Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp368-369

Analysis of Forward Voltage and Reverse Recovery Charge Control of Silicon PiN Diodes

Yusuke Yamashita[1], Satoru Machida [1]

[1] Toyota Central R&D Labs., Inc., Yokomichi, Nagakute, Aichi 480-1192, Japan
Phone: +81-561-71-7107 E-mail: e1407@mosk.tytlabs.co.jp

Abstract

The forward voltage V_f and the reverse recovery charge Q_r of Silicon PiN power diodes can be controlled by carrier lifetime or carrier injection control techniques to minimize the total power loss. The effect of the two techniques on the relationship between V_f and Q_r was investigated by theoretical analyses. This work showed that the carrier injection controlled diode could better minimize the total power loss than the carrier lifetime controlled diode.

1. Introduction

Silicon PiN power diodes are widely used in applications such as electric home appliances and automobiles. During the on-state of a diode, excess carriers are injected into the i layer from the P and N layers, and a forward voltage V_f is applied across the diode. At turn-off, excess carriers are removed from the i layer, producing a reverse recovery charge Q_r. Both V_f and Q_r influence the power loss, and have a trade-off relationship.

To minimize the total power loss, carrier lifetime control [1,2] or carrier injection efficiency control [3] can be used to reduce Q_r instead of increasing V_f. In previous studies, these two techniques had been investigated individually.

In this study, we investigate the effects of both the carrier lifetime and the carrier injection efficiency on the relationship between V_f and Q_r by theoretical analyses, and analyze which of the two techniques is better.

2. Method

Outline

In this section, the method of calculating V_f and Q_r is described. V_f and Q_r can both be calculated from the excess carrier density distribution [4]. First, we derived the formula for the excess carrier density distribution that takes into account the effects of the carrier lifetime and the carrier injection efficiency. We then calculated V_f and Q_r from the carrier density distribution.

Figure 1 shows the pattern 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 depths of the layers. respectively. C_i is the excess carrier density. J is the total current density, J_{Pn} is the electron current density at the P/i interface, J_i is the recombination current density in the i layer, and J_{Np} is the hole current density at the i/N interface. η_{Pn}, η_i, and η_{Np} are the current density ratios of J_{Pn}, J_i, and J_N, respectively.

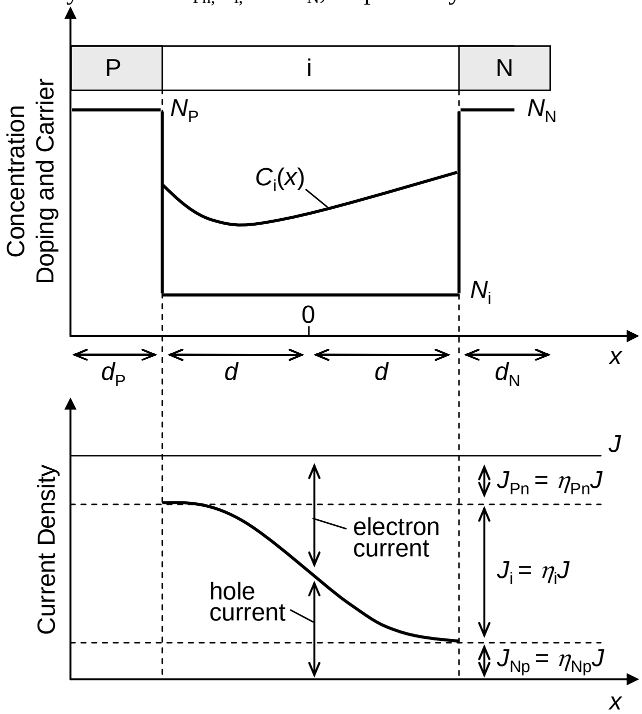

Fig. 1 Schematic of the PiN diode with distribution of doping and excess carrier concentration, and current density.

Excess Carrier Density Distributions $C_i(x)$

From Fig. 1, the excess carrier density distribution $C_i(x)$ is expressed as [5]

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

$$B' = \frac{1}{\eta_i} \left(\frac{\mu_{in}/\mu_{ip} - 1}{\mu_{in}/\mu_{ip} + 1} + \eta_{Np} - \eta_{Pn} \right) \quad (2)$$

where τ_i is the carrier lifetime, L_{ia} is the ambipolar length, and μ_{in} and μ_{ip} are the mobilities of electrons and holes in the i layer. The hole injection efficiency γ_p of the P layer can be represented as $\gamma_p = (1 - \eta_{Pn})$.

Forward Voltage V_f

From Eq. 1, the forward voltage V_f is calculated as

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

where the first term on the right-hand side represents the voltage across the i layer and the second term represents the junction voltage.

Reverse Recovery Charge Q_r

If the carrier recombination during turn-off is neglected, the reverse recovery charge Q_r can be approximately derived as

$$Q_\mathrm{r} = q\int_{-d}^{+d} C_\mathrm{i}(x)\mathrm{d}x \qquad (4)$$

3. Results and Discussion

The two control techniques were compared using Eqs. 1–4. Figure 2 shows the relationship between V_f and Q_r with varying τ_i and γ_p. The above equations can be calculated by moving the V_f–Q_r point along the trade-off curve with the variation of τ_i and γ_p. At the low Q_r region, V_f with τ_i control became higher than that with γ_p control. This result implies that decreasing τ_i causes an increase in the resistivity.

