（公財）日本板硝子材料工学助成会，41（2023）

SiC パワーデバイスにおける通電劣化抑制法の開発

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Suppression of Bipolar Degradation of SiC Power Devices

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SiC パワーデバイスは、積層欠陥の拡大による通電劣化という問題を抱えている。この問題は、エピタキシャル層内や基板との界面近くで起こる基底面転位から引き起こされる。本研究では、UV 照明下でプロトン照射を用いた 4H-SiC エピタキシャル層の積層欠陥拡大の挙動を調査した。その結果、プロトン照射が積層欠陥の拡大を抑制することが X 線トポグラフィー観察で明らかとなった。また、過剰キャリア寿命の測定により、1×10^{11} cm^{-2} のドーズ量でのプロトン照射が、過剰キャリア寿命の大幅な減少なしに積層欠陥の拡大を抑制することも示された。加えて、高温熱処理を行って過剰キャリア寿命を回復させた後でも、積層欠陥の拡大は抑制された。これらの結果から、プロトンによる転位芯のパッシベーションが UV 照明下での部分転位の運動を阻害することが示唆された。

SiC bipolar degradation, which is caused by the stacking fault expansion from basal plane dislocation in SiC epitaxial layer or near the interface between the epitaxial layer and a substrate, is one of the critical problems toward widespread usage of high-voltage SiC bipolar devices. In the present study, we have investigated the stacking fault expansion behavior in 4H-SiC epitaxial layer with proton irradiation under UV illumination. X-ray topography observation revealed that the proton irradiation suppressed the stacking fault expansion. From excess carrier lifetime measurements, the stacking fault expansion in 4H-SiC epitaxial layer with the proton irradiation at a fluence of 1×10^{11} cm^{-2} was suppressed without evident reduction of the excess carrier lifetime. Furthermore, the stacking fault expansion was also suppressed even after high-temperature annealing recovering the excess carrier lifetime. These results implied that the passivation of the dislocation core by protons hinders the recombination enhanced dislocation glide motion under UV illumination.

1. Introduction

Hexagonal silicon carbide (SiC) having 4H polytype is promising semiconductor materials for high-power and high-temperature devices [1–3]. Owing to the recent progress in SiC device technology, 1-kV-class SiC Schottky barrier diodes (SBDs) and metal-oxide-semiconductor field effect transistors (MOSFETs) have been already commercialized and used in various kinds of electronic systems such as power supplies for servers and workstations, solar inverters, uninterruptible power supplies, industrial motor drives, air-conditioners, fast chargers, elevators, electric vehicles, and railcars [4,5]. On the other hand, SiC bipolar devices such as p-i-n diodes, insulated gate bipolar transistors (IGBTs) and thyristors have a problem about device degradation, in which forward voltage is increased due to expansion of single Shockley-type stacking faults (1SSFs) in epitaxial layer under forward-bias condition [6–12]. The expansion of 1SSFs is originated from extended dislocations having the Burgers vector of 1/3<11-20> on the (0001) basal plane which is called basal plane dislocations (BPDs). 1SSF between two partial dislocations are expanding during the bipolar operation by the glide of the partial dislocation with the driving force of "negative" stacking fault energy due to the electronic energy lowering by the carrier trapping at the stacking fault [13–18]. Similarly, double Shockley-type stacking faults (2SSFs) in heavily nitrogen doped 4H-SiC are expanding during high temperature annealing [19–24]. These anomalous behaviors of stacking faults in 4H-SiC is considered to be due to the relatively low stacking fault energy, which was estimated to be 14.7 mJm^{-2} for 1SSF [25], and large energy gain due to the energy level of a localized state in the stacking fault estimated to be 0.22 and 0.59 eV below the conduction band edge of 4H-SiC for 1SSF and 2SSF, respectively [20,21].

