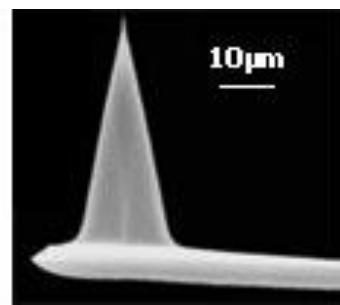
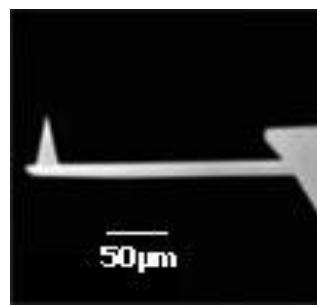
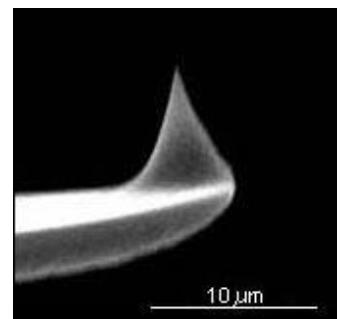
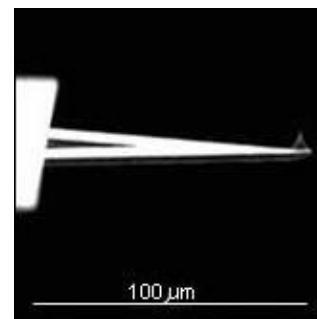
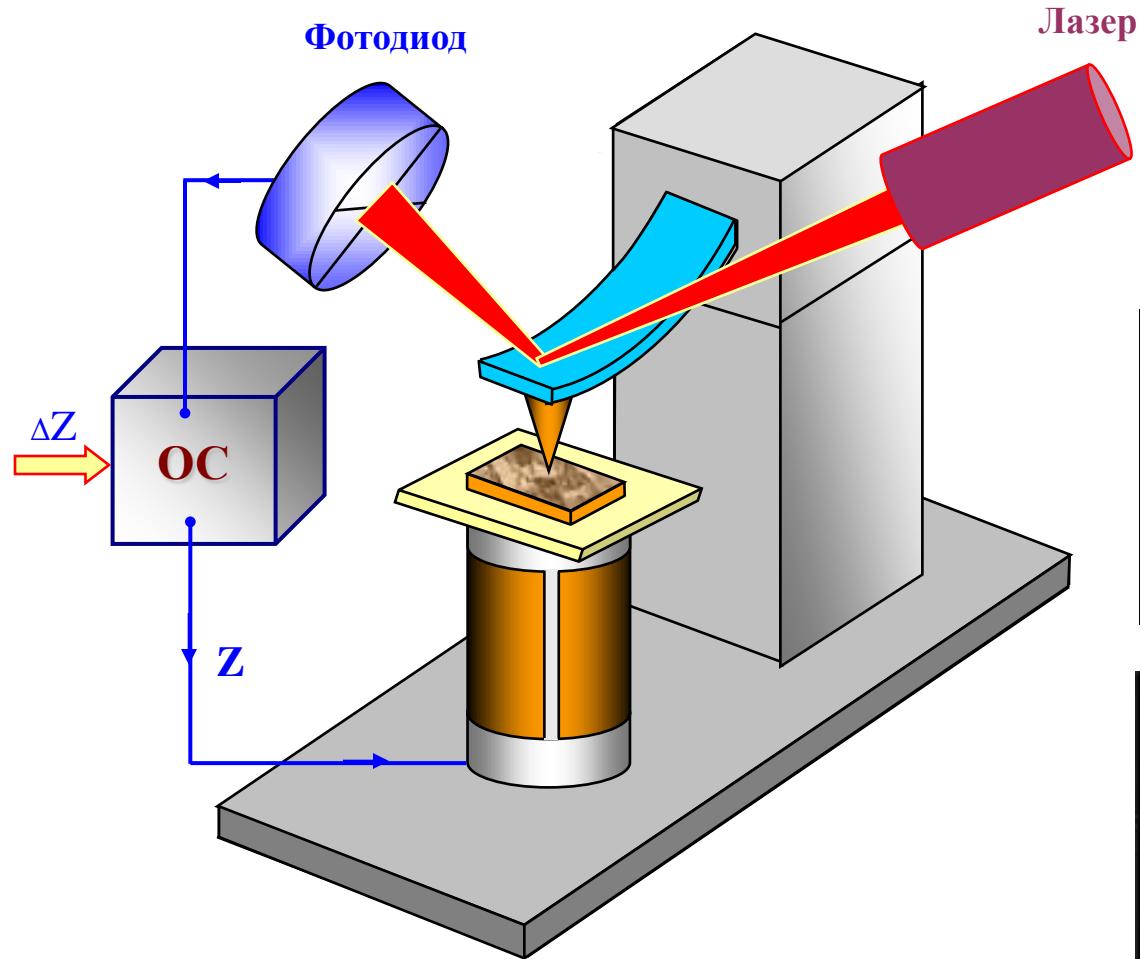


# **Магнитно-силовая микроскопия ферромагнитных наночастиц**

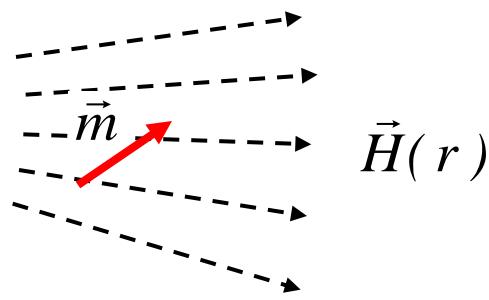
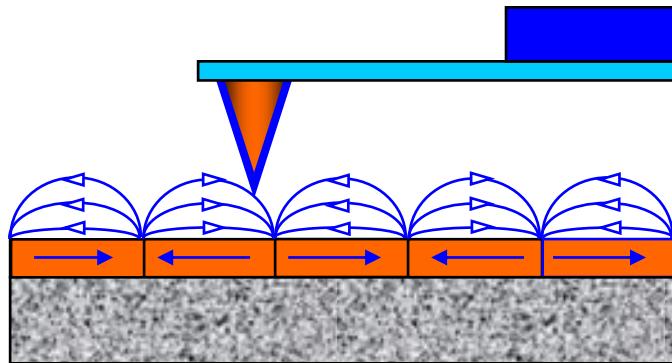
# **План доклада**

- **Принципы магнитно-силовой микроскопии (МСМ)**
- **МСМ вихревых состояний в наночастицах Со**
- **МСМ многослойных частиц на основе Со**
- **МСМ слабокоэрцитивных наночастиц**

# Магнитно - силовая микроскопия



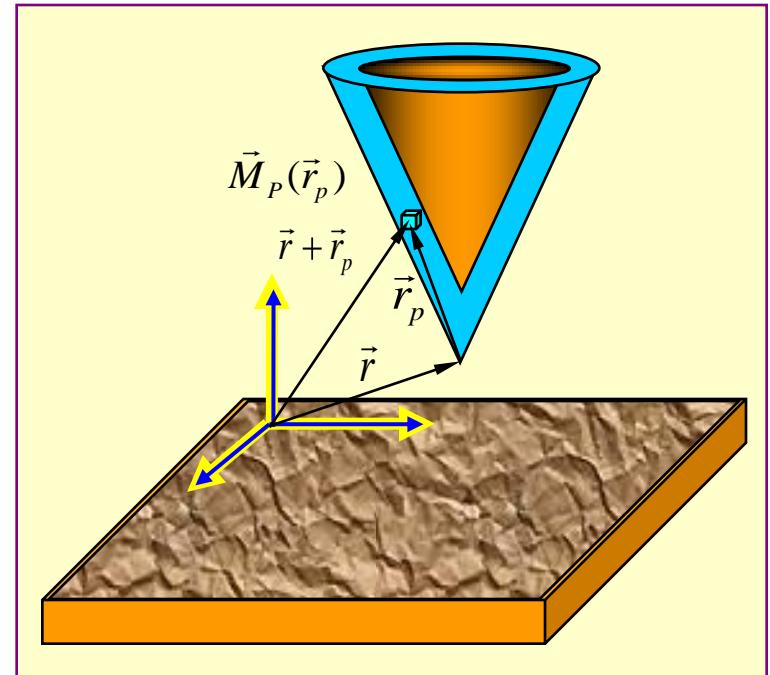
# Магнитно - силовая микроскопия



$$w = -(\vec{m} \vec{H})$$

$$\vec{f} = -\text{grad}(w) = \vec{\nabla}(\vec{m} \vec{H})$$

$$\vec{N} = [\vec{m} \vec{H}]$$



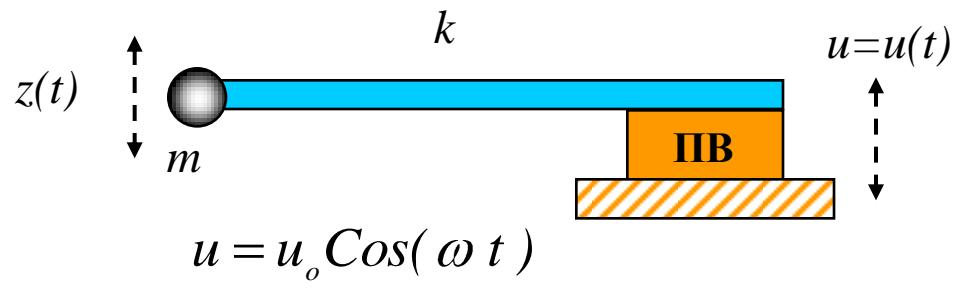
$$\vec{M}_p(\vec{r}_p)dV_p$$

$$E = - \int_{V_p} \vec{M}_p(\vec{r}_p) \vec{H}_s(\vec{r} + \vec{r}_p) dV_p$$

$$\vec{F} = -\vec{\nabla}E = \int_{V_p} \vec{\nabla} \vec{M}_p(\vec{r}_p) \vec{H}_s(\vec{r} + \vec{r}_p) \vec{d}V_p$$

$$F_z = \int_{V_p} \left( M_{px} \frac{\partial H_{sz}}{\partial x} + M_{py} \frac{\partial H_{sz}}{\partial y} + M_{pz} \frac{\partial H_{sz}}{\partial z} \right) dV_p$$

