Capacitively Coupled Atmospheric RF Microplasma Devices

Wen Yuan\(^{a}\) and Massood Tabib-Azar\(^{a,b}\)
\(^{a}\)ECE and \(^{b}\)Bioengineering Departments, University of Utah
Salt Lake City, Utah, USA
Email: azar.m@utah.edu

Abstract—We designed and fabricated planar, four-terminal, atmospheric, capacitively coupled (CC), helium RF microplasma devices (MPDs). The operational characteristics of the MPDs are investigated. The microplasma field effect transistors (FETs) are fabricated and investigated, showing that the plasma current can be controlled by a gate bias. The stability of the MPDs is tested under harsh conditions of ionizing radiation and high temperature.

I. INTRODUCTION

Microplasma devices (MPDs) [1-8] are used in displays [4], medical applications [5], antenna, tip-based nanofabrication [6-8], material processing [4, 6-8], and other applications. Although MPDs can carry large current densities and can be immune to ionizing radiation (actually, they can be ionized by external radiation and become more efficient), their applications in switches and amplifiers are not extensively explored. Here we explore applications of atmospheric MPDs as plasma sources for tip-based nanofabrication, and switches and amplifiers for computation and control electronics. We use atmospheric devices to ensure large plasma density for large current densities and stability that is lacking in low-pressure plasma. In this paper, we present results using MPDs with 4 co-planar crossed electrodes that contact the plasma directly and a second MPDs with capacitively coupled electrodes to generate RF plasmas and co-planar electrodes that directly contact the RF plasma for dc characterization.

II. EXPERIMENTAL

A. Device Design

The MPDs have a four-electrode configuration as shown in Fig. 1(a) and 1(b). Two electrodes are used for the plasma ignition and sustention, while the other two electrodes are for the investigation of the plasma dc characteristics.

B. Plasma generation

The RF power is supplied by an HP 8656B Signal Generator and a Mini-Circuits TIA-1000-4 RF power amplifier (12.5 W max). A matching inductor is connected in series with the two electrodes for plasma generation and optimum RF power delivery. The capacitor between the two electrodes and the matching inductor forms an LC resonator which amplifies the voltage between the two electrodes by 20-40 times at its resonant frequency for plasma ignition. The working frequency of MPDs is tuned between 400 MHz to 600 MHz by adjusting the gap between the two electrodes and the matching inductor. Figure 1 (b) shows the image of an MPD with sustained helium plasma at atmospheric pressure. The other two electrodes are connected to a DC power supplier for plasma switch as described later. They can also be used to investigate the plasma dc characteristics.

III. CHARACTERISTICS OF MPDS

The MPDs are operated within helium gas at atmospheric pressure. The plasma-ignition RF signal is determined by the required breakdown voltage across the two electrodes and this voltage follows the Paschen’s Law and it depends on the gas pressure, temperature, electrode spacing and the gas characteristics.

Figure 2 (a) shows the frequency characteristics of plasma device obtained by an HP 8720C network analyzer. A deep and narrow valley indicates a large amplification of the voltage across the electrodes.

---

This work is supported by DARPA’s Tip-Based Nanofabrication program under Dr. Thomas Kenny.
The plasma intensity as a function of the RF input voltage is shown in Fig. 2 (b). The frequency is fixed at 485 MHz and the changing voltage proceeds along the arrows shown in Fig. 2(b) and it indicates that the switch-on voltage of plasma is much higher than the minimum sustention voltage of plasma. Once the RF plasma is generated, its intensity is almost linear with the input voltage at a fixed frequency, which can be expressed by (1)

\[ n = \text{plasma density}, V = \text{discharge voltage}. \]

In our experiment the index \( \alpha \) is about 1.

To investigate the frequency response of the RF plasma, the RF voltage was fixed at 18 V and the frequency was changed in the direction along the arrows shown in Fig. 2(c). The plasma-ignition frequency is near 500 MHz because the amplification of the voltage across the electrodes is frequency dependent and it will approach its maximum near the resonant frequency of 485 MHz as shown in Fig. 2(a).

In Figure 2(d), a dc bias is applied between the other two electrodes. The plasma intensity and the dc current are measured and plotted as a function of the applied dc bias. As the dc bias increases, the plasma intensity decreases until the plasma is completely switched off. The positive electrode acts as a gate and repels the positive ions. Due to the decrease of the ion concentration, the plasma intensity decreases as the DC bias increases as shown in Fig. 2(d). With a high enough DC bias, the RF plasma will be completely switched off due to the low ion density.

