletion region width for numerical calculation. Moreover, variations of hole and electron concentrations within the transition region have been neglected. Thus, the difference in comparison with the earlier work may be due to heavy doping effects and the stated assumptions.

**References**


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VARIATION OF PHOTOLUMINESCENCE LIFETIME IN HEAVILY DOPED Al_xGa_1-xAs/GaAs DOUBLE HETEROSTRUCTURE

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A model has been developed to study the variation of photoluminescence lifetime with concentration in heavily doped Al_xGa_1-xAs/GaAs double heterostructure (DH) taking into account bandgap narrowing and carrier degeneracy as heavy doping effects. The results so obtained by computational analysis are shown graphically.

1. Introduction

Time-resolved photoluminescence [1] is a useful technique to measure minority carrier lifetime in III-V semiconductors like GaAs and Al_xGa_1-xAs. Minority carrier lifetime is an important parameter, the knowledge of which is essential for the devices, viz., light emitting diodes (LEDs), photovoltaic cells, bipolar transistors, heterojunction lasers. There are various methods to determine the minority carrier lifetime as applied to photovoltaic devices [2-6]. Time-resolved photoluminescence decay method is useful for the measurement of the minority carrier lifetime in III-V compounds. Carrier lifetime in silicon is usually found by using pulse optical excitation and photoconductivity decay technique. Actual lifetime measurements on low moderately doped silicon were reported earlier [7]. The expression of effective steady state Shockley-Read-Hall (SRH) lifetime in arbitrary injection level has been derived by Blakemore [8]. Also, the illumination-effects on AlGaAs/GaAs modulation-doped-field-effect-transistor (MOD-FET) structure are understood [9]. It is found that absorption of optical radiation in AlGaAs can increase the number of electrons diffusing in GaAs. Recombination is an important feature in laser operation in double heterostructure diodes. Heavy doping effects produce high emitter efficiency in bipolar transistors and high open-circuit voltage in solar cells. Lifetimes for high carrier concentrations are important in band-band processes. There are several works on experimentally measured lifetimes [1,10] of heavily doped GaAs and quaternary alloy to study Auger effects.

In this presentation, assuming uniform distribution of SRH defects within specified region, an attempt has been made to develop a model to study the variation of photoluminescence lifetime with concentration in heavily doped Al_xGa_1-xAs/GaAs double heterostructure incorporating bandgap narrowing and carrier degeneracy as heavy...
doping effects. In the analysis, spatial variation of minority carrier density has been neglected due to the very low value of diffusion transit-time compared to the minority carrier lifetime. The results of the computational analysis are shown graphically.

2. Mathematical formulation

For Al$_x$Ga$_{1-x}$As/GaAs double heterostructure, when the interface recombination velocity becomes low, photoluminescence [11] lifetime approaches the bulk minority carrier lifetime. The linearised expression [12] for the photoluminescence can be given by

\[
\frac{1}{\tau_{PL}} = \frac{1}{\tau_R} + \frac{1}{\tau_{SRH}} + \frac{1}{\tau_S}
\]

where,

\[
\frac{1}{\tau_S} = \frac{2S}{d}
\]

\(\tau_{PL}\) is the photoluminescence lifetime; \(\tau_R\), the radiative lifetime; \(\tau_{SRH}\), the Shockley-Read-Hall lifetime; \(S\), the interface recombination velocity; \(d\), the active layer thickness, and \(\tau_S\) is the surface lifetime.

Minority carrier diffusivity \(D\) is related to decay time \(t\) and mobility \(\mu\) as

\[
D = \frac{d^2}{2t} \quad \text{and} \quad D = \frac{KT}{q\mu}
\]

where, \(K\) is the Boltzmann constant; \(q\), the electronic charge, and \(T\) is the absolute temperature. For n-type semiconductor with donor concentration \(N_D\), the electron mobility \(\mu_e\) is given by [13]

\[
\mu_e(N_D) = \frac{\mu_0}{1 + (N_D/N_{eff})^\alpha} + \mu_{min}
\]

\(\mu_{min}\) is the minimum mobility value expected; \(\mu_0\), the difference between the maximum and minimum mobility expected; \(N_{eff}\), a reference concentration, and \(\alpha\) is an exponential factor that controls the slope around \(N_D = N_{eff}\). Thus, from (1)–(3), one obtains photoluminescence lifetime for n-type semiconductor as

\[
\frac{1}{\tau_{PL}} = \frac{1}{\tau_R} + \frac{1}{\tau_{SRH}} + S\left(\frac{2q}{tKT}\right)^{1/2} z
\]

\[
z\left\{\frac{\mu_0}{1 - (N_D/N_{eff})^\alpha} + \mu_{min}\right\}^{-1/2}
\]

