Small-Signal Impedance of a Radio Frequency Plasma Capacitor

Peter Linardakis, *Student Member, IEEE*, and Gerard G. Borg

***Abstract*—A capacitor for radio frequency control is proposed that uses a gas discharge plasma as a variable dielectric. Experimental small-signal impedance measurements on a prototype device at 500 MHz–2.4 GHz show a capacitance ratio of 2–6:1 with a quality factor of 60 at 600 MHz. Results compare well with simple theoretical descriptions of the dielectric properties of plasmas.**

***Index Terms*—Capacitors, dielectric materials, plasma devices.**

I. Introduction

RADIO FREQUENCY (RF) control devices such as PIN diodes, RF microelectromecahnical systems (MEMS) and ferroelectric capacitors are becoming important in modern wireless communication systems. They are finding use in greater numbers in for example, adaptive antennas to increase system capacity and range through dynamic beam-forming [1]–[3]. Such applications dictate that the devices be capable of a high level of performance and flexibility at a low unit cost.

Existing devices do not necessarily satisfy this criteria. Semiconductor devices can suffer from high insertion loss, low quality factors, nonlinearity and other characteristics that cannot be compensated for at the end of the RF chain [4]. RF MEMS switches can outperform semiconductor equivalents but high-volume and therefore low-cost production of continuously variable RF MEMS capacitors is not expected until 2009 because of the industry's current focus on RF MEMS switches [5].

This letter therefore investigates the concept of an "RF plasma capacitor" as an alternative or complement to existing devices. It uses a gas discharge plasma to effect a continuously variable impedance. The use of plasma is motivated by its dielectric characteristics and previous applications in switching and telecommunications applications including plasma antennas [6], beam steering at 36 GHz [7] and audio switching in telephone exchanges [8].

II. Theory

Fig. 1 illustrates the general form of a plasma capacitor. A plasma "slab" is sandwiched in between two capacitor plates separated by a distance d_{RF}. The plasma slab itself consists of the main portion, or "bulk" and two "sheaths" that separate the bulk from the surrounding vessel walls. The sheaths arise in most plasmas and are regions that contain very few electrons.

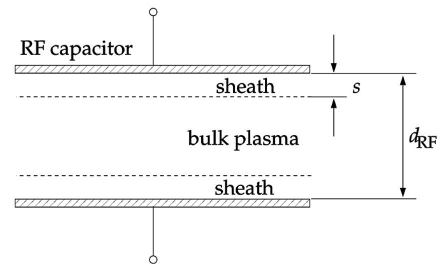

Fig. 1. Planar plasma capacitor geometry. A plasma is sandwiched between two capacitor plates. The plasma itself consists of two "sheaths" (effectively air-gap capacitors) and a "bulk" plasma with a variable dielectric constant.

The impedance of a discharge plasma in between two capacitor plates was discussed in the early part of last century as a method of determining plasma parameters in laboratory equipment [9]. Impedance models and experiments such as that of Schmitt and Lapierre [10] were presented from the late 1950s to the early 1980s, but none are from the perspective or on the scale of an RF device. These models predict complex behavior such as closely spaced resonances due to the thermal energy of the particles.

At moderate gas pressures however, thermal effects are suppressed by the increased rate of collisions between particles and a simple description of the bulk plasma's dielectric properties is possible. This description can be obtained by neglecting the thermal motion of the particles (a so called "cold plasma"):

$$\varepsilon_r = 1 - \frac{\omega_{pe}^2}{\omega(\omega - i\nu)} \tag{1}$$

where ω is the applied signal frequency and ν is the particle collision frequency. The plasma electron frequency, ω_{pe}, is the natural oscillation frequency of the electrons and is calculated by

$$\omega_{pe}^2 = \frac{n_e e^2}{\varepsilon_0 m_e} \tag{2}$$

where n_e is the electron density (m^{-3}), e is the electron charge, ε_0 the permittivity of free space and m_e is the electron mass.

