A TCAD Simulation Study for a New Technique to Calculate Carrier Recombination Lifetime Based on Open Circuit Voltage Decay Method

著者	Sasaki Shun, Mitsugi Noritomo, Samata Shuichi, Gollapudi Srikanth, Omura Ichiro
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A TCAD Simulation Study for a New Technique to Calculate Carrier Recombination Lifetime Based on Open Circuit Voltage Decay Method

Shun Sasaki[1,2]*, Noritomo Mitsugi[1], Shuichi Samata[1], Srikanth Gollapudi[2], and Ichiro Omura[2]

[1]*SUMCO Corporation, 1-2-1 Shibaura, Minato-ku, Tokyo 105-8634, Japan*
[2]*Kyushu Institute of Technology,2-4 Hibikino, Wakamatsu-ku, Kitakyushu-shi, 808-0196, Japan*
e-mail: sysasaki@sumcosi.com

Abstract

A new technique for calculation of correct carrier recombination lifetime in intrinsic layer of silicon PiN diode on the basis of the Open Circuit Voltage Decay method was invented. The new technique can remove the effects of carrier diffusion into p+ and n+ layer from intrinsic layer and carrier injection into intrinsic layer from depletion layer. The comparison of calculation results between the conventional and new technique by employing TCAD simulation indicated that the new technique can calculate more correct recombination lifetime value.

Introduction

The carrier recombination lifetime is an effective parameter to characterize the purity of semiconductor materials and devices. The Open Circuit Voltage Decay (OCVD) method evaluates the recombination lifetime in the intrinsic layer (i-layer) of PiN diodes. For this advantage, OCVD can be applied to evaluate recombination lifetime in epitaxial layer of silicon epitaxial wafer by employing the epitaxial layer as i-layer of PiN diode [1,2].

In the conventional technique of OCVD, the recombination lifetime values of high and low level injection (τ_{hl} and τ_{ll}) [3] are calculated from slope of voltage decay curve which is generated across anode and cathode of a PiN diode after carrier injection, by using equation (1) and (2) [1] :

$$\frac{1}{\tau_{hl}} = \frac{q}{2kT}\frac{dV}{dt}, \qquad (1)$$

$$\frac{1}{\tau_{ll}} = \frac{q}{kT}\frac{dV}{dt}, \qquad (2)$$

where, k, T, q, V, and t are Boltzmann constant, temperature, elementary charge, voltage across anode and cathode of a PiN diode, and time.

However, these equations do not consider the effect of carrier diffusion into p+ and n+ layer from the i-layer and carrier injection into the i-layer from depletion layer of p+ layer that occur during the carrier recombination in the i-layer. In practical, the voltage decay curve contains the effects of the carrier recombination, carrier diffusion, and carrier injection. Figure.1 shows schematic image of the carrier diffusion and injection during carrier recombination. Incidentally, the effect of the carrier diffusion and carrier injection to the voltage decay curve depend on thickness and dopant density of the p+, n+, and i-layer of the PiN diode. For example, the effect of the carrier diffusion and injection becomes strong in a PiN diode which has relatively thinner and lower dopant density of p+ layer. As a results of such effect, the slope of the voltage decay curve of the PiN diode changes in comparison with a PiN diode which has relatively thicker and higher dopant density of p+ layer. Therefore, calculation results of τ_{hl} and τ_{ll} by the conventional technique can not compare between two PiN diodes that have different thickness and dopant density of the p+, n+, and i-layer.

To solve this problem, we have invented a new technique for calculation of τ_{hl} and τ_{ll} which can remove the effects of carrier diffusion and carrier injection. In this study, we simulated the voltage decay curve of the OCVD by employing Technology Computer Aided Design (TCAD) to verify the validity of the new technique.

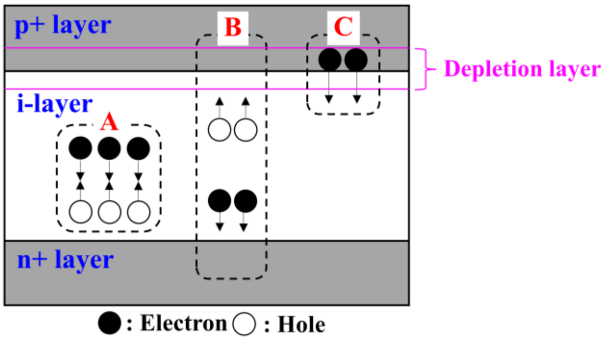

Fig. 1. The schematic image of the carrier diffusion and injection during recombination in i-layer of PiN diode. A: Carrier recombination. B: Carrier diffusion into p+ and n+ layer from i-layer. C: Carrier injection into i-layer from depletion layer.

