New UV Detector Concepts

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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 semiconductor materials (in particular diamond and Al-GaNitrides). This investigation is proposed in view of the Solar Orbiter UV instruments, for which the expected benefits of the new sensors, visible blindness and radiation hardness, will be highly valuable. Despite various advances in the technology of imaging detectors over the last few decades, the present UV imagers based on silicon CCDs or microchannel plates exhibit limitations which are inherent to their actual material and technology. Yet the utmost spatial resolution, fast temporal cadence, sensitivity, and photometric accuracy will all be decisive for forthcoming solar space missions. The advent of imagers made of large wide-bandgap semiconductors would surmount many present weaknesses. This would open up new scientific prospects and, by simplifying their design, would even make the instruments cheaper. As for the Solar Orbiter, the aspiration for wide-bandgap semiconductor-based UV detectors is still more desirable because the spacecraft will approach the Sun where heat and radiation fluxes are high. We describe the motivations leading to such new developments, and present a programme to achieve revolutionary flight cameras within the Solar Orbiter schedule.

28.1 Motivations

Current solar atmospheric studies show that the need for improved UV observations is paramount.

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, they are coupled by the physical processes to be observed. For example, smaller phenomena usually have less brightness, and evolve faster. This implies that the quests for high resolution, cadence and sensitivity are fundamentally indivisible, and the goal would be to maximize all of them consistently. These features unfortunately conflict from the instrumental perspective, putting constraints on the design and operation of the optical system and the focal plane instrumentation.
In the imaging instrument case, let us consider a small area, $A_{\text{Sun}}$, at the Sun with a homogeneous photon radiance $L (\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1})$ in the direction of one particular pixel $P$ of the instrument. The focal length is implicitly adjusted to have $A_{\text{Sun}}$ match this pixel. $\Omega_{\text{eff}}$ 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, $\epsilon$, 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:

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

(28.1)

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

$$\frac{SNR^2}{A_{\text{Sun}} T_{\text{ExposureTime}}} \leq \frac{LA_{\text{eff}}}{d^2}$$

(28.2)

Equation (28.2) relates the concrete values of an observation, on the left-hand side, to other conditions, on the right-hand side. This formulation stresses the mutual limitations of the spatial resolution, temporal cadence, and $SNR$. The left-hand side can be seen as a specification for a future instrument. It is restricted by external premises controlled by the Sun ($L$), the hardware design ($A_{\text{eff}}$), or the mission orbit ($d$). Under these circumstances, the operation of a given instrument may also carry out trade-offs between the cadence, limited by $T_{\text{ExposureTime}}$, the spatial resolution, which is adjustable by binning, and the signal-to-noise ratio, which ought to be kept at a significant level.

With fixed focal length and pixel size, solar structures will be resolved at much smaller spatial scales by going closer to the Sun. However, 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’. For Solar Orbiter [Marsch et al., 2000; Fleck et al., 2000] elements of 0.5’ or better are expected. Thus one 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 or TRACE. But the typical time constants then are much shorter, because structures evolve faster at these scales. By extrapolating the relationship between the areas and durations of quiet-Sun brightenings [Berghmans et al., 1998], such events should last less than 100 ms, whereas typical exposure times of current instruments are in the 10 s range; another factor of 1000 would be needed to sample the intensity curves 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, which would result from the improved resolution associated with the low filling factor of magnetic structures suggested by present observations. But 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 [Hocheder et al., 2000, 2001a, b, 2002; Monroy et al., 2002; Pau et al., 2002].

