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Characteristics of the Kinetics of Periodic Structures CMP for a Nonlinear Pressure Dependence of the Polishing Rate

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Abstract—For the kinetics of the chemical mechanical polishing (CMP) of wafers containing periodic metal–dielectric structures, a model is developed and theoretically investigated with the use of contact mechanics methods for the nonlinear pressure dependences of the polishing rate. In the steady-state regime, expressions for the dishing effect, which is characterized by the difference in the depths of the polishing metal and dielectric strips, are analytically derived and investigated. The specific characteristics of this effect, which are observed for different kinds of nonlinearities of the polishing rate depending on the pressure and the relative rotation velocity of the pad and wafer, are analyzed. Particularly, it is shown that, under certain conditions, the steady-state regime may be nonunique (the bistability effect).

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1. INTRODUCTION

The chemical mechanical polishing (CMP) process is widely employed for fabricating micro- and nanoelectronic structures. However, it involves so many factors that it has not yet been thoroughly investigated and is still being discussed in the literature [1–3]. This fact, in addition to the usefulness of this process, supports the development of adequate models to solve the problem of CMP optimization.

Modeling the rate of material removal from the surface being processed is a key element of the complete description of the CMP process. In [2], an approach was proposed that regards the formation and growth of a passivation layer at the interface between the metal and slurry as a factor restricting this rate. Presently, the development of models for the kinetics of change in the thickness of the layer being polished, which describe the rate of material removal with the use of phenomenological expressions [4] or expressions obtained from rather simplified macroscopic representations [5, 6], is also considered promising.

One of the practically important problems is to model the process of polishing the surface of the structures composed of alternating metal and dielectric elements, which results in a rather inhomogeneous distribution of the process rate. It was experimentally found that, due to the difference in the polishing rates of metal and dielectric, at every instant, a certain periodic distribution of the depths of the holes (dishes) formed in these materials was observed; this effect was called dishing [7].

In [8], it was shown that the most adequate quantitative description of the kinetics of dishing can be done only when taking into account the nonlocal effects that are due to the deformations of the pad and the geometry of the surface being polished. A step-by-step approach to modeling the nonlocal effects based on the contact mechanics methods [10] was proposed in [9]. In [9], for a one-dimensional periodic structure Cu/SiO_2, the time evolution of the contact pressure, contact area, and contact profile as functions of the system geometry and load distribution was evaluated. In [11], using model [9], the dependences of the steady-state regime of polishing the same structures on various parameters of the system were numerically modeled.

In [9, 11], for the polishing rate V_R of each material, Preston's phenomenological equation [4] in the form $V_R \sim pv$ (where p is the pressure with which the pad acts on the surface being processed and v is the relative velocity of their rotation) was used. However, some investigations [4, 5] showed that the experimental data are better described by relations that are nonlinear in terms of p and v, especially when the pressure range is expanded. A particular form of these relations is determined by the elasticity of the polishing material, composition of the slurry, pressure range, and distribution of the sizes of abrasive particles [5].

In this paper, a nonlocal model is developed that describes the kinetics of the dishing effect in periodic metaldielectric structures with the use of contact mechanics methods for nonlinear p- and v-dependences of the rate V_R. Using this model, the depen-

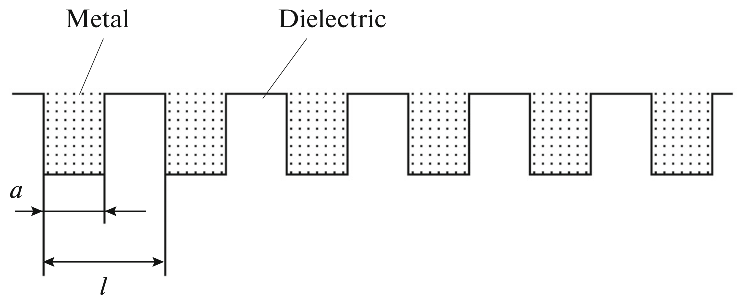

Fig. 1. Periodic metal–dielectric structure.

dences of the quantitative characteristics of the steady-state dishing on various system parameters are obtained and analyzed.

