Non-invasive plasma characterization through the ion velocity distribution function

イオンの速度分布関数による非侵襲的プラズマ特性解析

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The high level of miniaturization and degree of integration of modern integral circuits based on semiconductor technology would be unthinkable without the use of various plasma-based processing steps during manufacturing, such as deposition and etching. These processes, their quality and efficiency depend critically on a number of plasma parameters, such as flux, density and energy of the ions. To optimize and control the semiconductor processing it is therefore desirable to be able to measure these quantities without affecting the plasma, its homogeneity and the quality of the ongoing surface treatment process. This is now possible with the method developed by us. It is an extension of the well-known mass spectrometry diagnostics. The method uses the distribution in velocities of the ions, measured at the wall of the process chamber by an energy resolved mass spectrometer, to obtain the plasma characteristics in the plasma volume. The parameters that can be determined include the velocity distribution of the ions in the plasma, their density, flux, mean energy and temperature.

半導体の微細化の進展，高集積化のためには，プラズマを使った成膜，エッチング技術が必要不可欠である。プラズマは，イオンフラックス，密度およびエネルギーなどのプラズマパラメータに特徴づけられ，半導体工程を最適化し，制御するためには，プラズマの均質性やウェハー表面の反応に影響を及ぼすことなく，プラズマパラメータを測定できることが望ましい。我々は一般的なエネルギー分解質量分析計を用いて，プラズマパラメータを測定する新しい方法を開発した。プロセスチャンバの側壁で測定するイオンの速度分布を用いて，プラズマ中のイオンの速度分布，密度，磁束，平均エネルギーおよび温度を決定する事が出来る。

Introduction

The manufacturing of modern semiconductor chips and elements is a complex process that requires multitude of steps. Commonly, these include several stages of plasma processing, e.g. plasma deposition and plasma etching. The characteristics of these steps – efficiency and quality – are dictated by the parameters of the plasma used – ion composition, electric field at the surface, ion density, flux and energy. In some cases, the same plasmas can etch or deposit thin films, depending only on the energy of the incoming ions at the surface. Therefore, for process control and optimization it is important to measure these parameters. Further, a spatially resolved information on the plasma parameters over the processing surface is needed to monitor and adjust the homogeneity of the process.

Various methods exist for plasma characterization. However, some of the diagnostic techniques (e.g. electric probes) are invasive, i.e. they require the insertion of foreign objects in the plasma which disturbs the plasma and interferes with the requirement for plasma homogeneity. Other methods (e.g. spectroscopy methods) provide only line of sight values, i.e. they possess only limited or no spatial resolution. Further diagnostics (e.g. laser-based techniques) are too challenging and complex to setup and run under industrial environment. The method we have developed is based on mass-spectrometry and avoids these shortcomings. It is non-invasive, since it requires only a tiny hole in the plasma walls to sample the ions coming out of the plasma. The method is also easy to set up, as mass spectrometers are commercially available devices that only need to be mounted on the chamber. The data processing method we have developed then extracts spatially resolved information for the plasma based on a single measurement at the wall. The method requires that the mean distance between ion collisions is independent of the velocity.

Experimental setup

The measurements were performed in an inductively coupled plasma in neon gas. Figure 1 shows the discharge setup. The pressure was 1.3 Pa (10 mTorr) and the radio-frequency power was 600 W.

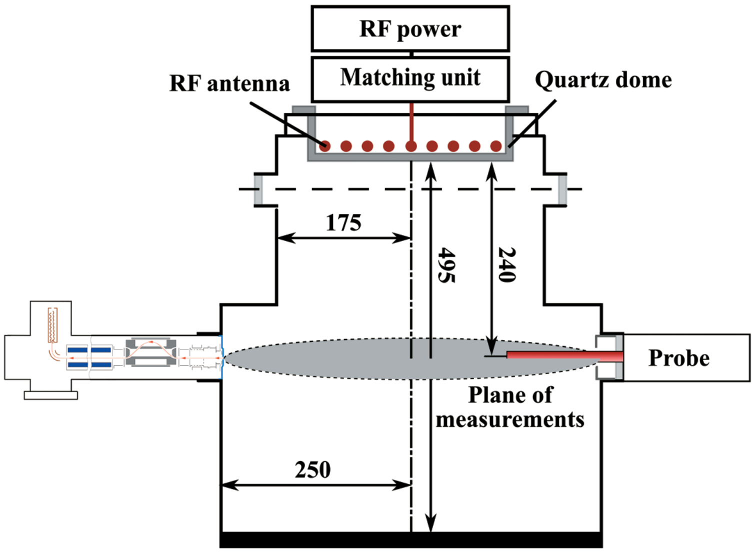

Figure 1 Schematic representation of the discharge chamber with diagnostics. Dimensions are in mm.

