Lifetime Measurement of Solar Cells using Steady-State Terahertz Spectroscopy

Bin Yun, Renee Sher

Department of Physics, Wesleyan University, Middletown, CT 06459

Introduction

Defining a semiconductor material's efficiency used in a solar panel is an essential part of developing renewable energy technology. The efficiency of the solar cell is directly related to the lifetime of photoexcited electrons, where the lifetime is the time for excited electrons to return to an original state. This implies that the instrument to measure the lifetime of photoexcited electrons should convey the characteristics of sunlight. In this project, we conducted the lifetime measurement using steady-state terahertz spectroscopy. In this setup, we used a tunable laser diode to mimic sunlight wavelength and intensity. From the experimental result, we have used the mobility and the terahertz signals to calculate the lifetime of a silicon sample.

Steady-State THz Spectroscopy Setup

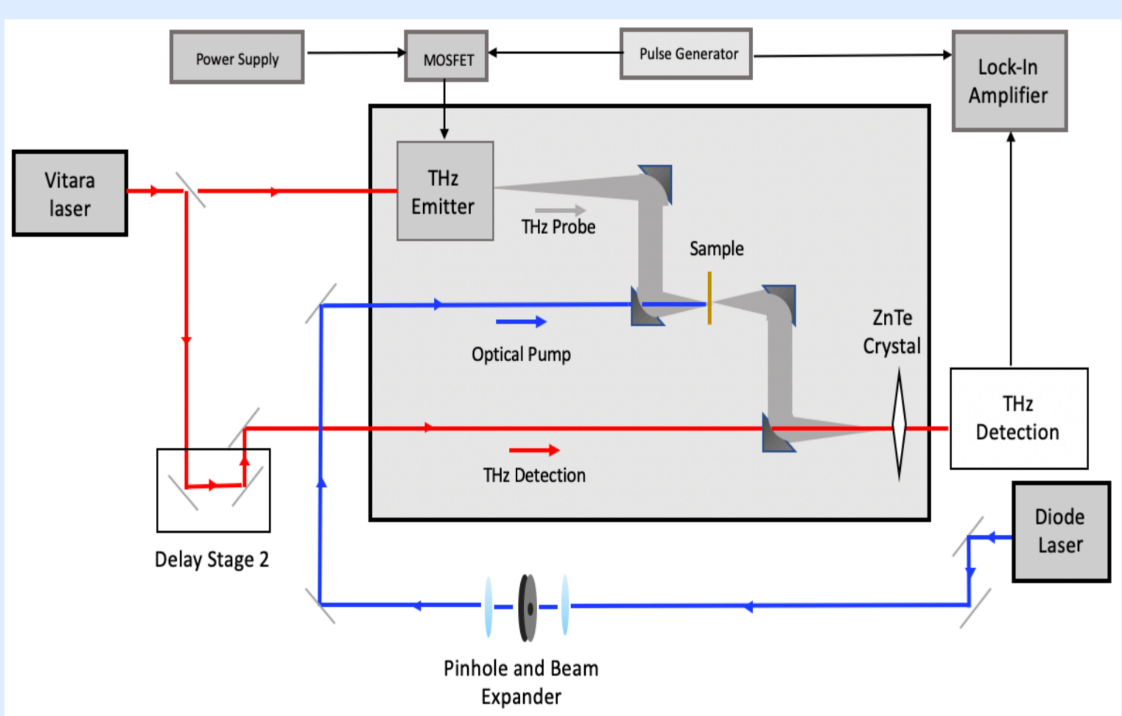

Fig. 1. Vitara laser is split into two paths for the THz emitter and the probe of a sample. A diode laser is used for the optical pump.

Our setup uses a tunable laser diode to excite the sample. We also use an 800 nm fs-laser and a THz emitter to create a THz signal and probe the sample. The continuous wave diode laser excites electrons to the conduction band and reaches a steady state. Then, the THz signal probes the sample, and the Lock-in Amplifier reads the THz value. We repeat the procedure for the condition when it is not excited. Then, we use the THz values to interpret the lifetime of our sample. Figure 1 shows the diagram of our setup, and Figures 2 and 3 show the components for the optical pump.

