On the Uniformity of Pure-Boron-Layer Depositions

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***Abstract*—In this paper, the uniformity of PureB-layers deposited on photodiode surfaces of a segmented photodetector is investigated and discussed. Low-energy E-beam (LEEB) measurements have been carried out to study the uniformity and PureB-layer thickness variations over the anode surface area. It can be conclude that the PureB-layer is thinner in the middle and thicker at the edges of the opening windows where it is adjacent to oxide on the one side, and it is thickest at the corners of the window where it is adjacent to oxide on two sides. This shows the effect of the oxide surfaces (a so-called loading effect) around the openings on the thickness of the PureB-layer.**

***Index Terms*—pure boron layer, chemical vapor deposition, low-energy E-beam, charged particle detectors.**

I. Introduction

PURE boron (PureB) depositions have in recent years been very successfully applied as a source of doping for fabricating extremely shallow, less than 10-nm deep, silicon p^+n junction diodes for a number of leading-edge device applications [1-3]. The most successful PureB-layer application at the moment is in photodiodes for detecting low penetration-depth beams. With the ultrashallow damage-free junction formation the PureB-layer photodiodes surpass the performance of other existing technologies on points such as internal/external quantum efficiency, dark current, uniformity and degradation of responsivity. This has led to a rapid industrialization of extreme ultraviolet (EUV) detectors for EUV lithography equipment and low-energy electron detectors for SEM systems. Record-high responsivity has been achieved particularly for detection of vacuum ultraviolet (VUV) light [4-6] and low-energy electrons down to 200 eV [7], by using the very robust PureB-layer itself as the only "dead"-layer covering the front-entrance window. Because of an extremely small penetration depth of the VUV radiation and low-energy electrons part of beam energy is adsorbed in this dead layer. Hence, the thickness of the PureB-layer become very important and any sub-nm thickness variations of the layer can have an impact on device performance. Therefore for having the same responsivity through the whole active area of a large photodetector, the uniformity of PureB-layer plays a very important role.

In this paper, the uniformity of the PureB-layer deposited on the photodiode surfaces of a segmented photodetector is investigated and discussed. Low-energy E-beam (LEEB) measurements have been carried out to study the uniformity and PureB-layer thickness variations over the anode surface area.

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II. Experimental Procedure

A. Boron deposition

The boron deposition is performed in an ASM Epsilon 2000 reactor for atmospheric-/reduced-pressure chemical vapor deposition (AP/RPCVD), using diborane, B_2H_6, and hydrogen H_2 as gas source and carrier gas, respectively [8]. The deposition itself was performed for processing temperatures ranging from 400ºC to 700ºC. Diborane was injected into the reactor chamber as the dopant gas with a typical flow rate of 490 standard cubic centimeters per minute (sccm), while hydrogen (H_2) was used as the carrier gas and for dilution of the doping source. Rotation of the sample can provide homogeneous exposure, preventing gas depletion phenomena. For a given temperature, ambient pressure and diborane concentration, the boron coverage of the Si surface and the doping of the crystalline silicon substrate can be controlled by the variation of the deposition time. The results presented here correspond to 20 min exposure time. It is known that the boron atoms will not be adsorbed on SiO_2,so it is crucial that an oxide-free Si surface be provided for the deposition. This is achieved by first treating the substrates by conventional wet cleaning and HF dipping followed by Marangoni drying. In the reactor itself, any remaining native SiO_2 is removed before B_2H_6 exposure by an in-situ thermal cleaning step in H_2 ambient at 800ºC for 4 min. In the case of a patterned SiO_2 layer being used as a hard mask for selective B deposition, the pre-bake step should be carried out at AP to avoid high-temperature silicon dioxide decomposition [9].

B. Comparison between Boron deposition and selective silicon epitaxy

Boron deposition has some similarity with selective silicon epitaxy in the case of selectivity feature. In selective silicon epitaxy technique monocrystalline silicon is grown on silicon openings surrounded by oxide masks without deposition of EPI on the oxide. However, in this process the loading effect [10] causes some non-uniformity at epitaxial film thickness on a substrate and variation of film thickness from substrate to substrate. Also these non-uniformities are pattern dependence for different growth rates at different pattern sizes. The epitaxial growth rate for different windows width and the schematic of the growth profile as a function of the Si window width and the Si/SiO_2 surface ratio are shown at Fig. 1.

