New UV detectors for solar observations

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ABSTRACT

BOLD (Blind to the Optical Light Detectors) is an international initiative dedicated to the development of novel imaging detectors for UV solar observations. It relies on the properties of wide bandgap materials (in particular diamond and Al-Ga-nitrides). The investigation is proposed in view of the Solar Orbiter (S.O.) UV instruments, for which the expected benefits of the new sensors –primarily visible blindness and radiation hardness- will be highly valuable. Despite various advances in the technology of imaging detectors over the last decades, the present UV imagers based on silicon CCDs or microchannel plates exhibit limitations inherent to their actual material and technology. Yet, the utmost spatial resolution, fast temporal cadence, sensitivity, and photometric accuracy will be decisive for the forthcoming solar space missions. The advent of imagers based on wide-bandgap materials will permit new observations and, by simplifying their design, cheaper instruments. As for the Solar Orbiter, the aspiration for wide-bandgap material (WBGM) based UV detectors is still more sensible because the spacecraft will approach the Sun where the heat and the radiation fluxes are high. We describe the motivations, and present the program to achieve revolutionary flight cameras within the Solar Orbiter schedule as well as relevant UV measurements.

Keywords: Ultraviolet, Detector, Imager, Diamond, Nitride, AlGaN, Sun, Corona, Observation, Solar Orbiter

1. MOTIVATIONS

1.1 FINER OBSERVATIONS OF THE SUN ATMOSPHERE

Current solar atmospheric studies show that improved UV observations would be of paramount value to future advances in the field. Practically, the observational data can be obtained by emphasizing apparently independent attributes: temporal, spectral, spatial resolutions, signal-to-noise ratio, field of view, etc. Scientific investigations benefit from all of these aspects. However, the physical processes are coupling them mutually. For example, smaller phenomena such as nanoflares usually have less brightness, and evolve faster than their larger equivalents, viz. flares. Another illustration is the case of the EIT waves, which are at the same time, fast, complex and subtle. Additionally, by complying approximately with self-similarity laws, coronal objects properties validate hidden smaller scales. This all signifies that the quests for high resolution, cadence and sensitivity are fundamentally indivisible, and the goal would be to consistently maximize all of them. This demand unfortunately does not concur from the instrumental standpoint; it calls for the greatest performance from the design and operations of both the optical system and the focal plane instrumentation.

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In the imaging instrument case, let us consider a small area, $A_{\text{Sun}}$, at the Sun with an homogeneous photon radiance $L$ (ph m$^{-2}$ s$^{-1}$ sr$^{-1}$) in the direction of one particular pixel $P$ of the instrument. The focal length is implicitly adjusted to have $A_{\text{Sun}}$ match the dimensions of $P$. $\Omega_{\text{eff}}$ will denote the effective solid angle of the whole telescope as seen from $A_{\text{Sun}}$, i.e. $\Omega_{\text{eff}} = A_{\text{eff}} d^{-2}$, with $A_{\text{eff}}$ being the effective area of the instrument, and $d$ the Sun-telescope distance. The responsivity $\varepsilon$ and the telescope aperture $A_{\text{aper}}$ are embedded into $A_{\text{eff}}$. The number of photons $S$ detected in the considered pixel $P$ then is:

$$S = L A_{\text{Sun}} T_{\text{Exposure Time}} \Omega_{\text{eff}}$$

Equation 1

Due to the Poisson statistics, the SNR (signal-to-noise ratio) is always smaller than $S/\sqrt{S} = \sqrt{S}$. Hence,

$$\frac{\text{SNR}^2}{A_{\text{Sun}} \times T_{\text{Exposure Time}}} \leq \frac{A_{\text{eff}} \times P}{d^2}$$

Equation 2

Figure 1 Extrapolation of the relationship between area and duration of EUV brightenings, down to typical Solar Orbiter scales and cadences. The original graph and power law on the upper right are courtesy of Berghmans et al. 2

