REACTIVE ION ETCHING OF Si_4N_4 IN CF_4 PLASMA[1])

BRČKA, J.,[2]) HARMAN, R.,[2]) Bratislava

The work deals with RIE of Si_3N_4 films in CF_4 plasma. The dependence of the etch rate of Si_3N_4, of electron temperature and density (probe measurements) and the emission of $\dot{F}$ (685.6 nm) upon the rf power and pressure were investigated. The effect of the dc bias on the rf electrode was investigated. The obtained experimental results were compared with a theoretical model of the RIE process.

I. INTRODUCTION

Recently, considerable interest has been paid to reactive ion etching RIE [1, 2]. In this technique, the sample is placed on the target or on the cathode which is capacitively coupled with the rf glow discharge in the reactive gas. Therefore, RIE includes both ion bombardment perpendicular to the sample surface (similar to rf sputter etching) and chemical reactions (like in plasma etching). As it was shown previously [3, 4], the ions play an important role in enhancing the reaction rates between the active gaseous species and the surface, thus giving rise to directional etching. Since our aim was to understand the properties of the process of RIE, we modelled the mechanism of the formation of $\dot{F}$ radicals in the discharge [5] taking into account the experimental results of direct observations such as electrostatic probe measurements and optical spectrometry. Also, the effect of ion bombardment upon the etching rate of Si_3N_4 was studied by measuring the negative dc bias of the rf cathode.

II. THEORETICAL BACKGROUND OF THE PROCESS OF RIE

As for the generation of $\dot{F}$ radicals, the dominant process of dissociation was considered to be

$$CF_4 \overset{e}{\rightarrow} CF_3 + \dot{F} \tag{1}$$

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[2]) Katedra mikroelektroniky, EF SVŠT, Mlynská dolina 842 15 BRATISLAVA, Czechoslovakia.

with the rate of dissociation

$$G_{dis} = n_0 n_e k_{dis} = n_0 n_e \sqrt{2/m_e} \int_{E_{dis}}^{\infty} q_{dis}(\varepsilon) f(\varepsilon) \sqrt{\varepsilon}\, d\varepsilon. \tag{2}$$

The major recombination mechanism of active radicals is taken to be a heterogeneous reaction with the surface of the reactor

$$\dot{F} \rightarrow F(S). \tag{3}$$

The surface recombination rate of $\dot{F}$ radicals is given by

$$R_{het} = \alpha_{int} n_r \sqrt{kT_r/(2\pi m_r)} \,.\, (S_p/V_p). \tag{4}$$

From Eqs. (2) and (4), the steady-state concentration of $\dot{F}$ radicals was derived

$$n_r = n_0 n_e k_{dis} / (\alpha_{int} \,.\, \sqrt{kT/2\pi m_r} \,.\, (S_p/V_p) + n_e k_{dis}). \tag{5}$$

It was further assumed that the interaction of $\dot{F}$ radicals with the etched surface was running in a kinetical mode [6]. The model took into account the transport of CF_3^+ ions towards the etched surface under the influence of their collisions with neutral particles in the space charge region [3, 4]. The rate of the surface reaction was calculated from the following equation, as suggested by Zarowin [4]:

$$v_{chr} = n_r \alpha_0 \,.\, \exp(-E_F/kT) \,.\, (1 + \gamma_{ion} \,.\, \exp(U/kT)). \tag{6}$$

In the used equations, n_e, n_0 and n_r are the concentrations of electrons, CF_4 molecules and $\dot{F}$ radicals, ε is the electron energy, T_r and T are the temperatures of radicals and of the etched surface, m_e and m_r are the masses of electrons and $\dot{F}$ radicals. Further, $f(\varepsilon)$ is the Maxwell distribution function, α_{int} is the probability of interaction of the $\dot{G}$ radicals with the surface (α_0 — at an infinite temperature), S_p and V_p are the area and volume of the reactor. The symbol U means the part of kinetical energy of ions by which the activation energy of $\dot{F}$ radicals on the surface of Si_3N_4 (E_F) is lowered, v_{chr} is the rate of the surface reaction, γ_{ion} is the ionization coefficient, G_{dis} and R_{het} are the rates of the generation and the recombination of $\dot{F}$ radicals, q_{dis} and k_{dis} are the cross-section and rate constant of the dissociative process in CF_4 plasma.

III. EXPERIMENTAL

The experiments were carried out in the RIE chamber of PDS 520/530 apparatus (Vacutec AB). The cathode (Al, diameter 28 cm, water cooled) was connected through a matching network to a 300 W generator operating at the frequency of 13.56 MHz. The reactor volume is approx. 7 dm^3. The probe

characteristics were obtained by means of a tungsten probe (diameter 0.16 mm, length 5 mm) connected via an rf choke to a dc power source.

The emission spectrum of the plasma at the line F (685.6 nm) was monitored by a monochromator M300 (Bentham) via a quartz window on the reactor.

The negative bias of the rf cathode was measured by means of a dc probe [7].

CF_4 was used as the etching gas, rf sputtered Si_3N_4 as the etched material. The etch rate was determined as a ratio of the height of the etched step (Talystep) and the etching time.

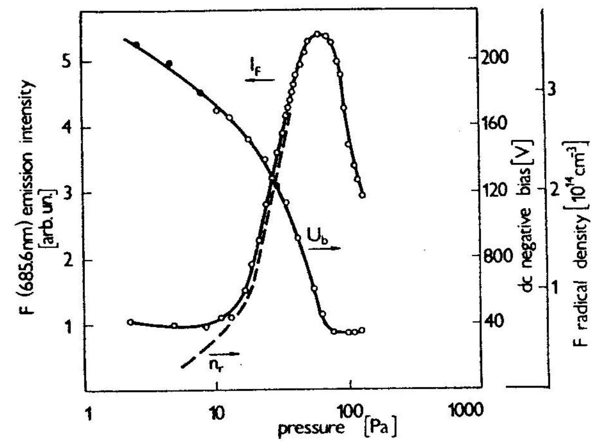

Fig. 1. The dependencess of the emission intensity of $\dot{F}$ (685.6 nm), of the modelled density of F and of the dc bias at the rf cathode upon pressure. Rf power — 200 W.