The radiative and SRH lifetimes [14] in terms of excess photogenerated carrier \((\Delta \mu)\) are given by

\[
\tau_R = \frac{\Delta n}{\beta n_p}, \quad \text{and} \quad \tau_{SRH} = \frac{\Delta n}{n_p}\left[\tau_p(n + n_t) + \tau_n(p + n_t)\right]
\]
where, $B$ is the radiative recombination coefficient; $n_i$, the intrinsic carrier concentration, and $\tau_p$ and $\tau_n$ are the hole and electron lifetimes, respectively. $n$ and $p$ are the electron and hole concentrations, which under heavy doping condition can be expressed as

$$n = n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{A \Delta E_g}{K T} \exp \left\{ \frac{E_{fn} - E_i}{K T} \right\}$$

(6a)

$$p = n_i F_{1/2}(\eta_p) \exp(-\eta_p) \exp \frac{(1 - A) \Delta E_g}{K T} \exp \left\{ \frac{E_i - E_{fp}}{K T} \right\}$$

(6b)

where, $F_{1/2}(\eta)$ is the Fermi-Dirac integral of order 1/2; $\eta$, the reduced Fermi energy; $A$, the asymmetry factor, $\Delta E_g$, the bandgap narrowing; $E_i$, the intrinsic Fermi energy, and $E_{fn}$ and $E_{fp}$ are the quasi-Fermi energies of electron and hole, respectively. At equilibrium, $E_{fn} = E_{fp}$. Again, the interface recombination velocity is defined as

$$S \equiv \frac{J_S}{q \Delta n}$$

(7)

where, $J_S$ is the recombination current density.

Moreover,

$$J_S = q [R_{SRH} + R_{Aug}]$$

(8)

$R_{SRH}$ is the interface recombination due to S.R.H. process [15,16] and $R_{Aug}$ is the net Auger recombination.

Now,

$$R_{SRH} = \frac{np - n_i^2}{\tau_n (p + n_i) + \tau_p (n + n_i)}$$

(9)

and

$$R_{Aug} = \gamma \left( \frac{np - n_i^2}{n_i^2} \right) (n + p)$$

(10)

where, $\gamma$ is the Auger recombination coefficient.

Thus, from (4)–(10), one obtains

$$\frac{1}{\tau_{PL}} = \frac{n_i}{\Delta n} \left[ \eta^2 B + \eta \left\{ F_{1/2}(\eta_n) \exp(-\eta_n) \exp \frac{(1 - A) \Delta E_g}{K T} \exp \left\{ \frac{E_i - E_{fp}}{K T} \right\} + 1 \right\} \right.$$  

$$+ \eta \left\{ F_{1/2}(\eta_p) \exp(-\eta_p) \exp \frac{A \Delta E_g}{K T} \exp \left\{ \frac{E_{fn} - E_i}{K T} \right\} + 1 \right\} \right]^{-1}$$  

$$+ \left( \frac{2q}{K T} \right)^{1/2} \left\{ \frac{\eta^2 B}{1 + (N_D / N_{eff})^n + \mu_{min}} \right\}^{-1/2} \times$$
Fig. 1 Variations of photoluminescence lifetime of $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}/\text{GaAs}/\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ D$_h$ ($d = 4 \mu m$) with concentrations under focused powers (60 mW for curve $a$, 20 mW for curve $b$, 2 mW for curve $c$) and unfocused power (2 mW for curve $d$).

\[
\begin{align*}
&\times \left[ \tau_n \left\{ F_{1/2}(\eta_p) \exp(-\eta_p) \frac{(1 - A)\Delta E_g}{KT} \exp \left( \frac{E_i - E_{fp}}{KT} \right) + 1 \right\} \\
&\quad + \tau_p \left\{ F_{1/2}(\eta_n) \exp(-\eta_n) \frac{A\Delta E_g}{KT} \exp \left( \frac{E_{fn} - E_i}{KT} \right) + 1 \right\} \right]^{-1} \\
&\quad + \gamma \left\{ F_{1/2}(\eta_n) \exp(-\eta_n) \frac{A\Delta E_g}{KT} \exp \left( \frac{E_{fn} - E_i}{KT} \right) \right\} \\
&\quad + F_{1/2}(\eta_p) \exp(-\eta_p) \frac{(1 - A)\Delta E_g}{KT} \exp \left( \frac{E_i - E_{fp}}{KT} \right) \right]^{-1} \\
&\quad \left[ F_{1/2}(\eta_n) F_{1/2}(\eta_p) \exp \frac{\Delta E_g}{KT} \exp \left\{ -\left(\eta_n + \eta_p\right) \right\} - 1 \right] \quad (11)
\end{align*}
\]

