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High Sensitivity and High Readout Speed Electron Beam Detector using Steep pn Junction Si diode for Low Acceleration Voltage

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Abstract

In this work, Si pn junction diode-based electron beam detector with high sensitivity for low acceleration voltage and high readout speed is reported, by using steep pn junction formation technology, low dopant concentration Si substrate and multiple signal outputs. The electron quantum efficiency of fabricated detector at acceleration voltage of 1.0kV, 10kV, 20kV are 51.8%, 70.3% and 90.8%, respectively, which is suitable for low acceleration voltage scanning electron microscope. Also, by dividing the detector area into multiple regions, the pn junction capacitance is significantly reduced to 1/3 and 1/7 compared to the conventional structure, which is suitable for high signal readout speed that is limited by RC delay of pn junction.

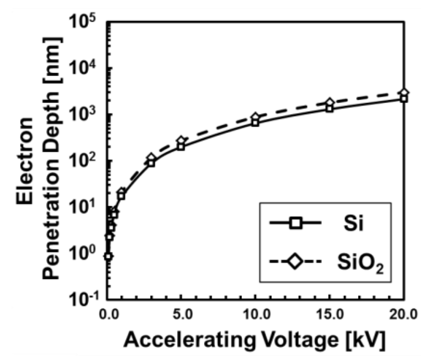
Introduction

Electronic microscope such as Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM) and Scanning Transmission Electron Microscope (STEM) has been widely used in various fields in order to observe and analyze materials such as metal, semiconductor, ceramic and organic samples [1-3]. Recently, high sensitivity at low accelerating voltage and high readout speed are required, especially in SEM. By observing at low accelerating voltage, damage and charge-up to the sample are to be reduced and only the surface of the sample can be observed with high resolution. Also, the measurement throughput becomes higher if signal readout speed improves. However, at low accelerating voltage, the energy of the electron becomes low and electron penetration depth into the detector becomes short. It is difficult for the conventional Si pn junction diode-based electron beam detector to detect this short penetration depth electron. In addition, when the electron scan speed becomes faster, the image lag appears because the signal readout time is long which is generally limited by the RC delay of detector. To solve these problems, a steep pn junction, low substrate concentration and multiple outputs are introduced in this work.

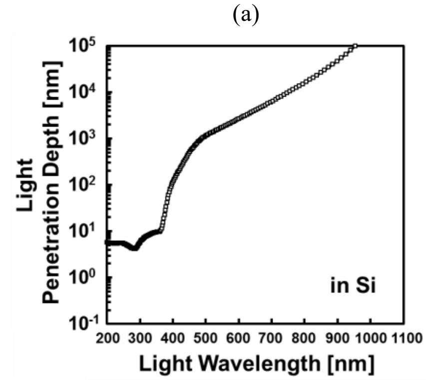
Figure 1 (a) shows the electron penetration depths in Si and SiO_2 as functions of accelerating voltage. The definition of this electron penetration depth is the average of calculated penetration depth by diffusion Monte Carlo simulation method. Figure 1 (b) shows the light penetration depth in Si as a function of light wavelength. Here, the definition of the light penetration depth is the depth in which the intensity of the incident light becomes 36.7% of the surface. From these characteristics, the electron penetration depth is less than a few nm at below 1kV. Also, the light penetration depth at 200-380nm wavelength is a few nm. A technology to produce silicon photodiode (PD) with almost 100% internal QE and high stability to UV light has been reported by forming a thin surface high concentration layer with steep dopant profile [4-6]. In this work, by using this steep pn junction formation technology, sensitivity for electron with short penetration depth at low accelerating voltage is to be improved.

Readout speed of the signal is slow because area of the detector is large and time constant of CR (Capacitance and Resistance) becomes long due to the large area of the detector. By using the low dopant concentration substrate, the depletion layer width increases. Further, by dividing the electron area into several regions, the capacitance per output reduces for high speed readout.

In this work, the detector was fabricated and evaluated with a steep pn junction technology, low substrate dopant concentration and multiple outputs to demonstrate high sensitivity for low accelerating voltage and high speed readout.



(a)

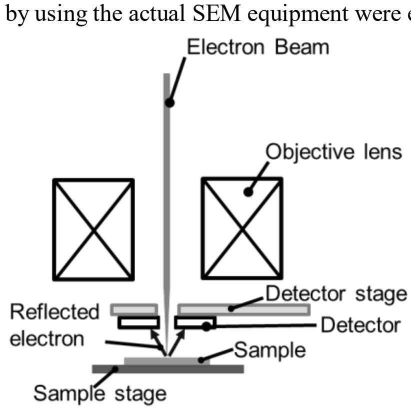


(b)

Figure 1. Electron and light penetration depths as a function of accelerating voltage and wavelength. The definition of the penetration depth; (a) is the average of calculated penetration depth by diffusion Monte Carlo method and (b) is the depth in which the intensity of incident light becomes 36.7% of the surface.

