Formation of Catalyst Model Dispersed of Pd on a thin MgO (100)

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Abstract
The nucleation kinetics or the formation of a catalyst model dispersed for the system Pd /thin MgO (100) are calculated by developing many programs using Fortran software. This simulation is based upon parameters studied in situ by transmission electron microscopy (TEM), related to the first quantitative study on the nucleation and the growth. Palladium nanoparticles deposited on thin MgO are tested in the temperature range 573–1073 K and deposition time of 1000 s. The nucleation kinetics are interpreted according to the theory of random nucleation. The general scheme is consisting of three stages namely, nucleation, growth and coalescence. The saturation density of clusters decreases when the substrate temperature increases following Arrhenius law. This behavior is in agreement with a recent AFM study for Ag/MgO and Au/MgO. The phenomenon of coalescence is explained via island migration process. It is shown that the coalescence occurs more rapidly when the substrate temperature is high.
Keywords: catalists, crystals, magnesium-oxide, nucleation kinetics, palladium

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1. Introduction

Nowadays, nano-objects provide a promising research for the identification of new fundamental properties of the materials and their potential technological applications. Much effort is devoted to understand the physical and chemical properties of materials, which can serve as model catalyst systems. Consequently, fundamental studies have been carried out on a range of heterogeneous catalyst, for example, metal islands grown on thin films [1-11] or on single-crystals surfaces [12-18]. Palladium deposits on the MgO(1 0 0) surface have become one of the most widely used model systems, and have given rise to many detailed experimental studies [19-21]. Although the main microscopic steps governing nucleation and growth of the films are now understood, detailed characterization of these processes has proven difficult. Earlier, empirical and theoretical studies of Pd over single crystals MgO, investigated defect nucleation [22-28] when nucleation centres occupy minority of sites. On the other hand, the results of nucleation kinetics over thin films governed by random nucleation [1,29], each atomic site is potentially a nucleation centre. In this study, we build upon many experimental and theoretical studies [1, 30-32] have been carried out to understand these processes. The aim of this work is to investigate the microscopic mechanisms, which can calculate various parameters related to the quantitative study focusing on the nucleation, growth and coalescence of Pd / thin MgO (100) using Fortran software.

1.1 Transmission electron microscopy experiments

To understand the first quantitative study of nucleation and growth of Pd on thin layer of MgO(100),we exploited the experimental work of Henry *et al* [1],who used transmission electron microscopy and electron diffraction at high energy to measure the Pd island density as a function of time a given temperature and a constant flux. Firstly, the MgO (100) / LiF (100) / NaCl (100) composite layer is achieved which serves as support. Palladium is then deposited with a flux of 1×10^{13} atoms $cm^{-2}\times s^{-1}$ and exposure time of 10 to 240 s on a substrate heated at temperatures between 573 and 673K. After deposition, the Pd islands are in situ characterized with a transmission electron microscopy (TEM) to determine the island density. The results are interpreted according to the theory of random nucleation. The energy of adsorption and diffusion of palladium on MgO (100) are derived from the latter theory. It was possible to vary the average size of particles in the range 0.8 - 3.5 nm. The obtained cluster density varies from 0.6 to 3×10^{12} cm^{-2} however the covered area of the substrate surface is of 0.4 to 15 percent.

1.2 Over view of nucleation and growth theories

Nucleation on a surface has been discussed in both classical thermodynamic and in atomistic terms, and both have a long history. Classical nucleation theory was developed by Volmer [33]. From this theory, the critical nucleus is only one atom, which means that the dimer is already stable. In that case, the classical nucleation theory is no longer applicable. The growth process occurs by accretion of adatoms. It is described by the atomistic nucleation theory, which has been developed by Zinsmeister [32]. In this case, the critical nucleus composites of two atoms and the supercritical nuclei do not dissociate. The probability of adsorption is equal to one and that only single atom can return in the phase steam. The frequency of nucleation is then determined by the frequency of meeting of adsorbed atoms.

1.2.1 Nucleation kinetics

The rate equations given by Zinsmeister express the variation with time of the number of clusters of size i:

$$\frac{dn_i}{dt} = \omega_{i-1}\, n_{i-1} - \omega_i\, n_i \quad \text{for i} = 2,3\ldots\infty \qquad (1)$$

ω_i is the attachment frequency of an adatom to a cluster containing i atoms which is expressed by:

$$\omega_i = \sigma_i D n_i \quad (2)$$

where σ_i is the capture number for a cluster of size i. We have to integrate the system of differential equations in order to calculate the number of nuclei present on the substrate. For sake of simplicity Zinsmeister assumes that it is a constant between 1 and 4. From this scheme the nucleation frequency is:

$$J = 2\,\omega_1\, n_1 \quad (3)$$

Supposing that the growth is negligible, the density of adatoms is equal to the stationary value:

$$n_1 = F\tau \quad (4)$$

where F is the flux of atoms impinging on the substrate and τ the mean life time of an adatom before desorption. Then, combining equations (2) and (4) the nucleation rate becomes:

$$J = 2\sigma_1\, D\, F^2\tau^2 \quad (5)$$

The nucleation rate is proportional to the square of the impinging flux for a homogeneous substrate without defects.

