Transactions of the Materials Research Society of Japan. Vol. 20

Excited conductivity and defect formation in photoconductivity-type Si sensor under particle irradiation

H. Amekura, N. Kishimoto, K. Kono and T. Saito

National Research Institute for Metals, 3-13 Sakura, Tsukuba, Ibaraki 305, Japan

Excited conductivity of Si, as an optical sensor under radiation fields, has been investigated under simultaneous irradiation of 17 MeV proton and ~1 eV light. The photoconductivity (PC) under the simultaneous irradiation decreases to 20~50 % of the value without the proton irradiation, that is, the PC is supressed by the simultaneous irradiation. Degree of the PC suppression depends on both the wavelength of the excitation light and the flux of the proton beam. The origin of the PC suppression is discussed.

1. INTRODUCTION

There has recently been a great demand for optical sensors usable under strong radiation fields, e.g., plasma diagnostics of nuclear fusion reactor, electric isolation in accelerator facilities, etc. Under the radiation fields, common optical sensors, such as photomultipliers and semiconductor photodiodes, however, tend to miscount or deteriorate by the ionization or the defect formation processes A radiation-resistant optical sensor is demanded.

In general, the electric conductivity σ increases by the ionization [1], and oppositely decreases by the defect formation [2] in silicon (Si). Since these changes induce instability of the σ and the photoresponse, the devices give rise to malfunctions. In developing the radiation-resistant devices, it is important to reveal the elementary processes in the semiconductor under particle irradiation. Recently, we have studied the photoconductivity(PC) of Si under 17 MeV proton irradiation, to understand the elementary processes as the optical sensors.

In this paper, the suppression of the PC due to the simultaneous irradiation of the proton and light is reported.

2. EXPERIMENTAL

The experimental procedures are similar to the ones described in the previous paper [3]. The specimen was mounted on a cold copper block of a cryogenic He-gas refrigerator, and was irradiated by 17 MeV proton and ~1 eV light, respectively with 7 and 45 degrees inclined from the normal axis. The monochromized light(~1 eV) was obtained from a halogen lamp(100W) and a single grating (300 l/mm). The bandwidth of the light was ~0.05 μ m. In some measurements, the light was mechanically chopped at ~10 Hz, and the signal was detected by a phase-sensitive method.

Figure 1 shows that the specimen temperature was almost constant even under the proton irradiations [4]. The temperature controller was set to keep the substrate temperature constant. The increases in the specimen temperature ΔT_{spc} were 0.3 K, 0.2K and less than the experimental error, at T_{sub} = 25 K, 50 K and 200 K, respectively. All the following experiments were carried out at T= 200 K.

Depth profiles of the ionization loss, damage and implanted proton in Si under 17 MeV irradiation were calculated by the computer code TRIM (TRansport of Ions in Matter) [5]. In this simulation, the value of 15.8 eV [6] was used as the displacement energy of Si. The projectile range calculated was 1.7 mm in Si, which is much larger than the specimen thickness 0.25 mm. The large

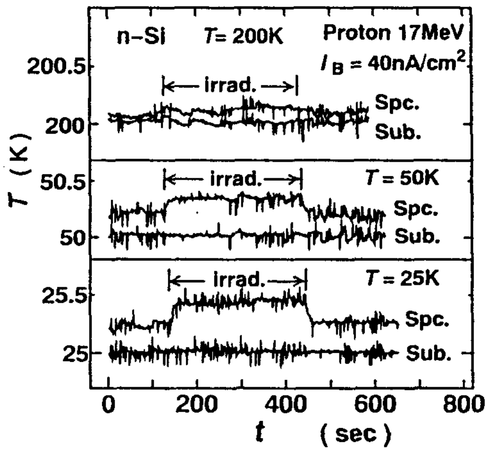

Fig. 1 Temperature change induced by the proton irradiation. Sub; substrate, Spc; specimen.

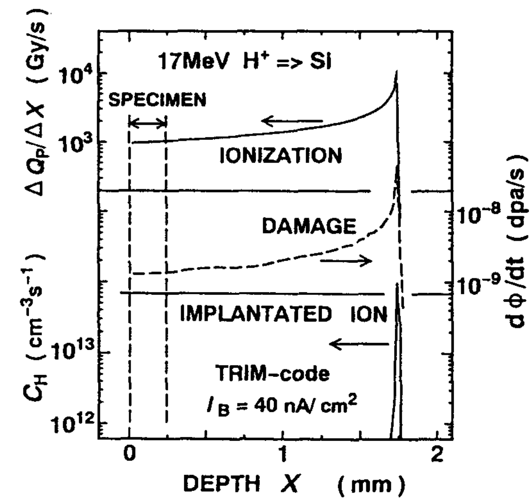

Fig.2 Depth profiles of the ionization, damage and implanted ion under 17MeV proton irradiation.

projectile range gives two advantages for experimental simplicity. One is that all the protons irradiated pass through the specimen and that the specimen is free from influence of the implanted protons. The other is that the depth profiles of the ionization and the defect formation are uniform along the depth.