Figures 3 and 4 show the distribution of the excess carrier density and the resistivity at the same Q_r and different τ_i. The excess carrier density of small τ_i is an order of magnitude lower than large τ_i around the middle of the i layer. V_f is inversely proportional to the carrier density. Therefore, the resistivity of the i layer increases at the same Q_r.

Thus, the carrier injection control is more suitable as the V_f–Q_r control technique from the perspective of power loss suppression.

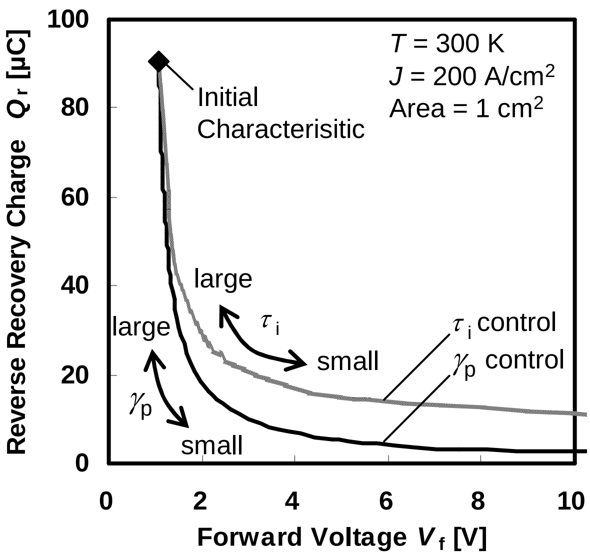

Fig. 2 Relationship between V_f and Q_r with varying carrier lifetime τ_i and hole injection efficiency γ_p. $N_\mathrm{P} = N_\mathrm{N} = 1.0 \times 10^{18}/\mathrm{cm}^3$, $N_\mathrm{i} = 5.0 \times 10^{13}/\mathrm{cm}^3$, $d_\mathrm{P} = d_\mathrm{N} = 3$ μm, and $2d = 140$ μm.

4. Conclusions

The effect of the carrier lifetime and the carrier injection efficiency on the relationship between the forward voltage V_f and the reverse recovery charge Q_r of the silicon PiN diode was investigated. With the decrease in the carrier lifetime, V_f was observed to increase at a given Q_r. This is because the small lifetime causes high resistivity at the middle of the i layer. Thus, carrier injection control is more suitable than carrier lifetime control from the perspective of power loss reduction in PiN diodes.

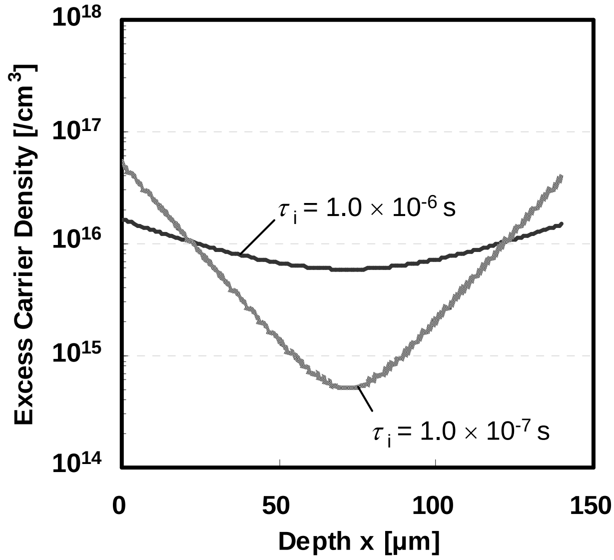

Fig. 3 Distribution of excess carrier density with varying carrier lifetime τ_i at a given reverse recovery charge Q_r

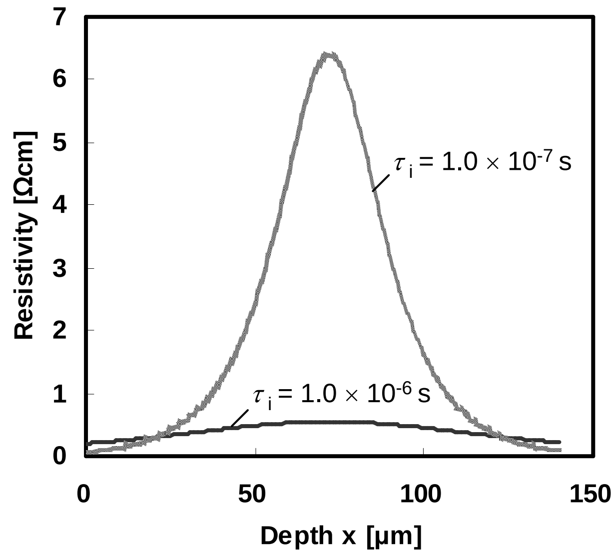

Fig. 4 Distribution of resistivity with varying carrier lifetime τ_i at a given reverse recovery charge Q_r.

References

[1] J. Vobecký et al., Nucl. Instrum. Methods Phys. Res., Sect. B **253**, 162 (2006)

[2] P. Hazdra et al., Microelectron. J. **35**, 249 (2004)

[3] A. Porst et al., Proc. Int. Symp. Power Semiconductor Devices and ICs (ISPSD), 1997, p. 213

[4] J. Lutz, *Semiconductor Power Devices* (Springer) p. 167

[5] A. Herlet, Solid-State Electron. **11**, 717 (1968)