3. Numerical analysis and discussion

The numerical analyses of (11) are presented for a fixed composition in Fig. 1 under
Variation of photoluminescence lifetime... different circumstances. It depicts the variation of photoluminescence lifetime of heavily doped Al$_{0.9}$Ga$_{0.1}$As/GaAs/Al$_{0.9}$Ga$_{0.1}$As DH (d = 4µm) with different concentrations under focused powers 60 mW, 20 mW, 2 mW and unfocussed power 2 mW. These are presented by curves a, b, c and d, respectively. The nature of variation reveals that the photoluminescence lifetime decreases rapidly with the increase of concentrations and always increases with the power excitation for a given cross-sectional area and thickness of a double heterostructure. Numerical computations of (11) have been carried out considering $\Delta E_g = 10.23(N/10^{18})^{1/2} + 13.12(N/10^{19})^{1/4} + 2.93(N/10^{18})^{1/2}$ mev [17], $T = 300$ K, $B \simeq 10^{-10}$ cm$^3$ sec$^{-1}$. The values of $\eta_p$, $\eta_n$, $F_{1/2}(\eta_p)$ and $F_{1/2}(\eta_n)$ are chosen suitably [18] for the specified dopant densities. Variation of carrier lifetime with different concentrations is also incorporated in the numerical analysis. The values of minority carrier lifetimes for the variation of majority carrier concentration in the range $10^{18} - 10^{20}$ cm$^{-3}$ have been chosen within $5 \times 10^{17} - 10^{-7}$ sec; while in the minority carrier concentration range between $(1 - 8) \times 10^{16}$ cm$^{-3}$, the values of majority carrier lifetimes are taken within $10^{-8} - 10^{-12}$ sec. Due to unavailability of experimental data of photoluminescence material, it is not possible to make a comparative study of this present result.

References

A model is developed to study the carrier lifetime and quantum efficiency in heavily doped InGaAsP. In the analysis, bandgap narrowing, carrier degeneracy, and nonparabolicity of the band structure are considered as heavy doping effects. The variations of carrier lifetime and quantum efficiency with nominal current density at a given temperature are studied through numerical analysis.

On a élaboré un modèle pour l'étude du temps de vie des porteurs et du rendement quantique dans InGaAsP fortement dopé. Dans l'analyse, le rétrécissement d'interbande, la dégénérescence des porteurs et la non-parabolicité de la structure de bande sont considérés comme des effets du fort dopage. Les variations du temps de vie des porteurs et du rendement quantique avec la densité de courant nominale à une température donnée ont été étudiées au moyen d'une analyse numérique.

1. Introduction

The In$_{1-x}$Ga$_x$As$_y$P$_{1-y}$ quaternary alloy system is considered to be the most promising for optical communication in the 0.95–1.75 μm wavelength range [1-4] because the epitaxial layer of this quaternary lattice matches InP substrates over a wide range of bandgaps for which devices such as LED's, lasers, and photodetectors, etc. can be produced. By proper choice of composition [5, 6], the bandgap $E_g$ can be chosen from a wide range. Laser performance shows poor temperature-dependence characteristics of the threshold current [7]. Carrier leakage from the InGaAsP active region to the InP confining layers shows a steep temperature dependence of the threshold current, which is interpreted in terms of the Auger process [8]. Considering the anisotropy of some band parameters, the Auger recombination rate in InGaAsP has been calculated [9]. Work on the determination of recombination rates in the material in various situations [10-12] has been published. Successful attempts have been made to develop empirical lifetime models in heavily doped GaAs and InGaAsP that predict the experimentally measured lifetimes [13–16].

In this paper, a model is developed for studying the carrier lifetime and quantum efficiency in heavily doped InGaAsP, where bandgap narrowing, carrier degeneracy, and nonparabolicity of the band structure [17] are considered as heavy doping effects. Expressions of the Auger recombination rate and radiative recombination rate are deduced to obtain carrier lifetime and quantum efficiency. Numerical analyses are carried out to investigate the variation of carrier lifetime and quantum efficiency with normal current density at a given temperature.

2. Derivations

2.1. Auger recombination rate

In this process, in generating a hole-electron pair, three free carriers are involved, i.e., two electrons and a hole or two holes and an electron. The recombination rate $r_a$ will be proportional to $n^2p$ and then

$$r_a = r_{a0} n^2 p = g_{a0} rac{n^2 p}{n_0^2 p_0}.$$  (1)

The generation rate $g_a$ is given by

$$g_a = g_{a0} \frac{n}{n_0}.$$  (2)

where $r_{a0}$ and $g_{a0}$ are the values of $r_a$ and $g_a$ in thermal equilibrium. $n_0$ and $p_0$ are the electron and hole concentration in thermal equilibrium, respectively.

The net recombination rate is written as

$$r_s - g_s = g_{a0} \left( \frac{np - n_1^2}{n_0^2} \right) \frac{n}{n_0}.$$  (3)

where $n_1$ is the intrinsic carrier concentration.

