The power depends on the voltage required to drive the panel, the panel capacitance, and the conductance decay-time of the photoconductors. This decay time must be as short as possible, because a voltage pulse applied to a lead to address one of the lines in the display generates currents to ground in all the other voltage-divider circuits connected to that lead, and unless most of the photoresistors have decayed to very high resistances, the power dissipation becomes prohibitive. Evaporated photoconductors with fast decay rates suitable for display-panel addressing are being developed in our laboratory, and an analysis of the power dissipation for these materials is in progress. Since the power dissipation is proportional to the square of the voltage used to address the panel, the low-voltage electroluminescent materials which have recently been described [9], [10] are particularly suitable for use with the proposed addressing scheme.

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The Concept of Generation and Recombination Lifetimes In Semiconductors

D. K. SCHRODER

Abstract—**The purpose of this brief is to discuss the concept of generation and recombination lifetimes, a concept frequently confused in the literature. The regimes of device operation where they apply is discussed and it is shown experimentally for the first time that the two can be very different in magnitude.**

The concept of electron and hole lifetimes in semiconductors is, in principle, very straightforward. However, in practice there are generally as many lifetime values for a given device as there are measurement techniques. While some methods give numerical values that differ little, others differ greatly. A survey of lifetime measurement techniques in 1968 [1] yielded 300 papers published during the period from 1959 to 1967. It is probably safe to say that another 50 to 100 papers have been published since then.

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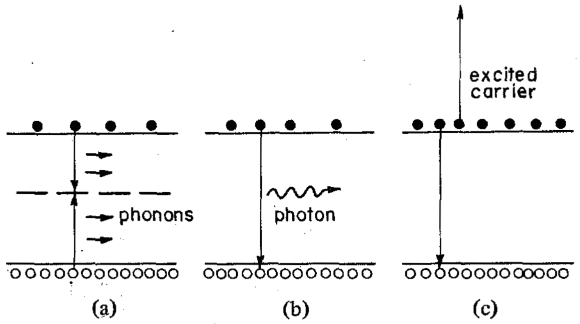

Fig. 1. Three recombination mechanisms. (a) Multi-phonon or Shockley–Read–Hall. (b) Radiative. (c) Auger.

Instead of discussing the various lifetimes in general, the concepts of recombination and generation lifetimes will be discussed, so that all lifetimes fall into one or the other of these two categories.

Recombination lifetime τ_r applies when excess carriers, introduced by light or a forward-biased p-n junction, for example, decay towards their equilibrium value as a result of recombination. The recombination rate R for minority electrons depends nonlinearly on the excess carrier density Δn and can therefore be written as

$$R = A\,\Delta n + B(\Delta n)^2 + C(\Delta n)^3. \tag{1}$$

The usual definition of $\tau_r = \Delta n/R$ gives

$$\begin{aligned} 1/\tau_r &= A + B\Delta n + C(\Delta n)^2 \\ &= 1/\tau_{\text{SRH}} + 1/\tau_{\text{rad}} + 1/\tau_{\text{Auger}}. \end{aligned} \tag{2}$$

Here high level injection is assumed. For low level injection, the Δn is replaced by p_0, the majority hole concentration.

The physical mechanisms giving rise to these three lifetimes are shown in Fig. 1. The Shockley–Read–Hall (SRH) lifetime is independent of Δn and the energy liberated during the recombination event is dissipated by lattice vibrations. The radiative lifetime, τ_{rad}, is inversely dependent on Δn because it is a band-to-band process and both electrons and holes must be present simultaneously. The energy is carried away by a photon. In the Auger process, characterized by τ_{Auger} and shown in Fig. 1(c), the energy is given to a third carrier, either an electron or a hole, and the lifetime is hence inversely proportional to $(\Delta n)^2$. SRH is dominant in indirect bandgap semiconductors such as Si, radiative recombination dominates in direct bandgap materials like GaAs [2], while Auger recombination requires a high density of carriers and therefore dominates under high doping and high injection condition [3]. Methods to measure τ_r include photoconductive decay, open-circuit voltage decay, reverse recovery, etc.

The generation lifetime, τ_g, is more difficult to interpret, because the very word lifetime implies that an entity ceases to exist. Such is not the case with τ_g, since it obtains when there is a paucity of carriers, as in the space-charge region of a reverse-biased junction. Instead of being destroyed, carriers are continually being generated and it is at first surprising that this process can be described by a lifetime, i.e., τ_g, which is closely related to τ_r. Nevertheless it can be, and the parameter τ_g is a very useful one to describe device behavior.

