Lifetime of excess electron–hole pairs measured with white noise performance of the photocurrent

C. H. Kuan^{a)} and C. H. Tu

Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan 10617, Republic of China

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A modified method to measure the lifetime of the excess electron–hole pairs generated by laser beams is proposed. Under the applied bias, excess carriers pass through the sample within the transit time and form the photocurrent I_p . The related white-noise component of the photocurrent can be written as $4egI_p$, where g is the ratio of the lifetime over the transit time. The lifetime can then be obtained by determining g from the white noise performance. Since the transit time can be adjusted with the applied biases and the sample length, the measured lifetime may be as small as 100 ns with the measurement system even having the analytic frequency range of 10 kHz only. A GaAs sample grown by molecular beam epitaxy is taken as an example to measure the excess carrier's lifetime. It is concluded from the experiments that the lifetime of excess carriers in our sample is primarily caused by the indirect recombination via the deep trap centers within the band gap. The nonradiative lifetime is not really a constant and its variation versus the laser intensity indeed follows the prediction of the Shockley–Read–Hall recombination theory. This confirms the accuracy of our measurement. © 2000 American Institute of Physics. [S0021-8979(00)03704-X]

I. INTRODUCTION

The lifetime of the excess carriers in a semiconductor is an important parameter for the material quality or the device performance since all the recombination and trapping processes are characterized by it. The recombination processes are related to the band-to-band transition due to the direct recombination of the electrons and holes, or involved with the impurities and crystal defects, which are named as trap centers and can capture the excess carriers injected by electric fields or photons. The associated lifetimes with the two recombination processes are called the radiative and nonradiative lifetimes, respectively. These two parameters are often utilized to evaluate the material quality and the optical performance of the devices such as photodiodes and photodetectors, etc.

There are several methods to determine the lifetime of the excess carriers in experiments. The first one is the measurement of the magnitudes of the steady-state photoconductivity and the photoelectromagnetic effects.^{1,2} The second method is the optical phase-shift technique^{3–5} and it measures the phase lag of band-to-band photoluminescence relative to the excitation, whose intensity is modulated with some radio frequency. The lifetime can be determined from its relationship with the radio frequency and the phase lag. The third method is to measure the transient response of the related capacitance.^{6,7} Among them the deep-level transient spectroscopy is a high-frequency capacitance transient thermal scanning method useful for observing a wide variety of trap centers in semiconductors and obtaining the corresponding lifetime. The fourth method is to measure the power

spectral density (PSD) of the generation–recombination noise resulting from the excess carriers generated by photons.⁸ The lifetime is determined from the cutoff angular frequency of the power spectral density since they have an inverse relationship. As a result, the minimum measurable lifetime is limited by the system frequency range.

In this article, a modified method is proposed to measure the white noise component of the generation–recombination noise with the system frequency range even much less than that in the fourth method, but the measured lifetime may be as small as several hundred nanoseconds. The experimental procedures and theoretical principles to measure the lifetime are described in Sec. II. In Sec. III, an *n*-type GaAs sample is designed to proceed the experiment. The density profile of the excess holes versus the distance from the sample surface is calculated for different lifetimes. The experimental results, including the power spectral density and the noise current gain, are given in Sec. IV. The functional behavior of the measured lifetime under various laser intensities is also determined with experiments. The analysis and discussion of the experimental results are described in Sec. V. It is concluded that the lifetime is primarily caused by the nonradiative recombination and agrees well with the Shockley–Read–Hall recombination theory. The comparison between our results and those from the optical phase lag shift technique is also described and discussed. Other experimental evidence is presented to further confirm the comparison arguments. In Sec. VI, a final conclusion is given.

II. MEASUREMENT PRINCIPLES

In the *n* or *p* type material, the power spectral density of the excess carrier number due to the incident laser and the generation–recombination process can be written as⁹

^{a)} Author to whom correspondence should be addressed; electronic mail: kuan@cc.ee.ntu.edu.tw

$$S_{\delta N}(f) = 4\overline{\Delta(\delta N)^2} \frac{\tau}{1 + \omega^2 \tau^2}, \quad (1)$$

where δN is the excess carrier number, τ is the carrier lifetime, and $\overline{\Delta(\delta N)^2}$ the variance of the excess carrier number.

