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Sensor materials of photoconductivity-type Si applicable to particle irradiation environments

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To explore radiation-resistant optical sensors, evolution of photoconductivity and particle-induced conductivity of Si has been investigated under 17 MeV proton irradiation. Both the excited conductivities do not greatly change up to a certain fluence ϕ_C, though they steeply decrease above the ϕ_C. The ϕ_C implies the tolerance limit against the particle irradiation and has a good correlation with the shallow impurity concentration of the specimen. The impurity doping has thus improved the radiation resistance of photoconductivity-type Si.

1. INTRODUCTION

Optical sensing has been one of the most important elements in modern technologies and semiconductors have commonly been used for the optical sensors, because of their high performance. The rapid progresses in the high-energy technologies have occasionally encountered radiation environments, such as in fusion reactors, spaceships and accelerators etc. Accordingly, radiation resistance of the semiconductors becomes an important issue in the optoelectronics.

High energy ions, injected into the semiconductors, excite electrons in the solids and generate electron-hole pairs of high density. At the same time, the ions displace the constituent atoms from their regular sites, and generate point defects. In crystalline Si, the electric excitation increases and the atomic displacement decreases electric conductivity σ. Since these two processes give opposite effects on the σ to each other, the σ becomes unstable under the ion irradiation. The instability is hazardous to operation of the semiconductor devices, under the radiation fields.

In this paper, we report evolution of photoconductivity (PC) and particle-induced conductivity (PIC) of Si under 17 MeV proton irradiation, considering possibility for a radiation-resistant optical sensor. In Section 3.1, deterioration of the PC with defect accumulation and improvement of the tolerant fluence limit by impurity doping are presented [1,2]. In Section 3.2, the particle-induced conductivity (PIC) with the defect accumulation is outlined. Finally, the radiation resistance of photoconcudtivity, attainable by the impurity doping [3], is discussed in Section 3.3.

2. EXPERIMENTAL

A 17 MeV proton beam from the NRIM cyclotron was used for the particle irradiation. The typical beam flux is about 40 nA/cm^2. Platelet specimens with electrodes were fabricated from commercially available Si wafers, and were mounted on the specimen stage of a cold copper block. Using a cryogenic He-gas circulator and a precise temperature controller, the block temperature was kept constant within ± 0.2 K, even under proton irradiation. The change in the specimen temperature due to irradiation was negligible. According to the computer code TRIM (TRansport of Ions in Matter) [4], the projectile range calculated was 1.7 mm in Si, which is much larger than the specimen thickness. The large projectile range gives two advantages for experimental simplicity. One is that all the incident protons pass through the specimen and that the specimens is free from the hydrogen implantation. The other is the uniform depth profiles of the ionization and the defect formation.

The proton fluence is occasionally expressed by a unit of dpa (displacement per atom), ie., primary defect concentration in ratio.

3. RESULTS AND DISCUSSION

3. 1. PC deterioration due to radiation damage

Fig.1 shows fluence dependence of the PC in nominally pure Si, and P- and B-doped Si. The conduction type and the carrier density are assigned by the specimen code, eg., *n*-type 3×10^{15} cm^{-3} as N3E15.

While the PC of the pure specimen (N2E12) steeply decreases with the irradiation, the PC of the doped specimen does not greatly decrease up to a certain fluence ϕ_C, indicated by arrows in Fig. 1. Above the ϕ_C, the PC steeply decreases. We named the ϕ_C the *critical fluence*. In other words, the critical fluence ϕ_C gives the tolerant fluence limit of the PC, against the particle irradiation.

Fig.1 indicates that the specimen with the higher ϕ_C is the more resistant to the proton irradiation. The relationship between the ϕ_C and the doped impurity concentration C_i is shown in Fig.2. The ϕ_C is proportional to the C_i. It is consequently stated that the specimen with the higher C_i is the more resistant against the proton irradiation, with respect to the PC. This statement is basically valid but there is another restriction for the higher concentration range. The restriction will be discussed in Section 3. 3.

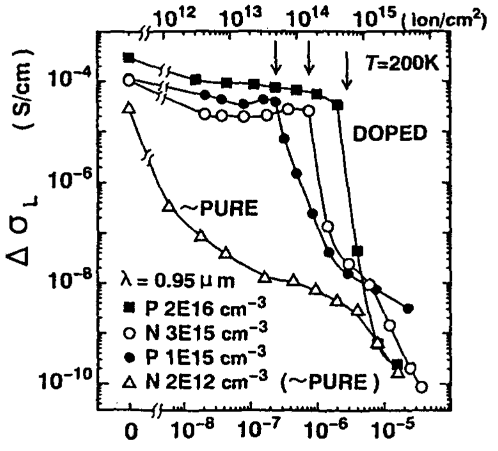

Fig. 1 Fluence dependence of photoconductivity for pure and doped Si. The arrows indicate the critical fluences ϕ_C's.

