Paper

PN Diode model Based on Divided Charge Distribution For EMTP-Type Simulators

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A physical-based model of a pn diode is extremely important for a successful design and development of not only electronic circuits but also power electronics systems such as a HVDC (high voltage direct current) system or FACTS (flexible ac transmission system), because the pn diode is a basic semiconductor device. This paper has proposed a pn diode model based on divided charge distribution for EMTP-type simulators such as EMTP and EMTDC. The proposed model physically represents drift and diffusion phenomena of a pn diode in model equations accurately to realize steady and transient characteristics including the forward and reverse recovery characteristics in the EMTP-type simulators. It has been also explained how the model parameters influence the diode voltage and current of the proposed pn model. With the diode voltage and current, the transient characteristic of the model variables have been also presented to understand a relation between the physical meanings of a diode and the model variables in the proposed model. Results calculated with a combined iterative method show a satisfactory coincidence with measured results.

Keywords : pn diode, divided charge distribution method, combined iterative method, nonlinearity, EMTP-type simulator.

1. INTRODUCTION

Power electronics technologies have been developing in the fields of energy and environmental issues, where a solar power and a fuel cell as a dispersal power source and a system interconnection between 50Hz and 60Hz systems have been exploited to use energy effectively and to control consumption of electrical power. With those developing technologies, it is expected that simulation technologies for power electronics circuits are improved and optimized, and simplified models of power electronics are exploited for EMTP-type simulators (EMTP[1], PSCAD/EMTDC[2]). It is very important how some factors like accuracy, shortening of a computation time, comprehension of physical meanings of the power electronics elements and simplification for numerical problems can be realized simultaneously.

Modeling methods of power electronics are classified as a lumped model and a numerical model for the EMTP-type simulators. The lumped model is expressed by nonlinear and linear lumped elements. The model may realize shortening of the computation time and physical characteristics in several simple power electronics elements, but those cases are not usual. When a power electronics element has a complicated characteristic, it is difficult to produce the lumped power electronics model which can accurately represent the complicated structures. A numerical model usually needs a longer computation time than a lumped model, but it is easier to produce an accurate model based on the complicated structure. Therefore, the numerical model is on the main current of the power electronics models.

A numerical power diode model in which the diode structure is divided into three dimensions has been proposed [3], but the model requires a huge computation time and has a difficulty to determine constants of the model equations. A one-dimension model of a diode, which expresses physical meanings separately, has been proposed [4], but the expression is not enough to produce a physical model.

This paper proposes a numerical model of a pn diode which is a basic semiconductor. The proposed model employs a one-dimension approach based on divided charge distribution, and several physical meanings of the diode are expressed simultaneously. Simulations of the proposed diode model are carried out using a combined iterative method [5] in an EMTP-type simulator.

2. DERIVATION OF PN DIODE MODEL

When a positive voltage applied to a pn diode turns rapidly to negative, the junction voltage keeps the forward bias for a while because of unmovable minority carriers around a middle region of the p- and the n-type semiconductors. Shortly after, the negative current flows by the minority carrier diffusion, and the depletion layer expands. Then, the conductivity becomes lower. When a negative applied voltage turns rapidly to positive, the drift influences the forward recovery characteristic because of few minority carriers in those semiconductors. Namely, the diode current flows in spite of the low conductivity. Therefore, the forward recovery voltage appears by the drift.

This chapter proposes a numerical model of a pn diode, whose structure is divided into six parts to approximate the carrier movements as in Fig. 1. The region 1 of p-type semiconductor and the region 3 of n-type semiconductor are defined as minute regions of metal-semiconductor junctions, the region 3 of p-type semiconductor and the region 1 of n-type semiconductor are defined as minute regions of a pn junction, and the regions 2 where recombination take place in the model show the middle regions of p- and n-type semiconductors. In Fig.1, v_s : voltage across the metal-semiconductor junction, v_J : voltage across the pn junction, v_p and v_n: voltages around a middle region of p- and n-type semiconductors respectively, d_p and d_n : length of p- and n-type semiconductors respectively, N_{p2} : total charge of electrons in the region 2 of a p-type semiconductor, P_{n2} : total charge of holes in the region 2 of a n-type semiconductor, n and p : electron and hole densities respectively, p_0 and n_0 : hole and electron density under an equilibrium state.

