THE BIAS VOLTAGE AND ITS INFLUENCE ON THE ETCHING RATE OF SILICON

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The influence of the bias voltage on the silicon etching rate in the plasma-chemical reactor (PCR) with controlled magnetic fields have been investigated. The dependences of the silicon etching rate on the power, discharge current and on the pressure in the chamber PCR are obtained. It is found that at high bias voltages the main mechanism influencing on the etch rate drop is a material sputtering of the working electrode and its redeposition onto the surface of processed silicon wafers.

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INTRODUCTION

The processes inside in plasma-chemical reactors have been insufficiently studied [1]. This is primarily due to the complexity of the diagnostic of the phenomena occurring in chemically active multicomponent plasma. In the investigation of the optical plasma spectra manage to identify only most intense lines belonging to the excited atoms [2]. Discharge in chemically active plasma often can cause chemical reactions; which are not occurring during normal chemical processes. Therefore, the optical spectra of molecules formed in these processes are absent in existing tables of molecular spectra. For example, in the etching process of silicon in a fluorine-containing plasma (SF_6) formed molecules such as SF_5, SF_4, SF_3, SF_3O, SF_2O_2, SF_2O, SFO and so on, excluding the products of reactions between fluorine and silicon and compounds of sulfur with oxygen [2]. The problems of electron and ion stimulation, as well as, the influence of energy stimulating of the particles on the etching rate of different materials are little-studied, including the most widely used material – silicon. At plasmachemical treatment of silicon the fluorine containing compounds are mainly used in a mixture with oxygen, argon and other gases that does not lead to the destruction of vacuum pumps and other elements of vacuum systems containing aluminum alloys.

The aim of this work is to study the influence of the magnitude and polarity of the direct current voltage applied to the active and grounded electrodes on the etching rate of silicon. This voltage can be as self-bias voltage that occurs automatically when the RF-discharge in the PCR, and as the voltage from an external source connected via appropriate filters. The self-bias voltage called the direct voltage between workers and grounded electrodes RF-discharge due to the different mobility of electrons and ions. It is necessary to ascertain the reasons for reducing the rate of etching of silicon with an increase in voltage on the electrode placed on it with the sample above -250 V. Many processes in the creation of element base of microelectronics, computer technology, solar energy and others require high plasma etching rate of silicon with minimal radiation damage. For example, the minimum time is important for the silicon wafers etching when creating isolation in photovoltaic converters [3]. Increasing the time of etching of the plates leads to diffusion of chemically active atoms and radicals between layers and the appearance of undercutting the surface closer to the ends, which leads to a reduction their efficiency. The results of the research allow to choose optimal modes of silicon etching with minimum radiation damage and they will give the possibility the use of photoresists with minimal thicknesses.

MAIN PART

Plasma chemical reactors which were developed in the Institute for Nuclear Research of NASU [2, 3], have an area of active electrode smaller than grounded electrode. This leads to the appearance of negative self-bias potential on the active electrode and, consequently, to the ion stimulation in the etching materials. In the case of RF-discharges without magnetic fields, the direct self-bias voltage determines the average energy of ions bombarding the target and is approximately equal to the amplitude of the RF-voltage, (proportionality factor is equal to unity) according to ref. [4, 6]. In the RF discharge with magnetic fields a directly proportional relationship of self-bias voltage and the RF-discharge voltage is not broken but changing the proportionality coefficient [7]. In the case of RF-discharges in magnetic fields, the self-bias voltage and, consequently, energies of the ions can use adjustable magnetic fields and changing their configurations [7]. The self-bias voltage is necessary to change regime from soft etching without radiation damage to the sputtering regime of different materials. Self-bias voltage is able to change from -20 to -1000 V or more.

The gases were fed in the reactor in a constant quantity and were controlled with the help by the oil flowmeter. The etching is occurred in gases: SF_6, CF_4, C_3F_8, CCl_4, their mixtures with oxygen, argon in different proportions, etc. Calibrated flowmeters were installed on each gas separately. The pressure was regulated in the discharge chamber by the pumping speed, or the change of the gas flow at constant pumping speed. The power RF-generator with frequency 13.56 MHz also remained constant during every experiment and regulated from 0.2 to 4 kW.