2. BASIC RELATIONS OF THE MODEL; STEADY-STATE REGIME

The model that describes the CMP process by using contact mechanics methods can be formulated as follows [9, 10]. Let an absolutely rigid body the form of which is given by a certain function $f(x, y)$ on the plane (x, y) (the surface being polished) come into contact with a massive elastic body that has an initially flat surface $(z = 0)$ (hereinafter, referred to as the pad). Then, solving equations of contact mechanics for the general 3D case yields the following relation between the height-wise displacement $w(x, y)$ of the pad surface and the distribution of the contact pressure $p(x, y)$:

$$w(x,y) = \frac{(1-\nu^2)}{\pi E}\int_{\omega} p(\xi,\eta)\frac{1}{\sqrt{(x-\xi)^2+(y-\eta)^2}}d\xi d\eta, \tag{1}$$

where ω is the contact region, E is Young's modulus (for the pad material), ν is the Poisson ratio (for the pad material), and

$$\begin{aligned} w(x,y) &= f(x,y) + C, \quad p(x,y) > 0, \quad (x,y) \in \omega, \\ w(x,y) &> f(x,y) + C, \quad p(x,y) = 0, \quad (x,y) \notin \omega. \end{aligned} \tag{2}$$

If the total load P (force applied to the pad) is known, then the additional relation

$$P = \int_{\omega} p(\xi,\eta) d\xi d\eta \tag{3}$$

holds. Relations (1)–(3) are used to find the penetration depth C and the contact area ω. These relations characterize the nonlocality of the contact interaction between the pad and the surface being processed: the local shape of the profile $w(x, y)$ is determined by the distribution of pressure all over the contact area.

Let us describe, using the proposed model, the dishing effect when polishing an infinite two-dimensional periodic structure composed of strips (lines) of metal, which are separated by layers of dielectric (see Fig. 1), the length (along the y axis) of which far exceeds their widths a and b (along the x axis). In this case, contact mechanics suggest that, in the half-space corresponding to the volume of the pad, the state of plane deformation [10] takes place due to the linear stress along the corresponding strips of metal and dielectric; in this state, the displacements along the y axis are zero, while the displacements along the x and z axes do not depend on y. Therefore, in relations (1) and (2), $w(x, y) \to w(x)$; in such a 2D formulation, according to [9, 10], instead of relation (1) for $w(x)$, we have

$$\frac{dw}{dx} = -\frac{2(1-\nu^2)}{\pi E}\sum_{i=1}^{N}\int_{a_i}^{b_i} p(s)\frac{1}{x-s}ds, \tag{4}$$

where a_i and b_i are the x coordinates of the boundary points for the alternating strips of metal and dielectric, while N is the number of boundary points. If the contact region can be partitioned along x into equal segments of length l (on which the periodical (period l) distribution of the pressure $p(x)$ takes place) and this region is assumed to be infinite in both directions along x (i.e., the summation over i in (4) is from $-\infty$ to $+\infty$), then, from (4), we obtain

$$\frac{dw}{dx} = -\frac{2(1-\nu^2)}{\pi E}\frac{\pi}{l}\int_0^l p(s)\cot\left[\frac{\pi(x-s)}{l}\right]ds. \tag{5}$$

Experiments [7, 11] showed that, after quite a short transition period, the kinetics of the dishing profile reaches the steady state, i.e., the pressures p_1 and p_2 of the pad in the metal and dielectric layers remain constant, while the profile continues to travel in these layers with the same constant rate. Thus, for a periodic structure, this takes place in the segments [0, a] and [a, l], where a is the width of the metal lines and l is the period of the structure (see Fig. 1). Thus, upon integrating in (5), we obtain the expression

$$\frac{dw(x)}{dx} = \frac{2(1-\nu^2)}{\pi E}(p_1 - p_2)\ln\left|\frac{\sin(x-a)\frac{\pi}{l}}{\sin x\frac{\pi}{l}}\right|, \tag{6}$$

where $w(x)$ is the displacement of the surface being polished with respect to the etching depth.

As a quantitative measure of dishing D, the height difference is generally used between the lowest point of the profile of a metal line and the highest point of the corresponding profile of a dielectric layer. For the periodic structure being analyzed, the parameter D can be found by integrating Eq. (6) from $a/2$ to $a/2 + l/2$ [9]. This allows finding the difference between the minimum ($w_{\min}$) and maximum ($w_{\max}$) heights of the polishing profile, i.e., the stationary value of D:

$$D = w_{\max} - w_{\min} = \frac{2(1-\nu^2)}{\pi E}|p_1 - p_2| l |\Phi(\rho)|, \tag{7}$$

where

$$\Phi(\rho) = \int_0^{1/2} \ln\left|\frac{\sin\pi(\xi-\rho/2)}{\sin\pi(\xi+\rho/2)}\right| d\xi \tag{8}$$

and $\rho = a/l$ is the parameter characterizing the density of the metal lines filling in the structure. It can be seen that the function $|\Phi(\rho)|$ vanishes for $\rho = 0$ and $\rho = 1$ and that it is symmetrical with respect to the point $\rho = 1/2$ (the maximum of the function) [12].

