Evaluation of surface carrier recombination of optically excited silicon using terahertz time-domain spectroscopy

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Abstract: In this study, the properties of optically excited silicon were investigated using terahertz time-domain spectroscopy (THz-TDS). The surface was illuminated with 365-*nm* ultraviolet (UV) light to excite charge carriers, and properties such as conductivity, charge carrier density and mobility were evaluated. The illumination effect significantly changed the conductivity as well as the surface recombination velocity (SRV) by altering the surface potential via photoexcited carriers. The SRV observed on the silicon surface varied from 1.56×10^4 to 3.45×10^3 *cm*/*s*, indicating that UV illumination greatly reduced the SRV depending on the photoexcited carrier density at the silicon surface.

Keywords: Terahertz spectroscopy, Silicon, UV light illumination, Surface recombination velocity

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1. Introduction

Charge carrier recombination lifetime and SRV are the key parameters in semiconductor technology for characterizing the quality of a material or device [1]. The SRV is particularly important as it reflects the surface property of materials. Loss of carriers due to recombination at or near the surface reduces the device operation efficiency. Thus, it is important to measure the value of SRV in order to optimize the device design and fabrication process. A surface is usually specified in terms of its SRV. It is well known that the recombination process occurs not only in the bulk but also on the surface of the sample. Free carrier absorption (FCA) [2], laser/microwave photoconductance (LM-PC) [3] and quasi-steady-state photoconductance (QSSPC) [4] are widely used for the measurement of photoinduced minority carrier lifetime consisting of bulk and surface components that are difficult to separate. Separation is possible by changing the wafer thickness [5], but this requires time-consuming sample processing. In actuality, it is more useful to individually identify the bulk and surface components. This can be achieved by illuminating the wafer at different wavelengths of light to excite free carriers at different depths during measurement using QSSPC [6]. As this technique requires electric contact for the evaluation of electric properties, it has the disadvantage that it cannot measure the spectrum of dielectric constants. However, contactless optical techniques are available for such measurement. Terahertz time-domain spectroscopy (THz-TDS) is an effective, noncontact and nondestructive method, which is widely used to study ultrafast carrier dynamics in a variety of nonpolar and nonmetallic materials including semiconductors [7, 8]. In this method, the material properties are probed with short pulses of terahertz radiation. The particular advantage of terahertz radiation is that most common materials are transparent. With this technique, a short wavelength of light is used to generate charge carriers near the silicon surface and their recombination is strongly influenced by the surface recombination. This unique effect makes it possible to study the surface recombination process of silicon wafer using THz-TDS. In the present study, we applied this method to measure silicon properties such as conductivity, charge carrier density and mobility, as well as the parameter SRV in the presence of UV light illumination. We showed that the illumination effect changes the conductivity as well as the SRV by altering the surface potential via photoexcited carriers.

2. Experimental methods

The sample used in the experiments was a p-type (100) silicon wafer with a resistivity value of 150–300 *Ω-cm*. The thickness of the sample was 531 *μm* measured by digital micrometer. The experiment was performed using a standard THz-TDS system with transmission geometry, described in detail elsewhere [9]. Optical pulses were generated by a mode-locked Ti:sapphire laser having a central wavelength, pulse width and repetition rate of 800 *nm*, 70 *fs* and 82 *MHz*, respectively. Both the terahertz emitter and detector were low-temperature-grown GaAs photoconductive antennas. A schematic of the experimental setup is shown in Figure 1. In addition, 365-*nm* UV light was introduced into the system, and the sample was illuminated at an incidence angle of 45^0 with power levels of 110, 220, 330 and 440 *mW* to generate charge carriers. The illumination area on the surface of the sample was 0.88 cm^2. In the THz-TDS data analysis, the complex refractive index and dielectric constant as well as the conductivity were directly deduced from the waveform measurements with and without the sample and their Fourier transformation. The SRV was determined using the Shockley-Read-Hall (SRH) model [10]. The entire THz path from transmitter to receiver was enclosed and purged with dry nitrogen gas to reduce the relative humidity to below 8%.

