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A Switched-Mode Power Amplifier for Ion Energy Control In Plasma Etching

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Keywords

«Physics research», «Industrial application», «Amplifiers», «Plasma».

Abstract

Plasma etching is an important process in the semiconductor manufacturing process. In order to precisely control the ion energy for better process quality, a tailored pulse-shape voltage waveform is applied to the plasma reactor table. Traditionally, a linear amplifier is used to generate this waveform, which results in poor efficiency. This paper proposes a switched-mode power amplifier as a substitute to the traditional linear amplifier. The electric equivalent circuit of the plasma reactor is introduced and a basic topology for the switched-mode power amplifier is derived. The basic topology is able to generate the required waveform but it has a low efficiency of charging the capacitive load in practice. Therefore, an efficiency-improved topology is proposed by adopting resonant charging. A prototype is built in order to validate the research. The experiments show that the presented solution yields a significantly reduced input power compared to the normally used linear amplifier in this application.

Introduction

Plasma consists of positive ions, negative electrons and neutral particles with an approximately neutral net charge [1]. It is widely used in semiconductor manufacturing, such as plasma etching and deposition process. Fig. 1 (a) shows a schematic diagram of a typical setup of an inductively coupled plasma etching chamber. Gas, such as argon or hydrogen, is infused from the top of the chamber. Plasma is ignited and sustained in the chamber by applying an external radio frequency (RF) power supply which is coupled with the gas through a matching network and coils. The pressure in the chamber is kept low by a vacuum pump in order to increase the distance between particles thereby reducing particle collisions. A substrate wafer is placed on the table and the material on the substrate surface is removed by chemical reaction or physical sputtering in a certain pattern, which is called etching. A chemical reactant gas can also be injected into the chamber to react with the surface of the substrate wafer.

An ion sheath is formed where plasma is near the substrate, which is a region where the ion density is larger than the electron density. The fast-moving electrons in plasma easily get lost when confronted with a surface like the substrate, thus leaving excess ions near the surface. As a result, the surface is negatively charged, forming an electric field which attracts ions and repels electrons [2]. By applying a

Fig. 1: (a) A typical setup of an inductively coupled plasma chamber and (b) its equivalent electric model.

negative voltage to the substrate with a power amplifier connected to the conductive table, the voltage potential of substrate can be controlled. As a result, ions are accelerated by the electric field and bombard the substrate surface. The bombarding ions supply additional energy to the surface and accelerate the chemical reactions. Additionally, the normal direction of ion bombardment to the material surface also enhances the anisotropy of the etching.

For a high-selectivity etching recipe, the ion energy must be within a specific limited range. Ions with too low energy cause a slow reaction rate while ions with too high energy causes sputtering, which decreases the selectivity. With the increasing demands on smaller semiconductor feature size, precise control of ion energy becomes critical in both plasma deposition and etching. In general, a narrow ion energy distribution (IED) falling into a specific energy range is desired.

A narrow IED requires a constant negative voltage potential on the substrate material surface. For a conductive substrate material, a negative dc bias voltage can be directly connected to the table in the plasma chamber. By varying the dc value of the voltage, the energy of the ions can be controlled correspondingly. However, for a dielectric substrate material, there is an equivalent substrate capacitance. An equivalent electric current caused by the bombarding ions is charging the substrate capacitance during etching, resulting in an increasing voltage potential on the substrate surface, thus making the ion energy variant during the process if left uncompensated.

To control the ion energy with a dielectric substrate, different kinds of voltage waveforms have been studied, including the radio-frequency (RF) sinusoidal waveform [3], square waveform [4] and tailored pulse-shape waveform [5], among which the tailored pulse-shape waveform is the most precise one. All of the tailored pulse-shape waveforms in previous researches were generated by class-A linear amplifiers [5, 6, 7], which are typically expensive and inefficient. In our literature research, no paper or combination of papers was found to consider the power amplifier from the perspective of the power consumption in the physics research. Therefore, in this paper, a power electronics concept based on a switched-mode power amplifier is introduced. It is able to generate the required waveform in order to obtain a narrow IED and at the same time reduce the input power by about 90% compared to the linear amplifier by improved amplifier efficiency. A prototype was built based on this concept and experiments were conducted on a plasma etching machine for validating the concept.

Power Electronics Concept

In order to illustrate the concept, a simplified equivalent electric model is built as depicted in Fig. 1 (b). The bulk plasma is modelled as a voltage source with a positive potential V_p with respect to ground, the magnitude of which is dependent on the temperature and pressure of the chamber and the power of the RF source. V_p is assumed to be constant during etching and is normally tens of volts.

