# **Impedance Matching and Matching Networks**

#### Valentin Todorow, December, 2009

Todorow,

2009

December,



think it. apply it.



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# **RF for Plasma Processing - Definition of RF**

■ What is RF?

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What is RF?

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The IEEE Standard Dictionary of Electrical and Electronics Terms<br>defines RF as: defines RF as:

> Radio frequency is the frequency in the portion of the electromagnetic spectrum that is between the audio frequency and infrared portion. Typically between 20 kHz and 300 GHz.

■ Band designation:  $R_{\rm gas}$ 

HF 3  $\sim$  30 MHz 3  $\sim$  30 MHz 3  $\sim$  30 MHz

VHF 30  $\sim$  300 MHz 300 MHz

Microwave above <sup>1</sup> GHz

UHF 300 MHz 300 MHz 300 MHz

 $-$  HF  $HF$  3 – 30 MHz  $\overline{\phantom{a}}$  – VHF VHF  $30 - 300$  MHz – $300 - 1000$  MHz – Band designation: above 1 GHz  $F = HF$  is the portion of th infrared portion. The settlement of th<br>The settlement of the settlement of th

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## **RF for Plasma Processing**



- **Service Service** Why RF for Plasma Processing?
- 1. To sustain plasma a closed loop circuit is needed. Current need to flow from generator through the wafer, plasma, chamber wall back to the from generator through the wafer, plasma, chamber wall back to the generator.

DC would be perfect for PVD sputtering because the target is conductive and DC current can flow through it. In the case of a semiconductor wafer which is under normal conditions dielectric DC current can not flow through it and plasma can not be sustained. From basic electrical science we know that AC current can flow through diplocations. So an AC spately is peodod drive surrent through a diplomation dielectrics. So an AC energy is needed drive current through a dielectric water for plasma processing wafer for plasma processing.

2. Plasma properties: Different frequencies create different plasmas densities and sheath voltages.

RF

Why RF

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2.

Plasma

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#### **Impedance Matching – Why?**



- **Impedance matching is needed to provide maximum power transfer** between the source or RF energy and its load. This is especially $\frac{1}{2}$  important if you deal with low amplitude signals. Imagine a radio or TV antenna. To get a good reception every bit of this signal needs to be used and the designer can not afford any signal loss – a perfect matching is used matching is needed to matching is in the matching. pe used and the designer can not afford any signal loss – a pe<br>match is desired. So the first reason for matching is just power efficiency.<br>-earv<br>Ioto I with low amplitude signals. Imagine a ra<br>a good reception every bit of this signal r between the control match is desired. So the first reason for matching is ju<br>officionery importantamplie alerties interesting in the product of the radio or  $\frac{1}{2}$
- The second reason is device protection  $-$  If RF circuit is not matched we get reflected power. This reflected power builds standing waves<br>In the transmission line between the source and load. Depending o on the transmission line between the source and load. Depending on the phase between the forward and reflected both waves can either subtract or add. Because of that on the line we can get places where the veltoge is the sum of both veltoges ar systemly places where subtract or add. Because of that on the line we can get places whe<br>the voltage is the sum of both voltages or eventually places where the voltage equals zero (maximum current). If the standing wave is the transmission line so that the positioned in such a way on the transmission line so that the  $p$  positioned in such a waves can either waves can expect the massive scale  $p$ maximum voltage or current is applied to the power FET's they can be dectroused. **be destroyed. and The second reason is device protection – If RF circuit is no<br>antenna needs to go and neglected in this signal needs to provide at anglic**  usedefficiency. $\Box$  The voltage is the sum of both voltages or eventually place the value of  $\Box$ subtract or $\gamma$ ed.

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in such <sup>a</sup> way on the transmission line so that the