For recombination all three mechanisms of Fig. 1 are important during device operation, even though they apply to differ-

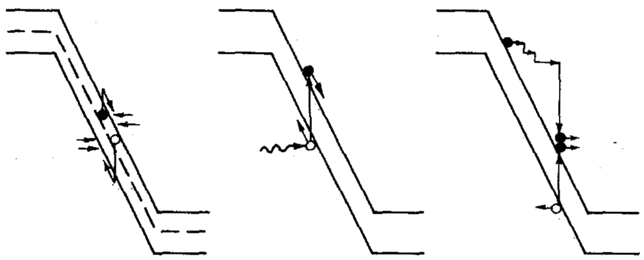

Fig. 2. The inverse generation mechanisms corresponding to the recombination mechanisms of Fig. 1.

ent devices and differing operating conditions. For generation, however, the most important process is the inverse SRH process of Fig. 2(a), under dark, low field conditions. Thermal generation of electron-hole (e-h) pairs proceeds via intermediate energy levels for semiconductors like Si and GaAs. The inverse radiative process in Fig. 2(b) is optical e-h pair generation which is absent in the dark, black-body radiation from the surroundings being negligible. Inverse Auger generation, better known as avalanche multiplication in Fig. 2(c) occurs only at high electric fields and can be neglected for low field conditions.

The concept of the two lifetimes τ_r and τ_g, which have not only different physical origins but can be very different in magnitude, was discussed in [4] and later recognized elsewhere [5]. However, even now, when discussing lifetime measurements by the pulsed MOS-C technique [4] the measured lifetime values are frequently referred to as minority-carrier lifetimes, which they are clearly not.

The following discussion will limit itself to simple concepts and dispense with carrier trapping and other subtle effects that may be important in certain measurements [6], but would only cloud the issue here. From the Shockley–Read–Hall theory [7], the recombination rate of electron-hole pairs is given by

$$R = (pn - n_i^2)/[\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)]. \tag{3}$$

For electron recombination (minority carriers in p-type material), (3) reduces to

$$\tau_r = \tau_{n0} \tag{4}$$

under conditions of low-level injection, using the definition

$$\tau_r = \Delta n/R. \tag{5}$$

Under reverse-bias conditions, where the mobile carrier concentration in the depleted space-charge region can be neglected, (3) becomes

$$R = -n_i/\tau_g \tag{6}$$

$$\begin{aligned}\tau_g &= \tau_{p0} \exp[(E_T - E_i)/kT] + \tau_{n0} \exp[-(E_T - E_i)/kT] \\ &= 2\tau_{n0}\sqrt{\sigma_n/\sigma_p} \cosh[(E_T - E_i)/kT + 0.5 \ln(\sigma_n/\sigma_p)]\end{aligned} \tag{7}$$

where E_T is the energy level of the recombination center and E_i is the intrinsic energy level.

The case of most interest is when $E_T \neq E_i$, i.e., when the center is asymmetrical. If σ_n and σ_p do not differ too greatly, say by a factor of 100 or less, then to first order the second term in (7) can be neglected and

$$\tau_g \simeq 2\tau_r\sqrt{\sigma_n/\sigma_p} \cosh[(E_T - E_i)/kT]. \tag{8}$$

For example, if

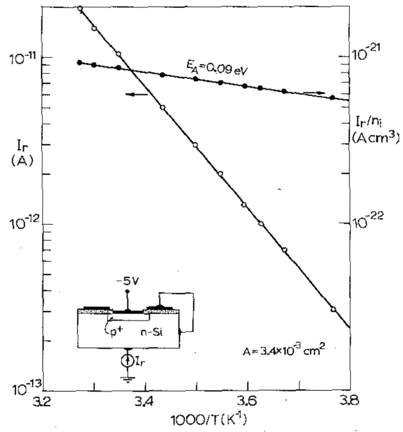

Fig. 3. The reverse-biased leakage current I_r, and I_r/n_i as a function of inverse temperature.

$$E_T - E_i \simeq 4kT, \qquad \tau_g \simeq 50\tau_r\sqrt{\sigma_n/\sigma_p} \tag{9}$$

i.e., τ_g is much higher than τ_r.

To test the theory and the entire concept of the two different lifetimes, a number of measurements were made on Si p^+n diodes. The recombination lifetimes were measured by the open-circuit voltage decay (OCVD) [8], reverse recovery (RR) [9], and by extrapolating the current of the log I_f versus V_f forward diode characteristic to zero volt [10]. This is done in the region where the diode current is diffusion-controlled and the intercept value yields the saturation current from which τ_r can be calculated.

