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ADVERTISMENT
Defect specific photoconductance: Carrier recombination through surface and other extended crystal imperfections

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The analysis of carrier recombination through defects using a unified approach, common to all extended defects independent of their dimensionality is presented. The considered crystal defects include surface, grain boundaries, dislocations, and clusters of crystal defects and impurities. It is shown that, at low carrier injection levels, carrier recombination through extended defects is controlled by the electrostatic potential barrier formed at the defects. The barrier model is applied to the analysis of the photoconductance in the defect controlled regions. Unlike in the case of recombination through point defects in the bulk, which is characterized by the linear dependence of the steady-state photoconductance on the light intensity and exponential decay of the photoconductance after cessation of the illumination, the photoconductance associated with recombination through extended defects under depletion conditions exhibits logarithmic dependence on the light intensity and characteristic logarithmic decay after cessation of the illumination. The predictions of the “barrier-controlled recombination” model are compared with the measurements of photoconductance in electronic grade silicon. Differentiation between time dependences of the photoconductance decay associated with recombination through the point defects and through the extended crystal imperfections is used as a basis of the defect specific photoconductance (DSPC) methodology. It is shown that DSPC allows for the separation of the bulk and surface characteristics without any additional surface treatments, enabling electrical characterization of both bulk and thin-film wafer structures critical for photovoltaic (PV) solar cell and high-brightness light emitting diode (HB-LED) manufacturing. The comparison of the “barrier-controlled recombination” and standard diffusion model based on surface recombination velocity is discussed. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4754835]

I. INTRODUCTION

The rapid expansion of semiconductors beyond conventional silicon device applications and the associated introduction of new, lower quality materials, and thin films necessitates a better understanding of the influence of defects in these materials on the recombination of charge carriers. The properties of these materials are frequently controlled not just by zero-dimensional (0-D) point defects but also by extended crystal imperfections. This class of extended imperfections includes 1-D edge dislocations, 2-D surfaces, interfaces and grain boundaries, and 3-D clusters of impurities or crystallographic defects. These extended defects may differ in their chemical composition and their crystallographic structure, resulting in a different electronic structure. However, all of them as a class exhibit one common and fundamental feature differentiating them from the point defects. Point defects, with few exceptions, act as an independent recombination centers. The capture of a charge carrier at one center does not affect recombination process at the neighboring centers. The situation for the extended defects is quite the opposite. Because electronic sites at the extended defects are close to each other, the capture of a carrier at one site will affect the recombination process at neighboring sites. The classical approach to considering recombination through the extended crystal imperfections, such as the surface, includes consideration of the electrostatic potential barrier. The concept of the surface recombination controlled by the potential barrier was successfully applied to the characterization of semiconductors using surface photovoltage (SPV) effect. This concept was also used to describe photoconductance controlled by carrier recombination at edge dislocations in Ge. In this case, the proposed model assumed that electronic states are associated with dangling bonds. It was subsequently shown that dangling bonds do not dominate the electronic structure of dislocations in germanium but instead are replaced with the amorphous and stressed dislocation regions. Furthermore, it was shown that photoconductance is, similarly to the dangling bonds model, controlled by the carrier recombination limited by the electrostatic potential barrier associated with the amorphous regions.

This paper goes beyond specific extended defects models and presents an analysis of the carrier recombination at all extended defects with unified approach, independent of the defect dimensionality. The recombination parameters, dependent on the dimensionality and symmetry of the potential barrier at the defect, characterizing recombination at the selected crystal imperfections are derived. Emphasis is placed on the effect of the recombination at the surface (the most studied type of “crystal imperfection”) on photoconductance. The predictions of the proposed model are compared with the results of measurements of photoconductance in electronic grade silicon. The model also matches the experimental results for the dislocations. Differentiation between time dependences of the photoconductance decay (PCD) associated with the recombination through point defects and through...
extended crystal imperfections is used as a basis of the defect specific photoconductance (DSPC) methodology. It is shown that DSPC allows for the separation of the bulk and surface characteristics including their contribution to the carrier recombination without any additional surface treatment.