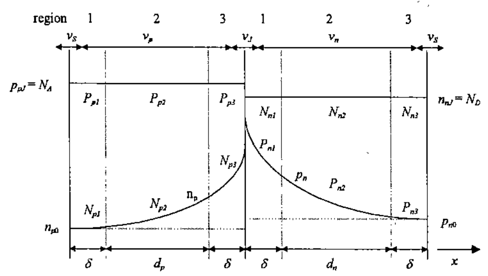

Fig. 1 Carrier distributions in the proposed pn junction model

2.1 Current Density Equation in Semiconductor

The current density in a semiconductor can be expressed as a sum of the drift and diffusion currents density.

$$J_e = J_{edr} + J_{edf} = en\mu_e E_x + eD_e \frac{dn}{dx} \tag{1}$$

$$J_h = J_{hdr} + J_{hdf} = ep\mu_h E_x - eD_h \frac{dp}{dx} \tag{2}$$

where J_e and J_h : electron and hole current densities respectively, e : electronic charge ≅ 1.602×10^{-19}, E_x : electric field to the direction x, μ_e and μ_h : mobility of electrons and holes respectively, D_e and D_h : diffusion constant of electrons and holes respectively. Therefore the total current density J is derived as the sum of eqs. (1) and (2).

The electron current i_{pe12} from region 1 to 2 in a p-type area is derived by multiplying the junction area A to the general current density equation (1), and using $\delta \to 0$ and Einstein's equation for minority carriers in a p-type semiconductor to the p-type area 1 – 2 in Fig. 1.

$$i_{pe12} = \frac{N_{p1}+N_{p2}}{4T_{pe12}\phi} v_p + \frac{v_p}{R_{pe0}} + \frac{N_{p2}-N_{p1}}{T_{pe12}}$$

$$\left(\begin{array}{l} N_{p1} = Aed_p n_{p1}, \quad N_{p2} = Aed_p n_{p2}, \\ N_{p0} = Aed_p n_{p0}, \quad T_{pe12} = d_p^2/2D_{pe}, \\ \mu_{pe} = \dfrac{D_{pe}}{\phi} = \dfrac{d_p^2}{2T_{pe12}\phi} \quad \left(\phi = \dfrac{k\cdot Temp}{e}\right), \\ R_{pe0} = \dfrac{d_p^2}{\mu_{pe}N_{p0}} = \dfrac{2T_{pe12}\phi}{N_{p0}} \end{array}\right) \tag{3}$$

where k : Boltzman constant ≅ 1.381×10^{-23}, $Temp$: absolute temperature

Similarly, i_{pe23}, i_{ph12}, i_{ph23}, i_{ne12}, i_{ne23}, i_{nh12}, i_{nh23} are derived from the general current density eqs. (1) and (2).

2.2 Carrier Continuity Equation

A carrier movement in a unit volume of a semiconductor can be calculated from the number of carriers brought by drift and diffusion, and from the number of disappearances of carriers due to recombination. The relation can be expressed as a continuity equation. The continuity equation is simplified in one dimension in this paper, and the hole density p is related in the following equation.

$$\frac{dp}{dt} = -\left(\frac{1}{e}\right)\frac{dJ_h}{dx} - \frac{p-p_0}{\tau_h} \tag{4}$$

where τ_h : average lifetime of holes.

The continuity equation for electrons can be expressed by :

$$\frac{dn}{dt} = \left(\frac{1}{e}\right)\frac{dJ_e}{dx} - \frac{n-n_0}{\tau_e} \tag{5}$$

where τ_e : average lifetime of electrons.

The first term of eqs. (4) and (5) means an inflow of holes and electrons respectively, because dJ_h/dx and dJ_e/dx are an outflow of a current, and (1/e) dJ_h/dx and (1/e) dJ_e/dx are the number of outflow holes and inflow electrons respectively. The second term means a decrease of carriers due to recombination.