The silicon etching rate under the same discharge conditions has a maximum and decreases with excess negative voltage of magnitude 250 V on the electrode. In ref. [8, 9], the self-bias voltage is changed by adjusting the current of the lower magnetic field coil at a constant current of the middle magnetic field coil. However, in this case, the ambiguity arises because with the change of the magnetic field is changed the etching rate. The dependence of the silicon etching rate from the tension of magnetic field with other unchanged conditions shown in Fig. 1. The silicon etching rate increases from 1.05 to 1.6 μm/min with decreasing self-bias voltage from - 270 to - 100 V. The feature of the dependence of the etching rate from the magnetic field tension is that the silicon etching rata, practically, does not increase with the increase of the field strength up to 50 Oe.

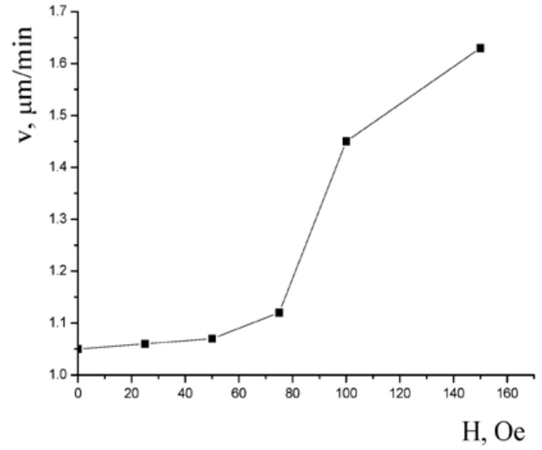

Fig. 1. The dependence of the etching rate of the magnetic field

The self-bias voltage decreases from -270 to -210 V. The increase in the magnetic field from 80 to 160 Oe induce increases in the silicon etching speed from 1.1 to 1.6 μm/min at other constant discharge conditions (while reducing self-bias voltage of -160 to -100 V). This is slightly contrary to the usual notions, because it was thought that the increase in the ion energy increases the etching rate. Therefore, it is not clear exactly which parameters are decisive for obtaining the maximum etching rate of silicon. Thus, the influence of the bias voltage and the of other discharge parameters on the silicon etching rate it is necessary to examine in more detail.

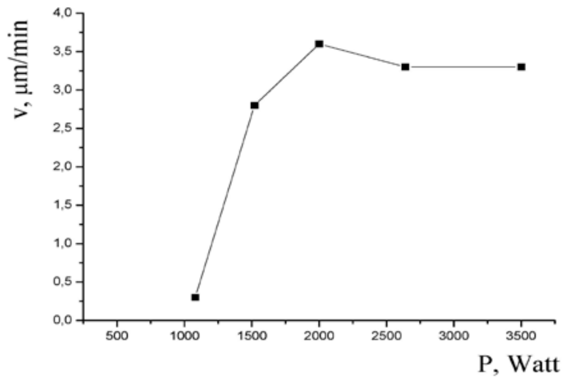

Fig. 2. The dependence of the etching rate of discharge power ($P=3.5\cdot10^{-2}$ Torr)

As is shown in the Fig. 2, the etching rate of silicon has a maximum and decreases with increasing power discharge. If only power discharge was increased and all other parameters, such as: pressure, the gas composition, magnetic field tension and configuration, the cooling temperature of the working electrode, etc. were unchanged.

These results are difficult to explain, therefore, we performed a series of special studies on investigating the causes of the observed effect.

The dependence of silicon etch rate of the discharge current is shown in Fig. 3. As in Fig. 2, a similar dependence is observed: in the beginning the silicon etching rate increase, after that maximum of the rate and then rate reducing with the continuous increase of the current (but in this case the self-bias voltage increases).

