Physical Characteristics of Ultra-Thin Pure Amorphous Boron Layers and Applications of the Layers in Silicon Detector Devices

Tihomir Knežević
Department of Electronics, Microelectronics, Computer and Intelligent Systems, Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia
tihomir.knezevic@fer.hr

Abstract – Challenges of the UltraViolet (UV) radiation and low-energy electron detection can be easily overcome if a novel pure amorphous boron (PureB) deposition technique is used for the p+ region formation in the p’n silicon photodiode detectors. Photodiodes with ultra-thin PureB layer demonstrate excellent electrical properties with ideal I-V characteristics and low dark currents which are crucial for a good photodiode detector operation. Optical characteristics of photodiodes with PureB layers also show an outstanding performance compared to the commercially available state-of-the-art photodiode detectors. In order to integrate PureB photodiodes into the commercial detector systems, an optimization of the photodiode structure should be performed. This is ordinarily done with semiconductor simulation software. In this paper an overview of the excellent characteristics of the PureB photodiodes for UV radiation and low-energy electrons is given. Structure optimization is performed for: reduction of the sheet resistance of the PureB layer, decrease of the diode capacitance and the decrease of the radiation damage influence on the dark current which is seen at the SiO2/silicon interface. Blocking mechanism that prevents the injection of electron carriers to the PureB layer is not yet fully explained. Physical and electrical characterization of the PureB layer should be performed in order to find out as much information on the physics of the carrier transport in the PureB layers.

Index Terms – Photodiode, ultrashallow junction, responsivity, pure amorphous boron (PureB), ultraviolet (UV) radiation, low-energy electrons, detector, optimization, physical characterization, X-ray photoemission spectroscopy (XPS), spectroscopic ellipsometry (SE), internal photoemission (IPE).

I. INTRODUCTION

Rapid boom of modern science and technology is definitely owed to the development of various radiation and particle detectors. Applications of the detectors span from simple usage, as in motion detector systems, to the state-of-the-art systems used for detection of the elementary and cosmic particles. Basic operation principle of all the detectors is interaction of particles or radiation with matter. Since every type of the interaction can be used in construction of detectors, there exist a vast number of detectors with a large potential for further development.

Semiconductor detectors were recognized to have excellent characteristics for detection of both particles and radiation. These characteristics include high operational speed, excellent energy resolution, smaller detector dimensions, easy integration with other electronic devices, etc. With the progress of semiconductor technology, silicon was soon promoted to a material of choice for processing electronic devices. This is also true for semiconductor detectors. Among many silicon detector structures, silicon photodiodes became most commonly used [1].

The latest optical projection lithography systems used for semiconductor manufacturing have created a constant demand for high-performance silicon photodiodes for radiation detection. Wavelengths of the radiation sources used in the optical projection systems fall in range of UltraViolet (UV) light which spans from 400 to 10 nm. The photodiodes are used, not only to extend the applicability of current 193 nm wavelength Deep-UltraViolet (DUV) lithography, but also for the development of 13.5 nm Extreme-UltraViolet (EUV) lithography [2]. The requirements of the photodiode detectors used in lithography systems are: high UV sensitivity, high stability, high operational speed and possibility for integration with other electronic devices. Other research fields and industrial applications also benefit with the development of the silicon photodiodes for detection of the UV radiation. These include: space observation, medical imaging, monitoring in harsh environments [3].

On the other hand, silicon photodiode detectors can be used for successful detection of charged particles. A fine example of this are the photodiode detectors used in the Scanning Electron Microscopy (SEM) systems. With the development of semiconductor industry, imaging of the feature sizes in the nanometer range is needed. For this to be accomplished, without the charging of the insulating layers in structures, low voltage SEM systems are used. Also, low-energy electrons are produced by the surface under investigation when it is exposed to a beam of electrons. Therefore, in modern SEM systems high-performance silicon photodiodes are needed to detect low-energy electrons.
The same analysis is valid for a photodiode structure with the radiation or particles. The current flowing through the diode is called dark current. The term dark current is interchangeable to the term saturation current. When the photodiode is exposed to the radiation or particles, the current flowing through the diode is called dark current. The term dark current is interchangeable to the term saturation current. The same analysis is valid for a photodiode structure with the n+-region on top of the p-type substrate.

Figure 1. Schematic cross section of a photodiode detector.