Equation (7) allows analyzing the dependence of the dishing value D in the periodic structure on the width of the metal lines and on their filling density in the structure, which is determined by the relation $\rho = a/l$. These dependences are of interest for improving and optimizing the microelectronic technologies [7, 11].

During the CMP process, the pressure distribution in the original expressions (4) and (5) varies with time, which causes a change in the profile of the surface being processed. The local rate of change in the profile of the surface, i.e., the rate of surface degradation and loss of material at a certain point, is a function of many factors [3, 5]: pressure distribution $p(x, y)$, velocity with which the pad slides over the surface $v(x, y)$, properties of slurry, mechanical characteristics of the pad and abrasive particles, etc. The thorough modeling of this parameter has not yet been carried out. Thus, in many works (including [9, 11]), to describe the polishing rate, the simplified empirical relation proposed by Preston (see in [4]) is used. For the periodic structure under consideration, on the assumption that the pressure distribution over the metal and dielectric strips is homogeneous and the velocity v is the same across the surface being processed, this relation is written as

$$V_{R,i} = \frac{\partial f_i(t)}{\partial t} = k_i p_i(t) v, \quad i = 1, 2, \tag{9}$$

where the subscripts $i = 1, 2$ denote the metal and dielectric strips, respectively, and k_i is the wear coefficient, which characterizes the effect of slurry on the ith material. In the steady state, the pressures p_i no longer depend on time. In [12], it was shown that the analytical results obtained using the model based on contact mechanics methods and on the linear dependence $V_R \sim pv$, are in good agreement with the experimental results and numerical calculations for the conditions in which the use of this dependence is reasonable enough.

There are, however, descriptions of the polishing rate that are more adequate (than (9)) that have the form

$$V_{R,i} = \frac{\partial f(t)}{\partial t} = k_i [p_i(t)]^{\gamma_i} v^{\varepsilon_i} \tag{10}$$

and better describe the experimental data for a wider value range of the polishing parameters (see [4, 6, 13]). In (10), the absolute values and signs of γ_i and ε_I depend on the material properties of the pad and surface being polished, on the ranges of the pressures and velocities, and on the characteristics of active suspension and abrasive particles.

Note that, for γ_i and $\varepsilon_i > 0$, relations (9) and (10) increase monotonically in terms of pressure and velocity, which generally takes place for pressures up to ~(10–30) kPa. However, some experiments [14] showed that, for higher pressures, due to the pressing through the elastic material of the pad in between the abrasive particles, the polishing rate decreases because of the blockage of the slurry flow and removal of the material [6]. In such conditions, the parameter $V_{R,i}$ can be modeled by γ_i and $\varepsilon_i < 0$ in relation (10). As to describing the polishing rate throughout the whole pressure variation range, instead of $p_i^{\gamma_i}$, a certain non-monotonic function of p_i that reaches its maximum in the region of 30–50 kPa [6] should be used.

3. DISHING EFFECT IN THE CASE OF THE POWER LAW FOR THE CMP RATE

For the stationary (steady) state of dishing, the pressures p_i in relations (7)–(10) are assumed to be constant. It is also assumed that the CMP parameters k_i, γ_i, and ε_i in (10), for both the metal lines and dielectric layers, do not depend on coordinates inside the regions [0, a] and [a, l], respectively. In addition, let the velocity v of the relative slide for the pad and for the surface being processed be the same at all points of their contact. Then, since the rates of changes in the profiles of the metal and dielectric lines in the stationary state become identical, we can obtain from Eq. (10) the following relation that links p_1 and p_2:

$$\beta p_1^{\gamma_1} v^{\varepsilon_1} = p_2^{\gamma_2} v^{\varepsilon_2}, \tag{11}$$

where $\beta = k_1/k_2$.

Another relation between p_1 and p_2 is obtained from (3):

$$p_1 a + p_2(l - a) = pl \equiv N, \tag{12}$$

where p is the average pressure in the structure and N is the load per period of the structure. The system of relations (11) and (12) defines the steady pressures p_1 and p_2 in terms of p (or N), l, and a or via the density ρ of the metal lines.

Below, we consider the effect of relations (11) and (12) on steady-state dishing (7).