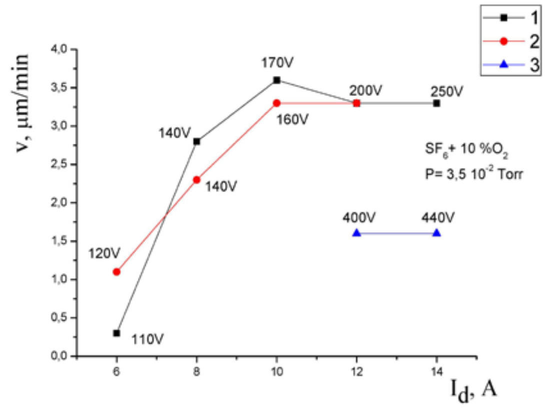

Fig. 3. The dependence of the silicon etching rate on the discharge current

The silicon etching rate begins to decrease when exceeding the bias voltage -170 V on the working electrode, despite increases the discharge current and its power. A similar result was obtained by etching silicon with connecting additional generator (adjustable frequency 40…500 kHz), which allows to remove the surface charge and increase the etching rate (see Fig. 3). After inclusion of middle magnetic field coil in antiphase to the other two coils, self-bias voltage is increase to minus 400…440 V. It led to the decrease in the etching rate of silicon in two times at currents in the range of 12…14 A. The dependence of self-bias voltages from the magnitude of the voltage drop in the discharge for the two cases shows in Fig. 4: 1 – without additional bias generator; 2 – with the connection of additional bias generator. In the first case, when the effective current in the discharge increases there is the voltage drop across the discharge increase and self-bias voltage increases in proportion to it (see Fig. 4, curve 1). RF-discharge effective current was measured with a high-frequency ammeter with a thermocouple transducer type T210. By increasing the voltage drop across the discharge from -180 to -250 V self-bias voltage is increased from -110 to -250 V.

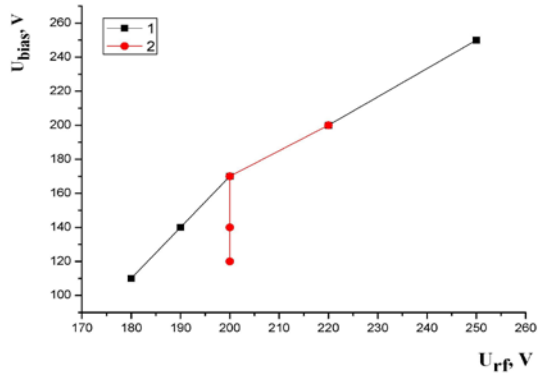

Fig. 4. The dependence of self-bias voltage from the magnitude of the voltage drop on the discharge for the two cases: 1 – without additional bias generator; 2 – with the connection of additional bias generator ($P=3.5\cdot10^{-2}$ Torr)

With the connection of additional bias generator the voltage drop across the discharge does not change with increasing discharge current (it is -200 to -220 V), and the self-bias voltage is increased from -120 to -200 V. The current, which produced an additional generator was 0.9…1.1 A. Thus, by applying an additional bias generator you can control self-bias voltage.

Such features of monosilicon etching rates dependencies from discharge currents and bias voltages led to the need of additional research.

Below are dependences of etching rates from the pressure in the PCR.

When the magnetic field strength is 100 Oe, the self-bias voltage is practically unchanged (220 V) with increasing pressure. At the same time discharge current increased from 9 to 10 A with the pressure from 10^{-2} to $5{\cdot}10^{-2}$ Torr, and then stabilized [7]. With increasing pressure, the etching rate increases [9], but when the pressure varies from 0.06 to 0.1 Torr, the etching rate almost no increases, as it reaches saturation and starts to decrease (Fig. 5). The self-bias voltage on the active electrode is changed from -60 to -85 V, and then increases to -60 V. Essential dependence DC self-bias in the discharge without a magnetic field with a change in pressure from 1.6 to 500 mT in ref. [5] was not observed.