1.2.2 Growth kinetics.

Zinsmeister has solved the system of differential equation assuming a constant value for the attachment frequency (ω_i) [18]. However by this treatment several characteristics of the growth of clusters are not taken into explanation. Several researches have tried to treat more precisely the calculation of the attachment frequencies [34–39]. In the typical growth, the diffusion of adatoms is limited by desorption and the diffusion length X_s of an adatom is:

$$X_s = (D\tau)^{1/2} \quad (6)$$

where D_s is the surface diffusion coefficient. It is expressed by:

$$D_s = (a_0^2 \nu_d) \exp\left(-\frac{E_d}{KT_s}\right) \quad (7)$$

Then the mean life time of a physisorbed molecule can be explained by:

$$\tau = (1/\nu_a)\, exp\left(\frac{E_a}{KT_s}\right) \quad (8)$$

where E_a and E_d is the adsorption and the diffusion energy, and a_0 the jump distance, of the order of the surface repeat distance, say 0.2-0.5 nm[40], ν_d and ν_a the frequency factors for the diffusion and the adsorption process, K the Boltzmann constant and T_s the substrate temperature. In a general case, the growth rate of a cluster can be expressed by a power law of the deposition time.

$$R(t) = R_0 t^p \quad (9)$$

The exponent for any experimental has been calculated in the case of the lattice approximation for 3D clusters.

1.2.3 Coalescence

The transformation of two touching nuclei into one nucleus can be described by a time constant shown by Nichols and Mullins [41]:

$$\tau_c = 0.2\left(\frac{R^4}{B}\right) \quad with\ B = \frac{\gamma\,\Omega^{4/3} D_s}{K\,T_s} \quad (10)$$

where R is the radius of the coalescing spheres, γ the surface free energy and Ω the atomic volume of Pd.

1.2.4 Algorithm

We have been developed many programs exploiting Fortran software. The following list details this mapping.

1. Pd deposition flux rate on MgO (100) is 1.13×10^{13} atoms $cm^{-2} \times s^{-1}$.
2. Pd atoms are deposited randomly onto the surface with activation energy of about 0.22 eV.
3. Pd nanoparticles deposited on thin MgO are tested in the temperature range 573–1073 K and deposition time of 1000 s.
4. Pd islands are approximated to be three-dimensional clusters.
5. The diffusion of adatoms is limited by desorption. Hence, the values of the surface diffusion are calculated by combination of Equations (6) and (7).
6. The entry parameters are: the velocity of nucleation, velocity of growth, the average mean life time, the surface repeat distance, the diffusion length, the surface free energy, the atomic volume of Pd, the activation and the diffusion energies.

2. Results

Fig. 1 shows the variation of cluster density as a function of exposure time at different substrate temperatures ranging from 573K to 1073K and a constant palladium flux 1×10^{13} atoms $cm^{-2} \times s^{-1}$. For Ts = 573K and 673K, we can see that the density of clusters is increasing rapidly after 10 to 70 s (see table 1) due to the large adsorption energy for the Pd adatom confirming the nucleation stage, up to a plateau (saturation density) corresponding to $n_s = 3\times10^{12}$ cm^{-2} and 1.6×10^{12} cm^{-2} respectively. A similar behavior is observed for the remaining substrate temperatures till the coalescence occurrence, were the cluster density decreases. It is worth to note that the cluster density decreases when the temperature increases.

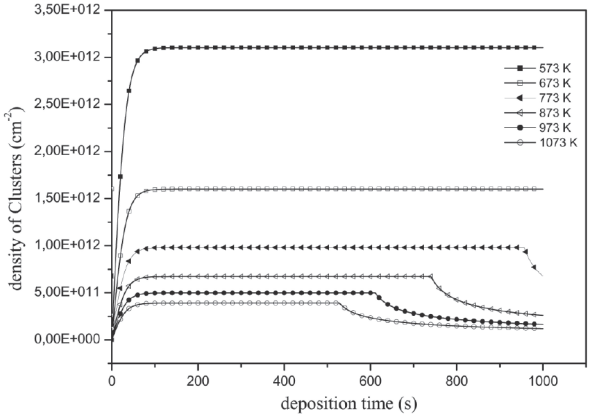

Fig. 1. Nucleation kinetics of Pd on MgO (100) at different substrate temperatures for a palladium flux 1×10^{13} atoms $cm^{-2} \times s^{-1}$.

