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Innovative diamond photo-detectors for UV astrophysics

E. Pace and A. De Sio

Dip. di Astronomia e Scienza dello Spazio, Università di Firenze, Largo E. Fermi 2, I-50125 Firenze, Italy, e-mail: pace@arcetri.astro.it

Abstract. Breakthroughs in UV astronomy are strongly dependent on technology improvements. In particular next generation UV space telescopes will require large optics, enhanced effective area, highly efficient UV detectors. Many efforts are currently addressing such issues, mainly focussed on detector technology and lightweight deployable mirrors. This paper will report on diamond-based UV photo-conductors that presently would provide a new opportunity for UV space telescopes in the very next future, because of its high sensitivity, low dark current, visible blindness, high radiation hardness and chemical inertness. This means that next generation focal plane arrays for UV observations would have highly enhanced signal to noise ratio not requiring cooling systems, filters or shielding. This makes diamond detectors suitable for space applications, being compact, lightweight and requiring very low power consumption ($10 \div 30$ V over tens of nanoamps).

Key words. UV astronomy – UV technology: detectors – Diamond photo-detectors – Space UV instrumentation

1. Introduction

The ultraviolet spectral region is of particular interest for astrophysics. It is a rich interval of emission and absorption lines due to species and states of ionization of atoms and molecules that provide diagnostics for a wide range of astrophysical plasma environments. Ultraviolet astronomy is a relatively new observational area because atmospheric absorption forces observations from space. This has caused major technological problems for instrumentation development. But presently, we are living an exciting transition time for UV astrophysics. Many planned missions have been launched, alas most are even finished, but new missions are still under definition. These are mainly solar missions, but also missions towards galactic and extragalactic regions, like the World Space Observatory (WSO/UV)(Pagano et al. 2007; Pace et al. 2009). This situation will allow some years for the developing of new technologies. The urgent demand for new technologies, which will push current observation limits, has induced the main space agencies (ESA and NASA) to form European and American research groups aimed at conceiving innovative optical and spectroscopic instruments and in particular to develop new generation detectors. The detector is the essential element of every astronomical experiment since it plays a critical role in determining the overall performance even if it represents only a small fraction of the instrument total cost. Therefore, de-

Send offprint requests to: E. Pace

tectors have been and are still very important for a notable technological investment.

2. Diamond detectors

Despite their steady improvement over the last decades, the UV imaging detectors currently available exhibit some limitations, inherent to silicon technology or to electron multiplication, that can represent serious constraints in the context of space missions where reliability, durability, low cost, sensitivity, radiation hardness and solar blindness are required. In order to produce an innovative solid-state detector that copes with this demand, the proper material must be selected among those having wide energy band-gap, because of their negligible absorption of visible photons and intrinsically very low dark currents. Currently, nitrides (GaN, AlGaN, InGaN), SiC and synthetic diamond are actively under investigation for these applications.

Diamond has a unique combination of superior physical properties, relative to current materials, which makes it the ideal candidate for detectors replacing silicon in UV applications (Pace et al. 2003). The synthesis of very high quality polycrystalline thick diamond substrates and single crystals is presently accomplished routinely using the Chemical Vapour Deposition (CVD) technique (Marinelli et al. 1999, 2006). Metal/diamond/metal ohmic junctions are produced by depositing electric contacts on the front surface (coplanar contacts) or on front and back (sandwich contacts) (Di Benedetto et al. 2001). The investigation of diamond properties in the wavelength range 100-300 nm is of considerable interest (Pace et al. 2006) in order to attain UV detectors having high quantum efficiency and reduced or no sensitivity to visible photons ("solar-blind"), along with radiation hardness and chemical inertness (De Sio et al. 2005, 2007). Improvements in the diamond synthesis techniques and processing technology now make available very high-quality polycrystalline diamond films as well as optical-grade single crystals with dimensions sufficiently large for developing detectors. Several problems limiting the performance have found solutions and single-pixel detectors are close to being suitable for exploitation.

A 'new frontier' in the field of UV detectors is the attempt to achieve 2-D pixel arrays on diamond. Applications in UV astronomy should benefit from the availability of such imagers. However, this research is presently at the forefront of the diamond device technology and the non-uniformity of diamond polycrystalline layers represents one of the main limitations to a full development. Single crystals may be the solution, but their size (max. 1 cm of diameter) prevents today the development of large formats.

