Measurement Time Reduction for Generation Lifetimes

Sang-Yun Lee, *Member, IEEE* and Dieter K. Schroder, *Fellow, IEEE*

***Abstract*—The defect properties of thin semiconductor layers (epitaxial and denuded zones as well as silicon on insulator) are not as easily characterized as those of bulk wafers. Recombination lifetime or diffusion length measurements, routinely used for bulk wafers, are unreliable when the layer thickness is significantly less than the diffusion length. Generation lifetime measurements are eminently suitable for such characterization because the characterized thickness of the sample is determined by the space-charge region width. However, the measurement times become inordinately long for high quality layers when pulsed MOS capacitors are used as test structures. Times of hundreds or even thousands of seconds per measurement are not uncommon. We present two methods to reduce this measurement time: optical excitation and elevated temperature. Optical excitation can only be used if the light is pulsed and the lifetime is measured from the remaining "dark" curve. Steady-state light leads to erroneous lifetimes and should not be used. Elevated temperature measurements lead to temperature-varying lifetimes, because the generation lifetime may be temperature dependent.**

***Index Terms*—Charge carrier lifetime, MOS capacitors.**

I. INTRODUCTION

EPITAXIAL (epi) wafers and wafers containing denuded zones are routinely used in the semiconductor industry. The quality of these regions is high because there is little metallic contamination and few oxide precipitates. Consequently, the carrier lifetime is very high in such layers. While this is an advantage for device performance, i.e., low junction leakage current and high oxide integrity, it makes the characterization of such layers difficult. The layers thicknesses are typically around 2–20 μm, but the minority carrier diffusion length is hundreds of microns. For epitaxial wafers, the epi layer is usually grown on a heavily-doped substrate, e.g., p-epi on p^+ substrate. Denuded zones contain low oxygen densities while the substrate with its higher oxygen density contains numerous oxide precipitates. In either case, the minority carrier diffusion length or recombination lifetime are high in the thin (epi or denuded) layer and low in the substrate. Hence, it is difficult or impossible to determine recombination lifetime or diffusion length. Similar considerations hold for silicon on insulator samples, where the active Si layer is very thin compared to the diffusion length.

Generation lifetime (τ_g) measurements, however, are suitable for these materials because they characterize the sample in the space-charge region (scr) whose width is typically on the order of a micron or so. Furthermore, the scr width is determined by an applied voltage which is under the control of the operator. Hence, generation lifetime measurements are well suited for the characterization of such thin layers. The problem with τ_g measurements of high quality layers is the long measurement time, making tg mapping of wafers not very practical. We present here several approaches to reduce the measurement time, yet maintain accurate generation lifetime extraction. We confine the discussion to generation lifetime measurements of pulsed MOS capacitor (MOS-C).

II. PROBLEM AND BACKGROUND

One problem with generation lifetime measurements is the long transient or measurement time. When a MOS-C is pulsed from accumulation to deep depletion, the time required for the capacitance to reach inversion from the initial deep depletion state is called the transient time t_f. When a semiconductor device, e.g., pn junction or MOS capacitor, is reverse biased in the dark, electron-hole pairs are thermally generated with the generation rate [1]

$$G = \frac{n_i}{\tau_g} \tag{1}$$

where n_i is the intrinsic carrier density. The t_f of a pulsed MOS-C, after being pulsed into deep depletion, is [2]

$$t_f \approx 10\frac{N_A}{n_i}\tau_g \tag{2}$$

where N_A is the substrate doping concentration. Hence, for $N_A = 5 \times 10^{15}$ cm^{-3}, $n_i = 10^{10}$ cm^{-3} (Si at room temperature [3]), and $\tau_g = 5 \times 10^{-4}$ s, we find $t_f = 2500$ s. For higher lifetimes, the transient times get even longer. Just measuring ten devices per wafer would take almost 7 h.

Because of unacceptably long measurement times, generation lifetime measurements are not easily amenable to whole wafer mapping. Many attempts have been made to reduce the measurement times. However, it has been difficult to achieve both accuracy and reasonable measurement time. Moreover, we need predictable constant measuring time, such as fixed 10 or 30 s, no matter how long t_f is. We divide previous attempts into three categories; classic capacitance versus time (C-t), voltage pulse or sweep, and external excitation. There

---

Manuscript received September 15, 1998; revised December 17, 1998. This work was supported by Komatsu Electronic Metals, MEMC Electronic Materials, Mitsubishi Silicon, SEH America, Nippon Steel, Sumitomo Sitix Silicon, and Wacker Siltronic Corporation through the Wafer Engineering and Defect Science Consortium. The review of this paper was arranged by Editor J. N. Hollenhorst.

S.-Y. Lee is with the Motorola, Advanced eDRAM Center, Motorola, SPS, Tempe, AZ 85284 USA.

D. K. Schroder is with the Center for Solid State Electronics Research and the Department of Electrical Engineering, Arizona State University, Tempe, AZ 85287-5706 USA.

