Plasma for Semiconductor Processing

Alexandre Efremov

Abstract

Plasma processing of semiconductor materials plays a dominant role in microelectronic technology. During last century, plasma have gone a way from laboratory phenomena to industrial applications due to intensive progress in both scientific and industrial trends. Improvement and development of new [illegible] experience together with development of plasma theory and plasma diagnostics methods. A most [illegible] parameters (pressure, flow rate, power density) and various levels of plasma system (energy distribution, volume gas chemistry, transport, heterogeneous effects) to understand the whole process mechanism. It will allow us to choose a correct ways for processes optimization.

Key Words : Plasma processing, semiconductor technology, high-density plasma, plasma modeling and diagnostics.

1. Introduction

Plasma processing of semiconductor materials has become one of the most important processes in the microelectronics industry. It is well known that plasma environment is characterized by sufficient advantages in comparison with traditional thermal processes due to the ability to supply low substrate temperature together with the achieving high processing rates. During last decade, the development of plasma processing technology has carried out by the two main ways. First way is the optimization and improvement (including both scientific and engineering aspects) of traditional systems, for example, such as plate parallel reactive ion etching (RIE) reactors to obtain a process characteristics for modern requirements. This seems to be the easiest way, but its ability is limited by a lot of principal factors. Second way is the development of new plasma systems, which should combine the advantages of "old" systems and be free from their disadvantages. This brings us to a development of "high-density" plasma (HDP) reactors. HDP reactors have additional advantages in comparison with traditional plasma diode reactors by providing the process with a separate and independent control of ion energy and ion flux to a substrate surface. In this way, high processing rates can be obtained without introducing excessive ion-induced damage on the wafer. For very large scale integrated circuits (VLSI), we already have developed important processes in semiconductor manufacture using high-density plasma reactors, such as plasma deposition of inter-metal dielectrics, dielectric etching,

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* : 공주대학교 정보통신공학부
(충남 공주시 신관동 182, Fax : 041-856-7958
E-mail : bgchoi@kongju.ac.kr)
** : 서울산업대학교 전기공학과
*** : 한서대학교 전자공학과
**** : 경남대학교 전기전자공학부
Department of Microelectronic Devices & Materials Technology, Ivanovo State University of Chemistry & Technology, Ivanovo, Russia
E-mail : efremov@mail.ru

poly-silicon etching, metal etching and photoresist stripping, and so on.

In this paper, we shall discuss a history, a main trends, achievements and problems of plasma technology in semiconductor industry. We shall also attract the attention on the comparison of characteristics and parameters of various etching systems, including gas chemistry and plasma diagnostics.

2. History and basic concepts

As a generally known, plasma is a "forth state of matter" and this term was first applied by a Langmuir in 1928. Nevertheless, the investigations of electrical discharge were started by W. Gilbert, B. Franklin and E. G. von Kleist 100 years earlier. A rapid progress in electrical discharge physics was made during 19th century due to the works by H. Davy and M. Faraday. They investigated a lot of effects using arc and DC discharges and described these effects by terminologies, which still uses up to modern time.

Nowadays, a term of "plasma" uses more frequently than a term of "electrical discharge". From the physical point of view, plasma is an environment, which contains both neutral and charged particles and satisfies the requirements of *quasi-neutrality* and a *spatial charge separation*. First requirement means that a whole plasma volume we should obtain an equal volume densities of positive and negative charged particles: $n_- + n_e = n_+$. Second requirement is connected with a correlation:

$$L \gg r_D = \left(\frac{KT_e}{8ne^2 n_e} \right)^{\frac{1}{2}} \qquad (1)$$

where L is typical linear size of plasma area, r_D is Debye shielding distance, T_e is electron temperature, n_e is electron volume density. There are a lot of systems, which satisfy both requirements, but only very limited numbers of them are used in a semiconductor technology. Fig.1 illustrates the real variety of plasma environments and a possibility of their applications for semiconductors processing.

Of cause, it does not mean that other kinds of plasma environments are absolutely unusable for semiconductor technology. Nearest examples include DC arcs and RF inductive plasma torches, which are characterized by a power density in the scopes of $10^2 \sim 10^4$ W/cm^3. These plasma environments are near or in thermodynamic equilibrium, and are used for thermal plasma processing. These plasmas are capable for melting or vaporizing materials and have an industrial applications such as welding, plasma flame spraying and arc furnaces.