Since the 1SSF expansion was reported to be originated from BPDs in the epitaxial layer, great efforts for the reduction of BPD density in epitaxial layer was made [26–29]. Thanks to the dislocation conversion from BPD to threading edge dislocations (TEDs) propagating to the [0001] direction during epitaxial growth process, the typical BPD density in commercial SiC epitaxial wafers was almost zero (less than 1 cm^{-1}) [3,5,30]. However, the 1SSF expansion underneath BPD-TED conversion points under high current stress has been reported [31–33]. To suppress the 1SSF expansion, proper design of buffer layer, which is the first thin layer grown on a substrate, is important. Tawara et al have clearly demonstrate the relationship between injected carrier concentration and 1SSF expansion and the recombination enhancing buffer layer in p-i-n diodes suppress the 1SSF expansion[33,34]. However, thick buffer layer is necessary to suppress the 1SSF expansion under a high current density resulting in the increase of process cost. Therefore, it is desirable to develop other strategy to suppress the stacking fault expansion. The other important aspect of the spontaneous expansion of 1SSF is decrease in critical resolved stress (CRSS) for the glide of the partial dislocation called "recombination-enhanced dislocation glide" in 4H-SiC reported by many researchers [9,13,35]. Thanks to the drastic decrease in the CRSS, the 1SSFs was reported to expand even below room temperatures [35]. Considering the critical resolved shear stress for basal slips in SiC was estimated to be as large as 5-10 GPa at room temperature without recombination-enhanced dislocation glide [36,37], anomalous decrease in the CRSS for the partial dislocation

Proton irradiation is widely used in semiconductor process for the purpose of doping and control of lifetime including SiC device process [38–41]. Proton irradiation results in the formation of radiational defects as well as hydrogen doping. It was reported that the defects by proton irradiation introduced $Z_{1/2}$ deep level and reduced the carrier lifetime [42–44]. In the present study, we have investigated the stacking fault expansion behavior in SiC epitaxial layers with proton irradiation. For the investigation of stacking fault behavior, we have used the ultraviolet (UV) illumination optically exciting excess carriers to stimulate stacking fault expansion [9,45,46].

2. Experimental procedure

An N-type 4H-SiC epitaxial layer with a thickness of 10 μm, a nitrogen concentration of $1.0\times10^{16}\,\mathrm{cm}^{-3}$ and an off-cut angle of 4° from the (0001) basal plane grown by the chemical vapor deposition (CVD) on a 3-inch SiC wafer (SiCrystal GmbH) was cut by laser scribing with a size of 5-10 mm in length. The specimens were irradiated at room temperature with 0.6-MeV and 0.95-MeV protons at fluences ranging from 1×10^{11} to $1\times10^{16}\,\mathrm{cm}^{-2}$. Hydrogen distribution of the specimen with a fluence of $1\times10^{16}\,\mathrm{cm}^{-2}$ was investigated by secondary ion mass spectrometry (SIMS) as shown in Fig. 1. Maximum hydrogen densities in the specimens with 0.6-MeV and 0.95-MeV proton irradiation were about 5 and 10 μm, respectively. Grazing incidence synchrotron reflection X-ray topography was performed using a monochromatic X-ray beam ($\lambda=0.15$ nm) with g vector of -1-128 or 11-28 at BL8S2 in Aichi Synchrotron Radiation Center and BL20B in the Photon Factory at the High-Energy Accelerator Research Organization (details of the condition were referred to [47]). The X-ray topography observation enable us to identify the Burgers vector of the dislocations [27,48,49]. Firstly, the positions of propagating BPDs into the epitaxial layer were confirmed, and then UV light was illuminated at these positions. UV light emission diode with a wavelength of 365 nm was focused to a diameter of 3 mm, and the illuminated intensity was adjusted to $10\,\mathrm{W cm}^{-2}$. During the UV illumination, the specimens were heated to 373 K and the temperature was measured by a radiation thermometer. Carrier lifetime of the specimens was evaluated by time-resolved photoluminescence (TR-PL) using a bandpass filter with transmission wavelength of 370-410 nm corresponding to luminescence from the band edge of 4H-SiC (～390 nm) as well as micro photoconductance decay (μ-PCD) [12,51].