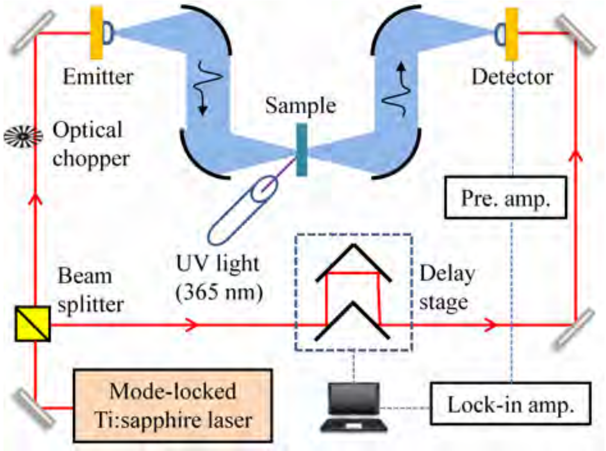

Fig. 1 Schematic of experimental setup for THz-TDS.

3. Results and discussion

Terahertz spectroscopic measurement was carried out on a silicon wafer that was illuminated by UV light to excite charge carriers. The temporal waveforms of the THz pulse transmitted through the Si wafer under different levels of illumination power are shown in Figure 2. It can be seen that the waveform amplitude is smaller in the presence of illumination than that in its absence and it decreases with increasing illumination power. These changes occurred because the increase in illumination power resulted in higher photocarrier densities in the wafer and therefore greater THz attenuation due to absorption by the photogenerated carriers.

Figure 3 shows the measured frequency dependence of the real conductivity at different levels of optical illumination power. It is obvious that the conductivity increased as the power of the light was increased. The complex conductivity depends on the carrier density and scattering time, which is explained by a simple Drude model that provides a good description of free carrier conduction in metals and semiconductors [11]. The characteristics of doped and/or illuminated silicon are close to those of metal. Thus, the simple Drude model is suitable for explaining the free carrier conduction in optically excited silicon. Solid lines are fitted to the real part of the complex conductivity at each level of illumination power to the simple Drude model, in which the complex conductivity is defined as $\sigma(\omega) = \Delta n e\mu(1 - i\omega\tau)$, where $\Delta n = m^{*}\sigma_0 / e^2\tau$ is the density of carriers, $\mu = e\tau / m^{*}$ is the mobility, τ is the carrier scattering time and m^{*} is the electron effective mass taken as 0.26 m_0 for silicon. Using τ and σ_0 extracted from the best fit of the data and the known value of m^{*}, the photoexcited carrier density Δn and mobility μ can be calculated. In this experiment, 365-*nm* UV light is used to illuminate the silicon wafer, which has an optical absorption coefficient of about 10^6 cm^{-1} [12]. Thus, the photoexcited carriers are generated very close to the surface, and the number density of electrons and holes are equal ($\Delta n = \Delta p$). The estimated photoexcited carrier density is plotted in Figure 4 as a function of the illumination power. It was found that the photoexcited carrier density increases linearly with the

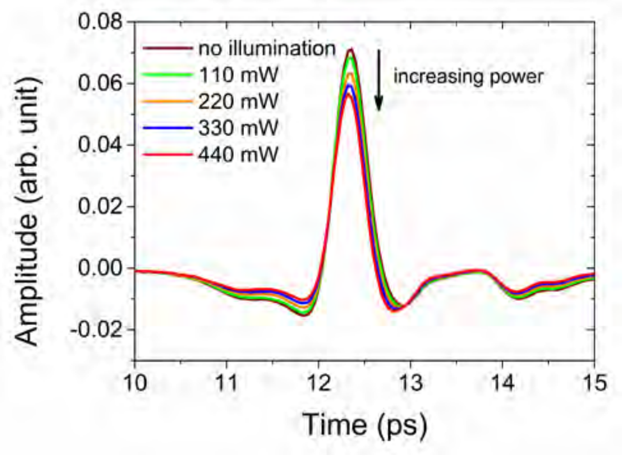

Fig. 2 Measured THz waveforms of Si wafer at different levels of optical illumination power showing efficient THz attenuation.