The following equation can be derived by applying the general continuity eqs. (4) and (5) to the n- and the p-type areas 2 in Fig.1.

$$\frac{dN_{p2}}{dt} = i_{pe23} - i_{pe12} - \frac{N_{p2}}{\tau_{pe}} \tag{6}$$

In the right-hand side of eq. (6), the first and second terms mean the outflow current by diffusion and the current by recombination respectively. The carrier continuity equation for an n-type semiconductor can be derived similarly.

$$\frac{dP_{n2}}{dt} = i_{nh12} - i_{nh23} - \frac{P_{n2}}{\tau_{nh}} \tag{7}$$

2.3 Boltzman's Relation at pn Junction

Boltzman related voltage v_J with minority carrier density n_{pJ} and p_{nJ} at a pn junction in following equations [6].

$$n_{pJ} = n_{p0}\exp\left(\frac{v_J}{\phi}\right) \tag{8}$$

$$p_{nJ} = p_{n0}\exp\left(\frac{v_J}{\phi}\right) \tag{9}$$

Eqs. (10) and (11) can be derived by applying general Boltzman's equations (8) and (9) to Fig. 1.

$$N_{p3} = N_{p0}\left\{\exp\left(\frac{v_J}{\phi}\right) - 1\right\} \tag{10}$$

$$P_{n1} = P_{n0}\left\{\exp\left(\frac{v_J}{\phi}\right) - 1\right\} \tag{11}$$

2.4 Carrier Density at Metal-Semiconductor Junction

The majority carrier density n_{nS} and the minority carrier density p_{nS} nearby a metal-semiconductor junction can be derived from the electron and hole density (n_{n0} and p_{n0}) under an equilibrium state in the following equation.

$$n_{nS} = n'\exp\left(\frac{V_D + v_s}{\phi}\right) = n_{n0}\exp\left(\frac{ev_s}{\phi}\right) \tag{12}$$

From a law of mass action, p_{nS} can be expressed by:

$$p_{nS} = p'\exp\left(-\frac{V_D + v_s}{\phi}\right) = p_{n0}\exp\left(-\frac{v_s}{\phi}\right) \tag{13}$$

where V_D : diffusion potential[6].

In a metal – p-type semiconductor junction, the majority carrier density p_{pS} and the minority carrier density n_{pS} can be derived from the electron and hole densities (n_{p0} and p_{p0}) under an equilibrium state in the following equations.

$$p_{pS} = p'\exp\left(\frac{V_D + v_s}{\phi}\right) = p_{p0}\exp\left(\frac{v_s}{\phi}\right) \tag{14}$$

$$n_{pS} = n'\exp\left(-\frac{V_D + v_s}{\phi}\right) = n_{p0}\exp\left(-\frac{v_s}{\phi}\right) \tag{15}$$

From Fig. 1, and eqs. (12) and (13) which give the relation between a majority carrier density and a junction voltage at a metal-semiconductor junction, the following equations are derived.

$$P_{p1} = P_{po}\left\{\exp\left(\frac{v_s}{\phi}\right) - 1\right\} \tag{16}$$

$$N_{n3} = N_{no}\left\{\exp\left(\frac{v_s}{\phi}\right) - 1\right\} \tag{17}$$

2.5 Junction Current Equation

The current density through a pn junction can be expressed as the diffusion current density at the both ends of the junction. A junction current equation can be derived from the electron density n_{pJ} in a p-type semiconductor by :

$$J_{peJ} = \frac{eD_{peJ} n_{pJ} L_{peJ}}{\tau_{peJ}} \quad \left(L_{peJ} = \sqrt{D_{peJ}\tau_{peJ}}\right) \tag{18}$$

where L_{peJ} : diffusion length of electrons nearby pn junction, D_{peJ} : diffusion constant of electrons nearby pn junction, τ_{peJ} : lifetime of electrons nearby pn junction.

