A miniature capacitive probe array for transient high voltage capillary discharges

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The design and construction of a millimeter size noninvasive capacitive probe array to investigate ionization growth phenomena in pulsed capillary discharges are presented. The probes estimated to be characterized by a time response better than 0.5 ns, with very good electric noise rejection. The probes have identified a fast ionization wave in the prebreakdown phase of a hollow cathode initiated fast pulsed capillary discharge.
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I. INTRODUCTION

Fast pulsed capillary discharges are currently being investigated as efficient radiation sources emitting in the vacuum ultraviolet to soft x-ray region. The properties of this type of device are unique in terms of spectral range, characteristic emission time, and source size.[1–3] To achieve such performance a high rate of current rise is needed, together with a very short current pulse duration. Under these conditions some kind of on-axis discharge initiation is required to achieve a high temperature transient plasma detached from the capillary wall. In this respect, we have recently reported on a pulsed hollow cathode capillary discharge device that combines the physics of the traditional capillary discharge with that of the transient hollow cathode discharge (THCD).[4]

The THCD is a low pressure, high voltage electric discharge, which is characterized by the presence of an axial aperture in the cathode.[5] The main effect of the cathode aperture is to modify the geometry of the externally applied field, as to create conditions for local ionization in the hollow cathode region, well before significant ionization builds up in the interelectrode space. The hollow cathode leads to the formation of an on-axis electron beam, which plays an important role in breakdown formation.

The pulsed hollow cathode capillary discharge couples a suitable hollow cathode design with a conventional capillary discharge and operates at low to medium pressure, usually below 1 mbar. Unlike a conventional THCD, the capillary typically has a very high length to radius aspect ratio. For fast pulsed discharges, the capillary is surrounded by a coaxial return conductor, in close contact with the outer surface of the capillary, in order to minimize circuit inductance. This leads to a geometry in which a large portion of the capillary length is shielded from the applied electric field. Breakdown formation in such shielded geometry requires the propagation of an ionization structure, which penetrates the shielded and practically field free region before complete voltage breakdown can occur. Recent theoretical studies[6] have shown that the on-axis electron beam produced in a pulsed hollow cathode capillary discharge assists the formation of a fast propagating ionization wave. Although indirect experimental evidence supports the existence of the ionization waves predicted by the computer simulations, no actual observations have been reported in pulsed capillary discharge investigations. However, similar types of ionization waves have been observed in more conventional shielded discharge tubes with large length-to-radius ratio.[7–9]

Capacitive probes have been used to diagnose several parameters in different types of transient electric discharges.[10–12] Their main advantage as compared to other types of diagnostics is that capacitive probes are nonintrusive. We have previously reported on the design and performance of an integral array of capacitive probes to investigate ionization growth in transient hollow cathode discharges.[13] A set of up to six ring probes was used to measure the formation of a moving virtual anode in a transient hollow cathode discharge.[13] The use of an array of identical capacitive probes provides information on a spatial dimension which is not available with traditional single capacitive probe. The design is particularly convenient for an axisymmetric discharge geometry, is noninvasive and easy to construct, with good electromagnetic noise rejection capabilities.

There are some difficulties in trying to implement an ionization growth diagnostics for capillary discharges based on such capacitive probes, the most important issue being the tight aspect ratio that characterizes fast pulsed capillary discharges devices. This geometrical constraint and the need of an outer capillary shield, which is axially symmetric and tightly coupled to the capillary in order to provide a low inductance current return path, precludes the use of individual wire probes, as even with a miniature size, they are comparable with the characteristic dimensions of the capillary, and thus, highly invasive.