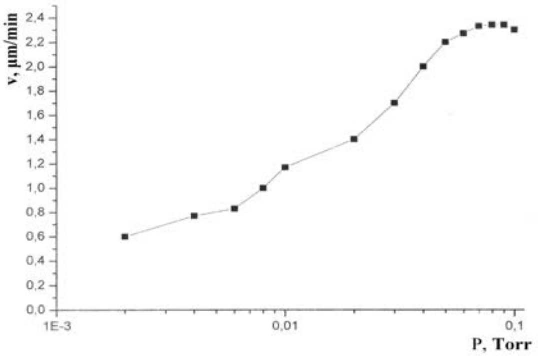

Fig. 5. The dependence of the etching rate from the pressure in the reactor (I_d=8 A, H=150 Oe)

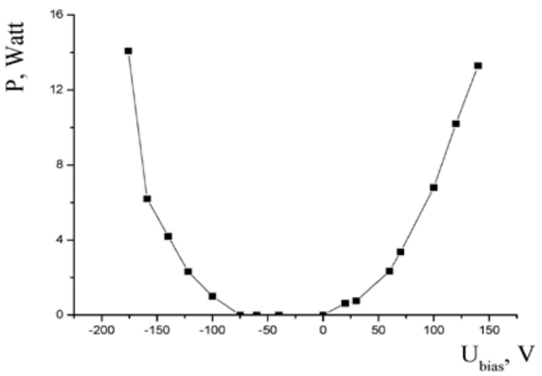

Fig. 6. The dependence of the power on the positive and negative polarity of the DC voltage

In ref. [4 - 9] have been shown the dependence of the silicon etching rate on self-bias voltage, which is obtained by different methods, including DC regulated voltage from additional power sources of different polarity, which is applied to the active and grounded electrodes. The DC voltage has a little effect on the RF discharge. In Fig. 6 shows the dependence of power, which is applied to the electrodes from an external source through a special filter, both in positive and negative polarity DC voltage.

When recalculation maximum power per unit area of the active electrode, which was introduced by RF-discharge and DC voltage, it is clear that the RF-power is under the same conditions of 0.89 W/cm^2, and the constant voltage is 0.0134 W/cm^2. The ratio of these quantities 1:67 and DC power does not exceed 1.5% of the RF-power. Therefore, the influence of a DC voltage from an external source on the plasma parameters is negligible. At the same time, the silicon etching rate is changed almost twice in contrast to other discharge parameters such as the discharge current, the gas pressure, the magnetic field magnitude and configuration, the size and temperature of the samples surface being treated.

Particular interest is the dependence of the silicon etching rate at the substrate ground (or near it) potential. At ground potential on the substrate holder occurs only pure plasma etching of silicon without ionic and electronic stimulation (Fig. 7). At zero constant potential between the active and grounded electrodes etching rate is slightly higher than at a small negative potential.

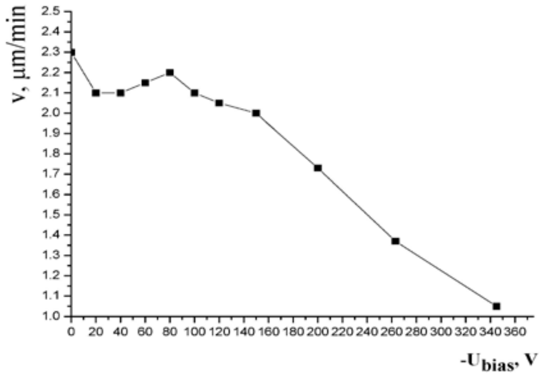

Fig. 7. The dependence of the etching rate of the bias voltage (I_d=6 A, P=$4{\cdot}10^{-2}$ Torr)

This can be explained by the influence of the negative ions which are formed in electronegative gases which are F and Cl. The binding energy of the electron in the negative ion F and Cl is respectively 3.4 and 3.62 eV [10]. Therefore the probability of formation of negative ions of fluorine and chlorine is large enough.

Usually etching of samples occurs at U_{bias} ≤-200 V. In this case, in emission spectra most intense lines are lines of fluorine or chlorine (Fig. 8). At values -(U_{bias}) above 250 V sputtering of the substrate masks and the active stainless steel electrode occurs [11, 12]. The emission spectra of the plasma at high negative self-bias voltage are shown in Fig. 9.