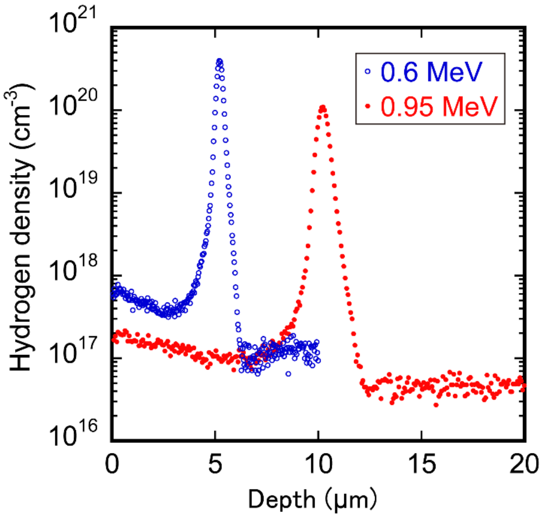

Figure 1. Depth profile of hydrogen density for the specimen with a proton fluence of $1\times10^{16}\,\mathrm{cm}^{-2}$ measured by SIMS [50].

3. Results

Figure 2 shows the X-ray topography image taken from the proton unirradiated 4H-SiC epitaxial wafer before UV illumination. Most of the linear contrasts corresponding to BPDs was accompanied by the small circular contrasts corresponding to TEDs at the right end of the BPDs like “BPD-I”. On the other hand, some BPDs were not converted to TEDs and propagated to the epitaxial layers like “BPD-II” and “BPD-III”. The propagated BPDs can be recognized by the characteristic contrast of BPD near the surface (on the right side in Fig. 1).

The contrast pattern of BPD was reported to depend on the depth below the crystal surface in 4H-SiC from the comparison of the ray-tracing simulation and the X-ray topography observation [52]. A BPD located shallower than about 5 μm from the surface (right side in Fig. 1) is imaged as a white line bordered by black lines and the BPD located deeper (left side in Fig. 1) is imaged as a pure black line contrast. Therefore, it is possible to judge whether the BPD was converted or not. We have carefully checked the positions of the propagated BPDs and illuminated UV light at the positions.

Evolution of 1SSF expansion in the proton unirradiated epitaxial wafer during UV illumination was shown in Fig. 3. In this X-ray topography geometry, SFs never have the contrast and the surrounding partial dislocations have the black and white contrast depending on the directions [53]. By UV illumination, the line contrast was appeared and the surrounding area corresponding to the SF expanding as the UV illumination time increases. After the further UV illumination with power densities of 5, 2.5 and 1 Wcm^{-2} for 1, 2 and 12 h, we have also observed the expansion of SF. The current SF expansion behavior was consistent with that reported by Tanaka et al. [46].

Figure 4 shows the X-ray topography images taken from the specimens with 0.6-MeV proton irradiation before and after the UV illumination for 120 h. Even after UV illumination for 120 h, apparent SF expansion was not noticed except for the specimen with proton irradiation at fluence of 1 × 10^{11} cm^{-2}, in which slight

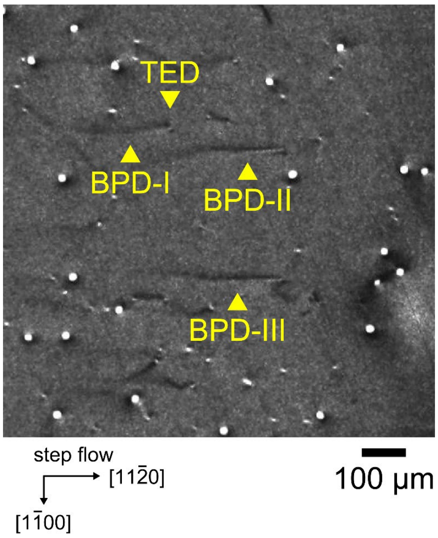

Figure 2. X-ray topography image taken from the specimen without proton irradiation before UV illumination. "BPD-I" is converted to TED, and the BPD/TED conversion is not noticed for "BPD-II" and "BPD-III" [50].

