An accurate PC aided carrier lifetime determination technique from diode reverse recovery waveform

Ichiro Omura and Akio Nakagawa
Research and Development Center, Toshiba Corp.
1, Komukai Toshibacho, Saiwai-ku, Kawasaki 210, Japan
Phone: 044-549-2150, Fax. :044-520-1254

Abstract

A novel technique for determining carrier lifetime from reverse recovery waveform of diodes is presented in this paper. The features of this technique are that the accuracy is significantly improved and lifetime is automatically calculated on a personal computer from waveform data measured by a digital oscilloscope. The proposed technique suits the recent digitization of measurement equipments, and hence simplifies the measurement procedure and improves accuracy of the lifetime measurement.

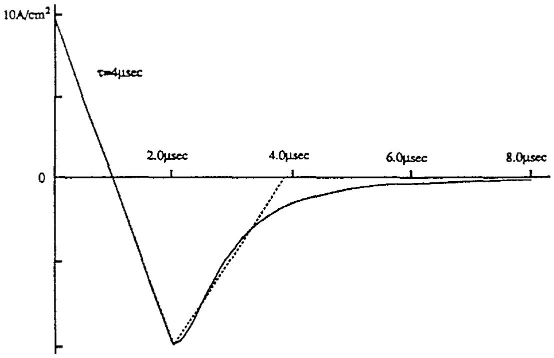

Fig. 1 Simulated diode reverse recovery waveform and a fitted ideal shape waveform (broken line) used for a conventional lifetime determination technique([2]). The determined lifetime is 30 % shorter than the given value.

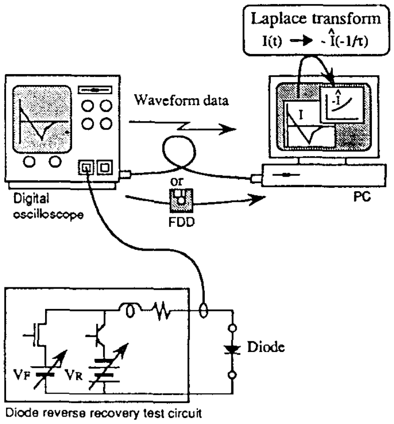

Fig. 2 Proposed lifetime measurement arrangement. Waveform data are transferred from an oscilloscope to a PC and it determines the lifetime automatically from any reverse recovery waveform.

1 Introduction

The diode reverse recovery technique has been widely used for determining high injection carrier lifetime of power semiconductor devices. In conventional techniques ([1]-[4] etc.), reverse recovery current waveform is assumed to have an ideal shape with linearly ramped current or constant reverse current. However, actual waveforms are different from the ideal shape, which results in large error. The estimated error for a simulated waveform shown in Fig. 1 is 30 % if the conventional technique([3]) is applied. Further, the determined lifetime depends on the choice of the approximated waveform (e.g. broken line in Fig. 1) fitted to the measured data. In this paper the authors propose an accurate lifetime determination technique which can be applied to reverse recovery waveform with arbitrary shape. Further, lifetime is automatically determined from waveforms using a personal computer (PC) as shown in Fig. 2 without any waveform fitting.

2 Principle of proposed method

The proposed lifetime determination technique from reverse recovery waveforms of p-i-n diodes is based on the charge control equation ([1],[3]).

$$\frac{dQ}{dt} = -\frac{Q}{\tau} + I(t). \qquad (1)$$

Where $Q(t)$, $I(t)$, and τ denote total charge of stored carrier in i-layer, diode reverse recovery current, and the high

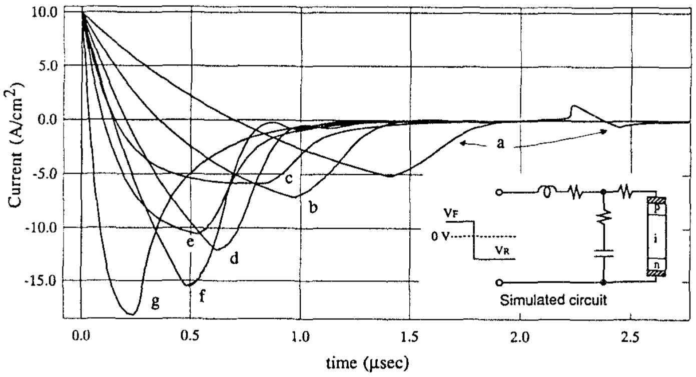

Fig. 3 Simulated reverse recovery waveforms of a p-i-n diode for $I_F = 10$ A/cm^2 for different test circuit conditions. Given carrier lifetime is 1 μsec.

