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## Optical Performance of B-layer Ultra-shallow-junction Silicon Photodiodes in the VUV Spectral Range

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### Abstract

In recent work, a novel silicon-based photodiode technology was reported to be suitable for producing radiation detectors for 193 nm deep-ultraviolet light [1] and for the extreme-ultraviolet (EUV) spectral range [2][3]. The devices were developed and fabricated at the Delft Institute of Microsystems and Nanoelectronics (DIMES), TU Delft. In this paper, we characterize the optical performance of the DIMES photo-detectors in the vacuum-ultraviolet (VUV) spectral range, in particular between 115 nm and 215 nm wavelength. We report an outstanding performance in terms of low dark current, high responsivity and irradiation stability. Owing to these features, the presented photodiode technology, which profits from low cost, reduced complexity and full compatibility with standard Si processing, offers a reliable solution for the implementation of detectors in applications making use of VUV radiation.

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*Keywords:* photodiodes, vacuum-ultraviolet, radiation detectors, responsivity, ultra-shallow junctions.

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### 1. Introduction

Nowadays, the demand for radiation detectors in the VUV spectral range (wavelengths below 200 nm) is noticeably increasing. For example, the ever decreasing feature size of the projected patterns on silicon wafers has led to the development of 193 nm wavelength lithography [4]. The metrology and the dose control of the VUV pulsed sources require the use of sensitive VUV radiation detectors. Therefore, the development and the fabrication of high-performance detectors for VUV radiation are becoming important for the future of nanoelectronics manufacturing.

Due to the low cost and well-developed technology, Si-based photodiodes are good candidates for the above mentioned applications. The extremely small penetration depth of the VUV radiation in silicon, as shown in Fig. 1, requires the depletion zone of the photodiode, where the photo-generated charge is collected, to be very close to the device surface [5]. The DIMES silicon-based photodiodes have an ultra-shallow junction depth of only a few nm and therefore they have a great advantage for radiation detection in the VUV spectral range.

### 2. Device description

Fig. 2(a) presents a photograph and a schematic cross-section of DIMES photodiode. As indicated in the

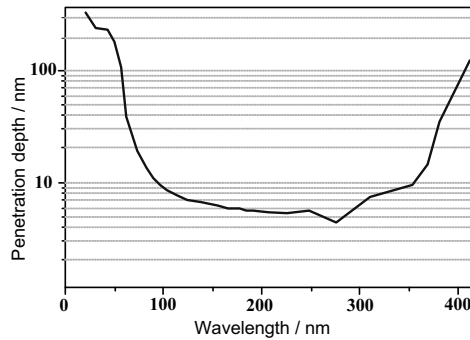


Fig.1. Penetration depth vs. incident radiation wavelength in Si.

schematic cross-section, a low-doped ( $< 10^{14} \text{ cm}^{-3}$ ) epitaxial layer is grown on a 1-10  $\Omega\text{cm}$  n-type Si(100) substrate. The epi-layer thickness sets the breakdown voltage and junction capacitance of the diodes and can be adjusted for specific applications. On the epi-layer, the diode anode, which is the delta-doped boron surface layer, is selectively deposited in an opening through an  $\text{SiO}_2$  layer, by using a pure boron atmospheric/low-pressure chemical vapor deposition (AP/LPCVD) at 700 °C with diborane ( $\text{B}_2\text{H}_6$ ) as the gas source [1]. Fig. 2(b) shows a high-resolution TEM image of the B-layer formed after a 2.5 min  $\text{B}_2\text{H}_6$  exposure along with the corresponding Boron SIMS profile. The boron coverage is uniform and from the electrical characterization of the  $\text{p}^+\text{n}$  diodes it has been determined that there is a well-controlled, ultrashallow  $\text{p}^+$  doping of the Si surface within a depth of a few nanometers [1][2]. Additional coating layers can be deposited on the B-diode surface, for protection, anti-reflection, or to facilitate the integration of thin film filters with radiation pass-bands optimized for specific applications.

