Performance Recovery of Silicon-Avalanche-Photodiode Electron Detector by Low-Temperature Annealing

Taizo Kawauchi, Shunji Kishimoto, and Katsuyuki Fukutani

***Abstract*—We report that the silicon avalanche photodiode (APD) for electron detection almost fully recovers from the damage caused by electron irradiation by annealing. With the electron irradiation at an energy of 8 keV, a prominent increase of the non-amplified component of the dark current was observed, and the gain and energy resolution for APD were significantly lowered. Upon annealing at 500 K for 10 h, the dark current was reduced and the gain and energy resolution were recovered. We also show that the dark current of APD depends on the material of the surface protection layer. The origin of the degradation and recovery is discussed.**

***Index Terms*—Annealing, avalanche photodiode, dark current, electron detector, pulse height analysis, recovery.**

I. INTRODUCTION

THE AVALANCHE photodiode (APD) can be used to detect both photons and charged particles [1], [2]. A problem in the electron detection is that the Si-APD suffers from degradation after a long period of use. From the physical point of view, no direct momentum transfer from electrons is expected at a low energy, and the main damage by electron irradiation is breaking of chemical bonds leading to creation of dangling bonds and localized in-gap states. We have studied the effects of electron irradiation on Si-APD to find that the dark current is increased and the gain is lowered with electron irradiation [3]. The origin of the lowered gain was attributed to the formation of defect levels in the band gap of the p$^+$ layer, which act as a recombination center of charge carriers [3]. In view of practical usefulness, the method to reduce the damage or recover from the damage due to electron irradiation has been strongly required, because regular replacement of APD is inevitable at the present stage. We have recently reported the effects of vacuum annealing on a fresh Si-APD electron detector [4]. By annealing at 500 K for 10 h, the gain and energy resolution of the APD were significantly improved. As the origin of the improvement of the detector property, passivation of defect levels by hydrogen was discussed on the basis of the hydrogen depth profiling data [4], [5]. At 500 K, the diffusion coefficient of hydrogen in silicon is sufficiently large, while dopants, defects and other impurities are virtually immobile [6], [7], [8].

The motivation behind the present study is thus to examine ifthe annealing of APD influences the performance of the Si APD degraded by electron irradiation. We found that the dark current at a low bias voltage corresponding to the non-amplified component as well as that at a high bias voltage corresponding to the amplified component was increased by the electron irradiation. The results suggest that the surface protection layer is degraded in addition to the electrode p$^+$ layer. Upon annealing at 500 K, the dark current, gain and energy resolution of APD were found to be almost fully recovered. It was also found that the dark current depends on the material of the surface protection layer, either SiO_2 or SiN. The present work definitely shows that the anneal process enables the Si APD to recover from the electron-induced damage.

II. EXPERIMENT

Two types of APD's investigated in the present work were the reach-through-type Si-APD with an effective sensitive area of 3 mm in diameter (S10937-9155 and SPL3989 of Hamamatsu Photonics K.K.). Both consist of a surface protection layer (20nm), highly-doped p (p$^+$) layer (0.8 μm), p (π) layer (30 μm), and highly-doped n (n$^+$) substrate (400 μm) in order of depth from the surface. The surface protection layers of S10937-9155 and SPL3989 are Si_xN_{1-x} and SiO_2, respectively. The Si_xN_{1-x} was deposited by low pressure chemical vapor deposition (LPCVD) with SiH_4 and NH_3, and the SiO_2 was grown by thermal oxidation. The property of the APD's was characterized by the dark-current measurement at various bias voltages and the pulse height analysis of the output signal upon electron incidence. For the pulse height analysis, electrons at an energy of 3–30 keV were incident on the APD through a set of apertures at an electron beam current of 1.5 pA, and the output signal of the APD

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T. Kawauchi and K. Fukutani are with the Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan (e-mail: kawauchi@iis.u-tokyo.ac.jp; fukutani@iis.u-tokyo.ac.jp).

S. Kishimoto is with the Institute of Materials Structure Science, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan (e-mail: syunji.kishimoto@kek.jp).