The method was developed using a commercial mass spectrometer system (Plasma process monitor, PPM 421, Inficon). The functional diagram of the device is shown in Figure 2. The mass spectrometer, PPM, samples the ions coming to the wall through an orifice with a diameter of 100 µm. The extraction hood around the orifice is at earth potential and, thus, constitutes part of the grounded metal walls of the plasma chamber. Consequently, no distortion is introduced in the plasma.

The ions that enter the PPM can be focused by electrostatic lenses onto the entrance of the next section of the device, which performs the energy selection by letting only ions in a narrow energy interval to pass through it. After that, the ions pass through a quadrupole mass spectrometer that sorts the ions according to their charge-to-mass ratio. A pair of electrostatic electrodes provides a 90° deflection to ensure that only charged particles, i.e. ions, will be able to reach the detector. This removes spurious signals from photons and excited atoms coming from the plasma. A secondary electron multiplier (SEM) acts as the detector. The SEM works in an ion counting mode, which additionally suppresses the noise and allows measurement with a dynamic range of about six orders of magnitude.

The energy and the mass of the ions that can pass through and reach the SEM are controlled by a set of voltages that are varied to obtain the distribution in velocities of the ions, hitting the chamber wall. The PPM measures the ion velocity distribution function[*1] (IVDF) as a function of the kinetic energy of the ions.

As a benchmark diagnostics, the standard method of Langmuir probes (LP) was used. The probe was positioned in the same plane as the PPM and the data were recorded simultaneously with the PPM data. The probe is movable in radial direction and provides the profiles of

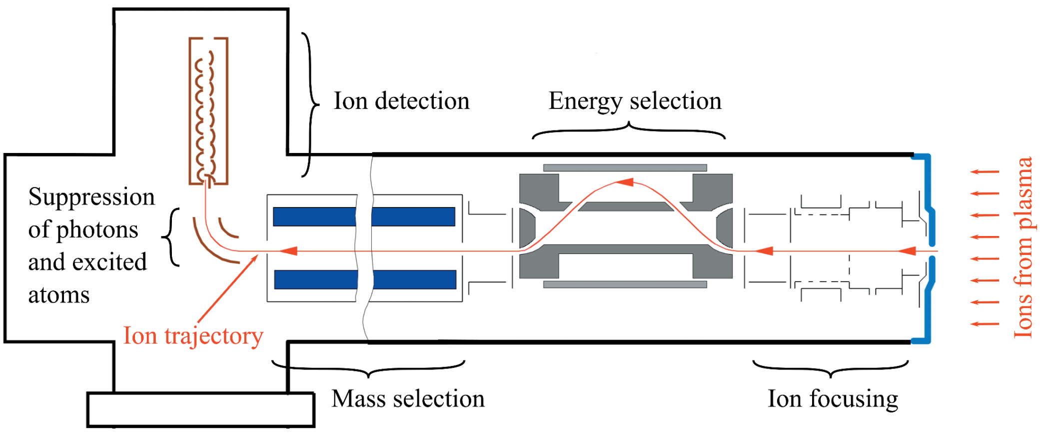

Figure 2 Schematic representation of the used mass spectrometer.

the plasma parameters: electric potential, electron density and temperature.

*1: The IVDF tells how many ions per unit volume are moving with a given velocity.

Data processing

The important contribution of the developed method is in the way the measurement data is processed to obtain additional information about the plasma parameters when the ions have constant mean free path. The idea is based on an exact solution of the Boltzmann equation*2 for the ions. It was shown[1] that the IVDF measured at the wall contains information on the IVDF at any other position along the line of sight. The IVDF there is obtained by a simple shift of the energy axis and scaling of the IVDF (the vertical axis in Figure 3). When the IVDF at a given point is known, then the plasma parameters – density, flux, mean energy and temperature of the ions – can be obtained as simple averages over the corresponding IVDF. The natural parameter for plotting these quantities is the potential shift of the IVDF, i.e. the shift in the energy axis of the IVDF. The solution of the Boltzmann equation reveals also that the ambipolar electric field*3 in the plasma can be obtained from the IVDF. The electric field allows a correspondence between position and potential shift to be established.

*2: Differential equation that determines the IVDF.

*3: The ambipolar electric field in a plasma arises in order to prevent the much faster electrons from leaving the plasma at a greater rate than the slow ions, i.e. to preserve plasma neutrality.

