A New Cosmic Dust Detector with a Novel Method Using a Resistive Grid Sensitive to Hypervelocity Impacts

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Abstract

A new method is demonstrated to detect impacts of hypervelocity particles in real-time and to determine the size of particles. It uses a resistive grid on a thin substrate (here Duroid). Penetration of the substrate in an impact breaks lines on the grid, changing the overall resistance of the grid. The change in resistance is proportional to the width of the damaged area (i.e. number of resistive lines that are broken), which is in turn proportional to the impactor size. This method provides a large area, low mass, low power detector for measuring the flux of small dust particles in space. Based on experimental data (taken in a two-stage light gas gun), we show that impacts at 5 km s\(^{-1}\) demonstrate that the principle works as described for particles 150 \(\mu\)m and above and that in theory could work for impacts down to size scales as small as 50 \(\mu\)m.

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Nomenclature

\textit{PVDF} Polyvinylidene fluoride, used here as a strain rate sensor.
\textit{Duroid} Polytetrafluoroethylene embedded with randomly oriented glass fibres. It is commonly used in spacecraft applications as a base layer for circuit boards due to its well characterised electromagnetic performance.
\textit{Hypervelocity} An impact at a speed which is comparable to or greater than the speed of compression waves in the materials involved. Typically this involves impact speeds of a few km s\(^{-1}\) or above.

1. Introduction

There is a significant flux of small particles in space which has a variety of sources, e.g. interplanetary dust, interstellar dust and man-made debris. Measuring this flux is important for several reasons, some scientific and some for engineering reasons. In the latter case it allows us to determine the hazard presented to space vehicles as a result of impacts by this dust (see [1] for an early discussion of this). The typical impact speeds on spacecraft are typically 7 – 11 km s\(^{-1}\) for man-made debris in Low Earth Orbit, or 15 – 20 km s\(^{-1}\) for interplanetary dust. Impacts at these speeds can be a significant hazard, causing penetration of any exterior surface wall and interior damage which may significantly degrade spacecraft...
performance. Or delicate individual components may be struck, such as CCD cameras on satellites (e.g. [2]). In addition, the flux is not constant. For example, by its very nature the man-made component is highly variable. It can arise from material accidentally shed by another spacecraft, or due to propellants used for orbital manoeuvres (such as small, micrometre scale Al₂O₃ spheres), it can be the fragments of upper stages or satellites which have exploded or undergone catastrophic failures, and at metre scale old space vehicles can themselves be considered debris.

As stated, this material (natural and man-made) then presents a hazard to spacecraft [3]. There is thus a need to be able to well characterise the population. This requires particle size, time of impact, speed, trajectory etc. all to be known. Given that much of the flux is at small sizes, the population needs to be measured down to the near micrometre scale. An in-situ method (carried on a spacecraft) which can provide as much of this information as possible is the ideal. It should also be low mass, low cost, low power, with readout in real time (although data may be stored for onward transmission to Earth) and large area (so even rarer large particles can be observed in a reasonable time period). There have been previous such instruments flown in space since the dawn of the space age. Devices which used penetration of shields and then measured hole size by loss of internal pressure or by passage of light through the shield from a known source to a sensitive detector, were used quite early on in the space era, e.g. [4]. The development of retrievable spacecraft allowed a more passive method (carried on a spacecraft) which can provide as much of this information as possible is the ideal. It should also be low mass, low cost, low power, with readout in real time (although data may be stored for onward transmission to Earth)

The cosmic dust influx rate to the Earth [5]. More recently thin films retrieved from LEO have been used to measure impacts of dust particles as small as 10 nm [6]. PVDF sensors have also been used as impact sensors [7, 8], these are permanently polarised polymers whose capacitance changes when struck (here by a hypervelocity impact). They have been used as dust detectors in space missions such as Vega to Halley’s comet [9], Cassini to Saturn [10] and Stardust to comet Wild 2 [11]. They have also been used in Earth orbit, on for example the AIM satellite [12].