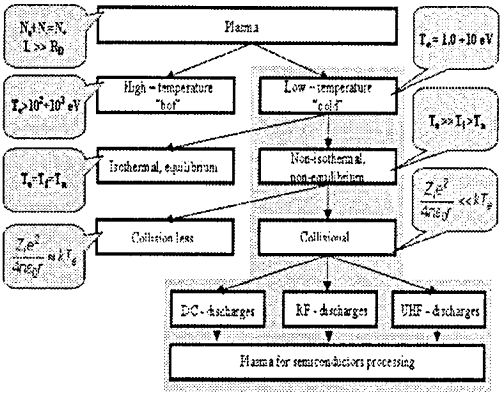

Fig.1. Scheme of various types of plasma environments. Colored area corresponds to semiconductor processing applicable plasmas.

In a further discussion, we shall discuss only on the "gas-discharge at low-temperature plasmas" which are formed by electrical discharge in gas under the pressure lower than atmospheric.

3. Trends of plasma for industrial applications

A large variety of industrial tasks, solved using gas-discharge plasma, is caused by a multi-channel interaction mechanism between plasma active species and solid state surface. It is evidently clear that plasma environment contains both charged (ions, electrons) and neutral (free atoms and radicals both ground state and excited) particles, which are not typical for the same gas under the standard conditions. Generally speaking, it is possible to select at least three big groups of plasma processes, which are directly determined by the type of working gas and solid state surface nature:

1. Removing of the material from the solid state surface (sputtering, etching, clearing);
2. Deposition of the material on the solid state surface (chemical deposition from the gas phase, physical deposition from the target, physical deposition from the target with a gas-phase modification of target material);
3. Solid state surface modification (oxidation, implantation, diffusion, annealing).

For each group and each concrete process, plasma plays different roles concerning the final process result. First, plasma may be only an environment supporting a transport of the particles. Second, plasma may be a source of the particles. Third, plasma may play a role of energy source and catalyst. And forth, plasma may combine two or more features mentioned above. A simplest classification of classical plasma processes according to the main application purposes is shown in Fig.2.

Trends of the modern development of plasma treatment processes are caused by two main reasons. First reason is base for a "qualitative trend". This is an increasing of process quality requirements (anisotropy, selectivity, uniformity, and surface damaging) for the processing of nano-scale structures, and for some specific devices such as a DRAM on the base of ferroelectrics films. Second reason is a base for "quantitative trend". This trend is connected with the involving in semiconductor technology of new materials, which have not been treated by plasma before. Both trends required a simultaneous efforts of engineers and scientists to create a new plasma systems and sources with an independent adjustment of various interactions mechanisms.

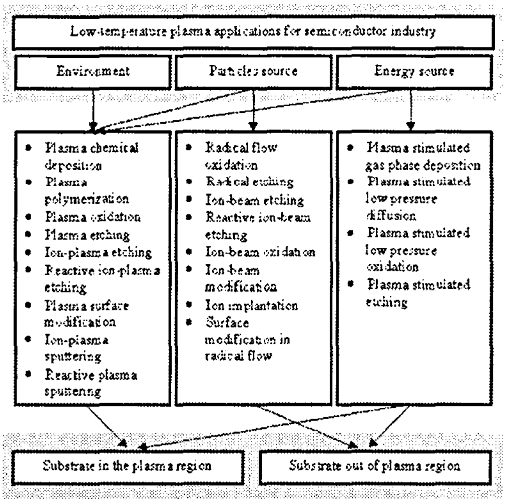

Fig. 2. Classification of plasma processes according to a dominant plasma role.

In a further discussion we shall overview in details one of the most important applications of plasma in semiconductor technology plasma etching.

4. Plasma etching: theory and applications

From the general point of view, any kind of plasma etching is a removing of material from the solid state surface in a quantity more than mono layer. According to a dominant active species and process mechanism, all etching processes may be classified on three groups:

1. Ion plasma etching (IE);
2. Reactive ion etching (RIE);
3. Plasma chemical etching (PCE).

IE process is ensured only by physical sputtering of surface species by the high -energy ions (E_i=0.12 KeV), which are chemically inert to the treated material. RIE process includes a combination of physical sputtering (E_i=100~200 eV) and chemical reaction. PCE process is based only on chemical mechanism, but the chemical reactions on the solid state surface are activated by the low-energy ion bombardment ($E_i < 100$ eV) and UV irradiation. Activation effect in PCE process may be realized, for example, through ion and radiation stimulated desorption of reaction products due to clearing of surface active centers.