II. SURFACE RECOMBINATION VELOCITY (SRV)

The standard treatment of surface recombination in photoconductance is based on the consideration of diffusion of carriers towards the surface and accounting for recombination at the surface using time independent “SRV.” From this point of view, the “barrier controlled recombination” approach discussed in this paper effectively replaces time independent SRV with the time dependent surface recombination rate. At sufficiently low injection levels, the time dependence of surface (or in general, extended defects) recombination rate can dominate over the time dependence associated with the carrier diffusion towards the surface.

The “barrier controlled recombination” model is valid for extended defects under depletion conditions, i.e., space charge regions (SCRs) depleted of majority carriers. The excess minority carriers generated within the surface SCR are swept towards the surface. As a result of this, the excess carrier density at the edge of SCR is zero, which from the recombination point of view means infinite SRV at the edge of SCR. This high SRV results in enhanced diffusion of carriers generated outside of SCR toward the surface and enhanced accumulation of the minority carriers at the surface. Accumulation of the minority carriers at the surface, and their isolation from the bulk due to the electrostatic potential barrier, causes barrier controlled surface recombination to dominate over the recombination of carriers in the bulk surrounding the SCR. However, excess accumulated minority carriers reduce substantially the height of the potential barrier which reduces the effect of the barrier on carrier recombination, causing conventional diffusion controlled effects to dominate.

As follows from the above discussion, control of the height of the surface (or defect) potential barrier is essential for the reproducibility of the photoconductance measurements. Preservation of the electrostatic potential barrier requires limiting of the accumulation of minority carriers at the surface (or defect). This accumulation depends not only on the background illumination and generation rate during the illuminating pulse but also on the frequency of pulses. If a pulse averaging measurement method is used, e.g., in the PCD method, the conductance of the sample needs to reach essentially its dark value before the next pulse is started. Not complying with this condition would affect time dependence of the photoconductance.

III. BASIC CONSIDERATIONS

A. Photoconductance associated with recombination through point defects

Zero-dimensional (0-D) point defects include single atoms and small clusters of impurities and/or crystallographic defects. Classic examples of such defects are interstitials and a two-atom FeB pair in silicon. Considering carrier recombination, the feature that distinguishes a 0-D defect from an extended crystal imperfection is that the 0-D defect is characterized by a single electronic site whose occupation is not dependent on the occupation of sites associated with neighboring defects. The photoconductance rise (i.e., the rise in photoconductance after commencing illumination of a sample) and photoconductance decay (i.e., the decay in photoconductance after terminating illumination of a sample) associated with recombination at point defects are characterized by an exponential dependence on time; the steady-state photoconductance exhibits a linear dependence on the intensity of the illumination or on the associated optical carrier generation rate. The photoconductance decay associated with point defects at low injection levels and for infinite sample is given by

\[ \Delta \sigma_{0-D}(\text{decay}) = \Delta \sigma_{0-D}(0) \exp\left(-\frac{t_d}{\tau_{0-D}}\right), \]

where \( \Delta \sigma_{0-D}(0) \) is the steady-state photoconductance or, more generally, the initial photoconductance at time \( t_d = 0 \), immediately at the cessation of the illumination pulse; and \( \tau_{0-D} \) is the effective minority carrier recombination lifetime due to recombination at point defects. The photoconductance rise associated with the point defects is given by

\[ \Delta \sigma_{0-D}(\text{rise}) = \Delta \sigma_{0-D}(0) \left[1 - \exp\left(-t_r/\tau_{0-D}\right)\right], \]

where \( \Delta \sigma_{0-D}(0) \) is the steady-state photoconductance or, more generally, the photoconductance reached after several (practically at least 3 to 5) time constants (carrier recombination lifetimes) after starting of the illumination pulse. Note that both photoconductance decay and rise are described by the same steady-state photoconductance \( \Delta \sigma_{0-D}(0) \); and \( \tau_{0-D} \) is the effective minority carrier recombination lifetime due to recombination at point defects, the same as for the photoconductance decay. If various types of point recombination centers are present in a sample, the effective recombination lifetime is a combination of the lifetimes associated with each type of point imperfection.

In the absence of carrier trapping effects, typically associated with multi-dimensional defects, the density of excess electrons and holes is equal and the steady-state photoconductance associated with point defects is given by

\[ \Delta \sigma_{0-D}(0) = q(\mu_e + \mu_h)G_{0-D}\tau_{0-D}, \]

where \( q \) is the magnitude of the elementary charge, \( \mu_e \) and \( \mu_h \) are the mobilities of the electrons and the holes, respectively, and \( G_{0-D} \) is the generation rate in the vicinity of a point imperfections.