3. RESULTS

Fig.3 shows photo-induced conductivity changes with and without proton irradiation. The conductivity σ under the proton irradiation increases at first, then decreases gradually. The rapid increase and gradual decrease are due to the ionization and the defect formation, respectively. The light irradiations (indicated by L) also increase the σ. The photo-induced conductivity changes $\Delta\sigma_L$ are almost the same, before and after the proton irradiation [1,2]. However, the $\Delta\sigma_L$ under the proton irradiation becomes too small to be observed with the DC method. Therefore, we modulated the light by a mechanical chopper, to detect the $\Delta\sigma_L$ by phase-sensitive (AC) method using a lock-in amplifier. The results are shown in Fig. 4. The time sequences of the light and the proton irradiations are shown in the upper side of the Fig. 4. First, the specimen is irradiated by the light of $\lambda = 0.9\ \mu$m ($1.2\ \mu$m) only, and then it is irradiated by both the light and the proton. The $\Delta\sigma_L$ is normalized by the value under the irradiation of the light only. With the simultaneous irradiation of the proton, the $\Delta\sigma_L$ decreases to 20 % at $\lambda = 0.9\ \mu$m and 40 % at $\lambda = 1.2\ \mu$m, of the value without the proton. It was confirmed under the proton irradiation

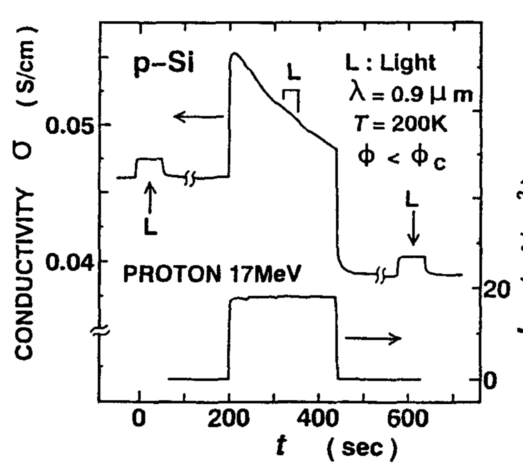

Fig. 3 Photo-induced conductivity changes with and without proton irradiation (upper), and the proton beam intensity (lower). The light irradiations are indicated by L.

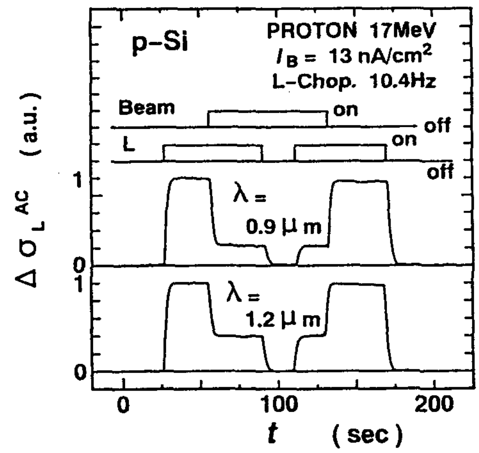

Fig. 4 Photoconductivity suppressed by the proton irradiation, detected by the phase-sensitive method.

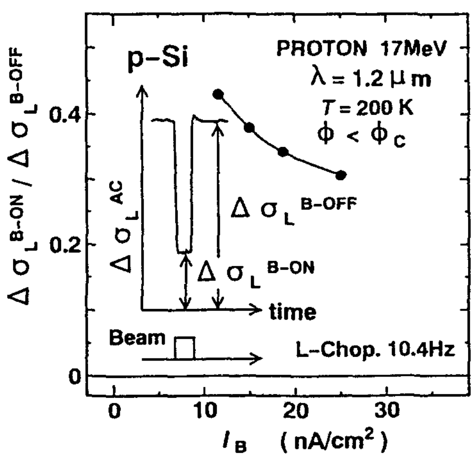

Fig. 5 Proton flux dependence of the photo-conductivity residual ratio (PCRR) $\Delta \sigma_L^{B\text{-}ON} / \Delta \sigma_L^{B\text{-}OFF}$.

that the $\Delta \sigma_L$ became zero without the light.

Now we define the PC residual ratio (PCRR) as the ratio of the $\Delta \sigma_L$ with the proton irradiation to the $\Delta \sigma_L$ without the proton irradiation, $\sigma_L^{B\text{-}ON} / \Delta \sigma_L^{B\text{-}OFF}$. As shown in Fig. 4, the PCRR depends on the wavelength λ. The λ dependence of the PCRR (not shown here) indicates that the PCRR is larger at the band edge and becomes smaller at the shorter λ.

The PCRR also depends on the proton beam intensity I_B. The dependence is shown in Fig.5. As the I_B increases, the PCRR decreases.

4. DISCUSSION

The PC does not consist of a single process, but photo-absorption (carrier-generation), electric transport and excess carrier relaxation. There are possible mechnisms for the origin of the PC suppression under high density excitation due to the proton irradiation.