Nevertheless, in the case of chemically active gas, it is impossible to realize only one etching mechanism. In all the cases an obtained total etching rate may be performed as a superposition of partial etching rates, which are characterized by a various qualitative contributions for the various etching systems. A simplest equation looks as:

$$R = R_{sp} + R_{sc} + R_{ac} \qquad (2)$$

where R is total etching rate, R_{sp} is rate of physical sputtering, R_{sc} is rate of spontaneous chemical reaction, R_{ac} is rate of activated chemical reaction. Note that equation (2) assumes, that a treated material is placed in a plasma region. Fig. 3 illustrates the main channels of plasma actions to the solid state surface.

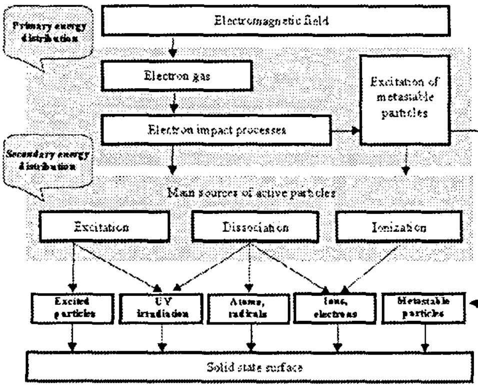

Fig. 3. A scheme of multi-channel plasma action to solid state surface

A total etching rate in the systems, where a chemical mechanism plays a dominant role ($R_{sp} << R_{sc}, R_{ac}$) may be represented as follows:

$$R = \frac{R_g K_e T}{1 + \frac{bSK_e T}{V_p}} \qquad (3)$$

where R_g is rate of chemically active species generation in plasma, k_e is etching rate constant, T is chemically active species life-time, S is treated material area, V_p is plasma volume, b is constant, which depends on the nature of treated material. The correlation between the values of S and $(V_p/k_e b)$ directly determines kinetic or diffusion regimes of etching process. In the first case, when $S << (V_p/k_e b)$, a kinetic regime is realized. Etching rate in kinetic regime is limited only by the heterogeneous steps and do not depends on treated material area. In the opposite case, when $S >> (Vp/k_e b)$, a diffusion regime is realized. Etching rate depends on the treated material area, which correspond to insufficient generation rate of active particles in plasma volume and lead to a well-known "loading effect". Low etching rates (at the conditions of low ion bombardment energy) and a "loading effect" are the important problems of industrial applications of plasma etching processes. There are at least four ways to avoid these problems:

1. Increasing of electrons mean energy up to the value, which corresponds to a maximum of a dissociation cross-section of working gas;
2. Increasing of electrons volume density;
3. Increasing of dissociation and ionization frequencies by the application of magnetic field;
4. Increasing of dissociation degree involving a stepwise dissociation with a participation of metastable particles of noble gases.

All these ways are realized independently or simultaneously in a various kinds of HDP etching systems including MERIE, CCP, ICP and ECR reactors. Typical working characteristics of plasma reactors are given in Table 1.

Table 1. Working characteristics of various etching systems.

System	p torr	n_e cm^{-3}	T_e eV
DC glow	10^{-2}~10^{-1}	10^{9}~10^{10}	1~10
RIE	10^{-2}~1	10^{10}	1~5
MERIE	10^{-2}~10^{-1}	10^{11}	1~5
CCP	10^{-2}~10^{-1}	10^{11}	1~10
ICP	10^{-3}~10^{-1}	10^{11}~10^{12}	1~3
ECR	10^{-3}~10^{-1}	10^{12}	5

An exact choice of chemistry-based etching process, which is required for a concrete task, should follow by the way of both volume and heterogeneous chemistry analysis. Usually this analysis is a rather complicate and required both theoretical investigations and experimental plasma diagnostics. We shall try to underline the basic principles below.

5. Plasma modeling and diagnostics

Plasma modeling and diagnostics are the powerful tools for plasma investigation both for scientific and industrial purposes. These two methods are able to complement one each other to obtain a full understanding of process mechanism. In this combination, plasma diagnostics play double roles. First, it gives an input data for plasma modeling. Second, it gives adequacies criteria for a model development.