Similarly, the net recombination rate for hole–hole recombination is given by

$$r_p - g_p = g_{pp0} \left( \frac{np - n^2_2}{n_0^2} \right) \frac{p}{p_0}.$$  (4)

In the steady state (3) and (4) yield the net recombination rate

$$R_{Aug} = r \left( \frac{np - n_1^2}{n_0^2} \right) (n + p).$$  (5)

where

$$r = \frac{g_s}{n_0} = \frac{g_{pp0}}{p_0}.$$  

The carrier concentrations $n$ and $p$ under a heavy doping condition, incorporating nonuniform band structure, are given by

$$n = \frac{\alpha_F \bar{F} \bar{F}_2 (n_0)}{\exp \left( \frac{\Delta E}{kT} \right)} \exp \left( \frac{E_{F0} - E_1}{kT} \right)$$

and

$$p = \frac{\alpha_F \bar{F} \bar{F}_2 (p_0)}{\exp \left( \frac{\Delta E'}{kT} \right)} \exp \left( \frac{E_{F0} - E_1}{kT} \right).$$
\[ p = \frac{a_n a_p F_{1/2}(n_p)}{\exp \left( \frac{1}{2} \frac{\Delta E_g kT}{kT} \right) \exp \left( \frac{E_i - E_{p \text{tri}}}{kT} \right) \exp \left( \frac{E_{n \text{tri}} - E_i}{kT} \right) \} \]

In thermal equilibrium \( E_{n \text{tri}} = E_{p \text{tri}} \)

Substituting the expressions of \( n \) and \( p \), (5) becomes

\[ R_{\text{Aug}} = m_0 \left( \frac{a_n a_p F_{1/2}(n_p)}{\exp \left( \frac{1}{2} \frac{\Delta E_g kT}{kT} \right) \exp \left( \frac{E_i - E_{p \text{tri}}}{kT} \right) \exp \left( \frac{E_{n \text{tri}} - E_i}{kT} \right) \} \right) \left( \frac{a_n a_p F_{1/2}(n_p)}{\exp \left( \frac{1}{2} \frac{\Delta E_g kT}{kT} \right) \exp \left( \frac{E_i - E_{p \text{tri}}}{kT} \right) \exp \left( \frac{E_{n \text{tri}} - E_i}{kT} \right) \} \right) \]

where \( F_{1/2} \) is the Fermi integral of order \( 1/2 \); \( n_n \) and \( n_p \) are the reduced Fermi energy of electron and hole, respectively. \( \Delta E_g \) is the bandgap narrowing; \( A \) is the asymmetry factor; \( k \) is the Boltzmann constant; \( T \) is the absolute temperature. \( E_i \) and \( E_{p \text{tri}} \) are the intrinsic Fermi level and the quasi-Fermi level for the electron, respectively. \( a_n \) and \( a_p \) are the parameters for nonparabolic band structure [17].

These are expressed as

\[ a_n = \frac{15\alpha m_e kT}{2\hbar^2} \quad \text{and} \quad a_p = \frac{15\alpha m_h kT}{2\hbar^2} \]

where \( \alpha \) is the measure of the deviation from parabolicity. \( m_e \) and \( m_h \) are the electron and hole density of states effective masses. \( h \) is the Planck constant/2\( \pi \).

After some algebraic manipulation, (6) yields

\[ \tau_{\text{Aug}} = \frac{1}{C_n n_n^2} \quad \text{and} \quad \tau_{\text{Aug}} = \frac{1}{C_p p_p^2} \]

where \( \tau_{\text{Aug}} \) and \( \tau_{\text{Aug}} \) are the Auger lifetimes for n-type and p-type alloy.

For the alloy InGaAsP, with \( y = 0.6 \) and \( x = 0.72 \), the values of \( C_n \) and \( C_p \) (Auger recombination coefficients for heavily doped condition) at 300 K become \((1.45 \pm 0.5) \times 10^{-29} \text{ cm}^6 \text{ s}^{-1} \) and \((2.65 \pm 1.15) \times 10^{-29} \text{ cm}^6 \text{ s}^{-1} \), respectively, within the range of doping \((10^{18} \text{ to } 10^{20}) \).

2.2. Radiative recombination rate

At thermal equilibrium, the radiative recombination rate for the frequency range \( \nu \) to \( \nu + \Delta \nu \) is equal to the corresponding rate of generation of electron–hole pairs by thermal radiation. In a unit volume and in a unit frequency interval, this rate is given by \( P(\nu \cdot \rho(\nu) \cdot d\nu \).

where \( \rho(\nu) \) is the density of photons in the alloy, \( P(\nu) \) is the probability per unit time that a photon of frequency \( \nu \) be absorbed in the frequency range \( \nu \) to \( \nu + \Delta \nu \).