B. Carrier recombination through extended defects

As discussed before, extended multi-dimensional (M-D) defects include one-dimensional (1-D) defects, such as edge dislocations, two-dimensional (2-D) defects, such as surfaces and grain boundaries, and three-dimensional (3-D) imperfections, such as large (i.e., consisting of a large number of atoms) clusters of impurities or lattice defects. Trapping of majority carriers by an extended defect causes the defect to
become electrically charged, producing an electrostatic potential barrier $\Psi_d$ at the defect that limits the further capture of majority carriers. In some cases, such as at a surface, a charge arises due to built-in charge, such as charge due to ions adsorbed at the surface or a fixed oxide charge at an interface between silicon and silicon dioxide. Charges at extended defects induce a Schottky-type depletion space charge region in the vicinity of the imperfection. Fig. 1 schematically illustrates band diagram at the surface of n-type semiconductor under depletion conditions (a) and at the 1-D and 2-D defects in the bulk of n-type semiconductor (b). In the case of grain boundary, the distance is measured perpendicular to the boundary and in the case of edge dislocation, the potential has cylindrical symmetry and the distance is a radial distance from the axis of the cylinder.

1. Basic relationships

This section focuses on the effect of carrier recombination through extended defects on photoconductance. These considerations are based on the previous analysis of the surface recombination in the surface photovoltage effect discussed in detail in Ref. 2 and carrier recombination at edge dislocations discussed in Refs. 4 to 6.

Let us consider an n-type semiconductor illuminated with light of photon energy higher than the band-gap energy of the semiconductor. It is assumed that we are dealing with a homogeneous single crystal whose dimensions are large compared to the width of the Schottky-type depletion layer present at the defect. The sample is uniformly illuminated, so that the problem for a defect is reduced to one dimension either linear for 2-D defects or radial for 1-D defects. The height of the potential barrier at the defect, $\Psi_d$, is assumed to be much greater than $kT$. Processes that control carrier recombination at the extended defects are illustrated in Fig. 2 using as an example band diagram at the surface of an n-type semiconductor.

Photogeneration of electron-hole pairs in the vicinity of an extended defect leads to an increase in the total density of the minority carriers (holes) at the defect. The minority carriers could be either trapped at the defect states or in the minority band by the potential barrier. However, at low illumination intensities considered in this paper, the density of the “free” minority carrier at the defect can be neglected. The rate of change of the defect charge density (1/cm$^2$), $Q_d$, (neglecting the charge due to free electron at the defect) is given by the following equation:

$$ q^{-1} \frac{dQ_d}{dt} = G_{sc} - R_c, $$

where $R_c$ is the net capture rate (1/cm$^2$ s) of electrons by defect states and $G_{sc}$ is an effective minority carrier (hole) generation rate (1/cm$^2$ s) in the vicinity of the extended defects that includes both the light induced generation rate in this region and the minority carriers diffusing, as discussed earlier, into the vicinity of the extended defects from outside of this region. Equation (4) reflects an assumption that all the minority carriers generated in the vicinity of the extended defects are trapped at these defects and that recombination of the carriers in this region proceeds mainly through the defect states.

Fig. 1. Energy band diagram at the surface of n-type semiconductor (a) and at the 1-D and 2-D defects in the bulk of n-type semiconductor (b). In the case of grain boundary, the distance is measured perpendicular to the boundary and in the case of edge dislocation, the potential has cylindrical symmetry and the distance is a radial distance from the axis of the cylinder.
Following Read’s considerations,10 the fraction of occupation approximation for a planar 2-D defect, $j_d$ to be much smaller than barrier height at thermal equilibrium, is given as
\[ N_t = \frac{q}{kT} \frac{d}{e_s} \exp \left( \frac{-\Delta \Psi}{kT} \right), \]
where $e_s$ is the permittivity of the semiconductor. In small disturbance approximation, when $\Delta \alpha/\Delta \Psi \ll 1$, we get from Eq. (6)
\[ \Delta \alpha = C_0 \frac{Q_{sd} \Delta \alpha}{e_s} \frac{\Delta \Psi}{\Delta \omega}, \]
and since $\Delta Q_d = \frac{Q_{sc}}{e_s} \Delta w = \frac{Q_{sc}}{e_s} N_t \Delta f$, we get $\Delta w = N_t \Delta f/ N_{sc}$ and hence
\[ \Delta \Psi_d = \Xi \eta, \]
where for 2-D planar defect,
\[ \Xi_{2-D} = \frac{Q_{sc} N_t \Delta f}{e_s N_{sc}} \]
and for one-dimensional defects, such as edge dislocations,4 the parameter $\Xi$ is given as
\[ \Xi_{1-D} = \Psi_{sd}. \]