# Магнитно - силовая микроскопия

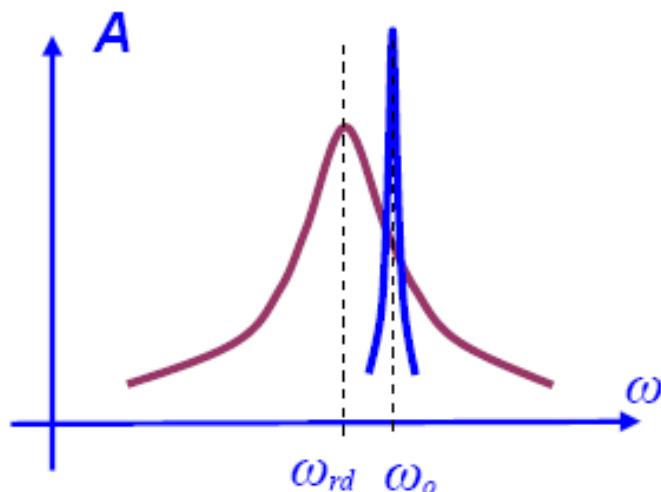


$$m\ddot{z} = -k(z - u) - \gamma\dot{z} + F_0$$

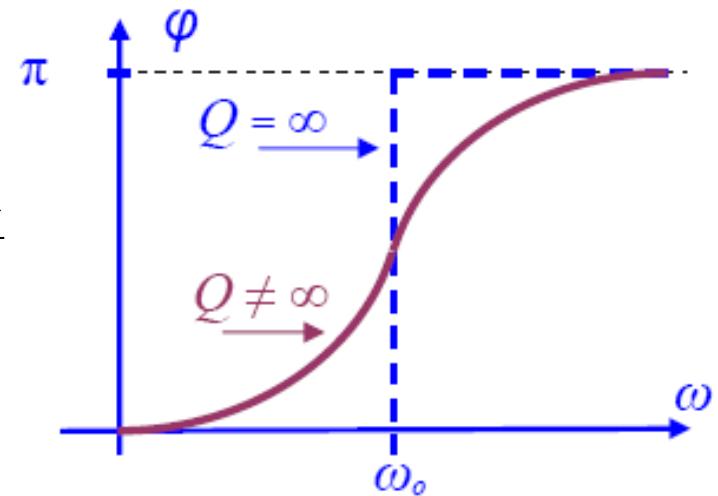
$$\ddot{z} + \frac{\omega_0}{Q} \dot{z} + \omega_0^2 z = \omega_0^2 u_0 \cos(\omega t)$$

$$A(\omega) = \frac{u_0 \omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + \frac{\omega^2 \omega_0^2}{Q^2}}}$$

$$\phi(\omega) = \operatorname{arctg} \left[ \frac{\omega \omega_0}{Q(\omega_0^2 - \omega^2)} \right]$$



$$Q = \frac{\omega_0 m}{\gamma}$$



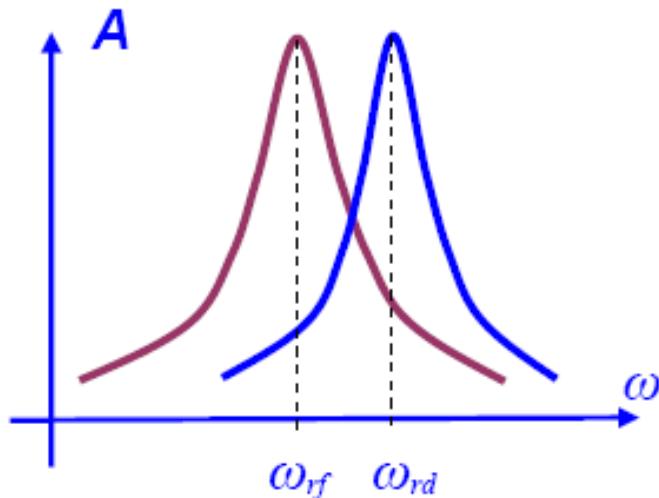
# Магнитно - силовая микроскопия

$$F_{PS} = F_{PS0} + \frac{\partial F}{\partial z}(z_0) \cdot z(t)$$

$$m\ddot{z} = -k(z - u) - \gamma\dot{z} + F_0 + F_{PS0} + F_z' z$$

$$m\ddot{z} + \gamma\dot{z} + (k - F_z') \cdot z = ku_0 \cos(\omega t)$$

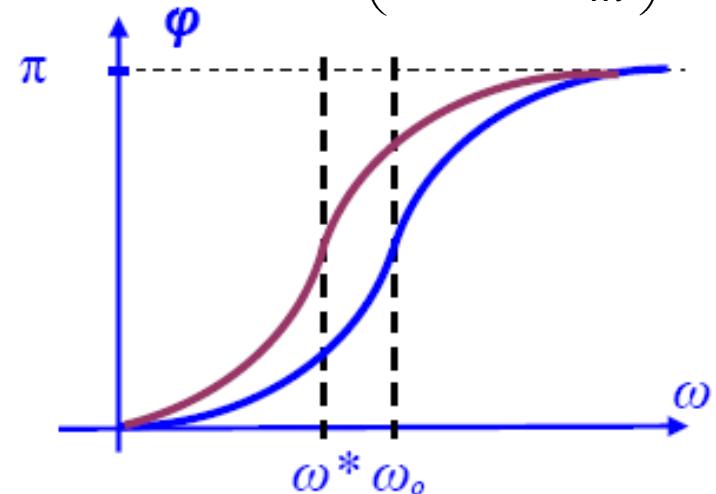
$$A(\omega) = \frac{u_0 \omega_0^2}{\sqrt{(\omega_0^2 - \omega^2 - \frac{F_z'}{m})^2 + \frac{\omega^2 \omega_0^2}{Q^2}}}$$



$$\ddot{z} + \frac{\omega_0}{Q} \dot{z} + \left( \omega_0^2 - \frac{F_z'}{m} \right) \cdot z = \omega_0^2 u_0 \cos(\omega t)$$

$$\Delta\omega = \omega_{rd} - \omega_{rf} = \omega_{rd} \left( 1 - \sqrt{1 - \frac{F_z'}{m\omega_{rd}}} \right)$$

$$\varphi(\omega) = \operatorname{arctg} \frac{\omega \omega_0}{Q \left( \omega_0^2 - \omega^2 - \frac{F_z'}{m} \right)}$$

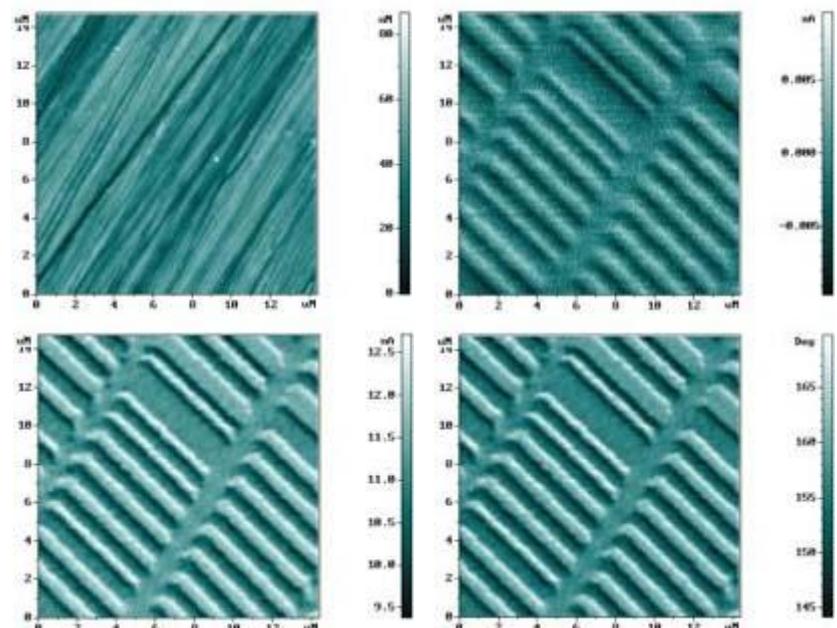


# Магнитно - силовая микроскопия

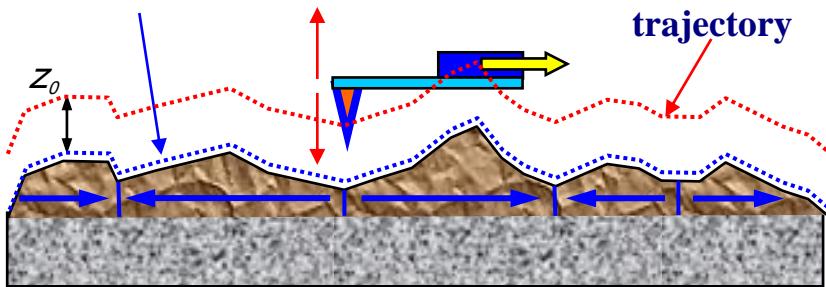
$$\varphi(\omega_0) = \operatorname{arctg} \left[ \frac{k}{QF_z'} \right] \approx \frac{\pi}{2} - \frac{QF_z'}{k}$$

$$\Delta\varphi = \varphi(\omega_0) - \frac{\pi}{2} = -\frac{QF_z'}{k}$$

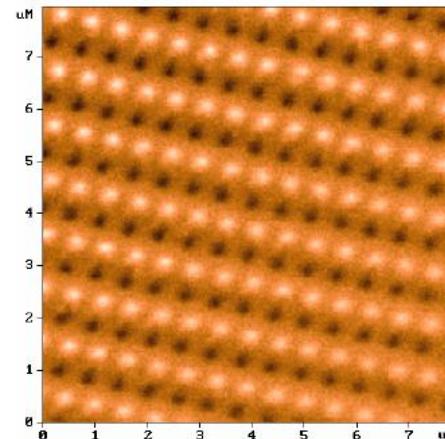
$$\Delta\varphi = -\frac{Q}{k} \frac{\partial F_z}{\partial z}$$



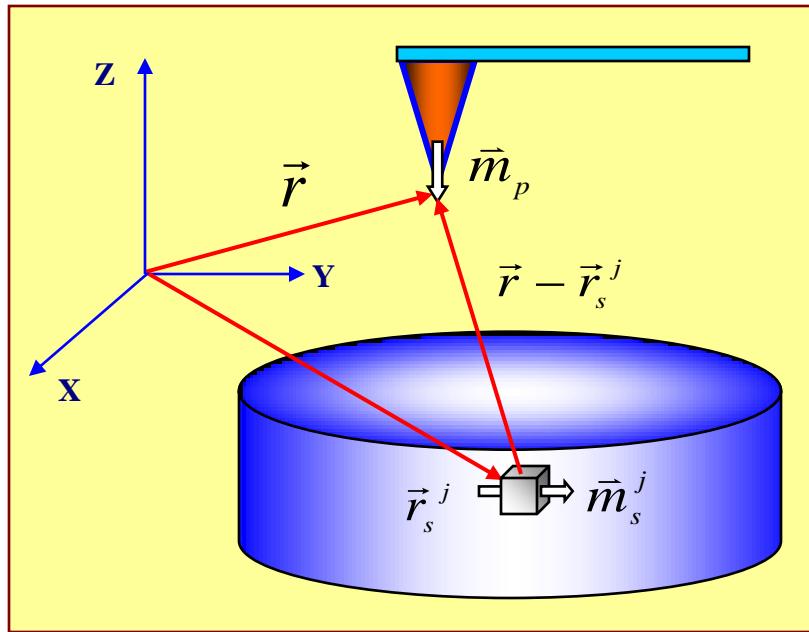
First pass trajectory



Second pass trajectory



# Моделирование МСМ контраста



$$\Delta\phi = -\frac{QF_z'}{k}$$

$$\frac{\partial}{\partial z} F_z(\vec{r}) = \sum_j ((\vec{m}_p \vec{\nabla}) \frac{\partial}{\partial z} H_z^j(\vec{r} - \vec{r}_s^j))$$

$$H_z^j(\vec{r} - \vec{r}_s^j) = \frac{3(z - z_s^j)(\vec{m}_s^j \cdot (\vec{r} - \vec{r}_s^j))}{|\vec{r} - \vec{r}_s^j|^5} - \frac{m_{sz}^j}{|\vec{r} - \vec{r}_s^j|^3}$$

$$\frac{d\vec{m}_s^j}{dt} = -\gamma [\vec{m}_s^j \times \vec{H}_{eff}^j] - \frac{\lambda}{|\vec{m}_s^j|^2} [\vec{m}_s^j \times [\vec{m}_s^j \times \vec{H}_{eff}^j]]$$

$$\vec{H}_{eff}^j = -\frac{1}{\mu_0} \frac{\partial E}{\partial \vec{m}_s^j}$$

# Магнитно-силовая микроскопия



“Solver P7LS”



“Solver PRO”