injection carrier lifetime of i-layer ($= \tau_n + \tau_p$, τ_n, τ_p:electron and hole lifetime), respectively. In the equation, injection efficiency of n-emitter and p-emitter are assumed to be unity, i.e. minority carrier current in each emitter is negligible compared to the diode current, or carrier recombination in each emitter is negligible compared to recombination in i-layer. Solving Eq.(1) for sufficiently long time interval from $t = 0$ [sec] to t_1 [sec] with the initial condition for the charge $Q_{init} = \tau \cdot I_F$ at $t = 0$ [sec], we have the equation which determines the carrier lifetime from the diode reverse recovery current (see Appendix).

$$\tau \cdot I_F = -\int_{t=0}^{t_1} e^{\frac{t}{\tau}} \cdot I(t) dt. \qquad (2)$$

Where I_F is the initial forward bias current. The initial condition $Q_{init} = \tau \cdot I_F$ is given by the charge control equation with $\frac{dQ}{dt} = 0$. We can estimate the lifetime τ by directly executing the numerical integration of the right hand side of the equation. It should be noted in the proposed method that the lifetime is determined from any reverse recovery waveform, thus no fitting procedure of measured waveform to the idealized waveform shape is needed to obtain the lifetime.

The physical meaning of this equation can be explained as follows. In the reverse recovery of a diode, stored charge in the diode is removed by both recombination of the carriers and reverse flow of carriers back into the emitters due to the reverse recovery current. The amount of stored charge decreases due to carrier recombination with the rate of $e^{-\frac{t}{\tau}}$. And the charge of $I(t)\Delta t$ coulomb is removed by the reverse recovery current in a time segment Δt. Thus, the original amount of charge at $t = 0$ with respect to the removed charge in the time segment Δt can be expressed by $e^{\frac{t}{\tau}} I(t)\Delta t$. The sum of the original amount of charge for all time segments must equal the amount of the initially stored charge in the diode, which gives Eq(2).

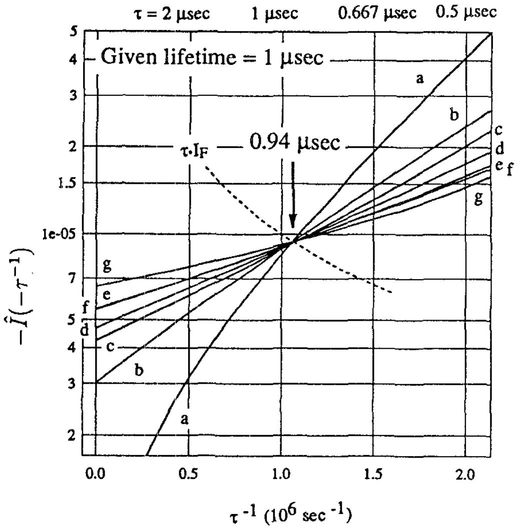

Fig. 4 The Laplace transforms $-\hat{I}(-\tau^{-1})$ for the simulated waveforms shown in Fig. 3 (solid lines) and $\tau \cdot I_F$ (broken line) as functions of τ^{-1}. Sufficiently accurate value of 0.94 μsec is determined for the given lifetime of 1 μsec.

The right hand side of Eq(2) is just the Laplace transform of the reverse recovery waveform $I(t)$, and thus the equation can be simply denoted by

$$\tau \cdot I_F = -\hat{I}(-\tau^{-1}). \qquad (3)$$

3 Verification of the technique by devise simulation

This technique has been verified by device simulations ([5]) for a p-i-n diode. In the simulation, physical models for doping- and electric-field-dependent mobility with velocity saturation, SRH recombination with doping-dependent lifetime, Auger recombination, and band-gap narrowing are included. The i-layer length of the simulated p-i-n diode is 50 μm and the impurity concentration of the i-layer is 1.0×10^{14} $/cm^3$. $1 \mu sec$ is given as the high injection carrier lifetime τ ($\tau_n = \tau_p = 0.5 \mu sec$).

