Self-Consistent Model of Minority-Carrier Lifetime, Diffusion Length, and Mobility

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***Abstract*—The minority-carrier mobility is an important parameter in the simulation of dc and frequency-dependent operation of bipolar devices. A self-consistent approach is proposed for extracting the minority-carrier mobility from fits to experimental data for lifetime and diffusion length and then comparing the extracted mobility to experimental mobility data. The good agreement between extracted and experimental mobilities justifies incorporating the results into numerical device and circuit CAD tools.**

I. Introduction

The minority-carrier mobility and lifetime are important parameters for modeling advanced n-p-n bipolar transistors. These parameters influence the base current and affect the speed at which charge removal from the emitter occurs. There have been several recent investigations into the minority-carrier mobility [1]–[5] and there is disagreement about the value to be used. All of these investigations have measured the minority-carrier diffusion length and used lifetime data to calculate the mobility. To perform accurate device simulations, it is necessary to have parameters that are self-consistent. In this work, an expression for minority-carrier hole lifetime is fit to hole lifetime data. This expression is then used in conjunction with the diffusion length data to extract a minority-carrier mobility that agrees with the diffusion length measurements. The resulting mobility is compared to experimental values in literature.

II. Carrier Lifetime

The carrier lifetime is modeled using a concentration-dependent Schockley–Read–Hall (SRH) lifetime, τ_{srh}, as suggested by Fossum *et al.* [6], and a band-to-band Auger impact process lifetime τ_{bba}. Mathiessen's rule is used to compute the total effective lifetime τ, where

$$\frac{1}{\tau} = \frac{1}{\tau_{srh}} + \frac{1}{\tau_{bba}}. \tag{1}$$

As a function of doping, τ_{srh} can be expressed [6] as

$$\tau_{srh} = \frac{\tau_0}{1 + N_D/N_{ref}} \tag{2}$$

where τ_0 is the low concentration lifetime, N_D is the doping concentration, and N_{ref} is the rolloff concentration. The largest scatter is in τ_0, which depends on wafer processing and trace metal contamination. The Auger lifetime is

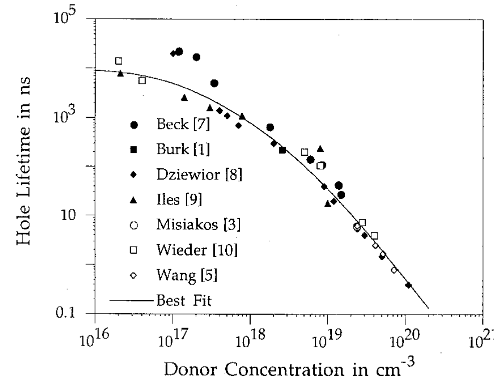

Fig. 1. Measured and best-fit hole lifetimes in heavily doped n-type silicon.

$$\tau_{bba} = \frac{1}{C_A N_D^2} \tag{3}$$

where C_A is the Auger coefficient.

Fig. 1 plots the experimental hole lifetime data [1], [3], [5], [7]–[10] and a best fit to this data. The parameters used in the fit are $\tau_0 = 10$ μs, $N_{ref} = 10^{17}/\text{cm}^2$, and $C_A = 1.8 \cdot 10^{-31}$ cm^6/s. These values are similar to those found by Dziewior and Schmid [8]. Fig. 2 shows the experimental data for electron lifetime [3], [7]–[9], [11] along with a best fit. The electron parameters are $\tau_0 = 30$ μs, $N_{ref} = 10^{17}/\text{cm}^3$, and $C_A = 8.3 \cdot 10^{-32}$ cm^6/s.

III. Hole Minority-Carrier Mobility

Several researchers [1], [3]–[5], [10], [12] have measured minority-carrier hole diffusion length, as shown in Fig. 3. Most measure the lifetime and then extract mobility using

$$L_D = \sqrt{\mu \tau V_T} \tag{4}$$

where V_T is the thermal voltage, μ is the mobility, and τ is the lifetime. Rather than use the reported mobilities, the minority-carrier mobility fit will use the best fit to the hole lifetime shown in Fig. 1, the diffusion length measurements, and (4). It is assumed the minority- and majority-carrier mobilities have a similar functional form [13], namely,

$$\mu_p = \mu_{\min} + \frac{\mu_{\max} - \mu_{\min}}{1 + \left(N_D/N_{ref}\right)^{\alpha}}. \tag{5}$$

Equation (5) is used in combination with the fit shown in Fig. 1 to optimally fit the experimentally measured diffusion length

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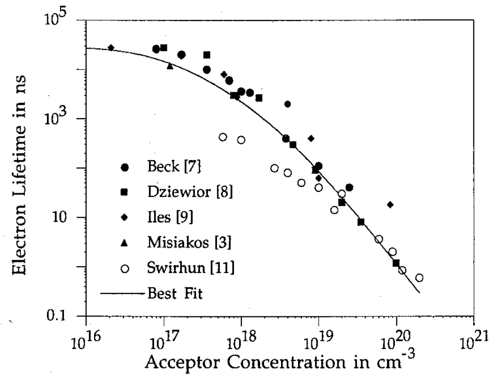

Fig. 2. Measured and best-fit electron lifetimes in heavily doped p-type silicon.