Proposal of the new technique for calculation of recombination lifetime

In the new technique, recombination lifetime values of high and low level injection (τ_{hl} and τ_{ll}) [3] are calculated by following equation (3) and (4) :

$$\frac{1}{\tau_{hl}} = -\frac{q}{2kT}\frac{dV}{dt} - \left(\frac{D_p}{L_i N_{n+} L_{n+}} + \frac{D_n}{L_i N_{p+} L_{p+}}\right) n_{s-hl}, \qquad (3)$$

$$\frac{1}{\tau_{ll}} = -\frac{q}{kT}\frac{dV}{dt} - \left(\frac{D_p N_i}{L_i N_{n+} L_{n+}} + \frac{D_n N_i}{L_i N_{p+} L_{p+}}\right) + \frac{1}{n_{s-ll} q L_i}\frac{dQ}{dt}, \qquad (4)$$

where D_p, D_n, L_i, N_i, L_{n+}, N_{n+}, L_{p+}, N_{p+}, Q, $n_{s\text{-}hl}$, and $n_{s\text{-}ll}$, are hole diffusion coefficient, electron diffusion coefficient, i-layer thickness, dopant density of i-layer, n+ layer thickness, dopant density of n+ layer, p+ layer thickness, dopant density of p+ layer, area density of injected carrier from depletion region, injected carrier density in high level injection, and injected carrier density in low level injection.

On the right hand of above equations, Q, $n_{s\text{-}hl}$, and $n_{s\text{-}ll}$ can be calculated from ref 1 and 4. As other variables of the right hand of above equations, dV/dt, L_i, N_i, L_{n+}, N_{n+}, L_{p+}, N_{p+}, and T can be known from the voltage decay curve, PiN diode structure, and measurement condition.

TCAD simulation to verify the validity of the new technique

To verify the validity of the new technique, the voltage decay curves of two silicon PiN diodes that have different thickness and dopant densities of p+ layer were simulated by employing TCAD. Figure.2 shows schematic cross section of the two silicon PiN diodes structures (PiN diode A and B). The p+ layer of PiN diode A is relatively thinner and lower dopant density than PiN diode B. On the other hand, thicknesses and dopant densities of i-layer and n+ layer are same between PiN diode A and B. Table I shows assumed values of recombination lifetime in i-layer and temperature in the TCAD simulation. Here, τ_n and τ_p are the recombination lifetime of electron and hole [3]. Incidentally, τ_{hl} and τ_{ll} are approximated as $\tau_{hl} \approx \tau_n + \tau_p$ and $\tau_{ll} \approx \tau_p$ [3]. Thus, same recombination lifetime values of i-layer were assumed to the two PiN diodes in each condition and voltage decay curves were simulated.

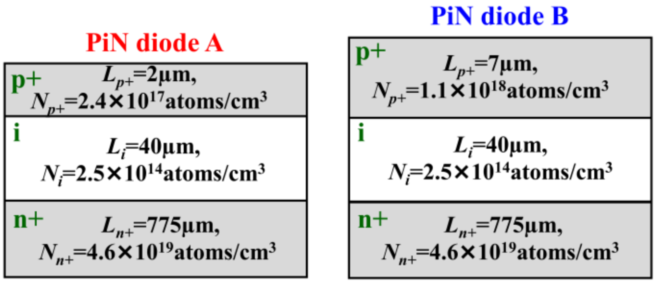

Fig.2. The schematic cross section of the two silicon PiN diodes for TCAD simulation.

Table 1. The recombination lifetime values of i-layer and temperature for the TCAD simulation.

Condition	Assumed recombination lifetime value of i-layer τ_n (μsec)	 τ_p (μsec)	Temperature (K)
1	55	20	300
2	75	25	300

Figure.3 (a) and (b) show the simulated the voltage decay curves of PiN diode A and B in condition 1 and 2. Apparently, PiN diode A which has relatively thinner and lower dopant density p+ layer shows faster voltage decay due to the effect of carrier diffusion and injection, in spite of same assumed i-layer recombination lifetime values. The *V'* which is the boundary of high and low level injection was determined as 0.45V from the change of the slope of voltage decay curves *dV/dt* (green dashed line).

The τ_{hl} and τ_{ll} were calculated from these voltage decay curves by employing the conventional and new technique. Finally, the calculated results of the conventional and new technique were compared to verify the validity of the new technique.