1. ábra A Pd nukleáció kinetikája MgO (100) vékony rétegen különböző szubsztrátum hőmérsékleten, ha a palládium fluxus nagysága 1×10^{13} atom/cm^2s.

t (s)	573 K	673 K	773 K	873 K	973 K	1073 K
10	9.39E11	4.85E11	2.97E11	2.03E11	1.50E11	1.18E11
70	3.02E12	1.56E12	9.58E11	6.56E11	4.86E11	3.81E11
τ_c	No	No	9.80E11	6.71E11	4.98E11	3.90E11
1000	3.02E12	1.60E12	6.77E11	2.59E11	1.64E11	1.19E11

Table 1. Calculated of the cluster density (cm^{-2}) at different substrate temperatures (K) and deposition times (s).
1. táblázat A különböző K hőmérsékletekre és „lerakódási" időkre (sec) számított klaszter-sűrűségek (cm^2).

In *Fig. 2*, the saturation density is plotted in an Arrhenius diagram. It is represented by the equation: $n_s = B_0 \times \exp(E / K \times T_s)$. When the activation energy E is equal to 0.22 ± 0.05 eV, B_0 (pre exponential factor) is 3.63×10^{10} cm^{-2}. We show that it increases when the substrate temperature decreases. This behavior is in agreement with a recent AFM study for Ag/MgO [42], Au/MgO (100) [43] and our previous studies by TEM [1] on the same system.

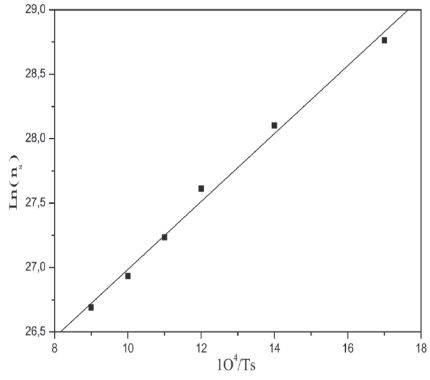

Fig. 2. Arrhenius plot of the saturation density of palladium clusters on MgO (100).
2. ábra A palládium klaszerek Arrhenius féle telítettségi sűrűsége az MgO (100) vékony rétegen.

Fig. 3 and *4* show the variations of the covered area (A) and the coalescence parameter (B) as a function of substrate temperatures obtained under the same conditions. We see that the fraction of covered area decreases when deposition temperature rises. An opposite behavior is observed for the coalescence parameter.

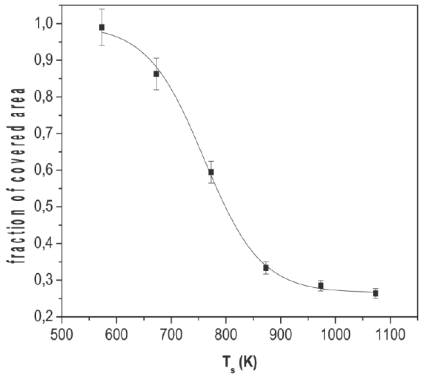

Fig. 3. Variation of the covered area (A) as a function of substrate temperatures with deposition times 1000s.
3. ábra Az 1000 másodperc idő alatt lerakódott felület (A) nagyságának változása a szubsztrátum hőmérséklet függvényében

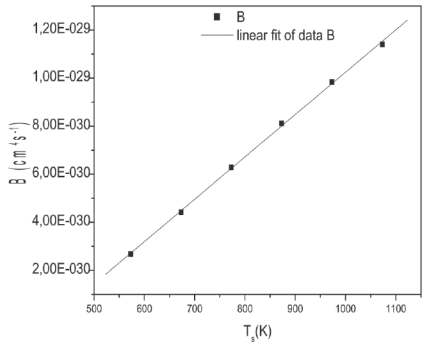

Fig. 4. Variation of the coalescence parameter (B) as a function of substrate temperatures with deposition times 1000s.
4. ábra Az 1000 sec. idő alatt létrejött egyesülések száma (B) a szubsztrátum hőmérséklet függvényében.