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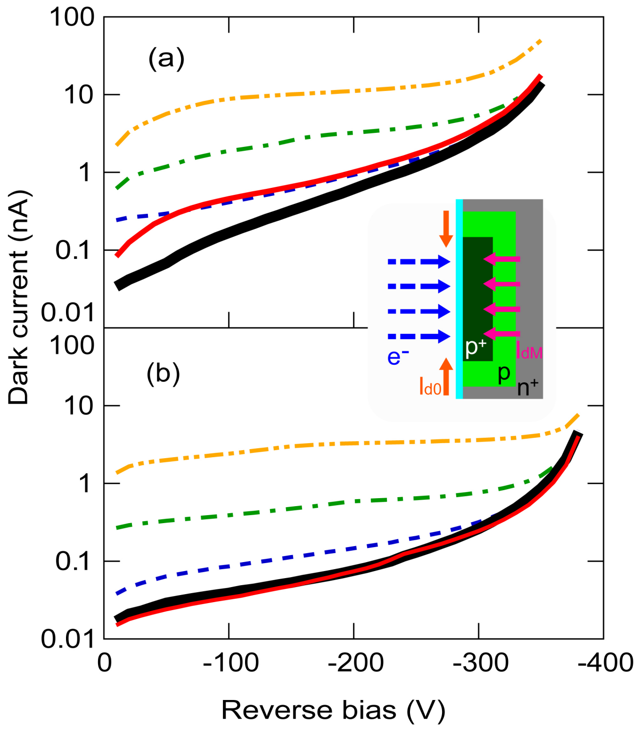

Fig. 1. Dark current (I_d) at several reverse-bias voltages (V_{p^+}) of (a) APD(S10937-9155) and (b) APD(SPL3989) before(black solid line) and after the electron irradiation of 8 keV at phased dosing-densities of 10^{13}(chain line), 10^{14}(dashed line), 10^{15}(two-dot chain line) cm^{-2} and annealing at 500 K for 10 h after the 8keV electron irradiation at the dosing-density of 10^{15} cm^{-2}(red solid line).

was analyzed by a multichannel analyzer through a charge-sensitive preamplifier and a spectroscopy amplifier [3]. The total electron dose for pulse height analysis was lower than 10^7 cm^{-2}, of which damage was negligible. For the examination of the electron irradiation effect, a center area of the APD's (2 mm in diameter) was exposed to electrons at an energy of 8 keV and a density of 10^{12} – 10^{15} cm^{-2} without the reverse bias. The electron beam current was monitored by the n$^+$ electrode of the APD. The annealing was conducted at 500 K for 10 h, because significant improvement of the APD property was observed at this temperature [4]. The measurements and anneal were performed in a vacuum of 10^{-4} Pa.

III. RESULTS

Fig. 1 shows the dark current measured for the two APD samples at various bias voltages applied to the p$^+$ electrode (V_{p^+}). Before the electron irradiation, the dark current was 0.1 – 1 nA for the SiN–capped APD and 0.01 – 0.1 nA for the SiO$_2$–capped APD as shown by the dotted curves. The dark current increased at a reverse voltage of larger than 300 V with increasing avalanche multiplication. With electron irradiation, the dark current was increased with increasing electron dose as shown in Fig. 1, which are in agreement with a previous study [3]. After annealing the APD's with an electron dose of 10^{15} cm^{-2} at 500 K for 10 h, on the other hand, the dark current was reduced at all bias voltages as displayed by solid curves. It should be noted that the dark current did not recover to the original level for the SiN–capped APD, whereas that of SiO$_2$-capped APD was almost completely recovered by annealing. The dark current (I_d) of APD is expressed with the avalanche multiplication factor (M) as

$$I_d = I_{dM} \times M + I_{d0}, \tag{1}$$

where I_{dM} and I_{d0} represent the amplified and non-amplified components of the dark current, respectively [9]. The gradually increasing region at $|V_{p^+}| <300$ V mainly reflects I_{d0}, while the steeply increasing component at $|V_{p^+}| >300$ V is attributed to I_{dM}. As schematically shown in the inset of Fig. 1, two possible leak paths between the p$^+$ and n$^+$ layers are in the surface protection layer and in the p–n junction region. Since only the leak through the p-n junction is amplified by the avalanche effect, I_{d0} and I_{dM} originate from the leak through the surface protection layer and the p–n junction region, respectively.

As shown in Fig. 1, I_{d0} was predominantly increased by electron irradiation. The substantial reduction of I_{d0} by annealing indicates that the leak current in the surface protection layer was reduced.

Fig. 2 shows the distribution of the output charge per electron incident on the SiN-capped APD at different electron energies (E). The mean output charge increases with increasing E. In Fig. 2(a), while the output charge reveals a narrow distribution above 12 keV, the shape is broadened below 10 keV. The output-charge distribution at 5 keV seems to be narrower than those of other energies. Although the reason is not clarified yet, this might be because the mean output charge is considerably small at 5 keV compared to those at other energies and the energy of 5 keV lies near the threshold-like level where the pulse output probability is substantially reduced. After electron irradiation of 10^{14} cm^{-2}, the center of the distribution is shifted to a lower value below 10 keV compared to the initial condition as shown in Fig. 2(b), which is in agreement with the previous results [3]. As the electron dose is further increased to 10^{15} cm^{-2}, the pulse detection of electrons was severely disturbed because of the considerable increase of the dark current as shown in Fig. 1. After annealing of the degraded APD with an electron dose of 10^{15} cm^{-2}, however, the dark current was reduced and the output charge distribution was remarkably recovered as shown in Fig. 2(c).