Publisher Item Identifier S 0018-9383(99)03517-0.

are several different approaches for classic C-t measurements. Heiman [4] used one point of a dC/dt plot. Rabbani [5] introduced the $\ln(W) - t$, where W is the scr width, and Yue [6] improved on Rabbani's method. Radzimski *et al.* [7] proposed the C_{ox}/C versus t method. As an alternate approach, the voltage sweep capacitance–voltage (C–V) method became popular in late 1980's. Taniguchi proposed the triangular voltage sweep C–V method [8] and Peykov *et al.* improved on this [9]. Zhang proposed a fast linear voltage sweep C–V technique [10]. Keller introduced the pulsed voltage method [11]. However, none of these methods can provide reasonable measurement time reduction and accuracy at the same time. Our goal is to measure generation lifetime always less than 30 s with virtually no error compared to the conventional generation lifetime measurement method.

To reduce t_f, external excitation methods are best, such as elevated temperature [12] or illumination [13], [14] We address both issues in this paper and point out some of the pitfalls to be recognized in the measurement.

The thermal electron-hole pair generation rate G is given by [2]

$$G = \frac{qn_i(W - W_f)}{\tau_g} + \frac{2qn_i s_g(W - W_f)}{r} + qn_i s_{\mathrm{eff}} \quad (3)$$

where

q	magnitude of electron charge;
W_f	final scr width;
s_g	surface generation velocity;
r	circular gate (disc type) radius;
s_{eff}	effective surface generation velocity.

In (3), the first term accounts for generation in the scr bulk, the second term represents surface generation in the lateral scr, and the third term accounts for scr width independent generation components of surface generation under the gate and quasi-neutral region generation. The quasi-neutral region is defined as the width from the end of the scr to the substrate contact. In (3), we simply assume that the generation width W_g is $W - W_f$. It is well known that this assumption underestimates the real W_g [15], [16]. However, since (3) is simple, it is widely accepted and we use (3) for our generation lifetime analysis. If a more accurate generation width analysis is required, we recommand [15] and [16].

Since, practically, it is difficult to determine the τ_g and s_g separately, (3) can be written as

$$G = \frac{qn_i(W - W_f)}{\tau_{g,\mathrm{eff}}} + qn_i s_{\mathrm{eff}} \quad (4)$$

where

$$\tau_{g,\mathrm{eff}} = \frac{\tau_g}{1 + 2s_g\tau_g/r}. \quad (5)$$

Pulsed MOS capacitor measurements yield the effective generation lifetime $\tau_{g,\mathrm{eff}}$ and the effective surface generation velocity s_{eff}. The generation components and their location are illustrated in Fig. 1.

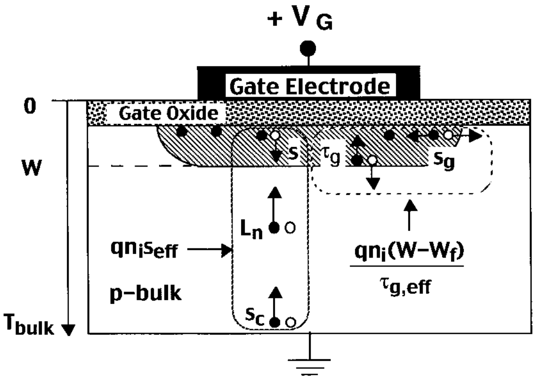


Fig. 1. Generation components and their location in the pulsed MOS-C, where L_n is the minority carrier diffusion length in p-type semiconductor.

III. Results and Discussion

A. Steady-State Light Method

As long as light is incident on the device, optical generation reduces the transient time duration and the measurement time. However, the light itself can influence the generation lifetime measurement. Consider the case with the light incident on the device during the lifetime measurement, which is defined as the steady-state light method in our work. Furthermore, let the light create electron-hole pairs in the space-charge region and in the quasi-neutral bulk. Light, represented by its photon flux density Φ (photons/cm^2·s), adds a component to each of the three generation terms in (3) as

$$G = q(W - W_f)\left(\frac{n_i}{\tau_g} + C_1\Phi\right) + \frac{2q(W - W_f)(n_i s_g + C_2\Phi)}{r} + q(n_i s_{\mathrm{eff}} + C_3\Phi) \quad (6)$$

where the constants C_1, C_2, and C_3 depend on the reflection and absorption coefficients, the diffusion length, etc. Because these constants depend on many unknown parameters, it is difficult to extract exact value of these constants. The effective generation lifetime of (5) and s$_{\mathrm{eff}}$ of (4) become

$$\tau_{g,\mathrm{eff}} \to \frac{\tau_g}{(1 + K_1\Phi\tau_g)(1 + 2(s_g + K_2\Phi)\tau_g/r)}; \qquad s_{\mathrm{eff}} \to s_{\mathrm{eff}} + K_3\Phi \quad (7)$$