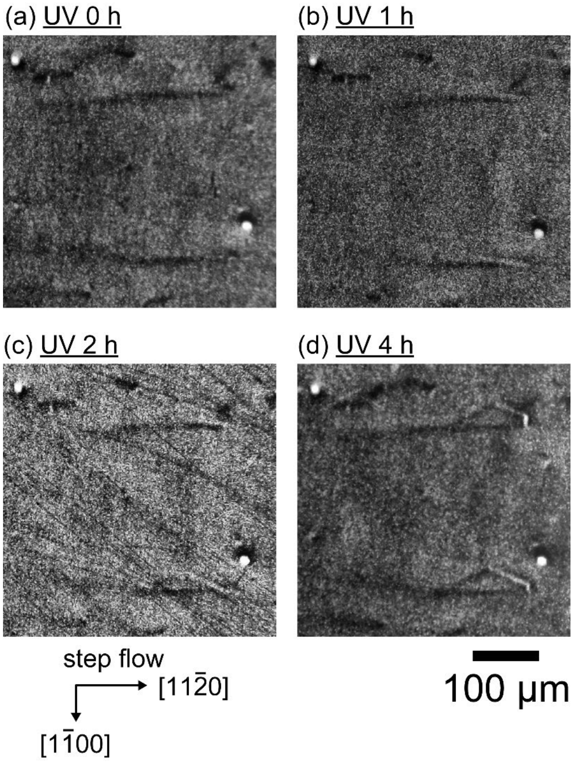

Figure 3. X-ray topography images taken from the specimen without proton irradiation with the different UV illumination time (a: 0 h, b: 1 h, c: 2 h, d: 4 h) with a power density of 10 Wcm^{-2} at 373 K [50].

expansion of SF was observed at the position indicated by the yellow arrow in Fig. 4 (f). The expansion of the SF is limited at the left side of the BPD indicating that the expansion took place at the bottom side of the epitaxial layer and the proton irradiation suppress the SF expansion at the top side of the epitaxial layer.

The lifetime measured by TR-PL and μ-PCD for the specimen of 0.95-MeV proton irradiation with the different fluences are shown in Fig. 5. Although absolute values of lifetime differ depending on the measurement method (the lifetime measured by TR-PL was always larger than that by μ-PCD), the same tendency in which the lifetime is almost unchanged by the proton a fluence of 1×10^{11} cm^{-2} and decreases with increasing proton fluences was observed in both TR-PL and μ-PCD measurements. Note that the lifetime had a distribution in the epitaxial wafer resulting in large deviation of the values of lifetime for the non-irradiated specimens and the lifetime tends to be small near the edge of the wafer, where the propagation of BPDs was frequently observed.

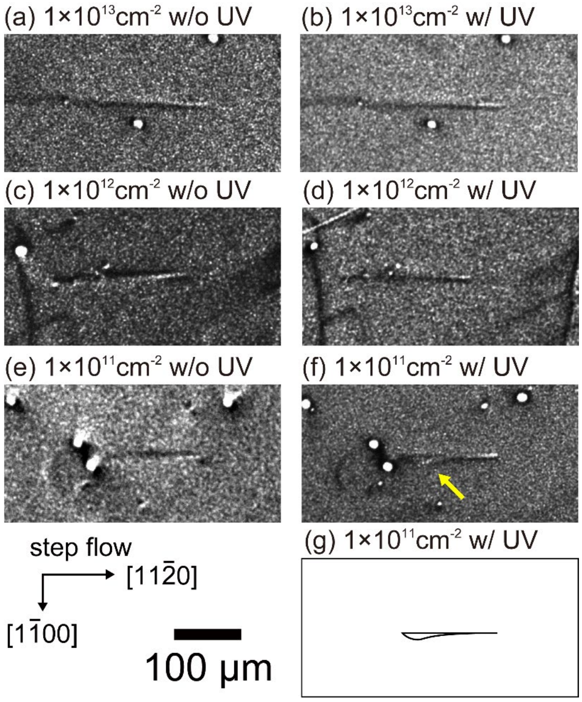

Figure 4. (a)-(f) X-ray topography images taken from the specimen with proton irradiation fluence ranging from 1×10^{11} to 1×10^{13} cm^{-2} before and after UV illumination for 120 h and (g) schematic illustration of the shape of SF shown in (f) [50].

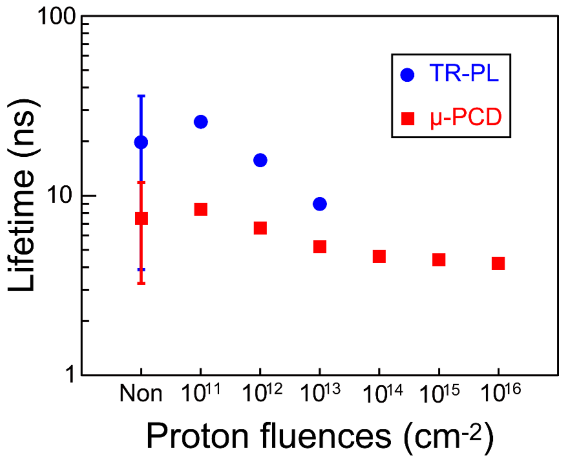

Figure 5. Carrier lifetime depending on proton fluences measured by TR-PL as well as μ-PCD [50].