3.1. Power Law for the CMP Rate When $\gamma_1 = \gamma_2 = \gamma$ and $\varepsilon_1 \neq \varepsilon_2$

Relations (11) and (12) suggest that this case is similar to that where the polishing rate is described by Preston's equation (9) (for more details, see [12]), but the dimensionless parameter k_1/k_2 that links p_1 and p_2 in [12] is substituted by the parameter χ given by the relation

$$\chi = \left(k_1 v^{\varepsilon_1-\varepsilon_2}/k_2\right)^{1/\gamma} = \beta^{1/\gamma} v^{(\varepsilon_1-\varepsilon_2)/\gamma}, \tag{13}$$

i.e., $p_2 = \chi p_1$. The dimensionless parameter χ depends on the velocity v of the relative motion of the pad and surface being processed, with $\beta = k_1/k_2$ in (13) being a dimensional quantity (in contrast to [12]).

Let us analyze the dependence of the dishing parameter D on the different quantities included in it. Using relations (7), (11), and (13), parameter D is written as

$$D(a, \rho, v) = a \frac{\left|\beta^{1/\gamma} v^{\sigma} - 1\right|}{\rho + \beta^{1/\gamma} v^{\sigma}(1-\rho)} D_0(\rho), \tag{14}$$

where

$$D_0(\rho) = \frac{2(1-\nu^2)}{\pi E} p \left|\Phi(\rho)\right|/\rho$$

is the dimensionless quantity and $\sigma = (\varepsilon_1 - \varepsilon_2)/\gamma$. Equation (14) implies that, for $\rho = \text{const}$, the dishing effect linearly depends on the width of the metal lines

$$D(a, \rho = \text{const}) = ka$$

with the slope k that is a function of v. Particularly, for $\beta^{1/\gamma} v^{\sigma} \ll 1$, we have $k = D_0(\rho)/\rho$ and have $k = D_0(\rho)/(1-\rho)$ for $\beta^{1/\gamma} v^{\sigma} \gg 1$.

It is also seen from (14) that, for a fixed width a, i.e., $D = D(a = \text{const}, \rho)$ (ρ varies due to the period l), the parameter D as a function of the density ρ depends heavily on χ (i.e., on the velocity v): the term $[\rho + \chi(1 - \rho)]^{-1}$ in (14) increases with increasing ρ for $\chi > 1$ and decreases for $\chi < 1$.

By asymptotically expanding the function $|\Phi(\rho)|$ for $\rho \to 0$ and $\rho \to 1$ (100%), we find that the dependence of $D(a = \text{const}, \rho)$ on ρ in these cases has the form

$$D(a = \text{const}, \rho) \sim \frac{(1-\nu^2)}{\pi E} pa\rho\left[1 - \ln(\pi\rho/2)\right], \tag{15a}$$

$$D(a = \text{const}, \rho_{\%}) \sim \frac{(1-\nu^2)}{\pi E} pa\left(1 - \frac{\rho_{\%}}{100}\right)\left\{1 - \ln\left[\left(1 - \frac{\rho_{\%}}{100}\right)\frac{\pi}{2}\right]\right\}, \tag{15b}$$

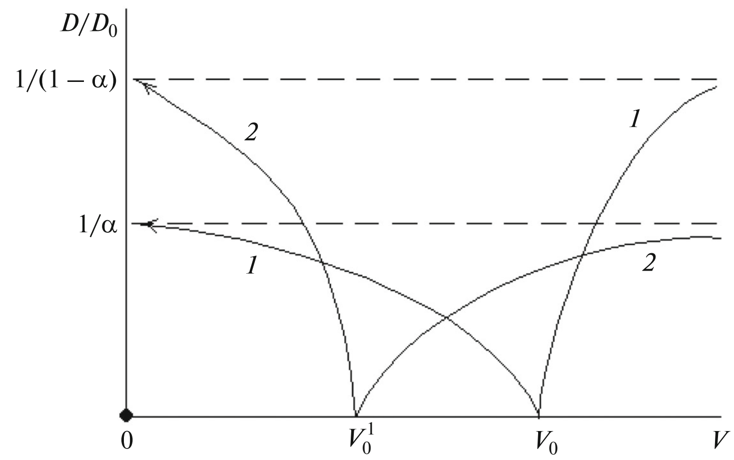

Fig. 2. Qualitative dependence of the dishing parameter D on the velocity v of the pad relative to the wafer ($1 - \varepsilon_1 > \varepsilon_2$, $2 - \varepsilon_1 < \varepsilon_2$).

respectively, where (15b) is written in terms of $\rho_{\%}$ (density of the lines in percentage terms) as is often done when processing the experimental data.