#### **Impedance matching – Definition**



- What do we mean by impedance matching?
- For DC it is well known theorem that maximum power transfer can be For DC it is well known theorem that maximum power transitive achieved if source resistance is equal to the load resistance.  $\begin{array}{ccc} & & -1 \\ & & \end{array}$ both theorem that maximum power transfer can<br>esistance is equal to the load resistance.<br>I impedances The condition for impedance r
- For RF we consider impedances. The condition for impedance matching  $\frac{1}{\sqrt{2}}$  is that real part of the impedance should be equal to the real part of the load and reactance's should be equal and opposite in character. For it is well known that maximum power for  $\mathbb{R}$  it is the achieve matching our le example if our source impedance is  $R + jX$  to achieve matching our load should be  $R - jX$ .  $F = \frac{1}{2}$  SHOUID DE  $H = \frac{1}{2} \lambda$ .<br>If we assume that we have a chamber with canacitive discha
	- If we assume that we have a chamber with capacitive discharge the impedance in general will be  $R - jX$ . Generator typical output impedance is 50 Ohms. Then the matching network has to make  $50 = \text{RI}$  and  $jX = 0$ . If we assume that we have a chamber with capacitive disch

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example

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■ Let us match a 50 ohm generator to a 2 Ohm load. One of the ways to match is to put a resistor in parallel to the output of the generator. Impedance*Material to put a resistor in parancheo the balpat of the general conditions* 



Z= R1+R2R1xR2 $\frac{1}{2}$  = 2 Ohm

 $Z = \frac{R1xR2}{R1+R2}$  = 2 Ohm<br>Matching will be achieved, however not a desirable solution because most of the power will be lost in the resistor we added. I have chosen here to make 50 Ohm side look as 2 Ohm because it is easier to correlate to the L circuit 50 Onm side look as 2 Onm bee<br>which we will derive later. =

ETCH PRODUCTS BUSINESS GROUPETCH PRODUCTS BUSINESS GROUP<br>Valentin Todorow 2009 will be achieved, however not a desirable solution because most a desirable solution because most a desirable the resistor we added. In the resistor we added. In the resistor we added. In the resistor  $\Delta$ PP

Matching

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■ Now lets see what will happen if we replace the resistor with a capacitor of 1150 pF which has impedance X=1/2ΠfC =-j10.207 **Capacitor of 1150 p**<br>Ohm @ 13.56 MHz  $\frac{1}{2}$ 



$$
Z = \frac{R.(-jX)}{R+(-jX)} = 2 - j 9.8 \text{ Ohms}
$$

One can see that by adding the capacitor we were able to transform 50 ohm in to a complex impedance with a real part of 2 Ohms. z-5\_j98h

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■ One can see that by adding the capacitor we were able to transform 50 ohm in to a complex impedance with a real part of 2 Ohms. So **Figure 1.5 Solution** to a complete Material Materi  $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$ 



$$
Z = \frac{R.(-jX)}{R+(-jX)} = 2 - j \ 9.8 \text{ Ohms}
$$

If we find a way to make the imaginary part equal to zero then the match will be complete. BA) <sup>=</sup> 2-—j9.8 Oh

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■ From electrical science we know that inductors and capacitors have impedances with opposite signs. Inductors have positive sign and<br>capacitors negative. capacitors negative.Impedances with operative



 Inductor and capacitance will cancel each other and our match will be complete.L=115 nH @13.56 MHzif we add an inductor which impedance value  $@$ <br>uctor and capacitance will cancel each other and<br>15 nH  $@$ 13.56 MHz

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Valentin Todorow 2009if we add an inductor which is a inductor which in the control of the co

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Capacitors

# **Basic L Matching Network**

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ideal. Real capacitors and



■ This way we arrived to the basic and most used L shape matching network. By using capacitors and inductances we can achieve included the y asing capacitors and inductances we can do never<br>impedance matching without power loss assuming the components are ideal. Real capacitors and inductors exhibit losses which need to **The minimized during the match design. The most critical component in the basic and most used to the most critical component** is the inductor. At high frequencies the skin effect and inter winding capacitance decrease the quality of the coil. network.impedance in the control of the control of



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# **Basic L Matching Network**



**Two types L matching networks – Until now we matched real load to real load. What to do when we have reactance?**



Parallel, also known as shunt or load capacitor is always on the high R side. Called "load" capacitor because it adjusts the real part of the load. Series sometimes called "tune" because it tunes out the reactive part of the load.

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#### **RF for Plasma Processing – Matching Networks**

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**Simplicity - Easy to build auto matching networks. It has only two** components to be controlled for adjusting the real and imaginary part of the impedance. The common  $\alpha$ used ancessing in plasma processing Is the circuit. In plasma processing Is the circuit  $\alpha$ 

> Practical component values - some of configurations require either very low inductance values or very high capacitance values which is impossible to make especially when you have to design auto matching components for an and imaginary controlled network with a wide tuning range. reasonsare: impedance.