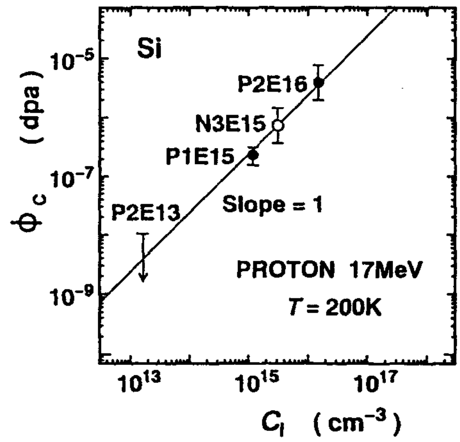

Fig. 2 Relationship between the critical fluence ϕ_C and the shallow impurity concentration C_i.

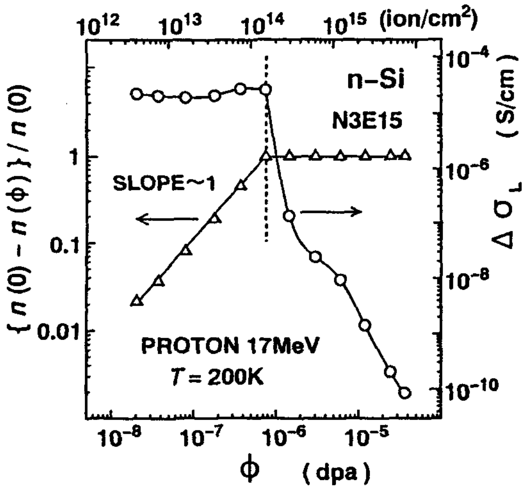

Fig. 3 Correlation between the trapped carrier density and the photoconductivity.

Fig. 3 shows the ratio of the carriers trapped by radiation-induced defects to the initial ones [5], as a function of the proton fluence. The fluence dependence of the PC is also plotted in Fig. 3. The $n(0)$ and $n(\phi)$ denote the free carrier densities at the irradiation fluences, 0 and ϕ, respectively. The difference $n(0)-n(\phi)$, is the trapped carrier density at the ϕ. The fraction of the trapped to the initial carriers, $\{n(0)-n(\phi)\}/n(0)$, increases linearly with the fluence ϕ. It implies that the (existent) defect density increases linearly with the ϕ, i.e., the primary defect density. When the fraction, $\{n(0)-n(\phi)\}/n(0)$, becomes unity, all the carriers are trapped. As shown in Fig. 3, the fluence at $\{n(0)-n(\phi)\}/n(0) = 1$ coincides with the critical fluence ϕ_C in the PC. Consequently, the ϕ_C is the fluence where all the carriers are trapped.

3. 2. Particle-induced conductivity

Fig. 4 shows the conductivity evolution of the doped Si under the irradiations of the proton((1)-(6)) or the light (L). The conductivity σ instantaneously increases on the proton or the light irradiation. They are caused by increases in carrier density via the electronic excitation. On the other hand, the σ gradually decreases under the successive proton irradiations. The deterioration is due to the defect accumulation.

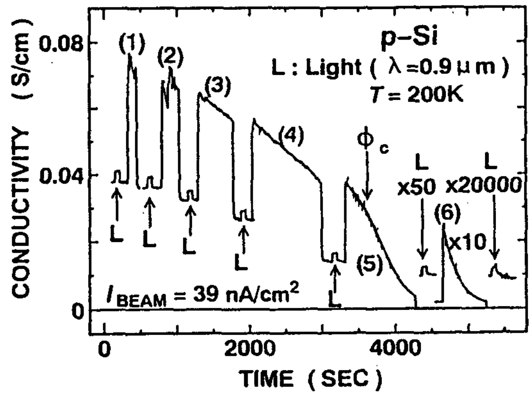

Fig. 4 Evolution of the conductivity due to photo- and proton irradiations. L : light and (1)-(6) : proton.

