Measurement of Effective Lifetime in Silicon using Modulated Free Carrier Absorption

R. R. Khabibrakhmanov, K. M. W. Boyd, R. N. Kleiman
McMaster University, Department of Engineering Physics
1280 Main Street West
Hamilton, ON L8S 4L7 Canada, khabibrr@mcmaster.ca

Abstract – **This paper presents a semiconductor carrier lifetime measurement technique based on modulated free carrier absorption (MFCA). This is a pump/probe modulation technique that uses an above-bandgap pump to generate free carriers and a below-bandgap probe to analyze the free carrier absorption signal. The effective electron-hole recombination lifetime is calculated by fitting experimental data with a mathematical model. The technique is applicable for both double-side polished and textured Si wafers. The measurements can be conducted in different experimental setups (reflection/transmission). A mathematical model is developed to analyze multiple reflections of the light in a double-side polished sample and to measure the reflection coefficient of silicon using a given experimental technique.**

I. INTRODUCTION

The recombination lifetime provides important information about the quality of semiconductor material. Knowledge about electrically active defects in a semiconductor such as their density and energetic location relative to the valence or conduction band edges can be extracted from studies of minority carrier lifetime [1]. For materials like silicon, where recombination is typically dominated by impurity assisted processes, lifetime measurements are the main characterization tool. In order to achieve best device performance, it is often necessary to have a semiconductor with high lifetime. Therefore, lifetime screening becomes a crucial operation before device fabrication. Lifetime measurements are extremely important in the field of photovoltaics, where high purity and long recombination lifetimes are necessary for high-efficiency cells [2].

MFCA is an all-optical non-contact technique that does not require calibration. The MFCA method uses two beams of light: an above-bandgap pump beam and a below-bandgap probe beam. The pump causes excitation of electron-hole pairs, thus generating excess carriers. The probe beam is used to monitor the decay of concentration of excess carriers, in either the time [3] or frequency [4] domain. The return of free carriers back to equilibrium follows a decaying exponential in the time domain and a Lorentzian curve in the frequency domain. Lifetime is extracted from fitting experimental data and it depends only on the shape of the curve, therefore no calibration is needed.

In this work, we develop an MFCA method for measuring the lifetime in silicon wafers. The lifetime of the double-side polished silicon wafer is calculated by analyzing reflected and transmitted parts of the probe beam. A mathematical model is developed to describe multiple bounces of light inside the silicon wafer. The technique is used to measure the lifetime for a double-side textured silicon wafer. Additional experimental techniques are applied to collect diffusely reflected and transmitted light from the textured sample.

II. EXPERIMENTAL

In this study, two unpassivated silicon wafers with (100) orientation have been used to examine their effective lifetimes. The specifications are listed in Table I. Sample 1 is double-side polished and Sample 2 is double-side textured. Sample 2 was conventionally textured by anisotropic etching in a weak solution of KOH with isopropyl alcohol at 70 °C resulting in randomly distributed pyramids [5].

TABLE I
SPECIFICATIONS OF SILICON WAFERS USED IN THIS STUDY

Wafer ID	Thikness (μm)	Doping Density ($\times 10^{15}$ cm^{-3})	Surface
1	575 ± 25	0.0015	Polished
2	325 ± 2	3.2	Textured

The experimental setup for this work is similar to [6] and presented in Fig 1. A Laser Quantum Opus laser (10 W CW at 1064 nm) is used for the pump. It is modulated by a custom Conoptics electro-optic modulator. The pump power is set to 2W and controlled by a half-waveplate /polarizer pair. In the experiment, the pump power is equal to 750 mW. The modulator is driven by a Conoptics Model 25 A Driver. The modulation sine wave is supplied by a Zurich multi-frequency lock-in (MFLI) amplifier. The probe is a Thorlabs FPL1009S fiber optics laser (1550 nm). The laser is driven by an LDC205C source set to 250 mA, providing about 55 mW of optical power. The pump and probe beams illuminate the sample on the same side. In the experiment with sample 1, the angle of incidence is approximately 20° and 45° for pump and probe beams respectively. In the experiment with the textured sample, the angle of incidence is approximately 45° and 55° for pump and probe beams respectively. In both experimental setups, the pump beam is expanded to a diameter of about 5 mm, and the probe beam has a diameter of 50 μm. After passing through or reflecting from the surface of the sample, the probe beam is focused into a New Focus Model 2033 Germanium photodetector set to 2000 × gain, which has a bandwidth of 200 kHz. Diffusely reflected and transmitted light is collected by a system of lenses. The AC and DC components of the detector signal are measured in the Zurich MFLI. For each measurement, the modulation frequency is scanned from 100 Hz to 100 kHz, in 50 logarithmically spaced steps. At each frequency, the amplitude and phase of the FCA signal are measured.

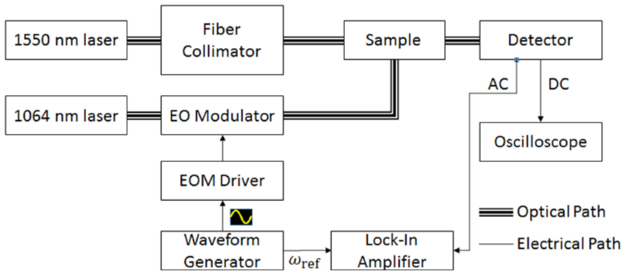

Fig.1. Block diagram of the experimental setup [6].

