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An Array of Bandpass Detectors for Measuring Beam Spectral Components

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***Abstract*— A clear understanding of the spectral components of an irradiated beam, or captured optical emission, is essential to optimize an optical system and increase its performance. Logically, for this purpose a grating-based spectrometer could be the first choice. However, in the case of a wide range spectrum, and for radiation with one dominant wavelength, this option may not work well. In this paper, we present a technique based on an array of bandpass detectors to measure accurately the power of a number of beam-specific spectral components in a wide spectrum range: from soft X-ray to infrared. The main unique features of this technique are: customization for specific wavelengths of interest; vacuum compatibility; and high sensitivity to low-energy spectral components in the presence of one or more dominant high-power spectral components.**

Keywords— radiation beam spectral components; detector array; integrated optical windows;

I. Introduction

Increasing the accuracy of optical devices and systems often entails the power of selected portions of a beam spectrum to be more accurately detected. In practice, many radiation sources, such as laser beams, thermal lamps and cosmic emissions, have an anticipated power spectral distribution. These beams often have one or two dominant components in specific wavelengths, plus other components in a neighboring or far spectrum [1]. Although in most applications the dominant component may be of greatest interest, information about the existence of other wanted/unwanted spectral components may be used to diagnose and optimize the performance of a radiation source or an optical system [2].

A radiation spectrum can be analyzed by a micro-spectrometer. However, even the most advanced micro-spectrometers have to compromise between covering a wide spectrum range and achieving high spectral resolution [3][4].

In ultra-wide spectrum-based applications, such as those developed for space industries, the accurate detection of specific bands without any sweep throughout the entire spectral range is preferred. However, if the spectral bands of interest are too far from one another, and the energy in each band varies significantly, detectors based on different materials and design techniques need to be used [5][6].

For instance, T. Bauer et al. have demonstrated the realization of high-performance bandpass filter arrays by micro-structuring processes at Optics Balzers [7]. Different band-pass filter arrays based on micro structuring have been coated in detector's array in range of visible (blue, green, red) and near infrared (800 nm to 900 nm). Similar works are also done by E. Huang et al. on etalon array reconstructive spectrometry as a portable compact spectrometry focused on the visible range [8].

In this paper we present an optical system consisting of an array of detectors, each with a narrow bandpass filter for a specific wavelength in an ultra-wide spectrum ranging from soft X-ray (0.1 nm to 10 nm), extreme ultraviolet (EUV) (10 nm to 100 nm), deep ultraviolet (DUV) (100 nm to 300 nm), and near infrared (NIR) (0.8 µm to 2 µm). An advantage of the proposed solution is the use of the same detector technology for all spectral bands. Section II presents the main design approach, the theoretical physical principle of efficient photocurrent generation, and the operation of an optical system based on this technique. Section III discusses in detail the aforementioned optical system and clarifies the choices made for the design parameters and materials of the detector, as well as presents the electrical and optical performance of the fabricated detectors. Finally, Section IV summarizes the study and highlights the achieved results.

II. Design Approach

A bandpass detector is composed of two components: (1) an optical filter consisting of a number of optical thin film materials functioning according to the interference principle, and (2) an engineered photodiode with the required responsivity and quantum efficiency for the desired wavelength [9]. Figure 1A presents the main concept. The irradiance beam including all wavelengths of interest illuminates the array of detectors. The first stage of filtration is carried out by the optical filter stacks. Most of the out-of-band irradiance is either absorbed or reflected by the filter. The spectral part of interest is transmitted through the filter and reaches the detector's surface. In the second filtration stage, the transmitted component is absorbed by the detectors. Note that only photons with energy equal to or higher than the semiconductor bandgap can be absorbed in the detector [10]. Moreover, not all absorbed photons play a role in the generation of photocurrent. Only those absorbed in the active area of the photodiode (the depletion region) can produce effective electron-hole carriers which will result in a photogenerated current [11]. In Figure 1B a schematic of a bandpass photodiode is shown. The photons allowed through the optical stacks are absorbed at various depths inside the detector, depending on the photon energy and the attenuation coefficient of the detector material. By tuning the width (W) and depth (D) of the depletion region, an additional filtering of the unwanted spectrum is realized. In this way the final quantum efficiency of the bandpass detector can be presented as the product of the attenuation factor of the bandpass optical filter and the percentage of absorbed photons in the depletion region.

