STUDY AND ANALYSIS OF SURFACE CHARGE COLLECTION AND EMISSION SPECTRUM OF PLASMA ASHING PROCESS

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Specially dedicated to my beloved mother, Mrs Vejayaletchemee Sivapathy; my soulmate, Dr. Logeetha Kanthaan, father, siblings and friends who have encouraged, guided and inspired me throughout my journey of education…

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ABSTRACT

This research presents an important observation on the total surface charge collection using quantox wafers through the measurement of surface voltage (V_s) on wafer surface with contactless Kelvin Probe for changes in parameters during plasma ashing. In this report, it is covered on the plasma characteristics and performance using the optical emission spectroscopy (OES) measurement, the study on how processing condition change can impact the total surface charge collection and also the uniformity of the charges on the wafer surface, using the quantox measurement. In this study, 3 different types of ashers are tested with varying 5 processing parameters, which where the process time, pressure, gas flow, power and temperature. It is seen that changes in the condition of these parameters do impact on the total surface charge collection and also the uniformity of the charges on the wafer surface. Based on the processing conditions, it is observed that Inductively-Coupled Plasma (ICP) asher model is better in terms of total surface charge collection and uniformity compared to Barrel asher model, which has lower total charge collection but with higher non-uniformity due to the machine chamber configuration. On the other hand, Helical Resonator Plasma (HRP) asher model contributes to higher total surface charge collection with the lesser uniformity, which could potential contribute to plasma induced damage (PID).

ABSTRAK

Kajian ini membentangkan pemerhatian penting terhadap pengumpulan caj permukaan menggunakan wafer *quantox* menerusi pengukuran voltan *(Vs)* pada permukaan wafer dengan pengukuran tanpa kontak *Kelvin Probe* terhadap perubahan parameter semasa proses *plasma ashing*. Laporan in merangkumi ciri-ciri dan pretasi plasma menggunakan spektroskopi emisi optik (OES), kajian mengenai bagaimana perubahan parameter semasa proses memberi kesan kepada pengumpulan caj keseluruhan dan keseragaman caj pada permukaan wafer, dengan menggunakan pengukuran *quantox*. Dalam kajian ini, 3 jenis *plasma ashers* diuji dengan mengubahkan kondisi 5 parameter proses, iaitu masa proses, tekanan, aliran gas, kuasa dan suhu. Adalah dilihat bahawa perubahan pada parameter ini memberi impak kepada pengumpulan caj keseluruhan dan keseragaman caj pada permukaan wafer. Berdasarkan parameter pemprosesan, diperhatikan bahawa model *asher Inductively-Coupled Plasma (ICP)* adalah lebih baik dari segi jumlah kutipan caj permukaan dan keseragaman caj berbanding dengan model *asher Barrel*, yang mempunyai jumlah pengumpulan caj yang lebih rendah tetapi keseragaman yang rendah yang disebabkan oleh konfigurasi ruang mesin tersebut. Sebaliknya, model *asher Helical Resonator Plasma (HRP)* menyumbang kepada kutipan caj permukaan yang lebih tinggi dengan keseragaman yang lebih rendah, yang boleh menyumbang kepada kerosakan akibat plasma (PID).

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LIST OF SYMBOLS & ABBREVIATIONS

Å	-	Angstroms
AC	-	Ashing process chamber
AR	-	Antenna ratio
Ashrate	-	Ashing rate; photoresist removal rate over time
BOX	-	Buried oxide
C	-	Carbon
℃	-	Degree Celcius
CD	-	Critical Dimension
CF_4	-	Tetrafluoromethane gas
CH_4	-	Tetrafluoromethane gas
CMOS	-	Complementary Metal Oxide Semicondutor
CO	-	Carbon monoxide gas
CO_2	-	Carbon dioxide gas
CVD	-	Chemical Vapour Deposition
C_xH_y	-	Hydrocarbon; commonly known as photoresist
DoE	-	Design of Experiment
EC	-	Etching process chamber
EPD	-	Endpoint Detector
H_2	-	Hydrogen gas
H_2N_2	-	Forming gas
H_2O	-	Water
H_2O_2	-	Hydrogen peroxide
H_2SO_4	-	Sulfuric acid
HRP	-	Helical resonator plasma
IC	-	Integrated circuit
ICP	-	Inductively-coupled plasma