It is of interest to analyze the dependence of parameter (14) on the relative velocity v of the pad and surface being processed for the fixed width a and fixed density ρ, i.e., $D(a, \rho = \text{const}; v)$. Such a dependence does not exist (see expression (13)) if the polishing rate is described by Preston's law (9); it also has no place in (14) for $\varepsilon_1 = \varepsilon_2$, i.e., $\sigma = 0$. Thus, assuming that $\varepsilon_1 \neq \varepsilon_2$, from (14), we obtain the following dependence of the dishing effect on the velocity v:

$$D(a, \rho = \text{const}; v)/aD_0(\rho) = \frac{\left|\beta^{1/\gamma} v^{\sigma} - 1\right|}{\rho + \beta^{1/\gamma} v^{\sigma}(1-\rho)}. \tag{16}$$

Figure 2 shows the qualitative form of dependence (16) for $\rho > 0.5$ (for $\rho < 0.5$ curves *1* and *2* exchange their places). Relation (16) implies that there are values of v_0 and v_0' for which the dishing effect vanishes:

$$v_0 = (k_2/k_1)^{1/(\varepsilon_1 - \varepsilon_2)} \quad (\varepsilon_1 > \varepsilon_2), \tag{17a}$$

$$v_0' = (k_1/k_2)^{1/(\varepsilon_2 - \varepsilon_1)} \quad (\varepsilon_1 < \varepsilon_2). \tag{17b}$$

However, it should be noted that, for a number of structures and polishing conditions, $\varepsilon_1 < \varepsilon_2 < 1$ (see experiments with the structure Cu/SiO_2 in [14]). Hence, relation (17b) can lead to unrealistically high velocities required for the dishing effect D to vanish in the stationary mode.

Note also that the point $v = 0$ is critical for the dependence of the dishing parameter on the velocity. Indeed, for $v = 0$, the rate of the real CMP process must become zero, i.e., $D = 0$. At the same time, relation (16) for the steady state yields $D \neq 0$ for $v = 0$. In fact, for $v \to 0$, the time of reaching the steady state must tend to infinity. Thus, for $v = 0$, the real dishing value is surely $D = 0$, and the point $v = 0$ (see Fig. 2) should be regarded only as the right-hand limit one (a "punctured" point of curves *1* and *2*). Therefore, for the shallow depths of the trenches and fairly slow velocities v, the steady state may not be reached. Hence, for the given depth of the structure being polished, the velocity dependences of type (16) actually hold only beginning with certain finite values of the velocity.

3.2. Power Law for the CMP Rate when $\gamma_1 \neq \gamma_2$ and $\varepsilon_1 \neq \varepsilon_2$

In this case, from the condition of steady-state regime (11), we obtain

$$p_2 = \left(k_1 v^{\varepsilon_1 - \varepsilon_2}/k_2\right)^{1/\gamma_2} \times p_1^{\gamma_1/\gamma_2} \equiv \varsigma p_1^{\gamma_1/\gamma_2}, \tag{18}$$

where $\varsigma = \left(k_1 v^{\varepsilon_1 - \varepsilon_2}/k_2\right)^{1/\gamma_2} = \beta^{1/\gamma_2} v^{\sigma_2}$, $\sigma_2 = (\varepsilon_1 - \varepsilon_2)/\gamma_2$, and $\beta = k_1/k_2$.

By substituting (18) into (12), we obtain the following transcendental equation for p_1:

$$\rho p_1 + (1-\rho)\varsigma p_1^{\gamma_1/\gamma_2} = p. \tag{19}$$

When analyzing Eq. (19), two cases can be distinguished. The first case $\gamma_1/\gamma_2 > 0$ describes a situation where, for both the materials of the structure, the polishing rates either increase with increasing pressure ($\gamma_1 > 0,\ \gamma_2 > 0$) or decrease ($\gamma_1 < 0,\ \gamma_2 < 0$). In this case, the left side of Eq. (19) is a monotonically increasing function of p_1 that vanishes for $p_1 = 0$. Hence, for any pressure p, there is only one solution of Eq. (19) for p_1 that monotonically increases with increasing p. According to (18), a similar monotonic p-dependence holds for p_2.