IV. RESULTS AND DISCUSSION

From the probe characteristics, n_e and T_e could be evaluated. Depending upon CF_4 pressure (2 to 35 Pa) and power supplied to plasma (50 to 250 W), the electron density ranges between 5×10^9 and 6×10^{10} cm^{-3}, the electron temperature varies between 1.4×10^4 and 3.1×10^4 K (1.2 to 2.7 eV). The negative bias of the rf electrode increases linearly with the supplied power and decreases with increasing pressure (Fig. 1). The dependence $U_b(p, P)$ can be described by the empirical formula

$$U_b \simeq -190 \exp(-3.87p/P). \tag{7}$$

Knowing the experimental values of n_e and T_e, the dependence was modelled of the density of radicals $\dot{F}$ in the reactor volume and compared with the intensity of emission of $\dot{F}$ (685.6 nm) determined by optical spectrometry (Fig. 1). When modelling the transport of active particles towards the etched surface and their interaction with the surface, diffusional, kinetical and intermediate modes were considered. We assume that in the used range of pressure the interaction runs in the kinetical mode. Experimental and calculated dependences of the etch rate upon pressure and rf power are presented in Fig. 2. At first sight, the dependences $v_{etch}(p)$ given in Fig. 2a seem to be qualitatively different. The maximum of the theoretical curve is shifted towards a lower pressure ($\sim$ 6 Pa). The maximum of the experimetal curve lies at the same pressure ($\sim$ 15 Pa) as the calculated maximum of the dissociation rate constant ($k_{dis} \sim 1.44 \times 10^{-10}$ cm^3/s).

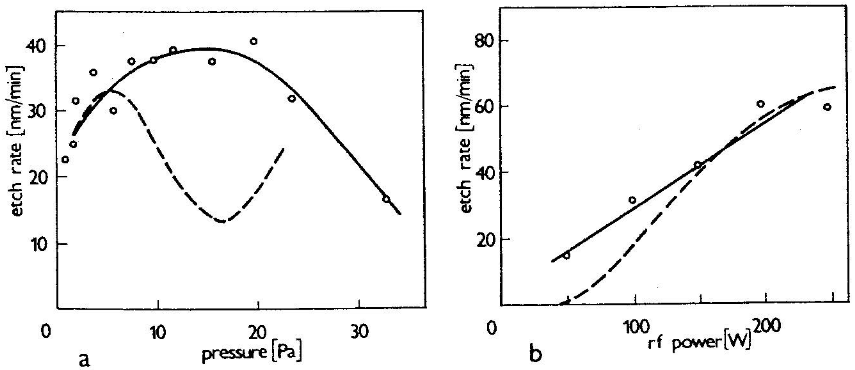

Fig. 2. The dependences of the etch rate v_{etch} (Si_3N_4) upon the pressure of CF_4 (a) and upon rf power (b): (———) experimental and (– – –) theoretical curves. Rf power — 200 W, pressure — 5 Pa.

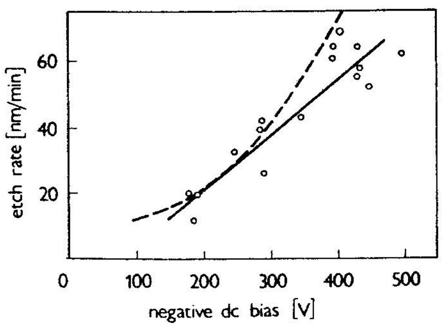

Fig. 3. Experimental (———) and theoretical (– – –) dependences of the etch rate upon the negative bias at the rf electrode supplied from external dc source. Rf power — 200 W, pressure — 5 Pa.

The power dependences show a good agreement between experiment and the used model. Similarly, the influence of U_b upon the etch rate of constant pressure and rf power shows the same tendencies both in theory and experiment (see Fig. 3).

V. CONCLUSIONS

In the present work, experimental results were compared with the results of a simplified model of the reactive ion etching process of Si_3N_4. The model is in a good agreement with experiment, especially as far as the P and U_b characteristics are concerned. The change of the operating pressure can result in the change of the mechanism of plasma processes which is not taken into account in the proposed model. Mutual dependences can manifest themselves between many plasma parameters such as the bias of the rf electrode, the thickness of the space charge region, energy of ions, collision characteristics, etc. These dependences were taken into account only approximatively in the model, or the parameters were considered to be constant.

The model enables — in spite of the simplcity of the theoretical approach — to describe qualitatively and analyse the fundamental properties of the RIE process in CF_4 plasma.

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РЕАКТИВНОЕ ИОННОЕ ТРАВЛЕНИЕ СЛОЕВ Si_3N_4 В ПЛАЗМЕ CF_4

В статье рассмотрена проблематика реактивного ионного травления слоев Si_3N_4 в плазме CF_4. Исследована зависимость скорости травления Si_3N_4, температуры и плотности электронов (зондовые измерения) и интенсивности излучения $\dot{F}$ (685,6 нм) от высокочастотной мощности и давления газа. Изучено влияние постоянного напряжения смещения на высокочастотном электроде на процесс травления. Проведено сравнение полученных экспериментальных результатов с результатами теоретической модели процесса реактивного ионного травления.