The quality factor Q of the circuit is determined only from the source (generator) and load (plasma impedance) and does not depend on the external components - this is may be the most important property of the circuit. What this means is that for certain load impedance there is only one combination of L and C to match that load.



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# **Basic L Matching Networks**



- T and Pi network require more complex control algorithm for automatic matching network design. Need to control three components which makes it more expensive.
- The disadvantage of the L circuit it can match loads equal or less **than 50 Ohm. If the L circuit is reversed it can match loads equal or** higher than 50 Ohm. It can not match on both sides. For example If the load is changing from 35 to 100 Ohms a reversed L network will match only from 50 up to 100 Ohms and will not match from 35 to 50 **Ohm.** automatic

Basic

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14Can be represented as two L circuits connected together matching in to an Imaginary load Rx which has to be smaller than Rs and RI and is used to calculate<br>
Q of the circuit. Q of the circuit.

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 $X1 := Rs \cdot \left( \left| R\right| \cdot \frac{(1+Q^2)}{R} \right)$ Rs $X1 := Rs \sqrt{\left[Rl \cdot \frac{(1+Q^2)}{Rs}\right]} - 1$ 

Could be represented as two L circuits connected together through their shunt 2Component. The imaginary resistor  $Rx$  this time has to be larger than both  $Rs$ and RI. Q is defined as the ratio between Rx and the smallest load resistance.

> ETCH PRODUCTS BUSINESS GROUP resistor Rx this time has to be larger than both Rs

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circuits connected to gether through the through their shunters and their shunters of the through their shunters

# **Smith Chart**

Smith

Values:

Freq

Points:|1

(ohms): <sup>50</sup>

(ohms): |59

(ohms): |0

Sample

Terminations:Reference

Load

Load

Sweep Range: Freq



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**Increased untill the trace crosses the 50 Ohm circle.** Lets match a  $Z=2-j35$  to 50 ohm which is representative of capacitive plasmas. We will be using an L circuit and will be moving from the load to the generator. The first step will be to add the series inductor. The value of the inductor should be

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matches

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The next step will be to add the shunt capacitor. The value is increased until the trace crosses the 50 Ohm point. The design is ready. Component values can bered from the chart.

ETCH PRODUCTS BUSINESS GROUPwill be to add the shunt capacitor. The shunt capacitor is increased until the value is increased until th

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19Lets match a Z=2+j35, which is representative of inductive plasmas. Will be also using L circuit and will be moving from the load thoward the generator. Normally a L circuit consists of series inductor. Here the inductor is part of the load and it is larger than what we need. Because of that our series component will be a capacitor to compensate for the excessive inductance. Cap Value will decrease untill we cross 50 Ohm circle. match

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Second step will be to add the shunt component and the impedance transformation is completed.

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 ADVANCED ENERGY INDUSTRIES INC. Exhibit 1008step will be to add the shunt component and the shunt component and the shunt component and the impedance of  $27$ 

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- Match range determined by plasma impedance range. Usually determined empirically. One can use existing matches or design its own box with variable components. Use this matches to manually tune in to plasma condition. Plasma impedance can be determined **two ways:** Matchingdetermined by plansma impedance range. Usually,  $\alpha$ determined by the con-
	- Load the input of your box with a 50 ohm load and measure the impedance on the match output.
		- Measure the values of the series and shunt component and calculate the impedance.
	- $\blacksquare$  Logal the Why chamber impedance is important?

Determine range of values for the series and shunt component.

Determine current and voltage capabilities of the components

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**Market Communication** 

ways:

- Superstanded in the series and shunt component.
- $\blacksquare$  Determine current and voltage capabilities of the components



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 Determining RF current through the match – We will use the already known equation for the quality factor:MatchingNetworks Design Considerations ©).

$$
Q := \sqrt{\left(\frac{R\,\text{source}}{R\,\text{load}}\right) - 1}
$$

Use the lowest value for Rload you have measured and calculate Q. From resonant circuit theory we also know that the current within the circuit = outside current  $\times$  Q. outside current can be calculated from Ohms law using the maximum power which<br>the metab will bendle and 50 Ohms as asures impedance. For example for 3 kW the match will handle and 50 Ohms as source impedance. For example for 3 kW **Current will be:** equation $f_{\alpha}$  the lowest value for be calculated from<br>e and 50 Ohms as

$$
R := 50 \qquad P := 3000
$$

$$
I := \sqrt{\frac{P}{R}}
$$

 $I = 7.746$  $=$   $=$ 

For Rload= 1 ohm Q will be 7. Then match current will be 54A.

