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Numerical modeling of reverse recovery characteristic in silicon pin diodes

Yusuke Yamashita*, Hiroshi Tadano

University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan

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ABSTRACT

A new numerical reverse recovery model of silicon pin diode is proposed by the approximation of the reverse recovery waveform as a simple shape. This is the first model to calculate the reverse recovery characteristics using numerical equations without adjusted by fitting equations and fitting parameters. In order to verify the validity and the accuracy of the numerical model, the calculation result from the model is verified through the device simulation result.

1. Introduction

Silicon pin power diodes are one of the most important components in power electronics. The main concern in such diodes is the large power loss, and attempts have been made to reduce this. Therefore, it is important to understand the behavior of the electrical characteristics of pin diodes. Especially, since the forward characteristic and the reverse recovery characteristic are strongly related to the power loss, several numerical models of pin diodes have been reported in previous studies.

For example, equations capable of calculating the carrier distribution in the i-layer have already been proposed [1,2], using which forward IV characteristics can also be calculated [3,4]. In addition, there exists a numerical reverse recovery model based on the change in the carrier density distribution in the i-layer [5,6]. Recently, since exhaustive analysis is possible, the numerical model of the reverse recovery was applied to SiC pin diodes [7,8]. However, since these models assume a resistive load, the reverse recovery current becomes constant within a certain period, and it is not possible to calculate the reverse recovery characteristic assuming an inductive load. For this reason, the carrier distribution model has been applied to circuit simulation to calculate reverse recovery characteristics [9]. Another study calculated the surge voltage from a numerical model [10], but other characteristic values such as the reverse recovery waveform, reverse recovery charge, and maximum reverse recovery current were not calculated. Therefore, there is no numerical model that calculates reverse recovery characteristics.

In our previous study, the reverse recovery characteristics were analyzed with a triangular current waveform by ignoring the tail current [11]. In this paper, we propose a new numerical model for computing the reverse recovery characteristics of the Si-pin diode with high accuracy including tail current, and report the result of verification using device simulation to demonstrate its accuracy of proposed model.

2. Modeling of reverse recovery characteristic

2.1. Method

Table 1 shows the definitions of notations used in the figures and equations in this paper. The Ambipolar diffusion constant of i-layer D_{ia} in the table is defined by the following equation.

$$D_{ia} = \frac{2\mu_{ie}\mu_{ih}}{\mu_{ie} + \mu_{ih}}\frac{kT}{q} \tag{2.1.1}$$

Fig. 1 shows a schematic diagram of the pin diode used in this analysis. This diode is set in the circuit as shown in Fig. 2. When the circuit switch shifts from off state to on state, the diode shifts to a reverse recovery mode. Fig. 3 shows the diagram of the reverse recovery waveform, which is divided into five phases [12]. These phases are separated by inflection points of the reverse recovery waveform. Table 2 shows the definitions of the current density J, voltage V, and charge Q at each phase. In addition, Table 3 shows the values of reverse recovery characteristics at the inflection point of the reverse recovery waveform ($t = 0 \sim t_5$).

Conventionally, the reverse recovery characteristics is necessary to calculate the transient phenomena of the electron and hole current distribution in the i-layer [6]. Therefore, it was calculated by the device simulation using a finite element method. In proposed model, the reverse recovery waveform was approximated as a simple shape and divided five phases. Therefore, it is possible to define the time dependent equation of each phase without calculating the transient phenomenon. The sequence of steps followed in the modeling method is as follows.

* Corresponding author.
E-mail address: e1407@mosk.tytlabs.co.jp (Y. Yamashita).

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Table 1
Definitions of symbols and parameters used for calculation.

Symbol	Definition
N_p	Doping density of p-layer
N_i	Doping density of i-layer
N_n	Doping density of n-layer
d_p	Depth of p-layer
d	Half depth of i-layer
d_n	Depth of n-layer
J	Total current density
J_{rr}	Maximum reverse current density
V	Applied voltage
V_{cc}	Supply voltage
V_s	Surge voltage
Q	Stored charge
Q_{rr}	Reverse recovery charge
W	Width of depletion layer
L_h	Parasitic inductance
dJ_f/dt	Rate of recovery current density decreasing
dJ_r/dt	Rate of recovery current density increasing
dJ_t/dt	Rate of tale current density increasing
dV/dt	Rate of voltage increasing
η_i	Recombination current density ratio in i-layer
τ_i	Carrier lifetime of i-layer
L_{ia}	Ambipolar diffusion length in i-layer
L_{pe}	Electron diffusion length in p-layer
L_{nh}	Hole diffusion length in n-layer
μ_{ie}	Electron mobility of i-layer
μ_{ih}	Hole mobility of i-layer
μ_{wh}	Hole mobility of depletion layer
D_{ia}	Ambipolar diffusion constant of i-layer
D_{pe}	Electron diffusion constant of p-layer
D_{nh}	Hole diffusion constant of n-layer
$\hat{E}$	Mean electric field in recovery
p	Hole density in recovery
k	Boltzmann constant
T	Temperature
q	Elementary charge

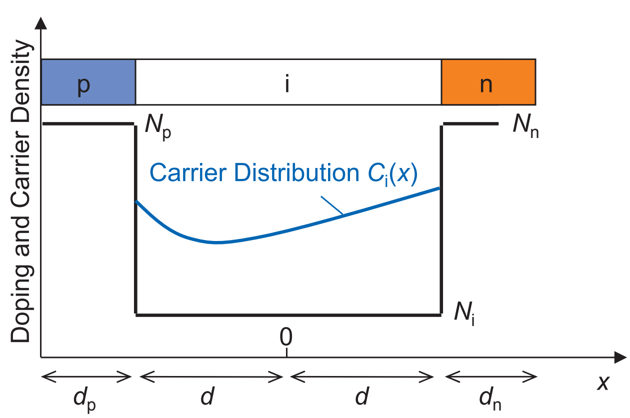

Fig. 1. Schematic diagram of pin diode.