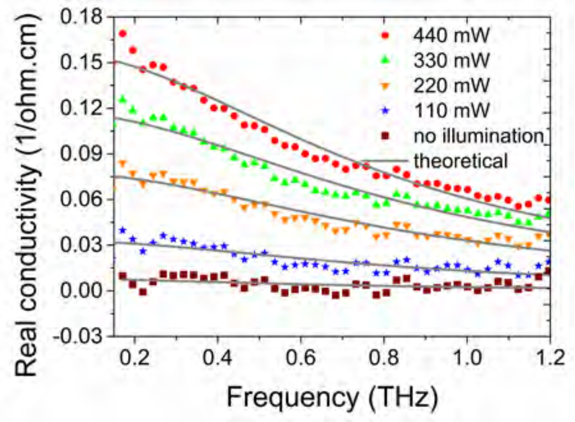

Fig. 3 Real part of conductivity of Si wafer at different levels of illumination power. The solid lines are the fitted curves using the simple Drude model.

level of illumination power. The photoexcited carrier density can significantly change the SRV, and the Δn dependence of SRV can be explained by the SRH model.

According to the SRH model [10], SRV is given by

$$S_r = \sigma_s v_{th} N_{st} \frac{N_A}{\Delta n_s + \Delta p_s + 2n_i} \tag{1}$$

Here, Δn_s and Δp_s respectively denote the electron and hole density (cm^{-3}) at the surface. In addition, n_i is the intrinsic carrier density, v_{th} is the thermal velocity, N_{st} is the surface trap density, σ_s is the carrier capture cross section and N_A is the acceptor concentration in the p-type semiconductor. SRV depends not only on the surface trap density but also on the doping density and the surface charge density Δn_s and Δp_s. The SRV also depends on the individual treatment at the silicon surface. In the presence of continuous wave UV light, photoexcited electron-hole pairs are generated very close to the surface within several tens nanometers. However, an estimation of the diffusion length from the values of electron diffusion coefficient, 36 cm^2s^{-1},

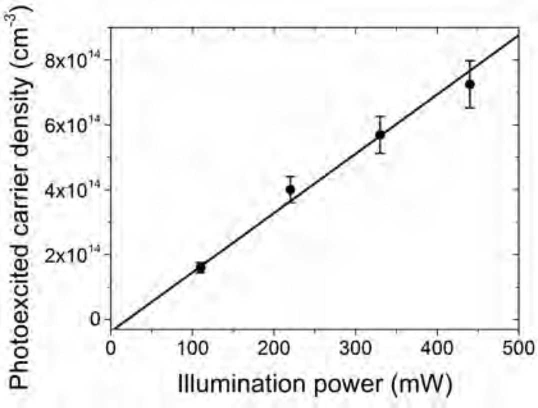

Fig. 4 UV illumination power dependence of photoexcited carrier density deduced from the simple Drude model fitted to the real conductivity.

and the typical electron lifetime, 2.5 *μm* of silicon gives the diffusion length ~0.3 *cm* [13]; this value is much larger than wafer thickness. This means that the gradient of electron distribution is very low. Therefore, the photoexcited carrier density can be considered as a surface carrier density. Then the value of SRV can be calculated by using the photoexcited carrier density by Equation (1). For the calculations, doping density $N_A = 5\times10^{15}$ cm^{-3}, surface trap density $N_{st} = 10^{11}$ cm^{-2}, carrier capture cross section $\sigma_s = 10^{-15}$ cm^2 and thermal velocity of carrier $v_{th} = 10^7$ *cm/s* were assumed [10]. The calculated values of SRV in the presence of illumination are in the range of 1.56×10^4 to 3.45×10^3 *cm/s* depending on the photoexcited carrier density. Figure 5 shows the photoexcited carrier density dependence of SRV. It can be seen that the SRV decreases with an increase of the photoexcited carrier density. This indicates that UV illumination is effective for reducing the effect of surface recombination in silicon wafer.

Bare (nonpassivated) Si surfaces have very high SRV in the range of 10^3 to 10^4 *cm/s* or higher. Bail and Brendel measured the SRV values (593±167) *m/s* for nonpassivated Si wafer by the QSSPC technique [6]. Usually, thermal oxidation is used for surface passivation to reduce the SRV. An oxidized Si surface has been reported with SRV from 0.25 [5] to 45.8 *cm/s* [14]. Ling and Ajmera reported that the value of SRV for a polished etched silicon surface is 500–1400 *cm/s* [15]. Our data show the values of SRV are much smaller than that for nonpassivated and larger than that for a passivated silicon wafer. This means that UV illumination partially passivates the surface of the silicon wafer. This tendency corresponds to results reported elsewhere [16-19], where the effective carrier lifetime increases with UV irradiation.

