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On the Method of Monitoring and Optimal Control of RF-Plasma

A. Aghajanyan, A. Hakhoumian, N. Poghosyan, T. Poghosyan, and T. Zakaryan*

Institute of Radiophysics and Electronics, Armenian National Ac. Sci.
Alikhanian brs. 1, Ashtarak, 0203, Armenia

*e-mail: tigr@irphe.am

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Abstract – A new strategy of reaching efficient matched conditions at the maximum speed in RF power delivery systems for plasma processes is proposed and analyzed. Presented method incorporates unique properties of high speed, automatic discrete matching networks, allowing creation of shortest trajectories and bypassing inhibited states of network parameters. The special matching network model is used to test optimal matching path finder method which allows to maximize the delivered power at the minimum time.

Keywords: RF plasma, maximum delivered power, impedance matching.

1. Introduction

Plasma processing of semiconductor materials is relatively new technique used for etching and deposition of various materials on a substrate, as well as cleaning and modifying its surface. Plasma processing is used for manufacturing of microelectronic devices, MEMS devices, thin films and for other applications in nanotechnology. Plasma etching has several advantages over other methods of etching (e.g., photolithography), especially at the extremely small feature sizes. However, in practice, this technique can’t be used in all cases. Plasma and phenomena associated with it have greatly complicated nature and are not fully explained yet in terms of existing models [1].

To generate and sustain plasma discharge in vacuum chamber for processing semiconductor products it is required to apply a DC, an AC (low frequency) or an RF signals. Typically, RF sources are used with frequencies ranging from several to tens of MHz There are two major methods for plasma generation: inductive and capacitive. The basic problem to be solved while developing plasma processing tools is the standard 50 ohm RF generator and plasma chamber impedance matching in order to ensure maximum energy transfer from the RF source to the plasma discharge. To solve this problem it is necessary to measure the electric and magnetic components of the electromagnetic field [4] and the phase shift between them, which will give ability to adaptively adjust matching network parameters to achieve a real-time matching.

During the process impedance of the plasma changes depending on various factors, such as concentration of gaseous components filling the plasma chamber and the pressure of gas. Furthermore, as plasma is a complicated nonlinear object, the change of its impedance is observed depending on the level of RF power. All these impedance changes are causing instabilities in plasma which brings weak process parameter control and repeatability. Usually real-time automotive matching networks are being applied. In such matching networks there are two main challenges. First one is the increase in maximum operation power of applied RF signals for high plasma densities. Second and the most important one is the matching speed which is required for high stability and precision control of the process. Respective selection of matching circuits and adaptive algorithms allows to solve the majority of problems mentioned above.

In well-known analog matching networks the values of variable reactive elements (such as capacitors and inductors) are adjusted via electro-mechanical nodes, while in the discrete matching networks – via discrete arrays of reactive elements. Meanwhile the ordinary analog networks allow to match an impedance at higher forward power values, the matching speed of discrete networks significantly exceeds the one of the analog networks. In order to increase the forward power level, both high-power and high-speed switching devices are used. At the same time, the maximum allowed forward power level depends not only on the switching device capabilities but also on the matching algorithms which are used.

In this article we propose and analyze the efficient high speed strategy to reach the matching condition in RF plasma processing chamber.

2. Typical matching network

The equivalent circuit of the matching network [2] for inductively coupled plasma is shown in Fig 1.

