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Development of Double Discharge Pulsed Electron Beam Generator and its Preliminary Applications in Material Processing

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Abstract

This article presents the construction of a fast, intense electron beam generator, several of its operational properties and its preliminary applications. A fast filamentary discharge produced in a tube filled with Argon gas at pressure of about 0.1 torr. An electron beam is obtained with a current intensity of about 0.6 A for a 25 ns duration. The length of the filamentary discharge and the behavior of the beam in the magnetic field are examined. The interaction of the beam with different targets was investigated by Scanning Electron Microscope. It is also demonstrated that the device can be used to drill holes of several tens of microns in diameter and it can be used for material coating.

Key Words: Electron beam, Fast pulsed discharge, Material processing

1. Introduction

Highly focused electron beams are required in many applications because they are amenable to rapid and accurate control in space and time. Such electron beams can be produced via plasma-based pseudospark or double discharge devices. The pseudospark devices [1] can generate approximately 200 A, 100 ns electron beam discharges. The maximum electron energy has been found equal to the energy supplied by the applied voltage. However, the mean energy of the electron has been measured to be only 50-70 percent of the applied voltage. The discharge in the pseudospark device is enhanced by the insulator surface, which is a long term disadvantage for industrial applications.

The double discharge pulsed electron beam generator [2] (DDPEBG), on the other hand, operates without any contact with an insulator surface and an intense filamentary discharge is developed along a low pressure gas tube. This type of device was developed by using a common hollow cathode [3,4] for both DC discharge and pulsed discharge. This leads to an increase of the length of the filamentary discharge that helps the stability of the discharge and extends the range of the working pressure range. The capability of the device to operate at high repetition rate is important for the demands of material processing experiments. The electron beam energy distribution has been extensively investigated at [5,6], and it has been found that the main energy of the energetic electron spectrum is 60-76 percent of the applied voltage.

Well-known are the abilities of high power pulsed lasers to drill small diameter holes. However, the costs of such laser devices are high and the task of drilling into metals is difficult because of the target reflectivity (the metal surface) and, as the hole is being drilled, the reflectivity of the plasma layer that forms just above the surface. At the beginning of a pulse the reflection is more than 90%, and the total efficiency is only about 20% over its duty cycle. Further loss is incurred as the expanding plasma acts as a shield between the radiation and the target surface.

With electron beams, the energy can be deposited only within a small layer at the target surface. An intense pulsed electron beam can be used more effectively for material processing than lasers, because there is less energy loss than the loss due to reflection of a laser beam. Pulsed electron beams offer a simpler and cheaper solution for material treatment and drilling in the micrometric domain. (Indeed, DDPEBG has been used for fine drillings in metals such as tantalum, tungsten, and copper.) Also, applications such as hard coatings, thin film technology, and electron beam lithography might be taken into consideration.

Thus, it is with these considerations in mind that the DDPEBG technique might prove to be an excellent alternative to laser drilling.

2. Experimental set-up

The main aim of these studies is to generate an intense electron beam via a new method by superposing a fast pulsed discharge over a continuous glow discharge. An apparatus was constructed as shown in Figure 1. The main part of this apparatus is a quartz tube of 20 cm in length with 30 mm internal diameter containing three hollowed cylindrical electrodes positioned some distance from each other, as shown in the Figure. The first electrode K_{12} acts as a cathode for both the steady glow discharge and the pulsed discharge. $A_2$is the anode to establish glow discharge. The anode A_1 is used for the pulse discharge. The continuous discharge is achieved in between common cathode K_{12} and anode A_2 by using a 5kV/100 mA DC power supply, which is current-limited by ballast resistor R_2. High voltage pulses are generated in between the common cathode K_{12} and anode A_1 by a ceramic bank of capacitors C_1 that are charged through the resistor R_1. The capacitors are rapidly discharged by means of a rotary spark gap (SG) switch, wherein the high voltage pulse is applied to the electrodes while the glow discharge is present. For a specific value of the DC current and a specific pressure, a filamentary pulse discharge is obtained along the axis of the tube, producing an intense electron beam.