With fixed focal length and pixel size, solar structures will be resolved at smaller spatial scales by going closer to the Sun. However, within the homogeneous radiance assumption, the signal observed by one resolving element (pixel) will not change. The angular resolution of instruments presently flown on space missions is of the order of 1 Arcsec. For Solar Orbiter (S.O.) 3, 4, values such as 0.5 Arcsec or better are expected. One thus anticipates spatial resolving elements of 75 km at the Sun from 0.21 AU for the EUV spectrograph (EUS), and 35 km for the EUV imager (EXI). This corresponds to an area at the Sun of more than a factor 100 smaller than achieved by SUMER on SoHO or TRACE. But the typical time constants will consequently be much shorter.
By extrapolating the relationship between the areas and durations of quiet-Sun brightenings, such events would last less than 100 ms (See Figure 1), while typical exposure times of current instruments are in the 10 s range; another factor of 1000 is therefore needed to sample the time series with 10 ms intervals. Assuming the contrast will be the same, which is not guaranteed due to line-of-sight effects, the radiation collected by one pixel (at 0.5") will be comparable to TRACE. Fortunately, the radiance $L$ may happen to be locally higher than the spatially averaged radiance seen in current measurements. This would result from the improved resolution associated with the low filling factor of magnetic structures suggested by present observations. Nevertheless, it is very apparent that the effective area of the instruments has to be maximized. It is the purpose of BOLD to increase, as much as possible, the effective area of the UV instruments by using innovative imagers.

1.2 CURRENT STATE OF UV IMAGERS AND A NEW PERSPECTIVE

Due to the large temperature range of the solar atmosphere, the wavelength region of coronal observations includes -but does not confine to- the UV spectrum, from the XUV to the NUV. It is a difficult range as to the optics and sensors technologies. The performance of ultraviolet detectors has improved over the last few decades in different respects. The astrophysical instrumentation has taken advantage of the enhancements, and observations have developed accordingly. Large, sensitive silicon CCDs and microchannel plates contributed significantly to the achievements of recent solar missions, such as SOHO, Yohkoh, TRACE and others. But the properties of the focal plane are still limiting solar telescopes. Present UV imagers exhibit shortcomings that are difficult to overcome within their technology. Back-illuminated CCD detectors suffer from several drawbacks:

- The penetration depth of the photons in the silicon determines a pan-chromatic sensitivity that is deleterious when observing a bright visible source such as the Sun. One therefore adds filters in the optical path. They block the undesired visible light, but they regrettably attenuate the throughput and the image quality in the ultraviolet.

- Cooling must be implemented to reduce the dark current and to prevent degradation from ionizing radiation. This is a challenging and costly concern in space missions.

- Additionally, the cooled detector turns into a cold trap for contaminants, which stick to the sensitive surface. As a result, bake-out resources are needed to frequently drive off the volatile condensable material from the detector surface. Furthermore, organic contaminants (including hydrocarbons) have longer residence times on the cold surface. They polymerize under the UV signal, and this degrades the detector operations irreversibly.

- The ionizing radiation of the space environment leads to pollution of images with “cosmic-ray hits” (points and streaks) that are hard to disentangle from the solar signal.

- The surface and interfaces can charge under particle or UV doses. This deteriorates the charge collection efficiency (CCE), and hence the stability and spatial homogeneity of the quantum efficiency (QE)\(^7\). The resulting evolution is partially reversible by means of bake-outs. The applicability of the pre-launch calibration is thereafter compromised.

- The various kinds of degradation reported above damage the functionality of the focal plane, jeopardizing the lifetime of the whole instrument.

In the VUV range, microchannel plate intensifiers have to be used because no imaging devices presently exist that are intrinsically sensitive in this wavelength range. They still need pixel sensors for position encoding, which may be CCDs, incorporating thereby some of the previous problems, or anode arrays that sense the position of the incident photon by centroiding the electron cloud produced by the channel plate, and converting it into a pixel array. The latter avoids the drawbacks of CCDs, is inherently less sensitive to cosmic rays, and needs no cooling. But microchannel plates have major additional drawbacks.

- They need high voltage for amplification.

- Due to scrubbing, their gain reduces continuously during usage. This makes the calibration difficult to maintain. The high voltage must be increased to compensate for scrubbing.
• Their resolution is limited by the pore size to about 10 µm.

• Their count-rate capability is limited due to gain saturation.

• The image is distorted in two ways: due to alignment errors of the fibers, and due to inhomogeneity of the electric field between the channel plate and the anode.

Figure 2 Attenuation lengths (units are indicated on the graphs) as functions of wavelength (in nm) for silicon (A, light gray), diamond (A, black), and aluminum-nitride (B) \(^8\). It is interpreted that a 1 µm thick layer of diamond would be transparent outside 1-200 nm, and a 0.2 µm thick layer of AlN, transparent above 170 nm, contrarily to silicon, which remains opaque in the near UV and the blue for such thickness. All data come from the Henke \(^7\) and Palik \(^10\) handbooks.