min - minute (time)
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
N_2 - Nitrogen gas
N_2O - Nitrus oxide gas
NIST - National Institute Standard and Technology
nm - nanometer
NMOS - Negative-channel Metal Oxide Semiconductor
O_2 - Oxygen gas
OES - Optical emission spectrocopy
OH - Hydroxide
PID - Plasma induced damage
PMOS - Positive-channel Metal Oxide Semiconductor
PR - Photoresist
PRS - Plasma resist strip
RF - Radio frequency
RF - Radio Frequency
sccm - Standard cubic centimeter per minute
SF_6 - Sulfur hexafluoride gas
SiO_2 - Silicon dioxide
SOI - Silicon On Insulator
Torr - a unit of pressure equals to 133.32 pascals
UTHM - Universiti Tun Hussein Onn Malaysia
UV - Ultraviolet
V_{kp} - Kelvin probe voltage
VLSI - Very Large Scale Integration
V_s - Surface voltage
W - Watt
WRS - Wet resist strip

CHAPTER 1

INTRODUCTION

1.1 Research background

In the last 50 years, development in the semiconductor industry has rapidly grown and newer technology has been introduced to the vast market for faster and efficient usage. Ranging from the technology of 10 um to the currently developed 7 nm, plasma induced damage (PID) is something that cannot be measured in-line on production wafers and can only be tested during the electrical test and functional test. Many studies were carried out and many solution were implemented, such as implementation of antenna rules, protection diodes and connection of antenna to the drain, in order to eliminate PID. However, PID cannot be eliminated fully as improvement of devices occured and some newer device technology such as silicon on insulator (SOI) have serious PID threat. Various kinds of plasma processes in the industry such as deposition, implantation, oxidation and dry etching, are known for their risk of causing PID, which can be defined as the damage caused by the charges in the plasma that get trapped in the thin gate oxide and change the transistor characteristics [1 – 6]. This eventually impacts the electrical and functional characteristics, as well as the reliability of the device [1 – 5], [7]. Plasma ashing; also known as plasma resist strip (PRS) process is known to have a high risk of contributing to PID. PRS is a process of removing the photoresist (PR) with residues and polymers formed at the post-etching or post-implant step [8 – 10]. The PID caused by the plasma ashing process is generally random. The common causes for PID are due to the electron charges present in the plasma and the continuous ion bombardment on the surface of the wafer during processing [1 – 2], [9 – 10]. Many types of PRS tools and conditions are present in the industry, which exhibit different impact during the process. Generally, there are single wafer processing PRS and batch processing PRS. Different conditions are utilized for different post-process steps, as it will impact the defect density as well as the performance of the device [11 – 13]. The commonly used method of measuring PID is through the measurement of the surface voltage (V_s) on the wafer surface using a contactless Kelvin Probe [14]. A V_s is usually the result of surface or insulator charge or work function difference and it is most commonly detected with a non-contacting probe, Kelvin Probe [14]. The aim of this study is to understand the plasma characteristics and conditions that will increase the risk of PID on the devices across the different asher models that are commonly used in the industry.

1.2 Problem Statement

Plasma ashing process is a conventional and preferred method of removing the photoresist from wafer surface since it leaves minimal by-product wastes compared to the WRS. On the other hand, plasma ashing process known to contribute to PID on devices, which is not measurable on the product and can be detected only during the electrical or functional test of the device. PID has a major impact on the reliability of the device, causing sudden or early device failure. This has always been a serious threat to the wafer fabrication industry. Although many studies were carried out and many solution were implemented, such as implementation of antenna rules, protection diodes and connection of antenna to the drain, but newer technology such as the SOI has the PID risk.

1.3 Objectives

The objectives of this project are:

i. To characterize the mechanisms of plasma ashing and types of plasma asher models used in the industry.

ii. To characterize and analyze the emission spectral line during O_2 plasma ashing for different plasma ashers.

iii. To investigate and analyze the V_s collection on wafer surface.

