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Contactless determination of current–voltage characteristics and minority-carrier lifetimes in semiconductors from quasi-steady-state photoconductance data

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A simple method for implementing the steady-state photoconductance technique for determining the minority-carrier lifetime of semiconductor materials is presented. Using a contactless instrument, the photoconductance is measured in a quasi-steady-state mode during a long, slow varying light pulse. This permits the use of simple electronics and light sources. Despite its simplicity, the technique is capable of determining very low minority carrier lifetimes and is applicable to a wide range of semiconductor materials. In addition, by analyzing this quasi-steady-state photoconductance as a function of incident light intensity, implicit current–voltage characteristic curves can be obtained for noncontacted silicon wafers and solar cell precursors in an expedient manner. © *1996 American Institute of Physics.* [S0003-6951(96)02743-X]

Measurements of minority-carrier lifetime in silicon wafers are extremely valuable for process control and device optimization as well as for material and device physics research. A common technique is based on the analysis of photoconductance decay transients after a very short light pulse from a laser, flash lamp, light-emitting diode (LED) array or laser diode. The effective lifetime is obtained from the slope of the decay curve. This method has been widely developed and many techniques have been used to sense the photoconductivity without contacting the wafer, including microwave reflectance, capacitive coupling, and the use of a coil to couple inductively the wafer conductivity. For a typical induction-coupling apparatus with a 5 μs light pulse and a radio frequency of 10 MHz, effective lifetimes greater than 50 μs are easily and accurately measured.[1] Lower lifetimes, in the 10 ns range, have been determined with more sophisticated instruments using shorter light pulses and higher frequency circuits.[2] In the case of very low lifetimes, surface recombination transients and minority-carrier spreading effects are present that complicate the interpretation of the measurements.

An alternative method based on measuring the photoconductance under steady- or quasi-steady-state illumination is presented in the following sections. The method is aimed at simplifying the determination of very low lifetimes, although it can also be used for moderate and high effective lifetimes.

For clarity, we begin with a summary of the classical analysis of the photoconductance. In a semiconductor under steady-state illumination, a balance exists between the generation and the recombination of electron-hole pairs. Expressing the photogeneration and recombination rates as current densities:

$$J_{\mathrm{ph}}=J_{\mathrm{rec}}. \tag{1}$$

As a consequence of this balance, an excess concentration of electrons and holes is established in the material. The total recombination in a sample of thickness W can be conveniently expressed in terms of an average excess minority carrier density, Δn_{av}, and an effective minority carrier lifetime, τ_{eff}, leading to

$$J_{\mathrm{ph}}=\Delta n_{\mathrm{av}} qW/\tau_{\mathrm{eff}}, \tag{2}$$

which essentially is a version of the classic relationship, $\Delta n=G_L\tau_{\mathrm{eff}}$. The photogenerated excess electron and hole densities, $\Delta n=\Delta p$, also result in an increase in the conductance of the sample. The excess photoconductance is given by

$$\sigma_L=q(\Delta n_{\mathrm{av}}\mu_n+\Delta p_{\mathrm{av}}\mu_p)W=q\Delta n_{\mathrm{av}}(\mu_n+\mu_p)W. \tag{3}$$

For many semiconductors, and for silicon in particular, the electron and hole mobilities are well known and their dependence on both the sample doping and the injection level can be found in the literature.[3,4] Equation (3) can be iterated to find both Δn_{av} and $(\mu_n+\mu_p)$ consistent with the measured conductance. A measurement of the photoconductance is, therefore, a nearly direct way of probing for the excess carrier density.

The effective minority carrier lifetime can be determined from Eqs. (2) and (3)

$$\tau_{\mathrm{eff}}=\sigma_L/[J_{\mathrm{ph}}(\mu_n+\mu_p)]. \tag{4}$$

The conductance and the incident light intensity can be measured using a calibrated instrument and a reference solar cell or photodiode, respectively. For a given irradiance, J_{ph} can be easily and accurately estimated using available computer programs or lookup tables. In a typical 380-μm-thick silicon wafer with low reflection losses, the standard global AM1.5 solar spectrum produces a total photogeneration, J_{ph}, of approximately 38 mA/cm^2. The value of J_{ph} relative to the reference solar cell can be adjusted for a particular sample to take into account different front surface reflectivities, wafer thicknesses, light-trapping features, or illumination spec-

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trums. In most practical situations, J_{ph} lies within a tight range of 34–42 mA/cm^2, even after these possible variations have been considered. A similar evaluation of J_{ph} is possible for other semiconductor materials.

In general, the excess carrier density is position dependent. The total number of carriers divided by the wafer thickness gives the average density, Δn_{av}, used in Eqs. (2) and (3). Note, however, that the effective lifetime determined from a photoconductance measurement does not depend on the details of the minority-carrier distribution, except for the very weak dependence introduced by evaluating $(\mu_n+\mu_p)$ at the average carrier concentration.