In a previous paper [13], we outlined the need for a new generation of dust detectors which can be deployed on spacecraft. Several schemes have been proposed by various groups which permit not just real time detection, but also trajectory and velocity measurements of the incident dust, e.g. [14]. In [13] we described a type of detector which used acoustic signals measured by PVDF vibration sensors, which allowed us to detect the impacts on a plate in real-time and locate the impact position to ~½ cm. Unlike the PVDF sensors described above, in [13] we impacted large plates which vibrated when struck, and it is this vibration which triggered the PVDF sensors attached to the plates. Two type of plate were used in [13], metal (aluminium plates 25.4 × 25.4 cm square) and Duroid. Duroid is a polytetrafluoroethane composite which contains randomly oriented glass microfibres embedded in its structure. In [13] two Duroid types were used: Duroid 5880 (a plate 22.9 × 10.2 cm face and 0.788 mm thick), the other was of Duroid 6002 (with 15.2 × 15.2 cm face and 0.763 mm thick). In [13] we described the damage (craters and holes) arising from the impacts, along with the magnitude of the acoustic signals measured by the pvdf sensors. Here we demonstrate another type of impact detector, one which uses a resistive grid etched onto a Duroid base-plate. The idea is that impacts on the Duroid plate cut resistive lines in the grid, changing its resistance. This change in resistance gives a measure of the number of lines that have been broken and hence the size of the damaged area. If this size is related to the impactor size, we then obtain the size of the impactor.

2. Method

This work was conducted using a two-stage light gas gun at the Univ. of Kent to provide impacts [15]. The gun fires a projectile in a sabot that is discarded in flight, thus the size and composition of the projectile can be varied from shot to shot. We can vary the speed of each shot by selecting the amount of gun-power used, and/or the initial pressure in the pump tube (see [15] for details). The projectile speed is measured in flight (after the sabot is discarded), as a result of its passage through two laser light curtains. The light from these curtains is focussed onto photo-diodes and interruption of the light by passage of a particle through the curtain changes the output from the photo-diode. Interrogation of the relative timing of the two signals on the photodiodes, combined with the known separation of the light curtains, provides a speed inside each shot. This is accurate to usually better than ±1%. The target chamber of the gun was a cylinder with diameter of 40 cm. It was evacuated to low pressure (approx. 0.5 mbar) during each shot.

The targets used were plates of Duroid 5880 which had had circuit board like copper lines etched onto their surface on top of FR4 prepreg (a typical procedure in etching copper circuitry onto Duroid base-plates). A typical board is shown in Fig. 1. It was 1.03±0.01 mm thick (slightly thicker than in the previous tests), with a surface area of 151 × 151 mm (i.e. approx. 6 inches by 6 inches). The board in Fig. 1 had copper lines running from left to right (see Fig. 2). It has 3 regions of such lines. We measured the strip dimensions under an optical microscope, and found that the copper strips were 64.2±2.5 μm wide, with the gap between strips being 85.4±3.2 μm wide. Thus from the top edge of one strip to the top edge of the next strip was a total of 149.6±4.1μm. A close up optical image of a region of strips is shown in Fig. 2. Each strip terminates in a slightly wider pad which can be connected to an external circuit or an ohm-meter. The rear of the boards had PVDF
strain-rate sensors (type FDT1-028K, Measurement Specialities Inc., Wayne, Pa, see NRL 7130 for a description) attached to detect vibrations.

Fig. 1. A Duroid sheet as used in this work. In the left hand image the front face is shown, complete with fine spaced copper grid. A 6 inch rule is also shown for scale. In the right hand image, the reverse side of the board is shown with two rectangular PVDF sensors (white in the image) shown attached to the board, these read out acoustic vibration signals.

Fig. 2. A close up optical image of the copper grid etched onto a Duroid board. Note that the copper strips are the lighter colour material.

