Self-consistent determination of the generation rate from photoconductance measurements

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The determination of effective excess carrier lifetimes from photoconductance measurements generally requires knowledge of the absolute generation rate within a sample. Measurements of the generation rate typically involve measurement of the sample absorption spectrum and of the incident light intensity. This letter presents an experimental and analytical method by which both the effective lifetime and the generation rate can be self-consistently determined. The method involves only relative measurements of the generation rate, greatly simplifying the experimental requirements. Good agreement is found experimentally between the results achieved using this method and results from *transient* photoconductance measurements. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1807961]

The use of photoconductance (PC) measurements to determine the effective excess carrier lifetime τ_{eff} in semiconductor samples is a well-established experimental technique, which has been widely employed for the characterization of silicon samples in photovoltaics.[1,2] In a typical experimental setup the excess carrier concentration, $\Delta n(t)$, is measured inductively upon illumination from a flash-lamp. The generalized relation between τ_{eff} and Δn is given by[3]

$$\tau_{\mathrm{eff}} = \frac{\Delta n(t)}{G(t) - \dfrac{d\Delta n(t)}{dt}}, \tag{1}$$

where $G(t)$ is the time-dependent generation rate of excess carriers within the sample. Formulas representing the transient and steady state limiting cases, used to analyze photoconductance decay (PCD) and quasi-steady-state photoconductance (QSSPC)[4] experiments, can be recovered from Eq. (1) by setting the first and second terms in the denominator to zero. Generally Eq. (1) requires that both $G(t)$ and $\Delta n(t)$ be measured in absolute units for the calculation of τ_{eff} except in the strictly transient regime (PCD) where the generation rate is zero. Accurate direct determination of $G(t)$ involves the determination of the spectral absorptance *of each optically distinct sample* to be studied. In addition, the time-dependent spectral distribution of the incident photon flux must be known in absolute units. In typical practice the latter measurement is not made; rather a calibrated reference solar cell is used to measure the total photon flux.[1] Since the incident spectrum is in general not known, the sample spectral absorptance data can only be used to approximately correct the absolute generation rate for samples with dissimilar spectral absorptance to the reference cell.

The aim of this letter is the description of a PC method that eliminates the above mentioned experimental difficulties. In this method, the incident light intensity may be measured in relative units and no knowledge of the sample absorptance or of the spectrum of the light source is required, provided that it is constant. The main characteristic of the method is a self-consistent calibration of $G(t)$, in an intermediate photoconductance (IPC) regime (i.e., intermediate between transient and steady state). The calibration of $G(t)$ obtained in the IPC regime can be used subsequently for QSSPC experiments on the same sample.

For clarity the method is explained first on the basis of a simple numerical example. The time dependence of Δn is given by

$$\frac{d\Delta n(t)}{dt} = G(t) - \frac{\Delta n(t)}{\tau_{\mathrm{eff}}(\Delta n(t))}. \tag{2}$$

The time dependence of Δn was numerically calculated according to Eq. (2) for a triangular temporal generation profile with a frequency of 10 Hz and with a peak intensity of 1.5×10^{17} cm^{-3} s^{-1} (Fig. 1). We assumed a hypothetical material with a lifetime that varies linearly from $\tau_{\mathrm{eff}}=1$ ms at $\Delta n=0$ to $\tau_{\mathrm{eff}}=10$ ms at $\Delta n=10^{15}$ cm^{-3}.

We now imagine that the excess carrier density from Fig. 1 is observed experimentally together with the *relative* generation rate $G_{\mathrm{rel}}(t)$. The absolute generation rate is then given by $G(t)=f_s G_{\mathrm{rel}}(t)$ where f_s is an unknown scaling factor and

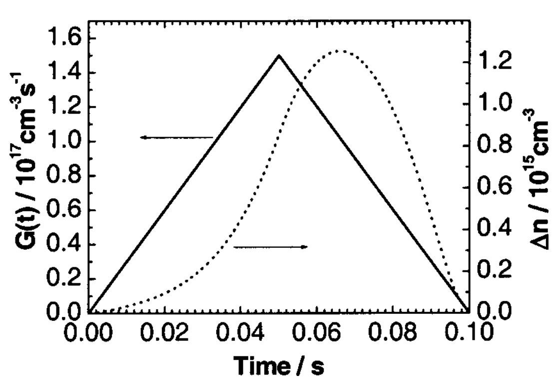

FIG. 1. Numerically calculated excess carrier density Δn (dotted, right scale) for a triangular generation rate (left scale) and an effective lifetime that varies linearly from $\tau_{\mathrm{eff}}=1$ ms at $\Delta n=0$ to $\tau_{\mathrm{eff}}=10$ ms at $\Delta n=10^{15}$ cm^{-3}.