During etching when the substrate potential v_{sh} is negatively biased, the positive ions are attracted to the substrate. As a result, the bombardment of ions generates an equivalent current I_i , which is assumed to be constant in this paper [8]. A sheath capacitance is present between the plasma potential and substrate surface. Besides, there is also a parasitic capacitor between the substrate and the chamber wall [3]. Since the wall is grounded and the plasma potential is constant during the etching phase, they are modelled in total as C_{sh} . C_{sh} is variant during etching phase unless the substrate potential is constant.

Depending on the material and composition of the substrate, the substrate can be either dielectric or conductive. For a dielectric substrate, it is modelled as a capacitor C_{sub} . In addition, there are also parasitic capacitances between the table and the chamber wall and between the table and the sheath respectively, which are modelled in total as C_t . In practice, both C_{sub} and C_t are much larger than C_{sh} . As a result, during etching, a series of equations can be used to describe the electric model and given by

$$i_t = C_t \frac{dv_{out}}{dt}, \quad (1)$$

$$i_{sub} = C_{sub} \left(\frac{dv_{sh}}{dt} - \frac{dv_{out}}{dt} \right), \quad (2)$$

$$i_{sh} = C_{sh} \frac{dv_{sh}}{dt}, \quad (3)$$

$$I_i = i_{sh} + i_{sub}, \quad (4)$$

$$i_{out} = i_t - i_{sub}. \quad (5)$$

In order to obtain a narrow ion energy distribution, a constant v_{sh} is desired thus $\frac{dv_{sh}}{dt} = 0$. By further manipulating the above equations, the required characteristics of the power amplifier can be derived and are governed by

$$\frac{dv_{out}}{dt} = -\frac{I_i}{C_{sub}}, \quad (6)$$

$$i_{out} = -I_i - \frac{I_i C_t}{C_{sub}}. \quad (7)$$

Therefore, the output voltage v_{out} of the amplifier is a negative voltage ramp and the output current i_{out} of the amplifier is a negative constant current in etching process.

However, since C_{sub} is continuously charging during etching, it is required to discharge it periodically to avoid over-voltage on substrate. A short positive voltage pulse can be used to discharge the substrate. During discharge, the voltage potential of the substrate surface is reset to a positive value by the discharge voltage. The fast-moving electrons are then attracted to the substrate surface rapidly so as to compensate the excess ions accumulated on the substrate surface, after which a negative voltage pulse should be applied to the table to restart the etching process. It should be noted that the equivalent electric model is only applicable to the etching phase. The discharge phase is rather complex and lasts for only a very short moment, moreover it is not the main focus of this paper.

The typical waveforms of v_{out} , v_{sh} , $v_{C_{sub}}$ and i_{out} are shown in Fig. 2, among which the waveform of v_{out} is the so-called tailored pulse-shape voltage waveform. The waveform is divided into a discharge phase and an etching phase with a duration of T_{dis} and T_{pro} respectively. V_d , V_s and V_e are the discharge voltage, start and end voltage of the etching respectively. The ion energy is controlled by varying V_s and it is approximately equal to $e(V_p + V_s)$, where e is the element charge.

Fig. 2: The typical waveforms of v_{out} , v_{sh} , $v_{C_{sub}}$ and i_{out} .

At the beginning of the discharge and etching phase, the voltage of C_t should be charged promptly to V_d and V_s respectively. During the etching phase, there are two possibilities for generating a narrow IED: using a voltage source with a negative voltage ramp output or using a dc current source with a constant negative current output. The dc current source has the benefit of lower bandwidth requirement. Therefore, a basic switched-mode power amplifier concept is derived, which consists of two dc voltage sources and one dc current source, as shown in Fig. 3. By turning on S_d , V_d is connected to the table and the discharge phase starts. Similarly, by turning off S_d and turning on S_s , it turns to the etching phase. By turning off both S_d and S_s , etching starts properly.

Fig. 3: The basic topology switched-mode power amplifier concept.

Topology

Fig. 4: The topology of the switched-mode power amplifier.

Fig. 5: The operation of the switched-mode power amplifier.