The electrical and optical properties of diamond results from its wide energy band-gap, i.e., $E_g = 5.470 \pm 0.005$ eV at 295 K. Electrically, diamond is an insulator, but it behaves like a semiconductor by introducing donor or acceptor atoms. Therefore, intrinsic diamond devices possess negligible thermal current and no cooling is required; the dark current is typically ¡ 1 pA/cm^2. Optically, pure diamond exhibits no photon absorption or luminescence in the visible spectral range, at $\lambda > 225$ nm. This property is very important for UV visible-blind photo-detectors: visible rejection factors of 10^7 are routinely achieved. On the other hand, photons with $\lambda < 225$ nm are absorbed when they impinge on diamond. This excites valence band electrons into the conduction band and, therefore, diamond exhibits photo-induced electrical conductivity. Absorbance and reflectance are other important optical properties that contribute to the performance of detectors (Binari et al. 1993; Collins et al. 1997; Fong et al. 1995).

Typically, diamond-based photon detector are photo-conductors and their structure is in the form of two-terminal metal-insulator-metal device (see Fig.1). The insulator is intrinsic diamond. The metal contacts can be ohmic (titanium, chromium, graphite) or rectifying (aluminum, gold). UV photons are typically absorbed in a very thin layer (a few tens of nanometers) below the illuminated surface; so coplanar structures, i.e., two electric contacts, usually interdigitated, lying on the same surface generally with a 20 μm gap, are generally

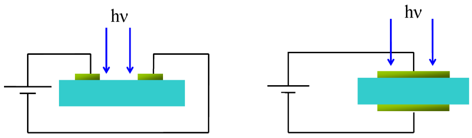

Fig. 1. Electric contact geometry of diamond photo-conductors. A couple of electric contact having a gap of 20 μm can be deposited on top of the substrate surface providing a planar structure (left) or one contact can be deposited on both the surfaces providing a sandwich structure (right). Electrical connections are also shown.

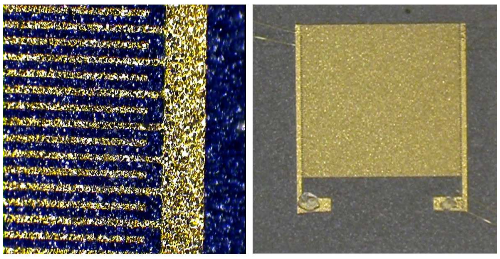

Fig. 2. Coplanar electric contacts produced at the University of Rome Tor Vergata on top of the substrate of a polycrystalline substrate. The full area of the 2×2 mm^2 single pixel (right) is obtained by two interdigitated electric contacts (left) separated by a 20 μm gap.

preferred for fabricating detectors (see Fig.2). However, sandwich structures – consisting of two metal electrodes separated by a high resistivity $50 \div 300$ μm thick diamond layer – have been studied recently (Brescia et al. 2004) especially for single crystal substrates in order to improve their performance under UV illumination. This is a central issue for pixellated detectors since they can be integrated more easily in arrays. Large array formats require many electrical connections to bias and read out each pixel. Currently, unfortunately, it appears nearly impossible to achieve them using coplanar contacts.

Single pixel photo-detector have been developed and studied on both polycrystalline and single crystal diamond materials. The first issue that has to be assessed for detectors is its sensitivity; detector sensitivity in the visible range is also crucial for UV and VUV in order to evaluate its solar blindness. Fig.3 shows the very high sensitivity of diamond photo-detector in the wavelength range ranging from 120 nm to 230 nm where the efficiency decreases sharply. Photo-conductors based on very high quality material substrates have an important advantage relative to photodiodes: sensitivity is given by quantum efficiency multiplied by a gain factor, that is the photoconductive gain, which for very high quality material can achieve factor of $10^3 \div 10^4$ (Brescia et al. 2003). Unfortunately, the quantum efficiency and the photoconductive gain cannot be estimated separately; therefore, what is measured is the external quantum efficiency (EQE), as shown in Fig.3. The sensitivity at longer wavelengths, as reported in Fig.4, decreases rapidly as expected and achieves a visible rejection ratio of 10^8.

To fully understand this result, we have compared the sensitivity of both polycrystalline and single crystal diamond photoconductors with the efficiency of the most widely used detectors in the UV range: CCD and micro-channel plates (MCP) (Naletto et al. 1994; Wilhelm et al. 1995). This comparison is reported in Fig.5 and it shows the higher sensitivity of diamond detectors in the whole range up to 230 nm, i.e., in the far UV (FUV) and near UV (NUV).