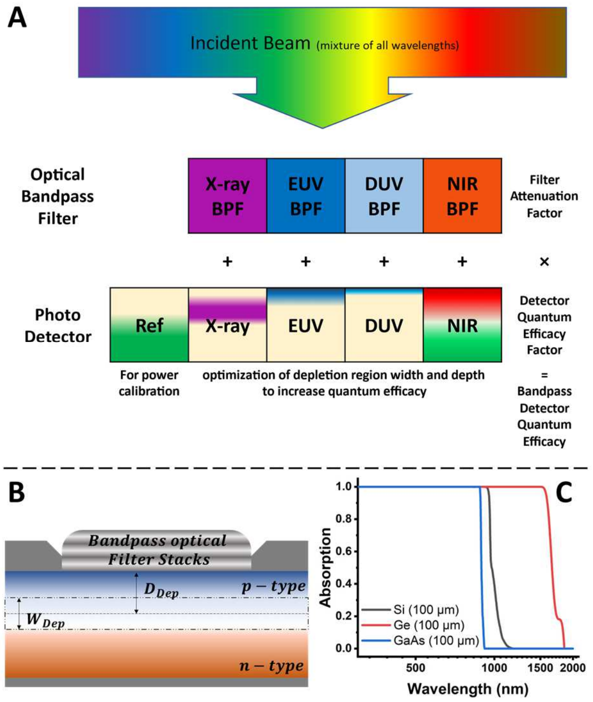

Fig. 1. (A) Concept of an array of detectors each with a unique bandpass filter. Here, five independent detectors work together to define the optical power distribution. A reference detector is essential for calibration and absolute power measurement. (B) Schematic of a bandpass detector containing bandpass optical thin film stacks over the active window and an engineered photodiode with a depletion region of a specified depth D_{dep} and width W_{dep}. (C) Relative absorption in the longer wavelength spectrum of three materials, Si, Ge, and GaAs, with thickness of 100 µm.

Next, we investigate the potential of applying this technique in a spectrum ranging from soft X-ray to infrared. The main reason to select this particular spectrum is to cover the vast majority of applications using semiconductor photodiodes as detectors [12]. Silicon is the preferred detector material, allowing on-chip integration with the CMOS readout circuit. The selection of the specific spectrums of interest is validated by: 2.5 nm, which is an important wavelength in the soft X-ray region for Si-based photodiodes [13]; 13.5 nm in the EUV region, which offers an attractive application option in photolithography [14]; 200 nm, which is one of the most challenging wavelengths in the DUV band due to the very short attenuation length (<10 nm) in silicon [15][16]; and 1000 nm, which is in the NIR region, at the edge of the sensitivity of Si detectors [17].

An attractive feature of the proposed spectrum analysis technique is its high selectivity to spectral components with very low energy, in the presence of a dominant high-power spectral component. For example, the radiation source may have a dominant high-power spectral component in the EUV spectrum, but also weak power components in the DUV and the near infrared spectrums. The array of detectors has to detect each weak component while remaining undisturbed by the high energy component.

All detectors are produced in the so called "PureB" technology, which exhibit not only excellent diode electrical characteristics (low dark current, high breakdown voltage, ideality factor close to 1), but also very good radiation hardness, vacuum compatibility, and high sensitivity throughout the entire spectrum range of interest [18][19][20].

III. Results and Discussion

A. Photodiode design

Figure 1C shows the radiation absorption of 100-µm-thick layers of three popular semiconductors—silicon (Si), germanium (Ge) and gallium arsenide (GaAs)—with bandgaps of 1.12 eV, 0.66 eV, and 1.42 eV, respectively, as a function of the wavelength [21]. It can be seen that Si and GaAs are not suited for detecting radiation above a wavelength of 950 nm, even with a depletion region of much wider than 10 µm. On the other hand, Ge would provide very good sensitivity above a wavelength of 1000 nm.

Even though silicon-based photodetectors can basically be used for the measurement of all photons with an energy level above 1.12 eV (1100 nm), the thickness of silicon required to enable sufficient absorption is essential. Regarding Figure 2A, the penetration depth of photons at different wavelengths in silicon illustrates that the full absorption of photons of 2.5 nm and 13.5 nm is around a depth of 2 µm. In contrast, a flux of photons of 200 nm is absorbed in silicon within the first 20 nm [22]. Furthermore, a flux of photons of 1000 nm attains less than 5% absorption in the first 10 µm of silicon, which can prove that an extremely wide depletion region (requiring a large reverse voltage and low doping level) is necessary to design a silicon-based detector for this wavelength. While silicon is not the most effective option for photons with a wavelength of 1000 nm, germanium absorbs the 1000 nm photons in the first 2 µm (Fig. 2B).