The generation lifetime was determined by the pulsed MOS-C method [4] and from the leakage current of a reverse-biased diode, defined as [11][1]

$$I_r = qn_iWA/\tau_g. \tag{10}$$

For both τ_r and τ_g measurements, the diodes and MOS capacitors were located next to one another on the wafer.

The results of these measurements are shown in Table I, clearly demonstrating the large difference between these two lifetimes. For this example, $\tau_g \simeq$ 25–30 τ_r. From (8) this could be due to a large σ_n/σ_p ratio or $E_T \neq E_i$. To discriminate between the two possibilities, the reverse-bias leakage current I_r was measured as a function of temperature. From (10) we see that

$$\begin{aligned} I_r/n_i &\sim 1/\tau_g \sim 1/2 \cosh[(E_T - E_i)/kT] \\ &\sim \exp[(E_T - E_i)/k_T] \end{aligned} \tag{11}$$

assuming σ_n/σ_p does not vary greatly with temperature.

A plot of I_r/n_i as a function of $1/T$ is shown in Fig. 3 with an activation energy of 0.09 eV. Using (8), we see that for $E_T - E_i$ = 0.09 eV, $\tau_g = 36\sqrt{\sigma_n/\sigma_p}\,\tau_r$. This implies that for this wafer $\sigma_n/\sigma_p \simeq 0.7$.

Equation (8) has important device design implications. By choosing a recombination center with the appropriate energy level, τ_g can be made much higher than τ_r. Hence a device property which depends on τ_r, e.g., the turn-off time of diodes or thyristors, can be varied independently from a device property that depends on τ_g, e.g., diode leakage current. This is the result of the exponential dependence of τ_g on E_T, while

[1]There exists some confusion between (10) and the leakage current expression used by Grove [11] which is $I = qn_iWA/2\tau_0$. The quantity τ_0 is similar to τ_g of (7), except that it assumes that $\tau_{n0} = \tau_{p0} = \tau_0$ and $E_T = E_i$; on the other hand, (7) is a general expression free of these assumptions.

TABLE I
RECOMBINATION LIFETIMES (τ_r) AND GENERATION LIFETIMES (τ_g) MEASURED BY VARIOUS METHODS

Method	τ_r (μs)	τ_g (μs)
OCVD	25	
RR	19	
I_f	20	
MOS-C		500
I_r		600

τ_r is relatively independent of E_T. This concept is already being employed in device design [12].

The concepts of bulk generation and recombination discussed here, apply equally well to *surface* generation and recombination. In that case, the process is characterized by a surface generation or recombination velocity, generally characterized by s_0 and s. As discussed in detail in [13], the recombination velocity is considerably higher than the generation velocity, i.e., the recombination rate is higher than the generation rate, just as it is in the bulk.

The combination bulk and surface generation current is given by [13]

$$I_r = qn_i WA_b/\tau_g + qn_i s_0 A_s \tag{12}$$

where A_b is the area of the bulk space-charge region while A_s is the surface area. Recent advances in process control have reduced the room temperature Si diode leakage current to values around 10^{-10} A/cm^2. Such low currents correspond to surface generation velocities of $s_0 \simeq 0.1$ cm/s [14].

For the case of surface recombination, considerable progress has also been made. The lowest values here are those of high/low junctions used in solar cells, for example. Here surface recombination velocities of $s \simeq 80$ cm/s are very low values [15], showing that just as for the bulk, surface recombination is more effective than generation, with $s \gg s_0$. At the surface, both recombination and generation are controlled by interface states, which do not have a well defined energy level and the independent control of s and s_0 is therefore more difficult, but the concept of generation and recombination velocities holds, nevertheless.

In summary, the concept of generation and recombination lifetime and surface generation and recombination velocity has been discussed and clarified. For the first time definite values of τ_r and τ_g have been measured clearly establishing the concepts.

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Erratum

An error occurred in the paper "A SEM–EBIC Minority-Carrier Diffusion-Length Measurement Technique" by Dimitris E. Ioannou and Charalabos A. Dimtriadis published in *IEEE Trans. Electron Devices*, vol. ED-29, no. 3, pp. 445–450, Mar. 1982. On p. 447 on the third line in Section IV. APPLICATIONS, the phrase "very long lifetimes (~50 s)," should read "very long lifetimes (500 μs)."

STEPHEN KNIGHT
Editor