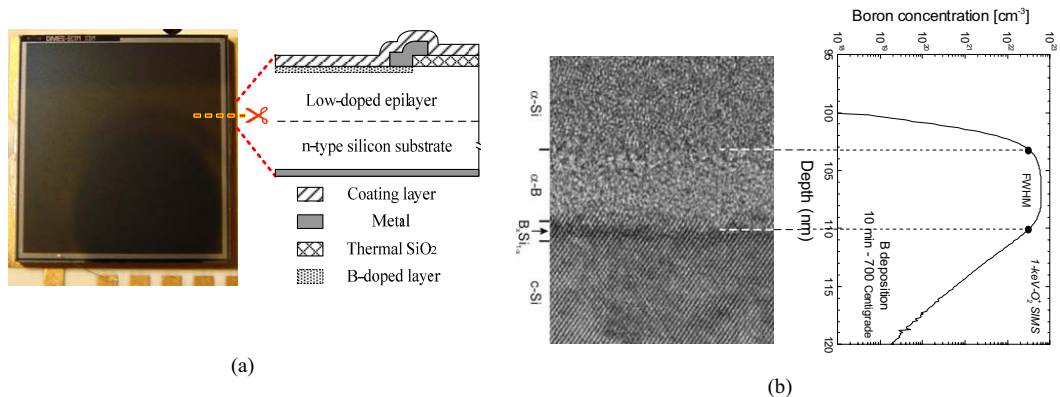


Fig.2. (a) Image and cross-section of DIMES photodiodes (Active area size  $\sim 1 \times 1 \text{ cm}$ ). (b) HRTEM image of a B-layer formed after a 10 min B deposition at 700 °C with a Boron SIMS profile. The sample has been covered with 20 nm PVD  $\alpha$ -Si for the TEM analysis.

**3. Measurement and characterization**

In this section, we illustrate the electrical and optical performance of the fabricated VUV photodiode and demonstrate the fundamental advantages of the pure boron CVD deposition for VUV radiation detection. DIMES photodiodes are also compared to some commercially available devices, which are representative of the current state-of-the-art UV silicon photo-detectors.

### 3.1. I-V characteristics

Fig. 3(a) shows the I-V characteristics of a Boron-doped  $p^+n$  diode as compared to a commercially available  $n^+p$  photodiode. Both measured diodes have the same circular geometry and a diameter of 3.7 mm. Excellent electrical performance is achieved in terms of low dark current ( $< 50$  pA at a reverse bias of 10 V) and ideality [2], as expected for a defect-free  $p^+n$  junction.

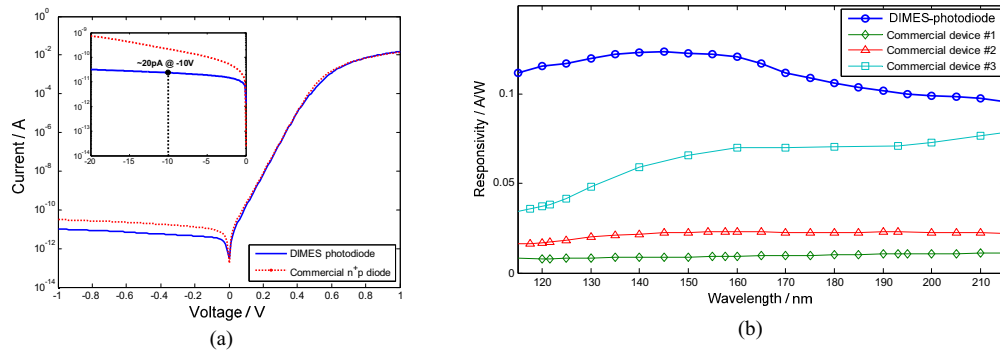


Fig. 3. (a) I-V characteristics of the DIMES as deposited DIMES photodiode compared to a commercial  $n^+p$  photodiode. The inset shows the dark current with reverse bias up to 20 V. (b) Responsivity of the DIMES photodiode in VUV spectral range compared with other state-of-the-art photodetectors.

