# Matlab minority carriers documentation
# What does the app do?

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The analysis of time-resolved photoluminescence lifetime data as a function of temperature is needed in order to understand the dominant recombination mechanisms of a material. This will give evidence of device performance, and can suggest whether material growth quality can improve. Here, a MATLAB application is created which allows for further analysis of lifetime results and it's subroutines are discussed. The format of the documentation will be closer to article-style, to allow for reference in future manuscript drafting. A walkthrough of the MATLAB application will be provided in a powerpoint format to understand the proper buttons that need to be pushed for data analysis.

**Usage:** The documentation will allow for quick and easy reference for understanding the MATLAB app, and will provide for discussion of recombination mechanisms and formulas used to model the lifetime.

## I. INTRODUCTION: MOTIVATION

The mechanisms that are attributed to the minority carrier lifetime contain multiple components. Understanding the constituents that make up the lifetime character of a sample provides evidence of device performance. For background limited performance (BLIP), the photon generation rate per unit area needs to be greater than the thermal generation rate per unit area,[1] or

$$\eta_a \Phi_B > \frac{n_{th} t}{\tau}, \tag{1}$$

where $\eta_a$ is the absorption efficiency, $\Phi_B$ the background flux, $\mathrm{n_{th}}$, t, and $\tau$ are the density of thermal carriers, thickness of the material and lifetime of the carriers, respectively. For best performance, the lifetime needs to be at a maximum. The minority carrier lifetime will be considered here because the material system of interest are direct band gap materials.

## II. DATA ANALYSIS

The minority carrier lifetime can be characterized by it's recombination mechanisms,

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{SRH}} + \frac{1}{\gamma \tau_{rad}} + \frac{1}{\tau_{Auger}}, \tag{2}$$

where $\tau_{SRH}$ is the Shockley-Read-Hall (SRH) lifetime, $\gamma$ the photon recycling factor, $\tau_{rad}$ the radiative lifetime and $\tau_{Auger}$ is the Auger lifetime. The lifetime components are added as recombination rates in order to calculate the total lifetime, which is why the reciprocals are added in Eq. 2.

### A. Shockley-Read-Hall Recombination

The recombination of photoexcited carriers with defects in a material is the SRH recombination mechanism. This is observed because there are defect levels, $\mathrm{E}_t$ that occur within the forbidden band gap of a material. The lifetime due to SRH recombination is[2, 3]

$$\tau_{SRH} = \frac{\tau_{p0}(n_0 + n_1) + \tau_{n0}(p_0 + p_1)}{n_0 + p_0}. \tag{3}$$

In the case of an n-type sample, and approximating with Boltzmann statistics and parabolic bands[4] we can define the quantities in Eq. 3 by

$$n_0 - p_0 = D \tag{4}$$

$$n_0 p_0 = n_i^2 = N_c N_v \exp\left(-E_g/kT\right) \tag{5}$$

$$\Rightarrow n_0 = \frac{1}{2}\left(\sqrt{D^2 + 4n_i^2} + D\right) \tag{6}$$

$$n_1 = N_c \exp\left(E_t - E_c\right)/kT \tag{7}$$

$$N_c = \frac{1}{4}\left(\frac{2m_e^* kT}{\pi \hbar^2}\right)^{3/2} \tag{8}$$

$$\tau_{p0} = \frac{1}{\sigma_p v_{th} N_t} \tag{9}$$

$$v_{th} = \sqrt{\frac{8kT}{\pi m^*}} \tag{10}$$

where $D$ is the doping concentration, $n_0$ is the concentration of electrons in thermal equilibrium, $n_1$ is the density of electrons for the case of the fermi level falling at the trap level $E_t$, $N_c$ is the effective electron density of states, $\tau_{p0}$ is the lifetime for holes injected in a p-type sample, and $v_{th}$ is the thermal velocity. The quantities $\tau_{n0}$, $p_0$, $p_1$, etc. can be found by similar equations and through the relation $p_0 = n_i^2/n_0$. When analyzing the total lifetime, the doping D, trap level $E_t$, and the product $\sigma N_t$ are fit parameters to the data. In the case of degenerate materials, such as highly doped materials, metals or

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materials with a negative band gap, Fermi-Dirac statistics will need to be considered. This then causes the approximation of the right hand side of Eq. 5 to become invalid.

