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Towards UV imaging sensors based on single-crystal diamond chips for spectroscopic applications

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Abstract

The recent improvements achieved in the Homoepitaxial Chemical Vapour Deposition technique have led to the production of high-quality detector-grade single-crystal diamonds. Diamond-based detectors have shown excellent performances in UV and X-ray detection, paving the way for applications of diamond technology to the fields of space astronomy and high-energy photon detection in harsh environments or against strong visible light emission. These applications are possible due to diamond's unique properties such as its chemical inertness and visible blindness, respectively. Actually, the development of linear array detectors represents the main issue for a full exploitation of diamond detectors.

Linear arrays are a first step to study bi-dimensional sensors. Such devices allow one to face the problems related to pixel miniaturisation and of signal read-out from many channels. Immediate applications would be in spectroscopy, where such arrays are preferred.

This paper reports on the development of imaging detectors made by our groups, starting from the material growth and characterisation, through the design, fabrication and packaging of $2 \times n$ pixel arrays, to their electro-optical characterisation in terms of UV sensitivity, uniformity of the response and to the development of an electronic circuit suitable to read-out very low photocurrent signals.

The detector and its electronic read-out were then tested using a 2×5 pixel array based on a single-crystal diamond. The results will be discussed in the framework of the development of an imager device for X–UV astronomy applications in space missions.

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1. Introduction

The use of synthetic single-crystal (SC) diamond films in the fabrication of electronic devices is solving most of the limitations related to polycrystalline diamond sensors. The absence of grain boundaries and a lesser internal stress than the polycrystalline material have improved the electronic performance of synthetic diamond [1–3]. Thus, using such a material in radiation and particle detector technology has led to high sensitivity and fast responses [4–7].

The synthesis of SC diamond is still improving and the results that have been achieved let foresee the adoption of diamond detectors in many research and industrial applications.

The present study is aimed to solve the problems related to the miniaturisation of the pixels and the designing of a suitable read-out electronics. The reduction of the pixel size, for instance, is presently limited by the short scale non-uniformity of the diamond samples.

Such anisotropies, in single-crystal diamond, are related to spatially localised defects, such as crystal twins or mesa structures, which are generated during the growth processes. The influence of these crystal defects on the

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photoconductivity process has not extensively studied yet. This problem is usually circumvented by using large-area single pixel devices.

Due to the wide bandgap of diamond (5.5 eV), the amount of free carriers for detectors in darkness is very low (detectors with contact area of several mm^2 and biased with 2–3 V/μm show dark current values of the order of 10^{-13} A [6]) and the dark current level is often limited by the leakage current of the read-out circuits and instrumentation.

Reducing the pixel area, the background signal becomes dominated by the leakage current of the electronics, while the photoconductive signal decreases proportionally to the sensitive area; so the dynamic range of the photocurrent (PC) and its S/N ratio are limited by the read-out circuit.

Therefore, it is necessary to develop a very low noise read-out electronics characterised by high sensitivity in order to exploit the noise performances of the detector. Such electronics should be also scalable in order to read-out the signal from hundreds or thousands of pixels.

Linear arrays are the first design to be approached, since they have a simple electric contact configuration that allows to study many of problematic related to the development of more complex bi-dimensional sensors.

Moreover, linear detectors are largely used in spectroscopic applications, where the spectral information is usually dispersed along one direction.

The pixel size of the array should be adequate to the required spectral resolution. Thus, many arrays for spectroscopic application have rectangular pixels. The shorter side of the pixel meets the requirement to keep high spectral resolution along the direction of the radiation dispersion, while the longer side allows collecting more radiation at each wavelength in order to improve the sensitivity.

Our groups have developed two-dimensional $2 \times n$ pixel arrays based on high-quality SC diamond grown by the chemical vapour deposition (CVD) technique [6]. Due to the short absorption length of the vacuum UV (VUV) radiation in diamond (e.g. at 160 nm the absorption length is about 20 nm), the coplanar configuration of the electrodes forming each pixel is to be preferred because it maximizes the collection efficiency. Unfortunately, such a geometry reduces the active area on the diamond chip that can be used for the array.

The use of electric contacts in sandwich configuration could solve this problem, but they are difficult to produce and would require the use of free-standing substrates of SC diamond having thickness comparable with the coplanar electrode distance (about 20 μm). This thickness maximizes the photoconductive signal by trading among some parameters such as the collecting material volume, defined by the absorption length, and the charge collection efficiency.

The problems related to the reduction of the pixel size, the packaging of high-density pixel arrays and the processing of many low current signals will be discussed in the following sections. To this purpose, a 2×50 and a 2×5 pixel linear arrays have been fabricated on selected diamond samples. A 10-channel electronic read-out circuit has been also developed to detect the photoconductive signal of the 2×5 pixels. Sensitivity, S/N, time response and spectral sensitivity in the VUV spectral range have been measured in order to evaluate the performance and the uniformity of the array coupled to the read-out electronics.

2. Experimental

2.1. Diamond growth and device fabrication

The homoepitaxial 150-μm-thick diamond substrates were prepared using a properly modified Microwave Plasma Enhanced CVD tubular reactor filled by a 1% CH_4 in H_2 gas mixture [8]. The films were deposited on 3×3 or 4×4-mm^2 0.3-mm-thick $\langle 1\,0\,0 \rangle$ 1b-type single-crystal diamonds, synthesised by the High Pressure High Temperature (HPHT) technique.

The photoconductive detectors were fabricated using the standard lift-off photo-lithographic process to obtain specific planar aluminum contacts on the diamond growth surface. The structure of the pixel array was formed by interdigitated contacts, composed by a central fishbone structure and a finger for each pixel. Therefore, two fingers of the fishbone common electrode and the central finger form a single pixel as shown in Fig. 1. The horseshoe-shaped gap between the two electrodes defines the sensitive area of each pixel. The spacing between the electrodes, as well as each electrode width, can be 20 μm, as in the case of the 2×50 pixels array, or 25 μm in the 2×5 array. The length of the pixels are, respectively, 100 or 150 μm. Thus, the pixel size ranges between 5×10^{-3} and $1 \times 10^{-2}\,mm^2$ and the filling factor is about 50%.

In particular, Fig. 1 shows a $100\times$ magnification of the electric contacts of the detector with 2×50 pixels fabricated on a $4 \times 4\,mm^2$ diamond substrate. Such coplanar pixel configuration limits the sensitive area, but actually it represents a trade-off between the needs for high-resolution and high collection efficiency of photo-generated carriers (i.e. high detector sensitivity).

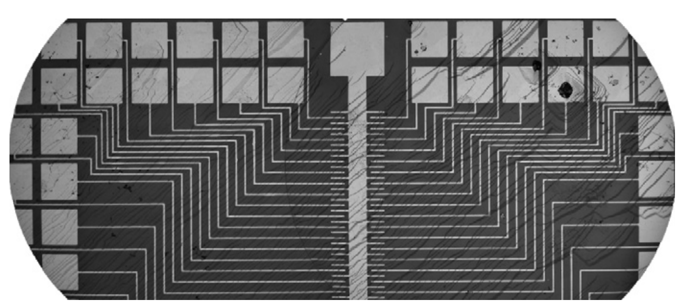

Fig. 1. Details of the electric contacts of the 2×50 pixels array device. The photograph is composed by a mosaic of pictures taken at the microscope with $100\times$ magnification.