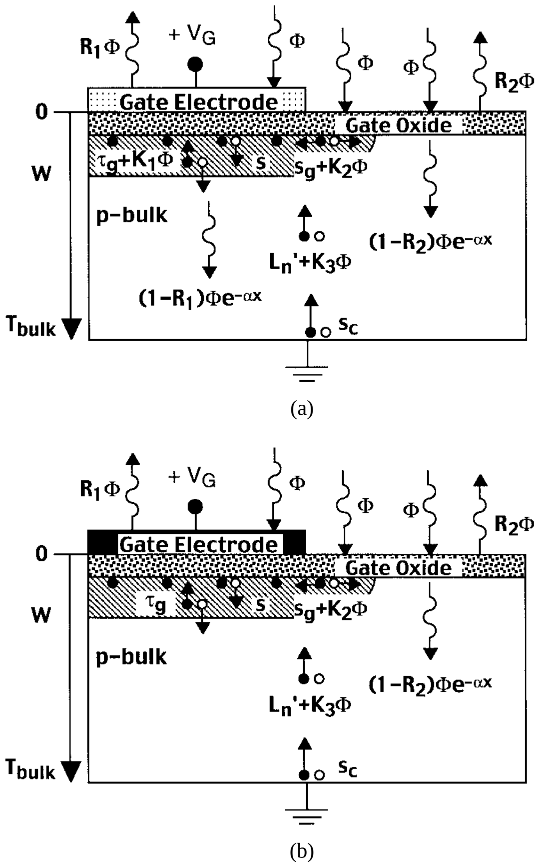
where $K_1 = C_1/n_i, K_2 = C_2/n_i$, and $K_3 = C_3/n_i$. Equation (7) shows clearly that $\tau_{g,\mathrm{eff}}$ will be in error, because $\tau_{g,\mathrm{eff}}$ depends on the photon flux density and constants K_1 and K_2.

Frequently, pulsed MOS-C measurements are made for process simplicity with devices containing opaque gates, e.g., evaporated Al gates. In that case, $t_{g,\mathrm{eff}}$ becomes

$$\tau_{g,\mathrm{eff}} \to \frac{\tau_g}{1 + 2(s_g + K_2\Phi)\tau_g/r} \quad (8)$$

which is still photon flux density dependent. Electron-hole pair generation in transparent and opaque gate devices is illustrated in Fig. 2.

In the steady-state light method, as the light intensity increases, t_f decreases drastically as shown in Fig. 3. However, according to (8), as we increase the light intensity, the measured $\tau_{g,\mathrm{eff}}$ decreases. We illustrate this effect in Fig. 4, where (8) is plotted together with measured lifetime data. In



(a)

(b)

Fig. 2. Optical excitation with light in the pulsed MOS capacitors: (a) with transparent gate and (b) with opaque gate. R_1 and R_2 represent different optical reflection coefficients for the gate and oxide, respectively.

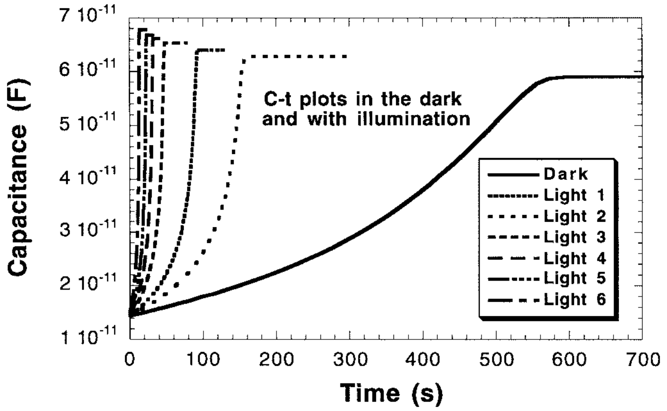


Fig. 3. Measured C-t plots in the dark and with steady-state light. "Light" refers to intensity, with "2" > "1," etc. The gate electrode is circular (disc type) with $r = 500$ μm and gate oxide thickness is 1000 Å. Substrate is n-type with $N_D = 2.5 \times 10^{15}$ cm^{-3}. This sample is used in all of our experiments unless otherwise specified.

contrast to [13] and [14], it is quite obvious that very erroneous lifetimes are obtained even with low-level light in the steady-state light method. Clearly, the steady-state light method cannot be used to reduce the pulsed MOS-C measurement time and to extract the correct $\tau_{g,\text{eff}}$.

B. Pulsed Light Method

A solution to this problem with the steady-state light method is to pulse the light during the initial C-t measurement in order to reduce the measurement time, then extract the lifetime from the remaining dark portion of the C-t transient. With the lifetime determined from the "dark" C-t curve, the correct lifetime will be obtained. We illustrate this in Fig. 5, where we show the complete dark C-t curve and dark curves after initial light pulses. The longer or the more intense the light pulse, the shorter will be the subsequent dark decay. Hence, we have achieved the goal of reducing the measurement time, yet maintained the correct C-t data. This is further illustrated in Fig. 6, where the C-t curves of Fig. 5 are shifted along the time axis to coincide with the dark curve. The coincidence is excellent as expected.