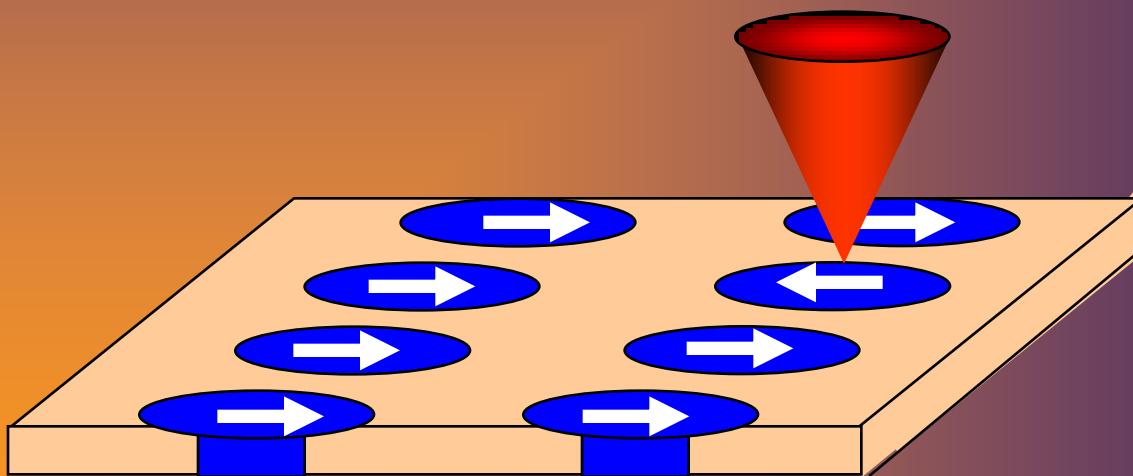


“Solver - HV”

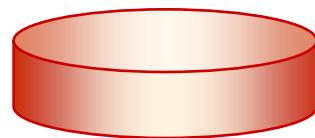
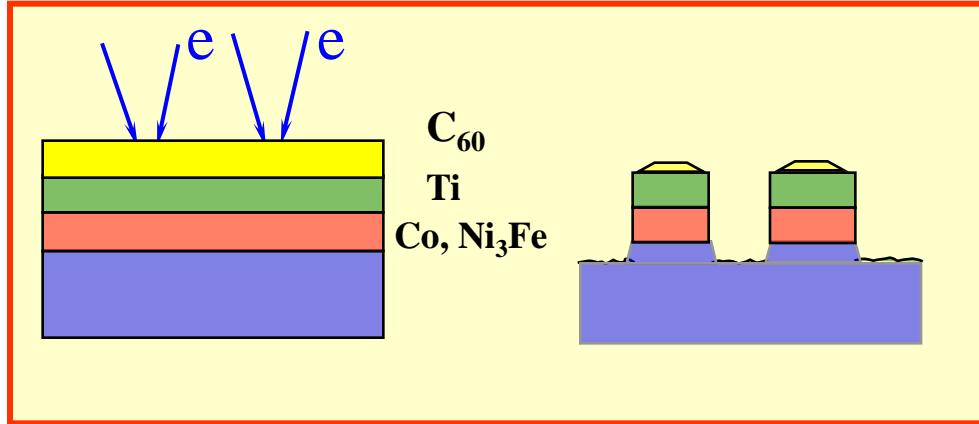
# Исследование многовихревых состояний в ферромагнитных наночастицах

# Введение

**Массивы магнитных наночастиц как среда для записи информации и как источники сильно неоднородного магнитного поля**



# Массивы магнитных наночастиц



**a, b, h**

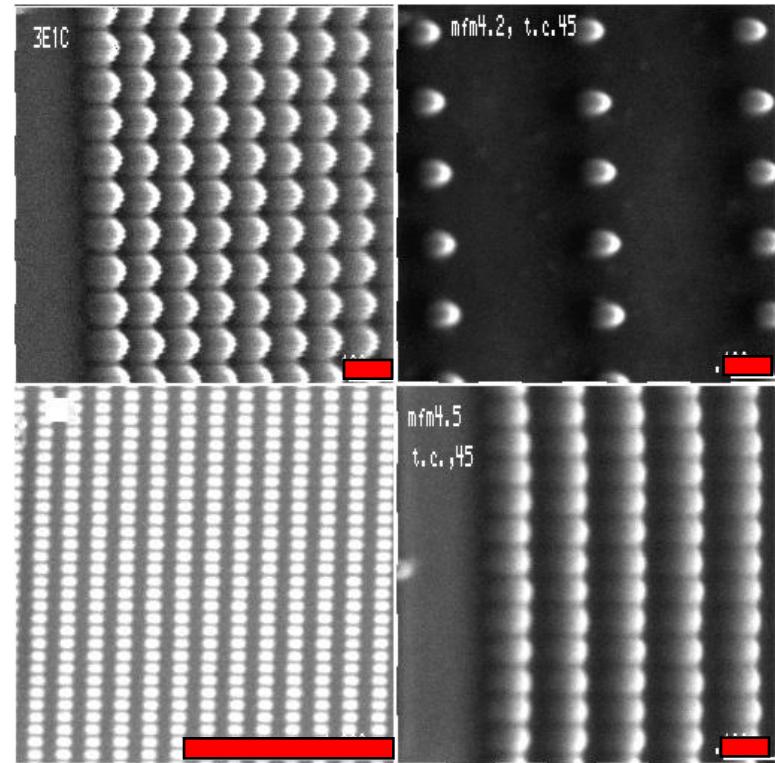
**Film thickness:**

$C_{60} \sim 20 - 100$  нм    $Ti \sim 20 - 30$  нм,

$Co, Ni_3Fe \sim 5 - 100$  нм

**Латеральные размеры частиц:**

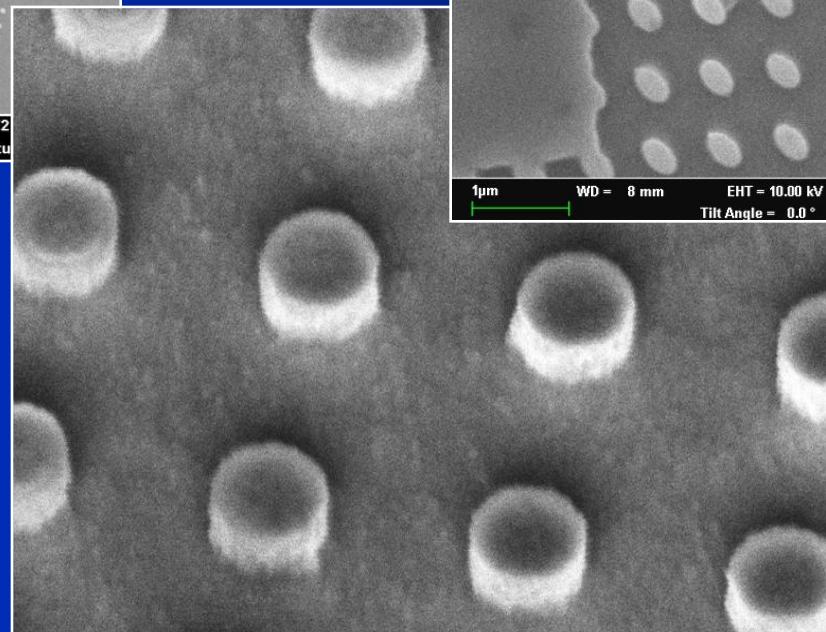
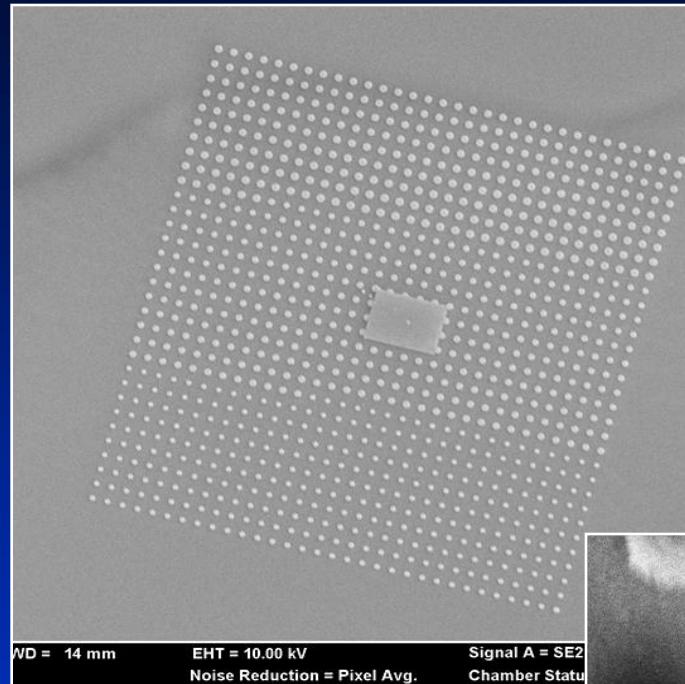
от 20 нм до 1 мкм



— 0.1 мкм

— 1 мкм

# Электронная литография

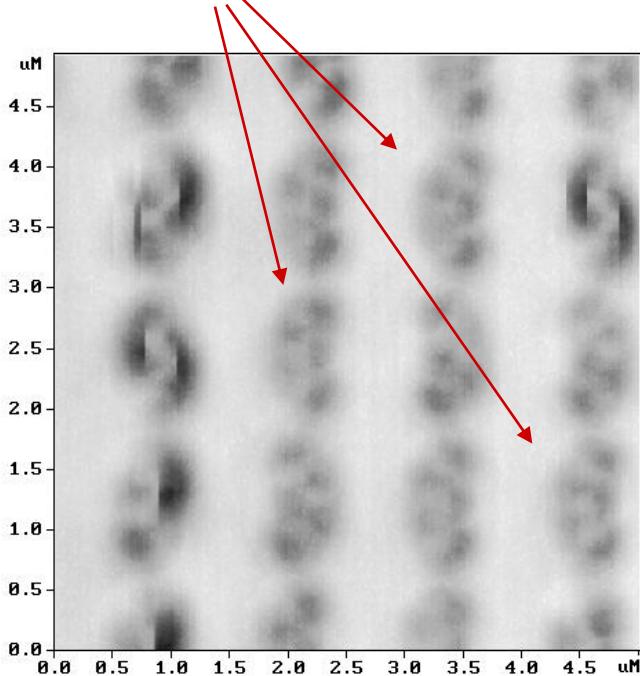


Латеральные размеры:

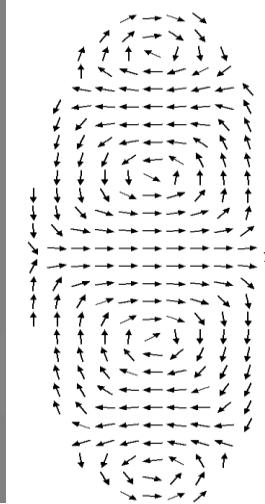
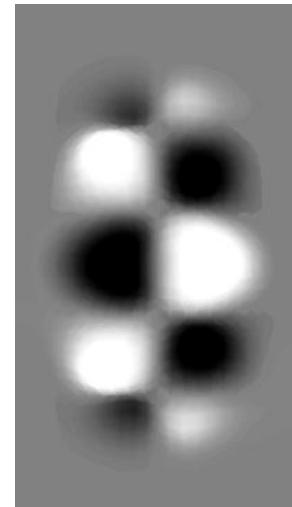
**15 нм - 1 мкм**

