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Operation of an electron beam initiated metallic plasma capillary discharge

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ABSTRACT

In this work, a simple and different technique of generation of a metallic capillary discharge plasma is being studied. The capillary is initially evacuated to a low pressure of below 10^{-2} Pa. The transient hollow cathode discharge (THCD) produces high energy electron beam that subsequently is employed to vaporize the anode material that will inject into the capillary and initiates the discharge through the capillary. The EUV energy emission produced is calculated to be an estimation in the order of tens of milijoules. At the peak of the current of around 9 kA, the electron temperature of the plasma achieved is estimated to be around 11 eV.

1. Introduction

Capillary discharge is a versatile plasma device that is being investigated for application as EUV source for few decades because of its capability in producing moderately hot and dense plasma [1–6]. In the past, the capillary discharge had been operated in two modes: ablative mode and gas-filled mode.

Ablative capillary discharge was first introduced in the 1950s. In this mode, the plasma is produced by initiating the discharge along the wall of polymeric material and the ablation of the capillary wall material acts as the fuel for the plasma. When the main breakdown occurs, a high current pulse is generated and it heats up and ionizes the ablated wall material rapidly to form the plasma within the capillary. Study of ablative capillary discharge by using different materials such as polyacetal [7], polyethylene [8] and Polyvinyl chloride (PVC) [1,2] to produce plasma that emits at the desired wavelengths has been carried out by many research groups.

The gas-filled capillary discharge was introduced in the 1990s. In this mode, a gas is used as fuel for producing the plasma. The operating gas is compressed and heated by a pulsed current to form plasma inside the capillary. Several types of gases (Ar, H_2, Ne and O_2) [3–6,9–11] have been tested.

Recently, pure metallic capillary plasma has been considered. Several methods of producing pure metallic capillary plasma have been explored. A pulsed laser has been used to evaporate Titanium or Aluminium in the hollow cathode region and subsequently diffuse into the capillary volume and produces metallic capillary plasma [12]. By using the same arrangement to evaporate titanium in the hollow cathode region, the alumina capillary is replaced by a set of titanium rings with alumina spacers. This modification aimed to enhance titanium plasma formation inside the capillary volume due to interaction between the hollow cathode emitted electron beams and the titanium rings [13]. Metal vapor gun concept was implemented in generating metallic capillary plasma [14]. In this experiment, Cd vapor was produced by heating up a cadmium electrode with capacitive discharge at room temperature and subsequently injected into the capillary. The discharge was initiated by pre-ionizing the Cd vapor filled capillary channel with a low current pulse. In another work [15], a silver electrode was heated up by a moderate current pulse at room temperature to produce silver vapor to be injected into the polyacetal capillary. The investigation of Ti capillary discharge was also reported in the year 2006 [16]. In this case, Ti wire was inserted into the secondary alumina capillary and was exploded in order to create titanium plasma jet to be injected into the main capillary.

In the present work, we have tested another mode of operation of the capillary discharge. Similar to the vacuum spark operated in our laboratory [17,18], we make use of the THCD electron beam to bombard at the anode to evaporate some anode

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material and fill the capillary channel, causing the main discharge to occur and eventually plasma of the anode material is formed in the capillary.

2. Experimental setup

The schematic diagram of the electron beam initiated capillary discharge system is shown in Fig. 1. In this system, a bullet-shaped stainless steel anode is threaded in order to screw it in the brass holder. The anode has a length of 18 mm. The diameter of the threaded end of the anode is 10 mm. The pointed end of the anode has a diameter of 2 mm. The distance between the anode tip and the capillary end is negligible as the anode tip is "attached" to the capillary end. The stainless steel cathode is a circular disk with a 5 mm diameter aperture at the center in order to allow the penetration of electric field generated from the anode-cathode potential to the hollow cathode region. This gives rise to the transient hollow cathode discharge (THCD) configuration that will assist in the initiation of the main breakdown [19]. A quartz capillary tube with a length of 10 mm is sandwiched between the stainless steel anode and cathode. The capillary channel has an inner diameter of 1 mm and it is aligned along the same axis with the tip of the anode and the cathode aperture. The whole system is evacuated to a low pressure of below 10^{-2} Pa by using a turbomolecular pump backed by a rotary pump.

The capacitor bank consists of six doorknob ceramic capacitors connected in parallel giving a total capacitance of 21.6 nF. The spark gap is closed completely in our experiment. Thus, there is no voltage divided capacitively between the spark gap and the capillary. The capacitor bank is discharged at a voltage of 24 kV to produce a discharge current of about 9 kA through the capillary channel. The discharge is triggered by a low energy discharge between the trigger pin and the cathode plate inside the hollow cathode region (Fig. 1). This low energy discharge inside the hollow cathode region leads to the initiation of the transient hollow cathode effect that gives rise to the formation of the pre-breakdown electron beam.