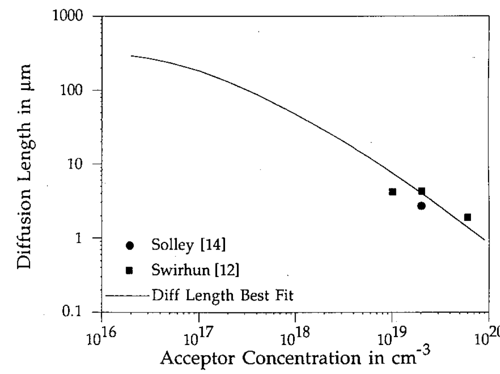

Fig. 5. Electron diffusion length measurement and best fit in p-type silicon.

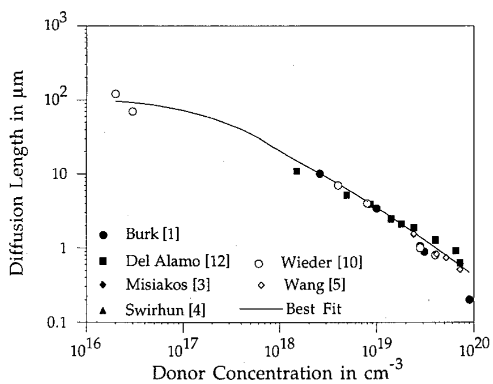

Fig. 3. Measured and best-fit minority-carrier hole diffusion lengths in n-type silicon.

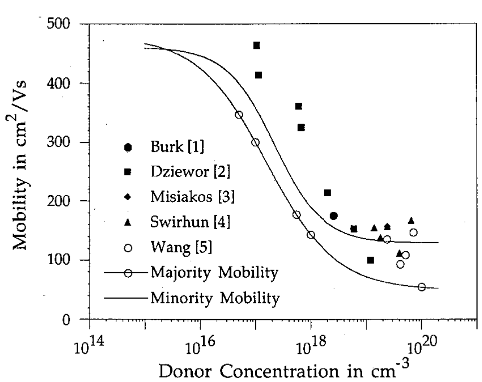

Fig. 4. Minority-carrier mobility in n-type silicon.

data in Fig 3. The lightly doped mobility $\mu_{\max}$ in (5) is chosen to agree with the value found in lightly doped acceptor material, 461 $cm^2/V \cdot s$ [13]. The best fit is obtained with $\mu_{\min} = 129\ cm^2/V \cdot s$, $N_{ref} = 2.2 \cdot 10^{17}\ cm^{-3}$, and $\alpha = 1.0$. The resulting fit for diffusion length is shown in Fig 3. This procedure results in a value of the mobility that is self-consistent with the diffusion length and lifetime measurements. In Fig. 4, the minority-carrier mobility best fit is compared with the majority-carrier mobility measurements [13] and minority-carrier mobility measurements [1]–[5]. There is considerably more scatter in the mobility measurements than in either the lifetime or diffusion length measurements, which is why it is important to fit to the latter data. This procedure helps to average out the experimental noise, which makes the data in Fig. 4 more difficult to fit.

IV. Electron Minority-Carrier Mobility

Unfortunately, there is less data on the electron minority-carrier diffusion length. Most of the measurements of electron minority-carrier mobility have used electroluminescence to extract the mobility. Using Swirhun *et al.*'s reported values [11] and the lifetime from Section I, a comparison to the existing diffusion length data can be performed. Fig. 5 shows that Swirhun *et al.*'s result and the lifetime extraction from Section I compare well with the limited data [11], [14] available. Further experimental work needs to be performed to assure that the electron minority-carrier mobility is correct.

V. Conclusion

A value for electron and hole lifetime was extracted using a doping-dependent SRH mechanism with an Auger process. The hole lifetime was used to extract a minority-carrier hole mobility that was consistent with the reported measurements of the hole diffusion length. Unfortunately, more limited data exist for the electrons, but Swirhun *et al.*'s value for the minority-carrier mobility is self-consistent with the limited diffusion length data available. This procedure has produced parameters that are self-consistent and suitable for use in simulation of bipolar devices.

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