τ_{peJ} becomes far shorter than τ_e and τ_h which are average lifetimes of electrons and holes in p- and n-type semiconductors respectively. Similarly, the current due to holes flowing through the pn junction can be written in the following form.

$$J_{nhJ} = \frac{eD_{nhJ} p_{nJ} L_{nhJ}}{\tau_{nhJ}} \tag{19}$$

The current flowing through a pn junction can be expressed as a diffusion current of minority carriers at the both ends of the junction. The current equation at the pn junction is derived by applying eq. (18) to the p-type semiconductor region 3 in Fig. 1.

From general carrier density relations around a pn junction, the following equations are derived.

$$n_{p3} = n'\exp\left(-\frac{V_D - v_J}{\phi}\right) \tag{20}$$

$$p_{p3} = p'\exp\left(\frac{V_D - v_J}{\phi}\right) \cong N_A \tag{21}$$

where N_A: acceptor concentration, p_{p3}: majority carrier density in p-type region 3 in Fig. 1.

When $v_J = V_D$, $n_{p3} = p_{p3}$ is formed, therefore,

$$p' = N_A\exp\left(-\frac{V_D - v_J}{\phi}\right) = n' \tag{22}$$

Substituting eq. (22) into eq. (20),

$$n_{p3} = N_A\exp\left\{-\frac{2V_D}{\phi}\right\}\exp\left\{\frac{2v_J}{\phi}\right\} = n_{p0}\exp\left\{\frac{2v_J}{\phi}\right\} \tag{23}$$

From eqs. (23) and (18), the following relation is derived.

$$i_{ne12} = I_{peJ}\left[\exp\left(\frac{2v_J}{\phi}\right) - 1\right] \quad \left(I_{peJ} = \frac{eAD_{peJ} L_{peJ} n_{p0}}{\tau_{peJ}}\right) \tag{24}$$

The current equation at a pn junction for an n-type semiconductor is similarly derived in the following form.

$$i_{ph23} = I_{nhJ}\left[\exp\left(\frac{2v_J}{\phi}\right) - 1\right] \quad \left(I_{nhJ} = \frac{eAD_{nhJ} L_{nhJ} p_{n0}}{\tau_{nhJ}}\right) \tag{25}$$

2.6 Diode Voltage and Current

A diode voltage v_d is given from v_J, v_p, v_n in Fig. 1 by :

$$v_d = v_p + v_J + v_n + 2v_S \tag{26}$$

Similarly, a diode current i_d is given as the sum of a hole and an electron current at an arbitrary place in a semiconductor in the following equation.

$$i_d = i_{pe23} + i_{ph23} = i_{nh12} + i_{ne12} = i_{pe12} + i_{ph12} = i_{nh23} + i_{ne23} \tag{27}$$

2.7 Contact Resistance and Junction Capacitance

When two semiconductors are combined mechanically, the electrical resistance at the junction is called "contact resistance", which can be classified to a convergence resistance and a transition resistance. A contact resistance is expressed as a lumped resistance R_s in the proposed pn diode model.

Donor and acceptor ions, which have a positive and a negative charge respectively, exist symmetrically with a diffusion potential V_D beside a transition region under heat balanced. The electrostatic capacity C_J per unit area, which is also called transition region capacitance, can be derived from the width of the transition region d and a specific inductive capacity ε_r in the following form.

$$C_J = \frac{\varepsilon_r \varepsilon_0}{d} \tag{28}$$

When a negative voltage is applied, d becomes longer, and positive and negative charges of the donor and the acceptor ions increase. On the other hand, when a positive voltage is applied, d becomes shorter, and the positive and the negative charges decrease. Those distributions depend on the donor and the acceptor densities. The approximation of junction impurity distributions are an abrupt junction, a graded junction and a hyperabrupt junction. This paper adopts the abrupt junction for proposed models, where d can be expressed in the following form.

$$d = \left\{\frac{2\varepsilon_r \varepsilon_0 (N_A + N_D)(V_D + V)}{eN_A N_D}\right\}^{\frac{1}{2}} \tag{29}$$

where N_D : donor density in an n-type semiconductor [6].