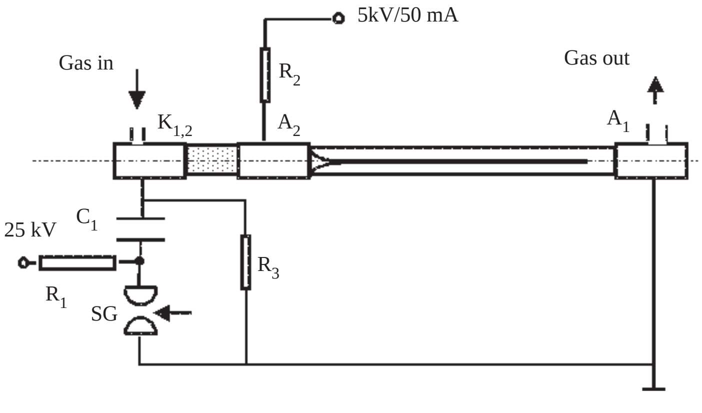


Figure 1. Experimental set-up of the DDPEBG (SG is spark-gap, R_1 = 80 MΩ, R_2 = 80 kΩ, R_3 = 110 MΩ, C_1 = 0.68 nF).

Reliable micro processing necessitates reproducibility and the stability of the discharge parameters. Shot to shot reproducibility was assured by stabilizing the rotary spark-gap switch and by optimization of the discharge geometry by using high quality ceramic capacitors.

3. Properties of the discharge parameters and discussion

A series of experiments were done to obtain properties of the discharge parameters. The high voltage was measured by using a fast high voltage divider and the current was measured by means of a homemade current shunt. The shunt was waveform-calibrated with respect to a Kenwood fast function generator. The waveforms were recorded by means of a 500 MHz, two channel digitizing Tektronix 620A oscilloscope. Typical voltage and current waveforms are shown in Figure 2. The voltage waveform, shown in the upper part of the Figure, describes the anode voltage evolution for a bank of 0.680 nF capacitor. As it is seen from the curve, voltage increases up to a certain value, at which there is breakdown of the gas, then the voltage decreases during the discharge through the tube. The curve in the lower part of the Figure 2 shows the current waveforms of the discharge. As can be seen in the Figure, the current reaches its maximum value in the second half of the corresponding voltage peak value. From Figure 2, the total discharge peak current is found to be 41.0 A.

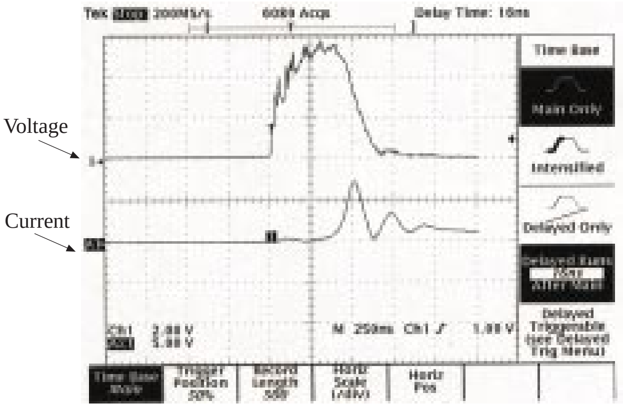


Figure 2. Typical voltage and current temporal behavior of the pulsed discharge. Each division of the vertical axis of the voltage and current curve represents 2 kV and 5 V, respectively.

The total current of the electron beam shown in Figure 3 was measured via a Faraday cup. A Faraday cage is constructed to eliminate electromagnetic noise. The electron beam current is found as $I_{beam} \cong 0.60$ A. The appearance of the total current in the Figure can be explained as follows: the sharp minimum corresponds to the peak electron current, it decreases slowly because of the ion production and increases again a little bit since the secondary electron production by the ions.

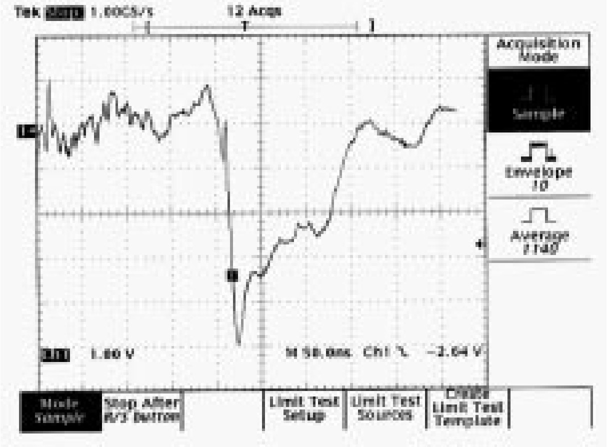


Figure 3. Typical current variation of the electron beam.

