Fast XUV 16 × 16 Array Hybrid Module for Plasma Imaging Applications

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A hybrid matrix array detector is developed for ultra-fast plasma imaging applications with the use of XUV Si photodiodes (SPD diodes) manufactured according to Ioffe Institute original technology. A basic 16 × 16 hybrid module is comprised of eight stacked sub-modules with 2 × 16 linear SPD diode arrays combined with a circuit board with a 32-channel preamplifier and four 8-channel fast multiplexers. Array front size is 31 × 31 mm^2 with ∼25 % sensitive area. The module has a "zero-edge" design providing an option of stacking into the larger arrays, if necessary. The data acquisition system (DAS) consists of eight 4-channel synchronous 12-bit ADC modules with 40 MS/s upper sampling rate, thus providing less than 1 μs minimum time for the complete read-out of the array. Each channel has a 64 MB on-board memory limiting the duration of the acquired period to 0.8 sec at the maximum sampling rate. A common TCP/IP Ethernet protocol is used for the data transmission into the main PC operating as a DAS control console, data preview and storage computer.

Keywords: XUV detector, matrix array, fast imaging

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1. Introduction

Absolute extreme ultraviolet (AXUV) Si photodetectors manufactured by IRD Inc. (USA) [1] are quite popular in plasma research applications owing to high sensitivity, fast response and an almost flat spectral curve in the 30. . . 5000 eV photon energy range [2–11]. Owing to this feature, AXUV detectors are frequently called "silicon bolometers" [2], related to being applicable to the absolute measurements of the photon fraction of plasma radiation loss [2–7]. Nevertheless, it must be kept in mind, that a number of factors could affect the accuracy of these measurements: e.g. responsivity drop in the UV range and its further reduction due to the aging and the deposition of an extra "dead" layer on the detector's open surface during long-term operation in plasma devices. Also, a remarkable sensitivity to particles [12], and the contribution of photoemission currents, which might reach the 14 % level of the total internal photocurrent [13, 14], should be taken into account as well.

However, the detector μs-scale response and high sensitivity are frequently more important for plasma imaging applications, than radiation power measurement accuracy, since they provide an opportunity to follow the evolution of MHD and other rapid events [15–17].

To our knowledge, currently there is no commercial manufacturer of matrix XUV arrays, suitable for plasma imaging applications, which would be quite helpful, e.g. for studies of impurity behavior in the scrape-off layer, its penetration and accumulation into the plasma core. This task had been set as a main goal of the present work, aimed at the development of a hybrid array approach with the use of SPD photodiodes similar to AXUV Si detectors, designed and manufactured according to Ioffe Institute original technology [18].

2. Detector Array Design

Since the absorption length of XUV radiation in solids ranges in the sub-micrometer scale, common Si photodetector technology based on a relatively thick SiO_2 passivation layer on the surface is not applicable. Special precautions are to be taken to draw the junction electric field as near as possible to the front-end surface in order to provide full collection of radiation-induced charge. In general, the design of SPD diodes is similar to AXUV detectors with an ultra-shallow p-n-junction and extremely thin (5. . . 10 nm) surface "dead" layer. Spectral responsivity curves of both detectors are shown in Figs. 1a, b. The details of the calibration procedure are described elsewhere [10, 11]. Absolute sensitivity values for both detectors are very similar, with a small difference depending on the passivation SiO_2 surface layer thickness.

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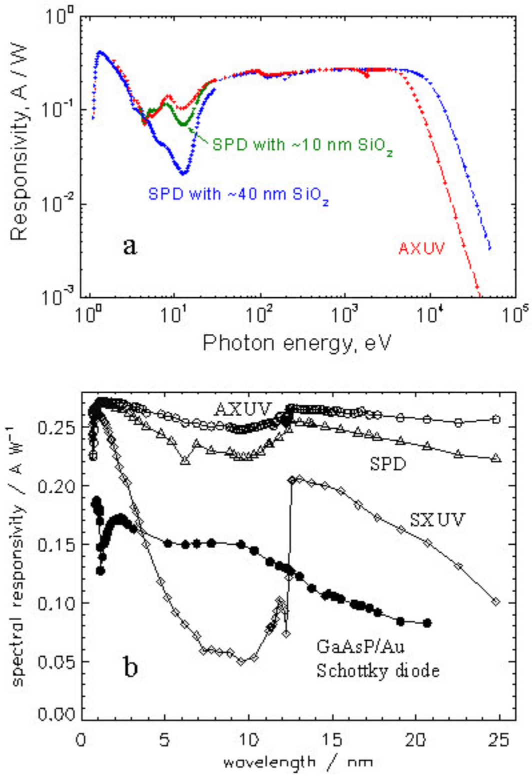