Analysis of the emission spectra shown that the qualitative composition of the plasma is changing cardinally. Mainly observed Fe, Ni, Ti, Cr lines emission. Occasionally it is possible to observe molecular lines stripes that could not be identified. It is quite clear that the levels of metal atoms with excitation energies of 3…6 eV have a higher population than the levels of emission lines of fluorine atoms with excitation energies of 14…15 eV at the same temperature of plasma. The reason is that the exponential dependence of the populations of the states of the atoms according to the Boltzmann distribution [10]:

$$N_j = N_0\, g_j\, e^{-E_j/kT},$$

where N_0 – the density of atoms in the ground state; g_j – the statistical weight of the state; k – the Boltzmann constant; T – gas temperature; E_j – excitation energy of the atoms in the corresponding state.

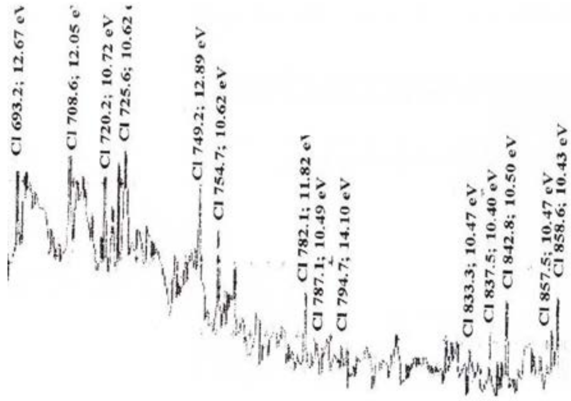

Fig. 8. The emission spectrum of the plasma at U_{bias} = – 120 V

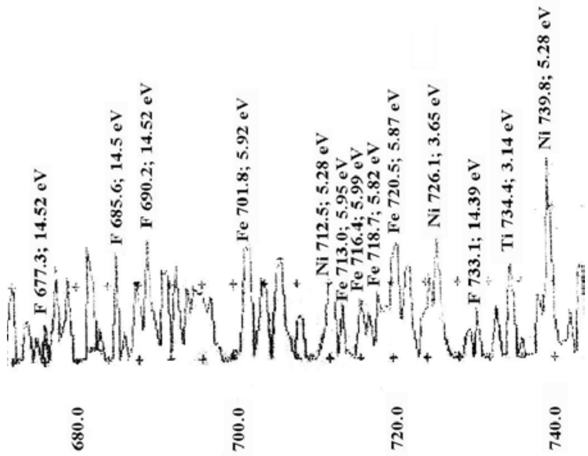

Fig. 9. The emission spectrum of the plasma at U_{bias} = – 300 V

In this case smaller number of excited atoms of metals with lower excitation potential can emit stronger than greater number of fluorine or chlorine atoms with high excitation energy. Fig. 9 shows that the main line spectra emitted by excited metal atoms of sputtered electrodes. Considering that the degree of dissociation of the chemically active complex molecules becomes smaller (SF_6, CF_4, CCl_4, etc.) and number of chemically active excited atoms becomes less then the emission lines intensity sharply reduced. There is the discharge operates in the mixture of working gas with the metal vapor, which is sputterred from the active electrode surface. This is indicated by the presence of metal emission lines in the spectrum. A significant amount of metal impurities on the substrate surface was also observed in X-ray analysis (Fig. 10). It is sufficiently convincing proof of sputtering product influence on reduction the silicon etching rate with increasing negative self-bias voltage (and thus with increasing the ions energy).

X-ray spectral analysis of the chemical composition of slice of the silicon wafer was performed on the X-ray analyzer MS-46 (France), which has four X-ray spectrometer. Two of them are equipped with LiF and quartz [10, 11] analyzing crystals, which are designed to check the hard radiation 1…3 Å, the other two have analyzers crystals, which are intended to analyzing soft radiation 2…70 Å. This selection of the analyzing crystals allows the analysis of all elements of the periodic system from ^{5}B to ^{92}U.