Fig. 3. Impact damage on the front face of board, after impact by a 1 mm stainless steel sphere at 5.12 km s\(^{-1}\). As well as a hole, there is peel back of the surface copper layer and evidence of lift and fracturing, all of which cause breaks in copper lines.
By measuring the resistance of strips it was readily possible to determine if a strip was intact or broken. In tests we cut several strips by hand and could see the resistance change dramatically, indicating an incomplete circuit. The strips can have their resistance read out individually by hand, or could be grouped together and read out in a large group. In both cases we could detect the change in resistance due to an individual line break. The boards also had a temperature sensor placed onto them, so we could correct for any change in resistance due to temperature drift over the course of an experiment.

3. Results

Two shots were carried out as part of this work. In shot 1 we fired a 1 mm diameter, stainless steel sphere at the targets. In the second shot we fired a cloud of nominally 150μm diameter soda-line glass spheres at the target. Before each shot we checked the board for broken lines and these were noted.

3.1. Shot 1

After the first shot we examined the board under a stereo optical microscope. An image of the front face (which was the surface that was impacted) can be seen in Fig. 3. As expected from previous work with Duroid plates [13], the impact penetrated the board. When viewed (not shown here) the rear face showed a circular hole as seen in [13]. However the damage on the front face had a more complicated nature. Instead of a circular hole, with some fibre-like fragments at its edges, the damage region had a more detailed nature (shown in Fig.3 and in more detail in Fig. 4.).

In Fig. 4 it can be seen that the surface layer on which the copper is etched has behaved differently in the impact to the underlying Duroid sheet. The centre of the impact region shows a circular hole in the Duroid, of which some 3/4s is visible (with the top right quadrant obscured by a raised, but not fully detached, region of the surface layer). The diameter of the hole was measured at 4.56 ± 0.13 mm when viewed from the front (i.e. 4.6 × projectile diameter). Note that this is in the surface plane. On the rear surface the diameter of the damaged area was 4.564 ±0.086 mm, i.e., essentially the same as on the front. These values are the averages of 10 measurements on the front and 7 on the rear. As previously noted with Duroid there is an inner throat in the hole (i.e. the narrowest region) which is typically situated at half the depth of the Duroid sheet[13]. The diameter of the throat was found to be 2.58 ± 0.13 mm. The hole size and shape are fully compatible with what one would impact from such an impact on a Duroid sheet [13].
The surface layer onto which the copper strips were etched, has however behaved very differently. It has detached itself from the underlying Duroid, but according to a pattern which runs parallel to the copper strips. What are in effect rectangular slabs of the surface layer (some 10 – 15 strips wide) have started to lift away from the Duroid. The main uplift is around the hole, and these slabs then pivot on a region off to one side away from the hole. These pivot lines can be a few mm away from the hole. There are in effect 4 of these slabs. Moving round the impact site in a clock-wise fashion we find: Top right quadrant – the slab is still present, and near the hole is raised above the surface slightly (this is more evident in the stereo microscopy), Bottom Right quadrant – this slab has detached and been removed altogether, Bottom Left quadrant – this slab is still attached and is again raised above the surface near the hole, its pivot is off to the left of Fig. 4 but can be seen in Fig. 3. Top Left quadrant – this slab has nearly detached altogether, it cannot be seen in Fig. 4 but is visible still just about attached in Fig. 3.

![Image](image.png)

**Fig. 5.** Close up of almost detached surface layer region in Shot 1. This is the upper left quadrant piece of material shown in Figures 3 and 4. It is attached (just) at its right (slightly out of focus due to depth of focus issues in the image). A series of regularly spaced rectangular “teeth” can be seen protruding from the top part of this slab of material.

In addition, more features can also be seen. In Fig. 5 we show a close up of the almost detached region in the top left quadrant. What is most evident are a series of regularly space, rectangular tabs (or “teeth”) protruding from the uppermost part of the lifted slab. These match similar indentations visible in the surface of the remaining board in Figures 3 and 4. These “teeth” are approximately 0.21 mm in width, and occur every 0.85 mm.