7.746<br>7.746<br>7.746 <u>7.746 7.746 7.746 7.</u>

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 Series leg design – If you have a look at the L matching network topography you will see that series leg is an inductor. In auto matches we use variable components and it is hard to design variable inductors. Because of that a corrier combination of L and a variable C is used. Erem the countion below series combination of L and a variable C is used. From the equation below one can see that if we vary Xc and Xc<XI the impedance of the series leg remains inductive. This was use are have a variable inductor. can see that if we vary xc and xc<xi the impedance of the series<br>inductive. This way we can have a variable inductor.  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  co  $\blacksquare$  inductive. This way we can have a variable inductor.

#### $X := XI - Xc$  $X := XI - Xc$

Inductor design consideration  $-$  coil is the major loss component in the match. Because of the high current and skin effect real losses in the coil can be significant if it is not sized properly. Coil temperatures can reach more that 150<br>degree C if the cross section is not selected taking in to consideration the skin degree C if the cross section is not selected taking in to consideration the skin dept at the frequency of operation, design consideration of many deptation  $\alpha$ inductive.

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- $\color{red} \textcolor{red}{\textcircled{\small{1}}}$
- Shunt leg design In many cases a large value for the shunt capacitor is required. In this case the designer has two optionsMatching
- Use fixed capacitance in parallel with the variable cap. The back draw of such design is that it shifts the impedance. It expands the range at higher end, however it limits you at the lower end.- Use fixed capacitance in parallel with the variable cap. The back draw o  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  a
	- Infilits you at the lower end.<br>- A better solution is a series combination of variable capacitor C and a small inductor. When Xc is at its max value and XI<<Xc the total X is almost unchanged. So there is no limiting at the upper end of the tuning range. If Xc is at its lower end and Xc is comparable but higher to XI the value of X will be drastically changed. For example if Xc is 2 Ohms and XI=1 Ohm, the total impedance will be 1 ohm which is like doubling the capacitance in value. With such design one needs to make sure is a series combination is a series combination is a series combination is a series combination of variable capacitor  $C$  and a small a smalle that you are not operating at series resonance (XI=Xc) at the operating frequency because currents in the leg will be enormous. There is no limiting at the upper end of the tuning range. - A better solution is a series compination<br>inductor M/bon Yo is at its may value are  $X$ comparable but higher to  $X$  the value of  $X$  the value of  $X$  the value of  $X$

$$
X := XI - Xc
$$



■ Parasitic reactance – every piece of wire will exhibit inductance and capacitance to ground. Previous circuits we analyzed do not include any of this stray inductance or capacitance. In real world design all this should be considered, especially at high frequencies. The rule is keep wires as short as possible and as far as possible from ground. Parasitic reactance — every <sup>p</sup>iece of wire will exhibit inductance and If not possible every parasitic should be analyzed and included in your schematic. This stray inductance or capacitance or c Matching S should

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#### **Matching Networks Design Considerations- Grounding**

**Straight wire inductor** 

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- L = 0.002l[2.3 log(4l/d 0.75)] uH<br>– Networks Design Considerations- Ground- Grounding and S
	- $l =$  wire length in cm
	- d= wire diameter in cm
- Lets assume a 2mm diameter wire with 30 cm and 100 cm length $\begin{array}{|c|c|c|c|}\n\hline\n\end{array}$  with wire inductor  $\begin{array}{|c|c|c|}\n\hline\n\end{array}$ 
	- $-$  L30 = 0.38 uH L100 = 1.5 uH
		- @50 Hz impedance will be:  $-\omega$ 50 Hz impos
	- $\frac{1}{2}$  X30 = 0.00012  $X100 = 0.00047$
	- $\overline{Q}$  @13.56 MHz the impedance will be:
	- $X30 = 32$  Ohm

 $X100 = 128$  Ohms

■ From the above example we can see that what is considered ground for AC is not a ground for RF. Higher the frequency higher the impedance of a wire.  $\blacksquare$  From the above  $\epsilon$ 





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