Diamond UV Detectors for Future Solar Physics Missions


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ABSTRACT

Despite their steady improvement over the last decades, the present UV detectors exhibit some limitations inherent to their silicon technology. Yet, the utmost spatial resolution, temporal cadence, sensitivity, and photometric accuracy will be decisive for the forthcoming space solar missions. The advent of novel diamond or nitride imagers would surmount many current weaknesses, thus opening up new prospects and making the instruments cheaper. As for projects like the Solar Probe of NASA, or the Solar Orbiter of ESA, the aspiration for diamond UV detectors is still more sensible for these spacecrafts will approach very near to the Sun where the heat and the radiation fluxes are tremendously high. This triggered the initiative of an original R&T programme entitled BOLD described in this paper. We depict motivations and intentions, and report on dedicated experiments with several devices under EUV synchrotron light, NUV laser, and micro-Raman spectroscopy.

Keywords: Detectors, Diamond, Nitrides, UV range

1. INTRODUCTION

The performance of XUV/EUV/VUV/NUV detectors has steadily increased over the last decades in every respect, and the astrophysical instruments taking advantage of them have improved accordingly. The focal plane properties are often the bottleneck in the modern telescopes. Such large sensitive linear sensors participate significantly to the achievements of the recent solar missions like SOHO, YOHKOH, TRACE, and others (e.g. [1]).

Nevertheless, CCDs designed for UV observations exhibit some shortcomings that are difficult to overcome within silicon technology:

1. Cooling must be implemented to reduce the dark current and to prevent degradations from ionizing radiations, but it is a thorny and costly solution in space missions.
2. Additionally, the cooled detector turns unfortunately into a cold trap for contaminants. Unavoidable hydrocarbon molecules not only stick to the sensitive surface but also polymerize under the UV signal degrading the detector operations irreversibly.
3. The isotropic ionizing radiations leads to images that are instantly covered by “cosmic hits” (bright points and streaks), which are hard to disentangle from the UV signal. Moreover, the ensuing degradation of the charge transfer jeopardizes the lifetime of the whole mission itself [2].
4. The evolving oxide deteriorates the Quantum Efficiency (QE), its stability, and its spatial homogeneity, resulting in poor pre-launch calibration reliability.
5. The minimal size of the silicon UV pixel is limited to circa 10 µm.
6. The penetration depth of the photons in the silicon determines a pan-chromatic sensitivity that is deleterious when observing a bright visible source like the Sun (See Figure 1). One therefore adds filters that absorb the undesired optical photons, but also attenuate regrettably the hunted ultraviolet ones.

These drawbacks become critical in the context of the future solar missions for which the highest spatial resolution, sensitivity, temporal cadence and photometric accuracy are sought after. The Sun is the only star that can potentially be observed with the spatial resolution of the fundamental physical magnetic processes at work. It is broadly agreed nowadays that we lack spatial resolution to fully comprehend its corona and hence, stellar objects in general (See Figure 2).

The building blocks of the solar atmosphere are the magnetic loops, but not all is ascertained about them. Their equilibrium is questioned. Their exact configuration is unclear. Their filling factor is low. Filamentary and threaded patterns are observed, etc. All these facts point at unrevealed unravelled sub-pixel structures. Not to mention that there are lots of various dynamical events (nano-flares, brightenings, explosive events, blinkers, etc...). Their properties approximately comply with self-similarity laws, validating hidden smaller scales. In order to fulfill this indubitable observational need, one has to somehow square the circle given the fact that the smaller the pixel, the lesser the signal and the more dynamical the target. Furthermore, the higher the cadence, the lesser is the signal too. This review of the stakes means that the quests for resolution, cadence and sensitivity are definitely inseparable. A markedly superior spatial resolution can be achieved either by going close to the Sun with a "standard" instrument, or by increasing considerably the aperture and the focal length of a telescope in an Earth orbit. In the first category (Solar Probe [3] and Solar Orbiter [4] missions), the whole package including the detector is submitted to a high radiative and particle flux. In the second case, the gain of spatial resolution happens inevitably at the expense of the signal level, especially if the temporal resolution is to be matched with the smallest expected observables. For instance, a resolution of tens of kilometres on the Sun (better than 0.1 arcsec) implies exposure times smaller than one second since expected velocities may be of a few 100 km/s (magneto-acoustic) and higher (Alfven).
2. THE BOLD INVESTIGATION

Diamond or nitride imagers would circumvent many of the restrictions listed above. They would open—just like the CCD in the past—new opportunities in the development of solar telescopes and spectrometers of higher capabilities. They will be more cost-effective as well by sparing the development and the weight of cooling hardware, radiative shields and bake-out resources.