An important property is the length of the filamentary discharge, for it is a measure of the stability of the discharge. The filamentary discharge length depends on both the gas pressure inside the tube and the continuous discharge current. The filamentary discharge length is plotted at a current around 20 mA and shown in the Figure 4 for different gas pressures. As it is seen from the Figure, beam length increases with decrease in pressure, and making it obvious that the pressure must be kept within a very restrictive range (0.05 - 0.5 torr) during operation of system.

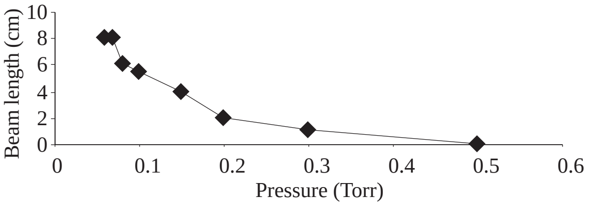


Figure 4. Variation of filamentary discharge length vs. gas pressure.

Sometimes, a particular breadth of area needs to be irradiated by the electron beam. In that case, the electron beam must be deflected and aligned to the given area. Figure 5 shows deflection of the electron beam in the magnetic field. A magnet having arbitrary field intensity is placed somewhere and moved toward the discharge tube, and the deflection distance from the axis of the tube is measured. Horizontal axis on the Figure is labeled from far to closer relative distance of the magnet to the axis of the tube. The vertical axis is the corresponding deflection of the beam from the axis of the tube. The curve is almost linear in the range between magnet position 1 (farther point) and magnet position 2 (a closer point). For closer distances, the deflection increases sharply, as one can observe in the Figure. In order to make a fine adjustment for the position of the beam on the target, this linear region might be used.

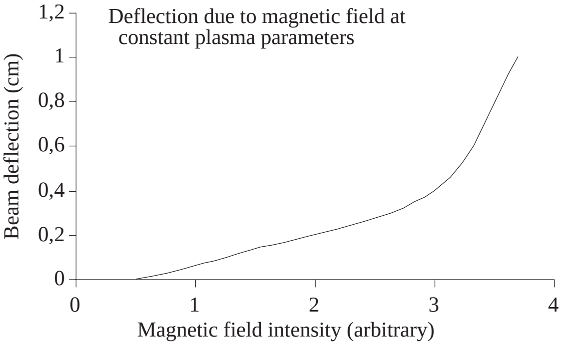


Figure 5. Deflection of the electron beam under the influence of a magnet with arbitrary field intensity, as the magnet approaches the discharge tube.

One example application for the constructed DDPEBG device, is using it for material processing. To test its usability, target materials (in the form of foils or wires) were placed in front of the anode A_1 (see Figure 1) and secured by using special holders. Preliminary studies were done to see the interaction of the electron beam with a target material. First, a copper foil was used as a target. After irradiating for a number of shots, the copper foil was drilled. Figure 6 shows a picture of the drilled copper foil taken by JSM-6400 scanning electron microscope (SEM).