As well as the hole and damage in the Duroid, the key issue for resistance measurements is the extent of damage to the surface carrying the copper lines. A circular region (centred on the hole) of lighter colour is evident in Fig. 3. This may be a region of partial delamination of some sort beneath the surface. The dia. of this region was found to be 10.92±0.26 mm. (i.e. approx. 11 × the projectile diameter). The damaged zone itself, where there are clear breaks in the lines, is less well defined and is not a regular shape. Taking the longest dimensions of damage, along the lines (horizontally in Fig. 5a) the extent of damaged lines is 9.8 mm, whereas transverse to the lines (vertically in Fig 3) it is 7.5 mm. It is the transverse dimension which will alter resistance by causing line breaks, and the suggestion here is that some 50 lines will have been broken by the impact. This is certainly a large enough number to permit a determination of the damage region’s size just by measuring a change in resistance.

### 3.2. Shot 2

Having determined that a large impact will generate sufficient damage to break lines in the resistance grid, we moved to determining if impact by smaller projectiles can still cause sufficient damage to break copper lines. Accordingly Shot 2 fired a cloud of 150 μm diameter soda-lime glass projectiles in a single shot at 5.0 km s⁻¹. Some of these beads may have broken up in flight giving a range of impactor sizes. There were multiple hits on the board and examples are shown in Figures 6 and 7. In these figures it can be seen that the impacts result in a central crater, which penetrates into the underlying Duroid board, but which does not penetrate all the way through. Also visible around the craters is a region of the surface which has raised-up somewhat. This is slightly lighter in colour.
Several large craters were visible on the board after this shot and an example is shown in Fig. 6. By measuring three such craters we found that crater diameters were 0.24, 0.206 and 0.181 mm, i.e. with an average of 0.21±0.03 mm. The size of the total damaged zones around these impact sites was 0.75±0.30 mm. If we normalise to projectile size we find that the crater diameter was typically 1.4±0.2 times projectile diameter and the total damaged zone diameter was 5.0±2.0 times projectile diameter. These values are significantly smaller than those for Shot 1, where penetration rather than cratering occurred. If such boards are used as impact detectors there are therefore different calibrations needed for the two case of penetration by larger particles and cratering by smaller particles. In the cases here we expect to see somewhere between 12 to 15 line breaks typically, the uncertainly depends on how many of the copper strips which only just cross the upper or lower edges of the total raised region, actually break as a result of the strain on the raised surface. By looking carefully at
the images in Fig. 6 we can see the beginning of the behavior which occurs in the surface layer around the impact penetrations which occur for larger projectiles such as in Shot 1. The delamination is starting to occur in the surface layer and internal structure in these layers is causing preferential tearing in lateral directions. This in turn causes almost rectangular slabs of material to start to lift away. In the case in Fig. 6 they are not of sufficient size to cause the larger scale effects seen in Shot 1.

There were also several smaller craters visible after the impact in Shot 2. These were typically half the size of the larger craters. Given that the size of these craters is only slightly bigger than the diameter of the original projectiles, it may be that these examples arise from impacts by fragments of projectiles that broke up in flight. These glass projectiles have been used in many shots in our gun. We have carried out test shots at thin (5 μm thick) aluminium foils and usually obtain holes that were the same size as the projectiles, indicating that usually the projectiles are launched intact. Similarly we have fired these beads into aerogel, a transparent, highly porous medium which can be used for capturing high speed particles relatively intact (see [17] for a recent review of aerogel as a dust capture medium). In our work with capture in aerogel we have been able to study damage to glass projectiles when shocked, and we find that just as with damage at low strain rates [18, 19], the initial damage is caused by fractures which lead to meridional splitting in the first case [20]. Accordingly, here we assume