Fig. 3 shows the waveforms for $I_F = 10$A/cm^2 for seven different test circuit conditions. According to Eq.(3), the carrier lifetime is determined as the value of τ at which the Laplace transforms of reverse recovery waveform and $\tau \cdot I_F$ coincide with each other. Fig. 4 shows the Laplace transforms $-\hat{I}(-\tau^{-1})$ for the simulated waveforms (solid line) and $\tau \cdot I_F$ (broken line) as functions of τ^{-1}. Each curve of $-\hat{I}(-\tau^{-1})$ for simulated reverse recovery waveforms and the curve of $\tau \cdot I_F$ cross at $\tau = 0.94$ μsec, when the assumed i-layer lifetime is 1 μsec. The error is only 6 %. Further, the lifetimes determined from the different waveforms exactly coincide with each other even when the waveform shape is much different from the ideal one. This shows that the present technique accurately determines lifetime from any reverse recovery waveform of a diode.

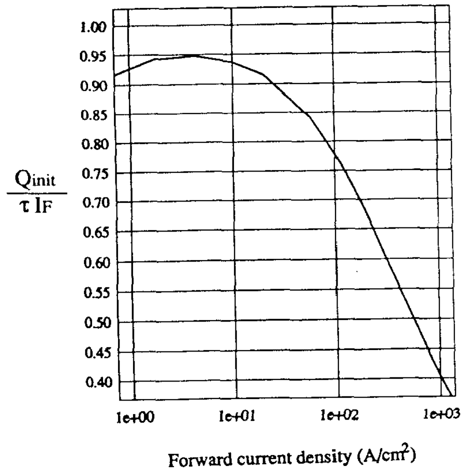

Fig. 5 The ratio of the amount of the initially stored charge Q_{init} in the forward bias condition obtained by device simulation to the assumed value $\tau \cdot I_F$ in the equation Eq(2).

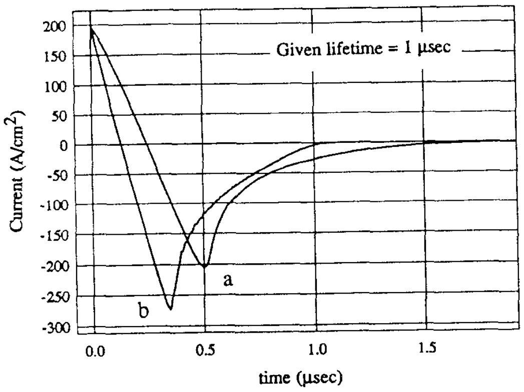

Fig. 6 Simulated two different reverse recovery waveforms at a high current density condition of $I_F = 200\ A/cm^2$.

4 Carrier lifetime determination from two different reverse recovery waveforms

Fig. 4 also suggests that lifetime can be determined as the value of τ at which the values of the Laplace transform $-\hat{I}(-\tau^{-1})$ of two different reverse recovery waveforms coincide with each other. In other words, the lifetime is determined from two different reverse recovery waveforms I_a and I_b by the following equation,

$$-\hat{I}_a(-\tau^{-1}) = -\hat{I}_b(-\tau^{-1}), \qquad (4)$$

without assuming the amount of initially stored charge Q_{init} equals $\tau \cdot I_F$. It is found that this technique is efficient for lifetime measurement under a high current density condition and for a diode with low injection efficiency emitter.

Under a high current density condition, carrier recombination in both emitters of a p-i-n diode can be intolerantly high, even though carrier recombination in both emitters is assumed to be negligible when carrier lifetime is determined from reverse recovery waveform. As a result, the determined carrier lifetime from the reverse recovery waveform can be much shorter than the actual i-layer carrier lifetime under a high current condition ([6]).