Results

Key element in the developed method is obtaining the IVDF at positions inside the plasma from the velocity distribution of the ions that leave the plasma and hit the wall. Figure 3a presents an example of the measured velocity spectrum at the fixed mass of 20 amu (the main isotope of neon). The same distribution is plotted as a function of the ion velocity in Figure 3b. The figure also shows the IVDF at a position inside the plasma. This IVDF was obtained from the measured one.

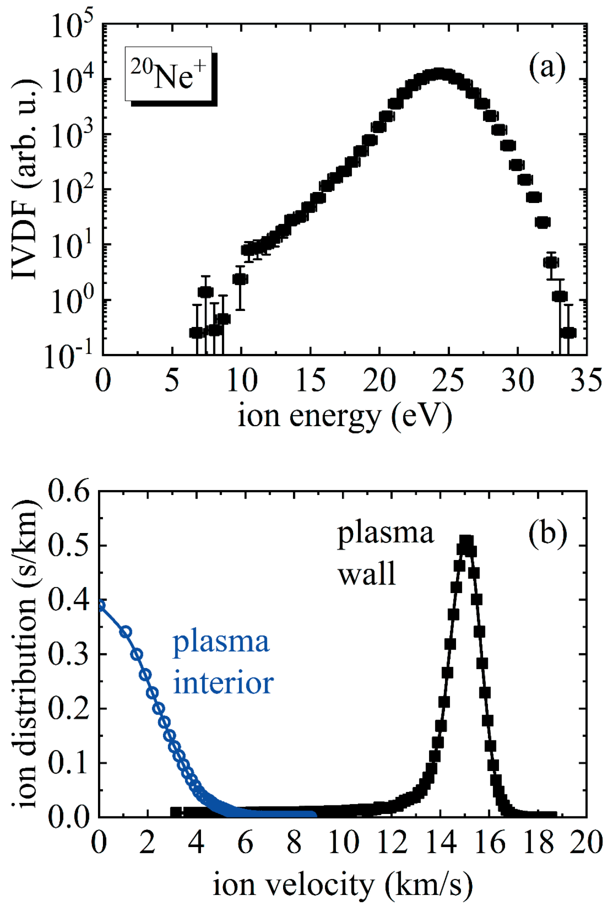

Figure 3 (a) Measured IVDF in neon plasma. (b) IVDF measured at the plasma wall and the IVDF obtained from it for the interior of the plasma. The distributions are normalized to have unit surface area.

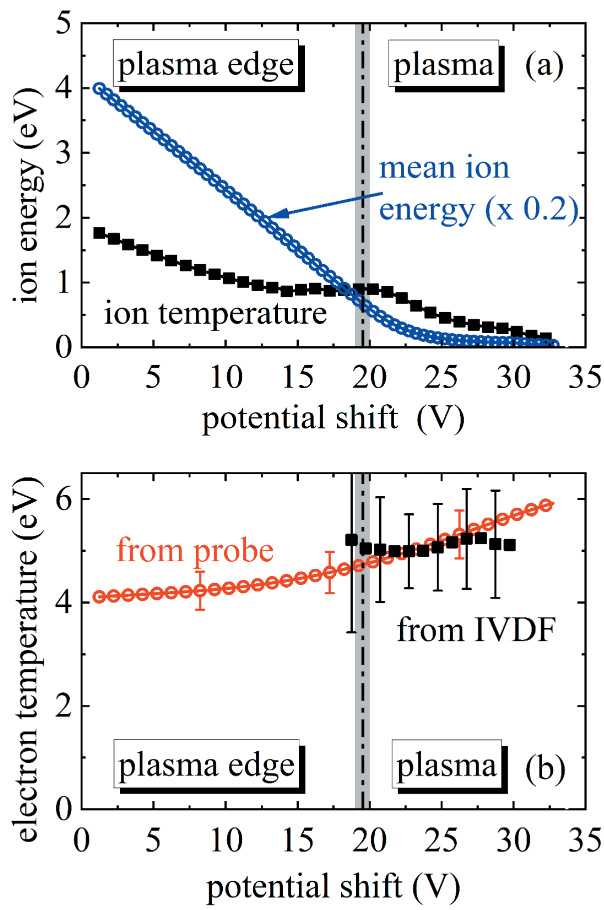

Figure 4 (a) Profiles of the mean ion energy and ion temperature obtained from the IVDF in Figure 3a. (b) Comparison of the electron temperature from the IVDF with the one obtained from conventional LP measurements.