Developed electron beam detector

Figure 2 (a) shows the schematic illustration around the detector of SEM. Electron beam generated from electron gun is irradiated to the sample through condenser lens, scanning coil and objective lens. By detecting the reflected electrons, the surface morphology of sample is observed. Figure 2 (b) shows the view of the detector from the sample side. In this work, the diameter of the detector and hole at the center of detector are 13 mm and 3 mm. Conventionally, the whole electron receiving area is divided into two, i.e., two semicircles. In this work, to speed up signal readout, capacitance of detector per output is reduced by dividing the whole electron receiving area into 8. The ratio of outer and inner area of each quadrant is 3.3:1. Figure 3 shows the process flow of the detector. Low dopant concentration p-type substrate (N_A: ~$3x10^{12}cm^{-3}$) was used to reduce the capacitance of pn junction. To obtain high sensitivity at low acceleration voltage, n^+ layer with high concentration and steep dopant profile was formed by ion implantation at p-Si surface. Dopant profile was formed so that the dopant concentration becomes the highest at the Si surface, and the measured slope of dopant concentration along Si depth direction was about 14nm/decade. By the electric filed formed due to the slope of carrier concentration and depletion layer, the electrons generated near the Si surface are detected and holes are moved to p-type substrate so as not to be recombined with the electron as shown in Fig.4. After pn junction formation, SiO_2 as interlayer dielectric film and Al wiring were formed. Next, to form electron receiving area, SiO_2 film was opened by wet etching. After Si was thinned and back surface contact was formed, Si through etching was carried out to form the through hole where electron beam passes though at the center of detector. Table 1 shows the methods of forming pn junction and the depth of pn junction of the evaluated detectors. Figure 4 shows the schematic image of the fabricated detector. I-V and C-V characteristic, sensitivities toward electron with various accelerating voltages and photosensitivity, and image by using the actual SEM equipment were evaluated.



(a)

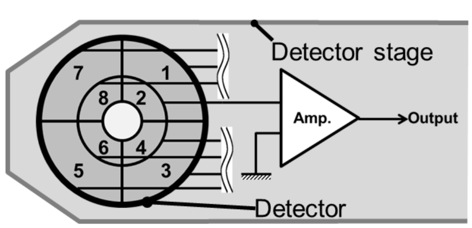


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Figure 2. (a) the schematic illustration around the detector of SEM and (b) view of the detector from the sample side. The numbers mean terminal names.

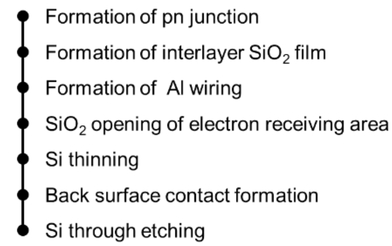


Figure 3. The process flow of the fabricated electron beam detector.

Table 1. the methods of pn junction formation used in this work and junction depth

Sample	Formation of pn junction	Depth of pn junction
A	Ion implantation	Shallow
B	Solid-phase diffusion	Deep

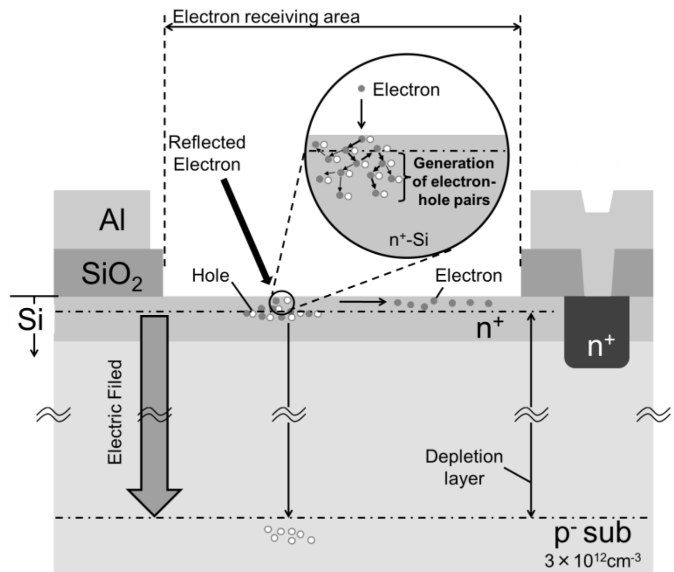


Figure 4.Schematic image of the cross section of fabricated detector.