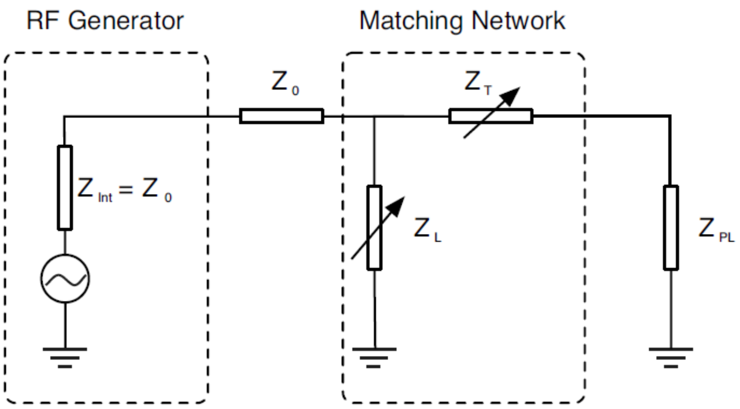


Fig.1. Equivalent circuit of the matching network.
Z_T and Z_L are reactive components and represent arrays of capacitors connected in parallel. Z_0 is the impedance of the transmission line and Z_{Int} is output impedance of RF generator.

To achieve impedance matching, Z_T and Z_L should be adjusted until the following condition satisfies:

$$Z_{Matcher} = Z_{PL}{}^{*}, \tag{1}$$

where $Z_{Matcher}$ is the complex impedance of the matching network, and Z_{PL} is the complex impedance of the plasma chamber.

As follows from Fig.1 the matching condition implies

$$Z_{Matcher} = \frac{Z_0 Z_L}{Z_0 + Z_L} + Z_T, \tag{2}$$

$$Z_T = \frac{1}{j\omega C_T} + j\omega L, \tag{3a}$$

$$Z_L = \frac{1}{j\omega C_L}. \tag{3b}$$

The solution of Eq. (2) for C_L and C_T results in

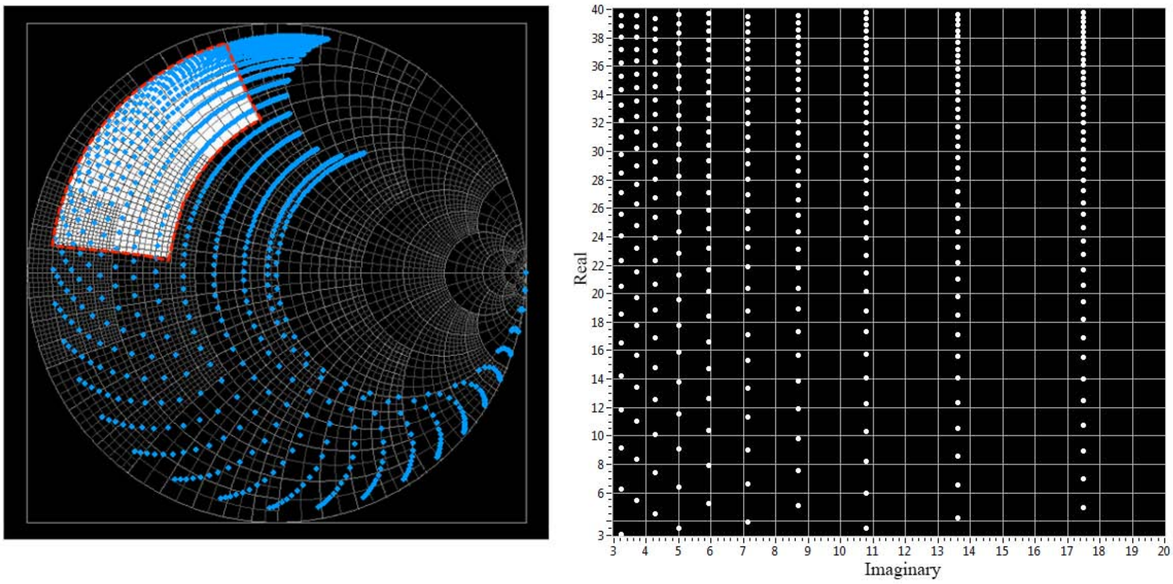
$$C_L = \frac{1}{Z_0\omega}\sqrt{\frac{Z_0 - R}{R}}, \tag{4a}$$

$$C_T = \frac{1}{\omega}\left(\frac{1}{\omega L - \frac{Z_0^2\omega C_L}{1+Z_0^2\omega {C_L}^2} - X}\right), \tag{4b}$$

where ω is the angular frequency, Z_0 is the generator's output impedance, R and X are real and imaginary parts of the load impedance respectively.

