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A DIRECT DIGITAL SYSTEM FOR COMPLEX IMPEDANCE MEASUREMENT VIA A PASSIVE V-I SENSOR

In this article the direct digital method for impedance measurement is introduced. The accuracy of the phase measurement is estimated. Initial system calibration technique is presented and several known load impedances are measured.

Keywords: Direct digital impedance measurement, plasma impedance, passive V-I sensor.

Introduction. Nowadays, in modern semiconductor manufacturing processes the use of dry etching has many advantages over the standard wet one [1]. For dry semiconductor etching plasma generated from high power radio frequency (RF) signal is used. From technological point of view, plasma generated from the RF power should meet several requirements. The most important one is the homogeneous and constant plasma density. The homogeneity of the plasma in the chamber is achieved in the development stage [2]. Meanwhile, the constant plasma density depends on the RF signal constant energy flow to the chamber. It is not a trivial problem because the generated plasma impedance changes nonlinearly and should be tracked in order to match the generator with the plasma. Plasma impedance precise measurement allows to achieve this goal. To put it in another way, the power delivered to the plasma chamber, namely the plasma density, will be constant. It should be mentioned that during the plasma material processing the plasma parameters' nonlinear changing causes the high order harmonics growing at RF generator and plasma section. In this respect, the high order harmonics should be tracked as well to know the process stage in the plasma chamber.

Plasma Impedance measurement techniques. There are two encountered common methods of plasma impedance measurement, but first of all it should be noticed that the accuracy of the measured phase has a huge impact on the impedance measurement. As it is evident:

$$\frac{\Delta P}{P} \bigg/ \frac{\Delta\varphi}{\varphi} = \frac{\Delta P}{\Delta\varphi}\frac{\varphi}{P} = \frac{\Delta(VI\cos\varphi)}{\Delta\varphi}\frac{\varphi}{VI\cos\varphi} = -\varphi tg\varphi, \tag{1}$$

where ΔP is the small deviation of power, P is the absolute power, $\Delta\varphi$ is the small deviation of phase, φ is the absolute phase, V and I are the values of voltage and current respectively.

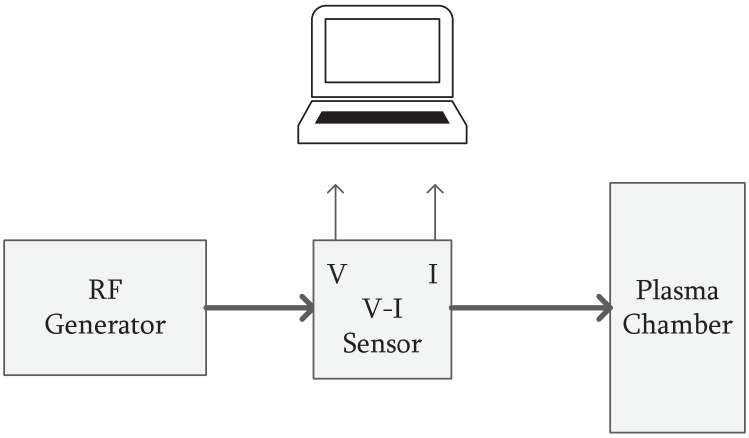

Fig. 1. General setup

The general setup of the plasma impedance measurement is shown in Fig.1: voltage-current (V-I) sensor has been placed between the RF generator and plasma chamber, V-I sensor [3] has two outputs shown the “voltage” and “current” proportional signals of RF flow through. Thereupon these two signals are used to measure the impedance of the plasma. Complex impedance is defined as:

$$\mathrm{Z} = \frac{V}{I} e^{i\varphi} . \quad (2)$$

The difference between the two methods of plasma impedance measurement, i.e. indirect and direct, lies in the V-I sensor output processing. Indirect processing uses ICs for voltage, current and phase measurements. Meanwhile the direct processing systems directly samples RF “voltage” and “current” proportional signals and then digitally extracts the voltage, current and phase. It should also be mentioned that the values extracted in both indirect and direct methods are proportional to the real RF signal and should be calibrated to describe it. The advantages of the indirect method are that there is no need for high computational power from the system, but such systems are relatively slow and cannot provide information about high order harmonics.

Direct digital impedance measurement. In this method, the output of the V-I sensor is connected to the high speed analog-to-digital converter (ADC). Two channels of ADC are in use: one for voltage and the other-for current. The digitized signal is sent to the PC through the high speed standard bus. Then the digital signal is filtered from the noise and high order harmonics. It is expedient to use the Fourier transform for the main harmonic extraction taking into account the possible nonlinearity of the overall system.