The total rate of radiative recombination \( R_{\text{rad}} \) per unit volume in heavily doped condition can be written as

\[ R_{\text{rad}} = \frac{n_p}{n_n} \int P(\nu) \rho(\nu) d\nu \]

Substituting the expression of \( n \) and \( p \), one obtains

\[ R_{\text{rad}} = \frac{n_p}{n_n} \frac{F_{1/2}(n_p)}{F_{1/2}(n_p)} \frac{\exp \left( \frac{\Delta E_g kT}{kT} \right) \exp \left( \frac{E_i - E_{p \text{tri}}}{kT} \right) \exp \left( \frac{E_{n \text{tri}} - E_i}{kT} \right) \} \]

where the distribution of photon density \( \rho(\nu) \) in thermal equilibrium is

\[ \rho(\nu) = \frac{8\pi \nu^2}{c^2} \left[ n' \cdot \frac{d \ln n' \nu}{d \ln \nu} \right] \left[ \exp \left( \frac{h\nu}{kT} \right) - 1 \right]^{-1} \]

and the probability of absorption of photon per unit time is \( P(\nu) = 4\pi \frac{\nu}{n'} \frac{d \ln \nu}{d \ln n' \nu} \) where \( n' \) is the refractive index and \( K \) is the absorption index.

Thus the total rate of radiative recombination at thermal equilibrium can be written as

\[ R_{\text{rad}} = 32 \pi^2 c \left( \frac{kT}{\hbar} \right)^4 \frac{a_n a_p F_{1/2}(n_p)}{\exp \left( \frac{1}{2} \frac{\Delta E_g kT}{kT} \right) \exp \left( \frac{E_i - E_{p \text{tri}}}{kT} \right) \exp \left( \frac{E_{n \text{tri}} - E_i}{kT} \right) \} \int_0^{n' \cdot \frac{\nu}{KU}} U^{-1} dU \]
Carried Density (cm$^3$)

Fig. Z. Curves (a)–(c) based on the present work show the variation of Auger, radiative, and carrier lifetimes, respectively, for 1.3 μm thick heavily doped InGaAsP with carrier concentration at 300 K. Curve (d) is the result given by Sermageei et al. [16]. The curves (a)–(c) represent p-type alloys. The values of $B_n$ and $B_p$ (radiative recombination coefficients for the stated range of heavy doping at 300 K) become $(3.3 \pm 0.7) \times 10^{-11}$ and $(3.9 \pm 1.1) \times 10^{-11}$ cm$^3$ s$^{-1}$, respectively.

3. Results and discussion

Numerical computations of (7) and (11) are carried out to investigate the variations of Auger lifetime and radiative lifetime with carrier concentrations. Carrier lifetime ($\tau$) and nominal current density ($J/d$) are also evaluated from the algebraic relations $\tau = (\tau_{Auger} + \tau_{n+})^{-1}$ and $J/d = \varepsilon \Delta n / \eta$, where $J$ is the current density, $d$ is the active layer thickness, $\varepsilon$ is the electronic charge, and $\Delta n$ is the injected current density. The Auger lifetime and radiative lifetime are computed for quaternary alloy In$\text{GaAs}_P$, considering the value of the composition parameters $y = 0.6$, $d = 1.3$ μm, $\eta = 1.76 \times 10^6$ cm$^3$ s$^{-1}$, $E_g = 0.96$ eV, and the bandgap narrowing relation $\Delta E = 1.6 \times 10^{-4}$ ($y^{11/3} + p^{11/3}$) eV. The lattice constant of the In$\text{GaAs}_P$ active layer is assumed to be matched with the InP substrate. Though the value of the Auger recombination coefficient $B_n$ or $B_p$ and the radiative recombination coefficient $B_n$ are concentration-dependent parameters, some fixed values are chosen from the physical background for the specified range of variation of concentrations at 300 K.

Since in the case of InGaAsP, sufficient data are not available on bandgap narrowing and lifetime as functions of doping, numerical analyses have been carried out by assuming that bandgap narrowing for InGaAsP is the same as for GaAs [15].

Figure 1 depicts the variation of carrier lifetime with nominal current density at 300 K for InGaAsP in a heavily doped condition. It reveals that the carrier lifetime reduces steadily with the increase of nominal current density. In Fig. 2, a set of curves are drawn showing the variations of lifetime with carrier concentrations. Curves (a)–(c) are the results of the present analysis under the given circumstances whereas curve (d) is the result given by Sermageei et al. [16]. The curves (a)–(c) represent...
the variations of Auger lifetime, radiative recombination lifetime, and carrier lifetime, respectively, in the presence of the heavy doping effects. In the work of Sermage et al. [16], some of the heavy doping effects are considered; curve (d) is comparable with curve (a). It indicates that the effects due to nonparabolicity of band structure, bandgap narrowing, and carrier degeneracy effectively reduce the Auger lifetime at higher carrier concentrations. Figure 3 shows the variation of quantum efficiency with nominal current density of heavily doped InGaAsP at 300 K. Quantum efficiency (\( \zeta \)) has been evaluated using the relation

\[
\zeta = \frac{R_{\text{rad}}}{(R_{\text{rad}} + R_{\text{Aug}})} = \left( 1 + \frac{C_n}{B_n} n \right)
\]

for n-type quaternary alloy. The (\( \zeta \)) value is expressed in terms of (\( C_n/B_n \))n in the highly injected region. Numerical calculation reveals that the dependence of \( C_n/B_n \) on n becomes more prominent as the temperature increases. This property may be useful for studying the variation of (\( \zeta \)) with temperature. Here the variation is presented only for 300 K. Figure 3 reveals that the quantum efficiency falls rapidly at lower values of nominal current density and that this rate decreases with increase in nominal current density. Thus, quantum efficiency decreases exponentially with the increase of nominal current density.