The junction capacitance C_J is derived from eqs. (28) and (29) by use of the junction voltage v_J and junction capacitance C_0 in an equilibrium state.

$$C_J = C_0\left(1+\frac{v_J}{V_D}\right)^{-n} \quad n=\frac{1}{2} \quad \text{for abrupt junction} \tag{30}$$

3. SIMPLIFICATION OF MODEL EQUATIONS

The above model equations are simplified without losing physical meanings of a pn-junction diode. The assumption of the symmetry of the pn-junction diode keeps its steady and transient characteristics, and the following new variables are defined.

$$\begin{aligned} Q_1 &= \frac{P_{n1}+N_{p3}}{2} = \frac{P_{p3}+N_{n1}}{2}, \quad Q_2 = \frac{P_{n2}+N_{p2}}{2} = \frac{P_{p2}+N_{n2}}{2} \\ i_1 &= \frac{i_{pe23}+i_{nh12}}{2} = \frac{i_{ph12}+i_{ne23}}{2}, \quad i_2 = \frac{i_{pe12}+i_{nh23}}{2} = \frac{i_{ph23}+i_{ne12}}{2} \end{aligned} \tag{31}$$

where Q_1 : total charge which influences around the junctions of semiconductors, Q_2 : total charge which influences in the middle regions of semiconductors. Eqs. (3,6,7,10,11,16,17,24,25,26,27) are transformed into the following equations from the above assumptions (See Appendix 1 for the derivation).

$$i_1 = \frac{Q_1+Q_2}{4T_q\phi}v_q + \frac{v_q}{R_0} + \frac{Q_1-Q_2}{T_q} \tag{32}$$

$$i_2 = \frac{Q_2+Q_1}{4T_q\phi}v_q + \frac{v_q}{R_0} - \frac{Q_1-Q_2}{T_q} \tag{33}$$

$$\frac{dQ_2}{dt} = (i_1 - i_2) - \frac{Q_2}{\tau_q} \tag{34}$$

$$Q_1 = Q_0\left[\exp\left(\frac{v_{JS}}{\phi}\right)-1\right] \tag{35}$$

$$v_d = 2v_q + 3v_{JS} + R_s i_d \tag{36}$$

$$i_d = \frac{i_1+i_2}{2} + C_J\frac{dv_{JS}}{dt} \tag{37}$$

$$i_2 = I_q\left[\exp\left(\frac{2v_{JS}}{\phi}\right)-1\right] \tag{38}$$

In eqs. (32)~(38), Q_1, Q_2, v_d, v_q, v_J, i_d, i_1 and i_2 are variables, and T_q, R_0, ϕ, Q_0, τ_q, I_q and C_0 are constants.

4. DETERMINATION OF MODEL PARAMETERS

An applied voltage to a diode appears around the pn junction, and the change of minority carrier density on a time region is negligible in a steady state as follows.

$$\frac{dQ_2}{dt} = 0, \quad v_q = 0 \tag{39}$$

When saturated values of Q_1 and Q_2 are defined as Q_{1S} and Q_{2S} respectively, and substitute Q_{1S} and Q_{2S} into eq. (34), the following equations is derived.

$$\begin{aligned} 0 &= \frac{Q_{1S}-Q_{2S}}{T_q} - \frac{Q_{2S}}{\tau_q} \\ \frac{Q_{2S}}{\tau'} &= \frac{Q_{S1}}{T_q/2} \quad \left[\frac{1}{\tau'} = \frac{1}{T_q/2} + \frac{1}{\tau_q}\right] \end{aligned} \tag{40}$$

An abrupt reverse recovery current with peak value I_{RM} flows when a bias voltage changes positive to negative as in Fig. 2. For $0 \le t \le T_1$, $Q_2(t)$ is written in the following equations by approximating $i(t)$ which is a linear function with the gradient $-a$.

$$Q_2(t) = a\tau_q\left\{T_0 + \tau_q - t - \tau_q \exp\left(-\frac{t}{\tau_q}\right)\right\} \tag{41}$$

The initial value of Q_2 is defined as Q_{2S} at $t = 0$. Therefore, eq. (41) becomes :

$$Q_2(0) = Q_{2S} = a\tau_q T_0 = \tau_q I_F \tag{42}$$

For there exist relations of $v_J \cong 0$ or $v_J < 0$, and $|v_J| > |v_q|$ for $t > T_1$, and $i_2 \cong 0$ in eq. (38), the following equation is derived.