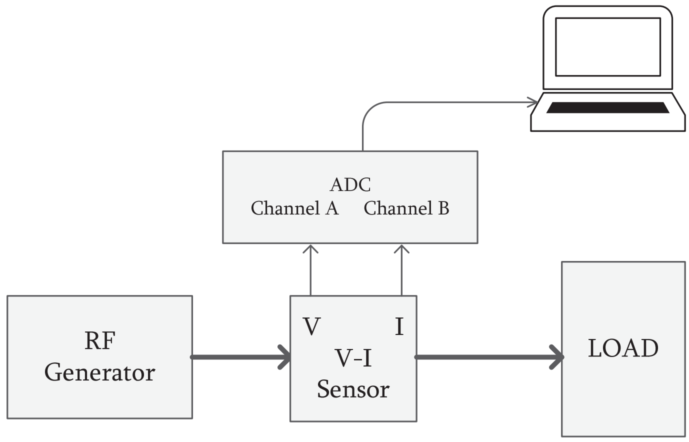

Fig. 2. Calibration setup

In our calibration setup (Fig.2), the sampling rate of ADC (F_S) is 250 *Msps*. If we consider that the generator main frequency is 13.56 *MHz*, this allows us to track up to 7th order harmonic. Appling the Fourier transform to the sampled signal, we will find the first harmonic signals

$$X_A(n) = A\cos\left(\frac{2\pi f_A}{F_s} + \phi_A\right),\ X_B(n) = A\cos\left(\frac{2\pi f_B}{F_s} + \phi_B\right), \qquad (3)$$

where A , f_A , ϕ_A are the amplitude, frequency and phase of the signal at the first channel, meanwhile B , f_B , ϕ_B are the respective values for the second channel. For ϕ_A and ϕ_B we have:

$$\phi_A = \varphi_A + \Delta\varphi_0\ ,\ \phi_B = \varphi_B + \Delta\varphi_0 + \Delta\varphi_{AB} \qquad (4)$$

where $\Delta\varphi_0$ is the phase offset between the generator and the ADC clock, $\Delta\varphi_{AB}$ is the phase offset between the two channels (originated from ADC sequential sampling) and $\Delta\varphi_{AB}$ is the constant.

Lets estimate the measurement phase resolution. The main frequency of the RF generator is 13.56 *MHz* which means that the period is about 73 *nsec* and further sampling period of ADC is about 4 *nsec*, which means that the measurement phase resolution is about 1.2 degrees.

In order to refine the measured values, we use moving averaging from 50 to 1000 *ms* time constants.

Let's consider the voltage proportional output of the V-I sensor connected to the ADC first channel (Channel A) and current proportional output to the second (Channel B). Then from the foregoing we have

$$U = \alpha \overline{U_A}\ ,\ I = \beta \overline{U_B}\ ,\Delta\varphi = \overline{\phi_A} - \overline{\phi_B} - \overline{\Delta\varphi_0}\ , \tag{5}$$

where α, β are constants; U, I voltage and current of the RF signal; $\overline{U_A}$, $\overline{U_B}$ are the extracted main harmonic amplitudes of the channel A and channel B respectively, $\Delta\varphi$ is the averaged phase offset between signals at channels A and B.

Calibration of direct digital impedance sampler. Now, when we have $\overline{U_A}$, $\overline{U_B}$, $\overline{\phi_{AB}}$ and the problem is to calibrate the system to get correct values of U, I and $\Delta\varphi$. Namely initial phase offset $\Delta\varphi_0$, and α, β constants should be determined.

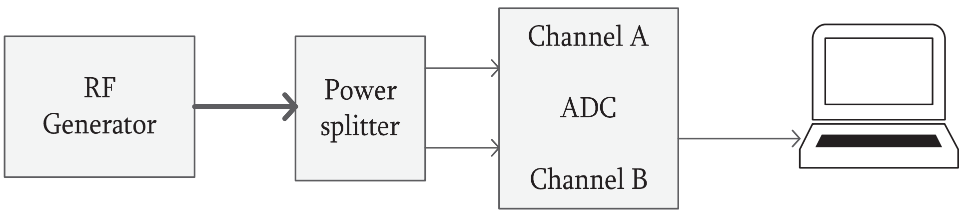

Fig. 3. Phase calibration setup

First, elimination of the phase offset between two channels $\Delta\varphi_{AB}$ is needed. The setup is shown in Fig.3. RF generator output is connected to the in-phase power splitter. Respective outputs of which are connected to ADC channels through equal length cables. Hence, the signal phases at ADC channels are equal $\phi_A = \phi_B$ and can be obtained from (4):

$$\Delta\varphi = -\overline{\Delta\varphi_0} \tag{6}$$

which is the initial phase offset between the ADC's two channels.

