Energetic Electrons Emission Observed During Light Particles Bombarded Graphite

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Abstract – We report the results for the generation of an intrinsic electrical breakdown, induced by light particles bombardment of graphite targets. The occurrence of a strong electrical field is evidenced by the observation of shifts in energy spectra recorded during the irradiation and energetic electrons detection. Deep tracks and fractures, attributed to electron jets impacts, were also revealed by SEM analysis.

1. Introduction

Materials exposed to radiations are subject to high level of deterioration. The most important deteriorating effect is the electric breakdown created as a consequence of defects creation and/or space charge build up. Despite the great number of studies dedicated to this subject [1–7], it is still lack in the fundamental understanding of microscopic breakdown mechanism. The main difficulties encountered in studying the electric breakdown triggering are the random character of defects distribution and the continuous motion of the electric charges. Under favourable conditions, breakdown avalanche may be induced by field emission effect. In RF environments, materials submitted to field strength of the order of 5–10 GV/m emit ions, clusters and fragments [8–11]. When fields of 10–30 GV/m are presents, fused metals and fractures are obtained.

In the present study, similar observations were made under deuteron irradiated graphite, in spite of the absence of any external field. It is believed that the atomic agglomerations created in the irradiated target act as localized field emitters that, at extreme conditions, induce electric breakdown at a microscopic scale. Moreover, intense and energetic particle emission, attributed to an electronic explosion, was observed. Recently, production of keV energy electrons by intense laser beams irradiated solids has been the subject of substantial studies [12–14]. Laser accelerated electrons has been reported by several experiments. In the context of laser-solid interactions, several mechanisms have been described to explain hot electrons generation, such as hydrodynamic expansion and coulomb explosion [15–21]. But, no such observations were made under light ion beams bombardment of solid targets.

In reference [22], an anomalous particle emission observed during deuteron irradiated graphite was reported with an attempt to explain its origin, according to the conditions of the experiment. In the present contribution, such observation is confirmed and the dynamic of the emission is followed even thought that the involved phenomenon is of hazardous nature.

2. Experimental

In the present study, a simple experiment is used in such a way to avoid any misinterpretation that could be caused by an experimental artefact. The material used consists of nuclear purity graphite, acquired from different manufacturers. The measured electrical resistivity, using the four point probe method, varied between $25\cdot10^{-3}$ ohm/square and $200\cdot10^{-3}$ ohm/square. The targets were irradiated in a vacuum chamber under a pressure of 10^{-5}–10^{-6} mb. Cleaned square samples, cut from mirror n-doped silicon wafers of 4–10 Ω·cm resistivity, serving to collect the ejected matter, were placed all around the target and were replaced for each new irradiation. Care was taken to avoid any contamination of the collectors. Before irradiation, the graphite samples were polished and cleaned by ultrasonic bath in distilled water and both target and collector surfaces were examined using SEM analysis.

A beam of 50 nA D^+, delivered by a 3.75 MV van De Graff accelerator, impinges on a thick target under an incident angle of 90°. The whole chamber plays a role of a Faraday cup and the beam current was measured using a current integrator. During irradiation, the emitted particles were detected with ORTEC surface barrier detectors of 11 keV energy resolution at an angle that could be varied between 0 to 360°. The acquisition was achieved with a standard ORTEC electronic chain.

Structural investigations were carried out in a Philips Environmental Scanning Electron Microscope (ESEM) XL30 FEG, equipped with an x-rays diffraction analysis.

3. Results and discussion

Fig.1 shows the energy spectra of $C^{12}(d,p)C^{13}$ nuclear products, obtained under 1.2 MeV deuteron bombarded thick target of graphite. During the irradiation, an anomalous emission appears at low energy. A continuous distribution is observed from the edge of the peak corresponding to the Compton electrons till a value exceeding 450 keV. In other experiments, localized emission, sharp shaped, was observed at about 300 keV [22]. The flat distribution is shown to be a characteristic of fresh targets, never irradiated before. The intensity of the emission does not depend on beam parameters. It may rather, depend on the history of the target. In Fig. 1, the typical $C^{12}(d,p)C^{13}$ spectrum was recorded few minutes after the exotic emission was observed, during the same irradiation. According to the conditions of the experiment, this emission may be attributed to an explosive electron emission. The existence of self-sustaining currents evidencing its electronic nature has already been given, elsewhere [22]. In the following, further proofs supporting this hypothesis, are given.

