Compact capillary discharges as sources of EUV radiation and plasma jets: physics and applications

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Pulsed capillary discharge (PCD) devices are currently investigated as pulsed radiation sources emitting in the extreme ultraviolet (EUV). Most of the performance of PCDs as EUV radiation sources depends on the formation of a uniform and reasonable stable plasma column inside the capillary. To achieve this condition some kind of discharge initiation is very often required. This is particularly important in the case of gas filled, low pressure PCD operation. A suitable mechanism to create initial conditions for fast and uniform capillary plasma formation is the injection of an electron beam into the neutral gas filling the capillary. Axial electron beams are produced naturally in transient hollow cathode discharges (THCD). Due to the penetration of the applied potential, the cathode aperture creates conditions for local ionization in the hollow cathode region (HCR), before any significant ionization takes place in anode-cathode gap. The appearance of the hollow cathode plasma leads to the formation of on-axis electron beams, which are extracted from the HCR by the electric field associated with applied voltage pulse. This discharge initiation mechanism has been used in a low inductance PCD device, which can achieve a nominal 2 kA, less than 10 ns, current pulse, when the capillary is surrounded by a coaxial return conductor that shields the capillary plasma. Time and space resolved observations of ionization growth indicate that the pre-breakdown processes are characterized by the formation of an electron beam assisted fast ionization wave, with characteristic speed of the order of 10^7 m/s. When the PCD is operated as an EUV radiation source, it differs from other discharge pinch plasma sources in using a much smaller amount of stored electrical energy (<1J) but at a higher energy input rate, leading to small instantaneous thermal input to the electrodes and reduced thermal loading problem in multi-kHz operation. Numerical simulations using the 2-D radiation MHD code Z* have been carried out to examine both the plasma dynamics and the electrodes thermal loading issues, within the context of optimizing EUV radiation efficiency. A PCD source working at 5 kHz in an Ar:He admixture has been developed. Continuous operation at 3 Khz has demonstrated a lifetime > 10^9 shots. The characteristic geometry of the PCD, a narrow open ends tube with a large aspect ratio, establishes natural conditions for the generation of plasma jets that propagate in the neutral background gas surrounding the capillary. Operation of the discharge in different gases, in a continuous pulsing mode, at frequencies up to 50 Hz, and in a pressure range between 0.5 to 1.0 Torr produces plasma jets of characteristic temperature and density n the tens of eV, and 10^{14} cm^{-3}, respectively. When the discharge is operated in methane, it is found that irradiation of Si (100) substrates with PCD plasma jets, results in the formation of carbon nanostructures. Experimental results and computer simulations addressing the main issues of an electron beam initiated PCD will be presented, including discharge initiation, radiation and plasma jets emission, EUV source characterization, and surface modification under PCD plasma jets irradiation.