splitting into 2 equal sized fragment, each typically ½ the original size, gives the largest fragments impacting our target. The resultant craters again have a central crater surrounded by a raised region (probably more visible in Fig. 7 than in Fig. 6). These raised, slightly lighter coloured regions are roughly elliptical in shape (with the major axis top – bottom) in the upper
image in Fig. 7 and more circular in the lower panel in Fig. 7 (this is clearer under the stereo microscope). They have a diameter of some 300 – 400 μm. In the upper panel in Fig. 7 there are also signs of clear radial cracking in the surface layer, starting at the lips of the crater and extending outwards into the raised surface region. This is a sign that the strain has caused the surface to break in the region. Although not visible, tests show that some of the strips which cross this raised region but which do not get clearly broken either by the crater or these visible cracks, have nevertheless undergone a change in resistance indicative of a line break. Therefore we infer that whilst not visibly damaged, the strain caused by raising the region has done sufficient damage to cause the copper strips to break. Thus these impacts have caused loss of electrical continuity in 4 or 5 strips in the cases shown in Fig. 7. Given that there is now only a small number of strips across the damaged region, and because the raised regions are not fully circular, the precision on determining the size of the damage zone by the number of broken copper strips is clearly at the 20 – 25% level of accuracy.

4. Conclusions

We have shown that copper lines etched as a grid onto surface of a (Duroid) substrate can serve to monitor the presence of hypervelocity impacts. Breaks in the copper lines change the resistance which can be monitored externally. A device consisting of such grids could thus be used to monitor impacts. If the resistance were read-out continuously, a sudden change could indicate an impact, giving the time of the impact. The size of the damage region can be found from the change in resistance.

There are however complications. There are two distinct impactor size regimes (see [16] for a general discussion of impacts in finite thickness plates). For small projectiles (those which don’t penetrate the Duroid substrate) the result of an impact is cratering. For larger impactors the result is penetration. The relation between the impactor size and crater diameter vs. penetration hole diameter differs (as reported previously in [13]). In addition the number of broken copper lines is not set by the size of either the crater or the penetration hole, but rather by the size of the larger damaged region around each, where the layer laid onto the Duroid to carry the copper lines starts to delaminate and tear. This process appears likely to be somewhat more variable than the more regular cratering and penetration phenomena. Hence the accuracy of the impacting particle size determination being some 20 – 25%. However, conveniently this increases the size of the damage zone and hence the number of copper lines broken for a given sized impactor. Thus the minimum detectable impactor size is not the size to give a crater equal in size to one copper strip plus 1 uncoated surface gap between strips (note that a smaller crater could break just the copper strip or could completely lie in the gap between strips and would thus go undetected). Instead it is the size of an impactor which gives a total damaged zone which corresponds to the width of one copper strip plus neighbouring gap. Given that here we have what appear to be fragments of a 150 μm glass bead giving breaks across 4 or 5 strips, if we assume the fragment size was ½ the original, i.e. of order 75μm, then even though we do not know the exact function dependence of damage zone diameter vs. impactor size, we can safely hypothesize that a 50 μm impactor would still give a reliable signal (and maybe even smaller ones than that). We thus have a detector which is sensitive to impacts of particles down to of order 50 μm.

We are currently undertaking a programme of work to see what happens as we vary the thickness and composition of the underlying substrate (here Duroid). This will allow us to determine an optimal design which maximizes the damage area in an impact, but does so in a reliable and reproducible fashion to minimize uncertainty in the results. Further, given that here the material between the resistive grid and the substrate is delaminating from the underlying substrate, and increasing the extent of the surface damage, we are investigating how to mount resistive grids with minimal preparation onto a substrate. However, whilst this may increase the accuracy of the particle size determination, it may also increase the lower limit on detectable particle size.

One limit of such a detector is that any calibration of crater or hole size will be impact speed dependent. Thus a separate method of determining impact speed is required in a fully functioning detector. We are currently working on a programme to develop the capability to determine particle speed as it approaches the target plate. And, this is not the whole story. Although not described here, the PVDF sensors shown in Fig. 1 can be read-out in the impacts and the data interrogated. We are currently working to determine the relationship between PVDF signal and impact energy (or momentum). If we can determine this in parallel to impactor size and impact speed, a more complete picture of an impact event then emerges from which we will be able to determine impactor size and speed. We thus hope to shortly have a complete detector package containing several new technologies (of which this current paper describes one) and which will provide the hoped for low mass, low power, real-time dust flux monitor for use in space. The need for such detectors is indicated by for example the increase in man-made debris in Low Earth Orbit as a result of the 2007 Chinese deliberate destruction of a satellite in orbit [21, 22].
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References