The basic topology shown in Fig. 3 illustrates a concept of generating the bias waveform by power electronics solution. As shown in Fig. 1, the load of the amplifier is capacitive and the equivalent capacitance C_{eq} is given by

$$C_{eq} = C_t + \frac{C_{sub} + C_{sh}}{C_{sub}C_{sh}}. \quad (8)$$

However, charging and discharging a capacitor by directly connecting it to a voltage source leads to only

a maximum 50% power efficiency. In order to reduce the power loss, resonant charging can be adopted by adding an inductor between the voltage source and the load [9, 10].

The power amplifier depicted in Fig. 4 shows one feasible topology, which is able to charge and discharge the capacitive load softly thus significantly reducing the power loss. The amplifier consists of four controllable dc voltage levels V_{dsn} , V_{fsn} , V_{rsn} and V_{ssn} and one controllable dc current source I_c . V_{dsn} and V_{ssn} are utilized to generate V_d and V_s at the output respectively. V_{fsn} and V_{rsn} are two intermediate voltage levels used to reduce the resonance. The dc current source can be realized by an inductor in series with a voltage source. L_s is the resonant inductor and it can be the stray inductance of the chamber and connection. A blocking capacitor C_b is used at the switch-node in order to produce an equal current flowing into both side of the amplifier [11]. A self-biasing dc offset voltage V_b is then formed over C_b , the value of which is determined by the plasma condition and the output waveform. Normally, the value of C_b should be much larger than C_t and C_{sub} so that V_b can be assumed constant during steady state operation. In this case, V_{dsn} , V_r and V_{ssn} are governed by

$$V_{\text{dsn}} = V_d + V_b, \quad (9)$$

$$V_r = V_r + V_b, \quad (10)$$

$$V_{\text{ssn}} = V_s + V_b. \quad (11)$$

The operation of the power amplifier is depicted in Fig. 5. The time of a complete cycle is $T_{10} - T_0$. The details of the operation is explained as follows.

- T_0 : at the end of the etching phase, S_d is turned on. The current I_c is connected in series with the voltage source V_{ssn} . At the same time, the switch-node voltage $v_{\text{sw}} = V_{\text{ssn}}$. The resonance between L_s and C_{eq} is then triggered. Since the resistance in the loop is small and can be neglected, the output voltage can be described by

$$v_{\text{out}}(t) = V_e + (V_s - V_e) [1 - \cos(\omega_r(t - T_0))], \quad (12)$$

where ω_r is the resonant frequency and determined by $\omega_r = \frac{1}{\sqrt{L_s C_{\text{eq}}}}$. The output current is given by

$$i_{\text{out}}(t) = \frac{V_s - V_e}{\omega_0 L} \sin(\omega_r(t - T_0)) - I_c. \quad (13)$$

I_c is typically much smaller than the magnitude of the current resonance thus it can be neglected.

- T_1 : S_{sn} is turned off and the current source I_c is disconnected from the switch-node. In order to minimize the resonance, the energy stored in L_s should be fully discharged, which leads to

$$i_{\text{out}}(T_1) \simeq \frac{V_s - V_e}{\omega_0 L} \sin(\omega_r(T_1 - T_0)) = 0. \quad (14)$$

Therefore, $T_1 = T_0 + \frac{1}{2}T_r$, where $T_r = \frac{2\pi}{\omega_r}$. In this time interval, $v_{\text{out}} = 2V_s - V_e$ and $i_L \simeq 0$.

- T_2 : S_r is turned on after S_{sn} is turned off. The switch-node voltage v_{sw} is equal to the intermediate voltage V_{rsn} . In order to prevent short circuit, $T_2 - T_1$ should be larger than the dead-time of the MOSFET. Similar to T_0 , the resonance is triggered again and the output voltage is given by

$$v_{\text{out}}(t) = 2V_s - V_e + (V_r - 2V_s + V_e) [1 - \cos(\omega_r(t - T_2))]. \quad (15)$$

- T_3 : S_d is turned on. Similar to T_1 , in order to minimize the resonance, T_3 should be equal to $T_3 = T_2 + \frac{1}{2}T_r$. In this time interval, $v_{\text{out}} = 2V_r - 2V_s + V_e$ and $i_L \simeq 0$. Since v_{out} should be equal to V_d , V_r is then given by

$$V_r = V_s + \frac{1}{2}(V_d - V_e). \quad (16)$$

- T_4 : S_r is turned off after S_d is turned on. The output voltage remains V_d .