$$\begin{aligned} &\frac{Q_2+Q_1}{4T_q\phi}v_q + \frac{v_q}{R_0} - \frac{Q_1-Q_2}{T_q} = 0 \\ &i_1 = \frac{Q_1-Q_2}{T_q/2} = i_d \end{aligned} \tag{43}$$

Eq. (43) shows that a reverse recovery characteristic is based on a diffusion characteristic. Shortly after, $Q_1 \cong 0$ is formed, and eq. (43) can be transformed into the following equation.

$$i_d = \frac{-Q_{2S}}{T_q/2} = -I_{RM} \tag{44}$$

A relation between T_q and τ_q is derived from eqs. (42) and (44) in the following form.

$$I_F\tau_q = T_q I_{RM}/2 \tag{45}$$

For $t > T_1$, the following equation is derived from $Q_1 \cong 0$, eqs. (34) and (43).

$$\begin{aligned} &\frac{dQ_2}{dt} = -\frac{Q_2}{T_q/2} - \frac{Q_2}{\tau_q} = -\frac{Q_2}{\tau'} \\ &\therefore Q_2(t) = \frac{I_{RM}T_q}{2}\exp\left(-\frac{t-T_1}{\tau'}\right) \end{aligned} \tag{46}$$

The new relation between T_q and τ_q is derived by the time constant of the reverse recovery current waveform τ'.

$$\frac{1}{\tau'} = \frac{1}{T_q/2} + \frac{1}{\tau_q} \tag{47}$$

Therefore, T_q and τ_q can be decided from eqs. (45) and (47), and Q_{2S} and Q_{1S} can be decided from eqs. (44) and (40) respectively. Q_0 is given by substituting $v_d/3$ and Q_{1S} into eq. (35). In a reverse bias state, from $Q_1 = Q_2 = 0$ and $v_J \ll 0$, $i_d = i_1$ can be shown, and I_q can be decided to satisfy the conditions $v_q \cong 0$ and $v_J = v_d/3$ for eq. (38). R_0 can be determined by the following equation.

$$R_0 = \frac{2T_q\phi}{Q_0} \tag{48}$$

The model parameters can be determined based on the above derivative method. An influence of the proposed model parameters to a steady characteristic and a transient one will be discussed in the following section.

5. MODEL PARAMETERS AND VARIABLES

5.1 Influences of Model Parameters to a Steady and Transient Characteristic

An Influence of the proposed model parameters to steady characteristic and transient one are discussed here, Q_0 affects the steady characteristic, T_q and τ_q affect the transient characteristic, and R_0 affects the forward recovery characteristic. On the other hand, I_q has almost no influence to the characteristics in satisfying the conditions given in Chap. 4. The influences of the parameters to the steady and the transient characteristics are very important to understand the physical meanings.

5.2 Steady and Transient Characteristics of Model Variables

When a positive or negative step voltage is applied to a single-phase half-wave rectifier circuit in Fig. 3, the steady and the transient characteristics of the diode voltage and current and the variables Q_1 and Q_2 in the proposed model are shown in Fig. 4. The model parameters for the simulations are given in Table. 1. The circuit for a transient test and a steady one, which include a proposed diode model, are carried out using the combined iterative simulator based on a EMTP-type algorithm, and the simulated results are compared with a measured result. The pn junction diodes for measurements are 1GH62 (Toshiba). Q_1 increases and saturates in a forward recovery characteristic, and decreases down to zero immediately in a reverse recovery characteristic. Q_2 saturates in a forward recovery characteristic, and is attenuated in a reverse recovery characteristic.

6. CONCLUSIONS

This paper has proposed the physical pn diode model, which is a basic semiconductor, based on a divided charge distribution method for an accurate simulation in an EMTP-type simulator. The proposed model employs a drift and a diffusion current from a middle region of a semiconductor to a junction region, and employ only the diffusion current near the junction. Therefore, the procedures in the proposed model make it possible to include transient characteristics of forward and reverse recovery with an accurate steady characteristic. For avoiding complicated and numerous model parameters, which make it difficult to determine those values and cause an instability in an EMTP-type simulator, a simplification of the model equations has been presented.