A complete evaluation of detector sensitivity also includes the dark current measured when the detector is not illuminated. The signal to noise ratio quantifies the real capability of detectors to measure weak signals. Detectors based on a diamond substrate benefit from its wide band gap limiting the number of charge carriers in the conduction band. Therefore, the expected dark current of diamond detector have to be very low even at room temperature. Fig.6 shows the dark current at room temperature for photo-conductors based on polycrystalline diamond substrates and single crystal diamonds.

Finally, the response time has been measured and a typical result at different applied electric field is shown in Fig.7.

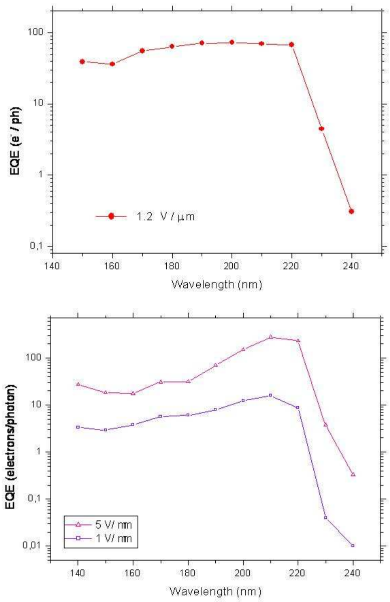

Fig. 3. External quantum efficiency of diamond photo-detectors. Single crystal diamond substrates provide very high gain and thus efficiency because of their higher purity (left). Lower EQE are obtained using polycrystalline substrates (right), but efficiency can be restored by increasing the electric field.

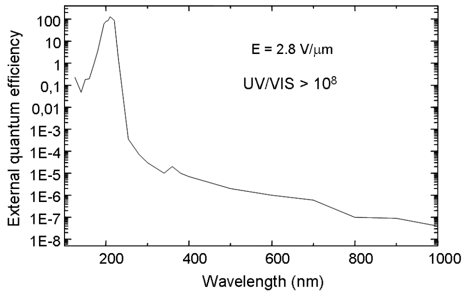

Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The high visible rejection ratio can be observed, being 10^6 after a few tens of nanometers and 10^8 at red and infrared wavelengths (Pace et al. 2000).

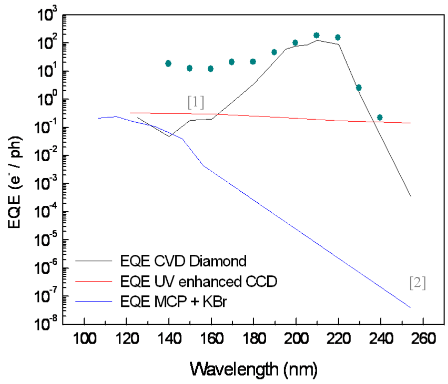

Fig. 5. Comparison between the sensitivity of different detectors (see Pace et al. (2001b)). Polycrystalline diamond detector (black line) and single crystal diamond detector (blue dots) sensitivities are compared to CCD (red line, after Naletto et al. (1994)) and MCP (blue line, after Wilhelm et al. (1995))

The next technological step is obviously to produce pixel arrays. The main problem to solve is the short absorption length of UV photons in the material layer. In fact, pixel arrays can be based only on the sandwich contact geometry in order to connect each pixel to a suitable read out electronics. This means that the electric charge that is generated very close to the illuminated surface should have high mobility and long lifetime in the material before being detected. These conditions are both satisfied in diamond but, being a highly resistive material, polarization effects in the bulk could dominate the charge transport mechanisms. This means that the sensitivity of diamond UV detectors could be highly reduced using such a configuration. Recently, De Sio et al. (2005) have demonstrated that high quality single crystal diamond substrates can be used for such a device and also thin layers of polycrystalline substrates obtained from thick films whose growth side has been removed can achieve comparable results. Fig.8 shows to different pixel array prototypes that have been studied for spectroscopic and imaging applications. This study is preliminary to our final goal of developing a pixel diamond detector that is based on the bump bonding

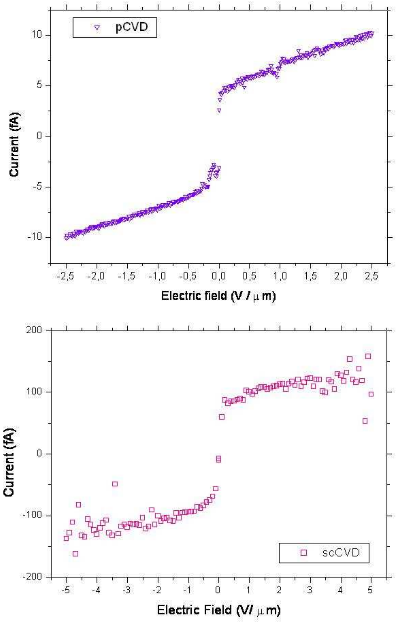

Fig. 6. Typical dark currents measured for diamond detectors based on polycrystalline (left) and single crystal (right) substrates. The higher dark current levels for the single crystals are due to nitrogen doping of diamond that is used in order to improve time response.

technology developed for IR imaging detectors (see Fig.9).