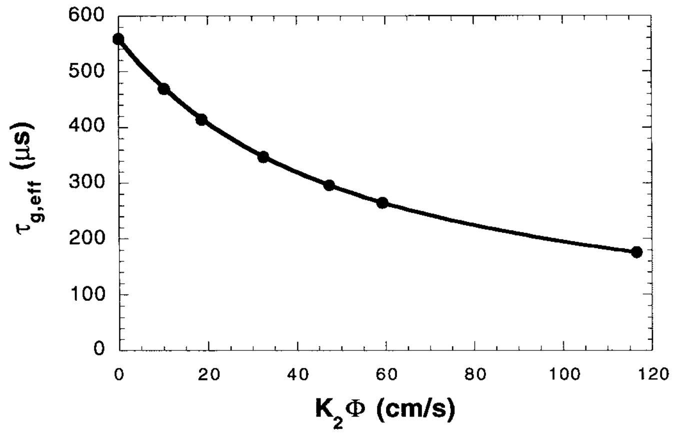


Fig. 4. $\tau_{g,\text{eff}}$ as a function of photon flux density; $K_2\Phi$ is experimentally extracted from the measured data using (8). The line is calculated according to (8) and points are experimental data. $T = 277$ K.

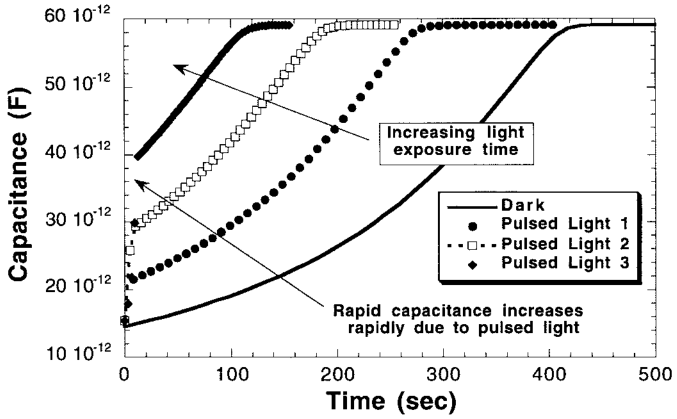


Fig. 5. C-t curves with varying light exposure time with same light intensity during the initial part of the transient. A green light emitting diode was used for the light source. "Pulsed Light" refers to light exposure time with same intensity, with "2" > "1," etc.

To prove that the correct lifetime is obtained, we show in Fig. 7 the Zerbst plot of the dark C-t curve and superimpose on it the portions of the Zerbst plot obtained from the pulsed light curves. The data coincide very well. This technique has the additional advantage that when the "dark" C-t data are taken, the surface is heavily inverted and surface generation is effectively suppressed.

We check how fast we can measure the generation lifetime with the pulsed light method in Figs. 8 and 9. The total C-t measurement time is set to 30 s as shown in Fig. 8. The light-

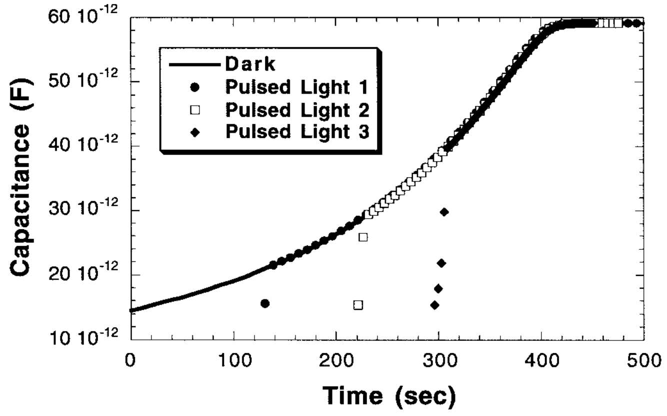


Fig. 6. The pulsed C-t curves shown in Fig. 5 are shifted along the time axis to coincide with the dark curve.

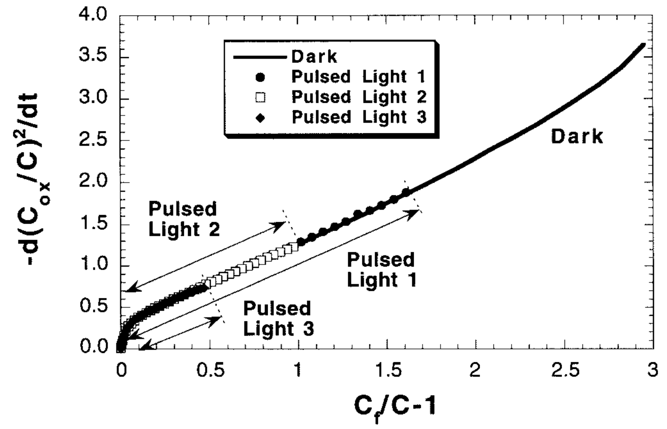


Fig. 7. Zerbst plots showing the dark curve and portions of the pulsed curves.