1.4 Scope of Research

In order to meet the above objectives, the project is executed as below:

i. Determination of the plasma conditions using the Ocean Optics HR4000 by collecting the optical emission of O and C in a plasma asher system and evaluate the relative wavelength of the spectrum for each ion species spectral line based on NIST database.
ii. Execution of quantox measurement in order to understand and analyze the total charges collection on the wafer surface and its correlation with PID using the quantox wafers.
iii. Three models of plasma asher system; ICP, HRP and Barrel plasma ashers are used and compared, for better understanding on the comparison between single wafer processing and batch processing models.
iv. Five process parameters; process time, pressure, gas flow, power and temperature, are varied to examine their effects on the total charges collection.
v. Fresh chamber after chamber cleaning is used and the effects of chamber condition are not covered in this study.

1.5 Thesis Outline

This research thesis consists of five chapters. First chapter describes on the overview of this research. The second chapter explains on the literature review of previous studies on this topic. The third chapter provides an elaborate explanation on the methodology used to obtain the results and the equipment, experiment and tools used for data collection. The fourth chapter delves into the analysis and discussion of the results obtained. Final chapter encompasses the summary of findings and the conclusion of the entire research.

CHAPTER 2

LITERATURE REVIEW

2.1 Fundamental of plasma ashing process

Plasma ashing is a technique used to strip photoresist (hydrocarbon), polymer and residues from a substrate for post-etch, post-implant or rework steps [8]. Normally, O_2 gas is used as the reactant gas. In some applications, N_2 and H_2 forming gases are used to remove hardened polymer and resist from the substrate. The use of O_2 gas for plasma ashing is conventional and is used for all types of asher models [10]. Based on the chemical equation in (2.1), no formation of solid by-product seen during the ashing process, thus it is known to be a cleaner way of removing resist, compared to wet resist strip, which will be explained later in this chapter [12 – 13].

Formation of H_2O is seen in ashing process. Since the processing condition of plasma ashing is typically more than 100 ^{o}C, no liquid by-product is formed and H_2O is pumped out as steam. Figure 2.1 and Figure 2.2 show the illustration of plasma ashing during and after process. During the plasma ashing process, O_2 gas are ionized and it reacts with the resist only, as it is highly selective towards photoresist/hydrocarbon and will not react with other substrate. Figure 2.2 shows the formation of by-products; consist of carbon dioxide (CO_2), carbon monoxide (CO) and water (H_2O) which will in gaseous state.

Typical resist strip equation:

$$C_xH_{y(s)} + O_{2(g)} \rightarrow CO_{(g)} + CO_{2(g)} + H_2O_{(g)} \qquad (2.1)$$

Chemical Equation 2.1 shows that hydrocarbon (PR) reacts with oxygen and forms carbon monoxide, carbon dioxide and water steam.