In the technique proposed in the previous sections, this problem should be also concerned. In the technique, the initially stored charge Q_{init} in the forward bias condition is assumed to be equal to $\tau \cdot I_F$ in Eq(2) and Eq(3). However, the amount of charge Q_{init} stored in a actual diode can be much less than the assumed value of $\tau \cdot I_F$ in a high current density condition because of carrier recombination in the both emitters. Fig. 5 shows the ratio of Q_{init} obtained by device simulation to the assumed value $\tau \cdot I_F$ for the p-i-n diode simulated in the previous section. Q_{init} is almost 100 % of the assumed value at the current density of $I_F = 10\ A/cm^2$, which result in small error. If the initial forward current is chosen to be $200\ A/cm^2$, Q_{init} is only 67.5 % of the assumed value. Thus, the assumption $Q_{init} = \tau \cdot I_F$ in Eq.(2) and Eq.(3) cannot be satisfied under a high current density condition.

However, sufficiently accurate value is determined from two different reverse recovery waveforms using Eq.(4) even under a high current density condition, which is verified by device simulations. The simulations are carried out at a forward current density of $I_F = 200\ A/cm^2$. The initially stored charge Q_{init} at $I_F = 200\ A/cm^2$ obtained by simulation is 1.35×10^{-4} $[coulomb/cm^2]$, which is 67.5 % of the assumed value $\tau \cdot I_F$ as shown in Fig. 5. Fig. 6 shows simulated two different reverse recovery waveforms for $I_F = 200\ A/cm^2$. Fig. 7 shows the Laplace transforms of the simulated waveforms (solid lines) as functions of τ^{-1}. Sufficiently accurate value of 0.85 μsec is determined from the two reverse recovery waveforms with Eq.(4) for the given lifetime of 1 μsec. While the determined lifetimes from the Laplace transform of individual reverse recovery waveform and $\tau \cdot I_F$ (broken line in Fig. 7) with Eq.(3) are 0.75 μsec and 0.73 μsec. It is found that the accuracy is improved if the carrier lifetime is determined from two different reverse recovery waveforms by Eq.(4) under a high current density condition.

The technique is also applicable to diodes with low injection efficiency emitters. The low injection efficiency emitters reduces the stored charge in the diode, thus enhancing soft recovery and reducing reverse recovery charge Q_{RR}. However, the reduction of stored charge causes large error in the carrier lifetime determination from reverse recovery waveform. It is found from device simulations that the accuracy is efficiently improved if the carrier lifetime is determined from two different reverse recovery waveform using Eq.(4) for diodes with low injection efficiency emitters.

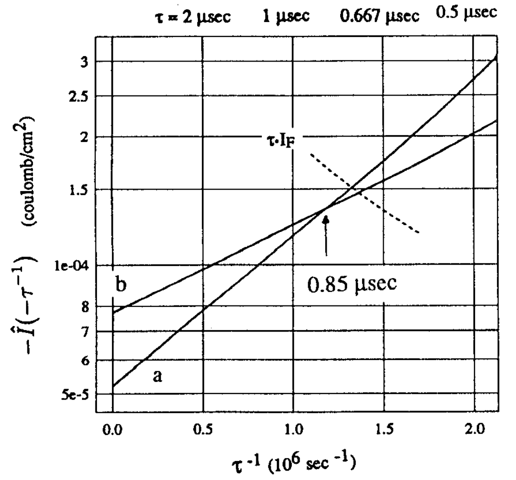

Fig. 7 The Laplace transforms of the simulated waveforms shown in Fig. 6 (solid lines) and $\tau \cdot I_F$ (broken line) as functions of τ^{-1} at the forward current density of $I_F = 200\ A/cm^2$. Sufficiently accurate value of 0.85 *μsec* is determined by the two reverse recovery waveforms for the given lifetime of 1 *μsec*.