A more detailed analysis of Eq. (19) can be carried out by introducing the dimensionless parameter

$$\begin{aligned} \varsigma' &= [\beta v^{\varepsilon_1-\varepsilon_2} / p^{\gamma_2-\gamma_1}]^{1/\gamma_2} \\ &= \beta^{1/\gamma_2} v^{\sigma_2} / p^{1-q} = \varsigma / p^{1-q}, \end{aligned} \quad (20)$$

where $q = \gamma_1/\gamma_2 > 0$. Then, Eq. (19) takes the form

$$\rho(p_1/p) + \varsigma'(1-\rho)(p_1/p)^q = 1; \quad (21)$$

its solution p_1/p is a certain function F of ρ and ς', i.e.,

$$p_1 = pF(\rho, \varsigma'), \quad p_2 = p\varsigma'[F(\rho, \varsigma')]^q. \quad (22)$$

For $\varsigma' \ll 1$ or $\varsigma' \gg 1$, this function can be represented as an expansion in ς' or $1/\varsigma'$, respectively. For example, given $\varsigma' \ll 1$, at a first approximation, we obtain

$$p_1 = \frac{p}{\rho}\left[1 - \varsigma'(1-\rho)(1/\rho)^q\right], \quad p_2 = p\varsigma'(1/\rho^q). \quad (23)$$

Taking into account relations (7) and (22), we find that the dishing parameter D is given by the equation

$$D(a, \rho, \varsigma') = \frac{2(1-\nu^2)}{\pi E} ap\left|F(\rho, \varsigma') - \varsigma'[F(\rho, \varsigma')]^q\right||\Phi(\rho)|/\rho. \quad (24)$$

Thus, as with the fixed density of lines ρ, the dishing parameter is proportional to the width of lines a. For $\varsigma' \ll 1$, substituting (23) into (24) yields

$$D(a, \rho, \varsigma') = \frac{2(1-\nu^2)}{\pi E} ap\left|1 - \varsigma'/\rho^q\right||\Phi(\rho)|/\rho^2. \quad (25)$$

This relation holds for the densities in the interval $(\varsigma')^{1/2} < \rho \le 1$. Then, for $\rho \to 1$ ($\rho_{\%} \to 100\%$), from (25), by finding the asymptotics of the function $|\Phi(\rho)|$, as in the case of (15), we obtain

$$D(a, \rho_{\%}, \varsigma') = \frac{(1-\nu^2)}{\pi E} ap|1-\varsigma'|\left(1 - \frac{\rho_{\%}}{100}\right)\left\{1 - \ln\left[\left(1 - \frac{\rho_{\%}}{100}\right)\frac{\pi}{2}\right]\right\}. \quad (26)$$

For the opposite asymptotics, when $\varsigma' \gg 1$, from (19), in a first approximation with respect to $1/\varsigma' \ll 1$, we obtain $p_1 = p[(1-\rho)\zeta']^{-1/q}$.

In fact, the quantity β included in the parameter ς' (see (20)), makes it highly sensitive to particular conditions of the CMP process (temperature, type of pad, composition of slurry, etc.). For example, let us estimate ς' under the following conditions of the experiments conducted in [13], in which the kinetics of the CMP of the structures composed of alternating Cu and SiO_2 stripes was investigated: $\gamma_1 = 0.55$, $\gamma_2 = 0.39$, $\varepsilon_1 = 0.43$, $\varepsilon_2 = 0.61$, $\beta = 4.6 \times 10^2$ (in units taken in [13]), $p \sim 40$ kPa, and $v \sim 1$ m/s (see also [4]). By substituting these values into (20), we obtain $\varsigma' \sim 5 \times 10^6 \gg 1$.

The second case for Eq. (19) assumes $\gamma_1/\gamma_2 < 0$; i.e., the range of polishing conditions is such that the polishing rate increases with increasing pressure (positive exponent) for one of the materials of the structure and decreases for the other (negative exponent). Such a situation can occur, for example, when polishing is performed in the region of rather high pressures [5, 14].

If $q = \gamma_1/\gamma_2 < 0$, then the left side of Eq. (19) has its minimum for $p_1 = p_1^*$, where

$$p_1^*/p = \left[\frac{(1-\rho)\varsigma'|q|}{\rho}\right]^{1/(1+|q|)}. \quad (27)$$

Since the left side of (19) tends to ∞ for $p_1 \to 0$ and $p_1 \to \infty$, it is clear that, for

$$\begin{aligned} &H\left(\rho, p_1^*/p, \varsigma'\right) \\ &\equiv \rho\left(p_1^*/p\right) + (1-\rho)\varsigma'\left(p_1^*/p\right)^{-|q|} > 1, \end{aligned}$$

where p_1^* is given by Eq. (27), Eq. (19) has no solutions; i.e., in this case, the steady state of the CMP process in the periodic system cannot be reached.

However, if $H\left(\rho, p_1^*/p, \varsigma'\right) < 1$, then Eq. (19) has two solutions, i.e., for certain values of pressure p, velocity v, density ρ, and parameter β, there can be two steady states of dishing (bistability effect). Generally speaking, in this case, the stability of both the steady states against small perturbations should be investigated. Such an analysis, however, is a rather complex independent problem that will be addressed in further works.