IV. MPDs WITH INSULATED ELECTRODES

The reaction between the plasma and electrode limits the device lifetime. In Fig. 3 (a) and 3 (b), we show an RF plasma device using thin glass slides (100 \( \mu \text{m} \) thick) as the barriers between the electrodes and the plasma, which can significantly increase the device lifetime and stability.

Figure 2: MPD characteristics: (a) frequency response analyzed by network analyzer; (b) plasma intensity vs. input voltage at 485 MHz; (c) plasma intensity vs. frequency at input voltage of 18 V; (d) switch-off characteristics: plasma intensity vs. DC bias.

Figure 3: (a) Schematics and (b) photo of RF plasma generated within two glass slides; (c) I-V characteristic of the plasma generated within two glass slides.

Figure 3 (c) shows the I-V characteristic of the plasma generated between the insulated electrodes. The I-V curve is almost linear, showing a resistive behavior of plasma under a dc bias.
Figure 4: (a) Images of RF plasma with no gate bias; (b) Images of RF plasma with a gate bias of 500 V; (c) Schematics of four probe setup showing the switching-off principle of plasma; (d) Design of the plasma transistor with sustained plasma at $V_{\text{gate}} = 0$.

Figures 4 (a) and 4 (b) show the images of the plasma with and without a dc bias, respectively. When a dc bias is introduced, the plasma intensity in Fig. 4 (b) significantly decreases. Figure 4 (c) schematically illustrates the plasma switch-off mechanism under a dc bias. The dc bias works as a plasma valve that controls the plasma flow between the source and drain. Therefore, a plasma field effect transistor (FET) can be fabricated based on this principle.

V. MICROPLASMA FET

Figure 5 shows the microscopic image of a microplasma FET fabricated on glass substrate. The gate is insulated by $\text{Al}_{2}\text{O}_{3}$. The plasma is introduced between the source and drain by an external RF plasma source. Figure 6 (a) shows the $I_{\text{DS}}$-$V_{\text{DS}}$ characteristics of the microplasma FET with different gate voltages.

Figure 5: Microscopic image of the fabricated microplasma FET device with source, drain and gate; (b) $I_{\text{DS}}$-$V_{\text{DS}}$ characteristics of microplasma FET with different gate voltages.

Figure 6 (b) shows the $I_{\text{DS}}$-$V_{\text{G}}$ characteristics of the microplasma FET at $V_{\text{DS}}$ of 10 V. From Fig. 6(b), the calculated tranconductance $g_{\text{m}}$ of the MPD is about $6 \times 10^{-8}$ S at the gate bias of 40 V.

It clearly demonstrates the control of the plasma current flow by a dc bias. For a dc current between the source and drain, the current is dominated by the ion current due to the sheath region between the electrodes and plasma. Therefore, a positive gate bias will result in a narrowed ion channel and a decreased source-drain current.

VI. APPLICATIONS

MPDs can be used as switches or amplifiers in harsh environment when temperature may exceed 100 °C and in the present of ionizing radiation. To demonstrate these capabilities, we used Ne filled larger MPDs shown above and obtained their switching characteristics as a function of time inside a 90 kW nuclear reactor as shown in Fig. 7.

Figure 6: (a) $I_{\text{DS}}$-$V_{\text{DS}}$ characteristics of microplasma FET with different gate voltages; (b) $I_{\text{DS}}$-$V_{\text{G}}$ characteristics of microplasma FET at $V_{\text{DS}}=10$ V.

Figure 7: MPD switching characteristics inside a reactor: switch-on voltage vs. radiation time.
Figure 8: MPD switching characteristics inside a heater: switch on voltage vs. environmental temperature.

Figure 7 shows that the switch-on voltage of the MPD changed less than 5% after 120 min radiation. The Ne filled MPDs are also placed in a heater to investigate its switch-on voltage as function of the temperature. In Fig. 8, the switch-on voltage decreases 1% when the temperature increased from room temperature to 100°C and 4% at 200°C.

The stability of MPDs under high temperature and high radiation conditions indicates the promising application of the microplasma FETs under these harsh conditions.

VII. CONCLUSION

We fabricated and investigated the MPDs for their characteristics at atmospheric pressure. The microplasma FET devices are designed and fabricated, demonstrating a gate-controlled source-drain current. The microplasma devices have unexplored potential in switch and amplifier applications. Microplasma FETs also possess a distinguished stability for applications under harsh conditions such as high temperature and high radiation.

ACKNOWLEDGMENT

This work was supported by a DARPA TBN grant under Dr. T. Kenny. We would like to thank Mr. K.N. Chappanda and Mr. F.K. Chowdhury for the assistance in the research work.

REFERENCES