(1) Reverse recovery waveform is divided into five phases [Section 2.1].
(2) Carrier distribution density at $t = 0$ is determined [Section 2.2].
(3) Time dependency equations of current density $J(t)$, voltage $V(t)$ and i-layer charge $Q(t)$ at per phase is derived [Section 2.3].
(4) The relational equation between $J(t)$,$V(t)$ and $Q(t)$ during the reverse recovery is derived [Sections 2.4 and 2.5].
(5) $J(t_1)$ to $J(t_5)$ and $V(t_1)$ to $V(t_5)$ are calculated from the expressions (2)–(4) [Section 2.6].

The relational equation between $J(t)$, $V(t)$ and $Q(t)$ cannot be derived directly. Then, it is derived from the relational equation between $Q(t)$ and the width of depletion layer $W(t)$, and the relational equation

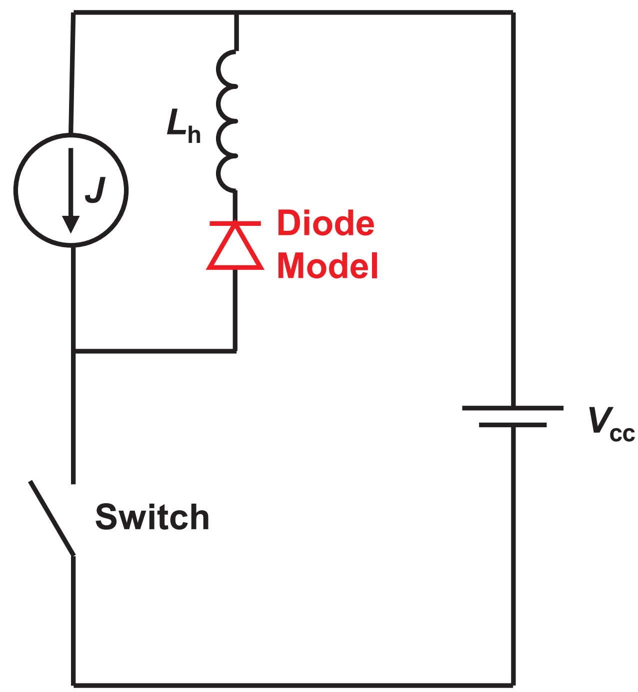

Fig. 2. Circuit diagram of reverse recovery model.

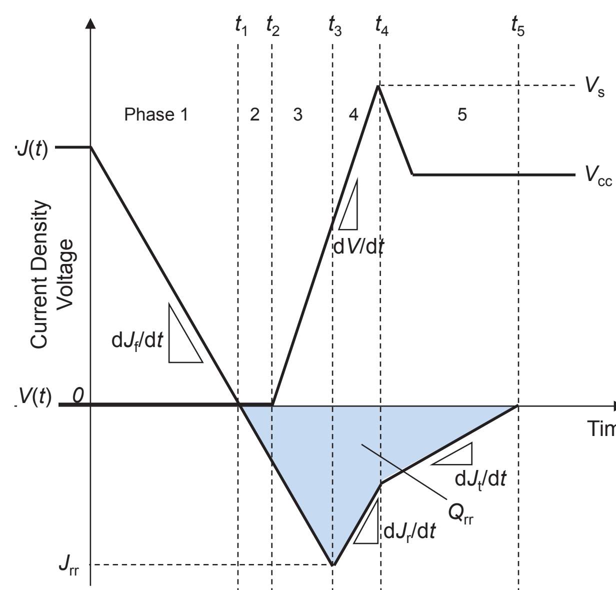

Fig. 3. Schematic diagram of reverse recovery waveform model.

Table 2
Definition of current density, voltage, and charge at each phase.

Phase	$J(t)$	$V(t)$	$Q(t)$
1	$J_{ph1}(t)$	$V_{ph1}(t)$	$Q_{ph1}(t)$
2	$J_{ph2}(t)$	$V_{ph2}(t)$	$Q_{ph2}(t)$
3	$J_{ph3}(t)$	$V_{ph3}(t)$	$Q_{ph3}(t)$
4	$J_{ph4}(t)$	$V_{ph4}(t)$	$Q_{ph4}(t)$
5	$J_{ph5}(t)$	-	$Q_{ph5}(t)$

between $J(t)$, $V(t)$ and $W(t)$. To confirm the accuracy of this numerical model, we used device simulation. In particular, device simulation of silicon is effective for confirming the accuracy since it can calculate the experiment result accurately.