# Четырехвихревые состояния в наночастицах Со

4 - vortexes

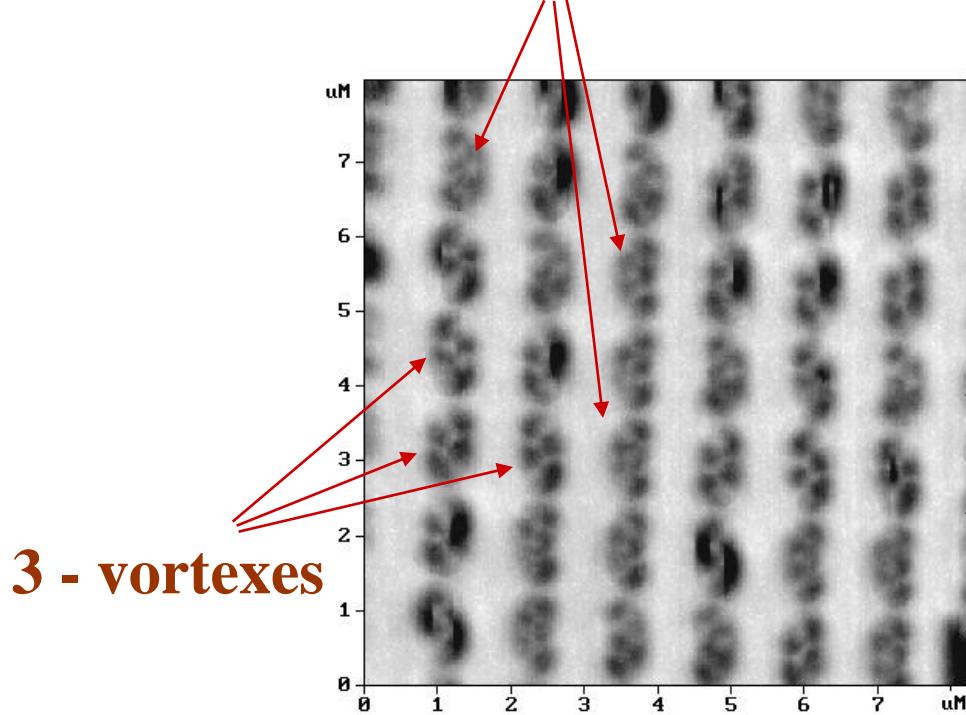


1000    550    35    нм



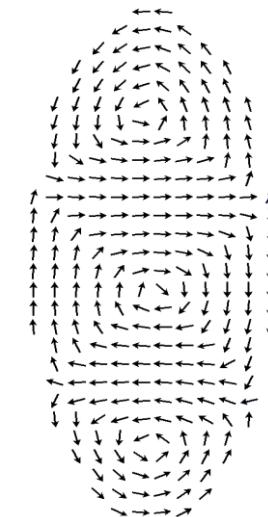
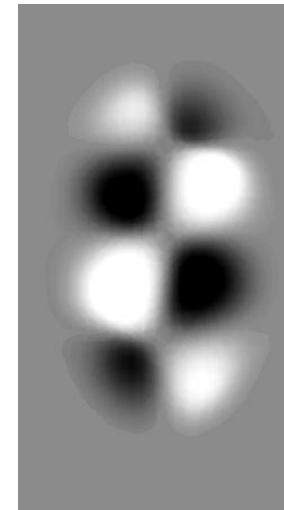
# Трехвихревые состояния в наночастицах Со

4 - vortexes

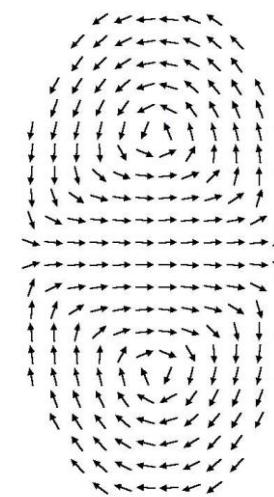
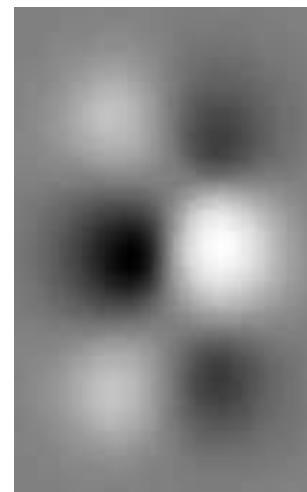
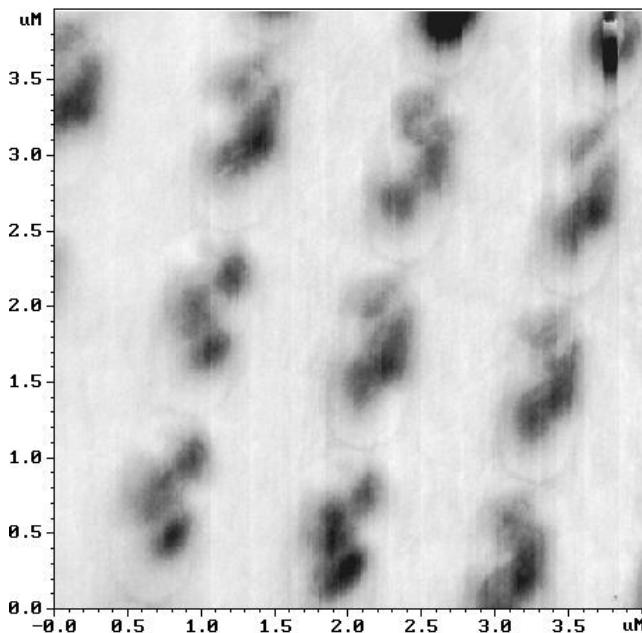


3 - vortexes

900    400    35    нм

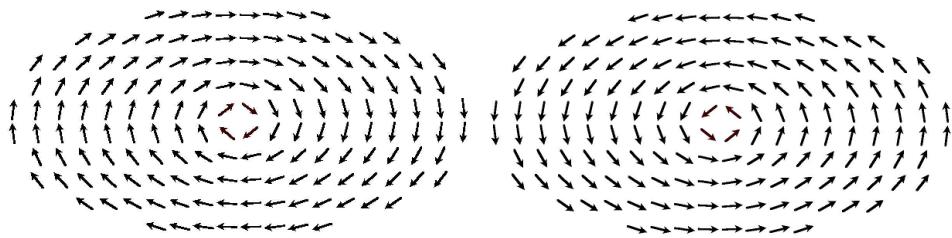
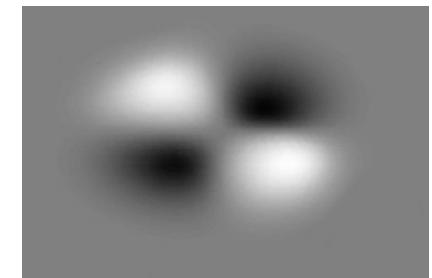
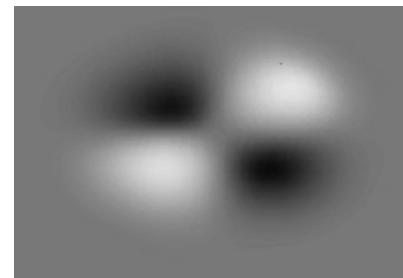
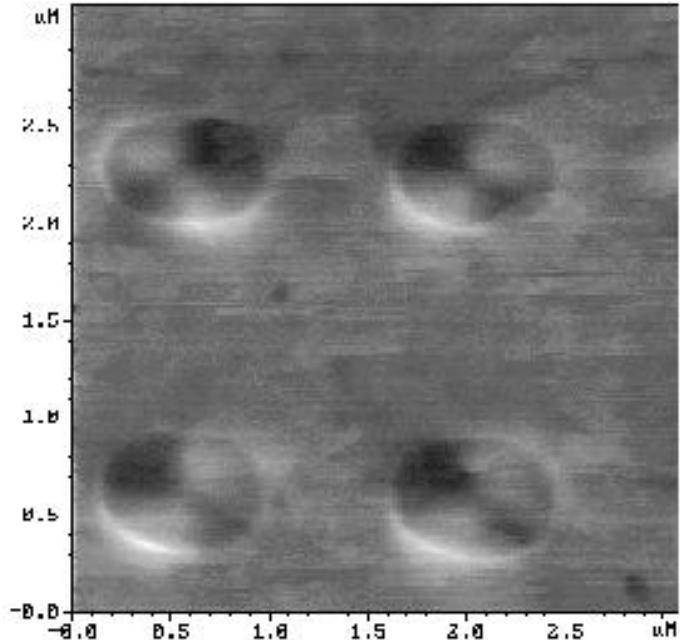


# Двухвихревые состояния в наночастицах Со



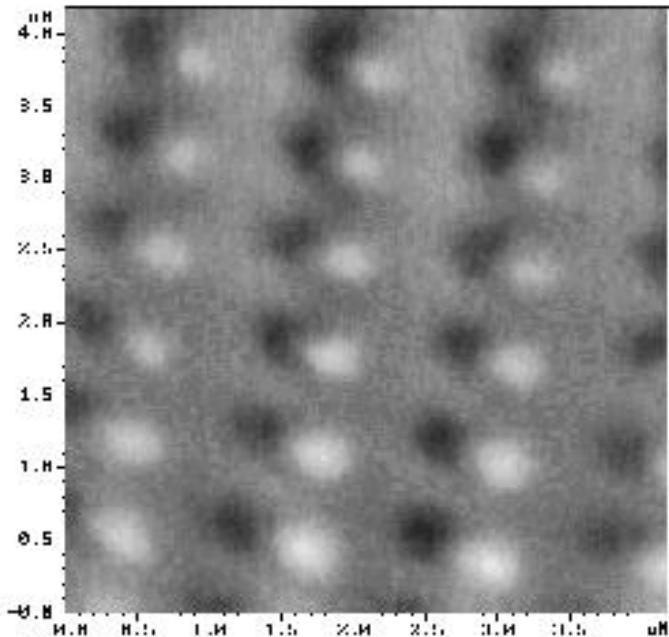
**700    400    35    нм**

# Одновихревые состояния наночастиц Со

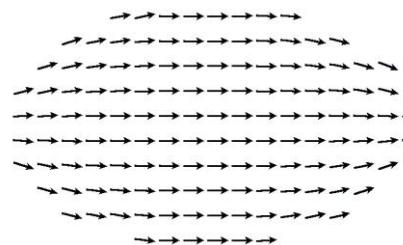
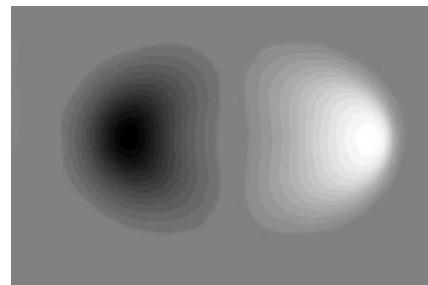


