# Growth and magnetism of low-dimensional structures

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Low-D magnetic structures -

-applications

-a bridge between atomic and solid state magnetism

-intrinsic magnetic properties

-moments

-order -anisotropy

Introduction to x-ray magnetic circular dichroism (XMCD)

Case studies



-Co clusters on Pt(111)

-Co atomic chains on vicinal Pt(111)

-Co on alkali metal films

nån 2001

### Why low-D structures?



### a 2D laboratory: single crystal surfaces

• support

• manufacturing environment

each process *i* has an energy barrier  $E_i$ and a rate v

$$\mathbf{v} = \mathbf{v}_0 \exp(-E_i / \mathbf{k}T)$$

diffusion processes:

$$\left< \Delta r^2 \right> = \mathbf{v} \, \mathbf{a}^2 t$$

$$D = \lim_{t \to \infty} \frac{\left\langle \Delta r^2 \right\rangle}{2dt} = \frac{1}{2d} a^2 v$$

a – lattice constant t – time, d = 1 (1D), 2 (2D)



# Aim: to control

• mean size

(size distribution)

- density
- shape
- composition

Control parameters:

•substrate temperature T

•deposition flux F

•surface coverage

•substrate/overlayer material

(strain, mixing, etc.)

•substrate symmetry or patterning

### Statistical growth: $T \rightarrow 0 \text{ K}$

- thermally-activated diffusion is frozen
- coverage determines mean island size *n*
- large size distribution

STM images: *n* = coverage/island density

0.03 ML, T = 50 K: n = 1.20.10 ML, T = 50 K: n = 2.9



Kinetic Monte Carlo simulation





### Cluster diffusion: Co/Pt(111)



Sequential activation of cluster diffusion results in size selection

T < 60 K: monomers

60 K < *T* < 90 K: dimers and trimers

100 K< *T* < 130 K: tetramers and pentamers



## Nucleation and growth:

- thermally-activated diffusion
- coverage and *T* determine *n* (avg size)

Ag/Pt(111) @ T = 75 K

- a) to b) Pure nucleation regime
- Ag deposition results in the formation of new nuclei (increase of island density, n is constant)
- c) Transition from nucl. to growth both island density and n increase
- d) Pure growth or steady state regime*n* prop. to coverage;
- The island density has saturated

a)  $\Theta = 0.0024 \text{ ML}$ 



 $n=2.4\pm0.4$ 

c)  $\Theta = 0.03 \text{ ML}$ 



 $n = 6.4 \pm 1.1$ 

b)  $\Theta = 0.006 \text{ ML}$ 



 $n=2.6\pm0.5$ 

d)  $\Theta = 0.06 \text{ ML}$ 







[H. Brune, Surf. Sci. Rep. 31, 121 (1998)]

Controlling the shape: <u>Ag/Pt(111)</u>

a) deposition at T = 130 K

b) deposition at T = 50 K, annealing to 280 K







Anisotropic corner diffusion at low *T* 

 $E_{C \rightarrow A} = 160 \text{ meV}$  $E_{C \rightarrow B} = 320 \text{ meV}$ 



B steps accumulate less atoms than A steps



[H. Brune et al., Surf. Sci. 349, L115 (1996)].

## Controlling the spatial distribution of 2D clusters: nucleation on patterned substrates

Isotropic (111) or (100) surfaces do not allow to control the spatial distribution of the adsorbates.

Ideally, one would like to obtain

•uniform spacing

•narrow size distribution





Use dislocation networks as deposition templates: Co clusters on the reconstructed Au(111) surface

[J.V. Barth et al., PRB 42, 9307 (1990)]

200 Å

### Site selective nucleation through exchange at dislocation elbows



[J.V. Barth et al., PRB 42, 9307 (1990)]



The Au(111) herringbone reconstruction: 23 surface atoms on top of 22 second layer atoms result in partial dislocations that separate fcc and hcp regions.





 $\overline{2}$  nm

[courtesy S. Rousset, CNRS, Univ. Paris 7 and 6]



Co clusters on Au(111)

20 nm

## Nucleation on dislocation networks:

Ag/ 2ML Ag/ Pt(111)

1st Ag layer on Pt(111) is pseudomorphic: Ag atoms are coherently strained due to the 4.3% Ag/Pt lattice mismatch;

2nd Ag layer: trigonal dislocation network relieves compressive strain.

Due to preferential nucleation on fcc sites, only one Ag islands grows in each unit cell of the dislocation superlattice.



[H. Brune et al., Nature 394, 451 (1998)]





### Growth of 1D structures: atomic-thin metal chains

Anisotropic surfaces as deposition templates

- (110) surfaces
- vicinal surfaces



fcc lattice : different net planes

High Miller indexed fcc surface with steps / kinks

[Hard-sphere models by K. Hermann, FHI, Berlin; http://www.fhi-berlin.mpg.de/th/member/hermann\_k.html] Anisotropic diffusion on (110) surfaces:

Cu/Pd(110)

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diffusion along [1-1 0]:
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E_m^{[1-1\ 0]} = 0.51 \text{ eV}
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diffusion along [001]:

 $E_m^{[001]} = 0.75 \text{ eV}$ 

[1-1 0]





c) T = 320 K



d) T = 350 K

b) T = 300 K





[H. Röder et al., Nature 366, 141 (1993)]

## Vicinal surfaces: periodic step structure

# Pt(997)







10 nm

## Vicinal surfaces: deposition templates for 1D atomic chains

# Potential energy surface for a Co adatom on Pt(997)



	Co/Pt	Cu/Pt	Ag/Pt
Terrace	-2.79	-2.17	-2.14
Step	-3.79	-2.75	-2.68

Tight-binding calculation of the adsorption energy (eV) of a single metal atom on Pt(997).