With the diode voltage and current, the transient characteristic of the model variables have been also presented to understand a relation between the physical meaning of a diode and the variables in the proposed model.

The calculated results by the proposed model agree well with the measured results on the reverse and forward recovery tests for a pn diode. It has been shown that the forward and reverse recovery characteristics can be realized accurately without a small time step in an EMTP-type simulator.

The proposed diode model has been simulated with a combined iterative method for an accurate simulation of nonlinear circuits. The model can be easily implemented into EMTP-type simulators such as EMTP and EMTDC.

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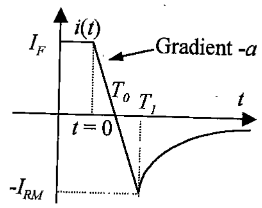


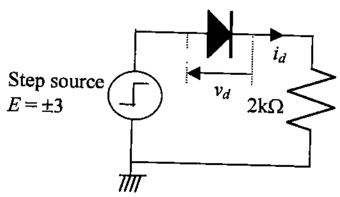
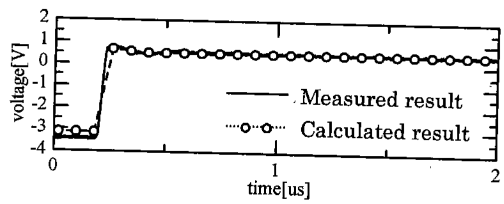


Fig. 2 Typical reverse recovery current waveform (left)

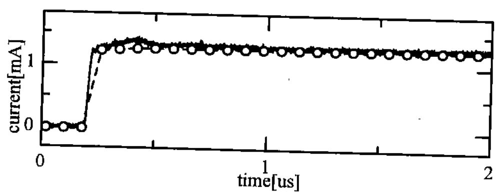
Fig. 3 Test circuit for forward and reverse recovery (right)

Table 1 Values of model parameters

T_q	R_0	Q_0	τ
1.4×10^{-6}	$2.5\times10^{+2}$	0.85×10^{-11}	0.85×10^{-6}
I_q	R	C_0	
1.0×10^{-17}	0.3×10^{-3}	1.0×10^{-12}	

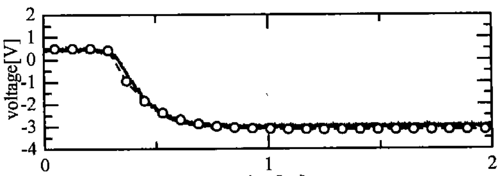


(i) Diode terminal voltage

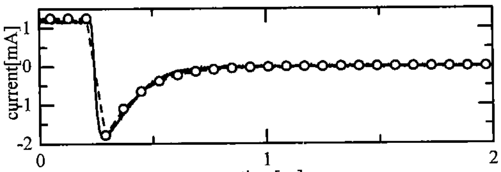


(ii) Diode terminal current

(a) Forward recovery

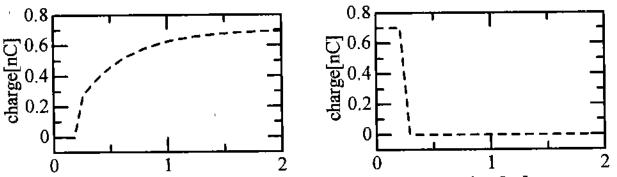


(i) Diode terminal voltage

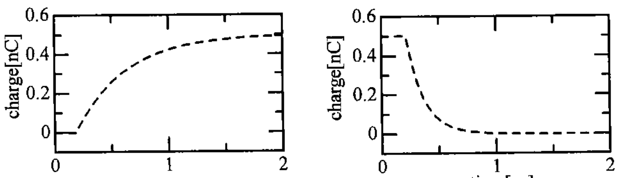


(ii) Diode terminal current

(b) Reverse recovery



(c) Forward and Reverse recovery of Q_1



(d) Forward and Reverse recovery of Q_2

Fig. 4 Characteristics of model parameters

A 1. Derivation of Eqs. (32) ~ (38)