In this article we present the design and implementation of a miniature capacitive probe array based on printed circuit technique for integrated circuit fabrication. The probes and

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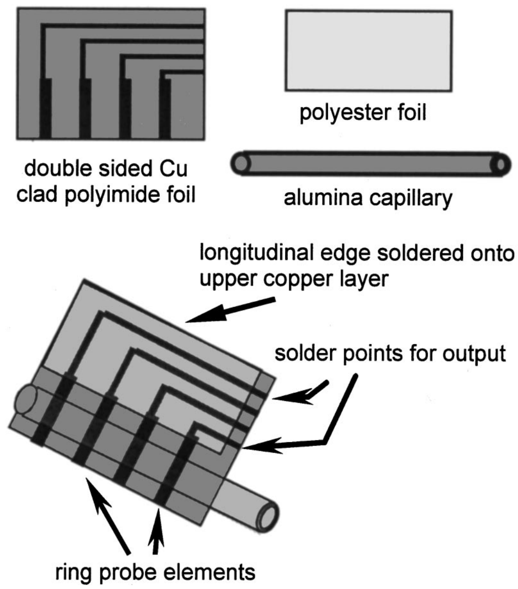

FIG. 1. Capacitive probe assembly.

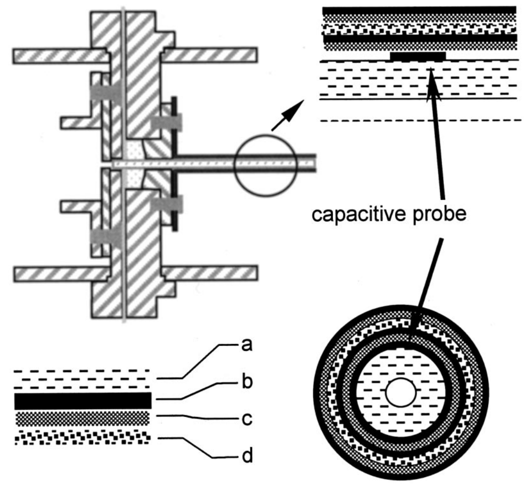

FIG. 2. Pulsed capillary discharge device and capacitive probe schematics. (a) Capillary wall, (b) copper clad, (c) polyimide, and (d) polyester.

the signal pickup are integrated into the current return structure and remain noninvasive, even when compared with the submillimeter dimension of a capillary tube. The probe array was used to investigate ionization growth in the prebreakdown phase of fast pulsed hollow cathode capillary discharges reported previously.[4] Preliminary results indicate that the prebreakdown process is characterized by a fast ionization wave, as predicted by theoretical consideration.[6]

II. EXPERIMENTAL DEVICE

Bearing in mind the earlier considerations, a set of four capacitive probes was designed and tested to investigate ionization growth in a 35 mm long, 1.6 mm inner and 3.2 mm outer diameter capillary. The probes are 1.5 mm wide conductive rings, which are coaxial with the capillary. The probes are equally spaced along the capillary, at 10 mm separation. The rings are etched from a double sided copper clad polyimide sheet of 50 μm thickness, using standard printed circuit board techniques. A master pattern of the probes structure was prepared accurately on a computer. Etch resistance ink was used to lay down the probes pattern on one side of the copper polyimide sheet and a ferric chloride etch was used to remove the unwanted area. The probes pattern is shown in Fig. 1. Copper on the other side is not removed and is used both for ground shielding of the probes and as the return path for the capillary discharge current, as described in the following.

The electric signal from each ring probe is brought out to a point near the main ground electrode of the discharge through copper strips as shown in Fig. 1. Each copper strip acts as a short transmission line, with characteristic impedance of $\sim$5 Ω. Under these conditions signal pickup point for each probe is at the same potential in the presence of inductive or capacitive voltage pickup. Subminiature 50 Ω coaxial cable is then used to bring each signal out to a bulkhead connector, through which the signal is passed outside the discharge chamber. When the polyimide copper clad sheet is wrapped around the capillary, the ring probes are formed. An additional layer of 50 μm polyester is added at the position shown in Fig. 1 to insulate the signal carrying strips from the ground current return of the probes. The wrapping continues to ensure that the ring probes are completely encircled. The longitudinal edge of the wrapped up foil assembly is then soldered onto the adjoining copper surface in contact, thus forming a complete cylindrical sleeve. This sleeve acts as the coaxial current return conductor for the main discharge. Furthermore, this sleeve completely shields the probes and the signal pickup conductors, providing excellent isolation of the probes from electrical noise. A schematic of the capillary discharge assembly is shown in Fig. 2. The insert shows the probe arrangement along the capillary, with the different conducting and insulating layers described earlier, both in axial and radial profile.

