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Studies on Surface Recombination Velocity in a Heavily Doped Abrupt n^+–p Junction

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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

$$R(x) = \frac{n(x)\,p(x) - n_i^2}{\tau_n(p(x) + p_1) + \tau_p(n(x) + n_1)} \tag{1}$$

and the net Auger recombination can be written as

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

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; τ_n, τ_p are the electron and hole minority carrier lifetimes, and γ is the Auger recombination

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coefficient. n_1 and p_1 are the Shockley-Read-Hall parameters, given by

$$n_1 = n_i \exp\left(\frac{E_t - E_i}{k_B T}\right), \qquad p_1 = n_i \exp\left(\frac{E_i - E_t}{k_B T}\right),$$

where E_t 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

$$n(x) = n_i F_{1/2}(\eta_n) \exp(-\eta_n) \exp\left(\frac{A\,\Delta E_g}{k_B T}\right) \exp\left(\frac{E_{fn} - E_i}{k_B T}\right), \tag{3a}$$

$$p(x) = n_i F_{1/2}(\eta_p) \exp(-\eta_p) \exp\left(\frac{(1 - A)\,\Delta E_g}{k_B T}\right) \exp\left(\frac{E_i - E_{fp}}{k_B T}\right), \tag{3b}$$

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

$$S \equiv \frac{J_S}{q\,\Delta n}, \tag{4}$$

where q is the electronic charge, Δn the injected carrier density, and J_S the surface recombination current density.

Moreover,

$$J_S = q[R(x) + R_{Aug}]. \tag{5}$$

Thus

$$\begin{aligned} S &= \frac{R(x) + R_{Aug}}{\Delta n} \\ &\equiv \frac{np - n_i^2}{\Delta n}\left[\frac{1}{\tau_n(p + n_1) + \tau_p(n + n_1)} + \frac{\gamma(n + p)}{n_i^2}\right]. \end{aligned} \tag{6}$$

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

$$\begin{aligned} S = \frac{n_i}{\Delta n}\Bigg[\Bigg[&\tau_n\left\{F_{1/2}(\eta_p)\exp(-\eta_p)\exp\left(\frac{(1 - A)\,\Delta E_g}{k_B T}\right)\exp\left(\frac{E_t - E_{fp}}{k_B T}\right) + 1\right\} \\ &+ \tau_p\left\{F_{1/2}(\eta_n)\exp(-\eta_n)\exp\left(\frac{A\,\Delta E_g}{k_B T}\right)\exp\left(\frac{E_{fn} - E_i}{k_B T}\right) + 1\right\}\Bigg]^{-1} \\ &+ \gamma\left\{F_{1/2}(\eta_n)\exp(-\eta_n)\exp\left(\frac{A\,\Delta E_g}{k_B T}\right)\exp\left(\frac{E_{fn} - E_i}{k_B T}\right)\right. \\ &\left.+ F_{1/2}(\eta_p)\exp(-\eta_p)\exp\left(\frac{(1 - A)\,\Delta E_g}{k_B T}\right)\exp\left(\frac{E_i - E_{fp}}{k_B T}\right)\right\}\Bigg] \\ &\times\left[F_{1/2}(\eta_n)\,F_{1/2}(\eta_p)\exp\left(\frac{\Delta E_g}{k_B T}\right)\exp\{-(\eta_n + \eta_p)\} - 1\right]. \end{aligned} \tag{7}$$

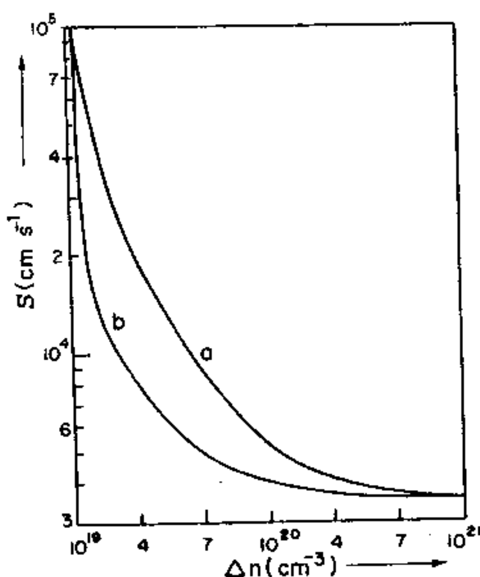

Fig. 1. Variation of the surface recombination velocity as a function of dopant density in a heavily doped abrupt n^+ p junction. Curve (a) is the result of the present model, (b) that of [9]

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 [13] $\Delta E_g = 10.23 \quad (N/10^{18})^{1/3} + 13.12 \ (N/10^{18})^{1/4} + 2.93 \ (N/10^{18})^{1/2}$ meV, $n_i = 1.5 \times 10^{10}$ cm^{-3}, $T = 300$ K, $E_g = 1.21$ eV. The values of η_p, η_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 τ_p for the variation of majority carrier concentration in the range 10^{19} to 10^{21} cm^{-3} have been chosen within 10^{-8} to 3×10^{-9} s; while in the minority carrier concentration range between (3 to 9) $\times 10^{16}$ cm^{-3}, the values of τ_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.

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