4. DISHING EFFECT FOR THE CMP RATE HAVING A MAXIMUM IN PRESSURE

Since, in the experiments at rather high pressures, the decrease in the polishing rate V_R (with an increase in pressure) was observed, the complete pressure dependence of V_R must have a maximum. Thus, generalizing the results of the analysis given in the previous section, let us consider a case where the rate $V_{R,1}$ of polishing the metal stripe (region $[0, a]$), as a function of p_1, is described by the dependence of the form

$$V_{R,1} = \varphi(p_1)v^{\varepsilon_1}, \tag{28}$$

where the function $\varphi(p_1)$ can have increasing segments (low pressures), decreasing segments (high pressures), and a transition segment near its maximum.

Let us consider the behavior of the dishing effect when the pressure p_1 enters the region of the maximum CMP rate. The function $\varphi(p_1)$ in the region of the maximum is represented by a quadratic approximation, i.e., relation (28) is written as

$$V_{R,1} = (b + k_1 p_1 - k p_1^2)v^{\varepsilon_1}, \tag{29}$$

where $b = \varphi(p_{1m}) - k p_{1m}^2$, $k_1 = 2kp_{1m}$, $k = \left|(\partial^2\varphi(p_1)/\partial p_1^2)_{p_1=p_{1m}}\right|/2$, and p_{1m} is the point of the maximum. In addition, for simplicity, we assume that the metal CMP rate $V_{R,2}$ in the dielectric region $[a, l]$ is given by the equation

$$V_{R,2} = k_2 p_2 v^{\varepsilon_2}. \tag{30}$$

By substituting (29) and (30) into relations (11) ($V_{R,1} = V_{R,2}$) and (12), we obtain the following system of equations for finding the pressures p_1 and p_2, which determine the dishing parameter in the steady state:

$$\begin{cases} (b + k_1 p_1 - k p_1^2)v^{\varepsilon_1} = k_2 p_2 v^{\varepsilon_2}, \\ \rho p_1 + (1-\rho)p_2 = p. \end{cases} \tag{31}$$

System (31) is reduced to the equation

$$x^2 - \frac{\rho + \delta}{\delta\sigma}x + \frac{\operatorname{sgn}\bar{p}}{\delta\sigma} = 0, \tag{32}$$

where $x = p_1/|\bar{p}|$, $\bar{p} = p - (1 - \rho)\varsigma_1 b/k_1$, $\varsigma_1 = k_1 v^{\varepsilon_1-\varepsilon_2}/k_2$, $\delta = \varsigma_1(1-\rho)$, $\sigma = k|\bar{p}|/k_1$ (α, ς_1, δ, and σ are dimensionless parameters), and

$$\operatorname{sgn}\bar{p} = \begin{cases} 1, & \bar{p} > 0, \\ -1, & \bar{p} < 0. \end{cases}$$

The solution of Eq. (32) is

$$x_{1,2} = \frac{\rho + \delta}{2\delta\sigma}\left\{1 \pm \sqrt{1 - \frac{4\delta\sigma}{(\rho+\delta)^2}\operatorname{sgn}\bar{p}}\right\}. \tag{33}$$

If $\operatorname{sgn}\bar{p} = -1$ (it is possible for $b > 0$), then only $x_1 > 0$ in (33).

If $\operatorname{sgn}\bar{p} = 1$, then both the roots $x_{1,2} > 0$ for $4\delta\sigma/(\rho + \delta)^2 < 1$; in this case, as in the previous section, we have two possible steady states, i.e., the bistability effect. Thus, it is required to investigate their stability and the possibility of transition of the system from one state to the other when some of the system parameters vary. For this purpose, again, a dynamic problem for small perturbations of these steady states must be solved and the dependences of signs of the corresponding Lyapunov exponents on the system parameters must be analyzed. Here, it should be noted that if the dependence $V_{R,2} \sim p_2^{\gamma_2}$, rather than linear relation (30), holds, then one can expect more than two stationary solutions. Note also that, for $4\delta\sigma/(\rho + \delta)^2 > 1$, Eq. (33) has no real roots and, therefore, the process of polishing the periodic structure has no steady state with $V_{R,1} = V_{R,2}$.