New detector devices based on wide-bandgap materials (WBGM) -diamond or aluminum-gallium-nitrides- can overcome many of the restrictions listed above \(^11, 12, 13\). Like the CCDs in the past they will open new opportunities in the development of solar telescopes, coronagraphs, and spectrometers of higher capabilities. They will be more cost-effective than previous detectors by sparing the development and the weight of high voltage power supply, cooling hardware, radiative shields and bake-out resources. Below are several of the relevant benefits, which make them promising UV imaging sensors.

• The wide bandgap allows the sensing elements to operate at ambient or even higher temperatures.

  1. Cooling hardware is no longer needed.
  2. The contamination is reduced.
  3. Heating resources for bake-out are not needed.
  4. Materials can be selected with such large bandgaps that they are insensitive to the most intense part of the solar spectrum, which makes the detectors “solar-blind”, yet still sensitive in the ultraviolet (Figure 2). As the filters rejecting the visible spectrum also reduce the heat input to the instrument, they usually cannot be suppressed altogether, but they would not be necessary for optical reasons anymore. Any filter suppression will significantly reduce the associated loss of effective area.

• Their compact crystal networks provide better radiation hardness; the smaller atomic numbers offer a smaller cross-section to damaging radiation, and fewer artifacts due to cosmic ray hits.

• The absence of an oxide layer will improve the QE, its uniformity (viz. flatfield), and its stability.
Thanks to a greater resistance to electrical breakdown, the field strength can be higher, and the pixel can potentially be in the sub-micrometer range, an order of magnitude smaller than present, silicon-based detectors.

Due to higher carrier velocities, the detector is fast, thereby reducing read-out overheads and the need for a shutter.

The new detectors are singularly sensitive to the VUV, which avoids entirely all the drawbacks related to microchannel plate intensifiers.

2. THE BOLD PROJECT

2.1 OBJECTIVES

More than six UV imagers are anticipated onboard the payload of the Solar Orbiter in its “assessment study report”\(^\text{14}\). The format requirements are all similar and very large (4k by 4k arrays), but the wavelengths differ, ranging from 4 nm to 150 nm. In addition to the large imaging arrays baselined above, simpler UV detectors, of one or a few pixels, may also be included as total irradiance or technological monitors. They would benefit from WBGM-based technologies too. To sustain the WBGM imager option for the S.O. instruments, their feasibility must be demonstrated shortly, that is to say within 2 years. Here, feasibility primarily refers to their superiority in term of improvement of the effective area, robustness to UV doses, and rad-hardness, but also in term of capability to reach large formats and small pixels. These criteria should furthermore appear as functions of wavelength. The wide bandgap semiconductor industry will not be ready in time to envisage imaging detectors for the S.O. mission only made of WBGM. As a consequence, we baseline hybrid detectors that will implement their sensing function from nitride or diamond, and their image read-out function through a CMOS active pixel sensor (APS)\(^\text{15}\).

The limited TM/TC rates of deep space missions make autonomous data selection and autonomous feedback, from the acquired information to the operation modes, a necessity. In this respect, the APS bring additional advantages since their readout schemes can be very flexible. Finally, the above strategy leads to heavier duty-cycle of the instruments, and particularly of their detectors. The lower telemetry and the non-synoptic character of the S.O. mission justify larger robustness than usual.

2.2 PROJECT PROGRAM

Diamond and aluminum-gallium-nitride materials are currently under investigation. They have the most promising properties with respect to our goals. The plan aiming at novel flight detectors must take into account several factors; in particular:

- The final devices must optimize their set of parameters: wavelength range, pixel array size. Their superiority to alternative technologies will be demonstrated in view of the science required of each instrument.
- The final devices must be ready in time: fully adapted, tested, selected, space-qualified and calibrated well in advance of integration.