In short, for measuring 2.5 nm, 13.5 nm and 200 nm wavelengths silicon-based detectors can be used, while for measuring 1000 nm wavelength Ge- or SiGe-based photodiodes need to be used. Both types can be produced in the PureB technology, which simplifies the production process.

B. Optical bandpass filter design

"Open Filters", the software developed by "Ecole Polytechnique de Montreal, Canada" for the design of interference optical filters, was used to design the optical bandpass filters with an optimized stack [23]. Figure 3A shows the optical transmittance of the three bandpass filters simulated for each of the requested wavelengths in the full spectrum of interest. The EUV/soft X-ray filter consists of a bilayer of Si/Mo with a total thickness of 215 nm. The DUV window was optimized for a 200 nm wavelength with stacks of five layers of $SiO_2/Al_2O_3/SiN/Al_2O_3/SiO_2$ with a total thickness of 128 nm, while the NIR window was tuned for 1000 nm by a quad layer of Si/SiO_2 with a total thickness of 1140 nm.

The integration of the detector and the optical filters results in the final quantum efficiency of the bandpass detectors. Figure 3B is extracted by the product of the semiconductor absorption profile and the optical window transmittance, which is called theoretical quantum efficiency (TQE). The theoretical quantum efficiency illustrates the number of irradiance photons in a specific wavelength which can be effectively absorbed and contribute to the photogeneration currents. Figure 3B presents the designed configuration of the bandpass detectors with a TQE of 34% (FWHM = 2 nm), 42% (FWHM = 4 nm), 82% (FWHM = 40 nm), and 78% (FWHM = 400 nm) for wavelengths of 2.5 nm, 13.5 nm, 200nm and 1000nm, respectively. Therefore, from the spectral characteristics shown in Figure 3B we can conclude that potentially the four separate detectors with integrated optical filters can achieve an accurate measurement of the beam spectral components with negligible disturbance by the dominant component.

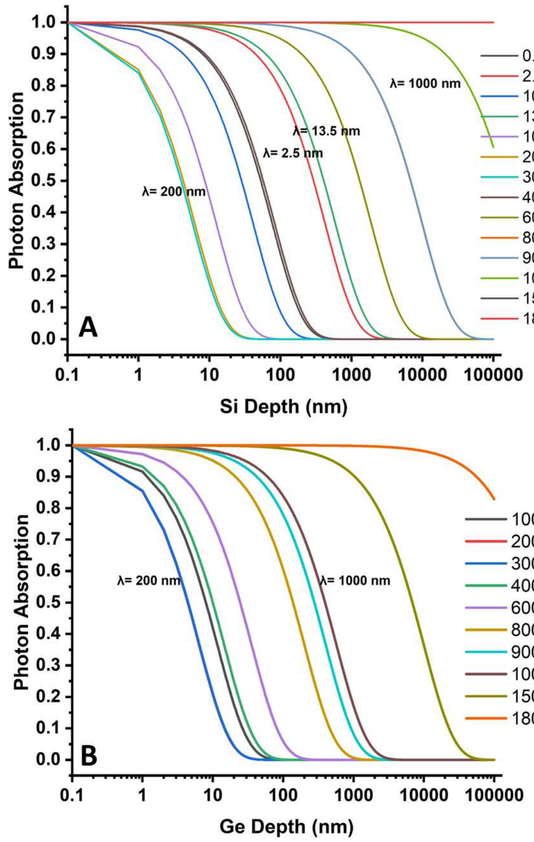

Fig. 2. Penetration depth of photons at different wavelengths in the ultra-wide spectrum in (A) silicon and (B) germanium.