### B. Radiative Recombination

Photoexcited carriers in the conduction band recombine with vacancies in the valence band and release the excess energy in the form of a photon, we can model the radiative lifetime through the thermal generation rate introduced by Van Roosbroeck and Shockley,[5]

$$G_R = \frac{8\pi}{h^3c^2}\int_0^\infty \frac{\epsilon(E)\alpha(E)E^2dE}{\exp(E/kT)-1}, \tag{11}$$

where $\epsilon$ is the relative dielectric constant which is typically aproximated by the static dielectric constant taken at energies below the fundamental absorption edge, $\epsilon_\infty$, $\alpha$ is the absorption coefficient, and E is the photon energy. The integral can be integrated numerically with indirect experiments[6] of the absorption coefficient, such as transmission. Another method is through simulation[7, 8] by using a 14 band **k.p.** theory software.[9] Here, we will compute the integral by giving an approximate analytic form of the absorption coefficient, where the same method was used on analyzing the radiative lifetime on Ge[10] and HgCdTe[11–13] material systems. The analytic form of the absorption coefficient is

$$\alpha_{direct} = \frac{2^{3/2}}{3\epsilon_\infty^{1/2}}\frac{m_0e^2}{\hbar^2}\left[\frac{m_e^*m_h^*}{m_0(m_e^*+m_h^*)}\right]^{3/2}\left(1+\frac{m_0}{m_e^*}+\frac{m_0}{m_h^*}\right) \times\left(\frac{E-E_g}{m_0c^2}\right)^{1/2}, \tag{12}$$

where $m_0$ is the free electron rest mass, $m_e^*$ is the conduction electron effective mass, $m_h^*$ is the valence heavy hole effective mass, and $E_g$ is the material band gap. Inserting this in Eq. 11, we have

$$G_R = n_i^2 5.8\times10^{-13}\epsilon_\infty^{1/2}\left(\frac{m_0}{m_e^*+m_h^*}\right)^{1/2}\left(1+\frac{m_0}{m_e^*}+\frac{m_0}{m_h^*}\right) \times\left(\frac{300}{T}\right)^{3/2}\left(E_g^2+3kTE_g+3.75(kT)^2\right). \tag{13}$$

The effective masses used for the group III-V material systems will be the effective masses of the major consitutents. For example, for an $InAs_{0.91}Sb_{0.09}$ alloy, the effective mass[14] and static dielectric constant of bulk InAs[15] will be used.

The radiative generation rate developed in Eq.13 is valid for the internal radiative generation and in a doped sample the internal radiative lifetime becomes

$$\tau_{rad} = \frac{n_i^2}{G_R(n_0+p_0)}, \tag{14}$$

but when analyzing the minority carrier lifetime from external measurements such as Time-resolved photoluminescence (TRPL) the simulations tend to underestimate the radiative lifetime. What needs to be considered is the photon recycling factor; this is where the emitted photon is reabsorbed in the active region of a material


[1] M. A. Kinch, J. Electron. Mater. **29**, 809 (2000).
[2] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).
[3] R. N. Hall, Phys. Rev. **87**, 387 (1952).
[4] J. S. Blakemore, *Semiconductor Statistics* (Pergamon Press, London, 1962).
[5] W. V. Roosbroeck and W. Shockley, Phys. Rev. **94**, 1558 (1954).
[6] L. Höglund, D. Z. Ting, A. Khoshakhlagh, A. Soibel, C. J. Hill, A. Fisher, S. Keo, and S. D. Gunapala, Appl. Phys. Lett. **103**, 221908 (2013).
[7] B. V. Olson, E. A. Shaner, J. K. Kim, J. F. Klem, S. D. Hawkins, and M. E. Flatté, Appl. Phys. Lett. **103**, 052106 (2013).
[8] B. V. Olson, E. A. Kadlec, J. F. Klem, S. D. Hawkins, E. A. Shaner, and M. E. Flatté, Phys. Rev. Appl. **3**, 044010 (2015).
[9] W. H. Lau, J. T. Olesberg, and M. E. Flatté, e-print arXiv:cond-mat0406201.
[10] R. N. Hall, Proc. IEE B **106**, 923 (1959).
[11] M. A. Kinch, M. J. Brau, and A. Simmons, J. Appl. Phys. **44**, 1649 (1973).
[12] S. E. Schacham and E. Finkam, J. Appl. Phys. **17**, 2001 (1985).
[13] V. C. Lopes, A. J. Syllaios, and M. C. Chen, Semicond. Sci. Technol. **8**, 824 (1993).
[14] I. Vurgaftman, J. R. Meyer, and L. R. Ram-Mohan, J. Appl. Phys. **89**, 5815 (2001).
[15] S. Zollner, P. P. Paradis, F. Abadizaman, and N. S. Samarasingha, J. Vac. Sci. Technol. B. **37**, 012904 (2019).