An equivalent electric circuit for a single probe is shown in Fig. 3. The probe couples capacitively to the capillary shield and capillary discharge plasma. The corresponding circuit equation can be written as

$$V_0 = R\frac{d}{dt}(C_p - V_p) - RC_s\frac{dV_s}{dt}, \quad (1)$$

where V_0 is the probe signal, V_p and V_s are the local plasma and shield potential, C_p and C_s are the probe coupling capacitance to the capillary plasma and capillary shield, and R can be taken as the 50 Ω signal cable impedance. A detail analysis of a similar capacitive probe equivalent circuit was presented previously.[4] In the present setup, if the capillary interior is assumed to be filled with a perfect conductor and the probes are tightly coupled to the alumina capillary, using

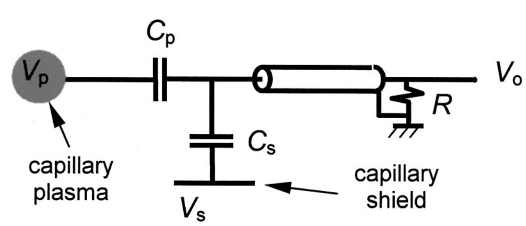

FIG. 3. Equivalent electric circuit for a single probe.

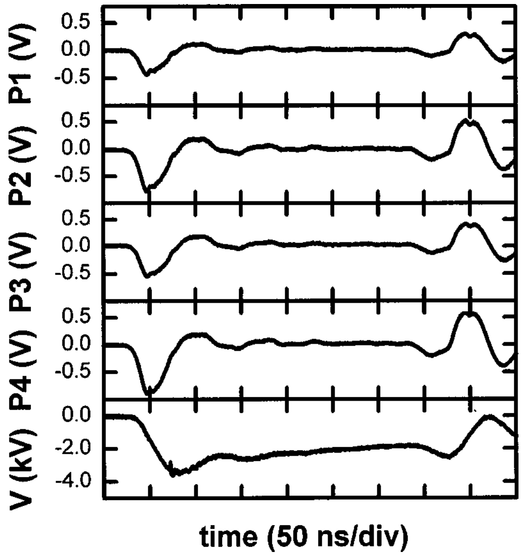

FIG. 4. Calibration signals for a four probe array. P1–P4 correspond to the capacitive probes signals, and *V* is the applied voltage.

available values of the dielectric constant of alumina and polyimide, the capacitances are estimated to be $C_p \approx 7 \times 10^{-13}$ F and $C_s \approx 1 \times 10^{-11}$ F, respectively. Under these conditions, if the characteristic time scale for variation of V_s is much longer than that $C_s R \approx 5 \times 10^{-10}$ s, the probe signals satisfy the relation

$$V_0 \approx R \frac{d}{dt}(C_p V_p). \tag{2}$$

This is in general a good approximation in the time interval associated with the prebreakdown phase of the discharge, as no significant current is expected to flow over the return path until a full conducting channel is established inside the capillary.

III. CALIBRATION

The time response and sensitivity of the probe array have been tested using a conducting wire inside the capillary. A 1 mm diameter copper wire sufficiently long compared with the capillary tube was placed inside the capillary. The wire was made to have a good contact at the cathode while leaving a small gap between the wire tip and the current return electrode at the end of the capillary, formed by the outer conducting sleeve described in the last paragraph. A calibration voltage pulse is then applied across the anode and cathode. Initially, the probes will follow the potential of the applied voltage pulse. At some point, a spark is formed between the wire end and the anode and the voltage will collapse. Characteristic signals from the four probes in the array are shown in Fig. 4. The signals P1 to P4 correspond to the probe array, with P1 closer to the ground electrode of the main discharge assembly, as shown in Fig. 2. Bottom trace corresponds to the applied voltage. Signals P1 to P3 and voltage have been recorded at 5 Gs/s sampling rate, and P4 at 1.25 Gs/s. In Fig. 5, Q1 shows a numerical integration of the signal P1 from Fig. 4, together with the measured voltage signal, *V*, across the electrode plates. It is seen that the inte-