[F. Picaud, C. Ramseyer, C. Girardet, Univ. Besançon]

[P. Gambardella et al., PRB 64, 045404 (2001)]

# Vicinal surfaces: deposition templates for 1D atomic chains



# Co monatomic chains on Pt(997)



# Ag/Pt(997): 1D chain formation

Preferential nucleation at the lower step edges: 1D Ag islands



10 Å



[P. Gambardella et al., PRB 61, 2254 (2000)]

# Coalescence of 1D islands: continuous atomic chains



### Ag growth vs substrate temperature



### Co growth vs substrate temperature: row-by-row and step bunching

T = 250 K, $\Theta_{\text{Co}} = 0.5 \text{ ML}$ 





Schwoebel barriers block interlayer diffusion: periodic stripe pattern





T = 385 K, $\Theta_{\text{Co}} = 0.5 \text{ ML}$ 





Formation of double-layer stripes, step bunching: aperiodic structure.



# <u>Growth modes</u> on stepped surfaces





rough growth



double-layer wires



non-periodic pattern



alloying

*T* window for growing periodic arrays of 1D wires

[P. Gambardella et al., Surf. Sci. 449, 93 (2000)]



### 1D alloy: Ni/Pt(997)

T = 200 K, $\Theta_{\text{Ni}} = 0.2 \text{ ML}$ 



Ni exchanges preferentially with Pt atoms at the step edges forming an ordered 1x2 alloy

Ni





At 300 K a 2D surface alloy forms with a 2x2 structure. 10 Å



[P. Gambardella et al., Surf. Sci. 475, L229 (2001)]

# **Deposition of mass-selected clusters**



[Courtesy W. Harbich, H. Jödicke, R. Schaub, IPE-EPF Lausanne]

# **Cluster Surface collision**

# Collision



Cluster size Incident kinetic energy Cohesive energy cluster Cohesive energy surface Cl.-surf. cohesive energy Impact angle

Timescale: fs-ps E<sub>kin</sub>= 20 eV to 5 keV

# **Outcome of the collision process**





# Crater formation: deposition of 1 keV Ag<sub>7</sub>/ Pt(111)

# Surface temperature 77K (deposition and imaging)

Molecular dynamics calculations predict crater formation



# Softlanding: sample preparation

Ag<sub>19</sub>/Kr/Pt(111)



Kr/Pt(111)

**Pt(111)** 



# Sample annealing







# Sample annealing



**12 Kr atoms** 

+ 19 Ag atoms





[R. Schaub et al., PRL 86, 3590 (2001)

Summary:

Microscopic view of heteroepitaxial growth isotropic surfaces anisotropic surfaces

mass-selected cluster deposition

Self-assembly of 2D and 1D structures

2D arrays of nm-size metal islands

1D nanowires

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S. Rousset, CNRS and Univ. Paris

#### The saturation island density $\rho_x$ depends on D(T), and F

at saturation:  $\rho_x \approx \left< \Delta r^2 \right>^{-1}$ 

 $\left< \Delta r^2 \right> \approx Dt$  where t is the adatom lifetime

1/t is the nucleation rate of an adatom. It can be estimated by

$$\frac{1}{t} = \frac{F}{\left\langle \Delta r^2 \right\rangle} \quad \text{where } F \text{ is the deposition flux, or by}$$
$$\frac{1}{t} = F \rho_I \left\langle \Delta r^2 \right\rangle = F^2 \left\langle \Delta r^2 \right\rangle^2 / D$$

where  $\rho_l$  is the density of adatoms (monomers) $\rho_1 \approx Ft \approx \langle \Delta r^2 \rangle F / D$ 

and  $\rho_1 \langle \Delta r^2 \rangle$  is the adatom probability to meet another adatom by visiting  $\langle \Delta r^2 \rangle$  sites in its lifetime *t* 

$$\Rightarrow \rho_x \approx \left(\frac{F}{D}\right)^{1/3} = \left(\frac{F}{\nu_0}\right)^{1/3} \exp\left(\frac{E_m}{kT}\right)$$

The above holds if only monomers are allowed to diffuse and dimers and larger clusters are stable islands [J. Villain et al.] The saturation island density  $\rho_x$  depends on D(T), and F

For diffusing monomers, stable dimers:

$$\rho_x \approx \left(\frac{F}{D}\right)^{1/3} = \left(\frac{F}{v_0}\right)^{1/3} \exp\left(\frac{E_m}{kT}\right)$$



Variation of the saturation island density with (a) T for 0.12 ML Ag/Pt(111); (b) Ag coverage for T = 75 K [H. Brune, Surf. Sci. Rep. 31, 121 (1998)].

$$\Theta_{Ag} = 0.12 \text{ ML}$$



b) T = 95 K



c) T = 110 K



200 Å

# <u>1 row Co - 1 row Ag superlattice</u>







Deposition: 20K< T<sub>s</sub><1200K Imaging: 8K<T<sub>s</sub><400K

[H. Jödicke et al ., Rev. Sci. Instr. 71, 2818 (2000)]