October 2001 • NREL/CP-520-31028

Conference Paper

Recombination Parameters of Photovoltaic Materials Measured by Resonant-Coupled Photoconductive Decay

Preprint

R. Ahrenkiel and S. Johnston

To be presented at the NCPV Program Review Meeting
Lakewood, Colorado
14-17 October 2001

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel
Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

♻ Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Recombination Parameters of Photovoltaic Materials Measured by Resonant-Coupled Photoconductive Decay

R. Ahrenkiel and S. Johnston
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

ABSTRACT

A novel contactless measurement technique is described that provides the minority carriers lifetime, as well as, ambipolar mobility and diffusion length. An independent system has been developed that measures these parameters at cryogenic temperatures. Finally, a compact, portable system provides further flexibility in the application of the technique. Data are presented that show the versatility of the technique.

1. Introduction

We have developed a family of techniques for the contactless measurement of recombination parameters in photovoltaic materials[1,2]. We have successfully measured the recombination lifetimes in Si, Ge, SiC, GaAs, InGaAs, CdTe, CdS and many other materials of interest to the photovoltaic community. We have named the technique "resonant-coupled photoconductive decay". This method is an improvement of earlier radio frequency photoconductive decay methods. In this technique, the sample becomes a passive component of an antenna array that operates in the 400 MHz to 1000 MHz frequency range. The sensitivity has been improved so that incident light pulses of less than 10^{11} photons/cm^2 have been used to successfully measure the lifetime in high mobility materials. At a pulse rate of 20 pps, this corresponds to an average light flux of less than 1.0 μW/cm^2. The technique is versatile and allows measurement of samples varying in size from small thin films to large diameter (8-10 inch) silicon wafers and ingots. We have four systems in operation including a new, compact system that is primarily dedicated to silicon measurements, although it can be successfully used for a number of other materials. A reliable infrared-pulsed light system uses a YAG laser pumped optical parametric oscillator (OPO) to cover the excitation wavelengths from about 700 nm to 2500 nm. A visible system uses a YAG-pumped OPO to cover the visible wavelength range from 400 nm to 700 nm. A flashlamp source allows measurement of recombination lifetimes using a broadband light spectrum that simulates photovoltaic energy sources. Finally, a new low temperature system allows RCPCD measurements to be made from 77 K to 300 K.

Figure 1 shows typical photoconductive decay data, which was obtained by measuring an 8-inch, thermally oxidized silicon wafer that is of integrated circuit quality.

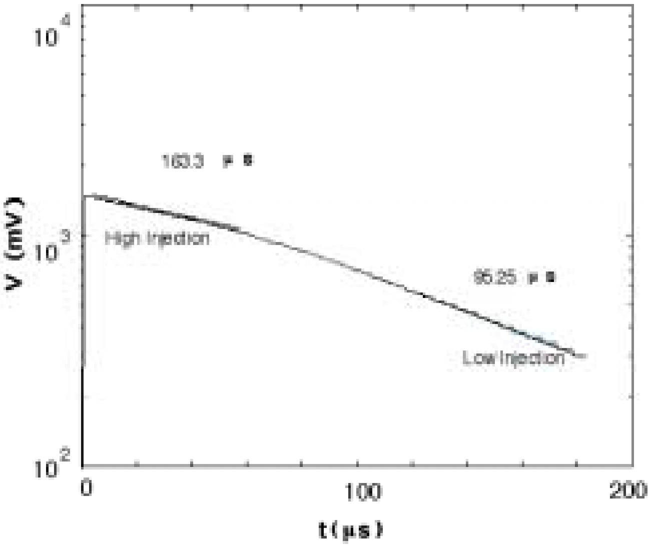

Fig 1. RCPCD data for 8-inch diameter, thermally oxidized integrated-circuit grade silicon wafer.

The data show the typical low- and high-injection lifetimes that are typical of recombination dominated by Shockley-Read-Hall defects.

2. Mobility and Diffusion Length

Recent expansion of the technique allows the determination of the minority-carrier mobility and diffusion length. Another new feature, using the energy-wavelength calibrated OPO sources, allows one to perform a contactless internal spectral response measurement of any material using the RCPCD diagnostic. This is especially useful in evaluation of materials prior to device fabrication. Figure 1 shows the spectral response of an IC grade silicon wafer after ion implantation with arsenic and after a rapid thermal anneal process to remove the implantation damage. The diffusion length and lifetime are, of course, markedly improved after the RTP process. For this work, we calibrate the OPO source in terms of photons/pulse cm^2 for the entire wavelength range. The RCPCD signal is normalized to the incident photon flux at each wavelength. It can be shown that the photoconductive signal per incident photon is given by:

$$Q(h\nu)=\frac{q^2}{KT}\sqrt{L_n^2+L_p^2} \qquad (1)$$

The response, Q, is obtained by numerically integrating the area under the photoconductive decay curve.