II. SILICON PHOTODIODE DETECTORS

Basic structure of a silicon photodiode is depicted in Fig. 1. The structure consists of the p+-region on top of the n-type substrate. Between the p+- and n-region, a depletion region is formed. Electron-hole pairs are created when the radiation or particles enter the silicon. Electric field is present only in the depletion region. Electron-hole pairs generated in the depletion region are separated by the electric field and reach the quasi-neutral region where they increase the photodiode current. Therefore, increased photodiode current, designated as photocurrent, holds the information on the detected radiation or particles. On the other hand, electron-hole pairs formed in the quasi-neutral region of the p+- and n-type substrate recombine and do not contribute to the photocurrent. When the photodiode is not exposed to the radiation or particles, the current flowing through the diode is called dark current. The term dark current is interchangeable to the term saturation current. The same analysis is valid for a photodiode structure with the n+-region on top of the p-type substrate.

Intensity of the radiation decreases exponentially from the surface. Defined as the reciprocal of the absorption coefficient at the incident radiation wavelength. Attenuation length is defined as the penetration depth where the intensity of the radiation is decreased to 1/e. Attenuation length for UV radiation is depicted in Fig. 2. DUV radiation has the lowest absorption length and the majority of generated electron-hole pairs will be situated in the first few nanometers of the silicon surface. Similar behavior is observed for low-energy electron interaction with silicon. Low-energy electrons penetrate the silicon surface by only few nanometers, where they interact with silicon and generate electron-hole pairs. Evidently, in order to collect majority of the generated electron-hole pairs, pn-junction (depletion region) in the silicon photodiode should be brought very close to the surface. The depletion region increases if the photodiode is reversely biased. However, the depletion region extends to a region with lower doping concentration, e.g. to n-type substrate in case of the pn-junction diode. Therefore, solution is to control the doping concentration profile of the p+-region to achieve shallow and abrupt p'n junction with sufficiently high doping. Other approach is to use photodiode structure different from pn-junction photodiode.

An example of the different photodiode structure that could be used is a Schottky diode. Schottky diode is formed by joining metal electrode with a semiconductor. Since there is no pn-junction, the depletion region starts directly at the surface of the photodiode. However, Schottky diodes have a considerably larger dark currents compared to the reversely biased photodiodes and also suffer from surface recombination loss. It is important that the dark current is low since it defines the sensitivity of a photodiode. This promotes the use of the pn-junction photodiode detectors because of the lower dark current that could be achieved. Processing techniques for formation of the p+-region with ultrashallow and abrupt junction profiles are available. These include ion implantation and Chemical Vapor Deposition (CVD). In the case of the ion implantation an ultrashallow implanted doping profile is broadened during the annealing due to the damage-induced transient enhanced diffusion. Also, implantation can disrupt the Si lattice which increases the generation-recombination currents that contributes the dark current. Broadening of the doping profile results in the decrease of sensitivity for radiation and particle detection. P+-region formation by CVD process can be tuned so the deposited layers are p-doped with thickness in the range of several nanometers. On the other hand, the concentration of dopants in such layer is mainly determined by the solid solubility. If the p+-region is not highly doped, a suppression of the electrons injection from the n-region will be insufficient and the diode current will be high.

III. SILICON PHOTODIODES WITH PUREB LAYERS

A novel deposition process, with a potential to solve aforementioned problems in photodiodes for UV radiation and low-energy electrons detection, was developed by the group of researchers at Delft Institute of Microsystems and Nanoelectronics (DIMES), Delft University of Technology, The Netherlands [4]. The deposition is done in commercially available CVD systems. During the deposition, the silicon surface is exposed only to diborane (B₂H₆) gas at atmospheric or reduced pressure and at temperatures from 500 °C to 700 °C. This is in contrast to the widely established use of diborane as a doping source during the silicon epitaxial growth. Other work [5]-[6] also reports the use of diborane for silicon surface doping. However, the formation of amorphous boron (α-B) was
prevented there. The novelty here is intentional deposition of the pure amorphous boron (PureB) layer. Exposure time controls the thickness of the PureB layer. When the temperature is high enough, the deposited PureB layer serves as a diffusion source of boron for doping the bulk silicon. However, in all cases, even at 500 °C, ultrashallow highly-doped p'+ regions are formed with depths below 10 nm [4],[7]. Some of the excellent properties of the PureB layers include: damage free junction formation, selectivity to silicon, spatial homogeneity, isotropy and compatibility with standard semiconductor device fabrication.