600    400    30    нм

# Состояния с однородной намагниченностью

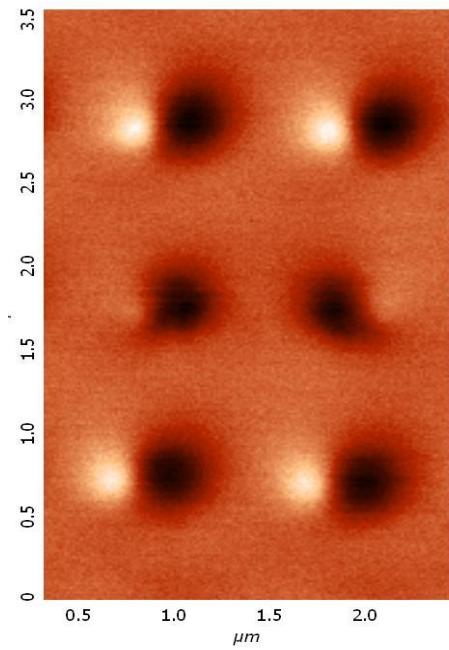
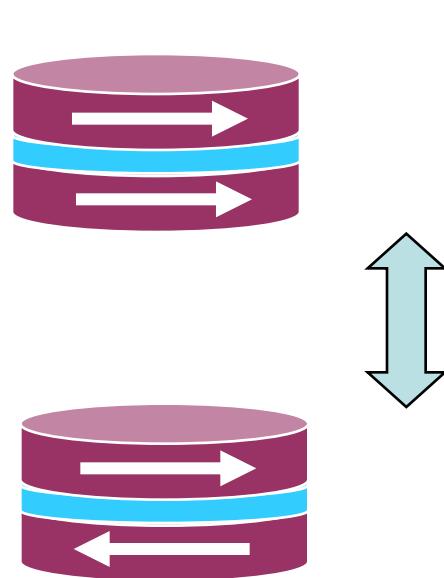
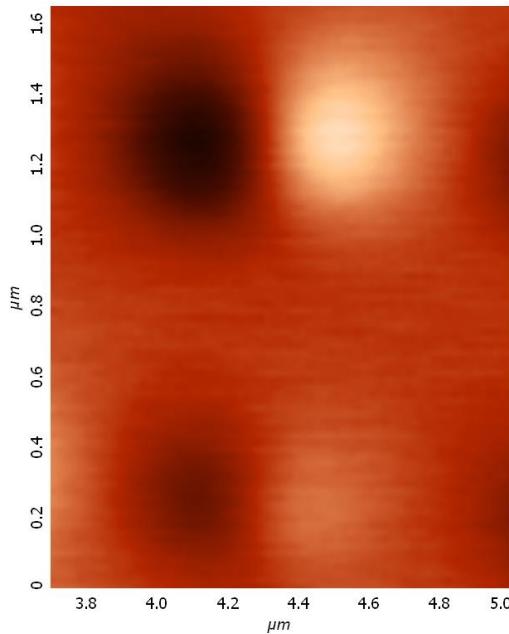


600    400    20    нм

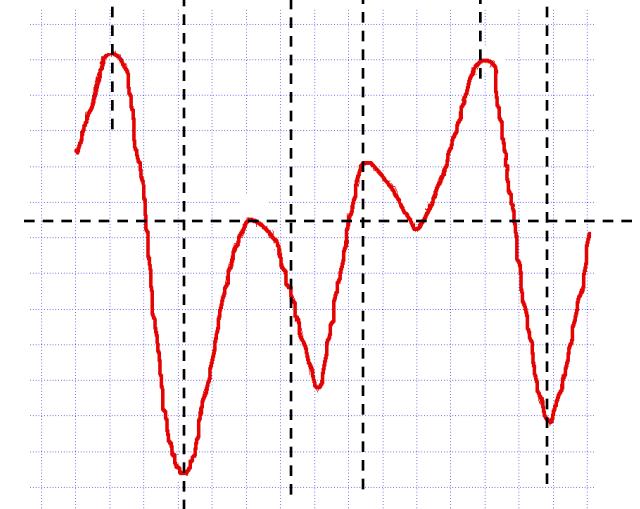
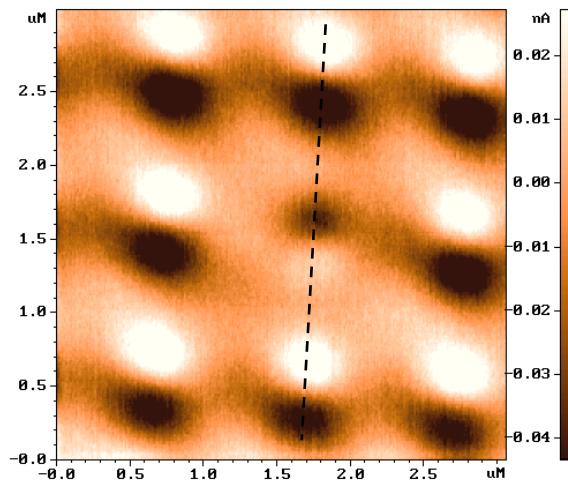
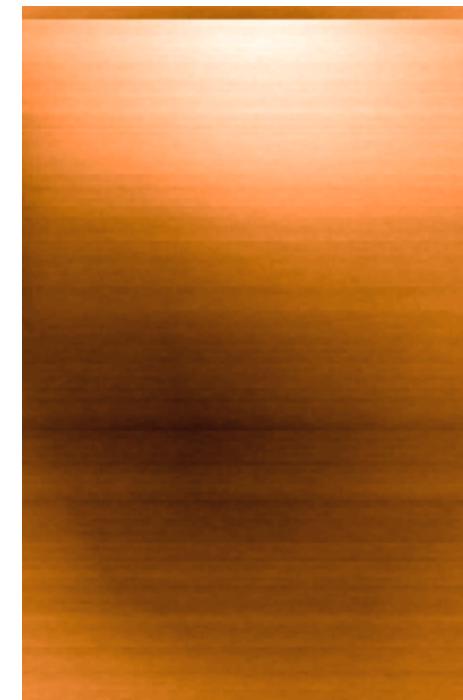
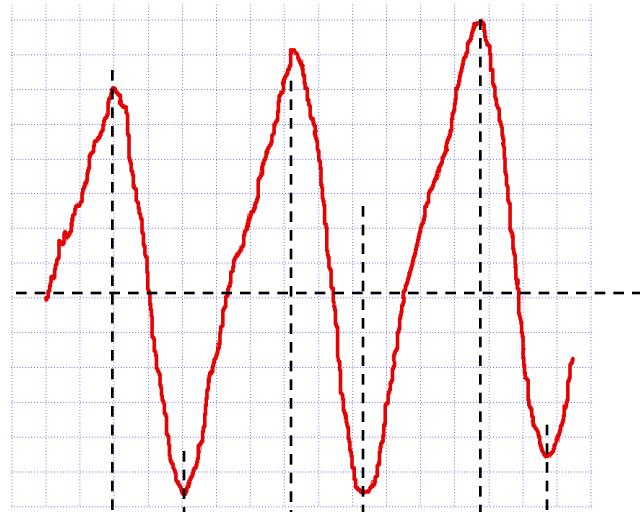
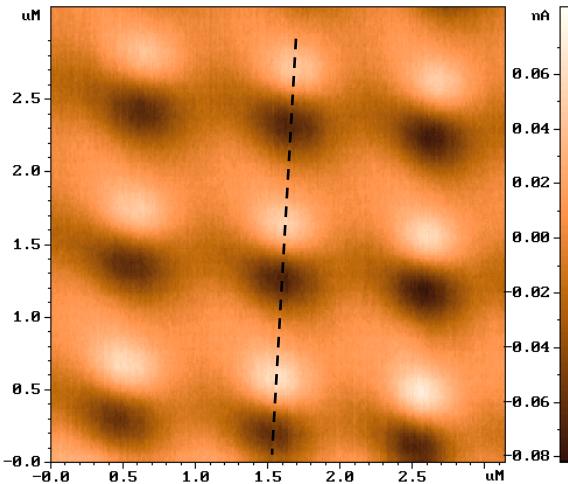


# **Магнитно - силовая микроскопия двухслойных частиц на основе Со**

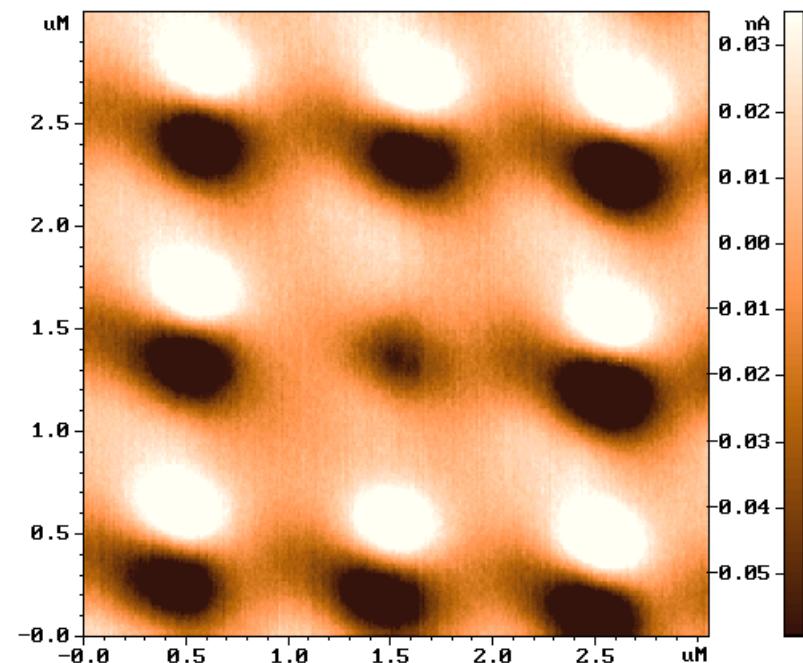
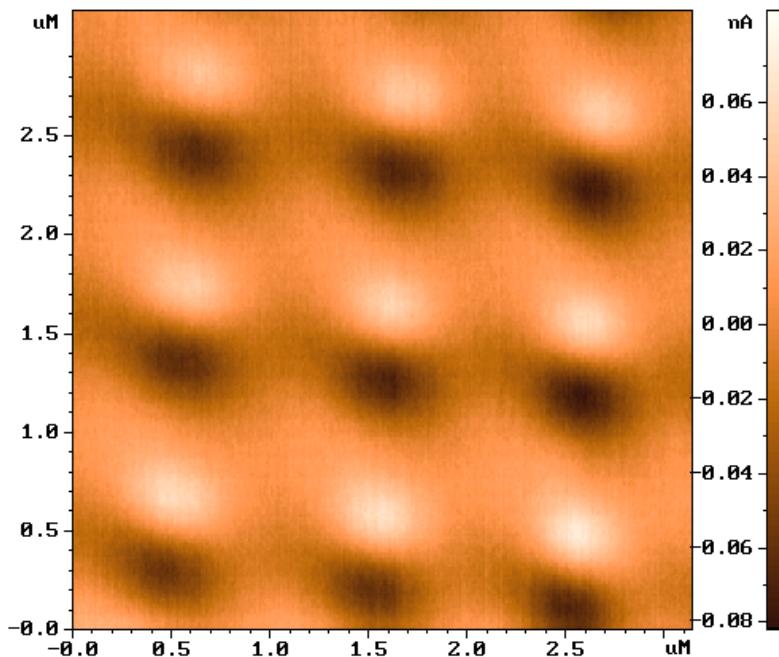
# Двухслойные частицы Со