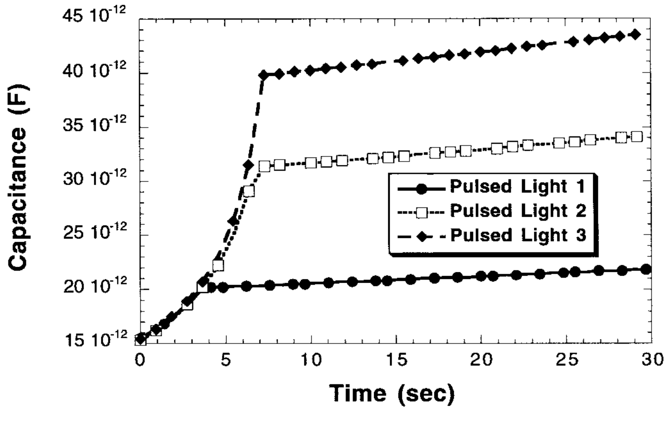


Fig. 8. C-t curves with the pulsed light method. The measurement time is set to 30 s.

on time is about 4–7 s and then the sample remains in the dark. The measured data are compared to the dark Zerbst curve in Fig. 9. Even with 30 s measuring time, it shows excellent agreement with the data in the dark. We may reduce the measurement time to less than 10 s, no matter how long t_f is in drak.

In our experiment, a light emitting diode (LED) was used for the pulsed light measurements because the LED has fast on/off time compared to incandescent bulbs. We also tested the pulsed light method with different wavelengths and with different light intensities. There was no difference with light intensity and with wavelengths. We varied the wavelength over the range 0.4 μm $< l <$ 0.8 μm using a monochromator. The energies with 0.4 and 0.8 μm wavelength are about 4.1 and 1.55 eV, respectively. Since these energies are higher than the silicon energy bandgap, 1.12 eV, there is no problem with electron-hole pair generation by optical excitation.

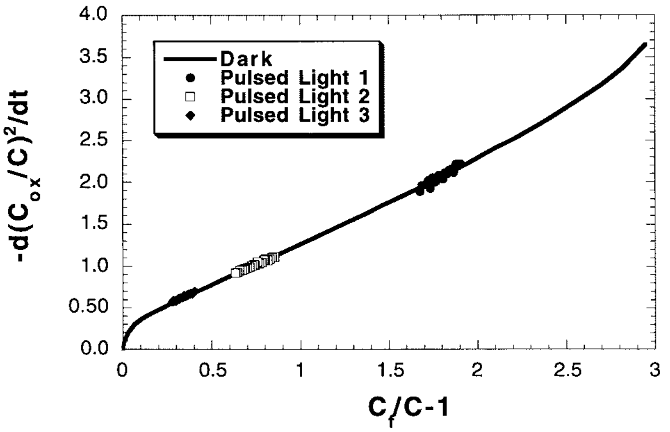


Fig. 9. Zerbst plots using the pulsed light method and in the dark for the C-t data in Fig. 8.

One concern with different wavelengths and intensities is the generation of excess carriers in the quasi-neutral region. The volume generation rate $G(x)$ of electron-hole pairs is given by [17]

$$G(x) = (1 - R)\Phi\alpha e^{-\alpha x} \tag{9}$$

where x is the depth from the surface and a the optical absorption coefficient. The excess carriers depend on the wavelength and intensity. However, these excess carriers recombine in a short time. How short? From (10) [18], we find for $\sigma = 10^{-15}$ cm^2, $v_{\mathrm{th}} = 10^7$ cm/s and $N_T = 10^{12}$ cm$^{-3}, \tau_r$ is 100 μs. It is too short to be measured in the pulsed MOS capacitor.

$$\tau_n = \frac{1}{\sigma_n v_{\mathrm{th}} N_T}; \tau_p = \frac{1}{\sigma_p v_{\mathrm{th}} N_T} \tag{10}$$

where σ_n and σ_p are the electron and hole capture cross sections, respectively, v_{th} is the carrier thermal velocity equal to $\sqrt{3kT/m^*}, m^*$ the conductivity effect mass, and N_T the trap density.

C. Thermal Excitation

The basic idea of thermal excitation in order to reduce t_f is simple. Equation (3) shows enhanced generation rates for increased temperatures, because n_i is strongly temperature dependent so is the generation rate. Since thermal generation does not introduce an additional generation rate the way steady-state optical generation does, it appears to be suitable for C-t measurement time reduction without introducing extraneous terms into the equations. For example, the transient time t_f derived from C-t curves is shown in Fig. 10 as a function of temperature for two different devices. Note the significant time reduction by a factor of about 100 in this case.