2. Steady-state
At steady-state $d Q/d t = 0$ and from Eqs. (4) and (5) using notation of Eq. (8)
\[ G_{sc} = c_e N_t n_0 \exp \left( \beta \Psi_{sd} \right) \exp \left( \beta \Delta \Psi_d \right) \exp \left( \beta \Xi \eta \right) - 1 - \eta \].

As discussed earlier, $G_{sc} = \frac{Q_{sc} N_t \Delta f}{e_s N_{sc}}$ is the total carrier generation rate (1/cm² s) in the defect region and includes both the carriers generated optically and those that diffuse from the outside of this region. All these carriers accumulate at the defect and recombine through the defect states.

a. $\beta \Delta \Psi_d \ll 1$. In the case when $\beta \Delta \Psi_d = \beta \Xi \eta \ll 1$, from Eq. (11),
\[ \eta = \frac{G_{sc}}{c_e N_t n_0 \exp \left( \beta \Psi_{sd} \right) \exp \left( \beta \Xi - 1 \right)} \]
Since the minority carriers trapped at the defects do not contribute to the photoconductance, the photoconductance associated with electron-hole pairs generated in the vicinity of the defects is due to excess majority carriers (electrons) only. Taking into account that the density of the excess electrons in the vicinity of the defects is equal to the density of holes trapped at the defect, $\Delta n = -N_t \Delta f$, and using Eq. (12)
\[ \Delta n = \frac{Q_{sc}}{e_s} \exp \left( \beta \Psi_{sd} \right) \exp \left( \beta \Xi - 1 \right) \]
and
\[ \Delta \sigma_{sc} = q \mu_e G_{sc} \tau_e, \]
where
\[ \tau_c = \frac{f_0}{b_c n_0 \exp(\beta\Psi_{d0})(1 - \beta \Xi)} \] (15)

represents carrier recombination lifetime analogous to the carrier lifetime in the case of point defects (see Eq. (3)). Therefore, at low enough carrier generation rates, such that \( b \Delta \Psi_d \ll 1 \), the photoconductance associated with the recombination at the extended (M-D) defects depends, similarly as for point (0-D) defects, linearly on the light intensity.

\[ \text{b. } b \Delta \Psi_d \gg 1. \] At higher generation rates in the vicinity of extended defects, such that \( b \Delta \Psi_d = \beta \Xi \eta \gg 1 \), non-exponential terms of the bracket in Eq. (11) could be neglected and
\[ \eta = \frac{1}{b^2} \left[ \ln \left( \frac{G_{sc}}{b_c n_0} \right) - \beta \Psi_{d0} \right] \]

and using Eq. (13)
\[ \Delta \sigma_{M-D} = -q \mu_e \frac{N_d f_0}{b^2} \ln \left( \frac{\exp(-\beta \Psi_{d0})}{b_c n_0} G_{sc} \right) \] (16)

For 2-D defect, using Eq. (9),
\[ \Delta \sigma_{2-D} = -q \mu_e \frac{e \tau_c}{b Q_{d0}} \left[ \ln(G_{sc}) + \ln \left( \frac{\exp(-\beta \Psi_{d0})}{b_c n_0} \right) \right] \] (17)

Therefore, at higher generation rates, such that \( b \Delta \Psi_d \gg 1 \), the steady-state photoconductance associated with the recombination at extended defects is logarithmically dependent on the light intensity. As shown in Fig. 3, the contribution of extended and point imperfections to the carrier recombination depends on the carrier generation rate (carrier injection level) with extended defects dominating at low generation rates and point defects at high generation rates. This feature can be used to distinguish between point and extended defects. In the case of the surface, the intersection of the point and extended defect generation rate dependencies is a function of the illumination wavelength. An increase in the wavelength, and associated with it increased light penetration depth into the bulk, increases contribution of the bulk recombination through the point defect.