PureB layers were used to process various silicon detector devices [8]-[13], all with excellent performance comparable to the state-of-the art photodiodes. The formation of ultrashallow pn-junctions promotes the use of PureB layers in semiconductor detector devices for detection of light with very shallow penetration depth, such as DUV and EUV light [8]-[10]. PureB layers are also used for low-energy electron detection in SEM systems [11]-[12]. Applications of PureB layers, other than semiconductor detectors, include silicon-on-glass varactor diodes [13].

Ideal I-V characteristics and low dark currents of the photodiodes with PureB layers were repeatedly proven [8][14]. Saturation current densities for photodiodes with PureB layer are depicted in Fig. 3. Here, the B₂H₆ exposure time used for PureB layer formation is varied. Saturation current density of the PureB layer photodiodes is compared to the Schottky diode and B⁺ implanted diode. As mentioned earlier, Schottky diodes have significantly higher dark currents. On the other hand, diode with implanted p' region has lower dark current but with the downside of a deeper pn-junction. Diodes with PureB layer have extremely shallow pn-junction while the dark current is comparable to that of a deep p' junction photodiode. I-V characteristic of the PureB diode was also compared to the commercial state-of-the art n'p photodiode (Fig. 4). Low dark current was achieved together with an ideal behavior of the I-V characteristic. This leads to a conclusion that PureB layer deposition forms defect free p'n junction. The dark current level is comparable to that of deep p'n junction which can be attributed to the high p' doping of silicon. Also, low dark current is a result of a stopping mechanism for electron injection which is present in the PureB layer.

Optical characterization of the PureB photodiodes was performed to investigate how the PureB layer influences the EUV radiation [8]-[9] and low-energy electron detection [11]-[12]. Responsivity is a measure of sensitivity of a detector. Responsivity is defined as a ratio of the photocurrent to the incident light power at a given wavelength. Responsivity of the photodiode with PureB layer is compared to the commercial state-of-the art n'p photodiode in the EUV spectral range (Fig. 5). The duration of the PureB layer deposition was 2.5 min. PureB photodiode outperforms commercial n'p photodiode with the responsivity of about 0.266 A/W which is almost the same as that of an ideal lossless system (0.273 A/W) [15]. The responsivity degradation under high-power exposure is negligible [9].

Photodiodes processed with the PureB layers used for low-energy electron detection were also compared to the state-of-the art detector devices. These include: Back

![Figure 3. Saturation current density of diodes processed with PureB layer for different B₂H₆ exposure time. For comparison, saturation current density for Schottky diode and deep p'n junction diode is plotted [14].](image)

![Figure 4. Forward and reverse I-V characteristics of photodiode with PureB layer compared to the commercial state-of-the art n'p photodiode [9].](image)

![Figure 5. Spectral responsivity of photodiodes with PureB layer. The duration of the PureB layer deposition was 2.5 min. Responsivity is compared to the responsivity of a commercial n'p photodiode [9].](image)
Scattered Electron (BSE) detector and “low Voltage high Contrast Detector” (vCD). Diodes were compared by the mean of the electron signal gain. This represents a ratio of the detected electron to the incident electron. Electron signal gain is depicted in Fig. 6. PureB photodiode outperforms commercially available detectors providing higher electron signal gain even for low-energy electrons. For the incident electron energy of 500 eV the PureB photodiode has more than a factor 5 improvement in sensitivity compared to the commercial BSE detector. Measurements also showed electron gain of 33 for incident electron energy of 200 eV. Excellent responsivity of the photodiodes with PureB is owed to the ultrashallow pn-junction formation.

IV. CHALLENGES OF THE PUREB LAYER DEVICES AND UNEXPLAINED ELECTRICAL CHARACTERISTICS OF THE PUREB LAYERS

The potential use of the photodiode detectors with PureB layers in commercial detector systems has led to additional problems regarding the demands of the whole detector electronics circuitry, i.e. the capacitance and resistivity of the photodiode detector are critical. The PureB layer has inherently high sheet resistance which together with capacitance of the detector can be a limiting factor to the operational speed of a photodiode. Also, radiation damage at the SiOx/Si interface can lead to the increase of the dark current. Some of these can be tackled by adjusting and optimizing the structure of the devices. This is ordinarily done with semiconductor simulation software and is a topic of this work. Structure optimization done in the simulation software will be discussed in the following sections.

