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Investigation of the secondary emission characteristics of CVD diamond films for electron amplification

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ABSTRACT

Chemical vapour deposition (CVD) diamond offers great potential as a low-cost, high-yield, easily manufactured secondary electron emitter for electron multiplication in devices such as photomultiplier tubes. Its potential for high secondary electron yield offers several significant benefits for these devices including higher time resolution, faster signal rise time, reduced pulse height distribution, low noise, and chemical stability.

We describe an experiment to characterize the secondary emission yield of CVD diamond manufactured using different processes and process parameters and discuss the degradation of secondary electron yield and experimental difficulties encountered due to unwanted electron beam-induced contamination. We describe techniques utilized to overcome these difficulties, and present measurements of secondary yield from CVD diamond dynodes in reflection mode.

We discuss the application of CVD diamond dynode technology, both in reflection and transmission mode, to advanced high-speed imaging and photon-counting detectors and describe future plans in this area.

1. Introduction

Despite the widespread success of solid-state imaging devices such as the ubiquitous CCD, there are many fields where the sensitivity to detect single-quanta accurately in time and space is required, a regime where signal amplification is essential. Despite advances in solid-state avalanche gain technologies, the physics of solid-state semiconductors limit the ultimate response time and signal-to-noise ratio (SNR) compared with the fundamental limitations for *in vacuo* electron gain devices, such as the photomultiplier tube (PMT) and microchannel plate (MCP).

PMT and MCP detectors are utilized in many fields of science, from space-based astronomical UV [1] and X-ray observations, to microscopic analysis and diagnosis of *in vivo* biological processes. PMTs are the workhorse detector for photon-counting applications, from medical imaging as PET scanners to detection of exotic particles as neutrino detectors. MCP detectors have the capability to achieve picosecond event timing resolution, and their planar geometry lends itself to high-resolution imaging, with formats exceeding 4000×4000 pixel^2.

The performance of *in vacuo* secondary electron gain devices such as PMTs and MCPs is fundamentally limited by the number of secondary electrons produced by a primary electron impacting the dynode surface. Since the gain progression is geometric, a technology providing improved dynode emission with the stability to use at high signal currents would produce a step advance in the performance. Boron-doped diamond film deposited using chemical vapour deposition (CVD) techniques has been shown to exhibit significantly enhanced secondary electron yield (SEY), especially at higher voltages, compared to traditional dynode materials [2] (see Fig. 1), and its application offers significant advantages:

1. *Enhanced SEY*: Diamond, along with several other high band-gap semiconductors, can exhibit negative electron affinity (NEA) with suitable surface preparation, a major factor enhancing SEY. However, unlike other higher band-gap materials (e.g. AlN, $Ga_{1-y}Al_yN$), synthetic CVD diamond is easy to produce [3].
2. *Simplified design*: Higher SEY results in a lower number of dynodes being required for a given gain, a distinct advantage in terms of device size, cost, and complexity.
3. *Enhanced timing*: Boron-doped (p-type) diamond surfaces produce a narrow energy distribution of low-energy secondary

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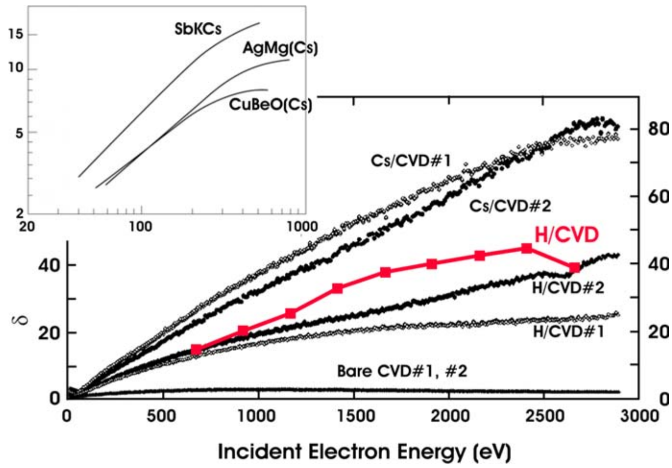

Fig. 1. SEY coefficients of three common dynode materials (inset—Photonis PMT Handbook) cf. CVD diamond for different surface terminations [2] and data (grey squares) from our research programme.

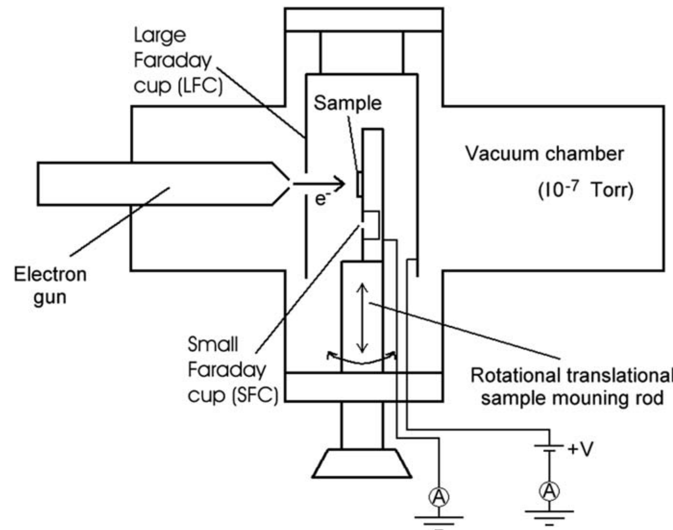

Fig. 2. A schematic diagram of the SEY characterization apparatus.

electrons [4] allowing improved confinement of trajectories with improved time resolution and reduced background [5].