# МСМ перемагничивание



# Двухслойные частицы Со



14

12

10

$\mu m$

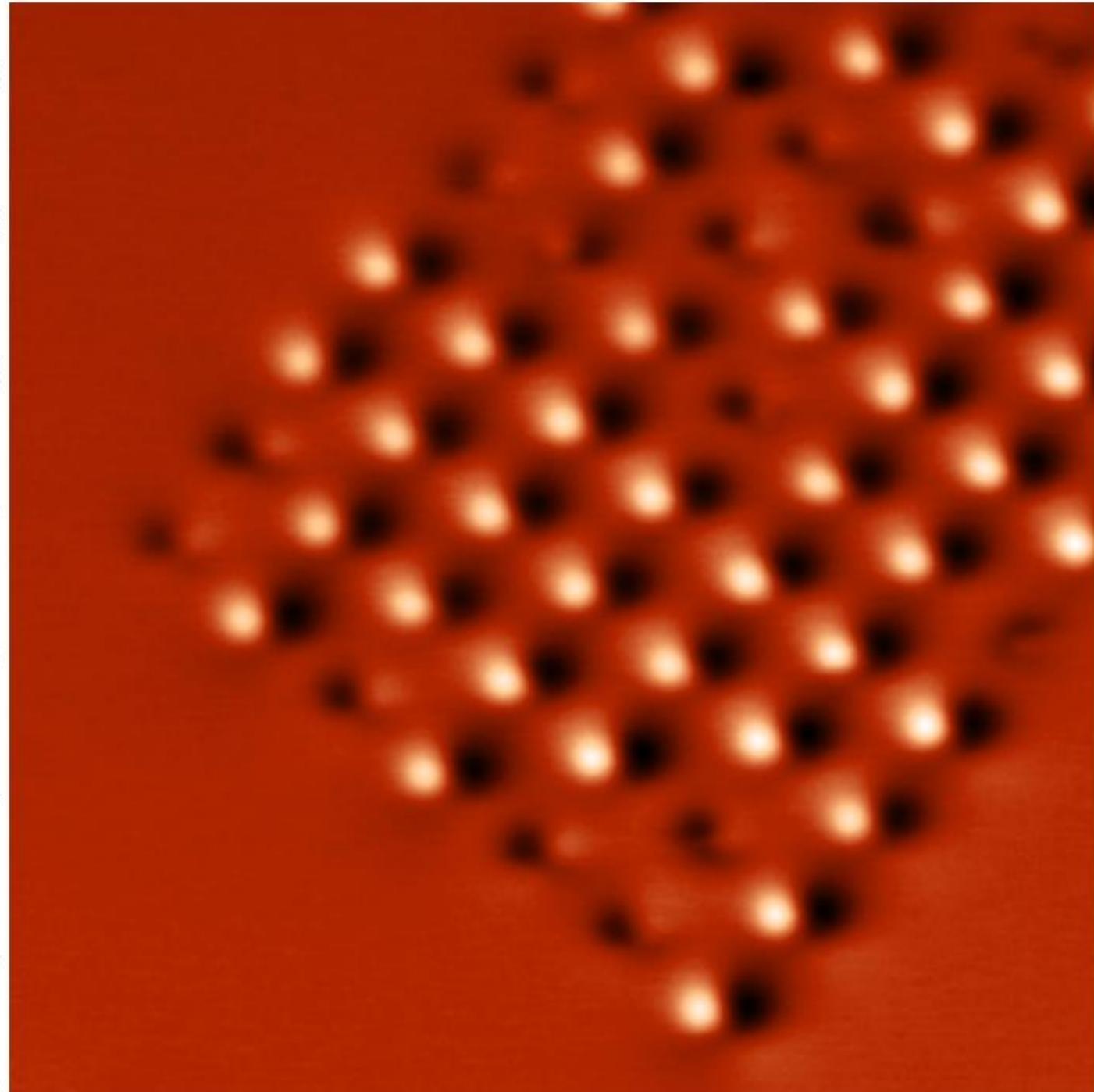
8

6

4

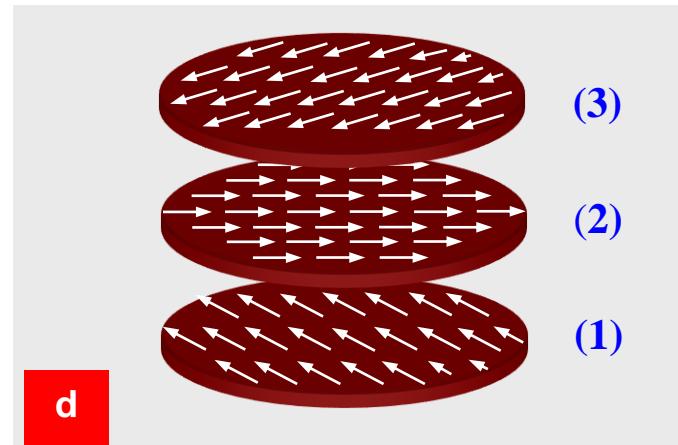
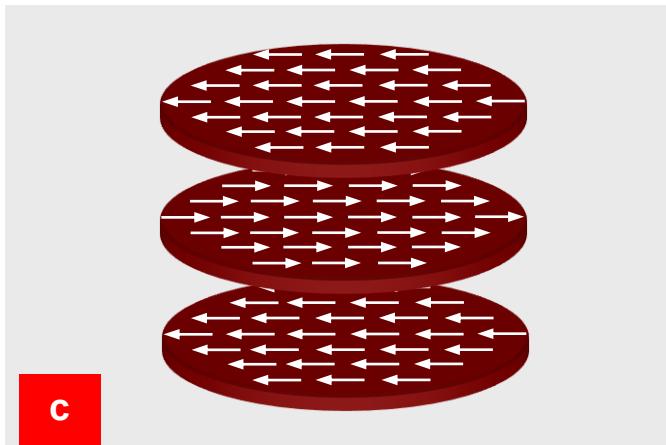
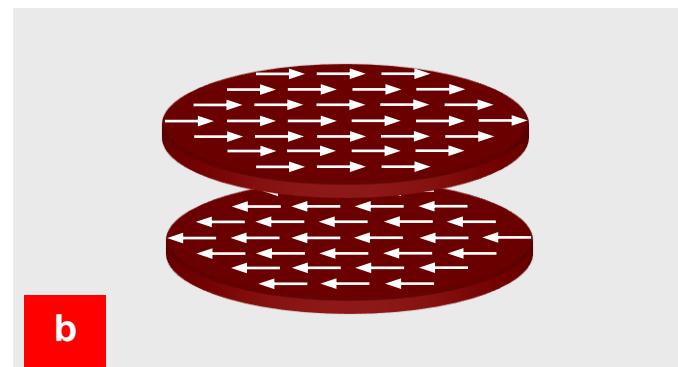
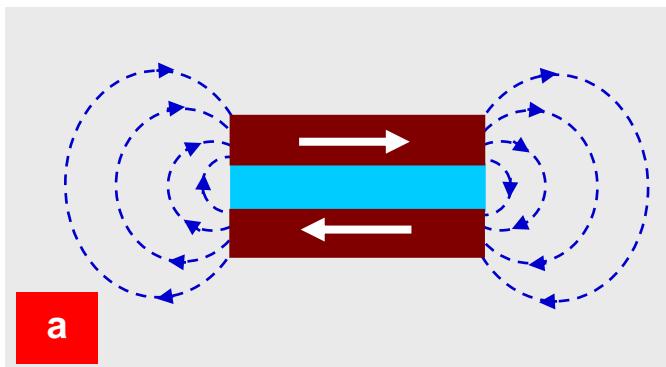
2

0

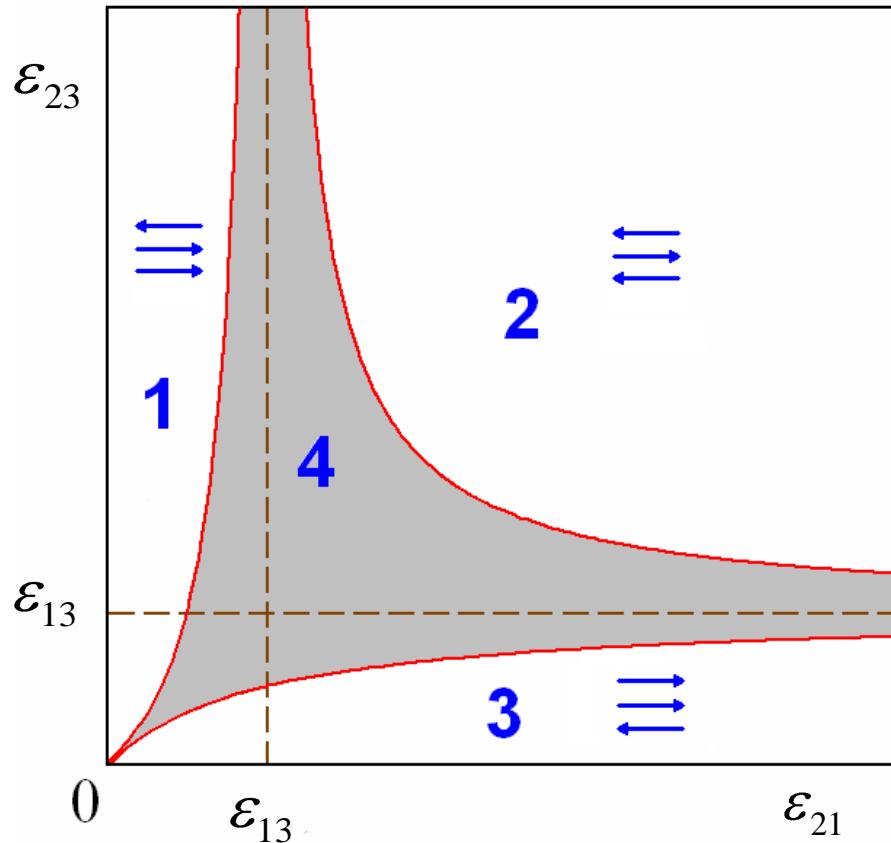


**МСМ исследования  
неколлинеарных  
геликоидальных состояний  
в многослойных  
наномагнитах**

# Магнитостатическое взаимодействие



# Диаграмма состояний

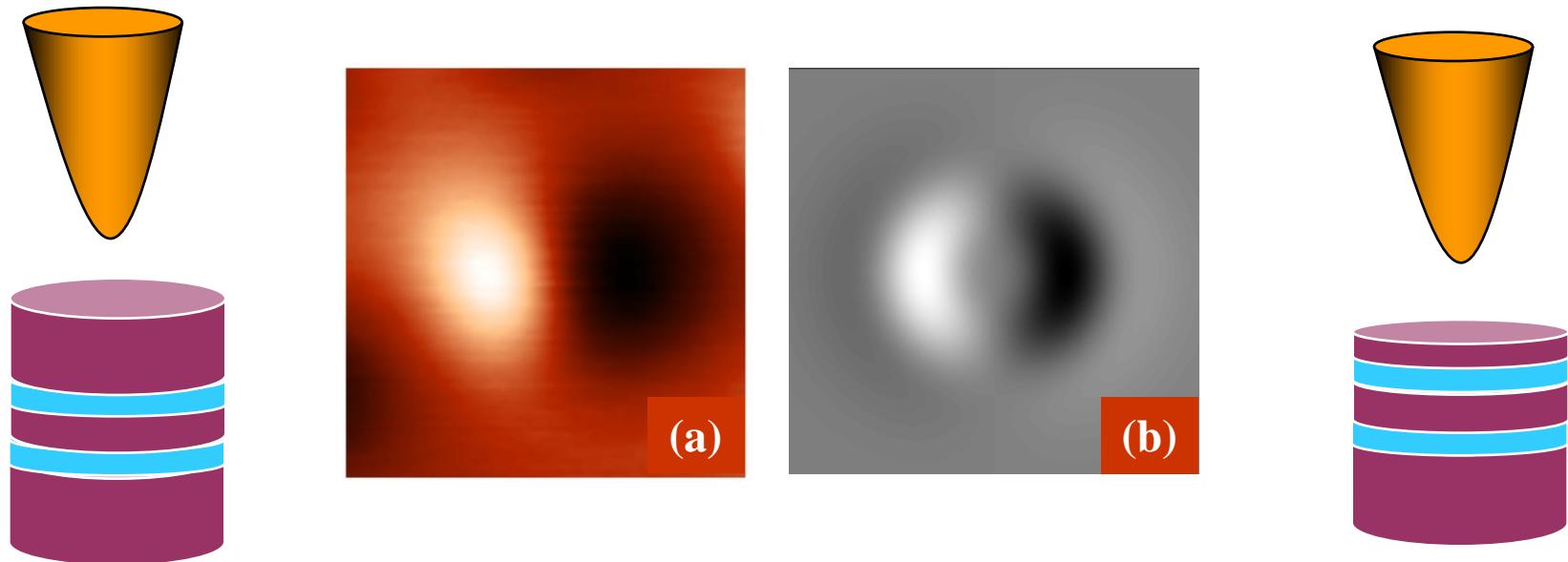


$$E = \varepsilon_{21} \cos \theta_{21} + \varepsilon_{23} \cos \theta_{23} + \varepsilon_{13} \cos \theta_{13}$$

$$\cos \theta_{21} = \frac{\varepsilon_{13}^2 \varepsilon_{23}^2 - \varepsilon_{21}^2 \varepsilon_{23}^2 - \varepsilon_{13}^2 \varepsilon_{21}^2}{2 \varepsilon_{21}^2 \varepsilon_{23} \varepsilon_{13}}$$