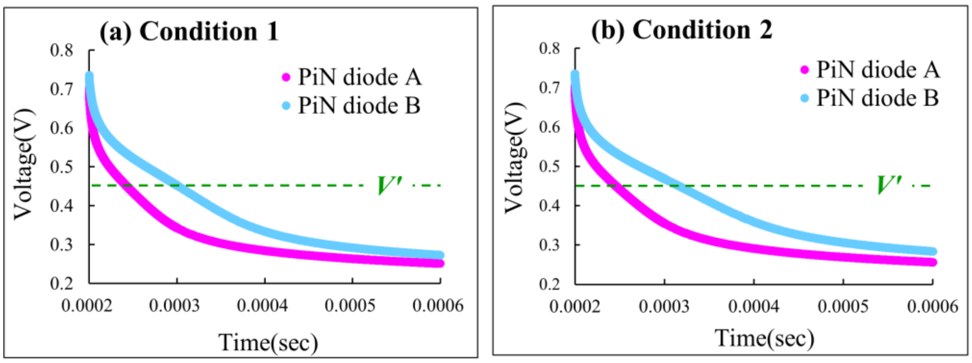

Fig.3. The simulation results of voltage decay curve of condition1 (a) and condition 2 (b) in the PiN diode A and B.

Recombination lifetime calculation and comparison between the conventional and new technique

In the conventional technique, values of *dV/dt* were estimated from slope of 0.475-0.45V and 0.45-0.425V in the voltage decay curves of PiN diode A and B, as 0.45V is the boundary of high and low level injection. The values of τ_{hl} and τ_{ll} by the conventional technique were calculated by substituting the estimated values of *dV/dt* into equation (1) and (2). Here, the slope of 0.475-0.45V was substituted into equation (1) and the slope of 0.45-0.425V was substituted into equation (2).

In the new technique, the values of *dV/dt* were estimated from same region of the voltage decay with the conventional technique. As mentioned above, the values of Q, $n_{s\text{-}hl}$, and $n_{s\text{-}ll}$ were calculated by employing the equations of ref 1 and 3. The values of L_i, N_i, L_{n+}, N_{n+}, L_{p+}, and N_{p+} were determined from the structures of PiN diode A and B. The values of τ_{hl} and τ_{ll} by the new technique were calculated by substituting the these values of into equation (3) and (4).

Figure.4 (a) and (b) are the comparison of the calculation results between conventional and new technique of τ_{hl} and τ_{ll} in condition 1 and 2. Although same assumed i-layer recombination lifetime values in each condition, the calculation results of the conventional technique are different between the two PiN diodes. This is due to difference of the effect of the carrier diffusion and injection. Thus, the conventional technique can not compare between two PiN diodes that have different thickness and dopant density of the p+, n+, and i-layer, as described in previous section. On the other hand, the calculation results of the new technique are mostly same between the two PiN diodes. This means that the new technique can calculate the correct recombination lifetime of i-layer by removing the effect of the carrier diffusion and injection. Accordingly, it was confirmed that the new technique can calculate more correct recombination lifetime value of i-layer.

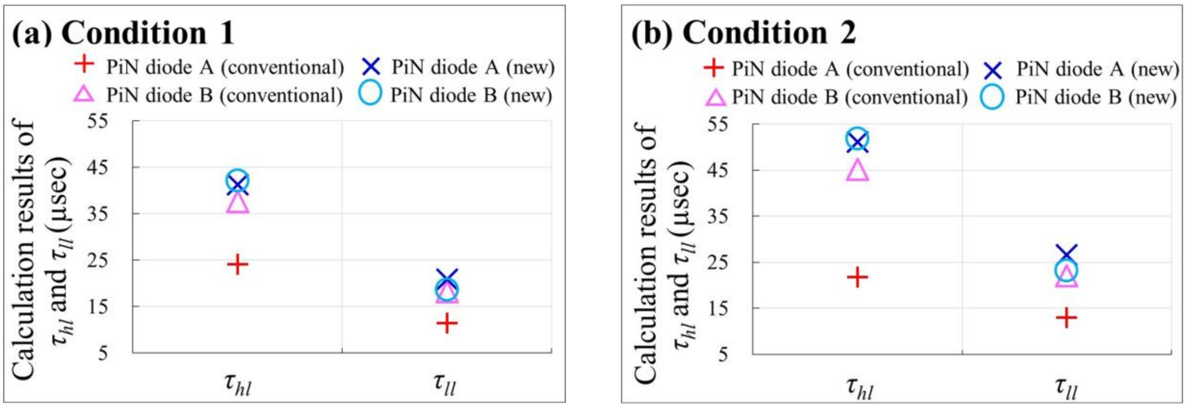

Fig.4. The calculation results of recombination lifetime by the conventional and new technique in condition 1 and 2.

Conclusions

A new technique to calculate the carrier recombination lifetime of i-layer of PiN diode on the basis of OCVD method was invented. This technique can calculate recombination lifetime value of i-layer by removing the effect of the carrier diffusion and carrier injection. To verify the validity of this technique, the voltage decay curves of PiN diodes that have same i-layer recombination lifetime and different p+ layer structure were simulated by TCAD. The calculation results of τ_{hl} and τ_{ll} by employing the new and conventional technique showed that the results of the new technique mostly same values of τ_{hl} and τ_{ll} in different p+ layer structures of PiN diodes. Therefore, it was confirmed that the new technique can calculate correct recombination lifetime of i-layer.

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