For the monochromatic light source of the laser, since the photons obey a Poisson counting distribution,¹⁰ the statistics of the excess carriers are expected to follow $\overline{\Delta(\delta N)^2} = \overline{\delta N}$ and the reason is described as follows.

Assuming there are N photons incident upon the sample, the probability for one photon to generate one excess carrier is β . According to the statistics of the binomial distribution, the average number of the excess carriers is $\overline{\delta N} = \beta \bar{N}$, and the variance is $\overline{\Delta(\delta N)^2} = \bar{N} \beta (1 - \beta) + \overline{\Delta N^2} \beta^2$. Since the photon number follows the Poisson counting distribution and $\overline{\Delta N^2} = \bar{N}$, we indeed have $\overline{\Delta(\delta N)^2} = \overline{\delta N}$ no matter what the value of β is.

In the case of generation of the electron-hole pairs by photons, both of the carrier numbers are the same and the corresponding photocurrent may be written as

$$I_p = \frac{e \overline{\delta N}}{V} (\mu_e + \mu_h) \frac{V_a}{\ell} A \approx e \overline{\delta N} \mu_e \frac{V_a}{\ell^2}, \quad (2)$$

where $V (= \ell A)$ is the total volume, V_a the applied bias, $\mu_e (\mu_h)$ the electron(hole) mobility, ℓ the sample length, and A the cross section of the sample. In the above equation, the assumption $\mu_e \gg \mu_h$ is made. Based on Eq. (2), the noise power spectral density of the photocurrent may be written as

$$S_p(f) = \frac{e^2 \mu_e^2 V_a^2}{\ell^4} S_N(f) = \frac{4egI_p}{1 + \omega^2 \tau^2}. \quad (3)$$

The noise current gain is defined as

$$g = \frac{\tau}{t_t} = \frac{\tau \mu_e V_a}{\ell^2} \quad (4)$$

and the transit time t_t is

$$\tau_t = \frac{\ell^2}{\mu_e V_a}. \quad (5)$$

Including the thermal noise, the total noise power spectral density we measure is

$$S_t(f) = 4kTG_0 + S_p(f), \quad (6)$$

where G_0 is the conductance of the sample at zero bias and with laser incident upon it.

Equation (3) is often used by some authors to characterize the noise performance of the quantum well infrared photodetectors.¹¹⁻¹³ As indicated in Eqs. (3)–(5), the lifetime τ may be determined with two different methods. From the cutoff frequency f_0 of the noise power spectral density $S_p(f)$, we can find $\tau = 1/(2\pi f_0)$.⁸ This method is primarily limited by the frequency of the spectrum analyzer. For the nanosecond range of the lifetime, the analyzer must have the capability to measure the noise power at several GHz. On the other hand, the lifetime τ can be measured with the unit of the transit time τ_t from the noise current gain g in the white-noise component of $S_p(f)$. It is noted that the transit time τ_t may be adjusted with the external applied bias as indicated

FIG. 1. GaAs sample structure with laser beams incident upon it. The doping density of the active layer is $1.5 \times 10^{15} \text{ cm}^{-3}$. Its dimensions are length $1000 \mu\text{m}$, width $30 \mu\text{m}$, and thickness $2 \mu\text{m}$.

by Eq. (5). Even with the spectrum analyzer only having the capability of 10 kHz frequency range, we can also measure the lifetime within the nanosecond range if the sample length ℓ is properly designed and an appropriate applied bias is used.