Semiconductors of n- and p-types being assumed symmetrical for the model simplification, the following relation is obtained.

$$v_p = v_n = v_q,\quad v_J = v_S = v_{JS},\quad \tau_{pe} = \tau_{ph} = \tau_{ne} = \tau_{nh} = \tau_q$$

$$T_{pe12} = T_{pe23} = T_{ph12} = T_{ph23} = T_{ne12} = T_{ne23} = T_{nh12} = T_{nh23} = T_q$$

$$R_{pe0} = R_{ph0} = R_{ne0} = R_{nh0} = R_0$$

Currents i_1 and i_2 are expressed as an additional average of i_{pe23}, i_{ph12}, i_{ne23} and i_{nh12}, or i_{pe12}, i_{ph23}, i_{ne12} and i_{nh23} as in the following equations.

$$i_1 = \frac{i_{pe23} + i_{ph12} + i_{ne23} + i_{nh12}}{4} = \frac{Q_1 + Q_2}{4T_q\phi} v_q + \frac{v_q}{R_0} + \frac{Q_1 - Q_2}{T_q} \quad (32)$$

$$i_2 = \frac{i_{pe12} + i_{ph23} + i_{ne12} + i_{nh23}}{4} = \frac{Q_2 + Q_0}{4T_q\phi} v_q + \frac{v_q}{R_0} + \frac{Q_2 - Q_0}{T_q} \quad (A.1)$$

As the current flowing near a pn junction is regarded as the diffusion current, the total current from or into the region 2 in Fig. 1 is transformed into :

$$i_1 - i_2 = 2 \cdot \frac{Q_1 - Q_2}{T_q} = \frac{Q_1 - Q_0}{4T_q\phi} v_q + \frac{Q_1 - Q_2}{T_q} - \frac{Q_2 - Q_0}{T_q}$$

$$\frac{Q_0}{4T_q\phi} v_q + \frac{Q_2 - Q_0}{T_q} = \frac{Q_1}{4T_q\phi} v_q - \frac{Q_1 - Q_2}{T_q}$$

$$\therefore i_2 = \frac{Q_2 + Q_1}{4T_q\phi} v_q + \frac{v_q}{R_0} - \frac{Q_1 - Q_2}{T_q} \quad (33)$$

From the addition of eqs. (3.9) and (3.10), eq (34) is derived.

$$\frac{d\left(\frac{N_{p2} + P_{n2}}{2}\right)}{dt} = \frac{i_{pe23} + i_{nh12}}{2} + \frac{i_{pe12} + i_{nh23}}{2} - \frac{\left(\frac{N_{p2} + P_{n2}}{2}\right)}{\tau_q} \quad (34)$$

$$\therefore \frac{dQ_2}{dt} = (i_1 - i_2) - \frac{Q_2}{\tau_q}$$

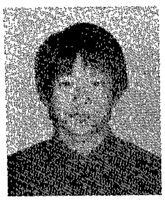
Similarly, eqs. (35)~(38) are transformed into follows.

$$Q_1 = \frac{N_{p3} + P_{n1}}{2} = Q_0\left[\exp\left(\frac{v_J}{\phi}\right) - 1\right] \quad (35)$$

$$v_d = 2v_s + v_p + v_n + v_J + R_s i_d = 2v_q + 3v_{JS} + R_s i_d \quad (36)$$

$$i_d = \frac{i_{pe23} + i_{nh12}}{2} + \frac{i_{ph23} + i_{ne12}}{2} + C_J \frac{dv_{JS}}{dt} = i_1 + i_2 + C_J \frac{dv_{JS}}{dt} \quad (37)$$

$$i_2 = \frac{i_{ne12} + i_{ph23}}{2} = I_q\left[\exp\left(\frac{2v_J}{\phi}\right) - 1\right] \quad (38)$$



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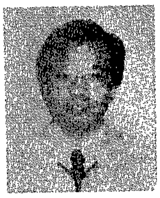

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