Energy conversion efficiency in solar cell depends upon the minority carrier lifetime. There are numerous silicon devices[1-4] with doping levels of the order of 10¹⁸ cm⁻³, based on the injection of minority carriers. Device performances in these cases depend upon the transport of the minority carriers through the heavily doped regions. Several earlier works considered the effects of heavy doping[5-8] on the basic parameters, e.g. energy gap, minority carrier diffusion constant, carrier mobility, and minority carrier diffusion length. Minority carrier lifetime in heavily doped quaternary alloy as function of dopant density and temperature is a useful variable for device design work and analysis[9,10].

The influences of doping on lifetime, diffusion length and mobility of minority carriers have been studied theoretically as well as experimentally. There are different complexities in device fabrication and in the choice of doping materials, which are resolved by making assumptions. There are attempts to overcome the disagreement between theoretical results and experimental values by proper choice of transport equations.

In this presentation, an empirical lifetime model for a heavily doped InGaAsP is proposed to derive an expression for minority carrier lifetime. The variations of minority carrier lifetime with dopant density and temperature are studied taking bandgap narrowing and carrier degeneracy as the heavy doping effects. The study may be useful to design devices with heavily doped quaternary alloy. The results of numerical computations are presented graphically, which reveal that the dopant density variation and the temperature variation have an important role on the minority carrier lifetime under the stated physical condition.

LIFETIME MODEL FOR InGaAsP

Minority carrier lifetime in heavily doped InGaAsP is empirically modeled as[11]:

\[ \tau_s = \frac{D_in_f}{C_in_f^2} \]  

(1)

where, \( \tau_s \) is the minority carrier lifetime (s = n or p stands for electron or hole); \( D_\text{i} \), the diffusion coefficient, and \( N \) is the net doping density (cm⁻³). \( C \) is a constant (cm⁻³ s⁻¹) for heavily doped quaternary alloy. Its value is to be chosen from experimentally measured data for different associated parameters. \( n_f \) is the effective intrinsic carrier density under heavily doped condition which incorporates heavy doping effects, e.g. bandgap narrowing and carrier degeneracy. \( n_f \) may be defined as[8]:

\[ n_f = n_p \]  

(2)

where,

\[ n = n_i F_{1,1}(n) \exp(-n_p) \exp \left( \frac{A \Delta E_n}{K T} \right) \exp \left( \frac{E_n - E_i}{K T} \right) \]

\[ p = n_i F_{1,1}(n) \exp(-n_p) \exp(1 - \alpha) \exp \left( \frac{A \Delta E_p}{K T} \right) \exp \left( \frac{E_p - E_i}{K T} \right) \]

\[ \alpha = \frac{\Delta E_p}{\Delta E_n} \]

\[ n \text{ and } p \text{ are the electron and hole concentrations; } n_i \text{ the intrinsic carrier density; } F_{1,1}, \text{ the Fermi integral of order 1/2; } n_i \text{ and } n_p, \text{ the reduced Fermi energy for electron and hole, respectively; } A, \text{ the asymmetry factor; } \Delta E_n, \text{ the bandgap narrowing; } K, \text{ the Boltzmann constant; } T, \text{ the absolute temperature; } E_n, \text{ the intrinsic Fermi energy, and } E_i, \text{ the quasi-Fermi energy of electron at equilibrium and is equal to quasi-Fermi energy of hole. Thus eqn (2) yields: } \]

\[ n_f^2 = n_i F_{1,1}(n) \exp \left( \frac{A \Delta E_n}{K T} \right) \exp \left( \frac{E_n - E_i}{K T} \right) \exp \left( \frac{\Delta E_p}{K T} \right) \exp \left( \frac{E_p - E_i}{K T} \right) \]

\[ \text{For } n = \text{InGaAsP, minority carrier lifetime may be obtained by using the following relations: } \]

\[ D_s = \frac{K T}{\mu_p} \]  

and

\[ L_s = \sqrt{D_s \tau_s} \]  

(4)

where, \( \mu_p \) is the hole mobility, \( L_p \) is the hole diffusion length. The electron mobility in quaternary compound semiconductors can be interpreted using different scattering mechanisms, e.g. (i) polar optical phonon scattering (PO), (ii) ionized impurity scattering (II), and (iii) alloy scattering (AL). Matthiessen's rule is applicable to combine these mechanisms, which yields the relationship for combining mobility limits \( \mu_p \) into an overall mobility \( \mu_p \), as:

\[ \mu_p = \mu_p \]  