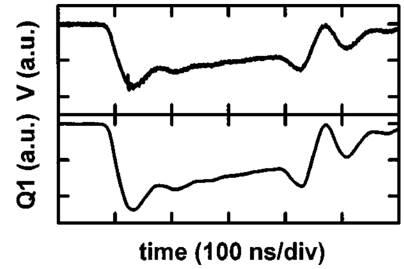

FIG. 5. Comparison between the applied voltage, *V*, and the numerically integrated signal from P1, Q1.

grated signal matches very well the time evolution of the voltage pulse, in agreement with Eq. (2). The voltage signal was obtained with a resistive monitor and has a lower frequency response compared with the capacitive probe.

IV. EXPERIMENTAL MEASUREMENTS

Theoretical consideration on the breakdown formation processes in long shielded capillary discharges indicates that the process is initiated by a fast ionization wave.[6] The miniature capacitive probe array has been applied to investigate such ionization waves in our pulsed hollow cathode capillary discharge device.

We have conducted a series of experiments in a compact fast pulsed hollow cathode capillary discharge device,[4] which is based on a very low inductance high voltage discharge geometry, in which the energy storage medium is a pair of parallel plate electrodes with the discharge capillary located on-axis. This device combines the features of a transient hollow cathode discharge with the special characteristics of the capillary discharge. The device is currently being used to investigate potential applications as a pulsed extreme ultraviolet radiation source[3] and vacuum ultraviolet to extreme ultraviolet (XUV) lasing schemes. Several diagnostics have been incorporated into the device. These diagnostics include current and voltage monitors integrated into the ground electrode of the storage capacitor, x-ray diode to measure fast radiation pulses, Faraday cup to measure pulsed electron beams, and time and space resolved XUV spectroscopy. Further details of the different diagnostics can be found elsewhere.[3,4] Although this combination of different diagnostics can provide a good characterization of the emission properties and plasma conditions during the discharge evolution, no information, apart from prebreakdown electron beams, is obtained from the physical phenomena associated with the prebreakdown phase.

Figure 6 shows characteristic signals for a discharge in argon, at -15 kV applied voltage. To enhance the hollow cathode effect, a pressure gradient is established across the capillary, with high pressure, 0.4 mbar, at the cathode side, and ~ 2 μbar at the anode side. In this case the capillary shield is at ground potential, acting as the anode. The signals, from top to bottom, correspond to the voltage *V* across the plate electrodes, the capillary discharge current I_D, the electron beam signal current I_{eb}, and the four capacitive probes, P1 to P4. P1 identifies the probe closer to the anode plate, and P4 corresponds to the probe closer to the capillary tip, as

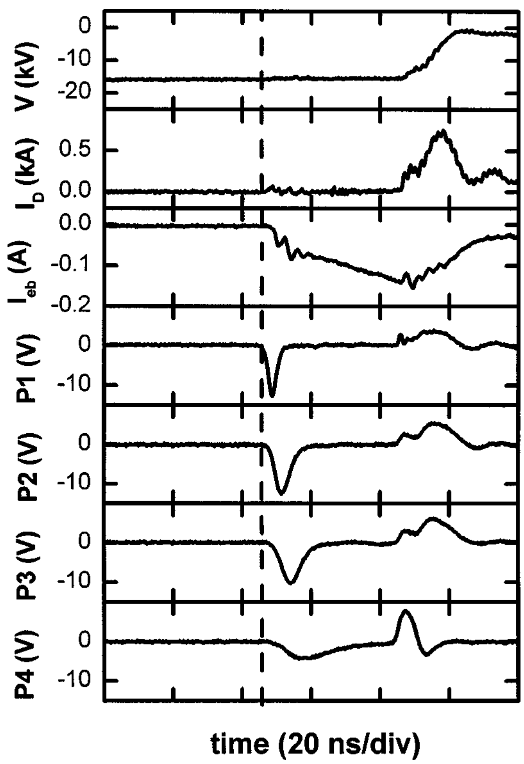

FIG. 6. Characteristic signals for a discharge in argon. The signals, from top to bottom, are V: voltage across the plate electrodes, I_D: capillary discharge current, I_{eb}: electron beam current signal, and P1–P4: capacitive probe signals. P1 identifies the probe closer to the anode plate, and P4 corresponds to the probe closer to the capillary tip.

