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Minimization of Reverse Recovery Charge and Forward Voltage of Silicon pin Diodes

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Abstract

The forward voltage V_f and reverse recovery charge Q_{rr} of silicon pin diodes are controlled by using the carrier lifetime or injection efficiency to reduce the power loss. In this study, the ideal lifetime and injection efficiency for minimizing the power loss is calculated by a theoretical analysis. The ideal lifetime has a current density dependency, and a decrease in the current density leads to an increase the ideal lifetime. Therefore, a shallow trap level indicates a smaller Q_{rr} at the same V_f.

1. Introduction

The forward voltage V_f and reverse recovery charge Q_{rr} of silicon pin diodes are proportional to the conduction and the turn-off loss, respectively [1]. In addition, they exhibit a trade-off relationship [1]. Therefore, it is a requirement to reduce V_f and Q_{rr}. To reduce the power loss, carrier lifetime control [2] or carrier injection efficiency control [3] can be used. In previous studies, we clarified that the power loss can be reduced by the appropriate choice of carrier control depending on dj/dt (rate of current density in turn off) [4].

In this study, we calculate the smallest V_f and Q_{rr} with the ideal carrier lifetime and carrier injection efficiency by theoretical analyses to minimize the total power loss.

2. Method

Figure 1 shows a diagram of the pin diode investigated in this study. N_p, N_i, and N_n are the doping concentrations of the p, i, and n layers, and d_p, $2d$, and d_n are the widths of the layers, respectively. C_i is the excess carrier density.

V_f and Q_{rr} can both be calculated from the excess carrier density distribution with the following equations [4]:

$$C_i(x) = \frac{J\eta_i\tau_i}{2qL_{ia}}\left\{\frac{\cosh(x/L_{ia})}{\sinh(d/L_{ia})} - B'\frac{\sinh(x/L_{ia})}{\cosh(d/L_{ia})}\right\} \quad (1)$$

$$B' = \frac{1}{\eta_i}\left(\frac{\mu_{ie}/\mu_{ih} - 1}{\mu_{ie}/\mu_{ih} + 1} + \eta_{nh} - \eta_{pe}\right) \quad (2)$$

$$V_f = \frac{J}{q(\mu_{ie} + \mu_{ih})}\cdot\int\frac{1}{C_i(x)}dx + \frac{kT}{q}\ln\left(\frac{C_i(-d)\cdot C_i(+d)}{n_i^2}\right) \quad (3)$$

$$Q_r = \frac{dj}{dt}\tau_i^2\ln^2\left(\frac{\sqrt{Q_1}}{\tau_i\sqrt{dj/dt}} + 1\right) \quad (4)$$

$$Q_1 = \left(\eta_i\tau_i^2\frac{dj}{dt} + \tau_i J\eta_i\right)\left(1 - e^{-t_1/\tau_i}\right) - \frac{dj}{dt}\eta_i\tau_i t_1 + Q_0 e^{-t_1\tau_i} \quad (5)$$

$$t_1 = J/\frac{dj}{dt} \quad (6)$$

$$Q_0 = \int_{-d}^{+d} C_i(x)dx \quad (7)$$

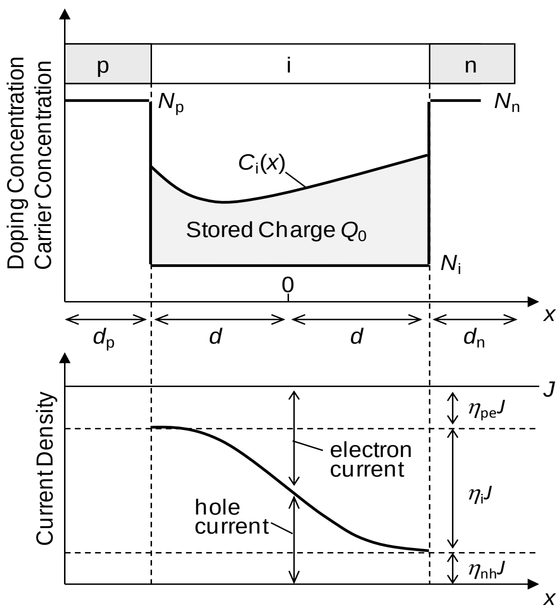

Fig. 1 Schematic of the pin diode with the doping distribution, excess carrier concentration, and current density. $N_i = 5.0\times10^{13}/cm^3$, $d_p = d_n = 3$ µm, and $2d = 140$ µm.