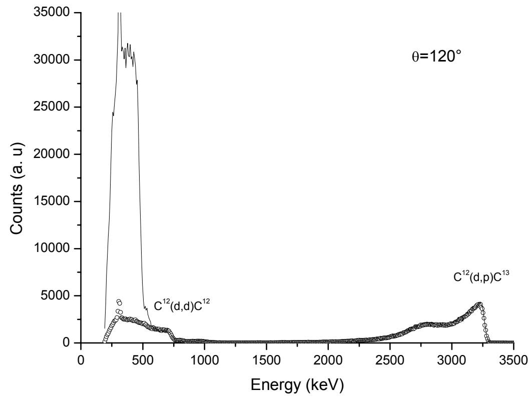


Fig. 1. (—) Energy distribution of the electron emission occurred under 1.2 MeV deuteron irradiated graphite. (o) typical $C^{12}(d,p)C^{13}$ energy spectrum, recorded during the same irradiation

Fig. 2 illustrates the dynamic of the emission. Successive spectra were recorded for a beam charge of 6 μC, during two ours irradiation time. In Fig. 2, *a*, the first run corresponds to the starting condition of the emission. No net peak appeared yet but, as it is seen in Fig. 2, *b*, corresponding to the high energy parts of the spectra, the energy distribution of the 3.27 MeV protons produced by the nuclear reaction is modified. This reveals the existence of electric field acting, first on the deuteron beam. The energy resonance of the reaction appearing at 1.2 MeV disappeared, revealing a reduction of the energy of the incident D^+ particles. The observed shifts are associated with the appearance of the exotic emission at low energy. The second run corresponds to the case where a 300 keV peaked energy distribution of the electronic emission appears. The corresponding protons lose energy of approximately 80 keV. In the remaining runs (3—5), a decrease in energy of about 50 keV is observed at low energy, for the observed exotic emission and in agreement with this, the high energy protons gain approximately 30 keV. It is clear that these opposing behaviours within the created electric fields disclose the electronic nature of the emitted particles. It is to be noted that the intensity of the emitted electrons increases with time until a certain saturation is reached and then, decreases but never falls to zero. It is seen that the only way to recover the initial energy spectrum is to stop the beam and change the target. The possible scenario to explain this phenomenon is that, due to the positive charges accumulated on the surface, high electric fields are developed, causing the emission of electrons from the surface and/or carbon clusters, formed under the irradiation, act themselves as electron emitters. Electron avalanches are then induced, giving rise to standing currents that persist for long periods after beam shut off.

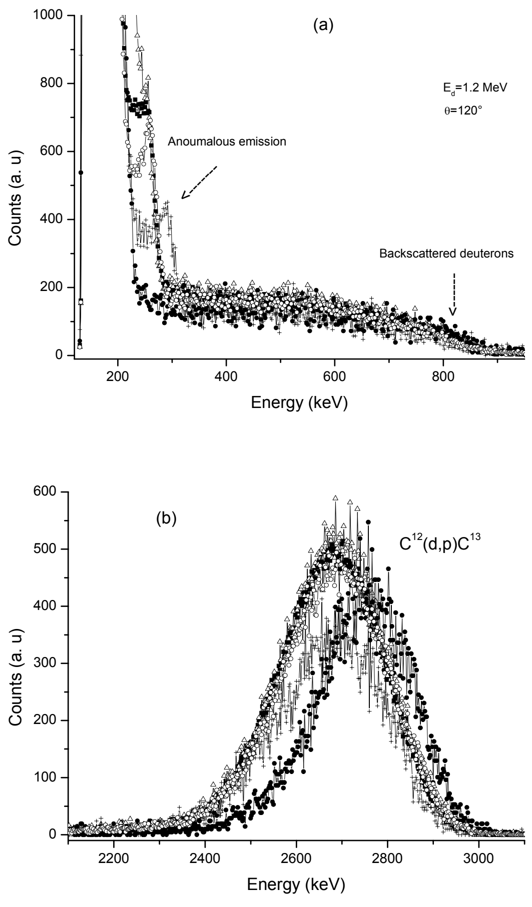
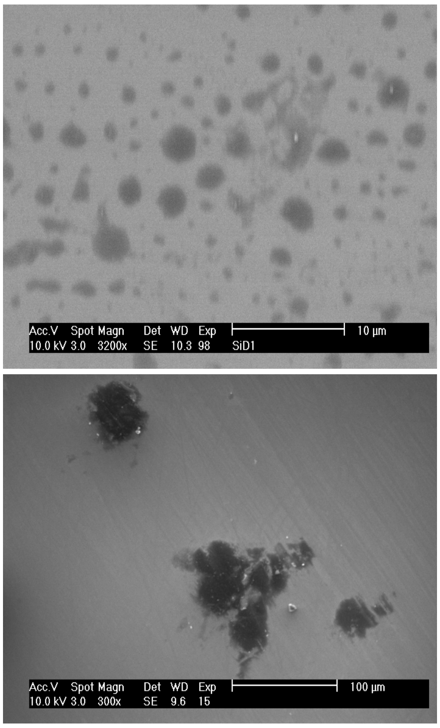


Fig. 2. (a) Energy distribution evolution of the observed emission, (b) Energy distribution evolution of the corresponding high energy protons of $C^{12}(d,p)C^{13}$ reaction. The recorded spectra correspond to 6 μC beam charge. (•) ≊ run 1, (+) ≊ run 2, (○) ≊ run 3, (Δ) ≊ run 4, (■) ≊ run 5

Another evidence of the developed electron avalanche is the energetic beam impacts observed on silicon samples placed around the irradiated targets, to collect the emitted particles. Fig. 3—5 show examples of SEM micrographs taken for the analyzed collectors. Fig. 3, *a* reveals a shower of single impacts, uniformly distributed on the silicon surface. The diameter of the impacts varies from hundreds nanometres to few micrometers. The fact that impacts with higher diameters are concentrated in the centre of the figure with no overlapping, and that their form is well ordered, let to speculate about an instantaneous emission of electron jets.