The value of Z_{PL} obviously changes during the control process. Hence the matcher impedance should be adequately adjusted in real time as fast as possible. The Z_T array matching network consists of 5-element various capacitors connected in parallel, and Z_L is similar 6-element capacitors array. The values of each individual capacitor depend on the dynamic range of Z_{PL} and should cover the range of equivalent impedance beginning from (3-3i) to (20-40i).

Depending on the configuration of individual capacitor values, efficiency of the whole matching network can significantly vary. The optimal configuration consists of more or less uniformly distributed 2048 combinations for $Z_{Matcher}$, evaluated from a view point of the $Z_{Matcher}$ state density. The most intuitive combination of capacitors array is two degrees series ($Z_T = [8, 16, 32, 64, 128, 256, 512]$, $Z_L = [64, 128, 256, 512]$). The results of simulation for this combination are presented in Fig.2.

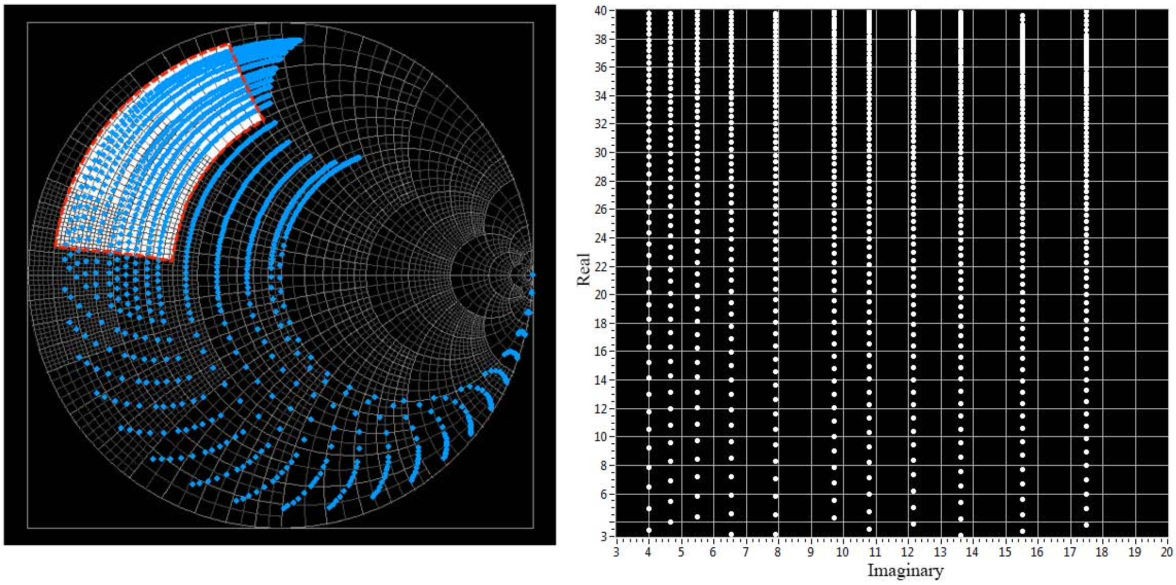


a b

Fig.2. $Z_{Matcher}$ state density for two degrees series for all possible 2048 combinations (a) Smith chart and (b) Cartesian graph of highlighted area.

The efficiency of such configuration to cover $Z_{Matcher}$ states in the matching area amounts only approx. 15 percent, while the efficiency of other less intuitive modified configuration

$Z_T = [8, 16, 32, 64, 128, 256, 172]$, $Z_L = [64, 128, 256, 350]$ surprisingly amounts 36 percent which more than twice exceeds and is presented in Fig 3.



a b

Fig.3. Z_{Matcher} state density for modified configuration for all possible 2048 combinations (a) Smith chart and (b) Cartesian graph of highlighted area.