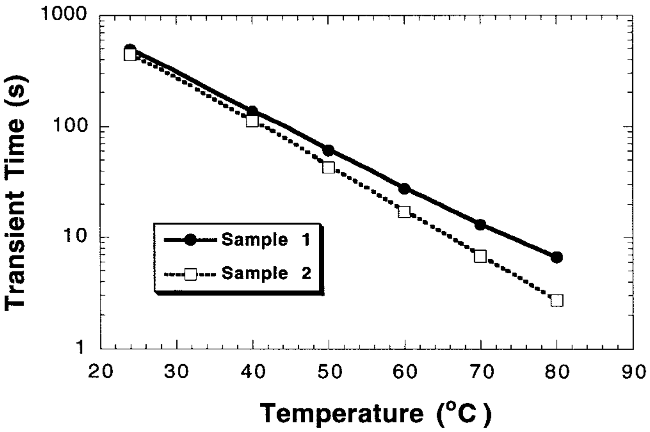


Fig. 10. Transient time t_f as a function of temperature. Squares: n-type wafer, which is the same as mentioned in Fig. 3; circles: p-type wafer, $N_A = 1.2 \times 10^{15}$ cm^{-3} oxide thickness is 360 Å.

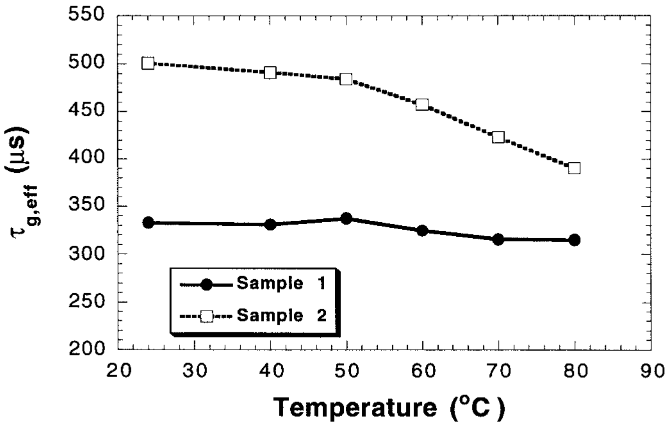


Fig. 11. Generation lifetime as a function of a measurement temperature. Circles and squares are the same as mentioned in Fig. 10.

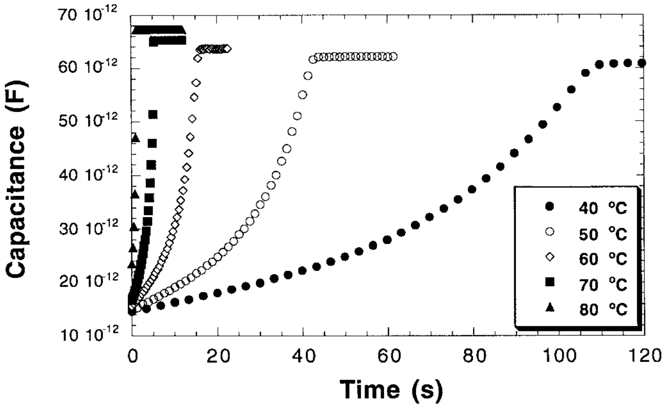


Fig. 12. C-t curves at different temperatures. The n-type sample measured in this figure is the same as used in Figs. 10 and 11.

However, using temperature as a measurement time reducer does present the following potential problem. The generation lifetime is given by the expression

$$\tau_g = \tau_p e^{(E_T - E_i)/kT} + \tau_n e^{-(E_T - E_i)/kT} \tag{11}$$

which is clearly temperature dependent. Furthermore, the temperature dependence is not unique, because it depends on $(E_T - E_i)$ and is likely to vary from sample to sample as $(E_T - E_i)$ varies. Even for $E_T = E_i$, the temperature variation will be that of the two minority carrier lifetimes τ_p and τ_n as shown in (10).

We show the two examples of Fig. 10 in Fig. 11. The lifetime is reasonably constant in one case, but decreases significantly in the other case. In general, then, it is not prudent to use temperature to reduce t_f and extract $\tau_{g,\mathrm{eff}}$ at an elevated temperature. Nor is it proper to compare high temperature $\tau_{g,\mathrm{eff}}$ from different samples because each lifetime may have a different temperature behavior. Moreover, s_g is also a function of temperature as shown in (12) [2] and s_g affects $\tau_{g,\mathrm{eff}}$ as shown in (5)

$$s_g = \frac{s_n s_p}{s_n \exp[(E_T - E_i)/kT] + s_p \exp[-(E_T - E_i)/kT]} \tag{12}$$

where $s_n = \sigma_{\mathrm{ns}} v_{\mathrm{th}} N_{\mathrm{it}}, s_p = \sigma_{\mathrm{ps}} v_{\mathrm{th}} N_{\mathrm{it}}$, and N_{it} is the interface trap density. σ_{ns} and σ_{ps} are the electron and hole capture cross sections at the surface, respectively.

It is, of course, possible to measure the generation lifetime over some temperature range and extrapolate to room temperature. However, we hoped to make a single elevated temperature measurement. That approach makes it impossible, in general, to say anything about the room temperature value.