Simulations are carried out for a diode with a p^- emitter. Ohmic contact is assumed at the interface of p^- emitter and electrode in the simulation. Fig. 8 shows the ratio of the initially stored charge Q_{init} in the forward bias condition obtained by the simulation to the assumed value of $\tau \cdot I_F$ for the diode. Reverse recovery simulations are carried out for $I_F = 10\ A/cm^2$. The initially stored charge is 2.6×10^{-6} [$coulomb/cm^2$], which is only 26 % of the assumed value $\tau \cdot I_F$. Fig. 9 shows simulated reverse recovery waveforms. Fig. 10 shows the Laplace transforms of the simulated waveforms (solid line) as functions of τ^{-1}. The determined lifetime from the two different waveforms is 0.74 *μsec* for the given life time of 1 *μsec*. While the determined lifetimes from the Laplace transform of individual reverse recovery waveform and $\tau \cdot I_F$ (broken line in Fig. 10) with Eq.(3) are 0.37 *μsec* and 0.34 *μsec*. This shows that the carrier lifetime is accurately determined from two different waveforms even for a diode with a low injection efficiency emitter.

5 Experiment

The proposed technique is applied to experimental waveforms. The measurement arrangement shown in Fig. 2 is used for the experiment. Waveform data are transferred from an oscilloscope to a PC and it calculates the Laplace transform of the waveform. Fig. 11 shows the waveforms for initial forward currents of I_F = 100 mA and 1 A. Fig. 12 shows the corresponding Laplace transforms $-\hat{I}(-\tau^{-1})$ for each waveform. The lifetime is successfully determined to be 390 nsec.

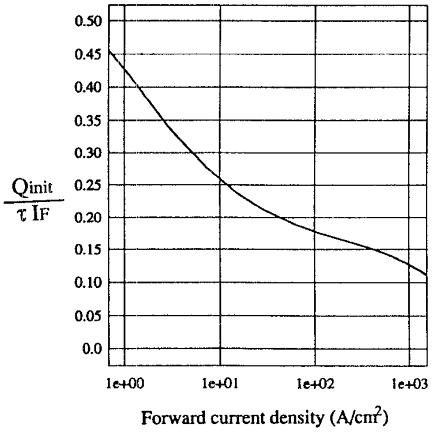

Fig. 8 The ratio of the amount of the initially stored charge Q_{init} for the diode with lightly doped p-emitter obtained by the device simulation to the assumed value of $\tau \cdot I_F$ in the equation Eq(2).

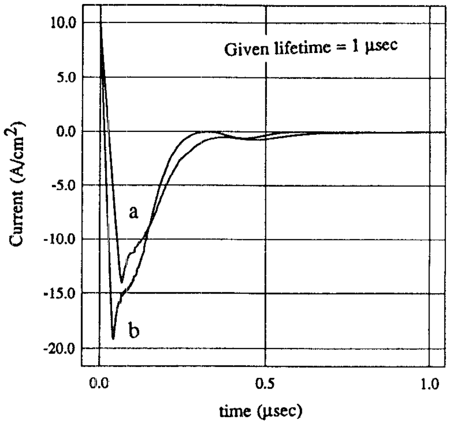

Fig. 9 Simulated two different reverse recovery waveforms for the diode with lightly doped p-emitter.

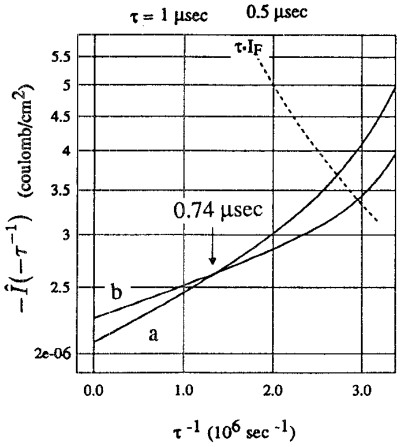

Fig. 10 The Laplace transforms of the simulated waveforms shown in Fig. 9 (solid line) and $\tau \cdot I_F$ (broken line) as functions of τ^{-1}. The determined lifetime from the two different waveforms is 0.74 *μsec* for the given life time of 1 *μsec*.