Result

Figure 5 shows the dark current of sample A as a function of applied voltage. At 1.0V and 12V, average of dark current at terminal 1, 3, 5, 7 was $3.5x10^{-9}$ A and $5.8x10^{-9}$ A and at terminal 2, 4, 6, 8 was $1.1x10^{-9}$ A and $1.7x10^{-9}$ A, respectively. The increase of current by applied voltage and the variability of dark current were very low, indicating the high quality pn junction is formed uniformly. At each terminal, stable electrical characteristics are obtained. Figure 6 shows the capacitance of each terminal and the sum of these terminals of the detector. The sum of terminals is the capacitance measured when terminals 1~4 were connected altogether. At the 0V and 12V, the capacitance of the terminal 1 and 3 was $2.2x10^{-10}$ F and $4.7x10^{-11}$ F, the capacitance of the terminal 2 and 4 was $7.7x10^{-11}$ F and $2.7x10^{-11}$ F, the sum of these terminals was $5.6x10^{-10}$ F and $1.5x10^{-10}$ F, respectively. The capacitance of the terminal 1, 3 and 2, 4 is about 1/7 and 1/3 of the sum of all terminals. By this structure, the CR time constant at each output reduced and readout speed can be improved.

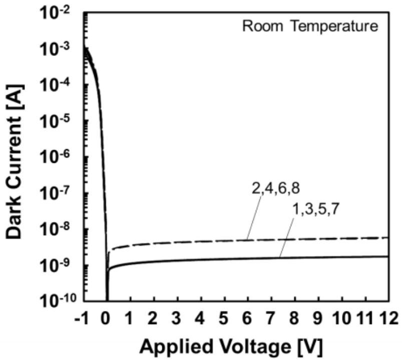


Figure 5. The measured dark current of sample A as a function of applied voltage.

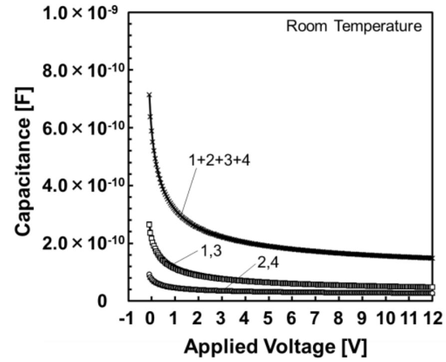


Figure 6. The measured capacitance of sample A as a function of applied voltage.

Figure 7 and 8 show the gain and electron quantum efficiency (QE) of sample A and B as a function of accelerating voltage. The gain and QE can be expressed by

$$Gain = \frac{\text{detector signal current}}{\text{electron beam current}} \tag{1}$$

$$QE = Gain / \frac{\text{electron accelerating energy [eV]}}{3.7\,[\text{eV}]} \tag{2}$$

where 3.7 eV is the direct energy bandgap of Si and it is the necessary energy for an incident electron to generate one electron-hole pair in the Si. QE for electron is calculated by dividing the measured gain by the ideal number of electron-hole pairs generated by the incident electron with the accelerated energy. For sample A at the accelerating voltage of 1.0kV, 10kV and 20kV, the gains were 190, 2400 and 4905 and QEs were 51.8%, 70.3% and 90.8%, respectively. Especially, at low acceleration voltage, high sensitivity was obtained. Figure 9 shows the photo sensitivity of the sample A as a function of the light wavelength. From this figure, high sensitivity for a wide range of waveband including UV light was obtained. This result shows that for the developed detector, photo-electrons generated at a few nm from the Si surface were able to be detected. Also, light sensitivity in long wavelength is also high, indicating the depletion layer was formed deeply. The obtained results verify the high sensitivity characteristic of the developed detector toward the low accelerating voltage.

Figure 10 and 11 show the images by using the scanning electron microscope, where images (a) were obtained by the sample A as the detector and images (b) were obtained by the sample B, respectively. The observed sample for the figure 10 is the Cu mesh on brass block, obtained at the accelerating voltage of 15kV and figure 11 is the Au on carbon obtained at 1.0kV. Other conditions of imaging are shown as follows; the working distance was 10mm and magnification was 1000 in the figure 10 and 5000 in the figure 11. At the accelerating voltage of 15kV, there is little difference of gain or QE between the sample A and B. Therefore, both of the images at 15kV are almost the same. However, there is a large difference of QE at 1.0kV. For the reference detector, there is no clear image and Au was not observed. On the contrary, for the fabricated detector sample A, Au can be clearly observed at 1.0keV low acceleration voltage. From these results, high sensitivity for low accelerating voltage was successfully demonstrated.

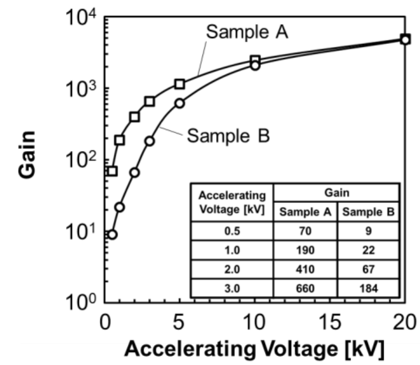


Figure 7. The gain of samples A and B as a function of accelerating voltage.