4. Discussion

4.1. Driving force of SF expansion by UV illumination

Excess carrier concentration in epitaxial layer (Δn) by UV illumination in steady state was estimated by the following equation for low excess carrier concentration assuming that surface and interface recombination is negligible [54];

$$-\frac{\Delta n}{\tau_{epi}} + G = 0 \qquad (1)$$

where τ_{epi} is the bulk carrier lifetime in the epitaxial layer and G is the generation rate of the excess carrier in epitaxial layer calculated from the photon flux and absorption [54]. The value of τ_{epi} is not identical to the measured values of carrier lifetime by μ-PCD and TR-PL[55]. Here the typical value for as-grown n-type SiC epitaxial layer (0.1-1μs) was adopted to the estimation. The excess carrier concentration was estimated to be 2×10^{14}-2×10^{15} cm^{-3}, which led to the electronic energy gain (Δ) around 0.5～3 mJ/m^2 from the calculation result of Ref. 17.

On the other hand, the driving force of the SF expansion (negative stacking fault energy γ) by UV illumination was possible to estimate from the curvature radius (R) of pinned partial dislocations under equilibrium of forces acting on dislocation by the following equation[24];

$$\gamma = -\frac{b^2}{4\pi R}\left\{K_{edge}\sin^2\theta + K_{screw}\cos^2\theta + 2\left(K_{edge} - K_{screw}\right)\cos 2\theta\right\}\ln\left(\frac{r_1}{r_0}\right) \qquad (2)$$

where b, K_{edge}, K_{screw}, θ, r_0 and r_1 stands for the Burgers vector of dislocation, the energy factors of edge and screw components, the angle between the line vector and the Burgers vector, and inner and outer cut-off radius. Judging from the shapes of the vertexes in Fig.3 (d), the value of R was ranging from 5 to 50μm corresponding to the values of γ ranging from -0.6 to -6 mJ/m^2. SF energy without UV illumination (γ_0) was estimated by the following relationship;

$$\gamma = \gamma_0 - \Delta \qquad (3)$$

From the obtained values of Δ and γ, the value of γ_0 was evaluated as+2～-5mJ/m^2. Considering the SF expansion took place with even lower UV illumination as tabulated in Table 1, it was expected that the SF energy without UV illumination near room temperature was much lower than the assumed value of γ_0 (5～20 mJ/m^2) based on SF energy evaluated by the dissociation width of partial dislocations deformed at high temperature[17,25], although the current estimation was a bit rough.

The shear stress acting on the partial dislocation by the negative stacking fault energy was estimated to be 3-30 MPa, which was much lower than the bulk critical resolved shear stress (4.5 GPa) for the basal slip in 6H-SiC estimated by microplillar compression test [37]. This indicates the occurrence of the drastic decrease in activation energy due to the recombination enhanced dislocation glide by UV illumination as was reported by carrier injection and electron beam irradiation [35,56].

4.2. Effect of proton irradiation

TR-PL and μ-PCD measurements indicate that the carrier lifetime decreases by the proton irradiation as was reported by Hazdra et al. [44] They have reported that the carrier lifetime reduction took place due to the introduction of $Z_{1/2}$ centers, which are related to the carbon vacancy. In the present study, 0.6-MeV proton irradiation at fluences ranging from 1×10^{12} to 1×10^{13} cm^{-2} resulted in the evident reduction of carrier lifetime and the suppression of the SF expansion, which was in good agreement with the results reported by Tawara et al. demonstrating a short carrier lifetime successfully suppress the SF expansion [34]. On the other hand, 0.6-MeV proton irradiation at a fluence of $1\times10^{11}\,\mathrm{cm^{-2}}$ also resulted in the suppression of the SF expansion although the carrier lifetime was almost unchanged by the proton irradiation. This result implies that the proton irradiation affects not only on the carrier lifetime but also on the dislocation motion. The interaction between dislocations and point defects such as protons and vacancies would increase the CRSS for the glide of the partial dislocation. Kwon et al. have reported that the increase in the CRSS with the proton irradiation by micro-pillar compression test for 6H-SiC crystals [57].