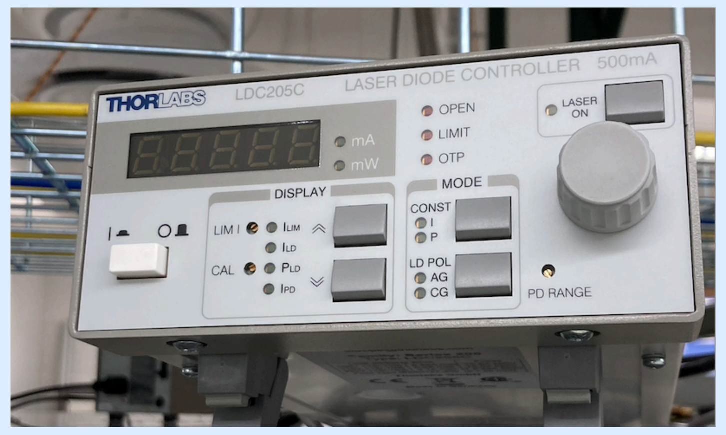

Fig. 2. ThorLabs LDC205C to drive the current and control the laser's intensity.

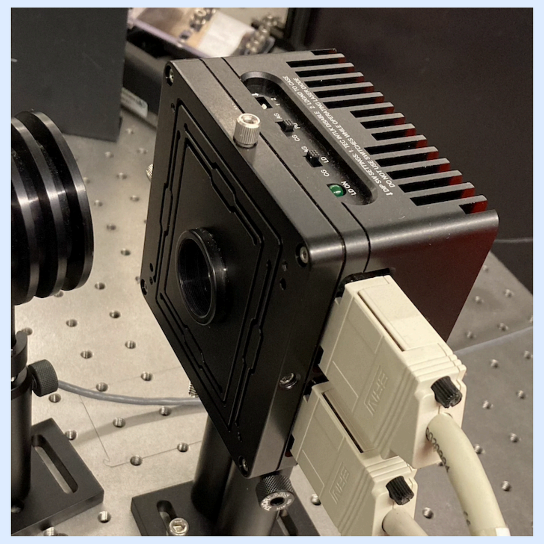

Fig. 3. ThorLabs LDM56 Laser Diodes to control the laser's wavelength.

Why THz Signal?

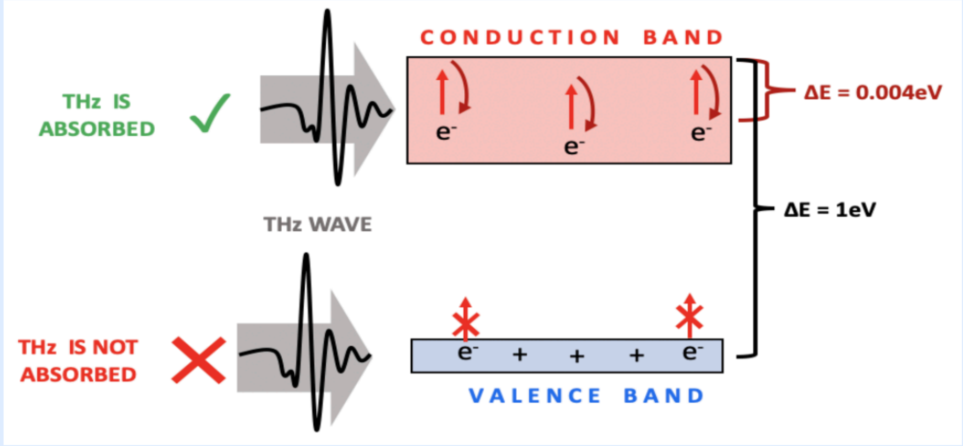

Fig. 4. Terahertz waves can only be absorbed by the electrons in conduction bands due to the energy gap.