An optical spectrometer (Ocean Optics HR 4000) which has a spectral response range of 200 to 1050 nm is employed to allow us to identify the chemical constituents in the plasma. The optical spectrometer is calibrated with a HG-1 Mercury Argon Calibration Source (Ocean Optics). The optical fiber is coupled to the spectrometer and it is mounted at the end-on position in order to collect maximum light emission from the capillary plasma. A 100-PIN-250 diode, also mounted end-on, is used to detect the X-ray emission produced by the bombardment of the THCD electron beam on the anode which indicates the occurrence of the electron beam. The PIN diode is covered by 24 μm of aluminized Mylar to eliminate radiation in the EUV, UV as well as visible regions. A SXUVHS5 Si/Zr 100/200 nm photodiode (see Fig. i in appendix) is employed to detect the time-resolved EUV emission of the capillary plasma. It is sensitive to the wavelength range of 11 to 18 nm. The discharge current is measured by a magnetic pick-up coil operated with a passive RC integrator. The signals of the magnetic probe, X-ray PIN diode, and EUV detector are registered by using a Tektronix DPO3054 high speed digital phosphor oscilloscope.

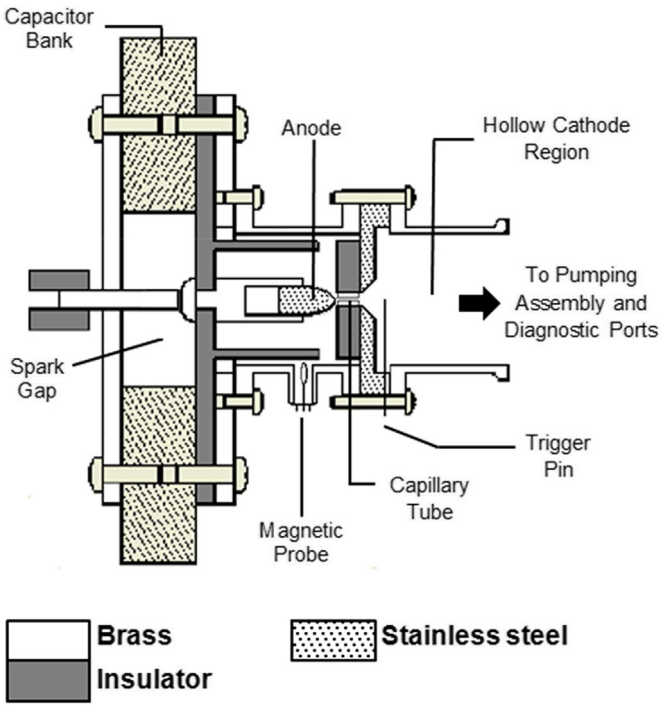

Fig. 1. Schematic diagram of the electron beam initiated capillary discharge setup.

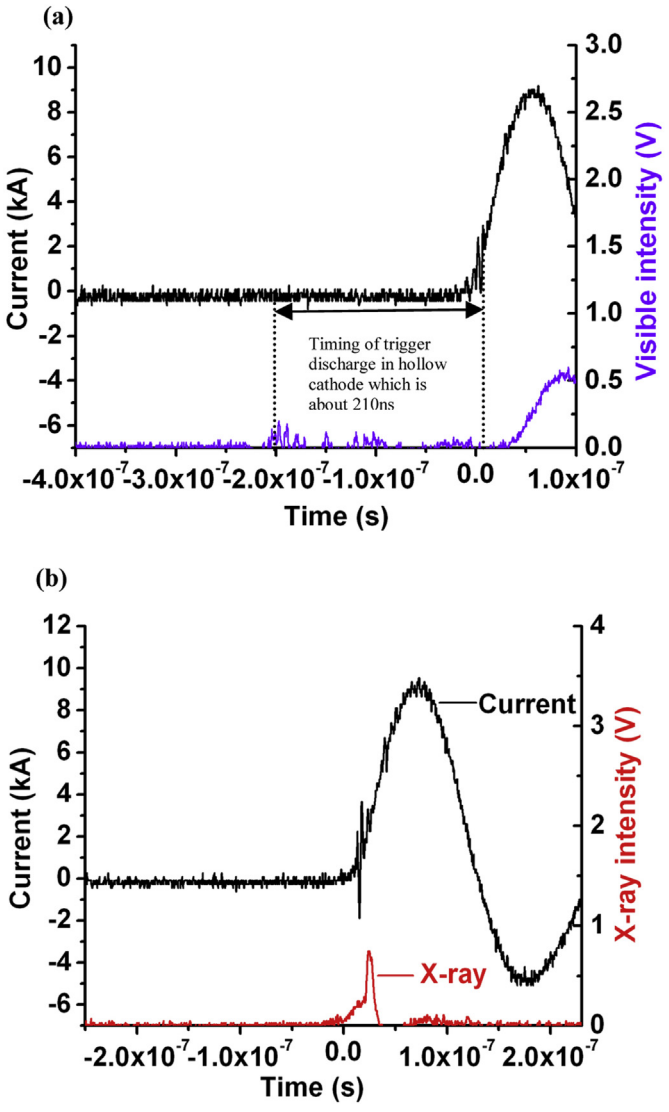

Fig. 2. (a) Low light emission at the HCR at the pressure of 10^{-3} Pa. (b) Typical current signal and X-ray emission at discharge voltage of 24 kV and pressure of 10^{-3} Pa.