Another important task of plasma diagnostics is to provide a real-time process control in industrial equipment. Partial tasks inside this direction may be specified as follows:

- Active species density control;
- Wafer temperature and conditions control;
- Etching rate control;
- Etching end-point detection.

Table 2 contains a list of plasma diagnostics methods and theirs abilities. Note that in this list, we included only methods, which are relatively simple in organization and form a group of "contact-less"methods.

As for plasma modeling, the task of primary importance for the etching process analysis is to establish intercoupling connections between an external process and equipment parameters, internal plasma characteristics and final process effect. A simplest scheme of such connections is shown in Fig. 4. It is evidently clear that the final etching effect, including all process parameters mentioned in Fig.4, is formed under the simultaneous action of the fluxes of various kinds of active species and plasma irradiation. These fluxes are qualitatively determined by internal plasma parameters, which are connected with input parameters (power, pressure, flow rate, reactor geometry), but depends on the large number of physical and chemical processes, both volume and heterogeneous. The best way for the analysis of internal plasma characteristics is to "divide" them to several coupled subsystems, which include processes described by a similar physical or chemical content. Such approach allow to select at least four subsystems:

- Subsystem of electron gas;
- Subsystem of charged particles;
- Subsystem of neutral particles;
- Subsystem of heterogeneous chemistry.

Table 2. Plasma diagnostics method

Method	Abilities
OAS	Density of neutral ground state particles
LAS	Density of neutral ground state and excited particle
OES, OEA	Density of neutral ground state and excited particles including reaction products, etching rate control, etching end-point detection.
MS	Density of neutral ground state, ions density, ions energy distribution.
LI	Wafer temperature, etching uniformity
Abbreviations: OAS-optical absorption spectroscopy, LAS laser absorption spectroscopy, OES optical emission spectroscopy, OEA optical emission actinometry, MS mass-spectrometry, LI laser interference methods	

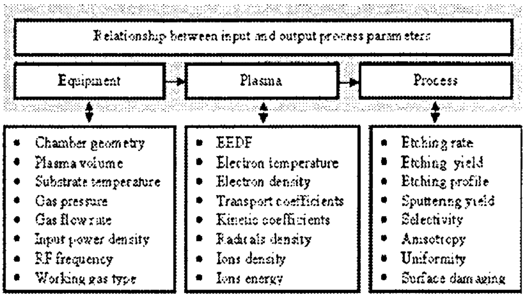

Fig.4. Scheme illustrated the relationships between input and output process parameters.

First subsystem is based on the Boltzmann kinetic equation (as a form of energy conservation law for plasma electrons) and power balance equation. This subsystem describes a combination of physical processes such as transition of energy from electromagnetic field to electrons and energy dissipation during the collisions of electrons with "heavy" particles. As an output parameters, this subsystem gives us electron energy distribution function (EEDF), electron temperature, transport coefficients (diffusion coefficient and mobility) and rate coefficients of electron impact processes. Second and third subsystems are based on the kinetic schemes of charged and neutral particles formation and decay including both chemical and transport effects. Basic equations for each kind of charged (4) or neutral (5) particles may be written as:

$$\frac{d}{dx}\left(-D\frac{dn_c}{dx}+n_c\mu_c E\right)=R_F-R_D \qquad (4)$$

$$n_n D\left[\left(\frac{1}{L}\ln\frac{n_n}{n_0}\right)^2-\frac{Q}{LD}\ln\frac{n_n}{n_0}\right] = R_F-R_D \qquad (5)$$

where n_c and n_n volume densities of neutral and charged particles, n_0 total density of neutral particles, D diffusion coefficient, Q gas flow rate, μ_c mobility, E electric field strength, R_F and R_D total rates of particles formation and decay. Forth subsystem includes adsorption-desorption equilibrium (taking into account both spontaneous and stimulated mechanisms) and a surface chemistry analysis from the point of view of active centers theory.

A simultaneous mathematical description and solution of all subsystems allow to create a general model of etching process which is directly connects an input process parameters with a final effect of treatment. One of the main advantages of such a model is the ability to predict the change of process characteristics after the changing of input parameters, working gas or plasma excitation method.

6. Conclusion

Plasma processes play an important role in semiconductor processing technology. Improvement and development of new plasma systems, such as high-density plasma reactors, required a development of plasma theory and plasma diagnostics methods. This way allow to abandon a "blind search" zone and help to find a direction to a future progress of plasma applications for semiconductor industry.

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