The relative dielectric constant (ε_r) therefore, can be controlled by varying the electron density. It has a maximum of unity and can be both positive and negative. In effect, this means that the properties can be varied so that the bulk plasma acts capacitively $(0 < \varepsilon_r \leq 1)$ or inductively $(\varepsilon_r < 0)$ with a resonance at $\varepsilon_r = 0$.

An imaginary component is introduced in (1) by the collision frequency, ν. In practical plasmas, where the proportion of gas

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The authors are with the Research School of Physical Sciences and Engineering, Australian National University, Canberra ACT 0200, Australia (e-mail: peter.linardakis@anu.edu.au).

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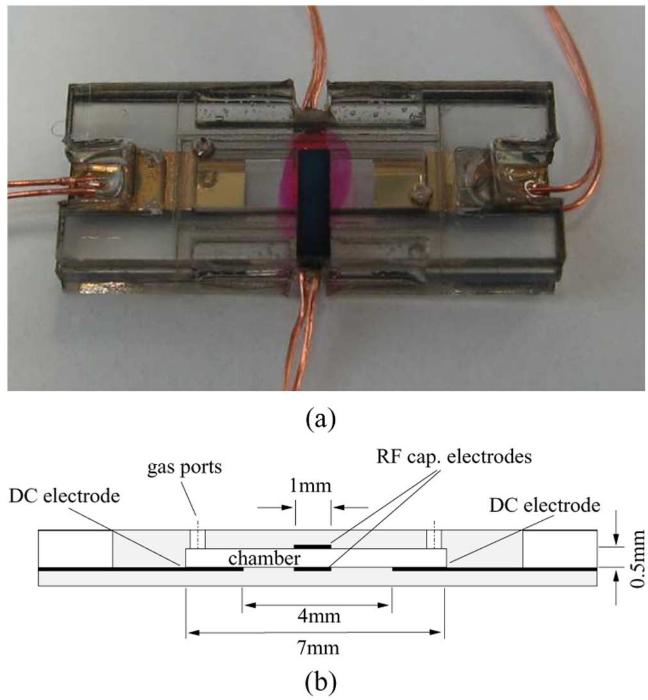

Fig. 2. Prototype plasma capacitor (a) actual and (b) schematic.

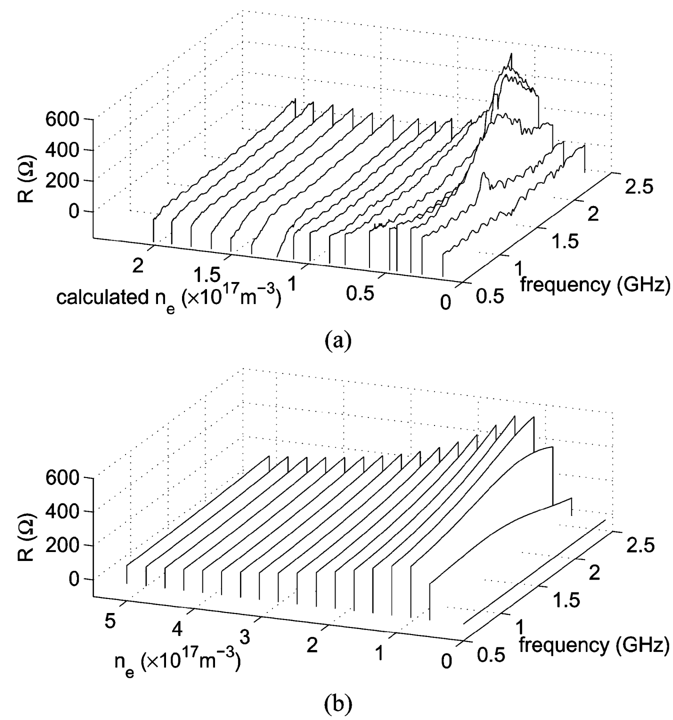

Fig. 3. (a) Measured and (b) modeled interelectrode resistance of the prototype plasma capacitor. Note the resonances observed at lower currents.

particles that are ionized is quite low, ν is dominated by collisions between electrons and neutral particles. The electron-neutral collision frequency can be calculated via [11]

$$\nu_{en} = n_n \sigma_{en}(T_e) \sqrt{\frac{8k_B T_e}{\pi m_e}} \tag{3}$$

where n_n is neutral particle density, σ_{en} electron-neutral momentum transfer cross section, k_B is Boltzmann's constant and T_e is the electron temperature in Kelvin.