(5)

The electron mobility[12] limited by the stated mechanisms can be written as:

\[ \mu_n = 2.6 \times 10^3 \left( \frac{T}{300} \right)^{1/2} \left( \frac{e^*}{e} \right)^{1/2} \left( \frac{m_e}{m^*} \right)^{3/2} \times M \Omega (\tau - 1) G(Z) \]

(6)

\[ \mu_n = 3.28 \times 10^3 \left( \frac{\epsilon^*}{\epsilon} \right)^{1/2} \left( \frac{m_e}{m^*} \right)^{1/2} \epsilon_n \ln(1 + b) - b \]

(7)

\[ \mu_{al} = \frac{8 \times 10^4 \epsilon^*}{\epsilon} \left( \frac{\epsilon^*}{\epsilon} \right)^{1/2} \left( \frac{m_e}{m^*} \right)^{1/2} \left( \frac{\epsilon}{\epsilon^*} \right)^{1/2} \]

(8)

where, \( e^* \) the electronic charge, \( e^* \) the Callan effective charge; \( M \), the reduced mass of the cell; \( \Omega \), the volume of the primitive cell, remaining constant at 5.05 \times 10^{-8} m³ throughout the alloy composition range; \( \theta \), the polar
Electron concentration (cm$^{-3}$)

Fig. 1. Variation of hole lifetime with electron concentration in a heavily doped n-InGaAsP at 300 K and the variations of hole lifetime with temperature.

The variation of hole lifetime with temperature at a fixed dopant density ($10^{15}$cm$^{-3}$) is presented in Fig. 2, which also depicts the fall of hole lifetime with temperature.

DISCUSSION

The results of numerical computations of eqn (14) are presented through graphs which depict the variations of hole lifetime with electron concentration in a heavily doped n-InGaAsP at 300 K and the variations of hole lifetime with temperature in the stated quaternary alloy for a fixed dopant density ($10^{19}$cm$^{-3}$). The work of Sermaje et al.[11] for lifetime measurement as a function of carrier density has been considered to study the minority carrier lifetime in this work, assuming that the (i) bandgap narrowing for InGaAsP is same as for GaAs[13,14], (ii) minority carrier lifetimes of either hole or electron are about the same[15].

In this model, only hole lifetime in heavily doped n-InGaAsP has been worked out for $E_g = 0.96$ eV, $K[TH] = 0.0259$ V, $n_i = 1.76 \times 10^{16}$cm$^{-3}$, $C = 0.0341$ cm$^{-2}$s$^{-1}$, $\Delta E(N) = 1.6 \times 10^{-5}$ Ncm$^{-2}$, $\mu_{p0}$ and $\mu_{n0}$ are chosen suitably[16] for the specified dopant densities. Similar analyses may be carried out for electron lifetime in heavily doped p-InGaAsP through eqn (9). In Fig. 1, hole lifetime as a function of temperature at a fixed dopant density ($10^{19}$cm$^{-3}$) is presented in Fig. 2, which also depicts the fall of hole lifetime with temperature.

Fig. 1. Variation of hole lifetime with electron concentration in a heavily doped n-InGaAsP at 300 K

Fig. 2. Variation of hole lifetime with temperature in a heavily doped p-InGaAsP for a fixed dopant concentration ($10^{19}$cm$^{-3}$).
REFERENCES

Temperature dependence of Auger lifetime in heavily doped Hg$_{1-x}$Cd$_x$Te

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An expression for Auger lifetime as a function of temperature has been derived for a heavily doped Hg$_{1-x}$Cd$_x$Te in the presence of a nonparabolicity of band structure, band gap narrowing, and carrier degeneracy. It is utilized to study the variation of Auger lifetime with temperature through numerical analysis.

I. INTRODUCTION

The influence of heavy doping produces high emitter efficiency in bipolar transistors and a high open-circuit voltage in solar cells. Band-band Auger lifetimes in heavily doped quaternary alloy as a function of dopant concentration and temperature are useful parameters for device design and analysis. The qualitative theory of Auger lifetime was first given by Beatie and Landsberg on the basis of a simple band structure. Beatie and Smith offered a more detailed theory considering band structure consisting of conduction, heavy hole, and light hole bands (called the CHLH process). Takeshima calculated Auger lifetimes considering transition through the conduction band-heavy hole band—spin split-off band mechanism (called the CHSH process). It includes two heavy hole bands (H), a conduction band (C), and an Auger excited split-off band (S). In the Auger process is an important factor: it helps to choose an alloy for devices. The Auger lifetime is very short. When the band gap energy approaches the spin-orbit splitting, the alloy will be unsuitable for light emitting diode (LED) devices. There are several works about Auger recombination in light emitting devices and in other materials. For semiconducting compounds, a pronounced diminution of the lifetime is found at low temperature. For semimetallic compounds, the temperature dependence of the Auger lifetime is weak and of the order of $10^{-10}$–$10^{-9}$ s. For different semiconductors, it has been investigated under different physical situations. The various effects due to heavy doping on the temperature dependence of the Auger lifetime had not totally been considered in these works.