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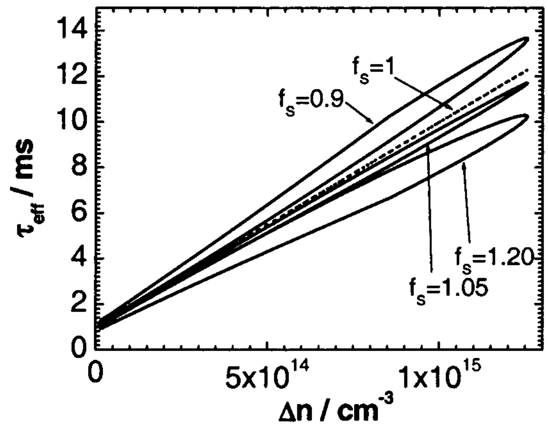

FIG. 2. Numerically calculated effective lifetime obtained from the data shown in Fig. 1 for different scaling factors f_s.

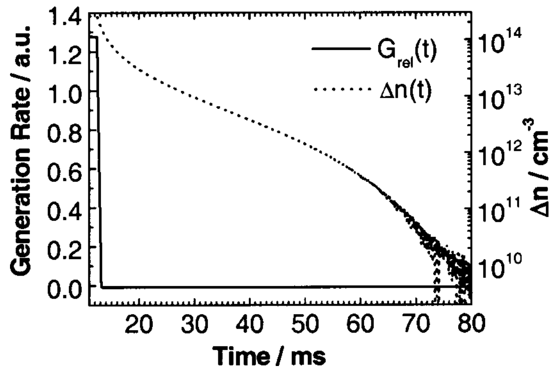

FIG. 4. PCD measurement on the test wafer [Δn: dotted line, $G(t)$: solid line].

Eq. (1) then becomes

$$\tau_{\mathrm{eff}} = \frac{\Delta n(t)}{f_s G_{\mathrm{rel}}(t) - \dfrac{d\Delta n(t)}{dt}}. \tag{3}$$

The numerically generated Δn data from Fig. 1 were analyzed using Eq. (3) with various trial values for f_s (Fig. 2). In general the correct value of f_s depends on several experimental variables. In this example $f_s = 1$ corresponds to the correct scaling factor. Only $f_s = 1$ (dotted) gives the correct injection level dependence of the effective lifetime while a hysteresis effect is obtained for values of f_s that deviate from unity. This is because the error in $\tau_{\mathrm{eff}}(\Delta n)$, due to the error in the denominator of Eq. (3), is different in the rising and falling branches of the generation profile. This difference arises from the different relative impact of $G(t)$ with respect to the derivative in the denominator and appears only in the intermediate regime, where $G(t)$ and the derivative of $\Delta n(t)$ are of a similar order of magnitude. For the analysis of experimental data, this implies that $G(t)$ can be very accurately calibrated using measured values of $G_{\mathrm{rel}}(t)$, if the derivative in the denominator of Eq. (3) is known in absolute units, which is the case in typical PC experiments in which absolute values for Δn are measured. Analysis of experimental data thus simply consists of varying the scaling factor f_s until hysteresis effects in the $\tau_{\mathrm{eff}}(\Delta n)$ curve are minimized. Figure 2 shows that fundamentally this procedure can be very accurate since a deviation in the generation rate of only a few percent (e.g., 5% for $f_s = 1.05$) from the correct value leads to a readily observable hysteresis effect.

In order to test the theoretically predicted effects experimentally we investigated a polished 420-μm-thick 4 in. Topsil 300 Ωcm n-type float zone silicon wafer that was passivated with a thermally grown oxide. For the PC measurements we used a commercial *Sinton*-flash-tester in which the flash was replaced by a $\lambda = 870$ nm LED array with a cw-optical output power of 1.5 W. Control of the light output from the LED array and the data acquisition were accomplished using a 16 bit data acquisition card.[5] The relative incident light-intensity, measured with a silicon *PIN* diode, was used as a measure of $G_{\mathrm{rel}}(t)$. Figures 3 and 4 show $\Delta n(t)$ from an IPC and from a PCD experiment, respectively. The incident light intensity in relative units, which is equivalent to $G_{\mathrm{rel}}(t)$, is plotted for comparison in both graphs.

We analyzed the data from Fig. 3 according to Eq. (3) using different scaling factors f_s (Fig. 5) with $f_s = 83$ leading to the smallest hysteresis effects. Note that this specific numerical value depends on the absorptance of the wafer, the size and sensitivity of the light sensor, the sample-detector geometry, the spectral light intensity of the excitation, and the gain of the preamplifier, i.e., exactly on those quantities which must normally be known accurately in absolute units. Importantly, the two other scaling factors used in Fig. 5 deviate from the best value by only roughly ±10%. Figure 5 shows that due to the observed hysteresis these values can clearly be discarded as inaccurate. The absolute generation

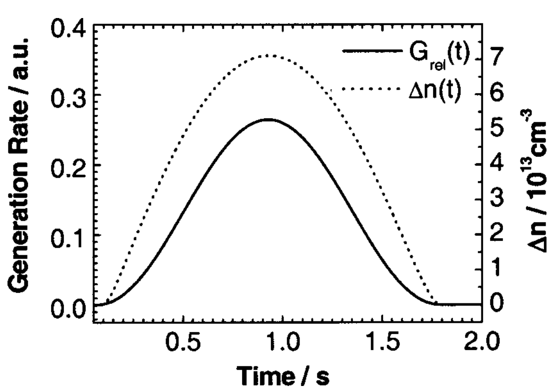

FIG. 3. Intermediate photoconductance (IPC) measurement on the test wafer. Δn (dotted) was measured in absolute units, while the incident light intensity (solid), equivalent to the relative generation rate $G_{\mathrm{rel}}(t)$, was measured in relative units.