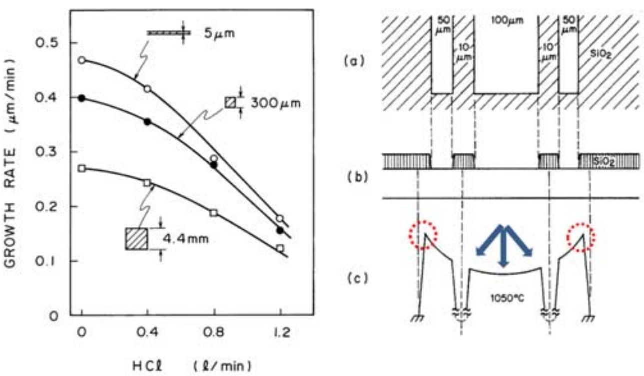


Fig. 1. (left) Selective epitaxial growth rate as a function of the amount of HCL injection for a width of 5µm, 300µm and 300µm windows [11]. (right) The schematic of the growth profile (a) Pattern view, (b) Cross section view, (c) EPI shape at openings [12].

The growth rate increases with decreasing aperture size. Notice that the EPI in the 50 µm wide openings is thicker than in the 100 µm openings. Also the growth rate is higher in areas adjacent to SiO_2 regions with a higher SiO_2/Si ratio (more distance between apertures separated by $Si0_2$), i.e., the edge of the silicon growth in the 50 µm wide opening is thicker on the side that is surrounded by a large area SiO_2 surface than by the smaller area SiO_2 surface. At the 100 µm wide opening has a same effect but to a lesser degree because the Si/SiO_2 area ratio is less. There is less growth in the center of the 100 µm wide opening than is observed at the edges, which are influenced by the presence of SiO_2 [12].

The same effect is also observed in the case of the boron deposition. More discussion is given in the next section.

C. Device Description

The photograph and a cross-section of the fabricated PureB-layer photodetector are shown in Fig. 2. As indicated in the cross-section, a low-doped (< 10^{14} cm^{-3}) epitaxial layer is grown on a 2-5Ωcm n-type Si (100) substrate. And then the PureB-layer is deposited selectively in opening windows in the SiO_2 isolation layer which is thermally grown. Excellent electrical performance is achieved in terms of extremely low dark current (~1 pA at a reverse bias of -40 V) and ideal I-V behavior, as expected for a defect-free p^+n junction.

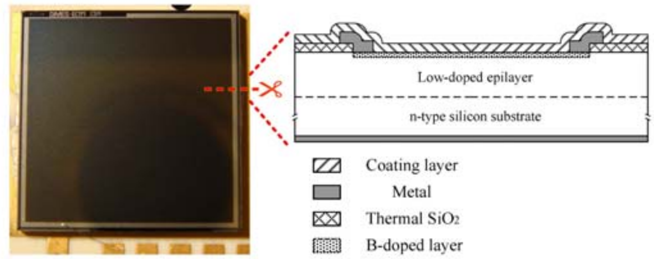
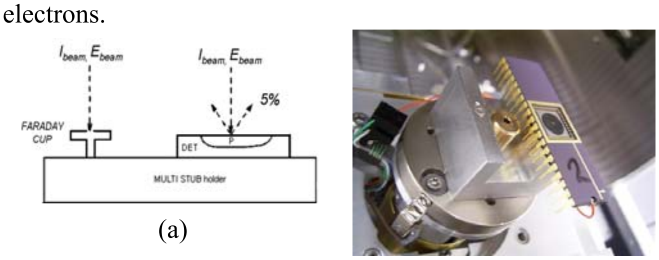


Fig. 2. Photograph and cross-section of a B-layer photodiode with an active area size of ~10×10mm^2

D. Low-energy E-beam Measurement

The responsivity of the fabricated photodetector was determined by using the low-energy electron-beam setup as shown schematically in Fig. 3(a). The responsivity decreases with increase the thickness of the PureB-layer and this method is used to evaluate the uniformity of the PureB-layer. In this setup, measurements are performed in a Scanning Electron Microscope (SEM) using electron gun as a source of electrons.



(a) (b)

Fig. 3. The SEM setup for measuring the B-layer uniformity

Before starting the measurement, the photodetector is mounted on the multi-stub of the SEM next to the Faraday cup (Fig. 3(b)). An electron beam with energy E_{beam}=1kev and a constant spot size is first focused into a Faraday cup, and the incident beam current, I_{beam} is measured. Then this beam was directed onto the photodetector with different linear scanning directions through the active area of the photodetector and the photocurrent, I_{ph}, was measured in different point in each direction. The linear scanning directions are shown schematically in Fig. 4.