Following the band structure given by Beatie and Landsberg, an attempt has been made in this presentation to derive an expression of Auger lifetime for a heavily doped Hg$_{1-x}$Cd$_x$Te, where nonparabolicity of band structure along with band gap narrowing and carrier degeneracy are considered as heavy doping effects. The expression is used to investigate the temperature dependence of Auger lifetime in the material up to 400 K. This investigation may be useful to design devices with a heavily doped alloy.
Auger lifetime as a function of temperature can be expressed as

$$\tau_{A,N}(T) = \frac{1}{C_N n^2 \exp \left( \frac{300 - T}{T} \right)}$$  \hspace{1cm} (6a)

and

$$\tau_{A,P}(T) = \frac{1}{C_P p^2 \exp \left( \frac{300 - T}{T} \right)},$$  \hspace{1cm} (6b)

where \( \tau_{A,N} \) and \( \tau_{A,P} \) are the Auger lifetime for heavily doped n-type and p-type semiconducting Hg\(_{1-x}\)Cd\(_x\)Te, respectively. \( C_N \) and \( C_P \) are the recombination constants for heavily doped alloy which would be determined in terms of different parameters of Eq. (5). \( C_N = (1.34 \pm 0.45) \times 10^{-29} \) cm\(^4\) V\(^{-1}\) s\(^{-1}\).
cm$^8$ s$^{-1}$ and $C_N' = (2.06 \pm 0.94) \times 10^{-29}$ cm$^6$ s$^{-1}$ for the doping range $(1 \times 10^{18} - 7 \times 10^{19})$ cm$^{-3}$ at 300 K.

At the steady state, the temperature dependence of Auger lifetime in Hg$_{1-x}$Cd$_x$Te under a lightly doped condition can be derived by adding Eqs. (3) and (4), without incorporating the influences of heavy doping. This yields the Auger recombination rate as

$$ R_{\text{Aug}} = \pi \left( \frac{n_e - n_h}{n_i} \right) (n + p). \quad (7) $$

Auger lifetime as a function of temperature for lightly doped condition can be written as

$$ \tau'_{x,N}(T) = \frac{1}{C_N' n_e^2 \exp(E_g/kT)} \quad (8a) $$

and

$$ \tau'_{x,p}(T) = \frac{1}{C_P' p^2 \exp(E_g/kT)}, \quad (8b) $$

where $\tau'_{x,N}$, $\tau'_{x,P}$, $C_N'$, and $C_P'$ are the corresponding quantities for lightly doped n-type and p-type semiconducting Hg$_{1-x}$Cd$_x$Te, respectively. Here, $C_N' = (1.50 \pm 0.16) \times 10^{-26}$ cm$^6$ s$^{-1}$ and $C_P' = (1.78 \pm 0.14) \times 10^{-26}$ cm$^6$ s$^{-1}$ for the doping range $(5 \times 10^{14} - 5 \times 10^{15})$ cm$^{-3}$ at 300 K.

III. RESULTS AND DISCUSSION

Numerical computation of Eq. (6a) has been made to study the temperature dependence of Auger lifetime in heavily doped semiconducting Hg$_{1-x}$Cd$_x$Te for a fixed value of band gap at a particular carrier density. The investigation has been extended for different fixed values of carrier concentrations. Computations are carried out with $m_p = 0.4 m_0$, $\Delta E_g = 1.57 \times 10^{-4} \times (n^{1/3} + p^{1/3})$ eV, $k = 1.38 \times 10^{-10}$ J s$^{-1}$ at 300 K, $C_N' = (1.34 \pm 0.45) \times 10^{-29}$ cm$^6$ s$^{-1}$ and $C_P' = (2.06 \pm 0.94) \times 10^{-29}$ cm$^6$ s$^{-1}$. Similar computation of Eq. (6b) may also be carried out for identical investigations. For numerical analysis, the expression of $E_g(x,t)$ has been chosen as, $E_g(x,t) = -0.31 + 1.88x + (1 - 2x) \times 5 \times 10^{-4}$ eV.

Figure 1 shows the variation of Auger lifetime for the alloyed sample with a fixed value of $x$ which yields $E_g = 0.156$ eV at 300 K. Graphs (a), (b), and (c) are plotted for $n = 5 \times 10^{18}$ cm$^{-3}$, $1 \times 10^{19}$ cm$^{-3}$, and $5 \times 10^{19}$ cm$^{-3}$, respectively. It is found that the nature of variation is similar for different fixed values of carrier densities.

The dependence of Hg composition ($x$) on the variation of Auger lifetime with temperature under heavy dop-