where J is total current density, η_{pe}, η_i, and η_{nh} is the ratio of the electron current density at the p/i, the recombination current density in the i layer, and the hole current density at the i/n, respectively, τ_i is the carrier lifetime in the i layer, L_{ia} is the diffusion length in the i layer, μ_{ie} and μ_{ih} are the electron and hole mobilities in the i layer, n_i is the intrinsic carrier density.

τ_i is determined by the Shockley–Read–Hall model [5]. Assuming a single energy level, τ_i is expressed as

$$\frac{1}{\tau_i} = \frac{\sigma V_{th} N_t Q_0}{2Q_0 + 4dn_i\cosh\left(\frac{E_t - E_i}{kT}\right)} + \frac{1}{\tau_{i0}} \quad (8)$$

where σ is the capture cross section, v_{th} is the thermal velocity, N_t is the trap density, and τ_{i0} is the intrinsic carrier lifetime in the bulk. E_t and E_i are the trap energy level of the trap and the midgap level.

3. Results and Discussion

Figure 2 shows the relationship between Q_{rr} and τ_i for $V_f = 1.2$ V and $J = 100$ A/cm^2. To maintain the same V_f, the carrier injection efficiency is coordinated with τ_i. For the conditions in Fig. 2, Q_{rr} achieves the minimum value around $\tau_i = 1.5$ µs. This Q_{rr} is the smallest value when V_f = 1.2 V and $J = 100$ A/cm^2. τ_i at the smallest Q_{rr} is defined as the ideal lifetime τ_{ideal}.

The smallest Q_{rr} can be determined for arbitrary values of V_f and J. Figure 3 shows the relationship between V_f and Q_{rr} for various values of J. The ideal lines represent the smallest Q_{rr} for any V_f and J. The black points are the diode characteristics, which are controlled to have the smallest Q_{rr} when V_f = 2.0 V and J = 200 A/cm^2 with various trap energy levels $E_t - E_i$. The current-density–voltage characteristics of these diodes are shown in Fig. 4.

At 200 A/cm^2, any point lie on the ideal line. On the other hand, at 50 and 100 A/cm^2, there is a difference between the points and the ideal lines. In addition, larger values of $E_t - E_i$ are located closer to an ideal line. This is implies that shallow levels (large $E_t - E_i$) are more suitable for achieving a reduced power loss.

Figure 5 shows the relationship between the lifetime and the current density for $E_t - E_i$ = 0.0 and 0.5 eV. The current-density dependency on the ideal lifetime is shown in same figure. Figure 5 indicates that a decrease in the current density leads to an increase in the ideal lifetime. From Eq. (8), τ_i has same dependency on the stored charge at large values of $E_t - E_i$. Therefore, $E_t - E_i$ = 0.5 eV indicates more ideal characteristics in Fig. 3.

4. Conclusions

The smallest Q_{rr} at the same V_f with the ideal lifetime were calculated. The ideal lifetime has a current-density dependency, and a decrease in the current density leads to an increase in the ideal lifetime. Therefore, a shallow trap level (large $E_t - E_i$) results in a smaller value of Q_{rr}.