One of the most plausible mechanisms is the bleaching of the photo-absorption due to the excited-state occupation. The carriers excited by the proton partially occupy the excited states above the band bottoms. The transitions from ground state to these states are partially inhibited. Accordingly, the photo-absorption could decrease. In this mechanism, the suppression of the PC should be stronger near the band edge, since the occupied probability of the excited states is higher near the band-edge. However, the observed dependence (described in Sec. 3) shows an opposite tendency, ie., the PC suppression is weaker at the band-edge. Consequently, the PC suppression is not explained by the bleaching.

The observed dependence may be explained by the wavelength dependence of the absorption coefficient $\alpha(\lambda)$. Near the band edge, the α is lower. The penetration depth of light is larger, and the spatial density of the excited carrier becomes lower. In the higher energy region, the α is higher, i.e., the penetration depth is the shorter and the density of the excited carrier is the higher. Consequently, the PC suppression becomes stronger in the higher energy region than the one near the band-edge.

The other candidate is the electron-hole "excess pair" recombination effect. The electron and hole density evolution under excitation (by light or particle) is given by the following rate equation [7],

$$\frac{d\Delta n}{dt} = G - C(np - n_0 p_0)$$
$$= G - C(n_0 \Delta p + p_0 \Delta n + \Delta p \Delta n) \qquad (1)$$

and a similar equation for Δp. The n and n_0 (p and p_0) denote the electron(hole) density with and without the excitation, respectively, i.e., $n = n_0 + \Delta n$ ($p = p_0 + \Delta p$). In n-type materials under low level excitation, i.e., $n_0 \gg \Delta n \sim \Delta p \gg p_0$, the leading term in the parentheses of the eq.(1) is $n_0 \Delta p$. Under the steady condition, the eq.(1) becomes $\Delta n = G / C n_0$. The excess carrier density Δn is proportional to the excitation G. Under the high density excitation, i.e., $\Delta n \sim \Delta p \gg n_0 \gg p_0$, the leading term is $\Delta n \Delta p$. Under the steady condition, the eq.(1) becomes $\Delta n = (G/C)^{1/2}$. The Δn is proportional to the square root of the excitation G. Though the PC increases linearly without the proton irradiation, it increase sublinearly under the irradiation. Fig.6 shows the excitation flux I_B dependence of the conductivity change $\Delta \sigma_B$ induced by the proton irradiation only, not the simultaneous one. The $\Delta \sigma_B$ is proportional to the square root of the excitation.

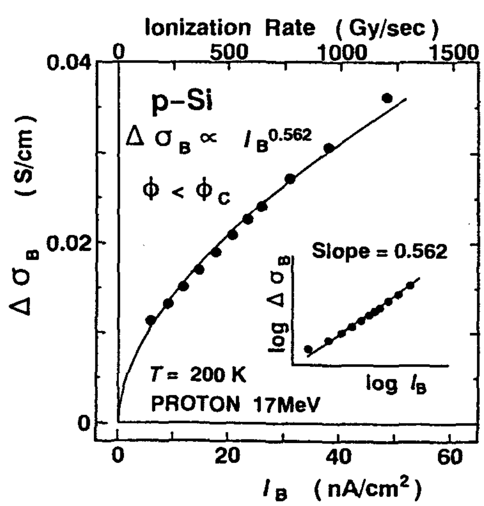

Fig. 6 Proton flux dependence of the proton induced conductivity $\Delta \sigma_B$.

The excitation-light-intensity dependence of the PC was also measured without the proton and was in a linear relation. This result agrees with the low excitation condition above.

It is concluded from the experimental results that the high-density excitation effect of electron-hole recombination is mainly responsible for the PC suppression. It should, however, be noted that the observed relation is on the $\Delta \sigma_B$, not on the Δn, but $\Delta \sigma_B = e\mu \Delta n$. The other possible mechanism of the excitation dependent μ can not be excluded and further study is necessary to draw the definite conclusion.

5. SUMMARY

The photoconductivity (PC) was studied under the simultaneous irradiation of 17 MeV proton and ~1 eV light. The PC under simultaneous irradiation decreases to 20 ~ 50 % of the value without the proton irradiation. The origin of the PC suppression is due to the saturation effect of the excitation intensity dependence on the conductivity increase $\Delta \sigma$, due to the high density excitation by the proton irradiation.

REFERENCE

1. N. Kishimoto, H. Amekura, K. Kono & T.Saito, J. Nucl. Mater. (1996) in press.
2. H. Amekura, N. Kishimoto and T. Saito, J. Appl. Phys. **77** (1995) 4984.
3. H. Amekura, N. Kishimoto, K. Kono & T. Saito, this issue.
4. H. Amekura, N. Kishimoto, K. Kono & T. Saito, Mater. Sci. Forum **196-201** (1995) 1159.
5. J. P. Biersack and L. G. Haggmark, Nucl. Inst. & Meth. **174** (1980) 257.
6. J. A. Van Vechten, Inst. Phys. Conf. No.31 (1977)441.
7. K. Seeger, *Semiconductor Physics*, 4th ed. (Springer-Verlag, Berlin, 1989) Chap. 5.1.