When electrons are excited and gain energy, they move up to the conduction band. This is how a current flow occurs in our solar panel. Due to the frequency range of the terahertz wave, photons in this frequency range carry a small amount of energy (on the order of 4 meV) and can only interact with electrons in the conduction band. This is why we use terahertz waves to study the lifetime of photoexcited electrons. Figure 4 illustrates the interaction between the THz signal and the electrons.

$$\tau_L \approx \left(\frac{-\Delta T}{T_0}\right) \times \frac{h\nu \times A}{P} \times \frac{(1+N)}{\mu \times e \times Z_o}$$

Equation 1. The equation used to calculate the lifetime of a sample.

The change in the terahertz signal tells us how many excited electrons there are. Using this relationship, we can estimate the lifetime of the photoexcited electrons. The variables in the equation are τ_L = Lifetime, ΔT = Change in terahertz signal due to photoexcitation, T_0 = THz signal without photoexcitation, h = Plank's constant, v = Frequency of photon, A = Area of the spot size, P = Power of the source laser, N = Index of refraction of our sample, μ = mobility of electrons, e = charge of an electron, Z_0 = Impedance of free space. All of the variables except the mobility and the terahertz values are constant.

Mobility Calculation

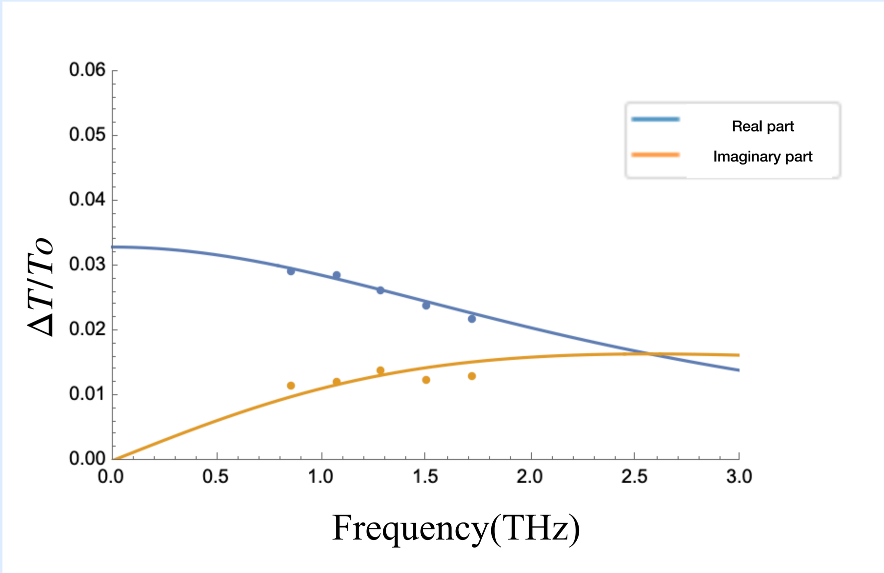

Fig. 5. The graph of real and imaginary values of the Fourier Analysis.

For an accurate lifetime measurement, knowing the mobility of our sample is essential. To find the mobility of an electron in our sample, we conducted a Fourier analysis of the THz signals with and without photoexcitation on the sample($\Delta T/To$) and plotted real and imaginary results in terms of frequency (THz) as in figure 5.

$$Drude\ Model = \frac{\sigma}{1+2\pi i \times f \times \tau_s}$$

Equation 2. Drude Model used for the mobility calculation.

Then, we used the Drude Model equation that relates the conductivity σ and the average scattering time of electrons τ_s to fit our plots. The fitted graph from our data estimated τ_s of our sample, which was τ_s = 62.14 fs. We are focusing on the average scattering time here.

$$\mu = \frac{e\tau}{m}$$

Equation 3. The relationship between a scattering time and mobility.

