Trapping in photoconductance data taken on solar grade silicon

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Trapping in photoconductance data, taken on silicon samples, has been observed since the early 1950s. Although its appearance is usually considered a nuisance, this work investigates if it contains useful information. This paper first reviews what is trapping and the current theory for simple defects as well as its implications for solar grade silicon. Experimental verification of this theory and following implications are then provided. Finally, an overview of trapping that exists in solar grade material is presented.

Introduction

Photoconductance measurements have been performed on silicon for over 70 years, with its main use being the determination of the free carrier lifetime, a metric used to monitor for material quality. These early measurements were often dominated by a signal unrelated to the excess carrier lifetime and said to be related to the trapping of minority carrier (Haynes and Hornbeck 1953; Fan 1953). While there are textbooks dedicated to lifetime measurements, significantly less attention has been given to the root cause and analysis of trapping, an area which this work seeks to address.

The measurement of trapping by means of photoconductance has several appealing aspects. These aspects include that it: is contactless, does not require any surface passivation for a wafer, and that has a high sensitivity to changes in bulk defects states. Hornbeck and Haynes demonstrated that a change in defect occupation of 10^9 cm^{-3} is possible: a rather impressive detection limit (Haynes and Hornbeck 1955).

We divide our current contribution in two parts. The first part is in regard to the theory by which trapping is understood and analysed, before confirming it with measurements on the well-studied defect of iron in p-type silicon. The second part follows with an investigation of trapping in solar grade silicon.

Theory

The photoconductance ($\Delta\sigma$) of a semiconductor is given by:

$$\Delta\sigma = qW(\mu_e \Delta n_e + \mu_h \Delta n_h)$$

where q is the elementary charge, W is the thickness of the sample, μ is the mobility and Δn is the change the excess carrier density. The subscripts e and h refer to electrons and holes respectively. The evaluation of lifetime from a photocondutance measurements often requires the assumption $\Delta n_e = \Delta n_h$. It is the breakdown of this assumption that occurs when there is trapping. This occurs as while the sample is illuminated, a defect will either net capture more electrons or holes resulting in $\Delta n_e \neq \Delta n_h$. Even after the light is turned off and the free carriers are recombined, there is still an imbalance in the charge caused by the charge held by the defect. The detrapping time constant of a defect in a transient photoconductivity measurement has been analytically derived for a single level defect as (Blood and Orton 1992; Zhu et al. 2019)

$$1/\tau_{pc} = e_h + e_e + c_{mjc} n_{mjc} \qquad (1)$$

where τ_{pc} is a detrapping time constant, e is the emission coefficient of carriers from the defect and c_{mjc} is the capture coefficient of majority carriers, and n_{mjc} is the number of majority carriers. Thus, the detrapping process can result from either the capture or emission of a carrier, unlike the more common assumption that the detrapping process is only via an emission process.

To determine which process is relevant for standard solar cell material, an order of magnitude calculation is provided. By equating defect capture and emission rates the dominate process can be found. The level at which they are equal, we will refer to as a demarcation energy level. If the energy level of the defect, an intrinsic electronic property, is closer to a band edge than the demarcation energy level, the detrapping time constant will be dominated by an emission process, otherwise it will be dominated by a capture process. For a defect with a capture cross section of 10^{15} cm^{-2} (Juhl et al. 2018, 2019), the demarcation energy level is calculated as

$$c_x = e_x$$

$$1 = n_i e^{\frac{E_d - E_i}{kT}}$$

$$E_d - E_i = kTlog(n_i) = 0.59eV$$

Thus, as long as the energy level of the defect is further from the intrinsic energy level by 0.59 eV, or a total energy span of 1.19 eV. This represents the entire band gap of silicon (1.12 eV), demonstrating that for standard solar grade silicon it is expected that the dominant detrapping mechanism is majority carrier capture.

Experimental demonstration

While the above presented theory is not new it has never been experimentally confirmed. This is now performed using the well-known impurity of Iron. Iron was chosen as it is both well characterised and metastable (Istratov, Hieslmair, and Weber 1999). The metastability enables the defect to be toggled into different states, existing either as an interstitial iron atom of paired with a boron atom. This property provides a unique and clear indication of the impact the defect has. As such, a set of p-type CZ silicon samples with a doping of ≈ 10^{14} cm^{-3}, as determined by Van De Paul measurements, were prepared. They were ion implanted with iron, before being annealed to redistribute the iron in the sample. The sample was not passivated, as to reduce the effective carrier lifetime to ≈ 1 μs.