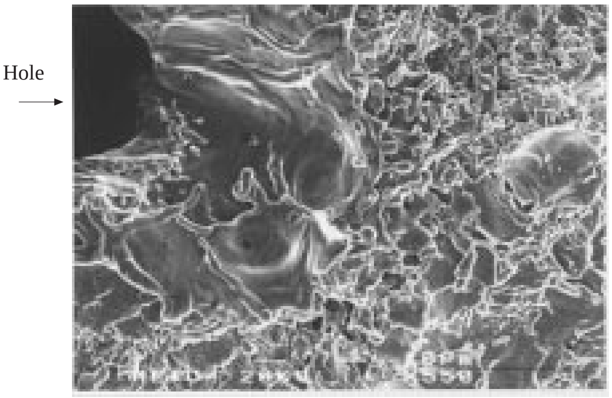
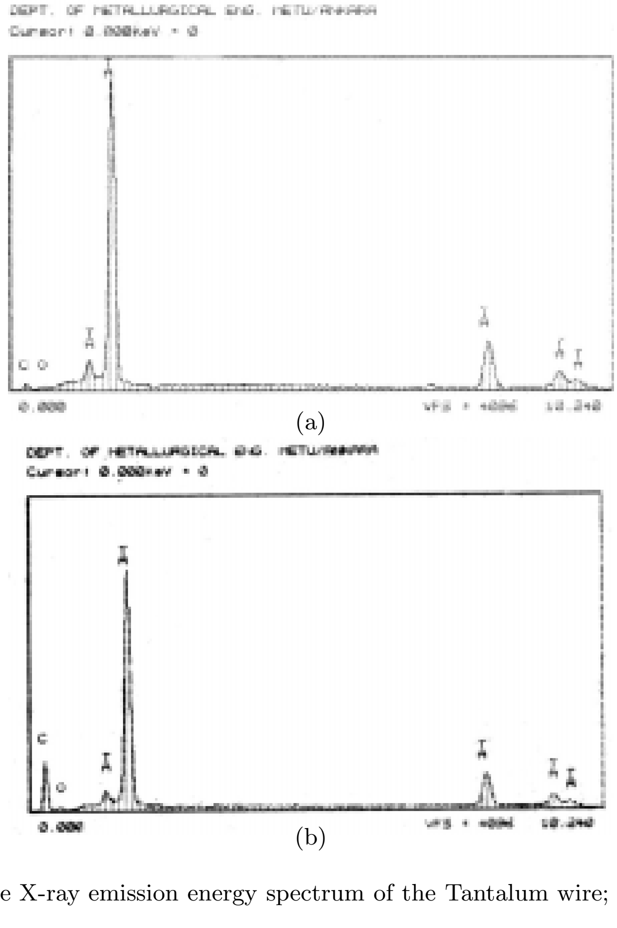


Figure 6. Typical SEM picture of a hole drilled by electron beam in a copper foil.

A conical hole drilled on the 70 μm thick copper foil in which about 30 μm maximum and 5 μm minimum diameter are measured. The shape of the hole is conical rather than cylindrical because the outer electrons of the beam lose part of their energy by colliding with the gas molecules. Several metallic targets such as copper, tantalum, titanium etc. were irradiated under different conditions. Experiments can be varied by changing the number of shots of the beam for different foil thickness and for different values of gas pressure and voltage values, for instance.

A wire can also be used as a target material. A tungsten wire of 200 μm in diameter was placed transversely to the incident beam, after irradiation a hole of about 50 μm was measured.

Tantalum wire had also been exposed to the beam. Figure 7 shows a spectral drawing taken by SEM for



(a)

(b)

Figure 7. Comparison of the X-ray emission energy spectrum of the Tantalum wire; (a) before irradiation and (b) after irradiation.

the element analysis of the tantalum before and after irradiation. The x-axis indicates the emission energy spectrum lines in the range from 0.0 to 10.240 keV and y-axis shows the relative intensity. The expected X-ray emission spectrum lines of tantalum wire are Mβ (1.765 keV), Mγ (1.964 keV), Lα (8.146 keV), Lβ_1 (9.343 keV), and Lβ_2 (9.651 keV), as is shown in Figure 7 (a) before irradiation. In Figure 7 (b) a carbon peak is observed in the spectrum lines after irradiation, via Kα_1-Kα_2 (0.277 keV). The carbon peak appears due to the residual of carbon at the vacuum environment. So it is possible to use a hydrocarbon gas such as CH_4, C_2H_2 as a precursor gas for carbon deposition at our device.

4. Conclusions

The operation of a new type of intense electron beam generator was achieved. Preliminary experiments regarding the interaction of the beam with different targets were performed. Drilling fine holes in metallic targets is easily obtainable. An alternative low cost method for drilling fine holes in metallic targets was put into evidence. Further experiments will deal with the optimization of the device, decreasing hole diameters, precise controlling of the position of the hole, thin film deposition and X-rays generation by using this device.

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