Under small-signal conditions, the impedances of the sheaths can be modeled as simple vacuum capacitances. The width of each sheath under these conditions can be approximated by $s \approx 4\lambda_{De}$ [11] where λ_{De} is the Debye length given by

$$\lambda_{De} = \sqrt{\frac{\varepsilon_0 k_B T_e}{e^2 n_e}}. \tag{4}$$

The total impedance is a series connection of the bulk plasma and two sheaths. Increasing n_e will cause an impedance change that is due to both the decreasing sheath width and the bulk.

III. Impedance Measurement

Fig. 2 shows the prototype device constructed to measure the impedance of a small scale plasma capacitor. It is constructed from polycarbonate and contains a small chamber through which argon gas is pumped at a pressure of 2.6 mbar. There are four gold-plated copper electrodes, two co-planar electrodes to fire a dc glow discharge and two plane-parallel electrodes that form the RF capacitor. The capacitor electrodes are each 4×1 mm^2, with an overlapping area of 2×1 mm^2. They are insulated from the gas discharge by thin layers of lacomit varnish. Two parallel lengths of 200 μm diameter wire connect the electrodes to external circuitry. A detailed description of the device operation and characteristics can be found in [12].

At the gas pressure used in this experiment, the discharge current (through the dc electrodes) is 50–550 μA with a power consumption of 22–495 mW. The voltage required to initiate the discharge is 650 V. Electron densities and temperatures are calculated from probe measurements in previous experiments [12] and from ω_{pe} by determining the frequency at which the capacitance ratio is unity. From these, n_e is of the order of $10^{16} - 10^{17}$ m^{-3} and $T_e = 70$–200×10^3 K.

Two-port S-parameters of the plasma capacitor were measured at 500 MHz–2.4 GHz at an input power of 0 dBm using a Rohde & Schwarz ZVRE vector network analyzer (VNA) with $Z_0 = 50\ \Omega$. This two-port treatment of the device allows us to determine if the plasma introduces an asymmetry ($S_{11} \neq S_{22}$) or does not follow reciprocity ($S_{12} = S_{21}$) displayed by normal passive devices. Asymmetry and non-reciprocity are possible because the plasma may behave as an active device. Measurement was by a direct method using a microstrip fixture and a custom microstrip short-open-load-through calibration fixture [13].

IV. Results

VNA results for the capacitor show a maximum of 10 dB increase in the transmission coefficient and a 3 dB improvement in the return loss. This is for a power consumption of approximately 400 mW.

Measurements also show that the device is symmetrical and reciprocal and so an equivalent π-model circuit can be found to isolate the contribution of the discharge plasma. This "inter-electrode" impedance can be calculated via the transadmittance using $-Y_{21}$ [14].