A convenient implementation of the steady-state approach described above is to use a light pulse that varies *very slowly* compared to the effective lifetime of the sample. This offers an expedient method for obtaining the photoconductance under a wide range of illumination intensities in a short time without significant sample heating. Analysis of the photoconductance as a function of irradiance provides additional useful information, including an implicit current–voltage $(I-V)$ characteristic curve, as shown below, and the ability to separate out different bulk and surface recombination mechanisms.[5]

Photoconductance instruments operating at 8–10 MHz were used for this work. A coil in a bridge circuit couples to the conductivity of the wafer. A signal proportional to this conductivity is observed on a digital oscilloscope and transferred to a computer for analysis. The voltage signal was verified to be linear in wafer conductivity over the entire range of interest. A flashlamp light source capable of 100 W/cm^2 (1000 suns) and having a fast rise time followed by a 2.3 ms decay time for a total time length of 7 ms was used.

In the quasi-steady-state technique, the effective lifetime is determined at every light intensity following the procedure and equations outlined in the previous section. Compared to a transient decay approach, the quasi-steady-state method allows the measurement of very low lifetimes without fast electronics or short light pulses. The range of measurable lifetimes is only limited by signal strength. The sensitivity of the instruments used here was 7–27 V/S. Considering that 5 mV constitutes an adequate signal, Eq. (4) implies that the detection limit of this instrument is 3 μs at one sun illumination. To measure very low lifetimes, the light intensity can be increased. If the irradiance is increased to 1000 suns the detection limit becomes 3 ns. An example of the capability to measure low lifetimes is given in Fig. 1. The effective lifetime of this small-grained p-type, 0.015 Ω cm multicrystalline silicon wafer with boron diffusions on both surfaces is approximately 370 ns. The effective minority carrier lifetime can vary with the injection level. In the case of Fig. 1 τ_{eff} was determined at high injection levels, where it is approximately constant.

When using an illumination that varies slowly instead of being truly constant, care must be taken that errors are not introduced into the analysis by the deviations from steady-state conditions. A numerical solution for the time-dependent photoconductance that would result from an exponentially decaying light pulse with a characteristic decay constant of 2.3 ms was compared to the steady-state Eqs. (3) and (4) to evaluate the possible error. For minority-carrier lifetimes less than 60 μs, the error is less than 1%. The error increases to 10% for 230 μs minority-carrier effective lifetimes. To maintain this accuracy, data must be discarded prior to a time equal to three minority-carrier lifetimes after the peak light intensity in order to avoid effects from the fast rise time of the light pulse.

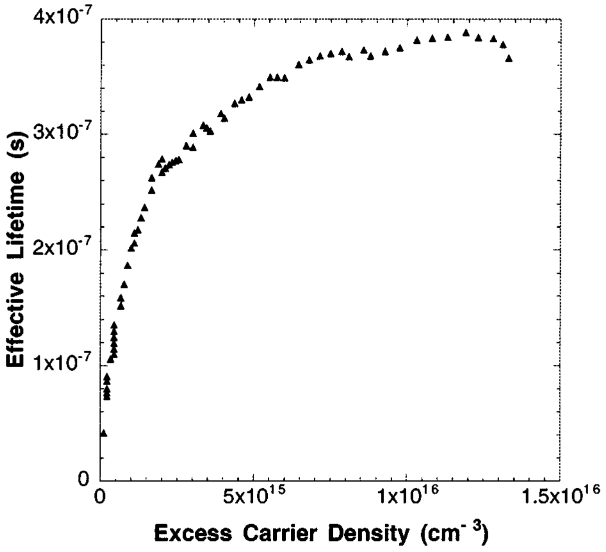

FIG. 1. Effective lifetime vs minority-carrier density for a small-grained multicrystalline silicon sample (p-type, 0.015 Ω cm, 500-μm-thick wafer, both surfaces passivated with boron diffusions). Temperature 25 °C.

This indicates an applicability of the quasi-steady-state technique (using this particular flashlamp) of nearly four orders of magnitude from about 10 ns to 60 μs. Note, however, that higher lifetimes can also be measured using the same basic apparatus. Several options exist, the first being to use a longer light pulse. The second alternative is to use a constant illumination, for example from a ELH lamp. The high photoconductance corresponding to high lifetime samples is easily measured even at relatively low light intensities. For example, we have measured a 3.5 ms lifetime at one third of a sun for an oxide passivated 1000 Ω cm FZ silicon wafer. The third option is to change the flashlamp pulse to its minimum duration and use the transient photoconductance decay method described in the Introduction. We have found a good agreement between the transient, steady and quasi-steady methods.