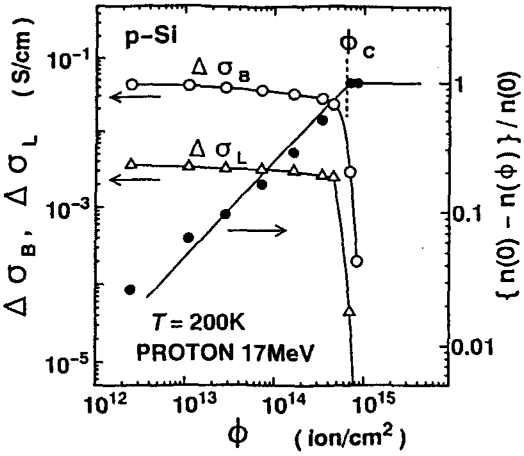

Fig. 5 Fluence dependences of the trapped carrier density, the photo- and the proton-induced conductivities.

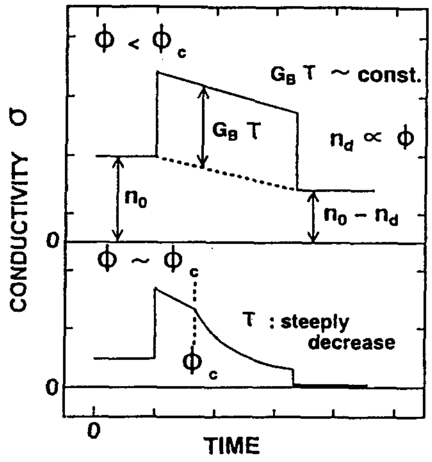

Fig. 6 Schematic diagram of conductivity evolution under the proton irradiation.

Here, the apparent instability in σ for the irradiation (1) and (2) is a spurious effect due to the beam fluctuation.

The light-induced increment $\Delta\sigma_L$ does not greatly decrease up to the proton irradiation (5). However, with the irradiation (5) and (6), the $\Delta\sigma_L$

steeply decreases to 1/50 and 1/20,000 of the value before the irradiation (5), respectively. Since a pronounced transition takes place around the irradiation (5), the fluence range is divided into two regions; the lower fluence region (1)-(4) and the higher region (5) and (6). In the lower fluence region, the dark-conductivity σ_{DARK} gradually decreases with the fluence, but the excited conductivity due to the proton beam, $\Delta\sigma_B$, does not greatly decrease. The $\Delta\sigma_B$ steeply decreases under the irradiation (5) and (6), in the same manner as the $\Delta\sigma_L$.

Fig. 5 shows the fluence dependences of the conductivity changes induced by the light and the proton. While the both do not greatly change up to 6×10^{14} proton/cm^2, they steeply drop beyond the fluence. This is the critical fluence mentioned in Section 3. 1. The transition is also observed as a slope change in the σ, at the ϕ_C in Fig. 4. The evolution of the PIC is schematically summarized in Fig. 6.

3.3. Application for radiation-resistant optical sensors

For high performance as an optical sensor, the ratio of the PC to the dark-conductivity, $\Delta\sigma_L/\sigma_{\mathrm{DARK}}$, must be large. It is a common sense that the shallow impurity doping is hazardous to the PC sensors increasing the dark-current. Deep impurity doping is commonly used for mid-IR sensors, eg., Ge:Cu, but the dark carriers in those sensors are frozen out at the low operating temperatures.

The coexistence of the dark-carriers turned out to be effective against the radiation damage, both for the PC and the PIC in Si. It has been shown in Section 3. 1. that the doping increases the tolerant fluence limit of the PC. The doping is also effective against the σ instability due to the PIC, since the doping increases the dark-conductivity σ_{DARK}. Namely, the relative instability $\Delta\sigma_B/\sigma_{\mathrm{DARK}}$ becomes small.

There is a trade-off relationship between the radiation resistance and the sensitivity in the doped PC sensors. Increasing the shallow impurity not only improves the radiation resistance but also increases the dark current. However, the considerable doping is possible, if we employ the phase-sensitive detection method to retain the PC sensitivity. Empirically, the doping levels up to 10^{16}/cm^3 are applicable.

It is remarked that the radiation-resistant optical sensor, of our proposal, consists of the impurity-doped Si of the PC type and the phase-sensitive detection.

4. SUMMARY

To seek optical sensors applicable for particle irradiation environments, evolution of the photoconductivity and the particle-induced conductivity of Si has been investigated under 17 MeV proton irradiation. At the critical fluence ϕ_C, the transition related to the excited conductivities takes place. While the dark-conductivity gradually decreases with the irradiation, the excited conductivities do not greatly decrease below the ϕ_C. The excited conductivities steeply drop above the ϕ_C. By use of the concentration region below the ϕ_C, the radiation-resistant PC is demonstrated. The shallow impurity doping is effective for both the photoconductivity and the proton-induced conductivity.

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