A further complication with elevated temperature measurements, is the calibration from the quasi-neutral region. As illustrated in Fig. 1, space-charge region generation is characterized by the generation lifetime and quasi-neutral region generation by the diffusion length. To see which component dominates, we will use simply first order concepts. The MOS capacitor is discharged by the space-charge region current I_{scr} and the quasi-neutral region current I_{qnr} given by

$$I_{\mathrm{scr}} = \frac{qAn_iW}{\tau_g}; \quad I_{\mathrm{qnr}} = q\frac{An_i^2\sqrt{D_n}}{N_A\sqrt{\tau_r}} \tag{13}$$

where A is the device area and D_n the minority carrier diffusion constant in p-type semiconductor. Equating these two leads to

$$n_i = \frac{N_A W \sqrt{\tau_r}}{\tau_g \sqrt{D_n}}. \tag{14}$$

Using $N_A = 10^{15}$ cm^{-3}, $W = 10^{-4}$ cm, $\tau_r = 100$ μs, $\tau_g = 1$ ms, and $D_n = 30$ cm^2/s leads to $n_i = 1.8 \times 10^{11}$ cm^{-3} or $T \sim 65$ °C.

For these parameters, measurements below 65 °C are dominated by space-charge region generation and above by quasi-neutral generation. With advancing fabrication requiring less metallic contaminants, the lifetime increase. Since both τ_r and τ_g depend inversely on the defect density N_T ,both increase and ratio $\sqrt{\tau_r}/\tau_g$ decreases. Hence the demarcation temperature will decrease. For example, for $\tau_r = 1$ ms and $\tau_g = 10$ ms, we find $n_i \sim 6 \times 10^{10}$ cm^{-3} and $T = 50$ °C. These consideration point out the difficulties of elevated temperature measurement data interpretation.

Sampled C-t and Zerbst plots, which are measured with thermal excitation are shown in Figs. 12 and 13 for references.

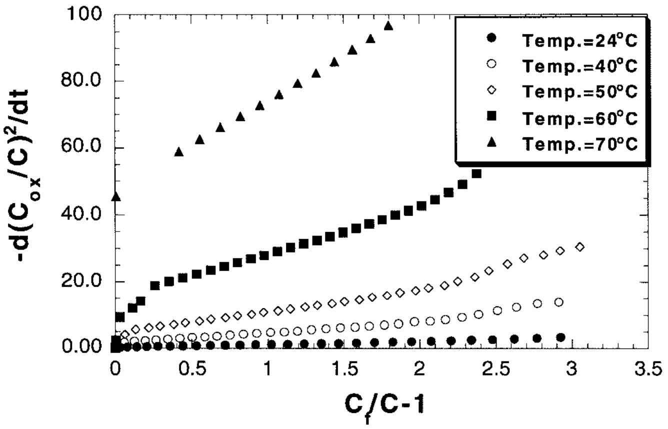


Fig. 13. Zerbst plots at different temperatures. The n-type sample measured in this figure is the same as used in Figs. 10 and 11.

IV. CONCLUSIONS

We have presented methods to reduce the generation lifetime measurement time for pulsed MOS capacitors. Both light and temperature can be used. However, for time reduction by optical techniques, one must use the pulsed technique, in which the device is exposed to an optical pulse during the initial portion of the C-t transient and the lifetime measurement is made in the dark for 30 s. The total measurement is significantly reduced and there is virtually no error compared to conventional C-t measurements in the dark. Moreover, the pulsed light method provides constant measurement time no matter how long t_f is.

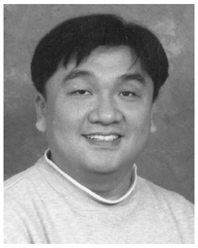
For steady-state light, optical carrier generation proceeds during the entire C-t transient and affects the lifetime because the conventional and "optical" lifetimes are combined into an effective value, which can be much lower than the true lifetime. Hence, this technique is not suitable. The measurement time is also reduced by elevated temperature, but this method is not recommended because the resultant generation lifetime may differ from its room temperature value. The temperature dependence of $\tau_{g,\text{eff}}$ is generally unknown and hence the elevated temperature lifetime may bear little resemblance to its room temperature value.

ACKNOWLEDGMENT

The authors thank C. Barbero, Wacker Siltronic Corporation, A. Buczkowski, and F. Kirscht, Mitsubishi Silicon, and W. Huber, Sumitomo Sitix, for supplying wafers.