- The wide bandgap permits to operate the detector at room temperature, with no need for cooling and with a reduced pollution risk. Such bandgaps also make the detectors “solar-blind” (i.e. insensitive to optical light, See Figure 1). As the filters have a thermal role, and anticipating incomplete solar-blindness, they cannot be suppressed; but their amount can be reduced, thus improving greatly the effective area of UV instruments (and allowing shorter integration times, improved Signal / Noise ratios, etc.).
- The compact crystal networks provide radiation-hardness.
- The absence of an oxide will improve the QE and its stability.
- Thanks to a larger breakdown field, the pixel is potentially in the sub-micrometer range, an order of magnitude smaller than present silicon detectors.
- Due to higher carrier velocities, the detector will be read out faster.

CVD diamond was identified as an outstanding material for UV detection years ago (See [6] and historical references in [7, 8]). In the past the material quality prevented the development of detectors rivaling those already existing. Recently, GaN nitride has become a promising competitor for UV photodetection [9]. Even now, the strategy toward useful devices has to be carefully evaluated. To this end, the BOLD investigation (Blind to the Optical Light Detectors) was instigated in 1999 via the coordinated expertises of most required disciplines (material growth, device design, characterizations, application definition). As seen from the list of authors many institutes, in different fields, contribute to BOLD (and the list is not closed). The project includes also the Centre Lasers Intenses et Applications (CEILIA), Bordeaux, France, the Instituut voor Materiaal Onderzoek (IMO), Diepenbeek, Belgium, the Laboratoire de Physique des Milieux Ionisés (LPMI), Palaiseau, France, the Laboratoire de Physique des Solides et de Cristallogénèse (LPSC), Meudon, France, the Laboratory of Solid State Physics and Magnetism (LVSM), KU Leuven, Belgium, and the University College London (UCL), Great Britain. Several places not only have the appropriate equipment, but also a need for the intended device [10, 11, 12, 13, 14, 15]. Other teams are advancing in similar directions (e.g. [16, 17]). Our strategic line focuses on the following selected approaches:

1. So as to avoid the detrimental grain boundaries, solutions are considered in two directions:
   A/ the superior properties of the intra-crystallite characteristics are being verified, and geometrically adaptable designs are sought after. B/ structures are fabricated and tested on homoepitaxial layers.
2. The same equipments compare diamond and nitride devices of various architectures.
3. The methodology traces all devices through the largest available set of relevant experiments.
4. In particular, the UV tests extend from the XUV range to the visible covering the scope of penetration depths.
5. Transitional objectives are conceived, as it is unlikely to attain straight away a solar-blind 2000 x 2000 UV imager with sub-micrometer pixel and 100% QE in the EUV range. Nonetheless, experiments aim at demonstrating its feasibility within the time slot compatible with the previously cited solar missions (a decade). In parallel, we identify immediate and short-term applications.
6. Empirical and theoretical modelling is seen as a key condition to control the expected improvements and feedbacks from the experiment to the fabrication process.

The remaining of this paper is organized as follows: the BOLD investigation is first introduced, the experimental section then describes briefly the devices under study, preliminary measurements, and interpretations. The conclusion presents the outlook for the various aspects of the current endeavour.

Figure 1 Compared QE between Silicon and Diamond detectors estimated by a simple “dead layer” model [5]. The plain curves correspond to diamond, the dotted curves to silicon. The thick ones show the modeled QE with no dead layer. In all instances, the depletion depth is 10 µm.

Figure 2 A strong enhancement of spatial resolution is essential to explore the dynamical structures of the chromosphere, transition region and corona. The left image is a full field image of the Sun made by EIT/SoHO in the Fe XV line (284 Å). Instrumental artefacts like the grid pattern of the mesh supporting filters and the QE degradation at the limb are visible. The central image was made on the same day by TRACE in the Fe IX/X line (171 Å). Many cosmic hits are noticeable.
3. EXPERIMENTS

Four measurement campaigns were already accomplished; they are accounted here briefly. In Nov.1999, photoemission and photocurrent measurements were done with synchrotron light around the Carbon C_6 edge on LETI devices to address surface effects. During Feb.2000, micro-Raman spectroscopy was performed on one of the synchrotron-tested layer to confirm the absence of sp³ bonds, and assess sub-grain variations of the crystal characteristics. More diamond samples could later be gathered originating from the GPI and the LEPES (homoepitaxial layer), and nitride devices from UPM/CRHEA. Standard LETI inter-digitated electrodes were deposited on the GPI layers, whereas the LEPES and the UPM/CRHEA devices are Schottky photodiodes. The mobility-lifetime product of the LETI and GPI devices was measured in continuous mode at LGEP. Finally preliminary laser tests were carried out at LPL in July 2000. The NUV and UUV lasers serve to produce micro-spots probing the detector efficiency at small scales.