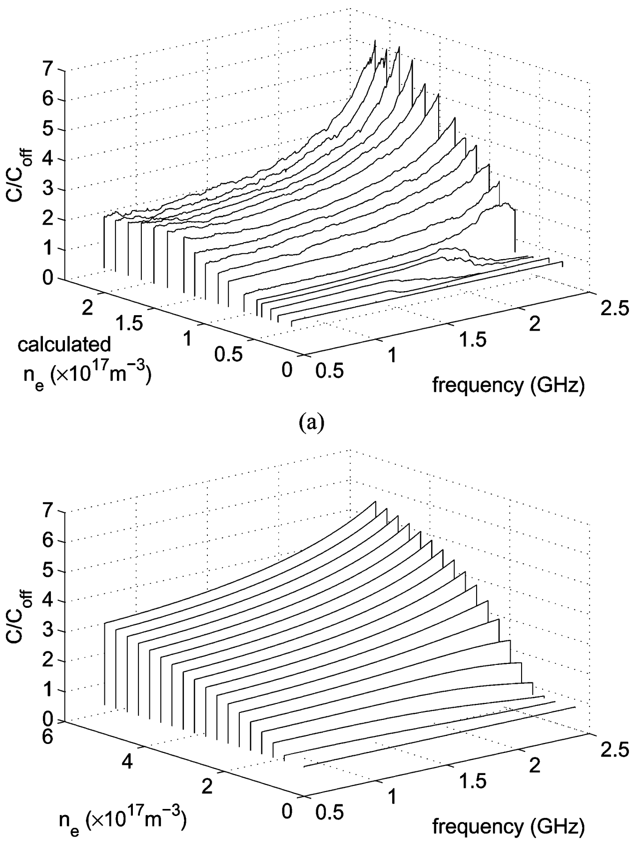

Fig. 4. (a) Measured and (b) modeled interelectrode capacitance ratio of prototype plasma capacitor. Aside from the six-fold change at high frequencies and currents, reductions in capacitance are observed. These features are predicted by the theory.

TABLE I
PARAMETERS TO (1)–(4) USED FOR THEORETICAL IMPEDANCE CONTOURS IN FIGS. 3(b) AND 4(b)

RF electrode separation ($d_{\rm RF}$)	0.5 mm
plasma density ($n_{\rm e}$)	0-5×10^{17} m^{-3}
gas pressure	2 mbar
electron temperature	12×10^{3} K
electrode dimensions	2 mm × 1.7 mm
insulation thickness	5 μm
collision frequency ($\nu_{\rm en}$)	1.4×10^{10} s^{-1} [15]
sheath width (s)	2$\lambda_{\rm De}$

Figs. 3 and 4 show the inter-electrode resistance and capacitance ratio from measurements and application of (1)–(4) using the parameters in Table I [15]. Calculations assume a constant density in the bulk and sheath widths of $2\lambda_{De}$. Increasing the sheath width reduces the volume available to the bulk and therefore decreases the change in impedance.

A 2–6:1 capacitance ratio with tens of ohms of resistance is observed with a quality factor (Q) of up to 60 at 600 MHz. A reduction in the off-state capacitance is also observed at low discharge currents due to resonances at the plasma electron frequency. These resonances are also accompanied by peaks in the resistance.

Performance of the prototype could theoretically be improved. Increasing the electron density to over 10^{18} m^{-3} and reducing the pressure to 0.2 mbar to reduce ν_{en} could create a 20:1 ratio with $Q = 100$ at 600 MHz and a 10:1 ratio at 2.4 GHz. In this geometry, several watts of power would be required to achieve this but optimization of surface-to-volume ratios could create the necessary electron densities with lower input powers. A detailed analysis should consider that the total collision frequency may not be dominated by ν_{en} at reduced pressures and increased electron densities. The electron mean free path length would become comparable to the chamber dimensions, increasing the importance of wall collisions, and there will be an increase in electron-ion collisions.

Under comparable conditions, the inter-electrode impedance predicted by (1)–(4) compares well with experimental results.

V. CONCLUSION

We have investigated the performance of an electronic RF device which employs plasma as the active medium. Such a device could prove to have advantages over competing technologies that provide electronic switching or variable impedances in future wireless or radar systems. Experimental impedance measurements on the prototype device show a 2–6:1 capacitance ratio with $Q = 60$ at 600 MHz. These results are comparable to theoretical results using a simple description of the plasma's dielectric properties. We have performed our experiments on relatively pure argon discharges. Investigation of other gas types or Penning mixtures may lead to increased electron densities with lower bulk resistances and capacitance variations exceeding 10:1.

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