Fig. 3, *b* evidences the occurrence of energetic electron beams. The induced impacts are deep overlapped tracks, scarcely distributed with diameters of few tens of micrometers.



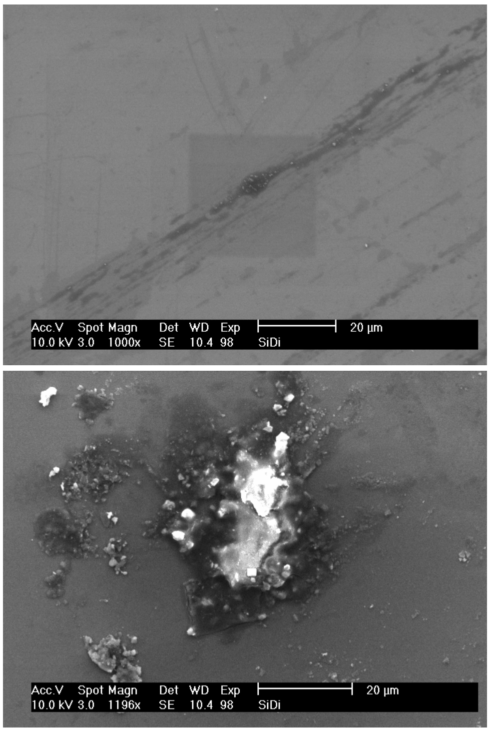
(a)

(b)

Fig. 3. SEM micrographs revealing the nature of the damages induced on the silicon collectors. (a) uniformly distributed small diameter tracks. (b) electron jets impacts

The other aspect of the created damage lies in the fractures observed on the collectors. Fig. 4, *a* shows ejected matter embedded in such created fractures. Sometimes, the ejected matter is just deposited on the collector surface, building up a large variety of structures such as microflakes, fibres, nonowires, coral-like and well ordered carbon microparticles [23]. In Fig. 4, *b*, the deposited matter seems to fit the morphology of the electron beam impact with a dispersion of light particles all around the impact, demonstrating the high strength involved. Fig. 5 demonstrates that the collectors were subject to high temperature, exceeding the melting temperature of graphite. The worm-shaped material evidences the occurrence of fluid-grown carbon particle, caused by heat deposited during arcing as it is evidenced by tree initiation.

The inspection of these collectors by means of x-ray spectroscopy, incorporated in the scanning Electron Microscopy, shows that the deposits are formed mostly of carbon. An example of x-rays diffraction analysis of the deposited matter is given in Fig. 6.



(a)

(b)

Fig. 4. SEM micrographs showing (a) ejected matter embedded in the fractures created on the exposed silicon collectors, (b) just deposited ejected matter, transported by the electron beam

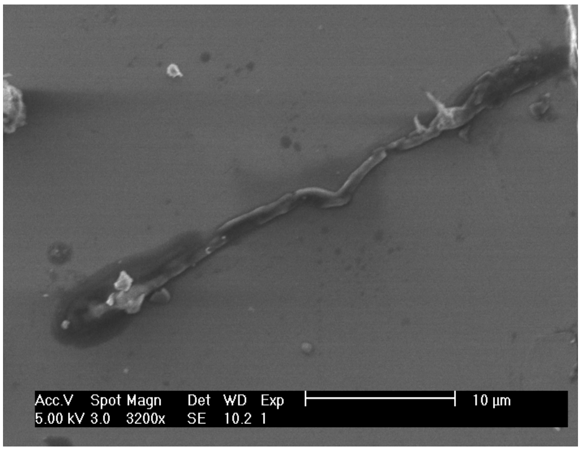


Fig. 5. SEM micrograph revealing the worm-shaped deposited carbon with tree initiation configuration, characterizing an electric discharge occurrence

Two of the most characteristic features of the described emission are the unpredictability of its behaviour and the variability of its properties. It happens occasionally during an irradiation, independently on beam parameters.

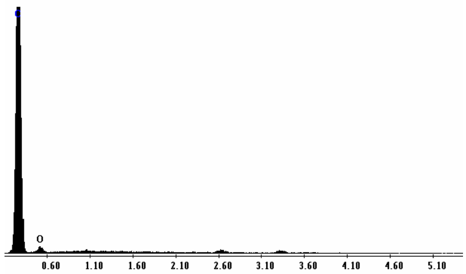


Fig. 6. Typical x-rays diffraction analysis of the ejected matter

4. Conclusion

Fast electrons emission was observed under D^+ ions irradiated graphite. The evolution of the energy distribution of the described emission indicated direct evidence for intrinsic electric field occurrence. The formation of tracks and fractures on the exposed collectors with embedded pure carbon structures constitute a signature of an electric discharge production and an electron beam that originated in the irradiated target. According to the conditions of the experiment, the only possible interpretation of the described findings is that they are induced by an explosive emission at a microscopic scale.

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