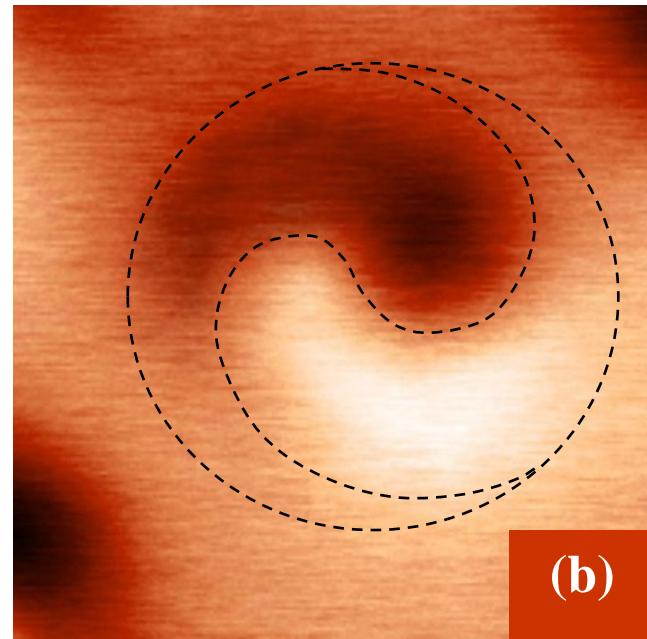
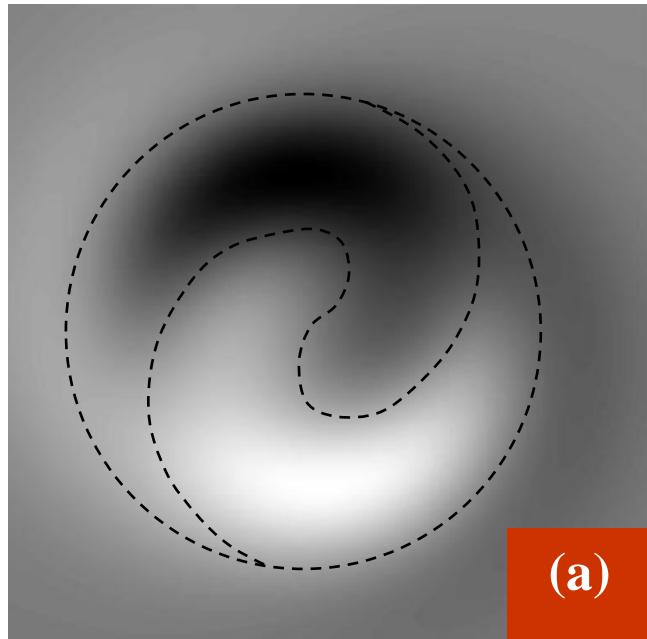
$$\cos \theta_{23} = \frac{\varepsilon_{21}^2 \varepsilon_{13}^2 - \varepsilon_{21}^2 \varepsilon_{23}^2 - \varepsilon_{13}^2 \varepsilon_{23}^2}{2 \varepsilon_{21} \varepsilon_{23}^2 \varepsilon_{13}}$$

# Оптимизация структур для МСМ измерений



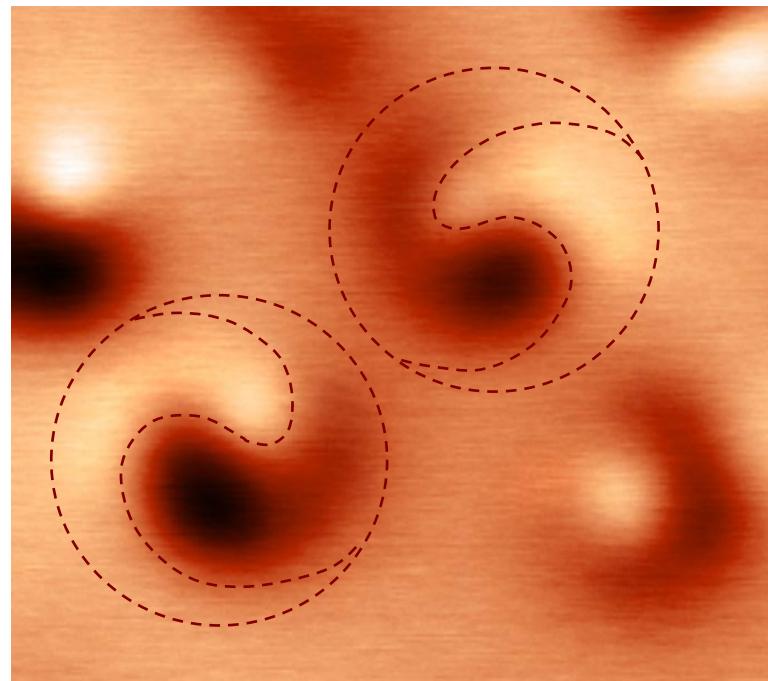
Слои Со - 16, 11, 8 нм  
Прослойка Si - 3 нм  
Диаметр - 300 нм

# Регистрация спирального распределения МСМ контраста



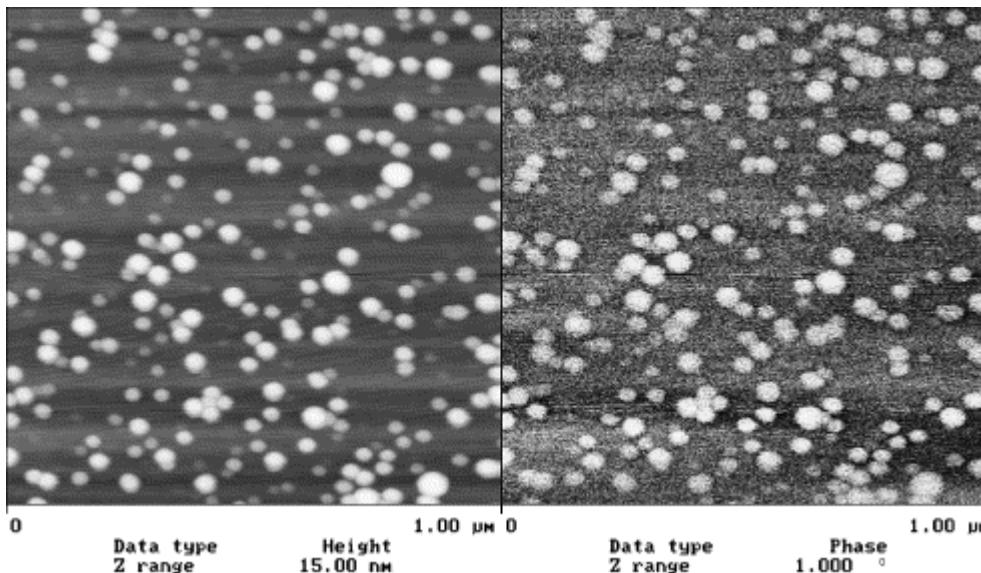
$$\theta_{21} = 109^\circ \quad \theta_{23} = 257^\circ$$

# Правая и левая ориентация геликоидальных состояний



# **Магнитно-силовая микроскопия слабокоэрцитивных наночастиц**

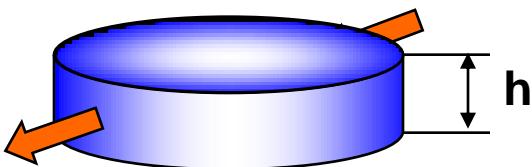
# МСМ нанокластеров Co



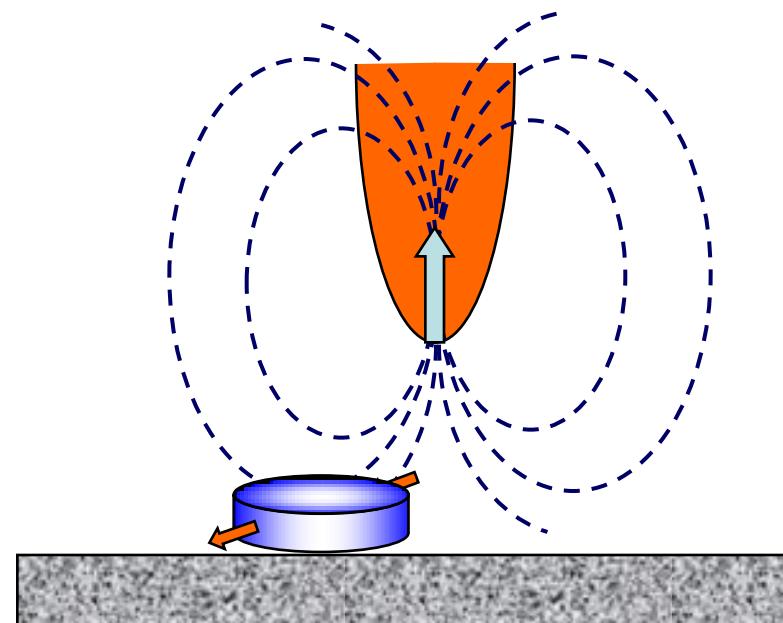
S. A. Koch , R. H. te Velde , G. Palasantzas, J. Th. M. De Hosson  
**Appl. Surf. Science, 226, 185 (2004).**  
**Appl. Phys. Lett., 84(4), 556 (2004).**