Devices other than photodiodes were processed with the PureB layers. Some of the measured electrical characteristics of these devices, i.e. emitter Gummel number \(G_E\) of \(pnp\) transistors, processed with PureB layers are not yet fully explained [14]. Emitter Gummel number gives an estimate on how successful is an electron injection from the base to the emitter region. Electrical measurements were performed on semiconductor devices with PureB p’n junction incorporated as the emitter region in \(pnp\) bipolar transistor. Measured \(G_E\) for PureB layer \(pnp\) transistors are comparable to that of the conventional \(pnp\) transistors with deep p’n junctions (Fig. 7). Here, exposure to B,H6 was varied which results in change of the thickness of the PureB layer. The theoretical \(G_E\) extracted from simulations of \(pnp\) transistors is two orders of magnitude lower compared to the measured \(G_E\) for B,H6 exposure times longer than 1 min. Large discrepancy between the simulations and the measurements posed questions on the physical mechanism responsible for the suppression of the electron injection from base to emitter which lead to high \(G_E\). Only the electrical properties of the PureB layer, e.g. carrier diffusion length, low effective carrier concentration, etc., are responsible for suppression of the electron injection [14]. If assumed that PureB layer has the same properties as a bulk amorphous boron, i.e. larger bandgap than that for c-Si, the difference in the bandgap will result in efficient blocking of electrons. These assumptions are confirmed with simulations which show an excellent fit to the measurements [16]. However, the electron blocking could also be a result of the interface states at the PureB/Si interface [17]. All the proposed explanations are not conclusive and additional physical and electrical characterization should be performed.

In this work I present some of the excellent characteristics of the PureB layer detector devices and also the work done in optimization of such devices. There are many unanswered questions regarding the physical and electrical characteristics of the PureB layers. Therefore, I first give an overview of the physical and electrical measurements that could be conducted on the PureB layers. The knowledge on the physical and electrical characteristics of the layers can help further development and use of such layers in other semiconductor devices.

V. PHYSICAL AND ELECTRICAL CHARACTERIZATION OF THE PUREB LAYERS

The following measurements should be performed on the PureB layers: X-ray photoemission spectroscopy, spectroscopic ellipsometry, internal photoemission spectroscopy, Raman spectroscopy, UV photoemission

![Figure 6. Measured electron signal gain for photodiode with PureB layer. Electron signal gain is compared to commercially available BSE and vCD detector [12].](image1)

![Figure 7. Measured Gummel number for the emitter region formed by PureB deposition at 700°C for various B,H6 exposure times. Gummel numbers of the convention deep p’n junction diodes are plotted for comparison Gummel number extracted from simulations is also plotted[14].](image2)
spectroscopy, and photoluminescence spectroscopy. The goal of these measurements is to find out as much information as possible on the composition, physical and electrical characteristics of the PureB layers.

A. X-ray photoemission spectroscopy measurements

Photoemission spectroscopy is a surface technique that is used to determine chemical composition at the surface and the band structure of the surface layer [18]. In photoemission spectroscopy a sample is irradiated with photons of energy \( E_{ph} = h\nu \). Depending on the photon source the spectroscopy can be divided into ultraviolet \((E_{ph} < 50\text{eV})\) and X-ray \((E_{ph} > 1\text{keV})\) photoemission spectroscopy, UPS and XPS, respectively. Photons are absorbed by the atoms at the surface. Excited atoms emit photoelectrons which leave the material and are collected by the energy analyzer. In the XPS the energies of the emitted photoelectrons give information on the: identification of elements and chemical states of the elements present on the surface; relative composition of the constituents in the surface region and valence band energy [19]. On the other hand, UPS can give more information on the band structure of the material i.e. valence and conduction band [20].

Only the photoemitted electrons that did not suffer the inelastic collision carry information. This is described by the inelastic mean free path that represents the distance the electrons can travel without inelastic collision. If the electrons do suffer the energy loss through the collision, they can still escape the material and this contributes the background signal. The inelastic mean free path depends on the energy of the electron but also on the density, composition and the structure of the material being analyzed. It can be assumed that for the energies of interest for XPS, the inelastic mean free path of photoemitted electrons is 1-4 nm [21]. This means that the electrons collected by the energy analyzer come from few nanometers of the sample depth [22].