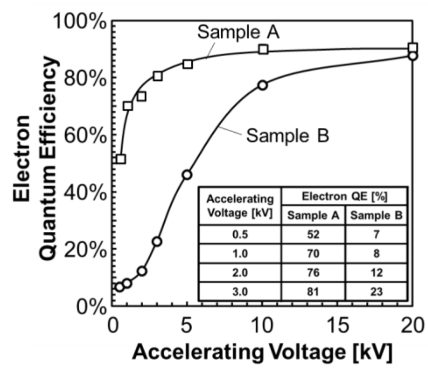


Figure 8. The electron quantum efficiency of sample A and B as a function of accelerating voltage.

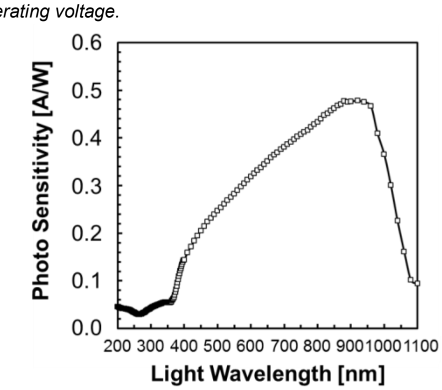
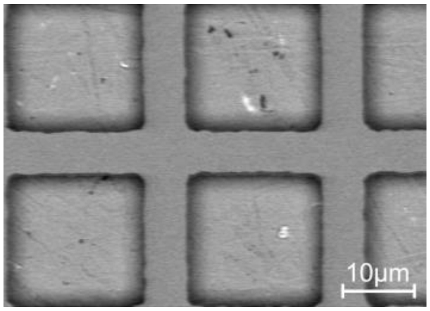


Figure 9. The photo sensitivity of sample A as a function of light wavelength



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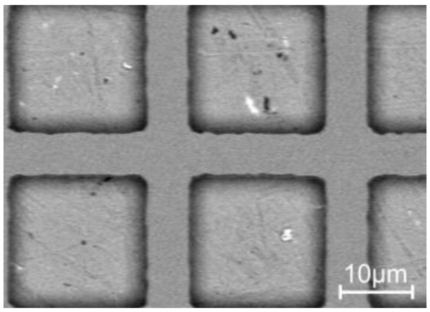
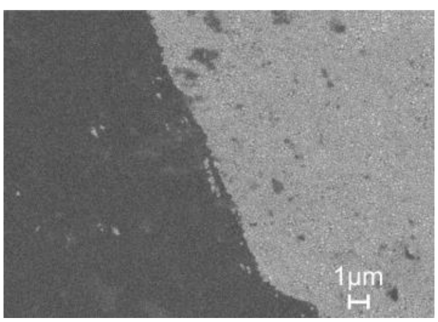


(b)

Figure 10. The image of Cu mesh on brass block by using the scanning electron microscope at accelerating voltage of 15kV. (a) was taken by sample A and (b) was taken by sample B as the reflection electron detector.



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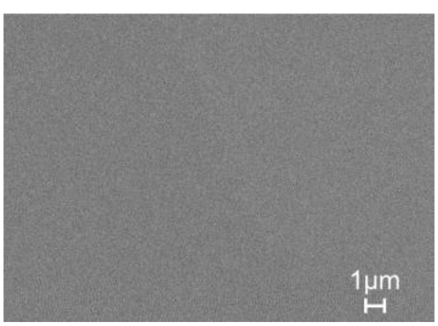

(b)

Figure 11. The image of Au on carbon at accelerating voltage of 1.0kV. (a) was taken by sample A and (b) was taken by sample B as the reflection electron detector

Conclusion

In this paper, using steep pn junction, low concentration substrate and multiple outputs, Si diode-based electron beam detector with high sensitivity for low acceleration voltage and low capacitance for high speed readout was presented. At each output, stable I-V electrical characteristic was obtained. To detect generated electrons at short depth from Si surface and obtain low capacitance, the pn junction was formed steeply from near the Si surface. The obtained QE at the acceleration voltage 1.0kV, 10kV, 20kV were 51.8%, 70.3% and 90.8%, respectively, which is suitable for low accelerating SEM. The capability of detecting signal electrons from near Si surface region also by verified high photo sensitivity toward UV light was obtained. By dividing the electron receiving area into multiple regions, the pn junction capacitance became 1/3 and 1/7 of the conventional structure, which is suitable for achieving high signal readout speed.

The measurement results show that it is capable to enhance sensitivity and readout speed with the developed detector. The developed technology is beneficial upon analyzing objects with low acceleration voltage with high measurement throughput.

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