As shown in Fig. 2(b), the mean output charge was decreased and the width of the output charge distribution was broadened by electron irradiation. Fig. 3(a) shows the ratio of the output charge after electron irradiation and annealing with respect to the initial condition. The energy resolution is plotted as a function of the incident electron energy in Fig. 3(b). With the electron irradiation, the output charge was decreased by about 30 % at $E \leq 8$ keV, and the energy resolution was lowered by about 7 % at $E \leq 16$ keV. Both output charge and energy resolution recovered to those at the initial condition after annealing. It should be noted that the performance of the electron detection was almost fully recovered although the dark current was not recovered to the initial condition [Fig. 1(a)].

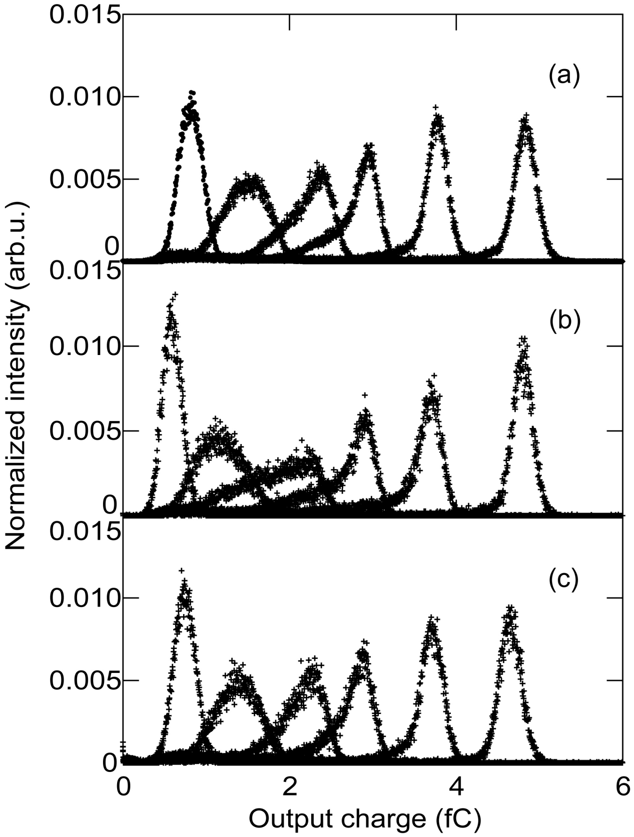

Fig. 2. Distribution of the output charge per electron of APD (S10937-9155) at incident-electron energies of 5–20 keV (a) in the initial condition, and (b) after the electron irradiation of 8 keV at a dosing density of 10^{14}cm^{-2} and (c) at a dosing density of 10^{15}cm^{-2} and annealing at 500 K for 10 h. $V_{p^+} = -320V$.

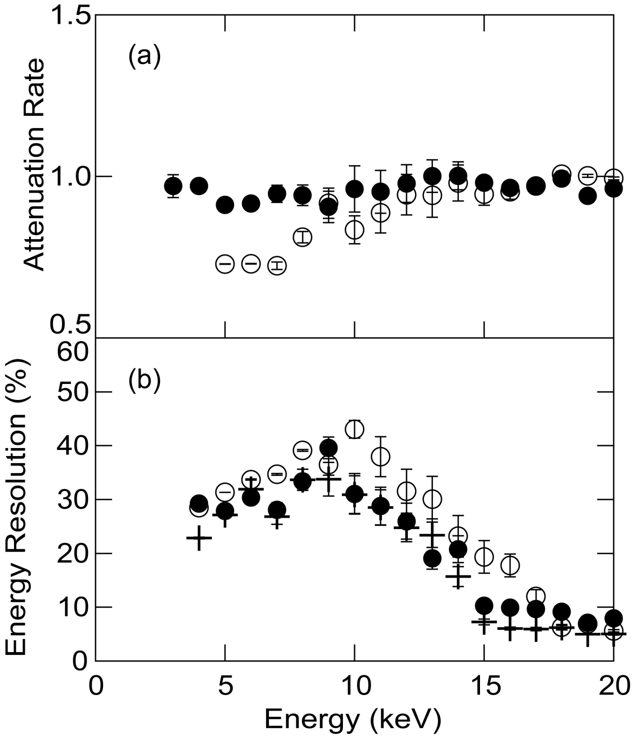

Fig. 3. (a) Ratio of the output charge in Fig. 2(b)(○) and (c)(●) with respect to the initial condition of Fig. 2(a). (b) Energy resolution ($\Delta E/E$ (in %)) estimated from Fig. 2(a). (+), (○) and (●) indicate the initial condition, the conditions after the electron irradiation of 8 keV at a dosing density of 10^{14}cm^{-2} and annealing at 500K for 10 h after the electron irradiation of 8 keV at a dosing density of 10^{15}cm^{-2}, respectively.