Due to the large temperature range of the solar atmosphere, the wavelength region of coronal observations includes the UV spectrum, from the XUV to the NUV. It is technologically a difficult range as far as the optics and sensors are concerned. The performance
Figure 28.1: A Comparison of QE between Silicon and Diamond detectors estimated by a simple dead-layer model. The plain curves correspond to diamond; the dotted curves to silicon. The thick lines show the modeled QE with no dead layer. In all instances, the depletion layer is 10 \( \mu \text{m} \) thick.

of ultraviolet detectors has improved over the last few decades in different respects, and astrophysical instrumentation has taken advantage of that, and developed accordingly. Large, sensitive silicon CCDs and microchannel plates contributed significantly to the achievements of recent solar missions, such as SOHO [e.g., Thompson, 1999], Yohkoh, TRACE and others. But the properties of the focal plane units are still the limiting factors in the performance of modern telescopes. Present UV imagers exhibit shortcomings which are difficult to overcome within their technology. CCD-based 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 (Figure 28.1). One, therefore, adds filters in the optical design which block the undesired visible light, but, which then, regrettably, attenuate the throughput 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. Organic contaminants (including hydrocarbons), furthermore, have longer residence times on the cold surface, and they polymerize under the UV signal, which 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) [Defise et al., 1997]. The applicability of the pre-launch calibration is thereafter compromised. Moreover, the ensuing degradations reduce the sensitivity of the focal plane, i.e., they jeopardize the lifetime of the 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 fibres, and due to inhomogeneity of the electric field between the channel plate and the anode.

New detector devices based on wide-bandgap semiconductors (diamond or aluminium-gallium-nitrides) can overcome many of the restrictions listed above [Goldberg, 1999; Mainwood, 2000]. 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 cooling hardware, radiative shields and bake-out resources. Below, several of the relevant benefits which make them promising UV imaging sensors.

- The wide bandgap allows the detector 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. (See Figure 28.2.) 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. Nevertheless, whether one is kept or not, the associated loss of effective area will be significantly reduced.

- The compact crystal network of, for example, diamond, provides better radiation-hardness; the smaller atomic numbers offer a smaller cross-section to damaging radiation, and less artefacts due to cosmic-rays.

- The absence of an oxide layer will improve the QE, its uniformity (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.

- In particular, the new detectors are directly sensitive to the VUV, which avoids entirely all the drawbacks related to microchannel plate intensifiers.

**28.2 The BOLD Project**

**28.2.1 Specifications**

More than six UV imagers are anticipated in the Solar Orbiter assessment study report. The format requirements are similar (arrays from 2k by 2k, to 4k by 4k pixels), but the
wavelengths differ, ranging from 4 nm to 150 nm. The limited telemetry rate of deep space missions makes partial read-out (windowing) and random pixel access necessary to reduce the readout overheads. Read-out on the chip, developed for active pixel sensors (APS-CMOS technology), is also compatible with the current concepts for BOLD sensors, and will be demonstrated during the feasibility phase. In addition to the large imaging arrays baselined above, simpler UV detectors, of one or a few pixels, will also be included as total irradiance or technological monitors. They would benefit from wide-bandgap semiconductor-based technologies too.

28.2.2 Programme

Diamond and aluminium-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).

7. Hybrid devices, which may combine the merits of the APS-CMOS and BOLD concepts, are foreseen.

8. Empirical and theoretical modelling are key components to control the expected feedback from the experiments to the fabrication process.

Another important ingredient to success comes from an appropriate organization and a policy of rapid disclosure of the measurements through modern communications media (http://bold.oma.be) and publications.
Hybrid structures have been designed (Figure 28.3). The indium-bumps technology and the flip-chip integration allow interfacing of the sensitive membrane with standard CMOS circuitry. Special read-out electronics can be included for example for random access to subarrays, which takes full advantage of the APS concepts and preserves most BOLD features. Amorphous membranes could also be appropriate for such hybridization. All selected solutions encompass the required objectives of solar-blindness, better quantum efficiency, stability and uniformity of response, radiation-hardness, fast read-out, random pixel access and contamination reduction. The manufactured devices will be radiometrically characterized with synchrotron beam lines, laser sources and monochromated UV lamps in several European facilities. Nitride and diamond imagers will be systematically intercompared and will be judged 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 detectors’ radiation-hardness, UV efficiency, solar-blindness and ageing robustness, in addition to testing their fundamental functions.

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