3. Discussion

From our previous empirical result for Pd/MgO thin film, the initial nucleation curves suggest the occurrence of a random nucleation mechanism. The theory of this nucleation process is expressed by the kinetic equations of Zinsmeister [32]. Robinson and Robins [30] have given analytical solutions in two limit cases, namely at low and high temperature. In this work, we focus on the high substrate temperatures(regime of incomplete condensation), where the particle number density is given by:

$$n = n_s \tanh\left(t/\tau\right) \quad (11)$$

when the random nucleation model is used ,the calculated curves in the first stage agree well with the experimentally measured [1] time dependencies of island density (see nucleation regime in *Fig. 1*). Hence, the curves show a plateau as a maximum particle density reached at the end of the nucleation regime characterizing the Volmer Weber growth. The value of saturation of the island density is an important parameter which determine the mode of thin film growth. The latter has an evident influence on the physicochemical properties of the obtained thin films [28]. The linear behavior of the Arrhenius plot observed for the temperature dependence of the saturation density of clusters has been also found in the case of Ag / Ar-cleaved MgO(1 0 0) [42], Au /MgO(1 0 0) [43] and Pd/ UHV-cleaved MgO(1 0 0) [44,45].

$$n = n_s \left(1 + t/\tau\right)^{-3/m} \text{, with m = 7} \quad (12)$$

The coalescence curves were better fitted with a Cluster diffusion model [31] rather than Ostwald ripening model.

The most crucial parameter in our results is the coalescence time. It is defined as the mean time for two clusters that come into contact to coalesce. From Eq. (10), we can note that two parameters are important to determine the duration of the coalescence stage, which are R and B. One can also notice the influence of the deposition temperature, that modifies the clusters coalescence time. It is clearly seen that clusters coalesce more rapidly at high temperature [46]. This phenomenon is explained by the process of island migration.

The process of island migration in this calculation is essentially described by the parameter B. The derived B values from *Fig. 4* are not high enough meaning that the process of island density coalescence is not ignored even at the initial stages of deposition [47]. The mechanism of coalescence which can be expected at

such a low value of surface coverage is the migration of islands on the surface, prior to the mechanism of immobile islands in which the coalescence occurs at high values of surface coverage when the islands touch each other [48].

The surface coverage does not depend on B parameter, but it strongly depends on the cluster density and the shape of the particles. The fraction of the substrate covered by the clusters, which is considered as the contact surface of the half sphere is a circle can be written as:

$$A = \frac{\pi}{4} n D^2 \quad (13)$$

In this range of temperatures, the diameter (D) of the clusters follows a power law: $D_o t^P$ with 0.33 <P<0.55. At 573K and 673K, our previous experimental work yielded values of D_o; P equals 0.024 nm, 0.8 and 0.372 nm, 0.39 respectively [1]. The obtained values are used for the calculated curves of the covered area of the substrate surface.

As indicated in the last section the cluster density decreases when the substrate temperature increases due to the increased ad-atom mobility [34]. In addition, we assumed that D is relatively constant with a low error (ΔD / D=11%). Accordingly, the fraction of the substrate covered by the particles decreases and the decrease is more pronounced when the coalescence occurs. This behavior is in good agreement with growth rate of the particles in the case of the random nucleation theory [49].

4. Conclusions

In the present study, we have simulated the microscopic mechanisms, which can calculate various parameters related to the formation of Pd / thin MgO (100) using FORTRAN software. The formation kinetics follows a general scheme consisting of three stages: nucleation, growth and coalescence. It is determined that saturation density obeys an Arrhenius law with activation energy of 0.22 eV as a fit parameter. It is observed that the variation of island density upon time reaches the saturation. In some cases the cluster density decreases slowly after a saturation regime. The latter decrease is interpreted via the processes of islands migration .It is shown that the coalescence time and the fraction of the substrate covered by the clusters decrease when the temperature increases. Furthermore, the clusters coalesce more rapidly when the temperature increases.

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Pd diszperz katalizátor modell képződése a vékony MgO (100) rétegen

A szerzők a Fortran szofter felhasználásával egy szimulációs katalizátor modellt dolgoztak ki a diszpergált Pd palládium nanoszemcsék alkalmazásával vékony MgO magnézium-oxid rétegen. Ez a szimulációs modell a transzmissziós elektronmikroszkóppal (TEM) in-situ végzett csiraképződési és növekedési vizsgálati adatokon alapszik Az első kvantitatív vizsgálat a nucleation és a növekedést. A palládium nanorészecskék beépülését a vékony MgO rétegbe az 573-1073 K-fok hőmérséklet-tartományban tesztelték 1000 sec hőkezelési időtartam alatt. Azt tapasztalták, hogy a folyamat az alábbi három szakaszra osztható: a véletlenszerűen (random) csiraképződés; a növekedés; és végül az egyesülés. Az Arrhenius törvénynek megfelelően a létrejött klaszterek telítettségi sűrűsége csökken a szubsztrátum hőmérsékletének növekedésével – hasonlóan mint ahogyan ezt megfigyelték az Ag/MgO illetve Au/MgO AFM (atomic force Microscopy) tanulmányozásakor. Az egyesülési jelenség az úgynevezett sziget-migrációs folyamattal magyarázható; mely folyamat annál gyorsabb, minél magasabb a hőmérséklet.
Kulcsszavak: katalizátorok, kristályok, magnézium-oxid, csiraképződés, palládium