IV. DISCUSSION

We discuss the origin of the degradation due to electron irradiation and recovery by annealing. The penetration depth of the electron at an energy of 8 keV in Si is estimated to be 1.2μm [10], indicating that the effect of the electron irradiation is caused in either the surface protection layer (20 nm) or p$^+$ layer (0.8μm). As discussed above, both layers were significantly degraded by the electron irradiation. In our previous paper [3], we discussed that the reduction of the output gain due to the electron irradiation is caused by creation of carrier-recombination centers in the p$^+$ layer. Since the output gain was recovered by annealing as shown in Fig. III, the carrier-recombination centers are considered to be removed by annealing. We have also shown that the hydrogen concentration in APD increases by annealing in a previous paper [4]. On these bases, we discussed that passivation of the carrier-recombination centers by hydrogen is a possible cause for the improvement of the output gain in electron detection [4], because a hydrogen atom is known to be bound to both the boron dopant and the Si dangling bond to passivate the in-gap levels [11], [12]. Considering these results, a possible reason for the degradation and recovery of the APD gain is that electron irradiation induces depassivation of hydrogen from Si-dangling bonds or dopants and annealing drives hydrogen diffusion and re-passivation of the defect levels. Although the source of hydrogen is not known at present, it is noted that the diffusion coefficient in silicon is sufficiently high at 500 K for hydrogen to migrate within the device structure. [6]

We finally discuss the degradation and recovery of the surface protection layer. As shown in Fig. 1, the dark current of the SiO$_2$-capped APD was recovered at all bias voltages, whereas that of the SiN-capped APD was not recovered completely, particularly at $|V_{p^+}|$ <300 V, which corresponds to non-amplified component of the dark current in Eq. (1). As described above, the dark current at $|V_{p^+}|$ <300 V reflects the leak current at the surface protection layer. It is therefore suggested that electron irradiation induces the formation of in-gap states in the surface protection layer as well as the p$^+$ layer, which leads to a leak path. The results of Fig. 1 then imply that the in-gap states are not completely removed by annealing whereas those in the SiO$_2$ layer are removed.

V. CONCLUSION

In conclusion, the effect of electron irradiation and subsequent annealing on the Si-APD electron detector was investigated. With annealing at 500 K for 10 h, the leak current at the surface protection layer was reduced and the gain and energy resolution for electron detection were substantially recovered from the degraded condition. We discussed that depassivation and passivation of defect levels in the p$^+$ layer by hydrogen are a possible cause for the degradation and recovery of the

APD gain and energy resolution. We also showed that SiO_2 is favored for the surface protection layer of APD over SiN.

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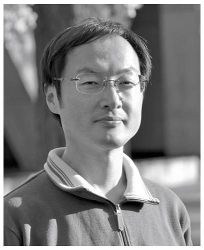

Taizo Kawauchi received the Bachelor of Science in physics from University of Tsukuba, Ibaraki, Japan in 1996. He is currently a technical and research staff at Department of Fundamental Engineering,Institute of Industrial Science, The University of Tokyo, Japan. He contributes to design and construction of vacuum apparatuses, thin-filmformation, surface-analysis, and Mössbauer spectroscopy with a use of radioisotope and synchrotron radiation. He has published seven papers in scientific journals as a first author. His research interests include process techniques of solid state detectors,synthesis technology of clathrate hydrate and surface and interface magnetism.

Shunji Kishimoto received the D.Eng. degree in radiation measurements and the detector-development research from Kyoto University, Japan, in 1987. After graduation, he joined Photon Factory, National Laboratory for High Energy Physics, Japan, where he worked on Detector development for Photon Science. He is now an Associate Professor in Institute of Materials Structure Science, High Energy Accelerator Research Organization, Japan.

Katsuyuki Fukutani received the Bachelor of Science in Physics in 1985, and D. Sc. in Physics in 1990 from the University of Tokyo, Japan. After working as a research associate for Institute for Solid State Physics, the University of Tokyo from 1990 to 1995, he was appointed to an Associate Professor and has been a Professor of the surface and interface group since 2006 at Institute of Industrial Science, The University of Tokyo, Japan. His group has developed unique experimental techniques of nuclear-reaction analysis for hydrogen depth profiling, resonance-enhanced multiphoton ionization for state-selective detection of molecules, and Mössbauer spectroscopy for magnetism analysis. His research activities cover a broad range of surface and interface phenomena including hydrogen effects on semiconductor devices, electronic structures and reactions at surfaces and interfaces of metals and oxides, and surface and interface magnetism. He was the chief editor of J. Vac. Soc. Jpn. from 2005 to 2007, and currently an editorial board member of J. Phys. Soc. Jpn. and J. Phys. Condens. Matter. He has published over 150 peer-reviewed papers.