III. SAMPLE STRUCTURE

We took the n -type GaAs sample shown in Fig. 1 as an example to measure the excess carrier lifetime. The sample was grown on the semi-insulating substrate by molecular beam epitaxy and its mesas were formed with wet etching. The size of the active n -type layer is the thickness $d = 2 \mu\text{m}$, length $\ell = 1000 \mu\text{m}$, and width $W = 30 \mu\text{m}$. The estimated resistance under the two contact pads is less than 3% of that in the active layer and is negligible. The laser beam is incident upon the sample along the x direction. The concentration δp of the excess minority holes obeys the equation

$$D_p \frac{d^2 \delta p}{dx^2} - \frac{\delta p}{\tau} + g_0 \exp(-\alpha x) = 0 \quad (7)$$

and the related boundary conditions are

$$D_p \frac{d\delta p}{dx} \bigg|_{x=0} = s\delta p(0)$$

and

$$D_p \frac{d\delta p}{dx} \bigg|_{x=d} = 0, \quad (8)$$

where D_p is the hole diffusivity, g_0 the carrier generation rate per unit volume at $x=0$, α the GaAs absorption coefficient of the incident laser, and s the surface recombination velocity of the holes. The first boundary condition is rendered by the surface states between GaAs and the air environment while the second one results from the semi-insulating substrate. The reported s/D_p value for GaAs ranges from 0.5×10^5 to $7.4 \times 10^5 \text{ cm}^{-1}$.^{4,14,15}

Figure 2 shows the calculation results of the relative excess holes' density versus the distance along the x direction from the surface for a GaAs sample with $n = 1.0 \times 10^{15} \text{ cm}^{-3}$, $s/D_p = 1.0 \times 10^5 \text{ cm}^{-1}$, $\mu_p = 400 \text{ cm}^2/\text{V s}$, and $\alpha = 4.4 \times 10^4 \text{ cm}^{-1}$. The temperature of the sample is $T = 300 \text{ K}$. The generation rate is kept constant for the lifetime τ ranging from 1 ns to 1 μs . The extra low density around the surface results from the surface recombination. The noise of the photocurrent is expected to come from the excess

FIG. 2. Relative density profile of the minority holes vs the distance along the x direction. The adopted values of some specific parameters are typical for GaAs. The laser intensity is the same for all the curves. The lifetime ranges from 1 ns to 1 μ s. For $\tau \geq 0.1 \mu$ s, all the density profile approaches the same limit, which is almost constant for $x > 0.5 \mu$ m.

holes in the bulk. The interesting feature is the almost constant density profile at $x > 0.5 \mu$ m for the lifetime larger than 0.1 μ s. It is because of the long diffusion length for the large lifetime that the holes can be distributed uniformly. If the diffusion length is not large enough, the excess hole density would peak somewhere within the thickness, as indicated by the density curve for $\tau = 1$ ns.

IV. EXPERIMENTAL RESULTS

Our noise measurement system consists of a low-noise current amplifier and a spectrum analyzer. The system was well grounded and shielded to prevent pickup noise and its background noise was also calibrated in advance. The sample's noise PSD was given by subtracting the background noise from the apparent one. The PSD was taken 200 times for the frequency range from dc to 10 kHz and averaged to improve the signal-to-noise ratio. The wavelength of the laser beam is 1064 nm. Typical data for the SPD are shown in Fig. 3 where Pr is defined as the ratio of the photocurrent over the total current and stands for the laser intensity. As shown in Fig. 3, the PSD increases dramatically at around zero frequency and the phenomenon is attributed to the $1/f$ noise, which is not our interest. The plateau at a frequency higher than 3 kHz represents the total white noise component of the $S_i(f)$ in the sample.

As indicated in Eq. (6), subtracting the thermal noise from the $S_i(f)$ gives the $S_p(f)$. It is obvious that the cutoff frequency f_0 of the $S_p(f)$ does not appear in our frequency range. The excess carrier's lifetime is hence expected to be less than 1.6×10^{-5} s and may be found out with the white noise component.

FIG. 3. Power spectral density of the photocurrent vs the frequency for the GaAs sample at different biases. The Pr is the ratio of the photocurrent over the total current.

The noise current gain g can be extracted from the ratio of the white-noise component of the $S_p(f)$ over $4eI_p$. Figure 4 shows the noise current gain versus applied bias with respect to different Pr . The important feature is that the noise current gain is proportional to the applied bias and the corresponding slopes increase with the increment of the laser intensity. According to Eq. (4), the lifetime can be solved from the slope if the electron mobility is found.