References

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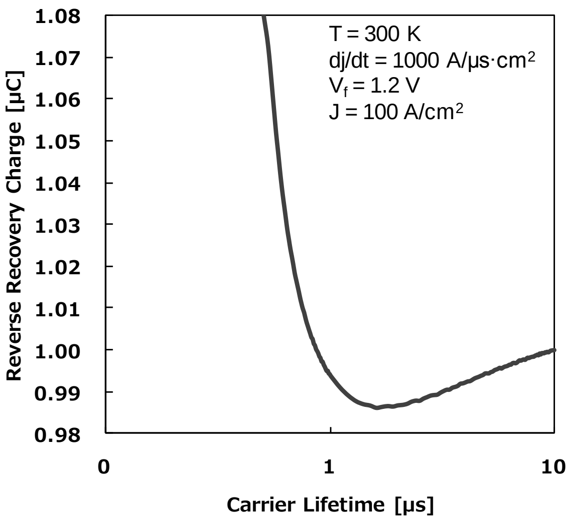

Fig. 2 The relationship between Q_{rr} and τ_i for V_f = 1.2 V and J = 100 A/cm^2.

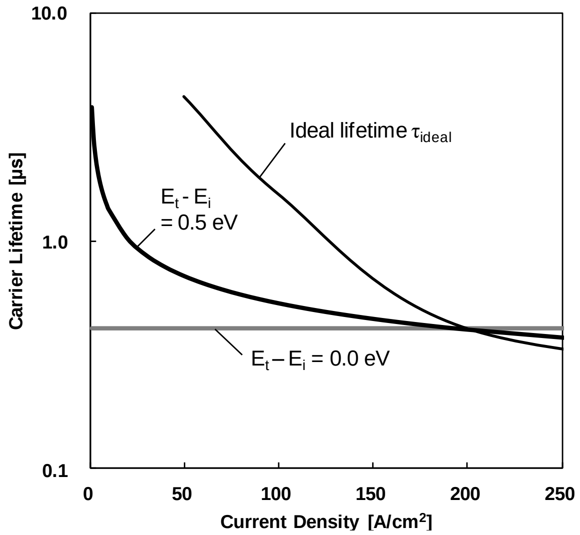

Fig. 4 Diode current–voltage characteristics for $E_t - E_i$ = 0.0 and 0.5 eV.

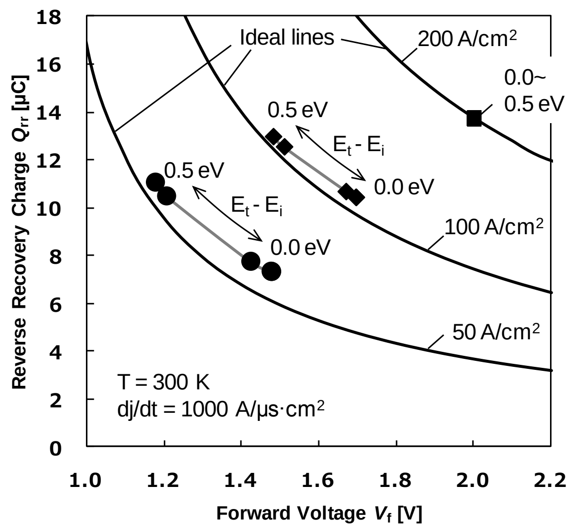

Fig. 3 The relationship between V_f and Q_{rr} for various values of J.

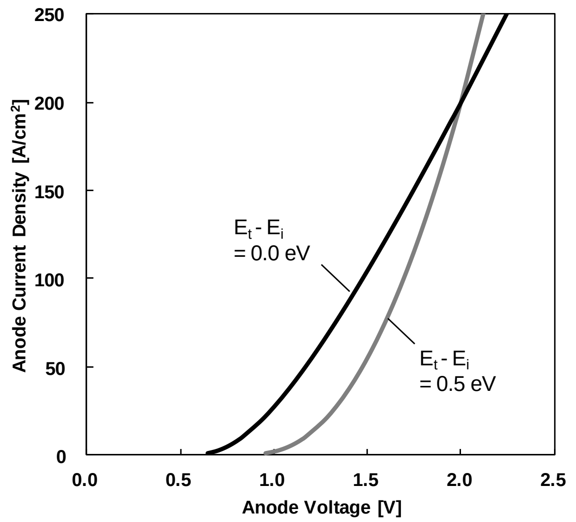

Fig. 5 The relationship between the lifetime and the current density for $E_t - E_i$ = 0.0 and 0.5 eV.