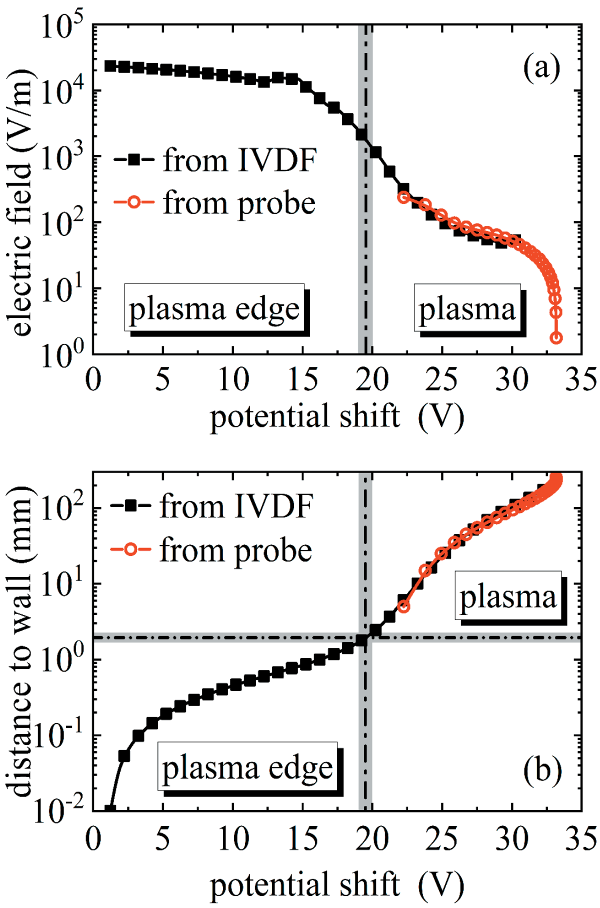

Figure 5 (a) Profile of the electric field obtained from the IVDF and comparison with the field from LP measurements. (b) Correspondence between position and potential shift and comparison with LP measurements.

From the IVDF at different positions in the plasma, the mean energy and temperature of the ions is obtained and shown in Figure 4a. From the profiles of the ion parameters also the temperature of the electrons can be obtained. The result is shown in Figure 4b where it is compared with the data from conventional LP measurements. The grey vertical lines in this and the next figures present the division between the near-wall edge region of the plasma and the plasma interior. This division is important for the description of the plasma and was also determined from the measurements. The LP measurements are confined to the plasma interior.

The IVDF provides also information on the ambipolar electric field in the plasma. The values obtained from the IVDF are compared with those from LP measurements in Figure 5a. Figure 5b shows the correspondence between potential shift and position in the plasma. With this correspondence established, the profiles of the ion and electron density can be obtained. They are presented in Figure 6. The edge region is characterized by strong electric field and large difference of the two densities, whereas in the plasma interior the two densities nearly coincide.

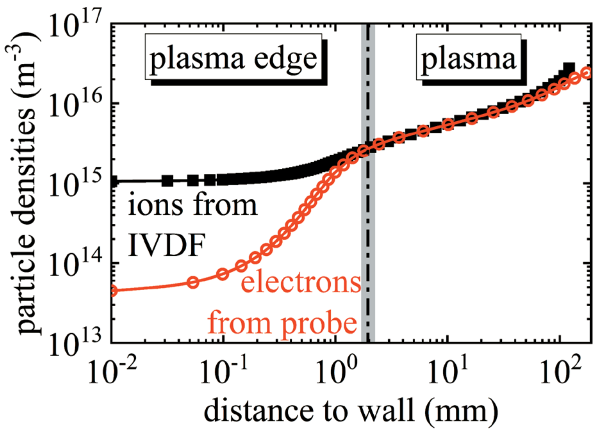

Figure 6 Profiles of the ion density from the IVDF and of the electron density from LP measurements.

Conclusions

A method has been developed that uses a single non-invasive measurement of the ion distribution in velocities at the plasma surface. The method allows from this measurement the spatial variation of the velocity distribution function of the ions to be determined. Using the profiles of the IVDF, various plasma parameters can be obtained. These include the density, the mean energy and temperature of the ions, as well as their flux. Further, the electric field and potential in the plasma and the electron temperature are also obtainable with the method.

The method will be further developed and applied to plasmas containing multiple ion species, molecular plasmas and electronegative discharges. In the future it is expected the method to be applied under industrial conditions for control and optimization of semiconductor manufacturing processes.

References

[1] T. V. Tsankov and U. Czarnetzki, "Information hidden in the velocity distribution of ions and the exact kinetic Bohm criterion," Plasma Sources Sci. Technol., vol. 26, no. 5, p. 055003, 2018.

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