To achieve this, strategic lines have been worked out:

1. The project aims to provide large, solar-blind, UV-sensitive cameras within the schedule of the Solar Orbiter: prototype demonstrated five years before launch.
2. All Solar Orbiter UV instruments are addressed.
3. Progress will be via a set of transitional objectives. The key solutions are demonstrated separately first.
4. Comprehensive tests evaluate diamond and nitride devices of comparable architectures.
5. The methodology traces all devices through all relevant experiments.
6. The tests extend from the XUV to the visible covering the range of anticipated benefits. Appropriate facilities are available: synchrotron (XUV to VUV), lasers and lamps (VUV-visible), ionizing radiation facilities.

7. Hybrid devices combine most merits of the APS-CMOS and BOLD concepts. They will be assessed.

8. Empirical and theoretical modeling is key to controlling the expected feedback from the experiments up to the fabrication process.

Another important ingredient comes from an appropriate organization and a policy of rapid disclosure of the measurements through modern communications media (http://bold.oma.be) and publications.

![Figure 3](image)

**Figure 3** (A) Schematic view of an hybrid structure interfacing a wide bandgap semiconductor membrane with a CMOS APS sensor via indium bumps by way of the flip-chip technology. (B) Photograph of 7 µm electroplated Indium bumps on 10 µm pitch (under development, density of bumps: 10^6 cm^-2). Courtesy of IMEC, Leuven, Belgium.

Hybrid structures are being designed (**Figure 3**). The indium-bumps technology and the flip-chip integration allow interfacing of the sensitive membrane with standard CMOS circuitry.

The selected solution encompasses the required objectives of solar-blindness, better quantum efficiency, stability and uniformity of response, radiation-hardness, fast readout, random pixel access, and contamination reduction. The manufactured devices will be characterized with synchrotron beam lines, laser sources and monochromated UV lamps in several international facilities. Nitride and diamond imagers will be systematically inter-compared, and will be evaluated against competing technologies so as to drive the development process and the final selection of flight hardware. The main focus will be on assessing the detector radiation-hardness, UV efficiency, solar-blindness, and ageing robustness, in addition to testing their fundamental functions.

### 2.3 PAST AND FUTURE MEASUREMENT CAMPAIGNS

Several measurement campaigns^5,16^ have already provided results that this section briefly reports. The measurements are arranged as functions of the wavelength ranges (XUV, EUV-VUV, NUV-VIS), and the material (nitride or diamond). The extreme UV evaluations occurred on synchrotron beamlines of the Super-ACO in Orsay, France. A new campaign is foreseen in BESSY, Berlin, Germany at the end of 2002. Two promising results are presented in **Figure 4A** (diamond in the XUV), and **Figure 4B** (GaN in the VUV). The NUV-VIS measurements (visible-blindness, speed) will be done on lamps at the LGEP, Gif/Yvette, France, and on lasers at the LPL, Villelanneuse, France. Achieved rejection rates exceed five orders of magnitude within BOLD (**Figure 5**), but we anticipate still higher rates in the future due to thinning techniques and improvement of the crystal quality of the most recent films.
Figure 4 (A) Quantum Efficiency (QE) of a diamond photoconductor manufactured by CEA-LIST Saclay, and tested at Super-ACO, Orsay, France in the XUV range. The change of sensitivity at the carbon edge is apparent. The two curves correspond to inverted biases. (B) QE of a GaN diode manufactured by CRHEA, Valbonne, France and UPM, Madrid, Spain, and tested at Super-ACO in the EUV and VUV ranges. The two curves correspond to different references (AsGa et Al₂O₃).

Figure 5 (A): Measurement of the number of electrons created per incident photon for a diamond photoconductive detector. The wavelength range 120-1000 nm covers the diamond bandgap energy, the near-UV and the visible. The visible-blindness is 7 orders of magnitude at 200 nm, and higher than 4 orders around 120 nm. From Pace et al. (B) Spectral responses of a natural Iia type diamond with a polycrystalline CVD sample grown by CEA-LIST Saclay. Courtesy of J. Alvarez, LGEP.

3. CONCLUSION

The support from ESA will permit to bring to reality the concepts that have emerged after several years of effort, and to take advantage of the remarkable breadth of expertise gathered in BOLD. We expect in the near future, innovative detectors that will give a new leap to UV imaging. It will benefit to the astrophysical observations, but to many other applications as well. We think for example of Earth global change monitoring from space (ozone hole), of aurora borealis studies, of lithographic process going into the EUV (13.5 nm) to limit diffraction, of flame detection, of plasma research, and of diagnostics for the scientific facilities such as UV and X-ray lasers, synchrotron beamlines, etc.
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