3.1. SAMPLE SELECTION

3.1.1. POLYCRYSTALLINE DIAMOND DEVICES FROM LETI

The plasma enhanced chemical vapour deposition technique (PECVD) enables the fabrication of large area diamond layers. The material obtained has a polycrystalline structure with a grain size of about 10% of the layer thickness. The growth conditions (0.5% methane in hydrogen, and 750°C substrate temperature) had previously been optimised in order to yield the best electronic properties [18].

Typical growth rates are of the order of 0.2-0.5 μm/hr for these films. Prior to the formation of electrical contacts, the diamond samples were annealed and chemically treated. This constitutes a critical step in the device fabrication resulting in a reduction of the device leakage current (by up to 7 orders of magnitude compared to untreated samples) down to values below 1 pA at 50 kV/cm [19].

Gold pads were deposited to form electrodes, using an e-beam evaporator. Contact geometries were obtained using the standard photolithographic techniques. At the typical operating voltages of 10⁵ V cm⁻¹, the barrier height that results from the use of gold on diamond is negligible with respect to the bias.

3.1.2. LEPES

Undoped and heavily boron doped homoepitaxial diamond films were deposited on Ib diamond substrates at 830°C by MPCVD of a mixture of (B₂H₆)/CH₄/96% H₂. Heavy doping allows the achievement of very low resistance contacts. Studies are under progress to achieve multilayer structures comprising Schottky barrier metal/undoped diamond/heavily doped diamond/Ib substrate, with low residual boron content in the "undoped" film, and good Schottky barrier behaviour.

3.1.3. POLYCRYSTALLINE DIAMOND DEVICES FROM GPI

GPI diamond films were grown in a microwave plasma assisted CVD reactor (5 kW, 2.45 GHz) using 1-2% CH₃C≡CH₄/94% H₂. Heavy doping allows the achievement of very low resistance contacts. Studies are under progress to achieve multilayer structures comprising Schottky barrier metal/undoped diamond/heavily doped diamond/Ib substrate, with low residual boron content in the "undoped" film, and good Schottky barrier behaviour.

3.1.4. GaN & AlGaN DEVICES FROM DIE/UPM AND CRHEA

Si-doped AlGaN samples were grown on c-sapphire by metal-organic vapor phase epitaxy (MOVPE) in CRHEA (devices X262 and X300), and on Si(111) by molecular beam epitaxy (MBE) in DIE/UPM (device M395). Mirror-like surface morphologies were typically obtained for all AlGaN layers. MOVPE GaN samples present a typical full width at half maximum (FWHM) of 300 arc sec for the (0002) X-ray diffraction peak in the configuration, which increases up to 800 arc sec for material with a 35% of Al. Room temperature Hall mobilities range from 140 cm²/Vs in GaN to 50 cm²/Vs in Al₀.₃Ga₀.₇N layers. Surface roughness was evaluated by atomic force microscopy (AFM) obtaining typical rms values of 0.5 nm in GaN, increasing up to 1.5 nm for Al₀.₃Ga₀.₇N. Growth and characterization details were published elsewhere [21]. Si-doped GaN samples grown on Si(111) by MBE present a FWHM of 8 arc min for the (0002) X-ray diffraction peak, increasing up to 15 arc min for an Al content of 35%. A surface roughness of around 4 nm rms was determined by AFM, without any significant dependence with the Al content. Growth details are given elsewhere [22]. The nitride photodetectors received from the DIE/UPM are planar AlGaN Schottky barrier photo-detectors [23, 24]. The schematic structure of the devices is shown in Figure 4. Ohmic contacts consist in a Ti/Au (300 Å / 700 Å) bilayer, and Schottky contacts consist in semitransparent 100 Å disks with a Ni/Au (300 Å / 1000 Å) pad. All the photodetectors present an active area of 200 to 400 μm.

Figure 3 Scheme of the simple MSM configurations tested. The results presented in this paper mostly relate to the coplanar structures (d).

The membranes actually used are 20 or 200 μm thick, making the grain size of the order of a few microns. The electrodes are deposited on the topside. The electrode width and inter-electrode gap are 200 μm.