Transient photoconductance decay measurements were performed with a microwave-based tool MDP-Map (Freiberg Instruments). Measurements were performed with the iron paired with boron atom and in their interstitial form, with separation caused by a flash lamp (Zoth and Bergholz 1990). The results of the measurements are shown in Figure 1, along with the fits indicated with the dashed line of the same colour.

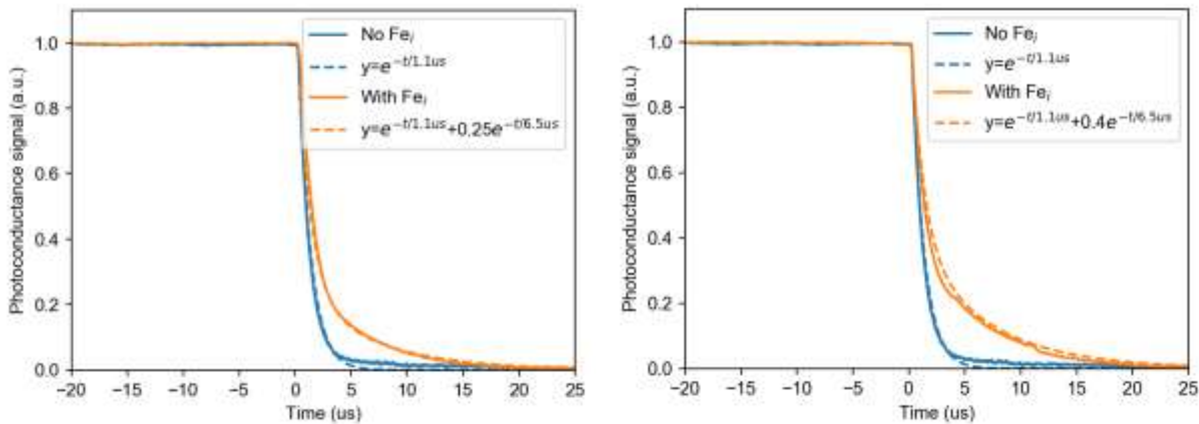

Figure 1: Photocondutance measurements of p-type silicon samples with iron acting as a trap.

The results show a difference between when the iron is paired as iron boron and when it is as interstitial iron. In the first case, only a single time constant is observed, and it is indicative of the expected free carrier lifetime on an unpassivated wafer of this thickness (~ 1 μs). When the iron is in the interstitial form two different decays are observed, indicating that iron could be behaving as a trap. Calculation of the detrapping time constants using Equation 1, provides detrapping time constants for when iron is: paired with boron in the nanosecond range (hole capture coefficient ≈ 1e15 cm^{-2}) (MacDonald et al. 2006; Paudyal, McIntosh, and Macdonald 2009; Rein and Glunz 2005; Juhl et al. 2018); and in a interstitial form as ≈ 7 μs (hole capture cross sections ≈ $7e^{-15}$ cm^{-3} (Lemke 1981; Paudyal, McIntosh, and Macdonald 2009; Istratov, Hieslmair, and Weber 1999; Juhl et al. 2018)). Both these time constants are dominated by a majority capture process, and the mangitude of the interstitial detrapping time constant being in reasonable agreement with the experimental data, providing validation of the theory.

Trapping in solar grade material

Progress in our ongoing work will also be reported. There are two different streams, one focusing on multi-crystalline and one on mono-crystalline silicon.

The first project is looking at “trapping signals” in multi-crystalline silicon. This project focuses on determining if the trapping signal seen in multi and cast mono silicon is related to bulk defects (Sinton et al. 2010). It has been suggested that it is not due to bulk defects, but rather a result of the large defects at grain boundaries that cause this trapping. We will present strong evidence to support this theory.

The second project is looking at trapping in solar grade mono-crystalline silicon. Specifically, we are investigating the claim that the so-called BO pre-state state results in significant trapping in photocondutance measurements (Markevich et al. 2019) using a common tool, being a WCT-120.

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