Fig. 1 Spectral responsivity of extreme UV photodiodes (for details see Ref [10, 11]).

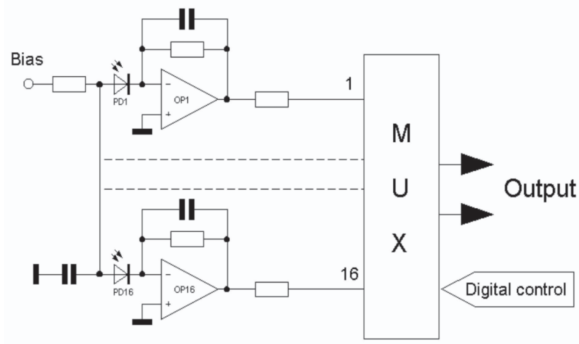

Fig. 2 Simplified detector front-end circuit.

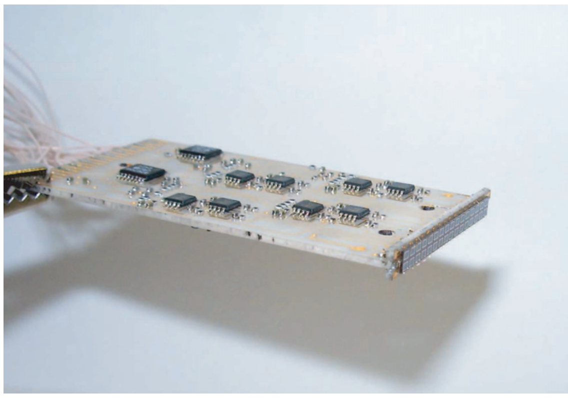

Fig. 3 Hybrid sub-module with 2×16 photodiode array.

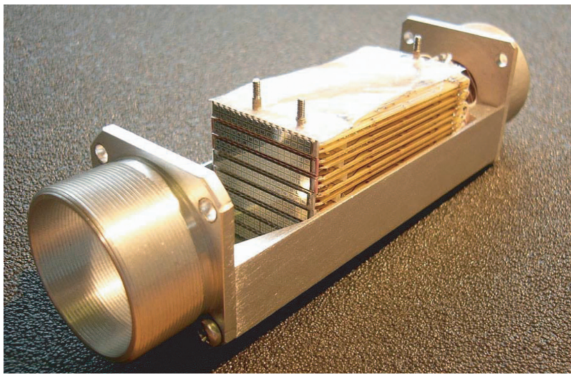

Fig. 4 Prototype 16×16 hybrid matrix array packed into the test pinhole camera.

An optimal choice of the passivation layer type and thickness is a trade-off between the detector spectral responsivity flatness, long-term and radiation stability.

The SXUV-type diodes were developed by IRD Inc. to overcome the latter problem, but their spectral response flatness is much worse (Fig. 1b). A 10...20 nm thick SiO_2 layer had been used in the SPD array detector, which provides an acceptable compromise of the sensitivity drop in $E < 30$ eV region and the radiation hardness and stability.

Making an optimum choice between the read-out cycle frequency (frame rate), the spatial resolution (pixel No.) and the number of parallel electronic channels, is the main problem to be solved by the designer of a camera with a large-scale array. The task is much harder for XUV plasma diagnostics due to the restrictions related to the in-vessel camera location: high vacuum compatibility, limited number of vacuum feedthroughs, ability to withstand thermal baking at 150...200 °C, wall conditioning procedures, etc. The frame rate of $> 2 \times 10^5\,s^{-1}$ together with proper detector and electronic circuit bandwidths are needed for impurity behavior studies, since the characteristic times of rapid events related to impurity propagation in plasma during disruptions, magnetic reconnections, ELMs and other fast processes, are of the 10...100 µs range [15, 16].