3.1.2. LEPES

Undoped and heavily boron doped homoepitaxial diamond films were deposited on Ib diamond substrates at 830°C by MPCVD of a mixture of (B₂H₆)/CH₄/94% H₂. Heavy doping allows the achievement of very low resistance contacts. Studies are under progress to achieve multilayer structures comprising Schottky barrier metal/undoped diamond/heavily doped diamond/Ib substrate, with low residual boron content in the "undoped" film, and good Schottky barrier behaviour.

Figure 4 a/ Schematic structure of AlGaN Schottky photodiodes, and b/ normalized spectral response of the devices measured with a Xe arc lamp.
Details of the devices under study are summarized below:

- M395: Al$_x$Ga$_{1-x}$N:Si (250 nm) over Al$_x$Ga$_{1-x}$N (150 nm) on an AlN buffer and a Si (111) substrate ($X \approx 0.08$)
- X262: Al$_x$Ga$_{1-x}$N:Si (1.8 µm) on a GaN buffer, and a sapphire substrate ($X \approx 0.35$)
- X300: GaN:Si (1.7 µm) on a GaN buffer, and a sapphire substrate

AlGaN produces UV detectors with a cut-off between 295 nm and the plain GaN cut-off at 360 nm, as shown in Figure 4b.

3.2. SYNCHROTRON TESTS AT THE CARBON EDGE

LETI MSM devices have been illuminated with monochromated synchrotron light around the Carbon C$_K$ edge (289 eV ≈ 43 Å) where the penetration depth of the photons spans from 100 nm to 1 µm. A channeltron collected the photoelectrons produced by the impinging XUV photons. The partial (PY) or total (TY) electron yield mode separated bulk from surface properties [25]. A bias potential was applied between the interdigitated electrodes. A floating picometer measured the current flowing through the electrodes as a function of the bias potential, impinging photon flux or energy. By varying the sample preparation (e.g. cleaning) and the electrodes geometry, some insight has been gained into the physics of the signal collection. Results were obtained on the surface vs. bulk properties as a function of post-processing treatments, and on the efficiency of inter-digitated devices. The detail of this campaign is given elsewhere [26]. Another similar XUV synchrotron campaign is accepted this year to test new devices, and gain more insights.

1. To the extent of the experiment sensitivity, the volume (500-1000 Å) was shown to be devoid of non-diamond bonds.
2. QE curves could not be obtained with sandwich geometries (b) or (c) of Figure 3; the electron emission subsequent to photon interaction on the diamond surface gives rise to the creation of a charged layer that screens the electric field in the device volume.
3. From current measurements and wavelength calibration curves (using a GaAs photodiode), the quantum efficiency of the diamond detectors could be estimated:

![Figure 5](image)

**Figure 5** QE as a function of photon energy for an inter-digitated device. 50 Volts were applied between the electrodes. The two curves correspond to opposite polarities. The QE is defined as being the number of sensed photon per incident photon at any given photon energy. The absolute value of the QE is 3-5 times smaller than in the simple model of Figure 1. This can be explained by a loss of signal under the electrodes, photoemission and trapping. An improved modelling is under investigation, but in any case with ~20% QE, these diamond devices prove already useful in the 150-600 eV range.

3.3. MICRO-RAMAN SPECTROSCOPY

Raman spectroscopy is a well-established method for characterizing CVD diamond films. Confocal micro-Raman imaging using a microscope and a motorized X-Y stage allows the study of both interfaces as well as intermediate planes inside the film. Because of its high spatial resolution (~1 µm), the potential presence of sp$^2$ bonded carbon or localized mechanical stress may be examined specially at the grain boundaries. We aimed at confirming the absence of graphite as observed on the same LETI sample in the synchrotron experiments reported above. We have been also training to learn how to correlate with electrical and UV properties in the future. The area was scanned with a LABRAM/Jobin-Yvon instrument over 50x35 µm with 2 µm steps, and a 633 nm (1.96 eV) laser excitation. Inspection of the recorded spectra did not reveal any presence of graphitic carbon. It was observed that the baseline of individual spectra contains frequently small lines at different wavenumbers changing from one point to another which origin is unclear at the moment. Raman images of the FWHM distributions demonstrate the quality improvement of the film with growth [27]. The overall FWHM diminishes when going from the substrate interface to the growth surface from 3.4 cm$^{-1}$ to 2.7 cm$^{-1}$. At both interfaces, the individual spectra exhibit particularly large lines but splitting is not observed.