When bistability takes place, under the additional condition

$$\delta/\rho = \varsigma_1(1-\rho)/\rho \ll 1, \tag{34}$$

which is met for $\rho \to 0$ or for $\varsigma_1 \ll 1$, in the state corresponding to the root x_1 in (33), we have

$$x_1 = \frac{\rho}{2\delta\sigma}\left\{1 + \sqrt{1 - \frac{4\delta\sigma}{\rho^2}\operatorname{sgn}\bar{p}}\right\} \sim \rho, \text{ i.e. } p_1 \approx \rho|\bar{p}|/2\delta\sigma. \tag{35}$$

Let us now estimate the pressure p_2. For this purpose, we use the approximation of the real dependence $V_{R,1} \sim \varphi(p_1)$ such that it, while preserving its quadratic form (29), covers (in addition to $\varphi(p_{1m}) = \varphi_m$) also $\varphi(0) = 0$. Such an approximation has the form

$$V_{R,1} = (k_1 p_1 - k p_1^2)v^{\varepsilon_1}, \tag{36}$$

where, in contrast to (29), $k_1 = 2\varphi_m/p_{1m}$, $k = \varphi_m/p_{1m}^2$, and $b = 0$ (due to the last condition, $|\bar{p}| = p$). Approximation (36) roughly describes the behavior of the CMP rate for $p_1 \geqslant 0$, including the transition region. Then, from (30), (35), (36), and equality $V_{R,1} = V_{R,2}$, under condition (34), we find that $p_1 \sim \rho p$ and

$$p_2 = (v^{\varepsilon_1-\varepsilon_2}/2\delta\sigma k_2)[k_1 - (k/2\delta\sigma)\rho p]\rho p,$$

and, therefore, $|p_1 - p_2| \approx C|A + B\rho|\rho$, where the coefficients A, B, and C are the functions of v and the CMP parameters, and the relation $\sigma \sim p$ is taken into account (see (32)). Given a low ρ (but such that condition (34) holds), from (7), taking into account the asymptotics of the function $|\Phi(\rho)|$ (see (15a)), for the dishing parameter $D(\rho)$, we have

$$D(a = \mathrm{const}, \rho) \sim a\rho|A + B\rho|[1 - \ln(\pi\rho/2)]. \quad (37)$$

For the fixed width of the line, this dependence decreases with ρ decreasing faster than the similar asymptotics obtained in [12] for Preston's low. Such behavior is consistent with the experimental data [7] on the dishing effect in the periodic structures Cu/SiO_2 for the widths of copper lines $a \leqslant 50$ μm. The experiments [7] show quite a sharp fall in $D(a = \mathrm{const}, \rho)$ to nearly zero when reducing the density in the interval $20\% < \rho_{\%} < 40\%$. Hence, it can be concluded that, for sufficiently narrow widths of the metal lines, the CMP mechanism and, therefore, the form of the CMP rate law are changed.

It should be noted that the results obtained in this work are due to the nonlinearity of the CMP rate law (36), which contains segments where the polishing rate increases and decreases with pressure. In this paper, we use the simplest parabolic approximation (36) to analytically demonstrate the key role of the transition region containing the polishing rate maximum. For a more detailed quantitative analysis and comparison with the experimental data, in the further works, we intend to use, for example, the model rate law derived in [6].

CONCLUSIONS

In this paper, for the kinetics of the CMP of wafers containing periodic metaldielectric structures, a model is developed and a theoretical investigation is carried out with the use of contact mechanics methods for nonlinear pressure dependences of the polishing rate. In the stationary (steady-state) regime, expressions for parameter D of the dishing effect, which is characterized by the difference in the depths of the polishing metal and dielectric stripes, are derived and analyzed. Moreover, the specific characteristics of the dependences of the dishing effect on different parameters of the system are analytically found and analyzed; these characteristics are due to the nonlinearity of the polishing rate V_R depending on the pressure p and on the relative velocity of the pad v. For certain types of nonlinearity of V_R, the dependences of the parameter D on the width of the metal lines, on their density, and on the period of the structure are found; these dependences are qualitatively consistent with the experimental data available for Cu/SiO_2 structures.

It is found that, in some cases, for the same values of the CMP parameters, there can be more than one (two or several) solution of the model equations for the stationary state of dishing. This is due to the expansion of the pressure region up to the values for which the polishing rate of at least one of the materials starts to decrease. In further works, we intend to analyze the stability of such stationary states, i.e., to investigate the kinetics of small perturbations. It may be that one solution branch is stable in one region of parameter values, while another solution branch is stable in the other (bistability effect). If these regions have a common border, then a small change in the parameters near this border should result in an intermittent transition of the CMP process from one steady state to the other.

The results obtained in this work can be used to develop new methods for controlling and optimizing the CMP of the micro- and nanoelectronic structures.

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