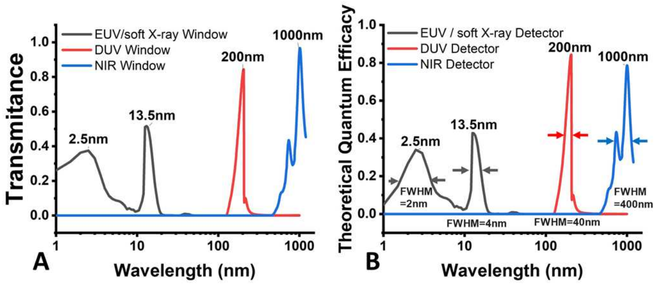

Fig. 3. Simulation results of (A) optical bandpass filter response (transmittance) to eliminate selectively irradiance beam and only pass the desired narrow band; (B) final expected quantum efficiency (QE) regarding integration of both the optical filter stacks and photodetectors.

C. Fabrication and experimental results

To prove the performance of the aforementioned technique, an array of detectors, each consisting of five customized pixels, was designed and processed (Fig. 4A). At this point we can present the measured I-V characteristic (Fig. 4B). Figures 4 C & D show the typical photoresponsivity in the VUV bands. The array is 6x6 mm^2 with an active area of 1.75 mm^2 per pixel. The pixel's reverse saturation current is ~20 pA with a -2V bias voltage, 7.16 Ω series resistance, 4.6 GΩ shunt resistance, and 99 pF junction capacitance. Table 1 summarizes the electrical properties in the dark mode, proving the excellent properties of the detector.

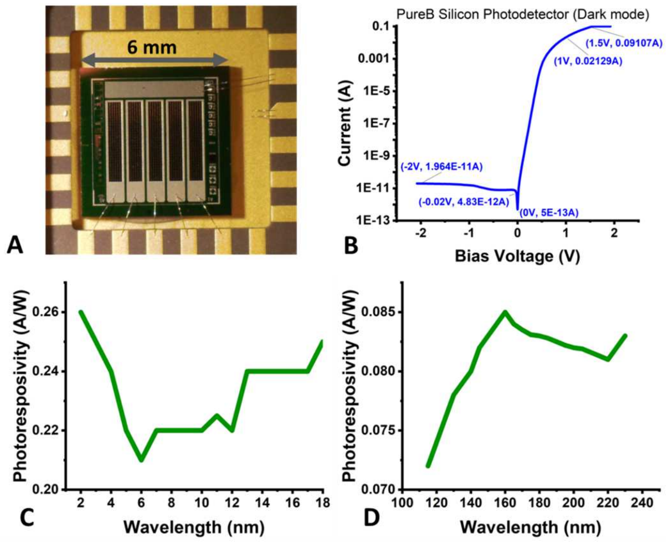

Fig. 4. (A) Fabricated PureB Si-based detector; (B) I-V characteristics; (C) and (D) photoresponsivity of the fabricated PureB detectors in the (C) EUV/soft X-ray, and (D) DUV bands, without optical filters.

TABLE I. ELECTRICAL PARAMETERS OF FABRICATED PUREB SI-BASED DETECTORS

Fabricated silicon-based detectors with PureB technology		
Electrical Parameter	***Symbol***	***Measured value***
Active area	A_a	1.75 mm^2
Dark current density	J_0	2.285E-5 A/m^2
Series resistance	R_s	7.16 Ω
Shunt resistance	R_{sh}	4.6 GΩ
Junction capacitance at zero bias	$C_{j(0V)}$	99 pF
Junction capacitance at -1V bias	$C_{j(-1V)}$	60 pF
Barrier height	φ_{bi}	0.697 V
Ideality factor	η	1.17
Breakdown voltage	V_{br}	-70 V

IV. CONCLUSION

This work presents a technique using an array of bandpass detectors to detect a number of spectral components in a wide spectrum range (0.1 nm to 2 µm). The array of detectors contains customized photodiodes, each integrated with its own optical filter stack to sense a specific wavelength. To prove this method, an optical system including an array of four bandpass detectors was developed using PureB technology to sense soft X-ray (2.5nm), EUV (13.5 nm), DUV (200 nm), and NIR (1000 nm) spectral components. Based on simulations, a theoretical quantum efficiency of 34%, 42%, 82% and 78% was achieved for wavelengths of 2.5 nm, 13.5 nm, 200 nm, and 1000 nm, correspondingly. The detectors were processed and their I-V characteristics presented. The processing of the filter stacks is underway.

The main application of the proposed detector array is to measure weak radiation at specific wavelengths in the presence of other much stronger dominant radiation sources. The PureB process guarantees very high radiation hardness and robustness to harsh environments, as well as high sensitivity and resolution.

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