3. Evolution and trajectories of matching states

The performance of matching network depends on both its configuration and on the matching states trajectories. As optimal is the algorithm as higher is the performance and stability of the network at whole. The simplest trajectory corresponds to jumping to the value representing the solution of Eq. (1). This method seems easy only for simplest circuits, but real matching networks are more complicated. Further complication of the model can reduce the performance and stability of the matching process. The impedance of real plasma demonstrates complex non-linear behavior. So if we dramatically change the matching network impedance then plasma will react and impedance will be changed as well. Hence some kind of adaptive feedback control like PID can satisfy the need (N.B. PID trajectories are widely applied in analog matching networks, but rarely used in discrete ones) [3].

Below we consider several sample adaptive algorithms. Let us discuss a situation in matching process when the impedance of matcher is equal to the value of A and then should be changed to the value of B (see Fig 4a). There is a path through C point, which means that the imaginary and real parts of impedance should be adjusted serially (in any sequence). Simultaneous adjustment of real and imaginary parts (see Fig 4b) leads to the straight line trajectory connecting A and B. Indeed the second method is faster than the first one.

Each individual capacitor in matching network is connected to the circuit through dedicated switching device. During the matching process applied voltage and/or current can lead to the huge degrading values. In the case when they exceed permissible values the matching network can be probably damaged. To avoid such scenario the smarter algorithm bypassing such "singularities" is implemented.

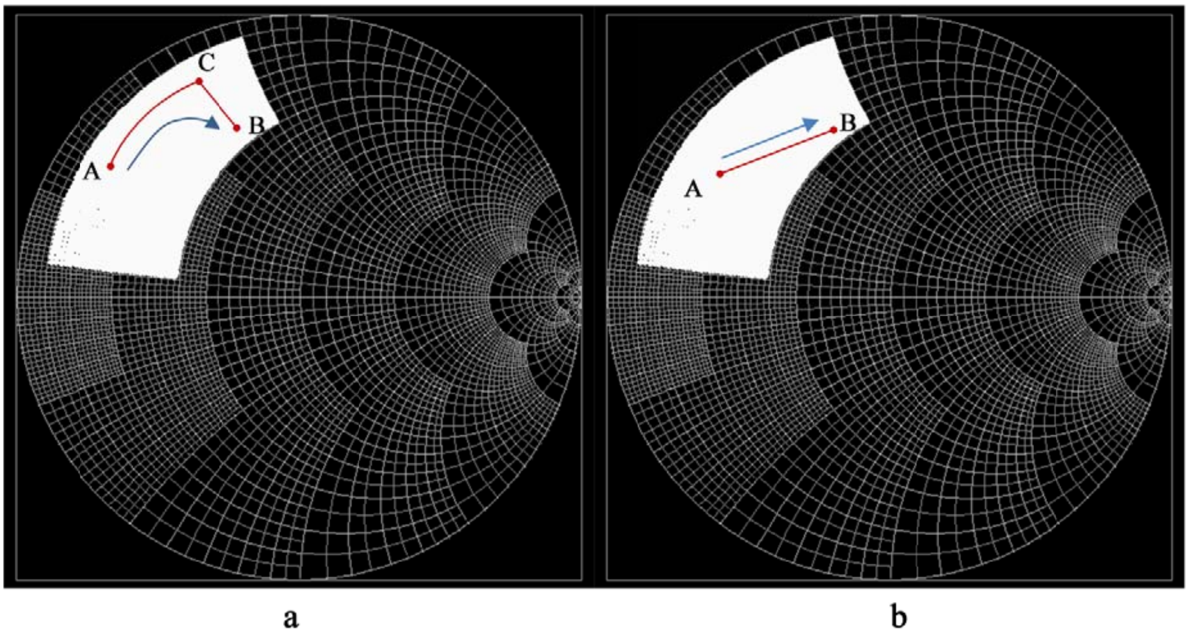


Fig.4. Matching network "evolution" trajectory
a. sequential and b. simultaneous adjustments