B. Spectroscopic ellipsometry measurements

Ellipsometry is a measurement technique in which a change in polarization of the light reflected from or transmitted through a material is measured. In ellipsometry, polarization of the light source is known and this represents a reference light beam. The sample material may consist of a number of layers. Thicknesses of the layers together with optical constants of the layers change the polarization of reflected/transmitted light. The change in the polarization of the light is measured as an amplitude ratio (\( \Psi \)) and phase difference (\( \Delta \)) between the reference and reflected/transmitted light beams [23].

The measurements can be performed using the variable angle spectroscopic ellipsimeter (VASE) [24]-[25]. The ellipsometer measures the change in polarization of the reflected light to a reference light beam for a range of wavelengths. It also changes the angle of the incident light. This provides a large amount of data which can be used to model the optical properties and determine the thicknesses of unknown layers. To calculate optical properties and the thicknesses an optical model should be constructed. For the proposed optical model, Fresnel equations are solved using the known light polarization as an input. Solving the Fresnel equations gives the polarization of the output light of the model. The calculated output light polarization is compared to the measured polarization. The difference between the modeled and measured polarizations is quantized by an estimator, i.e. mean squared error (MSE). Optical constants and the thicknesses of unknown layers are varied until minimum MSE is reached. Optical constants of the unknown layer can be calculated by applying various dielectric function models depending on the physical characteristics of the unknown material. Tauc-Lorentz model was proven to be a good choice for modeling thin-film amorphous semiconductors [26]. From the optical constants of the material described by the Tauc-Lorentz model, an optical bandgap can be easily extracted [27].

C. Internal photoemission spectroscopy

Heterojunction bandgap discontinuities can be measured using various techniques, one of which is internal photoemission spectroscopy (IPE) [28]. IPE spectroscopy is relatively simple and straightforward way of measuring bandgap discontinuity at heterostructures. Internal photoemission can be detected in different ways and the simplest method is by measuring the photocurrent of the irradiated sample [29]. Experimental setup is shown in Fig. 8 and it consists of a light source which is directed to a monochromator. Monochromator is used to select the wavelength of the light that irradiates the sample. The sample is biased in order to form a drifting field at the heterojunction. The carriers that are generated can overcome the energy barrier at the heterojunction only if they have sufficient energy. This is defined by the heterojunction band offset. The carriers that overcome the energy barrier drift from emitter to a collector. It is important that the internal photoemission transition of carriers from one material to the other provides dominant contribution to the total drift of carriers across the interface. This raises the questions of limitations of the internal photoemission spectroscopy. It is important to properly design the structure in order to eliminate all the currents that can drift across the heterointerface for different wavelengths of light. For example, thermionic emission can occur due to the absorption heat. Thermionic emission current can even become larger than the photocurrent due to the internal photoemission [30]. Tunneling current can also play a role for large electric fields between the materials. Another limitation is due to the recombination loss – carriers emitted from the material with lower bandgap must be majority carriers in the wide-gap material.

![Figure 8. Optical scheme of the IPE measurement setup](image-url)
VI. OPTIMIZATION OF SILICON PHOTODIODES WITH PUREB LAYERS

It is already mentioned that the semiconductor devices with PureB layer show excellent performance as a semiconductor detectors. This is especially true when the detector is used for detection of photons or electrons that have extremely shallow penetration depth. The performance of such devices can be significantly improved if the structure is adjusted and optimized using the advanced semiconductor device simulator software – Sentaurus Device [31]. In the next sections an overview of the work made on simulations of the various semiconductor devices with PureB layers is given.

Basic structure of the photodiode with PureB layer is a PIN diode. On the bulk silicon, an n-type epitaxial layer is grown with extremely low doping concentration. The thickness and the doping of the epitaxial layer may vary. On the epitaxial layer a PureB layer is deposited. The PureB deposition serves as a doping source for ultrashallow p-region formation. Aluminum contact is made to the PureB layer which represents the anode contact. The bulk is contacted at the bottom which represents the cathode contact.