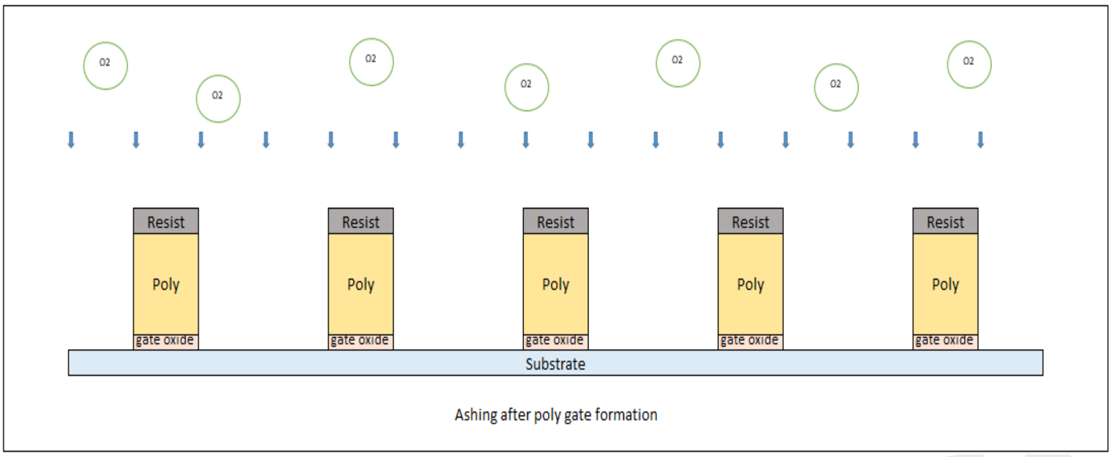

Figure 2.1 : During process - O_2 plasma ashing

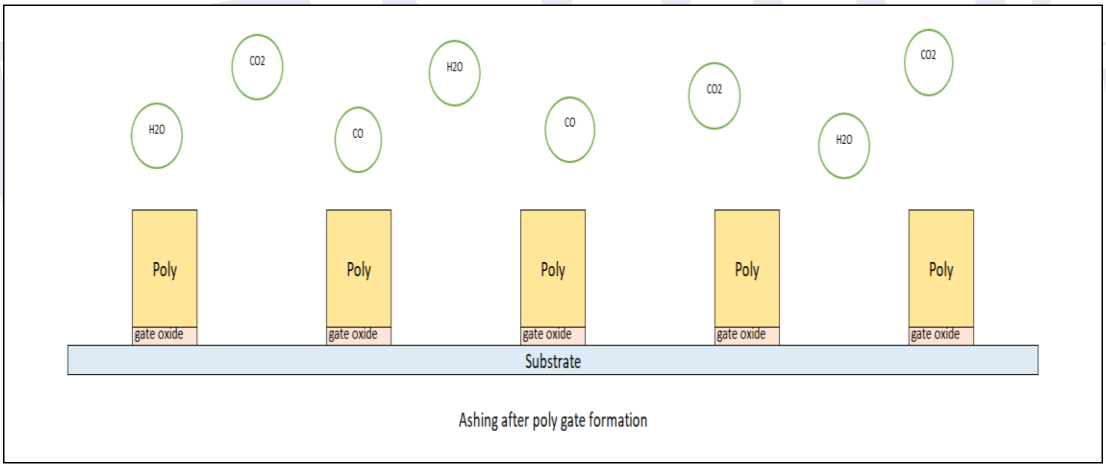

Figure 2.2 : After process - O_2 plasma ashing

Besides typical O_2 plasma ashing, forming gases are added (96% of N_2 + 4% of H_2) with O_2 gas, in order to remove hardened polymer and resist from the substrate. The gas ratio of H_2N_2 gases used with O_2 is generally 1:10. This is because forming gas is used to react with hardened polymers, formed at selected post implant steps that are chemically inert with O_2 gas. When forming gas is included, it will increase O radicals for the process, thus this increases the ashing rate performance [15 – 16]. Using conventional plasma ashers, the forming gas is used to react with the hardened crust of the resist; side effect of high dose and energy implants.

Resist strip with forming gas equation:

$$C_xH_{y(s)} + N_{2(g)} + H_{2(g)} + O_{2(g)} \longrightarrow CO_{(g)} + N_2O_{(g)} + CH_{4(g)} + CO_{2(g)} + H_2O_{(g)} \quad (2.2)$$

Chemical Equation 2.2 shows that hydrocarbon (PR) reacts with oxygen and forming gas that forms carbon monoxide, nitrous oxide, methane, carbon dioxide and water steam.

Besides forming gas, gases like SF_6 or CF_4 can be incorporated during the plasma ashing process. These impurity gases help to improve the plasma ashing rate, result of an increased level of oxygen radicals in the plasma chamber and initiation rate of hydrogen from the photoresist by the fluorine ions presented in the plasma [5]. However, this is not preferred since SF_6 and CF_4 will react with the substrate, resulting in substrate loss due to its reaction and reaction with the metal substrate, eventually causing corrosion of the metal structure.

After typical post etch or post implant steps, plasma ashers are used as the main stripper tool. For some steps, the wet resist strip (WRS) is inserted after plasma ashing step, in order to remove remaining polymers or residues that were unable to be removed by the typical plasma ashing process [5]. Illustration of remaining polymers or residues on the substrate is as in Figure 2.3. Figure 2.4 shows the typical process flow involving WRS after PRS.