At low-generation limit, corresponding to \( b \Delta \Psi_d \ll 1 \), the generation rate dependence for the extended defect becomes linear (see Eq. (14)) deviating from the straight line shown in Fig. 3. At higher generation rates, corresponding to \( b \Delta \Psi_d \gg 1 \), the slope of the generation rate dependence of the steady-state photoconductance is given, for the 2-D defects, by
\[ \frac{d(\Delta \sigma_{2-D})}{d(\ln G_{sc})} = -q \mu_e \frac{e \tau_c}{b Q_{d0}}. \] (18)

This slope depends on the ratio of the doping concentration and the density of charge at extended defects that, for surfaces under inversion conditions, can be used to determine doping concentration in the subsurface region. In semiconductors with several types of extended defects (e.g., multicrystalline material with different size and crystallographic orientation of grain boundaries) or even the same type of defect in different charging state, measurement of the slope, given by Eq. (18), as a function of generation rate (injection level) can be used to distinguish between different types of extended defects as well as their states.

3. Photoconductance decay

During photoconductance decay measurement, the decay of the excess carrier density is monitored after the carrier excitation source is turned off, \( G_{sc} = 0 \). Since \( \Delta Q_d = -q N_d f_0 \eta \), using Eqs. (4) and (5) and notation Eq. (8), we get
\[ \frac{d\eta}{d\tau} = \frac{c_e n_0}{f_0} \exp(\beta \Psi_{d0}) \left[ \exp(\beta \Xi \eta) - 1 - \eta \right]. \] (19)

\[ \text{a. } b \Delta \Psi_d \ll 1. \] In the case when \( b \Delta \Psi_d = \beta \Xi \eta \ll 1 \),
\[ \frac{d\eta}{d\tau} = \frac{c_e n_0}{f_0} \exp(\beta \Psi_{d0}) (\beta \Xi - 1) \eta \] (20)
and
\[ \eta = \eta(0) \exp(-t/\tau_c) \] (21)
where \( \eta(0) \) is the value of trapping level at \( t = 0 \) and \( \tau_c \) is given by Eq. (14). Since the excess density of electrons in the vicinity of the defects is equal to the density of holes trapped at the defect, \( \Delta n = -N_d f_0 \eta \), the decay of the photoconductance at
low enough carrier generation rates, such that \( \beta \Delta \Psi_d \ll 1 \), using Eq. (13) is given by

\[
\Delta \sigma_{M-D} = -q \mu \varepsilon \frac{N_{\varepsilon_d} \eta(0)}{\beta \Xi} \exp(-t/\tau_e) = \Delta \sigma(0) \exp(-t/\tau_e) \tag{22}
\]

and if during illumination, photoconductance reached steady-state conditions

\[
\Delta \sigma_{M-D} = q \mu \varepsilon G_{\Xi} \tau_e \exp(-t/\tau_e). \tag{23}
\]

Unlike bipolar photoconductance associated with recombination at point defects (Eqs. (1) and (3)), photoconductance decay associated with the recombination at extended defects is due to the majority carriers only.

b. \( \beta \Delta \Psi_d \gg 1 \). At higher generation rates in the vicinity of extended defects, such that \( \beta \Delta \Psi_d = \beta \Xi \eta \gg 1 \), non-exponential terms of the bracket in Eq. (19) could be neglected and

\[
\eta = -\frac{1}{\beta \Xi} \ln \left( \frac{\tau_0 + t}{\tau_e} \right), \tag{24}
\]

where \( \tau_0 \) depends on the initial conditions of the photoconductance decay measurement, and

\[
\tau_e = -\frac{f_{\varepsilon_0} \exp(-\beta \Psi_{\varepsilon_0})}{\varepsilon_c n_0 \beta \Xi}, \tag{25}
\]

which considering that in this case \( |\beta \Xi| \gg 1 \) (\( |\beta \Xi| \gg |\eta| \) and \( |\eta| \ll 1 \)), represents the same time constant as carrier lifetime in the \( \beta \Delta \Psi_d = \beta \Xi \eta \ll 1 \) case described by Eq. (15). Hence, the decay of the photoconductance at higher carrier generation rates, such that \( \beta \Delta \Psi_d \gg 1 \), using Eq. (13) is given by