4. Results and discussion

We have considered that the worst case occurs when the real part of plasma processing chamber impedance is about a couple of Ohms. In this case there are number of rejected combinations for matching element values. Let us consider matching network operating at 13.56 MHz and 1kW RF signal, with1kV and 20A permissible values for switching elements. In the initial state the plasma impedance amounts approx.$(3 - 40\mathrm{i})\Omega$ and Eq. (1) is closely satisfied ($Z_{\mathrm{Matcher}} \approx (3 + 40\mathrm{i})\Omega$). All common state parameters of the matching network in this state are presented in Fig.5.

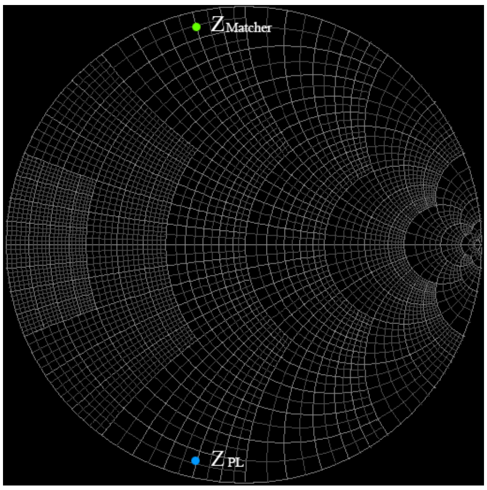


Fig.5. Initial condition of fully matched network
$I_T \approx 18.2A;\ U_T \approx 610V;\ I_L \approx 18.2A;\ U_L \approx 223V$;
reflection coefficient: ≈0.5%.

If then somehow the plasma impedance changes to $(3 - 3\mathrm{i})\Omega$, the network becomes unmatched. Before starting the matching process the map of allowed and inhibited configurations is defined (see Fig.6).