3. Conclusions

An innovative technological development of UV solid-state image sensors is ongoing at the University of Florence. Diamond exhibits unparalleled properties with respect to other wide band gap materials. The high crystalline quality achieved with present synthetic techniques and an activation energy of 5.5 eV makes diamond detectors intrinsically solar blind and with a very low dark current. Moreover high carrier mobility and radiation hardness makes diamond appealing for UV detectors development. A few sensors with a single crystal have exhibited photoconductive gains up to G=700 at 200 nm with rise and fall time shorter than one second (Brescia et al. 2003).

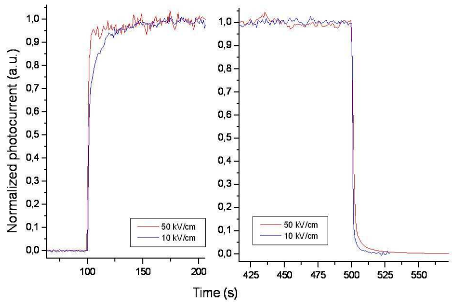

Fig. 7. Time response of diamond photo-detectors. Rise time (left) and fall time (right) are very fast and limited by the read out electronics. These plots show also the dependance from the applied electric fields.

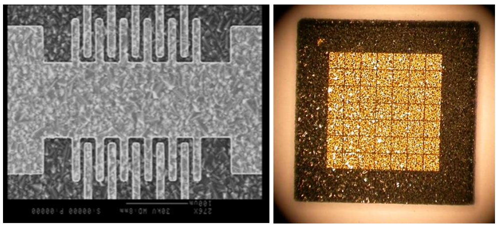

Fig. 8. Pixel arrays on diamond. A 2 × 5 pixel structure (produced at the University of Rome Tor Vergata, left) having pixel size of 60 × 60 μm has been used at the University of Florence for testing before producing a 2 × 50 pixel structure that will be tested in spectroscopic applications. A larger structure of 7 × 7 pixels of 1 mm^2 each (produced at the University of Florence, right) has been produced for imaging tests (De Sio et al. 2007). Pixel size is rather large because we are limited by wire bonding that is not feasible on smaller areas. Owing to the very high breakdown voltage of diamond, pixel size as small as a few micrometers might be fabricated.

The application of diamond detectors in astrophysics will bring:

a) technological advantages over the current detectors, such as lower power consumption, longer detector lifetime, lower electric insulation, and more compact detectors without coolers, radiation shields, optical filters.

b) performance advantages, such as longtime stability, owing to corrosion and radiation resistance, intrinsic solar blindness, low dark current levels, and high quantum ef-

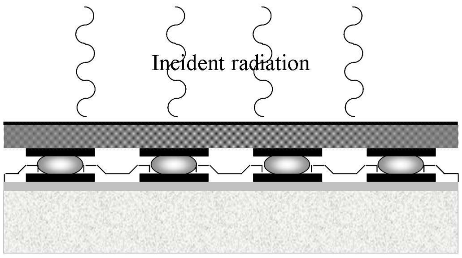

Fig. 9. Schematic sketch of a hybrid diamond detector as proposed by Pace et al. (2001b). The UV sensitive diamond layer is pixellated on the bottom surface and bump bonded on top of a silicon wafer with the electronic read out.

ficiency. The comparison between these results and the performance of a CCD detector and an MCP detector, generally used in space UV experiments, highlights the high sensitivity of diamond detectors, especially when they are based on single crystals. NEP values of $10^{-11} \div 10^{-12}$ Wcm^{-2} are already suitable for astronomical observations. Diamond can compete with silicon detectors owing to the unmatched visible rejection among the commonly used detectors (included GaN and AlN detectors) and its performance and technological advantages (Pace et al. 2001). Diamond UV imagers is the next hopeful step. Pixel arrays on diamond substrates represent a strong technological effort involving material synthesis and electronic processing. The advent of hybrid CMOS detectors offers the advantages of combining UV very sensitive layers with highly integrated and radiation-hard devices, also allowing strong mass reduction, owing to a very compact SOAC that requires only a 5 V power supply (Hochedez et al. 2001; Pace et al. 2001b).

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