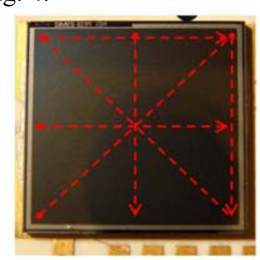


Fig. 4. The linear scanning directions.

With acquired data, the responsivity can be calculated as:

$$R = \frac{I_{ph}}{I_{beam}(\frac{E_{beam}}{e_0})}$$

Where $e_0 \approx 3.61$eV is the mean energy required to produce an electron-hole pair in silicon [13]. The results are shown in Fig. 5 at different scanning directions.

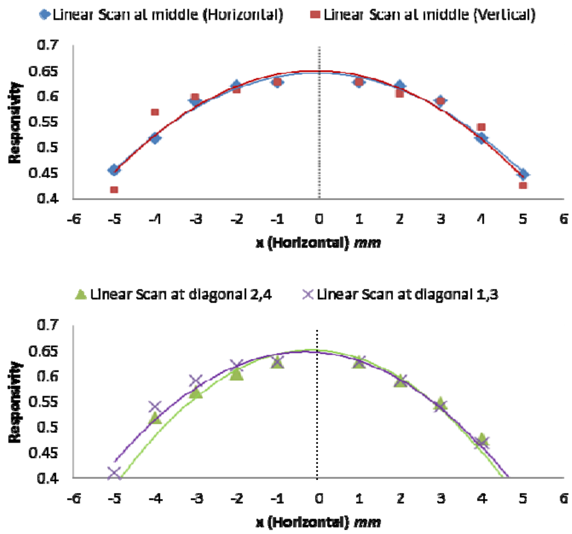


Fig. 5. Photodetector responsivity measured by low-energy electron-beam setup (upper) Horizontal and vertical scans at middle, (lower) two diagonal scans

As shown in Fig. 5 the results at different directions are quite same and can be deducted that the PureB-later thickness is almost symmetrical across the square window. Fig. 6 shows 3D surface plot of the LEEB responsively through the window and contour plot of the normalized PureB-layer thickness at whole active area. It can be seen that the pure B-layer is thinner in the middle and thicker at the edges where it is adjacent to oxide on the one side, and it is thickest at the corners of the window where it is adjacent to oxide on two sides.

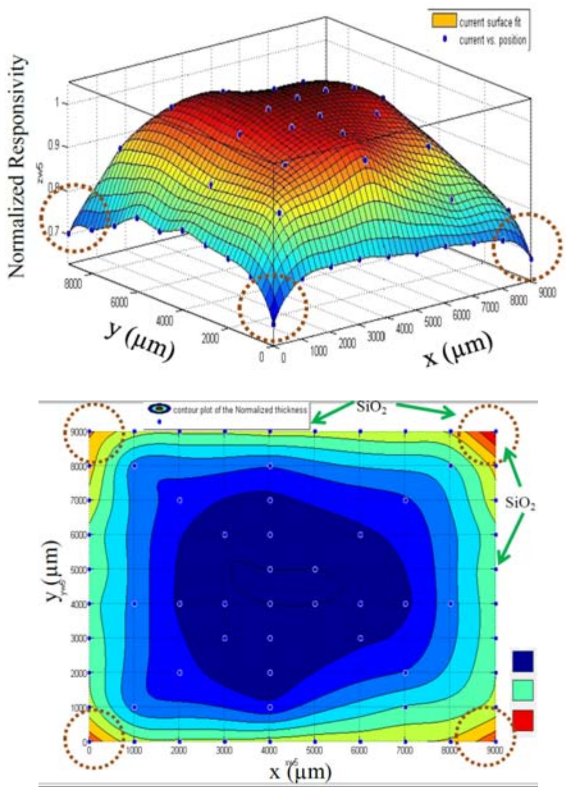


Fig. 6. (upper) 3D surface plot of the responsivity and (lower) contour plot the normalized B-layer thickness at whole active area of the 10×10*mm*^{2} photodetector.

III. Conclusion

The uniformity of PureB-layers deposited on the photodiode surfaces of a segmented photodetector is investigated and discussed. Low-energy E-beam (LEEB) measurements are identified to be very sensitive to *sub-nm* PureB-layer thickness variations and can be used as a very accurate method to study of the PureB-layer uniformity. On the uniformity of the PureB-layer, it can be concluded that its thickness suffers from an oxide loading effect and must be controlled by engineering the design and optimizing the deposition parameters.

Acknowledgment

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