\[
\Delta \sigma_{M-D} = q \mu \varepsilon \frac{N_{\varepsilon_d} \eta(0)}{\beta \Xi} \ln \left( \frac{\tau_0 + t}{\tau_e} \right) \tag{26}
\]

and if during illumination, photoconductance reached steady-state conditions

\[
\Delta \sigma_{2-D} = q \mu \varepsilon \frac{N_{\varepsilon_d}}{\beta Q_{\varepsilon_0}} \ln \left( \frac{\tau_0 + t}{\tau_e} \right), \tag{27}
\]

where

\[
\tau_e = -\frac{\varepsilon_c}{\varepsilon_{\varepsilon_0} \beta Q_{\varepsilon_0}} \exp(-\beta \Psi_{\varepsilon_0}) \tag{28}
\]

and

\[
\tau_0 = -\frac{1}{\beta Q_{\varepsilon_0} \varepsilon_{\varepsilon_0}}. \tag{29}
\]

IV. COMPARISON WITH EXPERIMENT

The logarithmic dependence of the steady-state photoconductance and logarithmic decay of the photoconductance after cessation of the illumination pulse attributed to recombination at dislocations were observed in plastically bent germanium by Jastrzebska and Figielski.6 Here, we focus on the effects associated with surface recombination in electronic grade silicon. Depending on the conductivity type of the wafer surfaces were conditioned to be in the accumulation or depletion (inversion) by HF etch or standard clean (SC)-1 clean.3,11 The measurements were performed using a system based on a modified RF bridge circuit with a non-contact surface coil separated from the surface by about 25 \( \mu \)m. Details of the measurement system are described in Ref. 8. The measurements were performed using 660 nm laser diode, the wavelength close to the peak of the standard solar spectrum.12

Figure 4 shows the photoconductance transient for 5.5 \( \Omega \)-cm n-type Si illustrating carrier recombination associated with point defects dominating in the bulk of the material.
characterizing recombination at point defects dominating in the bulk of the material.

SC-1 treatment is known to generate negative charge at the silicon surface producing depletion or inversion conditions at the n-type Si surface. Results for such wafer, exhibiting characteristic long tail, are shown in Fig. 5. The photoconductance decays logarithmically after cessation of the illumination pulse as predicted by Eq. (28). In the case of inversion conditions, doping concentration in the SCR, height of the surface potential barrier, $W_d$, and defect charge density, $Q_d$, are uniquely related. That allows, using Eqs. (28) through (30), to determine subsurface doping concentration, $N_{sc}$, carrier capture velocity at the surface, $c_e N_s$, and effective carrier generation rate in the vicinity of the space-charge region. For the wafer in Fig. 5, the doping concentration, determined using these equations, was $8.3 \times 10^{14}$/cm$^3$ in agreement with the resistance of $5.5 \times 10^{-3}$ cm determined using 4-point probe. The carrier capture velocity $c_e N_s = 1.75 \times 10^6$/cm/s assuming capture cross section of surface states $\sigma_e = 5 \times 10^{-14} \text{cm}^2$ and $c_e = \sigma_e \times v_{th} = 9.65 \times 10^{-7} \text{cm}^3$/s, results in density of surface states $N_s = 1.8 \times 10^{12}$/cm$^2$ which is typical for SC-1 treated surfaces. It should be noted that independent determination of the surface state and the surface charge densities could be of critical importance for monitoring wafer cleaning and etching processes. Determination of doping concentration and surface characterization could be also performed in such III-V semiconductors as GaN using DSPC method utilizing pinning of the Fermi level at the surface states.

It is important to note that detection of the logarithmic tail in photoconductance decay critically depends on measurement procedure. Achieving high sensitivity of measurements usually requires averaging signal over large number of pulses. However, unless enough time is given for the photoconductance decay to reach substantially thermal equilibrium before starting subsequent pulse, the decay transient will be distorted. In extreme case, this distortion would lead to apparent exponential decay with time constant only partially dependent on the sample properties.

Figures 4 and 5 illustrate extreme cases when either bulk or surface dominate carrier recombination process. Fig. 6 illustrates case when both surface and the bulk defects contribute to the carrier recombination. Since carrier recombination in these two regions is essentially independent, the regions contribution to the total photoconductance can be

![Graph showing photoconductance decay](image1)

**FIG. 5.** Photoconductance decay at inversion following 660 nm excitation pulse for the 5.5 $\Omega$-cm n-type silicon wafer after SC-1 treatment; dotted line represents logarithmic decay with $\tau_0 = 3.9$ ms for $N_D = 8.3 \times 10^{14}$/cm$^3$.