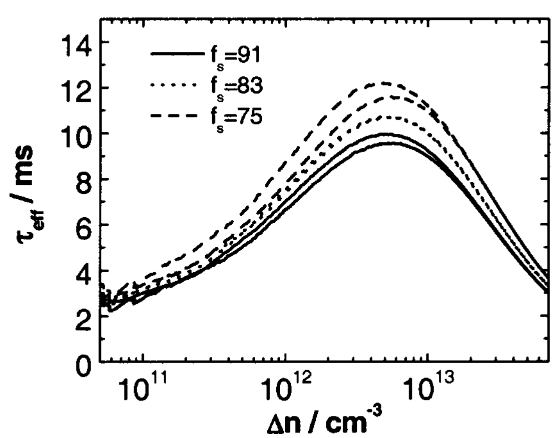

FIG. 5. Effective lifetime calculated from the experimental data from Fig. 3 using Eq. (3) with different scaling factors f_s.

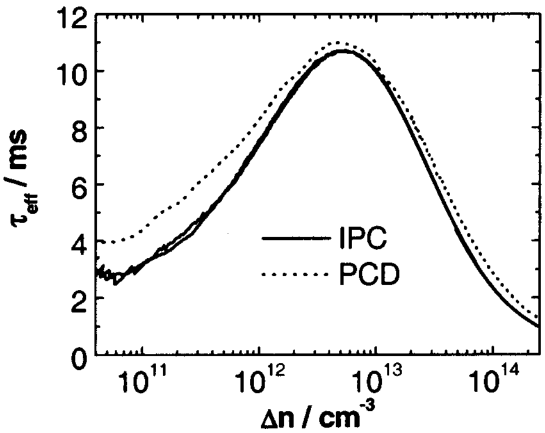

FIG. 6. Comparison of the effective lifetime obtained from the IPC data from Fig. 3 and from an additional IPC measurement at higher light intensity (both analyzed with $f_s = 83$) with the lifetime obtained from the transient (PCD) data shown in Fig. 4.

rate is thus determined with a relative error of only a few percent.

In Fig. 6 the injection level dependence of τ_{eff} from IPC (for $f_s = 83$) is compared to τ_{eff} calculated from the PCD experiment shown in Fig. 4. Good agreement is observed between the two data sets over the injection level range from 10^{12} cm^{-3} to 3×10^{14} cm^{-3}, with deviations $<3\%$ at the maximum of the curve. The deviation between the transient data and the IPC data at very low injection levels ($<10^{12}$ cm^{-3}) may be related to trapping effects.[6] The exact interpretation of the data in Fig. 6 is beyond the scope of this letter but it should be noted that the τ_{eff} data obtained from IPC can be fitted very accurately with a simplified SRH term and an emitter–current contribution.[2]

The analysis suggested here is restricted to experimental setups in which the external excitation can be varied in a controlled way. LED arrays are a near ideal tool in this regard, in contrast to the flash lamp widely used in PC measurements. Silicon samples used in commercial photovoltaic products typically have lifetimes on the order of tens to a few hundred microseconds, requiring modulation frequencies of up to hundreds of kilohertz to reach the IPC regime. LED light sources, which have a typical response time of tens of nanoseconds, do not represent a limitation in this regard.

Other advantages of the LED array include its longer lifespan, the ease of repetitive signal averaging under computer control, and the relative invariance of the LED luminescence spectrum with changing light intensity. Repetitive signal averaging results in lower noise and thus significantly higher sensitivity. The spectral invariance of the LED array avoids significant complications in the analysis of the experimental data that arise from spectral variations in the thermal emission of flash lamps. While all of the above-mentioned features are advantageous for PC lifetime experiments in general, the latter feature is particularly important in the self-consistent method described here, since it avoids a residual minimum hysteresis, which would otherwise reduce the accuracy of the method.

In conclusion, we have theoretically and experimentally demonstrated the self-consistent IPC technique, a method by which absolute values of the effective carrier lifetime can be accurately determined, without the usual need to measure the absolute generation rate. The suggested procedure simplifies the investigation of samples with different absorption spectra and is also potentially more accurate as any effects of uncertainties in the calibration of the absorbed light intensity are removed. Good agreement is found between the results achieved using this method and results from PCD measurements, thereby demonstrating the feasibility of the method. We expect that the method should be applicable to Suns-V_{OC} measurements[7,8] and we have also successfully applied it to photoluminescence lifetime measurements.[9]

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