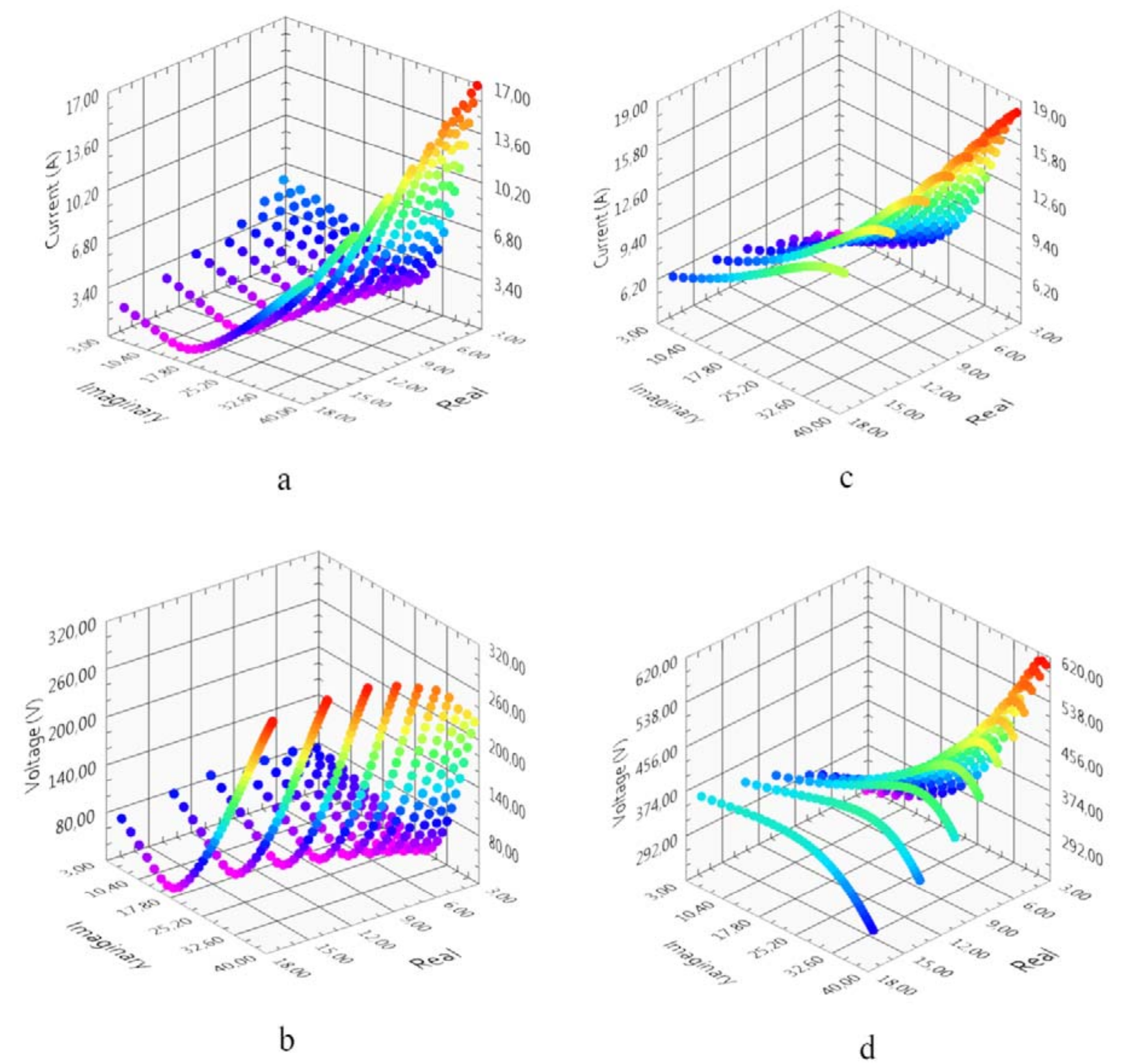


Fig.6. Map of allowed and inhibited configurations.
(a) and (b) 3D plots of serial element (Z_T) current and voltage, respectively;
(c) and (d) 3D plots of serial element (Z_L) current and voltage, respectively.

As soon as the matching trajectory is determined, the network strives for matching bypassing the inhibited states. For this typical scenario it takes a couple of iterations to achieve the goal. The state parameters of matching network for matched state are presented in Fig.7.

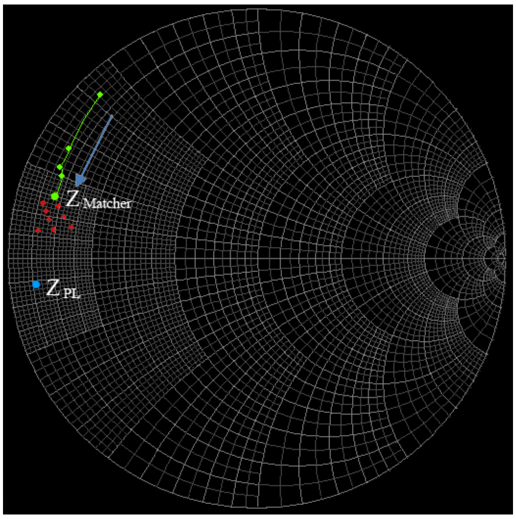


Fig.7. Trajectory to partially matched state
$I_T \approx 15A;\ U_T \approx 950V;\ I_L \approx 18.5A;\ U_L \approx 280V;$
reflection coefficient: ≈25%.

As one can see, the reflection coefficient Γ^2 amounts inadmissible value of about 25% from the view point of successful matching. Nevertheless this scenario is “best of the worst” compared to the excess of maximum allowed current and voltage values of switching elements.

The proposed automatic matching network allows creation of the shortest path trajectory bypassing the inhibited states of network parameters. The stability and convergence of the proposed method should be investigated on a real plasma processing chamber.

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