### 3.2. VUV optical performance

Optical tests were carried out at the synchrotron radiation laboratory of PTB (Physikalisch-Technische Bundesanstalt) in Berlin, Germany [6][7]. Fig. 3(b) shows the superior responsivity of the DIMES photodiode compared with other state-of-the-art photodiodes in the VUV spectral range (wavelengths from 115 nm to 215 nm) [8][9][10]. This excellent optical performance confirms that the B-deposition process can provide ultra-shallow and high-quality  $p^+$ -doped active surface layers, which can effectively enhance the quantum efficiency by reducing the VUV photon absorption in the front window.

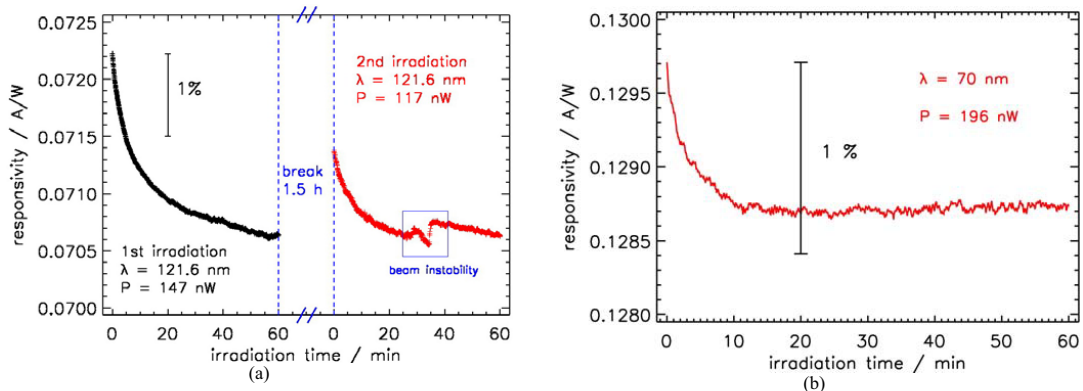


Fig. 4. Degradation of the responsivity of DIMES photodiodes during irradiation at 121.6 nm (a) and at 70 nm (b).

The degradation under irradiation of the DIMES photodiodes was characterized by a two-hour irradiation at 121.6 nm wavelength, followed by a one-hour irradiation at 70 nm wavelength. Fig. 4(a) and 4(b) show the spectral responsivity of the diode monitored during the irradiation. As indicated in the figures, responsivity decreases of about 2 % and less than 1 % were observed for the 121.6 nm wavelength irradiation and the 70 nm wavelength

irradiation, respectively. This initial small reduction of responsivity is followed by what appears to be a saturation of the degradation. In Fig. 4(a), within the 1.5 hour break between the two exposure runs, a regeneration of the responsivity could be clearly seen. In general, based on above experimental results, no significant responsivity degradation was observed on the DIMES VUV photodiode. Therefore, we can conclude that the boron surface layer is robust to VUV exposure.

#### 4. Conclusions

In summary, we have presented a high-performance silicon-based photodiode technology for VUV radiation detection that offers excellent electrical and optical performance in terms of extremely low dark current, outstanding responsivity, and high stability to VUV radiation exposure. Such impressive features are achieved by forming ultra-shallow boron-doped layers on the active area with a novel CVD doping technique which ensures the integration of high-quality p<sup>+</sup>n junctions. In addition, the process offers considerable flexibility in optimizing the device performance in relation to specific application requirements. Comparisons with commercially available VUV detector solutions show that the B-deposited photodiodes perform with superior characteristics and exhibit a great potential for radiation detection in VUV-based application, such as in 193 nm lithography systems.

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