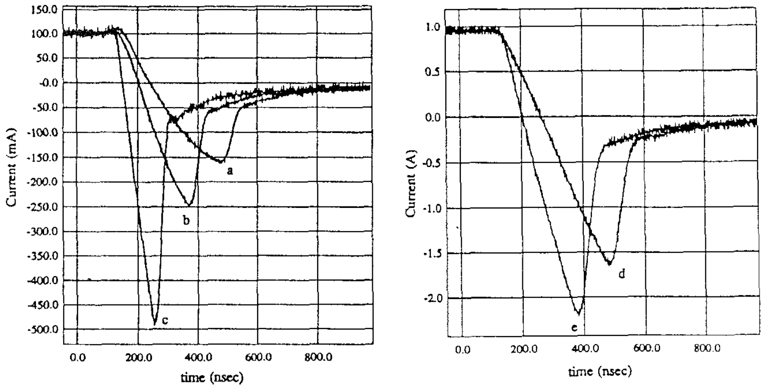

Fig. 11 Experimentally obtained reverse recovery waveforms for $I_F = 100$ mA and 1 A.

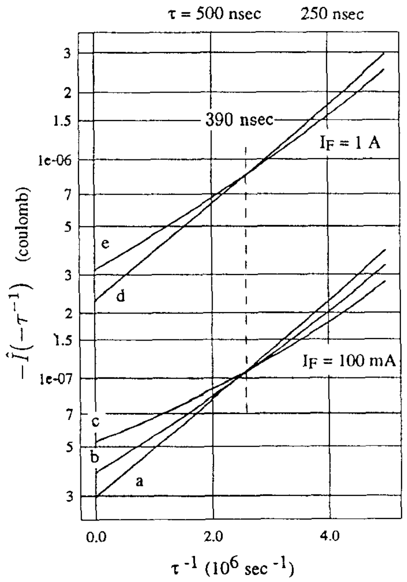

Fig. 12 The Laplace transforms $-\hat{I}(-\tau^{-1})$ for the experimentally obtained waveforms shown in Fig. 11. The lifetime is determined to be 390 nsec.

6 Conclusion

A novel technique for determining carrier lifetime from reverse recovery waveform of diodes is proposed. The features of this technique are that the accuracy is significantly improved and lifetime is automatically calculated on a personal computer from waveform data measured by a digital oscilloscope.

bibliography

[1] Y. C. Kao et al., IEEE Trans. Electron Devices, Vol. ED-17, No. 9, pp. 652-657, 1970.

[2] F. Berz, Solid State Elec., Vol. 23, pp. 783-792, 1980.

[3] K. Mayaram et al., IEDM'88 Tech. Digest, pp. 622-625, 1988.

[4] A. Yahata et al., Proc. of ISPSD'91, pp. 171-175, 1991.

[5] I. Omura et al., Proc. of 1991 International Workshop on VLSI Process and Device Modeling (1991 VPAD), pp. 126-127, 1991.

[6] H. Schlangenotto et al., Solid State Elec., Vol. 15, pp. 393-402, 1972.

Appendix

The charge control equation,

$$\frac{dQ}{dt} = -\frac{Q}{\tau} + I(t). \qquad (5)$$

is given by the volume integral of the current continuity equation of semiconductor

$$q \cdot \frac{dn}{dt} = divJ_n - q \cdot \frac{n}{\tau}$$

over the entire i-layer region of a diode. Where $Q(t)$, $I(t)$, and τ denote total charge due to stored carrier in i-layer, diode reverse recovery current, and the carrier lifetime, respectively. In the integration, injection efficiency of n-emitter and p-emitter are assumed to be unity. Solving Eq.(5) for time interval from $t = 0$ to t_1, the charge at $t = t_1$ is given by,

$$Q(t_1) = e^{-\frac{t_1}{\tau}} \left(\int_{t=0}^{t_1} e^{\frac{t}{\tau}} \cdot I(t)dt + Q_{init} \right).$$

Where Q_{init} is the initially stored charge in the diode. Choosing t_1 sufficiently long so that $Q(t_1) = 0[coulomb]$ is satisfied, we have,

$$Q_{init} = -\int_{t=0}^{t_1} e^{\frac{t}{\tau}} \cdot I(t)dt.$$

Since froward current I_F is initially constant, the relation

$$Q_{init} = \tau \cdot I_F$$

is given by Eq(5) with the condition of $\frac{dQ}{dt} = 0$. Then, the equation is rewritten as,

$$\tau \cdot I_F = -\int_{t=0}^{t_1} e^{\frac{t}{\tau}} \cdot I(t)dt.$$

Where I_F is the initial forward bias current.