- T_5 : S_d is turned off. The output voltage remains V_d .
- T_6 : S_f is turned on after S_d is turned off. The switch-node voltage v_{sw} is equal to the intermediate voltage V_{fsn} . In order to prevent short circuit, $T_6 - T_5$ should be larger than the dead-time of the MOSFET. The resonance is triggered and the output voltage is given by

$$v_{out}(t) = V_d + (V_f - V_d) [1 - \cos(\omega_r(t - T_6))]. \quad (17)$$

- T_7 : S_f is turned off and the etching phase is started. The resonance is minimized if $T_7 = T_6 + \frac{1}{2}T_r$. The output voltage in this interval is given by $v_{out} = 2V_f - V_d$. Since v_{out} should be equal to V_s , V_f is then governed by

$$V_f = \frac{1}{2}(V_s + V_d). \quad (18)$$

- T_8 : S_{sn} is turned on after S_f is turned off. The current source I_c is connected to the switch-node and ready to sink current from the load. In order to prevent short circuit, $T_8 - T_7$ should be larger than the dead-time of the MOSFET. The output voltage remains V_s .
- T_9 : S_{sp} is turned off after S_{sn} is turned on. All the voltage source are disconnected. The output voltage is decreasing linearly due to the the current source I_c . The slope rate of the output voltage is determined by

$$\frac{dv_{out}}{dt} = \frac{I_c C_{sub} - I_c (C_{sub} + C_{sh})}{C_{sh} C_{sub} + C_t C_{sh} + C_t C_{sub}} \quad (19)$$

- T_{10} : the etching phase is ended. The end voltage V_e is approximated by

$$V_e = \frac{I_c C_{sub} - I_c (C_{sub} + C_{sh})}{C_{sh} C_{sub} + C_t C_{sh} + C_t C_{sub}} T_{pro} + V_s, \quad (20)$$

where $T_{pro} \simeq T_{10} - T_7$.

Experimental validation

A prototype was built based on the introduced topology to validate the analysis. Experiments were conducted by testing the prototype in an Oxford Instruments FlexAL 2 plasma reactor, which is an atomic layer etching /deposition (ALE/D) machine, as shown in Fig. 6. The original integrated linear amplifier is uninstalled and the designed power amplifier is connected to the table instead. Argon plasma is excited and sustained with an RF power of 600 W and the constant pressure of the chamber is of 2.2 mTorr. A dielectric wafer is used as a substrate. It is hard to measure v_{sh} during the process inside the chamber but the ion energy distribution is measured by a retarding-field energy analyser (RFEA), as shown in Fig. 7.

Fig. 6: The FlexAL 2 ALE/D machine.

Fig. 7: The reactor table, wafer and RFEA.

The waveforms of v_{out} and i_{out} are measured with high-bandwidth differential voltage probe and current probe respectively and shown in Fig. 8. V_d is about 30 V and V_s is about -190 V. Constant I_c is measured to be about 15 mA. The repetition rate is 100 kHz and duty cycle of etching is 90%, resulting in $V_e = -228$ V. The measured normalized ion energy distribution is shown in Fig. 9. It can be seen that

the ion energy is mainly distributed around 232 eV, which is basically consistent with V_s . The plasma potential during etching can then be calculated by $V_p = 232 - 190 = 42$ V. The input power supplying to the power amplifier is only about 20 W. Compared to the linear amplifier used under the same condition [3] with a 200 W input power, a reduction of the input power of more than 90% is achieved while a narrow and single-peaked IED is obtained.

Fig. 8: The measured waveforms of v_{out} and i_{out} .

Fig. 9: The measured ion energy distribution.

Conclusion

Plasma etching requires a narrow ion energy distribution to improve the etching quality. In order to obtain precise ion energy control, a tailored pulse-shape voltage waveform generator is used for biasing the substrate. Typically a class-A linear amplifier is used, which is inefficient and expensive. In this paper, an electric equivalent model of the plasma chamber during etching is introduced and described analytically, based on which a switched-mode power amplifier concept is derived. Furthermore, an efficiency-improved topology is proposed by adopting resonant charging. The topology consists of four switched dc voltage sources and a dc current source. Two of the intermediate voltage sources are utilized during rise and fall transient of the voltage pulse in order to minimize the resonance.

A prototype amplifier is built and tested on a plasma etching machine. The measured ion energy yields a very narrow distribution while the input power of the prototype is reduced by more than 90% compared to that of a linear amplifier used in previous research, underlining the effectiveness of the concept. The paper shows a significant potential and prospect of bringing power electronics to the plasma physics application.

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