III. DISCUSSION

The modulated pump beam generates a time-dependent modulated concentration of excess carriers in the sample. The probe beam power becomes time-dependent being absorbed by the modulated concentration of excess carriers. Therefore, the probe beam is divided into DC and AC parts. The AC amplitude of the excess carrier density with changing frequency has a Lorentzian dependence. Detecting and fitting the AC part of the reflected or transmitted probe beam allows extracting the effective lifetime of the sample. In Fig. 2, the AC signal amplitude is plotted versus modulation frequency for the two samples.

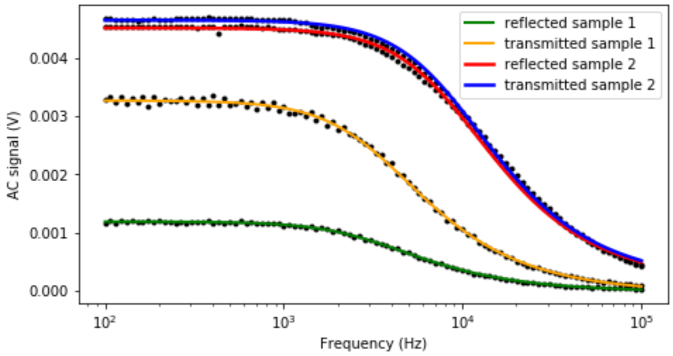

Fig.2. AC MFCA reflected and transmitted signal amplitude vs modulation frequency for two samples with different effective lifetimes. The symbols are experimental data points and the continuous lines are the best fit.

The effective lifetime of sample 1 is extracted from the reflected and transmitted AC signals, as 46 µs and 48 µs respectively. Because of the weaker interaction of the reflected beam with the polished sample, the signal from the reflected beam is lower than the transmitted signal. The effective lifetime of sample 2 is 18 µs extracted from both reflected and transmitted signals. Because of light trapping effects in the textured wafer, reflected and transmitted beams have similar amplitude. Even though only 10% of diffuse light was collected in the experiment, the amplitude of the AC signal from sample 2 is considerably higher in comparison with the signal from sample 1. Light trapping enhancement increases the AC signal.

Equations (1) and (2) describe the behavior of the reflected ($P_{r,AC}$) and transmitted ($P_{t,AC}$) components of the AC signal for the polished sample.

$$P_{r,AC} = 2RP_0(1-R)^2\alpha_{FCA}W/(1-R^2)^2, \qquad (1)$$

$$P_{t,AC} = (1-R)^2P_0\alpha_{FCA}W(1+R^2)/(1-R^2)^2 \qquad (2)$$

where P_0 is the incident power of the probe, α_{FCA} is the FCA coefficient, and W is the wafer thickness. The equations are shown to be correct by calculating the reflection coefficient R using experimental data and comparing it with the results obtained from the Fresnel equations.

IV. CONCLUSION

We have investigated a MFCA technique for measuring effective lifetime in silicon. It is shown that both reflected and transmitted components of the probe beam can be used to calculate effective lifetime. The technique is applicable for polished and textured silicon wafers and provides an even higher signal when working with the latter. A theoretical model has been developed to understand the behavior of the light beam in the double-side polished sample. The model experimentally proved its correctness and accuracy.

ACKNOWLEDGMENT

This work was supported by the NSERC CREATE TOP-SET program.

REFERENCES

[1] S. Rein, *Lifetime Spectroscopy: A Method of Defect Characterization in Silicon for Photovoltaic Applications; With 29 Tables.* Berlin, Germany: Springer, 2015

[2] A. Blakers, N. Zin, K. R. McIntosh, and K. Fong, “High efficiency silicon solar cells,” *Energy Procedia*, vol. 33, pp. 1–10, 2013.

[3] J. Linnros, “Carrier lifetime measurements using free carrier absorption transients. I. Principle and injection dependence,” *J. Appl. Phys.*, vol. 84, no. 1, pp. 275–283, 1998.

[4] S. W. Glunz, A. B. Sproul, W. Warta, and W. Wettling, “Injection-leveldependent recombination velocities at the Si-SiO2 interface for various dopant concentrations,” *J. Appl. Phys.*, vol. 75, no. 3, pp. 1611–1615, Feb. 1994.

[5] M.K. Basher, M. K. Hossain, M. J. Uddin, M.A.R. Akand, K.M. Shorowordi, “Effect of pyramidal texturization on the optical surface reflectance of monocrystalline photovoltaic silicon wafers,” *Optik*, vol. 172, 2018, pp. 801-811.

[6] K. M. W. Boyd and R. N. Kleiman, "Quasi-Steady-State Free Carrier Absorption Measurements of Effective Carrier Lifetime in Silicon," in *IEEE Journal of Photovoltaics*, vol. 9, no. 1, pp. 64-71, Jan. 2019.