With the Hall measurement the electron mobility was determined to be $8010 \text{ cm}^2/\text{V}$ and the electron density was $1.0 \times 10^{15} \text{ cm}^{-3}$. From the slopes of the straight lines in Fig. 4, the associated lifetime of the excess holes with different laser intensities was found to range from 1.5×10^{-7} to 4.0×10^{-7} s as represented by the solid squares in Fig. 5. The magnitudes of the measured lifetimes are consistent with Fig. 3 in which the expected lifetime is smaller than 1.6×10^{-5} s. They also fall within the wide limits from 10^{-12} to 10^{-6} s measured with the photoconductivity and photoelectromagnetic effects.¹⁶ Since the sample was grown with molecular beam epitaxy and doped with $1.0 \times 10^{15} \text{ cm}^{-3}$ only, we expect the lifetime to be very close to 10^{-6} s. It is also

FIG. 4. Noise current gain vs. the applied bias for various laser intensities. The noise current gain is proportional to the applied bias and the corresponding slope is a function of the laser intensity (Pr).

FIG. 5. Measured lifetime of the minority holes vs the photocurrent ratio. The result shows the lifetime is a function of the laser intensity and ranges in several 10^{-7} s. The solid line fits in with the Shockley–Read–Hall recombination theory. The slope and the intercept on the lifetime axis give the parameters τ_{n0} and τ_{p0} , respectively.

observed in Fig. 5 that the lifetimes increase with the photocurrent ratio, i.e., the laser intensity. Since the excess carrier density is a function of laser intensity, this result indicates that the lifetime may also vary with the density.

V. ANALYSIS AND DISCUSSION

Recombination phenomena can be classified into direct and indirect processes. Indeed the corresponding recombination rates are all functions of the electron and hole concentrations. According to the direct recombination and the Shockley–Read–Hall recombination theory,¹⁷ the net recombination rate of excess holes in the n -type sample may be given by

$$U = \frac{\delta p}{\tau_p} = \frac{G_r}{n_i^2} (n_0 + p_0 + \delta p) \delta p + \frac{(n_0 + \delta p) \delta p}{\tau_{p0}(n_0 + \delta p) + \tau_{n0} \delta p}, \quad (9)$$

where $n_0(p_0)$ is the electron (hole) concentration in thermal equilibrium, τ_p the excess holes' lifetime, and n_i the intrinsic carrier concentration. As usual, the notation δ means excess carriers produced by photons. The first term in the right hand side of Eq. (9) represents the direct (radiative) recombination and G_r is the radiative generation rate in thermal equilibrium. The second term is the indirect recombination via energy trap centers within the band gap. The parameter $\tau_{n0}(\tau_{p0})$ is given by $\tau_{n0} = 1/(\sigma_n v_{th} N_t)$ [$\tau_{p0} = 1/(\sigma_p v_{th} N_t)$] where $\sigma_n(\sigma_p)$ is the electron (hole) capture cross section, N_t the trap density, and v_{th} the thermal velocity. Here we have supposed $\delta p \gg p_0$, the energy level of the dominant traps be very close to the intrinsic one, and its degeneracy factor to be one.

Since δp is a function of x , and U varies with x in general. The excess holes' lifetime τ we measured with the white noise should be a macroscopic parameter and may be written in terms of $U(x)$ as

$$\tau = \frac{\int_0^d \delta p(x) dx}{\int_0^d U(x) dx}. \quad (10)$$

It is noted that δp increases with the laser intensity and the lifetime τ should be decreased if the radiative recombination is dominant. This result contradicts our experimental data. In addition, the numerical value of the parameter G_r/n_i^2 for nondegenerate GaAs at 300 K is $7 \times 10^{-10} \text{ cm}^3 \text{ s}^{-1}$.^{18,19} The corresponding radiative lifetime estimated with the first term in the right-hand side of Eq. (9) is 1.43×10^{-6} s and is at least 3.6 times larger than our experimental results. Based on the above mentioned reasons, the radiative recombination is then neglected in our following analysis.