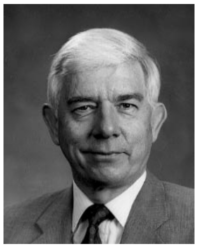
REFERENCES

[1] D. K. Schroder, "The concept of generation and recombination lifetimes in semiconductors," *IEEE Trans Electron Devices*, vol. ED-29, pp. 1336–1338, Aug. 1982.
[2] D. K. Schroder, *Semiconductor Material and Device Characterization*, 2nd. ed. New York: Wiley, 1998.
[3] A. B. Sproul and M. A. Green, "Improved value for the silicon intrinsic carrier concentration from 275–375 K," *J. Appl. Phys.*, vol. 70, pp. 846–854, July 1991.
[4] F. P. Heiman, "On the determination of minority carrier lifetime from the transient response of an MOS capacitor," *IEEE Trans Electron Devices*, vol. ED-14, pp. 781–784, Nov. 1967.
[5] K. S. Rabbani and D. R. Lamb, "A quick method for the determination of bulk generation lifetime in semiconductors from pulsed MOS capacitance measurements," *Solid-State Electron.*, vol. 24, pp. 661–664, July 1981.
[6] C. S. Yue, H. Vyas, M. Holt, and J. Borowick, "A fast extrapolation technique for measuring minority-carrier generation lifetime," *Solid-State Electron.*, vol. 28, pp. 403–406, Apr. 1985.
[7] Z. Radzimski, J. Honeycutt, and G. Rozgonyi, "Minority-carrier lifetime analysis of silicon epitaxial and bulk crystals with nonuniformly distributed defects," *IEEE Trans. Electron Devices*, vol. 35, pp. 80–84, Jan. 1988.
[8] K. Taniguchi, "Graphical technique to determine minority carrier lifetime and surface generation velocity using triangular-voltage sweep $C-V$ method," *Solid-State Electron.*, vol. 21, pp. 1057–1061, Aug. 1978.
[9] P. Peykov, J. Carrillo, and M. Aceves, "Triangular-voltage sweep $C-V$ method for determination of generation lifetime and surface generation velocity," *Solid-State Electron.*, vol. 36, pp. 99–102, Jan. 1993.
[10] X. Zhang, "Rapid determination of long generation lifetime," *Proc. Inst. Elect. Eng. G,* vol. 139, pp. 1–4, Feb. 1992.
[11] W. W. Keller, "The rapid measurement of generation lifetime in MOS capacitors with long relaxation times," *IEEE Trans. Electron Devices*, vol. ED-34, pp. 1141–1146, May 1987.
[12] W. R. Fahrner, D. Braeunig, C. P. Schneider, and M. Briere, "Reduction of measurement time of lifetime profiles by applying high temperatures," *J. Electrochem. Soc.*, vol. 134, pp. 1291–1296, May 1987.
[13] D. K. Schroder, "Bulk and optical generation parameters measured with the pulsed MOS capacitor," *IEEE Trans Electron Devices*, vol. ED-19, pp. 1018–1023, Sept. 1972.
[14] R. F. Pierret and W. M. Au, "Photo-accelerated MOS-C C-t transient measurements," *Solid-State Electron.*, vol. 30, pp. 983–984, Sept. 1987.
[15] K. S. Rabbani and D. R. Lamb, "On the analysis of pulsed MOS capacitance measurement," *Solid-State Electron.*, vol. 21, pp. 1171–1173, Sept. 1978.
[16] X. Zhang, "An improved model of generation width for pulsed MOS C-t transient analysis," *Solid-State Electron.*, vol. 33, pp. 1139–1142, Sept. 1990.
[17] D. K. Schroder, *Advanced MOS devices*. New York: Addison-Wesley, 1987.
[18] S. M. Sze, *Physics of Semiconductor Devices.* New York: Wiley, 1981.



Sang-Yun Lee was born in Seoul, Korea, in 1965. He received the B.S. degree in ceramic engineering from Yonsei University, Seoul, in 1988, the M.S. degree in electrical engineering from Washington University, St. Louis, MO, in 1995, and the Ph.D. degree in electrical engineering from Arizona State University, Tempe, in 1998.

From 1989 to 1993, he was with Semiconductor R&D Center of Samsung Electronics Company, Bucheun, Korea, where he was involved in Bipolar and BiCMOS process integration. In 1998, he joined Advanced eDRAM Center, Motorola, SPS, Tempe, AZ, as a Senior Staff Engineer. He is currently working on semiconductor device modeling and characterization.



Dieter K. Schroder (S'61–M'67–SM'78–F'96) received the B.S. and M.S. degrees in 1962 and 1964, from McGill University, Montreal, P.Q., Canada, and the Ph.D. degree from the University of Illinois, Urbana-Champaign, in 1968.

In 1968, he joined the Westinghouse Research Labs. where he was engaged in research on various aspects of semiconductor devices, including MOS devices, imaging arrays, power devices, and magnetostatic waves. He spent a year at the Institute of Applied Solid State Physics, Germany, in 1978. In 1981, he joined the Center for Solid State Electronics Research, Arizona State University, Tempe. His current interests are semiconductor materials and devices, characterization, low-power electronics, and defects in semiconductors. He has written two books *Advanced MOS Devices* and *Semiconductor Material and Device Characterization*, (New York: Wiley, 1998) and has published over 100 papers.

Dr. Schroder was a Distinguished National Lecturer, IEEE Electron Devices Society, in 1993 and 1994.