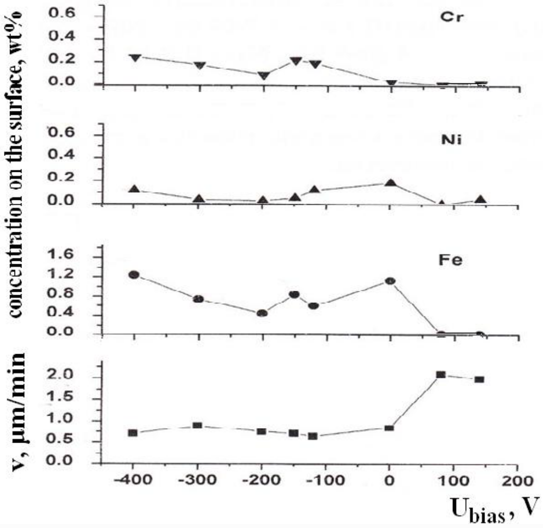

Fig. 10. X-ray analysis of the etched silicon samples depending on bias voltage

The quantitative analysis of the etched silicon samples was done at oblique slice at ten points of the probe regime 20 kV, 3 mA. This made it possible to raise the sensitivity of the method. The results of X-ray analysis of the etched silicon samples depending on bias voltage are shown in Fig. 10.

It is quite clear that there are not only excited atoms of the metal, but also positive metal ions, which under the influence of negative potential at the active electrode deposited on it and on the substrate. This leads to the decrease the etching rate of silicon or other material with self-bias voltage increasing to values ≥250 V and leads to manifestation of the sputtering effect of the active electrode. Iron, nickel and chromium do not form volatile compounds in the interaction with fluorine and chlorine. That is why it is difficult to remove them from the surface of the processed silicon samples. Proof of this can also become an increase in the amount of iron, nickel, chromium on the surface of silicon with increasing self-bias voltage. When the bias voltage is increased from -200 to -400 V, then the concentration of iron on the silicon surface increases from 0.4 to 1.2%, nickel from 0 to 0.1%, chromium from 0.1 to 0.3%. This is convincing evidence of the influence of the active electrode sputtered material and its redeposition onto the surface of processed silicon wafers. The etching rate of silicon in the range of bias voltage (150…400) V is decreased by 2 times or more (see Fig. 10) [5]. It is important to note that the actual amount of impurities of metal on silicon surfaces is ten times higher than that shown in Fig. 10 because X-rays penetrate into the silicon to about 0.5 μm, and metal atoms form on the surface a very thin layer that is tens to hundreds of angstroms.

CONCLUSIONS

When the self-bias voltage between the electrodes rises above -250 V, then there is an intense sputtering of the central electrode and redeposition of metal atoms (which do not form volatile compounds with fluorine and chlorine). This leads to a sharp decrease in the etching rate of the processed materials. At the same time lines of excited atoms of the material from which made the active electrode appear in the emission spectra. On the silicon surface by X-ray analysis were detected impurities of the same material. This indicates that sputtered material was reprecipitated onto the surface of treated materials. The amount of impurities increases with the self-bias voltage. Processing of silicon and other materials necessary to carry out at bias voltages smaller than -250 V.

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НАПРЯЖЕНИЕ СМЕЩЕНИЯ И ЕГО ВЛИЯНИЕ НА СКОРОСТЬ ТРАВЛЕНИЯ КРЕМНИЯ

О.А. Федорович, В.В. Гладковский, Б.П. Полозов, М.П. Кругленко

Экспериментально исследовано влияние напряжения смещения на скорость травления кремния в плазмохимическом реакторе (ПХР) с управляемыми магнитными полями. Установлено, что при высоких величинах напряжения смещения основным механизмом, влияющим на уменьшение скорости травления, является распыление материала рабочего электрода и переосаждение его на поверхность обрабатываемых кремниевых пластин.

НАПРУГА ЗМІЩЕННЯ І ЇЇ ВПЛИВ НА ШВИДКІСТЬ ТРАВЛЕННЯ КРЕМНІЮ

О.А. Федорович, В.В. Гладковський, Б.П. Полозов, М.П. Кругленко

Експериментально досліджено вплив напруги зміщення на швидкість травлення кремнію в плазмохімічному реакторі (ПХР) з керованими магнітними полями. З'ясовано, що при високих значеннях напруги зміщення основним механізмом, що впливає на зменшення швидкості травлення, є розпилення матеріалу робочого електрода і переосадження його на поверхню оброблюваних кремнієвих пластин.