The quasi-steady-state photoconductance data implicitly contain information about the short-circuit current versus open-circuit voltage, $I_{\mathrm{sc}}-V_{\mathrm{oc}}$, characteristics of the device or structure being measured. The short-circuit current is implied by the irradiance. The excess carrier density implies an open circuit voltage, the separation of the quasi-Fermi levels. In fact, photoconductance and voltage are both measures of the same excess minority-carrier density. For a solar cell made on a p-type wafer with dopant density N_A, the implicit voltage depends on the $p-n$ product at the junction:

$$V_{\mathrm{oc}}=(kT/q)\ln[(\Delta n(N_A+\Delta p)/n_i^2)+1]. \tag{5}$$

The *local* excess minority carrier density in Eq. (5) is essentially equal to the *average* Δn_{av}, obtained from Eq. (3) when the surfaces of the sample are passivated and the minority-

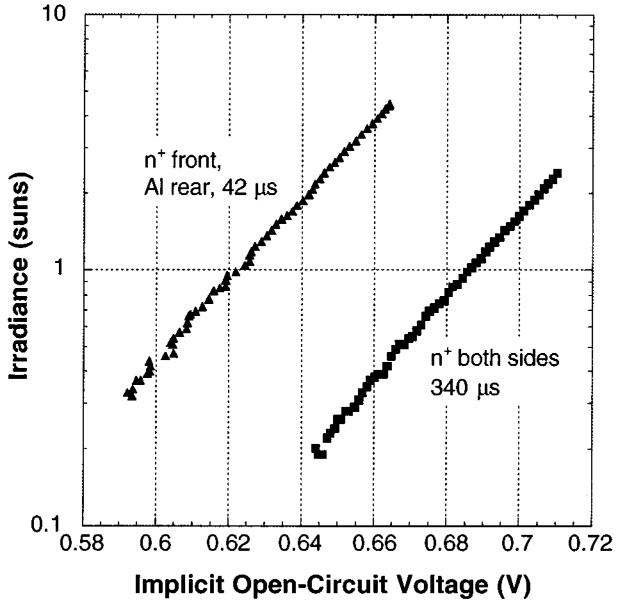

FIG. 2. Implicit open-circuit voltage vs illumination intensity curves at two stages during a solar cell fabrication sequence (*p*-type, 1 Ω cm FZ monocrystalline silicon wafers). The actual V_{oc} after cell completion was 620 mV. Temperature 25 °C.

carrier diffusion length is greater than the wafer thickness. It is also possible to find a simple relationship between the minority carrier density at a front junction and Δn_{av} in other relevant cases. For example, when the bulk minority carrier lifetime is very low, a better approximation is $\Delta n_{av}(W/L_{eff})$. When the rear surface recombination velocity is very high, $2\Delta n_{av}$ is appropriate.

Note that Eq. (5) is valid for any doping level or minority-carrier-injection level. A plot of irradiance versus implicit voltage will show the different ideality factors from all the recombination mechanisms and their injection-level dependence without additional assumptions. This is in contrast to the effective lifetime, whose definition becomes ambiguous due to the changing device physics at each injection level.

The techniques described above were applied to process monitoring through several stages of a Back Surface Field solar cell fabrication process. *p*-type, 1 Ω cm, float zone monocrystalline silicon wafers were used in the experiment. After phosphorus diffusion plus oxidation (with the diffused region on both sides of the wafer) the effective lifetime was quite high, 340 μs. This value can be interpreted as a lower bound on the lifetime of the bulk silicon material. After aluminum alloying at the rear, the effective lifetime decreased to 42 μs, mainly due to the additional recombination in the aluminum doped back p^+ surface region. In Fig. 2 the photoconductance data are displayed in the form of implicit $I_{sc} - V_{oc}$ curves. Both curves have a unity ideality factor from 0.3 to 5 suns illumination. The implied V_{oc} at one sun drops from 686 mV after the initial phosphorus diffusion step to 622 mV after the aluminum diffusion on the rear of the wafer. After the metal contacts were applied, the actual V_{oc} of the device was found to be 620 mV, in excellent agreement with the prediction from the quasi-steady-state photoconductance method. This agreement, which was also found in other experiments with different solar cell structures and materials, confirms the validity and usefulness of displaying photoconductance data in the form of implicit voltage.

In conclusion, quasi-steady-state photoconductance data have numerous applications for semiconductor material and device characterization. In particular, we have shown the implementation of a contactless current–voltage measurement technique for solar cells based on an expanded interpretation of these data. Except for the short-circuit current and resistive effects, many relevant parameters of a solar cell, including the open-circuit voltage, saturation current density and ideality factor can be determined without depositing the metallic contacts or using patterning techniques.

The method is simple and the data have a clear physical interpretation. It is compatible with the transient photoconductance decay approach and offers a means of extending measurement capabilities to very low effective minority-carrier lifetimes with the same apparatus. It has several additional advantages:

(i) Even when measuring lifetimes lower than 1 μs, the data acquired is from a ms-range slowly changing wave form, eliminating the fast electronics required for a transient decay measurement as well as the need for a very short light pulse.

(ii) In the range of applicability, it is effectively a steady-state measurement, similar to a solar cell in actual operation. The recombination components are weighted as in the actual device under open-circuit voltage conditions including the transport and nonuniform photogeneration effects on the carrier-density profiles.

(iii) By analyzing the data in the form of an implied $I-V$ curve or illumination-Vcurve, the data is in the form most useful for solar cell analysis and process development.

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