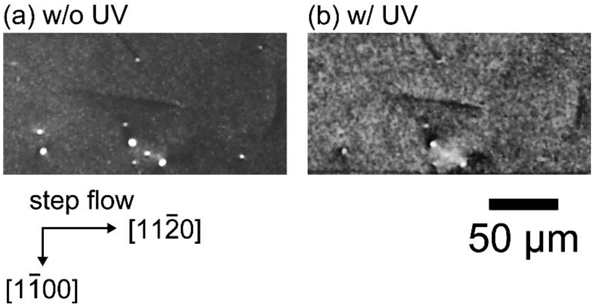

Figure 6. X-ray topography image taken from the epitaxial layer with a thickness of 5 μm, a nitrogen concentration of $6\times10^{15}\,\mathrm{cm^{-2}}$, a 0.3-MeV proton irradiation at a fluence of $1\times10^{15}\,\mathrm{cm^{-2}}$ after annealing at 1973 K for 1 hour (a) before and (b) after UV illumination with a power of 10 $\mathrm{Wcm^{-2}}$ at 373 K for 10 hours [50].

To further confirmed the effect of proton irradiation on the dislocation glide, we investigated the SF expansion behavior for the specimen with proton irradiation after high-temperature annealing to recover carrier lifetime. Figure 6 shows the X-ray topography image taken from the epitaxial layer with a thickness of 5 μm, a nitrogen concentration of $6\times10^{15}\,\mathrm{cm^{-2}}$, a 0.3-MeV proton irradiation at a fluence of $1\times10^{15}\,\mathrm{cm^{-2}}$ after annealing at 1973 K for 1 hour, of which carrier lifetime was confirmed to be unchanged after the annealing by μ-PCD measurements. The propagating BPD in the epitaxial layer was not expanded to SF even after UV illumination for 10 hours at 373 K as shown in Fig. 6. These results indicate that the proton irradiation increase the CRSS for the glide of the partial dislocation under the UV illumination and suppress the SF expansion. Hydrogen (proton) passivation of surfaces, point defects and dislocations in semiconductor crystals including silicon and 4H-SiC was reported by many researchers [58–61]. If the proton terminates the dangling bonds of the core of the partial dislocations in epitaxial layer, the mobility of the partial dislocation is expected to increase as well as the recombination at dislocation is expected to be suppressed resulting in the suppression of recombination enhanced dislocation glide by UV illumination. Current results implies that the bipolar degradation in SiC power device would be suppressed by the proton irradiation, which has a high affinity of semiconductor process.

5. Conclusion

The SF expansion behavior in n-type 4H-SiC epitaxial layers by UV illumination with the different proton irradiation was investigated by X-ray topography as well as the carrier lifetime measurements. The results obtained are summarized as follows:

(1) The SFs was expanded from the BPDs in 4H-SiC epitaxial layer without proton irradiation by UV illumination and the expansion was suppressed by the proton irradiation at fluences ranging from 1×10^{11} to $1\times10^{13}\,\mathrm{cm^{-2}}$.

(2) From the curvature radius estimated from the X-ray topography observation, the SF

energy without UV illumination at 373 K was evaluated to be+2～-5 mJ/m^2, which was much smaller than the expected value (5～20 mJ/m^2) based on SF energy evaluated by the dissociation width of partial dislocations deformed at high temperature

(3) The excess carrier lifetime was evidently reduced by the proton irradiation at fluences larger than 1×10^{12} cm^{-2} from both measurement of TR-PL and μ-PCD.

(4) The SFs expansion in 4H-SiC epitaxial layer with the proton irradiation at a fluence of 1×10^{11} cm^{-2} was suppressed without evident reduction of the excess carrier lifetime, which implies that the recombination enhanced dislocation glide is hindered by the interaction between the partial dislocations and the point defects introduced by the proton irradiation.

(5) The SFs expansion was also suppressed even after high-temperature annealing recovering the excess carrier lifetime, which support the proton irradiation hinder the recombination enhanced dislocation motion.

Present results implies that the bipolar degradation in SiC power device would be solved by the proton irradiation, which has a high affinity of semiconductor process.

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