These requirements defined the hybrid approach combining the detector array with front-end electronics, and a limited total number of pixels in a single module. The basic 16×16 hybrid module is comprised of eight stacked submodules with 2×16 linear SPD diode arrays combined with a circuit board containing two 16-channel preamplifiers and four 8-channel fast multiplexers. The pictures of a prototype simplified front-end circuit, 2 array submodule, and stacked 16×16 matrix are shown in Figs. 2-4, respectively. The matrix array front size is $31 \times 31\,mm^2$ with ~25 % filling factor (single element sensitive area is $0.88 \times 1.22\,mm^2$). The module total length is 65 mm.

The module has a "zero-edge" design providing an option of stacking them into the larger arrays, if necessary. For preliminary testing it is packed into a pinhole camera

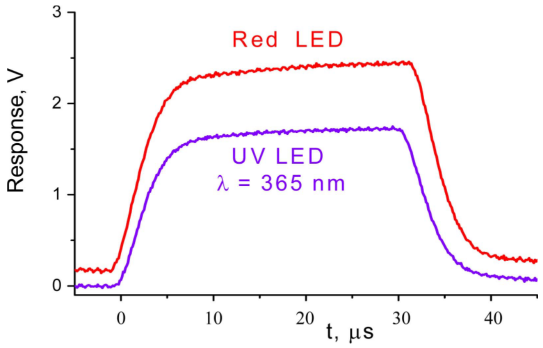

Fig. 5 Detector transient response with the front-end circuit shown in Fig. 2.

of 38 × 38 × 155 mm size with a variable field-of-view and 50-pin output connector (Fig. 4).

3. Data Acquisition System and Preliminary Tests

The data acquisition system (DAS) is based on the approach developed for short-pulse plasma diagnostic applications requiring fast simultaneous sampling of a number of analog signals. It is comprised of a controller of array multiplexers (MUX in Fig. 2), and eight 4-channel synchronous 12-bit ADC modules with a 40 MS/s upper sampling rate, thus providing ∼1 μs minimum time for the array complete read-out. Each channel has a 64 MB on-board memory limiting the duration of the acquired period to 0.8 s at the maximum sampling rate. A common TCP/IP Ethernet protocol is used for the data transmission into the main PC operating as a DAS control console, data preview and storage computer. That means any user PC with proper software could be easily connected over the existing local area network to the DAS unit, installed in the remote zone, e.g. in the plasma device hall.

Preliminary laboratory tests of detector performance together with the front-end circuit (Figs. 2, 3) and the DAS were fulfilled with the use of red and UV light-emitting diodes (Fig. 5), which provide various light absorption depths (short for UV and long for red light) relevant to actual UV to X-ray photon ranges in silicon. Satisfactory dynamic performance of the prototype device had been observed, with the 10/90 % rise/fall times within 5±2 μs range at 2.5 V bias.

The multiplexer charge-transfer switching transients were proved to be the dominant noise at the ultimate DAS sampling rates 10...40 MS/s thus requiring more precise development of the front-end circuit board and the inter-channel cross-talk suppression. More attention is to be paid also to the screening between the sub-modules and to the proper cable and multi-pin connector layout.

Further optimization of the module design to get better temporal resolution is planned after full-scale testing in the T-11 M tokamak environment. The development of improved vacuum-compatible array modules, and of a proper insertion mechanism into the T-11 M tangential diagnostic port, are underway.

4. Summary

A prototype of an ultra-fast 16 × 16 matrix array hybrid module is developed for plasma imaging applications in the XUV spectral region with the use of Si photodiodes. Together with a 32-channel synchronous 12-bit data acquisition system it provides microsecond-scale overall temporal resolution (frame rate up to 10^6 s^{-1}). Further development is needed to improve the detector noise performance at the ultimate DAS sampling rate.

Acknowledgments

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