seen in Fig. 2. The total duration of the voltage pulse is ~650 ns. The voltage trace shows the final 100 ns, prior to voltage collapse. About 60 ns before complete voltage collapse, as indicated by the dashed line across the different plots, a negative signal is seen to rise in sequence in the four capacitive probes, starting at P1, the capacitive probe closer to the plate electrodes. As the signal rises in P1, the electron beam signal is also seen to start growing. The initial signal in all capacitive probes is characterized by a single negative peak, after which the signal returns to zero. At the onset of voltage collapse a positive signal is seen to rise in all probes. To assist with the physical interpretation of the probe signals, a numerical integration has been performed. The result for P1 is shown in Fig. 7. The upper trace, V, is the voltage

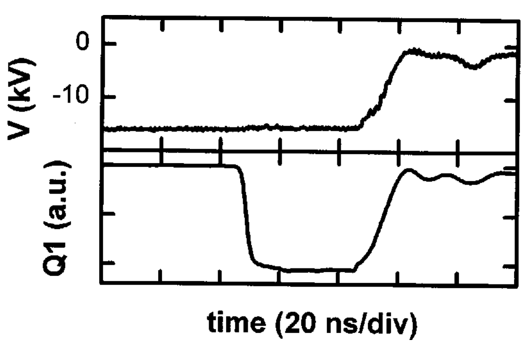

FIG. 7. V: applied voltage, and Q1: numerical integration of signal P1 in Fig. 6, showing the growth and fall of the plasma potential at the position of P1.

across the electrodes, and the lower one, Q1, is the numerical integration of signal P1 in Fig. 6. According to Eq. (2), $Q1 \propto C_1 V_1$, which corresponds to the product between the plasma potential V_1 and the coupling capacitance C_1 of the ring probe relative to a capillary plasma. The negative rise in Q1 indicates that a plasma has formed at the position of P1 and that the external potential has moved up to the position of P1. The sequential rise of signal from P1 to P4 seen in Fig. 6 can be interpreted as the signature of a potential wave propagating along the capillary, from the cathode towards the anode, with characteristic speed $\sim 3.5 \times 10^6$ m/s. For this process to take place, a weakly conducting plasma has to form inside the capillary. As in the case of the THCD,[5,14] ionization inside the capillary is assisted by electron beams emitted from the hollow cathode region located behind the cathode electrode. The time integrated signal Q1 in Fig. 7 indicates that the positive excursion in the probe signals corresponds to the collapse of the plasma potential. This collapse of the plasma potential matches the collapse of the external voltage, as shown in Fig. 7. At this time a fully conducting plasma has formed inside the capillary, electric breakdown occurs, and the discharge current I_D begins to rise (see Fig. 6). The main features of the observed ionization wave formation agree with numerical simulations for electron beam assisted ionization in shielded capillary discharges, reported elsewhere.[6]

V. DISCUSSION

It is known that plasma conditions in fast pulsed capillary discharges are strongly dependent on prebreakdown ionization phenomena. Our results show that even though the capillary discharge geometry imposes severe constraints associated with the tight aspect ratio and high voltage environment, millimeter size capacitive probes can be successfully used to investigate ionization growth and associated predischarge processes. The use of double sided copper cladded polyimide sheet allows integration of a millimeter size probe array with built-in electrical shield and capillary current return. Construction and installation of the probes is easy. Time response of the probes is only limited by the coupling capacitance to ground and the signal cable impedance, which is estimated at 0.5 ns. Preliminary application of this probe array has identified experimentally the presence of a fast ionization wave in long shielded pulsed capillary discharge.

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