As indicated in Fig. 2 for a lifetime larger than $0.1 \mu\text{s}$, the excess holes' density may be regarded as constant at $x \geq 0.5 \mu\text{m}$ and zero at $x < 0.5 \mu\text{m}$. As a result, Eq. (10) may be rewritten as

$$\tau = \tau_{n0} \text{Pr} + \tau_{p0}, \quad (11)$$

where the photocurrent ratio is $\text{Pr} = \delta p/(n_0 + \delta p)$. The measured lifetime indeed follows a straight line as shown in Fig. 5. The slope and the intercept on the lifetime axis reflect $\tau_{n0} = 2.94 \times 10^{-6}$ and $\tau_{p0} = 5.04 \times 10^{-8}$ s, respectively. These two values imply that the capture cross section for the holes is much larger than that for the electrons. This conclusion is consistent with the observation of deep-level transient spectroscopy.²⁰

When comparing the results with those obtained by other methods, especially the optical phase shift technique,⁴ their data show a constant nonradiative lifetime of about 20 ns for the melt-grown GaAs with Te doping $2.5 \times 10^{16} - 8 \times 10^{17} \text{ cm}^{-3}$. Our data conclude that the nonradiative lifetime is not really a constant and indeed follows the Shockley–Read–Hall recombination theory. The differences can be explained by Eqs. (9) and (10). If the laser intensity is so large that $\delta p \gg n_0$, the resulted lifetime $\tau = \tau_{n0} + \tau_{p0}$ is indeed independent of the carrier density and proportional to N_t^{-1} . Under this condition and because of the high quality of the sample grown by the molecular beam epitaxy, both results should have no common contradictions.

The lifetime under the high-injection condition in our sample cannot be observed because the large total current saturates our current amplifier. The limit of our measurement originates primarily from the low-noise current amplifier. Suppose the amplifier gain is A and the total current is $I_t = I_d + I_p$, where I_d is the dark current. The limitation conditions are $A I_t < 10$ and $4kTG_0 + 4egI_p > 0.1 \Delta i_b^2$. The first condition is to prevent saturation of the amplifier under the assumption that its maximum output voltage is 10 V. In the second condition, the Δi_b^2 is the equivalent noise current PSD of the amplifier itself. The sample noise must be at least one tenth Δi_b^2 in order for our measurement system to subtract Δi_b^2 from the total measured noise and derive the sample noise. The amount of the data points we present here has reached the limit of our system capability.

In order to further confirm the high-injection condition, we present the noise current gain of a commercial CdS photoconductor measured with the same principle. Without any light incident upon it, the resistance of the photoconductor is $2.0 \text{ M}\Omega$. Figure 6 shows the noise current gain versus applied bias when the resistance varies from 156 to $21 \text{ k}\Omega$ with laser intensity increasing. It is concluded from the change of

FIG. 6. Noise current gain vs applied bias for a CdS photodetector under various laser intensities. The detector is a commercial product of Hiemann incorporation and its model number is CDS A900-14. The resistance values indicate the detector is under high injection. The common slope for bias greater than 0.1 V implies the constant lifetime. The open squares for bias less than 0.1 V is distorted by the thermal noise.

the resistance that the photoconductor is under a high-injection condition. When the bias is greater than 0.2 V, the noise current gain is proportional to the bias and has the same slope for all the laser intensity. This indicates a constant lifetime as predicted by Eqs. (9) and (10). The behavior for the open-square data under a bias of less than 0.2 V is attributed to the distortion of the thermal noise.

VI. CONCLUSIONS

The lifetime of the excess electron-hole pairs is measured with the white-noise component of the photocurrent. The advantage of our measurement method lies in the flexibility of the transit time τ_t . It is the measurement unit of the lifetime and can be adjusted with the applied bias V_a or the sample length ℓ . Even with our measurement system having the capability of 10 kHz frequency range only, we can also derive the lifetime of several hundred nanoseconds. The ex-

ample of the GaAs sample shows the nonradiative lifetime is not really a constant and indeed follows the Shockley-Read-Hall recombination theory.

The same idea can also be applied to other material systems and device structures such as the quantum wells in which the generation-recombination noise is dominant. The development of our system for the sample under various temperatures is still going on. The most difficult part of this job is to avoid pickup noise and the problem of grounding. From our experimental results, it is worth our effort to improve this scientific instrument.

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