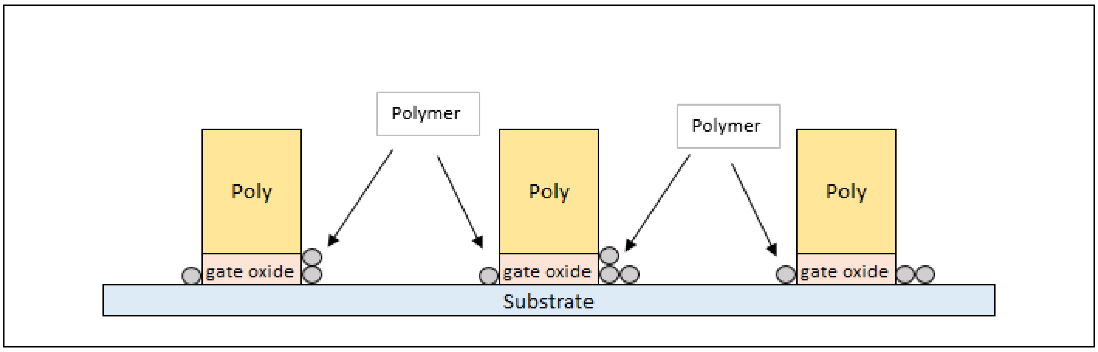

Figure 2.3 : Unremoved polymer after PRS

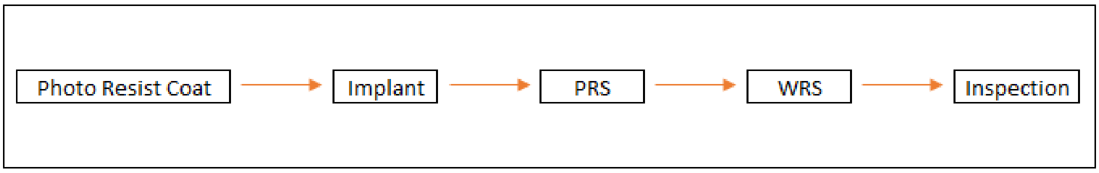

Figure 2.4 : Process flow with WRS

The WRS can be used directly for resist stripping since the chemicals used are sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2). However, there are many disadvantages of WRS. As it involves strong acids and hydrocarbon solvents that are expensive, these are highly toxic and harmful for humans and environment. As not being environmental friendly, the large volume of liquid reactants and by-products need to be handle with precaution. Meanwhile, the impact on the process will be that, under normal circumstances, the processing time is longer compared to PRS, which impacts on the throughput or wafers process per hour that affects the manufacturing productivity.

On the other hand, under certain circumstances, when the WRS bath is saturated with by-products, the stripping efficiently will be greatly affected and this will lead to photoresist/polymer residues on the substrates. This will definitely impacts the device performance [5], [17]. Besides, direct usage of WRS without plasma ashers will generate vast waste since the bath used for the WRS need to be changed frequently due to by-product formation. Meanwhile, for the PRS, the general advantages are that it is non-toxic and non-corrosive, easier to control and cheaper for the industrial applications [5], [17].

In general, there are two types of plasma ashers used. Firstly, there is the in-situ plasma ashing process. For etching tool groups, such as poly or metal etchers, the etching condition occurs at the etching chamber (EC) and the tool has an ashing chamber (AC). The usage of in-situ AC is to aid in the removal of the thin photoresist and polymer, in the case of the poly etching process. For the metal etching process, the in-situ AC is to remove the photoresist as well as provide passivation for the metal structure, in order to prevent metal structure corrosion.

Secondly, we have the ex-situ plasma ashing process. Ex-situ plasma ashing typically used for post-implant or post wet etch process. It can also be used for thick resist removal and rework of photoresist, such as in cases where the photolithography specification is out of control, whereby it requires the resist to be removed and recoated.

For both types of plasma ashers, no potential bias is applied on the subsrate, which is necessary to attract ions. This is due to the tool configuration of random substrate surface O_2 ion bombardment that is crucial in avoiding substrate loss due to oxidation as plasma ashing process uses high gas flow of O_2 [18]. On the other hand, this random ions bombardment on wafer surface creates a non-uniformed ions

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