A. Photodiodes for deep ultraviolet(DUV)/visible ultraviolet(VUV)/extreme ultraviolet (EUV) radiation detection

1) Optimization of the perimeter doping of photodiodes

The silicon surface is sensitive to ultraviolet (UV) radiation. Surface damage can give rise to degradation of various electrical and optical characteristics and part of the induced damage may not be fully reversible [32]. Experimental results for ultrashallow pn-junction photodiodes given in [33] show that the responsivity of the photodiode decreases less than 2 % for a 2 hour, 121.6 nm wavelength irradiation. However, the responsivity is recovered within a 1.5 hour break between two exposure runs. From this type of experiment, it has been concluded that the PureB surface layer is robust to VUV radiation and the sole source of degradation during exposure is the silicon/oxide interface at the diode perimeter. The depletion region of the analyzed photodiode structure reaches the silicon/oxide interface at the perimeter, as seen in Fig. 9, resulting in dark current degradation due to radiation exposure. It is shown in [9] that the very low dark current of these ultrashallow photodiode structures is degraded by damage at the silicon/oxide interface after EUV radiation exposure.

The solution for the problem of the radiation damage due to the EUV radiation exposure is to extend the p-region of the guard ring close to the n+ channel stopping region [34]. This would minimize the dark current increase caused by the radiation damage, but would also increase the electric field, reduce the breakdown voltage and increase the perimeter component of the junction capacitance. Therefore, a trade-off between the surface-depletion-region width, breakdown voltage and junction capacitance is investigated. The doping profile of the added p-region is varied and the surface depletion region width, breakdown voltage and junction capacitance were analyzed with respect to the distance of the added p-region to the n+ channel stopping region. Parameters of the doping profile analyzed are maximum doping concentration at the surface $N_{A0}$ and junction depth $y_j$. An example of the simulation results for $N_{A0} = 5 \times 10^{15} \text{cm}^{-3}$ is given in Fig. 10 (a) and (b). As suspected, perimeter capacitance increases with decrease of the distance between the added p-region and the n+ channel stopping region. At the same time, the breakdown voltage decreases.

The exact levels of the capacitance increase and breakdown voltage decrease due to the added p-region...
that can be tolerated are determined by the photodiode application requirements. If a low breakdown voltage (i.e. below 5 V) is acceptable, and/or the photodiode has a large area so that the increase of perimeter capacitance is negligible with respect to the total junction capacitance, a considerable reduction of the depletion-region width at the surface is feasible. This will result in minimization of the dark current increase due to the radiation damage.

2) Photodiode epitaxial region optimization

The response time of a photodiode detector is determined by two factors – the RC time constant of the photodiode equivalent circuit and the drift time of the generated charge. Since the sheet resistance of the PureB layer is in order of 10 kΩ/sq [4], the response time is mainly determined by the RC time constant [35]-[36]. The resistivity of the PureB layer is a characteristic of the material and by changing processing conditions it does not change significantly [4]. The possibilities for reducing the total series resistance of the PureB layer are to add a metallic grid on top of the PureB layer or to increase the annealing time [37]. Both of the solutions influence the responsivity of the photodiode to VUV/EUV radiation.

Another way of reducing the RC time constant is by decreasing the capacitance of the photodiode. The capacitance can be decreased by increasing the thickness of the epitaxial layer and at the same time reducing the concentration of dopants in the epitaxial layer. This increases the depletion region, which leads to the decrease of the total capacitance of the photodiode. The depletion region can be increased by increasing the reverse bias of the photodiode. In our case the reverse bias of the photodiode is determined to be 3 V. The analysis is conducted with the reverse bias voltage of 3 V and with the doping of the epitaxial layer of $5 \times 10^{15}$ cm$^{-3}$. It can be concluded that simply increasing the epitaxial layer thickness leads to a negative effect of increasing the rise time of the photodiode which is depicted in Fig. 11. If some of the epitaxial layer is left undepleted it increases the series resistance of the photodiode and consequently makes the diode slower.

One of the solutions for reduction of the photodiode capacitance is to add an additional p-region in the epitaxial layer (Fig. 12). The added p-region will deplete the epitaxial layer around the region and when the diode is reversely biased, the two depletion regions will merge. The minimum capacitance is determined by the total epitaxial layer thickness. On the downside, the depletion region is spreading throughout the whole epitaxial layer. This means that the two photodiodes located next to each other on a single wafer (as in multi-segmented photodiode) are not electrically isolated. The charge generated in one of the photodiodes/segments can drift to the other photodiode/segment. The solution for this problem is presented in the next section.