The effect of UV illumination on SRV can be discussed with the energy band diagram of the silicon wafer. Figures 6(a) and 6(b) show the energy band diagram of p-type silicon wafer before and under UV light illumination. Silicon wafers are normally covered with native oxide layers formed at room temperature at the interface. Some energy states, such as "fast" and "slow"states, also exist at the native oxide/silicon interface. The density of slow states is typically an order of magnitude larger and the carrier relaxation time is much longer than in the

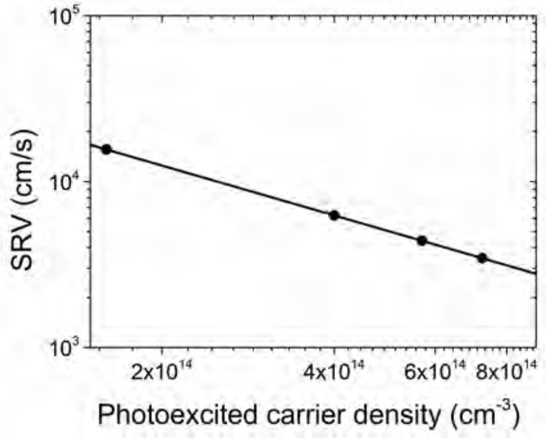

Fig. 5 Dependence of surface recombination velocity on photoexcited carrier density at surface region.

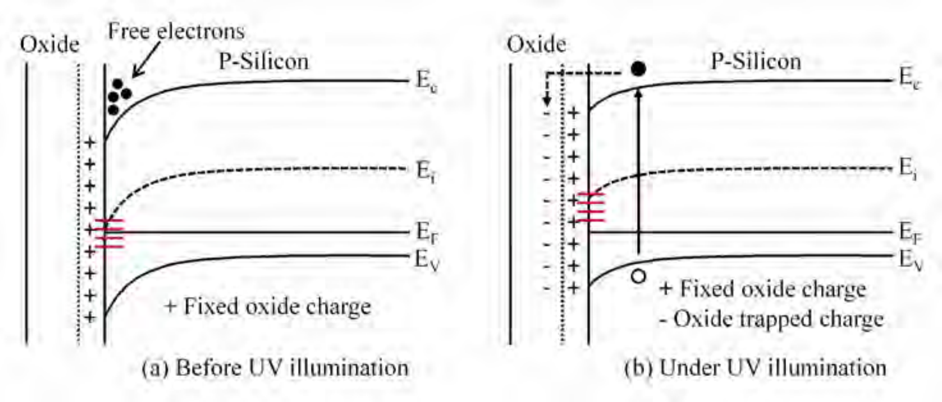

Fig. 6 Energy band diagrams of p-type silicon (a) before illumination and (b) under UV illumination.

fast states. The native oxide layer contains a positive charge of “fast states” at the interface, as indicated in Figure 6(a). This positive oxide charge induces a negative charge (free electrons) at the silicon surface, which introduces a negative surface band bending and a positive surface potential. Under UV light illumination [Fig. 6(b)], photocarriers are excited near the surface region. The minority electrons injected into the slow states could balance the positive charge of fast states in the oxide layer, thereby decreasing the negative surface band bending and resulting in a slight decrease in positive surface potential [17, 19]. The alteration of surface potential is due only to the charging of slow states within the native oxide [20]. This change in surface potential in the presence of UV illumination results in a decrease of SRV in the p-type silicon wafers.

5. Conclusions

We used THz-TDS to investigate the properties of photoexcited silicon wafer illuminated by UV light. From the measurement results, we determined the silicon properties such as conductivity, charge carrier density and mobility. We observed that the conductivity changes with changing level of illumination power. The measured conductivity fitted well with the simple Drude model at each level of illumination power. We also extracted the values for the SRV. It was found that the SRV is greatly reduced in the presence of UV light illumination due to the charge formation in the oxide, and depends strongly on the photoexcited carrier density at the surface region. Results indicate that the terahertz spectroscopic method is a promising candidate for investigating optical properties associated with the surface or interface of optically excited semiconductors.

Acknowledgements

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