4. *Narrow pulse height distribution* (*PHD*): The Poisson statistics of high-gain diamond dynodes intrinsically produce a narrower PHD with improved SNR, allowing detector operation at lower gain and better energy resolution for scintillation counters, PET scanners, etc.
5. *Low noise*: Its wide band gap (5.47 eV) precludes the thermal excitation of electrons at typical operating temperatures cf. materials with comparable SEY (e.g. GaP—2.26 eV). Conversely, it has lower thermal noise than traditional dynode materials at high temperatures.
6. *Large-area*: CVD deposition offers a low-cost, large-area coating technique and is applicable to shaped substrates c.f. expensive materials such as GaN and GaP, which can only be grown on lattice matched substrates e.g. sapphire. Inkjet printing of diamond nanoparticles and subsequent growth into patterned films has also been demonstrated.
7. *Stability*: CVD diamond has a stable SEY, little affected by long-term storage. Its SEY remains high after exposure and it can be reactivated [6].

One potential drawback of diamond's higher gain is the increased voltage required per stage. However, diamond's smaller pulse height variance and low noise promote operation at lower gain with a smaller number of stages, thus alleviating the overall voltage requirement.

2. Experimental setup

The SEY characterization apparatus is a bakeable stainless-steel vacuum system with a centrally mounted, electrically insulated conductive arm supporting up to four 1 cm^2 samples and a small Faraday cup (SFC) for beam current calibration. Fig. 2 shows a schematic diagram of the apparatus and Fig. 3a shows a photograph of the arm with three samples and the SFC aperture.

The sample support arm can be moved laterally by ± 25 mm and rotated 360° around its axis. Lateral motion is used to position one of the samples or the Faraday cup in the path of a beam of electrons generated by an electron gun and rotation allows the beam incidence angle to be varied or the samples placed out of sight of the beam. The ELS5000 electron gun, manufactured by PSP Vacuum Technology [7], produces a focussed electron beam with a spot size of $<50\,\mu m$ at 1 μA, working distance of

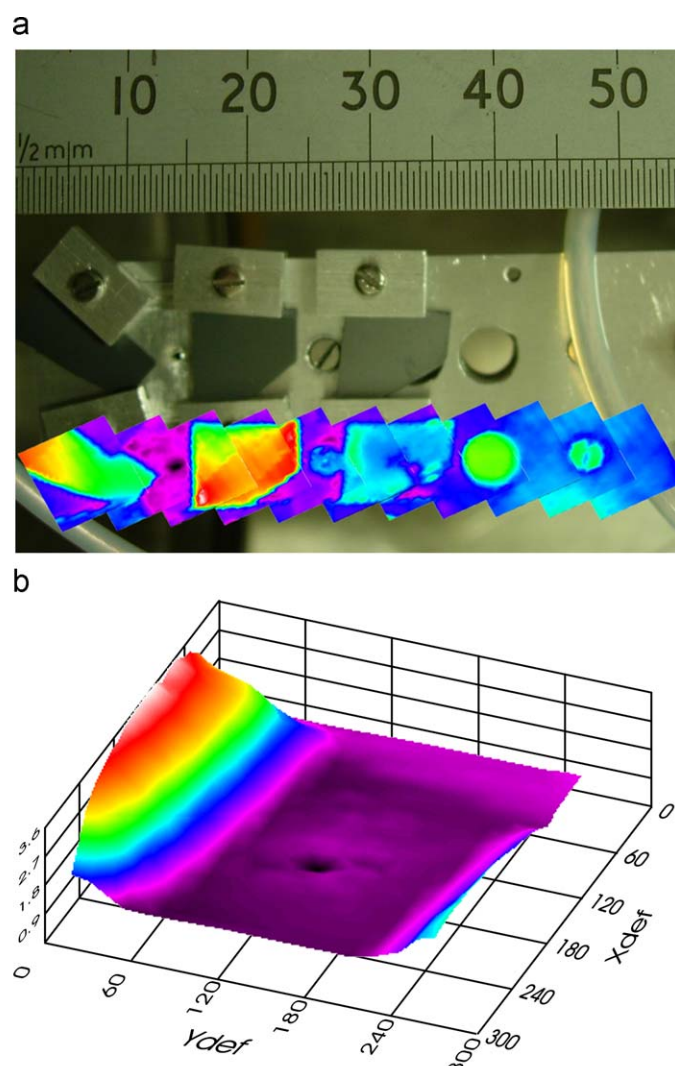

Fig. 3. (a). A photograph of the sample arm with three samples. The SFC is the aperture between sample 1 and 2. The montage below is the false colour SEY image produced by scanning the electron beam. Fig. 3b is an SEY image showing the SFC aperture (the black hole in the middle).