![Figure 6](image)

**Figure 6** A/ Video image of the scanned area as seen from the film-air interface. One large crystal surrounded by others of various sizes is clearly visible. B/ An image of the FWHM map in the diamond line obtained by a curve fitting of the recorded Raman spectra at a plane inside the sample provides a rapid inspection. The very high quality of the diamond film is ascertained by the low median FWHM (2-3.5 cm$^{-1}$). Important deviations are reported in three dark spots. C&D/ Individual spectra from the dark zones of (B). In (C) the diamond line is exceptionally wide, whereas in (D) the line splits into two components. This very localized behaviour has already been observed [28]. It is attributed to the effect of high shear stresses that enlarge the line abnormally and finally raise the triple degeneracy into two or even three components.
3.4. MOBILITY - LIFETIME PRODUCT

Electrical measurements have been carried out at LGEP on the GPI and LETI samples. The flux was $4 \times 10^{12}$ photons/cm$^2$s$^{-1}$ under steady-state illumination conditions at 190 nm. The photocurrent data were recorded in the ohmic region of the current - voltage characteristics. Owing to the large thickness of the samples, it is assumed that all photons are absorbed in the diamond film. Thus, from the photocurrent $I_D$ one can deduce the mobility-lifetime product $\mu t$ (representative of the majority carrier transport) as $\mu t = \frac{I_D q h x F}{q}$, $q$ being the electron charge, $h$ the electrode length, $x$ the applied electric field and $F$ the photon flux. The results are reported below. We observe that the photosensitivity significantly increases with the sample thickness.

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Configuration</th>
<th>$\mu t$ (cm$^2$/V-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPI #118</td>
<td>150 µm, 5x5 mm$^2$, polished both sides, 30 µm removed from nucleation side.</td>
<td>9.6 $\times 10^7$</td>
</tr>
<tr>
<td>GPI #117b</td>
<td>650 µm, 7x7 mm$^2$, polished both sides, 20 µm removed from nucleation side.</td>
<td>1.22 $\times 10^7$</td>
</tr>
<tr>
<td>GPI #81-1C</td>
<td>~80 µm, 5x5 mm$^2$, oxidized in chromium acid. Non-polished, cleaned surface.</td>
<td>5.9 $\times 10^8$</td>
</tr>
<tr>
<td>GPI #81-1R</td>
<td>~80 µm, 5x5 mm$^2$, oxidized in chromium acid. Non-polished surface.</td>
<td>5.74 $\times 10^9$</td>
</tr>
</tbody>
</table>

3.5. UV LASER

We report here on preliminary tests made with the UV lasers of the LPL facility in July 2000. GPI diamond photoconductors and UPM nitride diodes were submitted to UV pulses (a few ns, 12 Hz) from an ArF laser at 193 nm. The spot size was 20 µm at the focal point. These experiments will give essentially access to 2 types of results : evaluation of the dynamical $\mu t$ product at the same wavelength as in §3.4, and small scales sensitivity maps. However the quantitative interpretation is not yet done; raw measurements are presented. An XYZ picomotor stage is operational, but non-linearities currently prevent the production of homogeneity maps.

Figure 7 The left column corresponds to a nitride Schottky diode, the right column to an MSM diamond device. Responses are fast in both cases.

From the data, the diamond MSM is 3 to 5 times faster than the nitride Schottky. Conversely, the nitrides can lead to a signal 10 times larger under the same flux conditions. However, the GaN/AlGaN devices being Schottky barriers, they have a larger capacitance and thus a slower time response and higher responsivity, so differences are related to the different structure of the devices. Research on nitride metal-semiconductor-metal structures is currently been developed in the consortium with promising results [30]. Comparing the nitrides mutually to M395#5 gives 1 a.u. (arbitrary unit) for M395#5 ($\Omega = 400$ µm), 7.2 a.u. for X262#9 ($\Omega = 400$ µm) and 5.4 a.u. for X300#2 ($\Omega = 200$ µm) which sorts their performances like at higher wavelength. The lower response in M395 is due to the lower structural quality of AlGaN material grown on Si(111), as already reported [24].

4. CONCLUSION

Although preliminary, the reported results look promising. More work needs to be done, and this will happen in the following directions: the same samples will be characterized in the EUV using the IAS synchrotron beamline facility, and by AFM techniques at the LVSM/KUL laboratory. A new lot of optimised devices will also undergo a full range of characterizations, including the ones described in this paper. In parallel, electrical tests and modelling will be achieved in an attempt to correlate all spatially resolved properties. At present, whether diamond or nitride is superior is undecided, but by taking advantage of the gained insights, we expect to progress toward the advent of the predicted sensors. Updated information will be found at http://hbold.oma.be.

5. ACKNOWLEDGMENTS

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