B. Low-energy electron detectors

The basic structure of the PureB layer photodiode for low-energy electron detection is similar as the structure of the photodiode for photon detection. Excellent properties of the PureB layer enable the detection of very low energy electrons from 20 keV down to 200 eV [11]-[12]. Very high sheet resistance of amorphous boron of 10 kΩ/sq can be a problem for low-energy electron detectors. Low-energy electron detectors are used in SEM systems. The speed for electron scanning is crucial. Therefore, it is important that the sheet resistance of the detector is reduced below the 10 kΩ/sq range with the reduction of the capacitance. Structure optimization proposed in previous sections offers one way for increasing the detection speed. Another approach is reducing the sheet resistance of the detector by changing the annealing parameters after the PureB layer deposition. PureB layer is used as an abundant source for boron diffusion. Thereafter, boron diffusion from the PureB layer can be fine-tuned to match the desired characteristics by changing the annealing variables such as temperature and/or the duration of the annealing.

Process simulations using Taurus SUPREM [38] are made to investigate the influence of annealing on the depth of the pn-junction and the corresponding sheet resistances. The simulations were made without any point defect model because it was noticed that there is no transient enhanced diffusion and boron enhanced diffusion effect active during the deposition of the PureB layer [14]. This means that the doping profile is determined only by the solid solubility and thermal diffusivity at a given temperature. For substrate doping of $10^{13}$ cm$^{-2}$ simulation results for annealing temperature of 700 °C show that junction depth is 1.4 nm, 2.0 nm, 2.6 nm, and 3.7 nm for deposition times of 2 min 40 s, 6 min, 10 min, and 20 min, respectively (Fig. 13). The sheet resistance for
given deposition times is given in Table 1. The sheet resistance reduces from 300 to 67 kΩ/sq if the annealing time is increased from 2 min 40 s to 20 minutes. Even lower sheet resistance could be obtained if the photodiode is in situ annealed. Boron doping profile after the annealing for 1 min at 850 °C was also simulated and compared to the doping profiles of boron deposited at 700 °C (also depicted in Fig. 13). The simulations show the junction depth increases to 14 nm while the sheet resistance decreases to 2.5 kΩ/sq [14]. As was the case with photodiodes for photon detection, in the case of deeper diffused pn-junctions, the responsivity is degraded [39].

VII. CONCLUSION

Silicon photodiodes with PureB layers are state-of-the-art detectors for UV radiation and low-energy electron detection. Sensitivity of the both the EUV and low-energy electron detectors is reported to outperform commercially available detectors. Sensitivity together with excellent electrical characteristics, namely ideal I-V characteristics and low dark currents, makes these detectors a perfect choice for integration in complex detector systems to be used in SEM or even EUV optical lithography. For that to be accomplished a photodiode structure should be optimized to satisfy the demands of the electronic circuitry which are used in such systems. Since the PureB layer has inherently low sheet resistance the response time of the PureB photodiode will be mainly determined by the RC time constant of the photodiode equivalent circuit. In order to decrease the RC time constant two approaches were proposed and simulated. The first includes the capacitance decrease which is made by increasing the depletion region by adding a p-layer in the low doped epitaxial layer. The second approach tackles the problem of a large sheet resistance. If the annealing if performed after the PureB deposition, a sheet resistance can decrease to 2.5 kΩ/sq compared to the 10 kΩ/sq of the as deposited PureB layer. The downside is the increase of the pn-junction depth which will decrease sensitivity. Optimization of the structure was also done with respect to the dark current degradation due to the UV radiation damage at the Si/SiO₂ interface. The results show that considerable reduction of the depletion region width at the perimeter surface could be achieved if an additional p-region is added as an extension to the guard ring region. This comes with the price of decreased breakdown voltage and increased perimeter capacitance, so a trade-off should be made. Electrical characteristic of the PureB layer show that there exists an efficient stopping mechanism which successfully prevents the injection of the electrons from n-region to the PureB layer. Physical and electrical measurements should be performed in order to investigate this effect.

REFERENCES


Figure 13. Concentration of boron doping profiles achieved by drive-in from a constant boron surface doping. An anneal temperature is 700 °C or 850 °C.

Anneal time (T = 700 °C)
- 2 min 40 s
- 6 min
- 10 min
- 20 min
Anneal time (T = 850 °C)
- 1 min

Concentration (cm⁻²)
10¹⁶
10¹⁷
10¹⁸
10¹⁹
10²⁰

Arsenic conc.