**FIG. 6.** Decay of the photoconductance following 660 nm excitation pulse for p-Si (4.6 $\Omega$-cm) after HF treatment. The total photoconductance (solid line in (a)) is a sum of the surface ($\Delta \sigma_{surf}$) and bulk ($\Delta \sigma_{bulk}$) components. (a) shows $\Delta \sigma$ (linear scale) vs. time (log scale) and (b) shows $\Delta \sigma_{bulk}$ (log scale) vs. time (linear scale). The surface and bulk parameters, determined from the curve fitting using procedure described in the paper, were $N_A = 3 \times 10^{13}$ cm$^{-3}$, $G_{ab} = 2.16 \times 10^{16}$ cm$^{-2}$ s$^{-1}$, $G_b = 7.44 \times 10^{14}$ cm$^{-2}$ s$^{-1}$, $\tau_b = 16.1$ $\mu$s, $Q_{ab} = 1.4 \times 10^{11}$ q/cm$^2$, $\tau_0 = 0.83$ ms, $c_e N_s = 4 \times 10^5$ cm/s, and $N_s = 4 \times 10^{12}$/cm$^2$.
treated separately. The logarithmic (surface) component of the photoconductance (tail in Fig. 6(a)) was fitted for \( t \gg \tau_0 \) using only the magnitude of the signal and the time constant \( \tau_0 \). The magnitude of the signal is used to determine \( N_{sc}/Q_{d0} \) using Eq. (28). In the case of the surface under depletion conditions, an independent determination of \( N_{sc} \) would allow for the determination \( Q_{d0} \). In the case of inversion conditions both \( N_{sc} \) and \( Q_{d0} \) could be determined independently from the well-known dependence between the maximum depletion layer width and the doping concentration.\(^1\) In turn, \( N_{sc}, Q_{d0}, \) and \( \tau_0 \) allow, using Eqs. (28) and (29), the determination of the carrier capture velocity at the surface, \( c_{sc}N_{sc} \), and by using the known value of \( c_{sc} \) the surface state density \( N_s \) was determined. Furthermore, the determination of \( \tau_0 \) (from \( \Delta\sigma_{sc} \) at \( t = 0 \)) allows for the determination of the effective carrier generation rate lifetime and bulk carrier generation rate, \( G_b \) (\( G_b \) corresponds to \( G_{0,d} \) in Eq. (3)). It is interesting to note that for the sample in Fig. 6 less than 4\% of the e-h pairs, generated using 660 nm radiation, contributed to the bulk photoconductance. Most of the recombination, more than 96\%, happened at the surface. This confirms the importance of surface passivation in solar cells and demonstrates the capability of the DSPC method to monitor this process.

V. CONCLUSIONS

The DSPC discussed in this paper presents a new approach to the characterization of electronic properties of semiconductors using standard photoconductance techniques. The DSPC methodology takes advantage of analysis typically reserved for SPV effects. DSPC does not just offer alternative to the SPV. Some characterization of subsurface regions and thin films, such as determination of the doping concentration,\(^13\) requires measurement without disturbing surface space-charge region, preferably stopping illumination after initial illumination pulse, a task not possible with SPV. This is due to a fact that prolonged, even low intensity, illumination causes accumulation of the minority carriers at the surface and reduction of the surface potential barrier distorting the SPV effect. RF or microwave based DSPC methodology resolves this difficulty.\(^13,14\)

By allowing separation of the effects associated with the surface and the bulk, DSPC combines the advantages of PCD and SPV techniques and allows non-contact, simultaneous, electrical characterization of both bulk and thin-film wafer structures critical for PV solar cell and HB-LED manufacturing. By separating surface charge and surface state density, DSPC also allows a new approach to monitoring critical semiconductor manufacturing processes, such as wafer cleaning.

Finally, the DSPC approach takes unique advantage of electronic properties common to extended semiconductor imperfections, such as the surface. Further effort is expected to shed new light on other extended defects, such as grain boundaries, dislocations, conglomerates of point defects, and impurities.

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14E. Kamieniecki, U.S. patent pending.