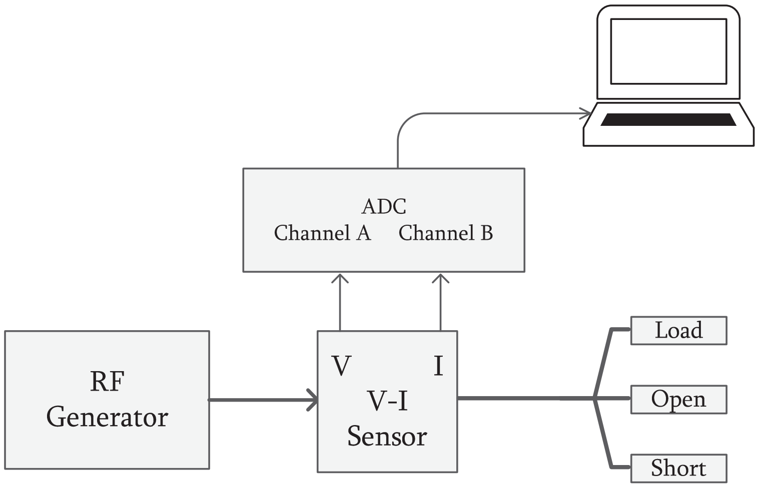

Fig. 4. Full calibration setup

The next calibration step is to find the missing α and β constants, which allows to measure the absolute voltage and current of the RF signal from the measured proportional ones. In such case, the used method represents modification of Short/Open Load/Thru (SOLT) [4]. The method is based on the measurement of voltage and current proportional values of V-I sensor outputs at three consequent conditions: when the V-I sensor is connected to the matched load, left open and shorted respectively (Fig.4). In these three steps the output power of the generator should remain unchanged. Here the ADC's channels A and B are connected to the V-I sensors voltage and current proportional outputs respectively. When we take into account the current-voltage relations in these three conditions of the circuit (Load / Open / Short), and the fact that the output power of the RF generator is known, we obtain:

$$\alpha = \alpha_L \left(\frac{\overline{U_L^A}}{\overline{U_o^A}} + \frac{1}{2} \right) \tag{7}$$

for the α voltage relation coefficient and

$$\beta = \beta_L \left(\frac{\overline{U_L^B}}{\overline{U_s^B}} + \frac{1}{2} \right) \tag{8}$$

for β current relation coefficient.

Here α_L and β_L are the voltage and current proportion coefficients when the output of the V-I sensor is connected to the load. $\overline{U_L^A}$ and $\overline{U_O^A}$ are the voltages measured at the ADC channel A when the V-I sensor output is connected to the load and left open respectively, $\overline{U_L^B}$ and $\overline{U_S^B}$ are the voltages measured by the ADC channel B when the V-I sensor output is connected to the load and shorted.

Now when we have the missing α, β, $\Delta\varphi_0$ constants, we are able to measure the unknown load impedance connected to the V-I sensor output by using Eq. (2).

The results of measurements with the calibrated V-I sensor are presented in the Table.

Table

Measurement results with calibrated V-I Sensor

Z_{load} $[\Omega]$	$Z_{measured}$ $[\Omega]$
50	51.4 - i0.04
13.2 + i32	13.3 + i33.3
46.6 - i107.6	41.6 - i102.3

As we have the absolute values of current and voltage, as well as the precise phase offset between them, the reflection coefficient Γ, load power P_{Load}, forward power $P_{forward}$, reflected power $P_{reflected}$ the reflection coefficient can be easily calculated.

The reflection coefficient of a load is determined by its impedance Z and the impedance toward the source Z_0:

$$|\Gamma|^2 = \left|\frac{Z - Z_0}{Z + Z_0}\right|^2 . \tag{9}$$

In (9) $|\Gamma|^2$ is the power reflection coefficient. From [5]:

$$P_{load} = P_{forword} - P_{reflected} , \tag{10}$$

$$P_{load} = V \cdot I \cos\varphi . \tag{11}$$

From (9), (10) and (11) it follows:

$$P_{reflected} = \frac{P_{load}\left|\Gamma\right|^2}{1-\left|\Gamma\right|^2} \ . \tag{12}$$

And finally the reflected power (12) is used to calculate the forward power.

Conclusion. The method of measurement of RF impedance is proposed based on direct digitalization of VI sensor signals. The accuracy of this method versus sampling frequency is estimated and testing results for several known loads are presented.

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ՊԱՍՍԻՎ V-I ՏՎԻՉԻ ՄԻՋՈՑՈՎ ԿՈՄՊԼԵՔՍ ԻՄՊԵԴԱՆՍԻ ՈՒՂԻՂ ԹՎԱՅԻՆ ՉԱՓՈՒՄԸ

Ներկայցվել է իմպեդանսի ուղիղ թվային չափման եղանակը: Կատարվել է փուլային ճշտության գնահատում: Ցույց է տրվել համակարգի նախնական համալարման եղանակը, և կատարվել չափումներ տարբեր հայտնի բեռների միջոցով:

Առանցքային բառեր. ուղիղ թվային չափում, պլազմայի իմպեդանս,V-I տվիչ:

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ПРЯМОЕ ЦИФРОВОЕ ИЗМЕРЕНИЕ КОМПЛЕКСНОГО ИМПЕДАНСА С ПОМОЩЬЮ V-I СЕНСОРА

Представлен метод прямого цифрового измерения комплексного импеданса. Проведена оценена точности измерения фазы. Показана техника начальной калибровки системы. Произведены измерения импеданса заведомо известных нагрузок.

Ключевые слова: прямое цифровое измерение, импеданс плазмы, пассивный V-I сенсор.