Next, the electron's mobility in the steady-state can be defined as the equation above. With the scattering time found above, we can find the mobility of electrons in our sample. e and m are both constants, which are the charge and the mass of an electron. We found μ to be 0.011 $\frac{m^2}{V \times s}$.

Lifetime Calculation

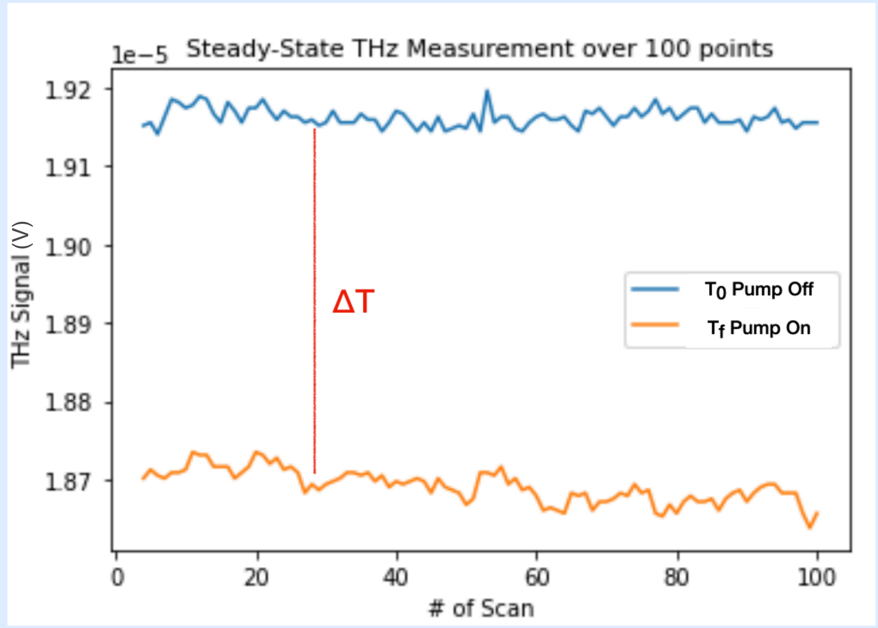

Fig. 6. Measured THz signals from the excited and not excited sample.

Variable	Value	Variable	Value
T_0	$19.15 \times 10^{-6}\ V$	$\lvert\Delta T\rvert$	$5 \times 10^{-7}\ V$
h	$6.626 \times 10^{-34}\ \frac{m^2 kg}{s}$	N	$3.41(Unitless)$
v	$6.662 \times 10^{14}\ Hz$	μ	$0.011\ \frac{m^2}{V \times s}$
A	$\pi \times 1.4^2\ mm^2$	e	$1.602 \times 10^{-19}\ C$
P	$60\ mW$	Z_0	$377\ \Omega$

Table 1. The values of the variables used to calculate the lifetime of our sample.

Figure 6 shows the raw data of the terahertz signal from our experiment. With the change in terahertz and the mobility computed, we plugged the values in Table 1. We calculated our lifetime to be 7.87 microseconds. This means it takes 7.87 microseconds for the photoexcited electrons to return to their original states.

Conclusion

Our original setup measured the lifetime of a silicon sample to be around 3 to 10 µs. Our experimental result falls into this range. This indicates that we can get a valid experimental value using the new tunable diode laser and electronics. For future work, this setup will be further studied to improve the noise-to-signal ratio for better accuracy. Now, we will work on the time-resolved terahertz spectroscopy based on the diode laser we used in this experiment, which can be obtained by pulsing the laser sources.

Reference

[1] Blinick, George A., The development of long timescale terahertz spectroscopy techniques to measure lifetimes of photovoltaic materials, Master Thesis, 2020

[2] Root, Jack., Measuring Lifetimes of Solar Cell Materials Using Terahertz Absorption and Continuous Wave Laser Excitation, Senior Thesis, 2022

[3] Hegmann, Frank A., et al., Probing Organic Semiconductors with Terahertz Pulses, 2005.