In Figure 2, the diffusion length is reduced by ion implantation damage, such that the average diffusion length is about a factor of 4 less after the implantation. The data for the initial, unimplanted wafer and the RTA-processed wafer are essentially identical. Thus, the RTA process restores the mobility transport to the condition of the virgin crystal.

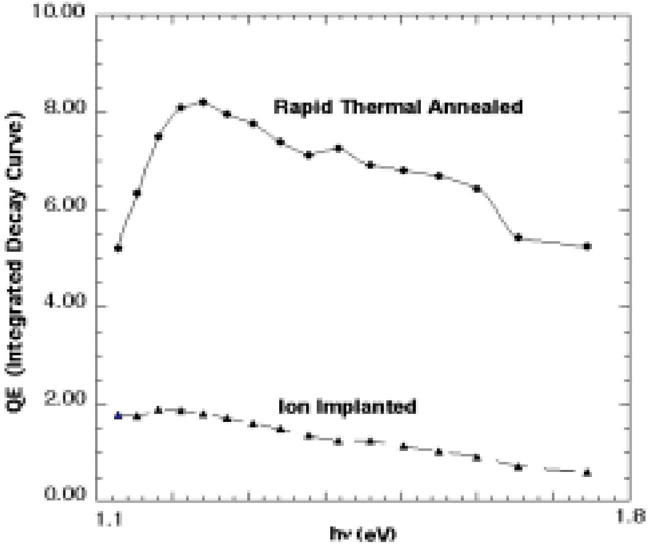

Fig 2. Internal spectral response of a high quality silicon wafer, before and after rapid thermal annealing.

In summary, by scanning the incident wavelength, we find the diffusion length corresponding to various penetration depths of the excitation light. In this way, a diffusion length profile is obtained as a function of depth from the incident surface. The pulse height of the RCPCD signal, when divided by the incident light flux, is a relative measure of the ambipolar mobility. If we use a calibration crystal, for which the mobility is known, an absolute value of mobility can be calculated.

Finally, wavelength tuning is also useful in identifying impurity-activated photoconductivity in semiconducting materials. We find sub-bandgap photoconductive peaks that can be linked to specific impurity transitions in the sample.

3. Temperature Dependent RCPCD

The temperature variable RCPCD system has been used to measure the energy levels of active traps or band offsets in semiconductors. Figure 3 shows an Arrhenius plot of the photoconductive decay time of epitaxial In(0.53)Ga(0.47)As grown on InP. The open data points are from measurements on an undoped sample, whereas the solid data points are from a Zn-doped sample. The time dependent decay characteristics are very different for the two sample types. The doped sample shows two decay regimes with activation energies of 130 mev and 22 mev. The latter, seen at the lowest temperature, corresponds to the Zn acceptor transition, whereas the higher energy decay is related to an unknown deeper defect level. The undoped sample indicates a decay time that increases with increasing temperature, and is indicative of a midgap recombination center rather than a trap.

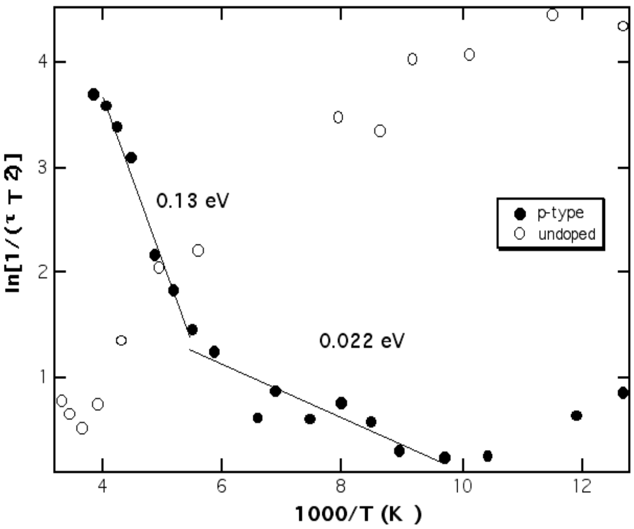

Fig 3. The emission rate (inverse photoconductive decay time) of In(0.53)Ga(0.47)As as a function of temperature.

Another presentation [3] at this conference will describe temperature dependent analysis of GaAsN.

4. Summary

In summary, the RCPCD technique produces data with a large amount of information about the minority-carrier properties of semiconductors. As the technique is contactless, it is highly suited for the characterization of photovoltaic materials.

REFERENCES

[1] U.S. Patent #5,929,652, R. K. Ahrenkiel (issued 7/29/99).

[2] U.S. Patent #6,275,060, R.K. Ahrenkiel and S.W. Johnston (issued 8/14/01).

[3] S.W. Johnston and R.K. Ahrenkiel, (presented at this Conference).