# Моделирование МСМ контраста

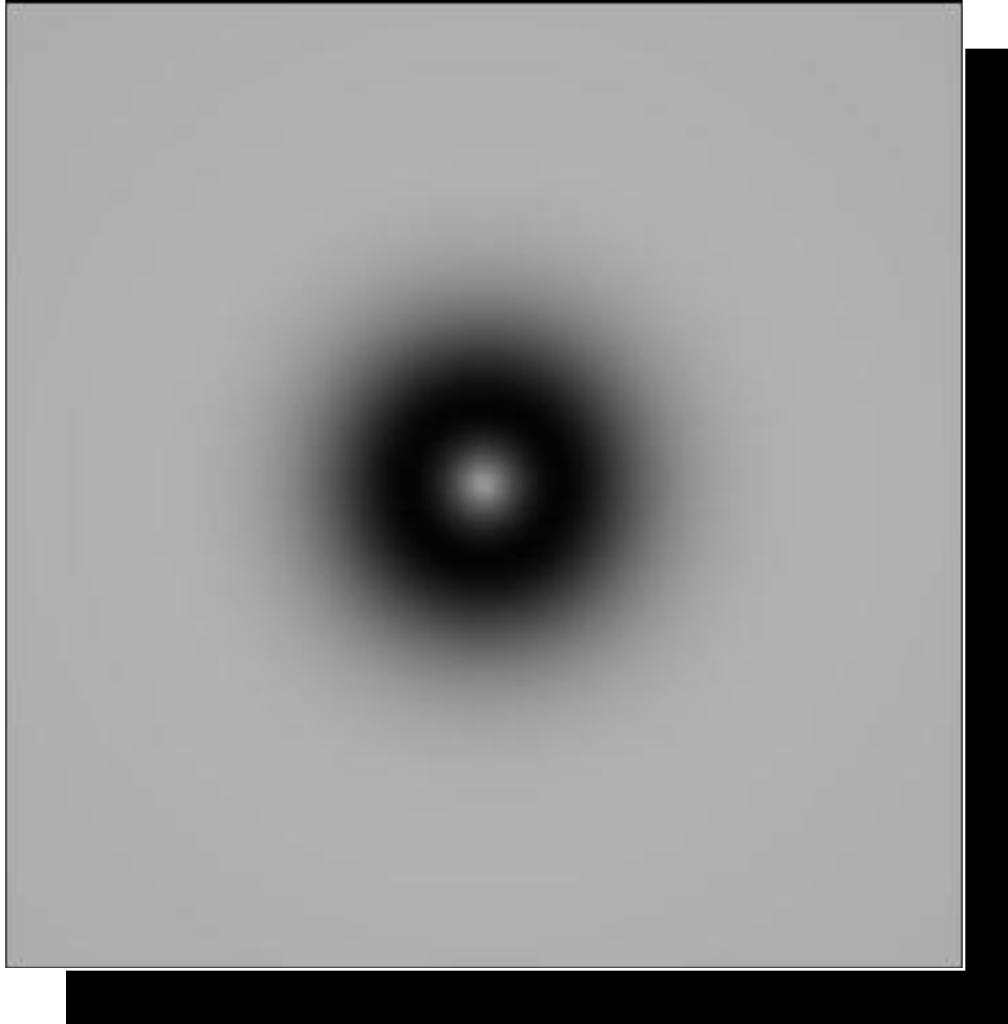
Низкоэрцитивные  
частицы



$$h \ll d < 100 \text{ nm}$$

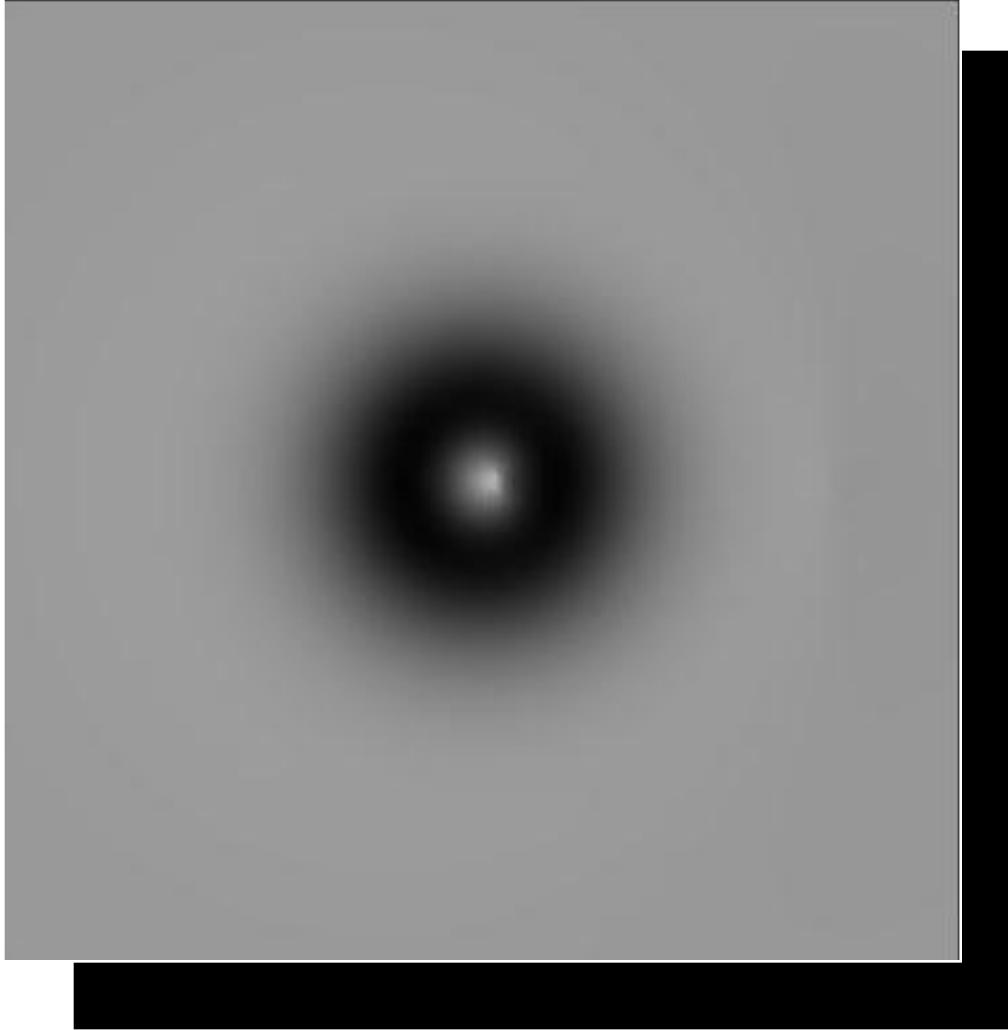


# Плоская частица во внешнем поле



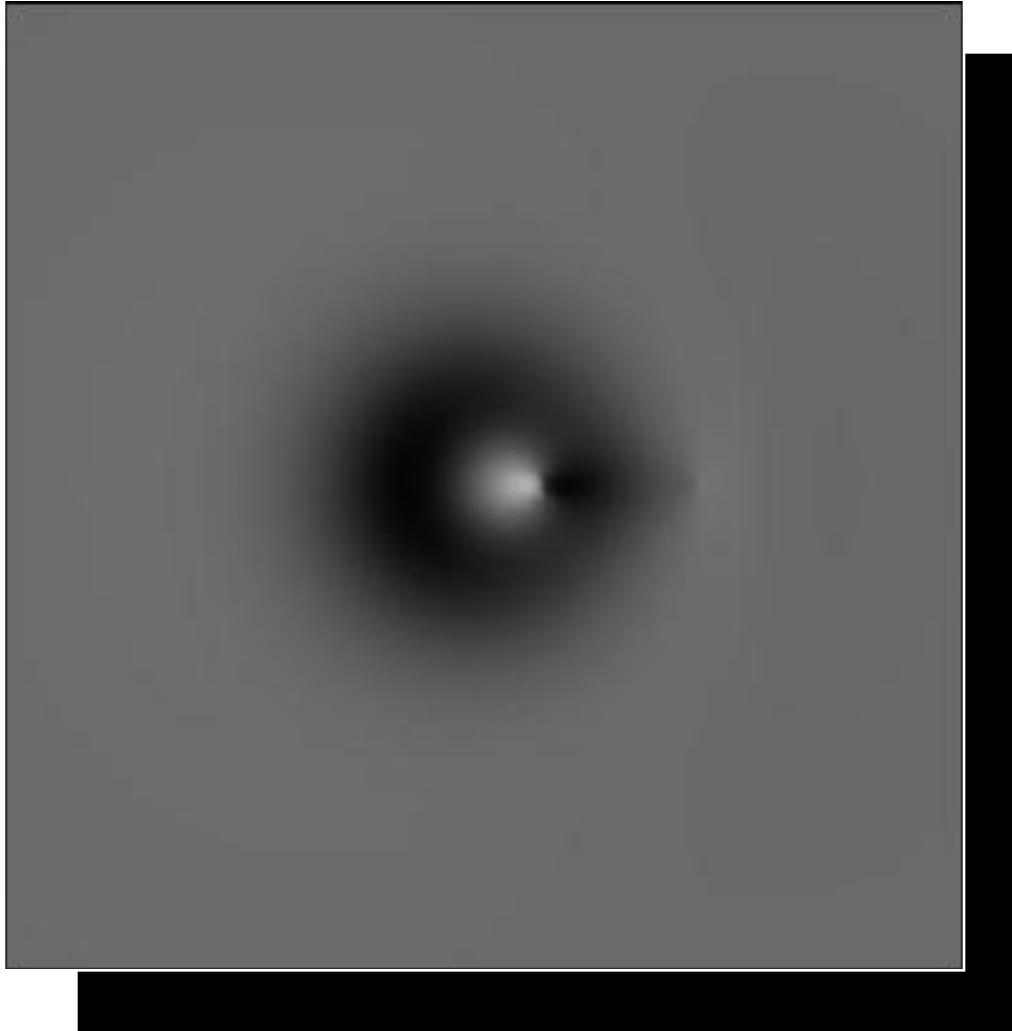
# Плоская частица во внешнем поле

$\vec{H}$



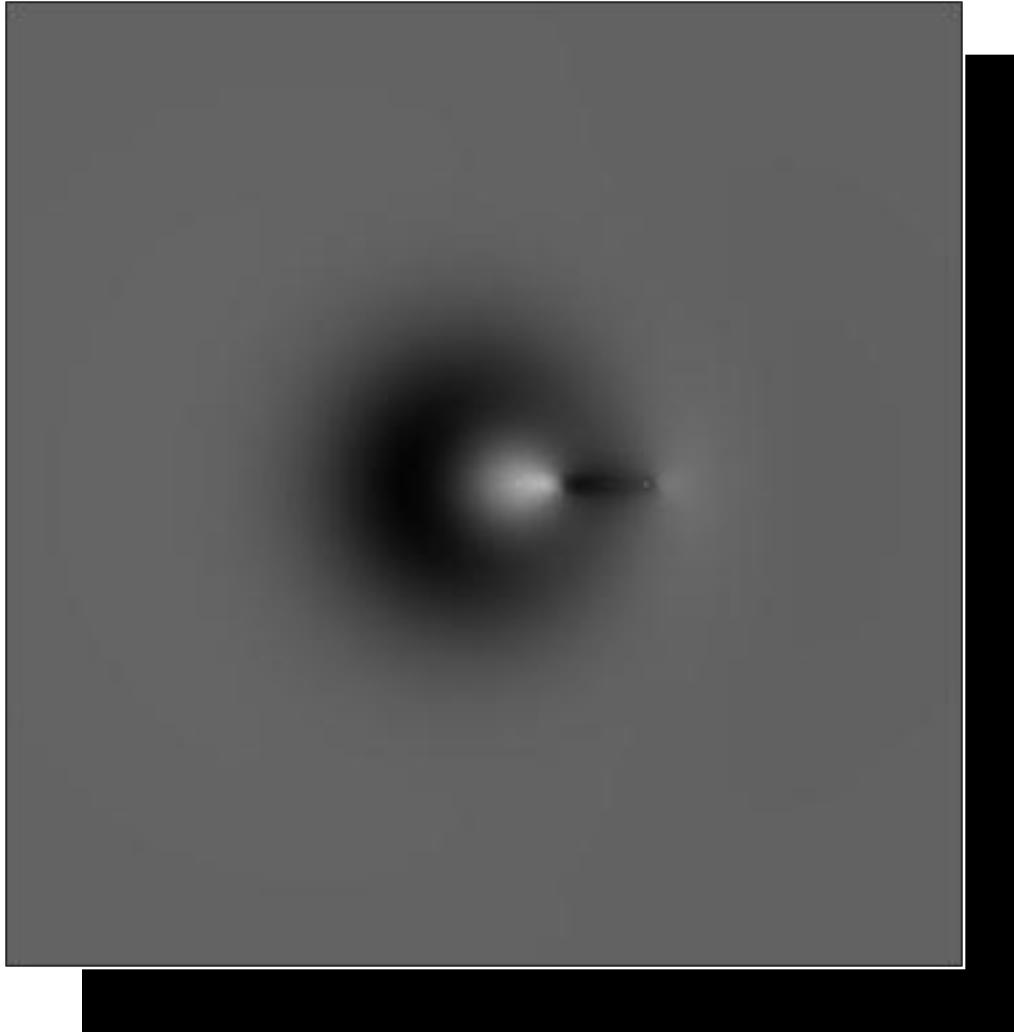
# Плоская частица во внешнем поле

$$\vec{H}$$



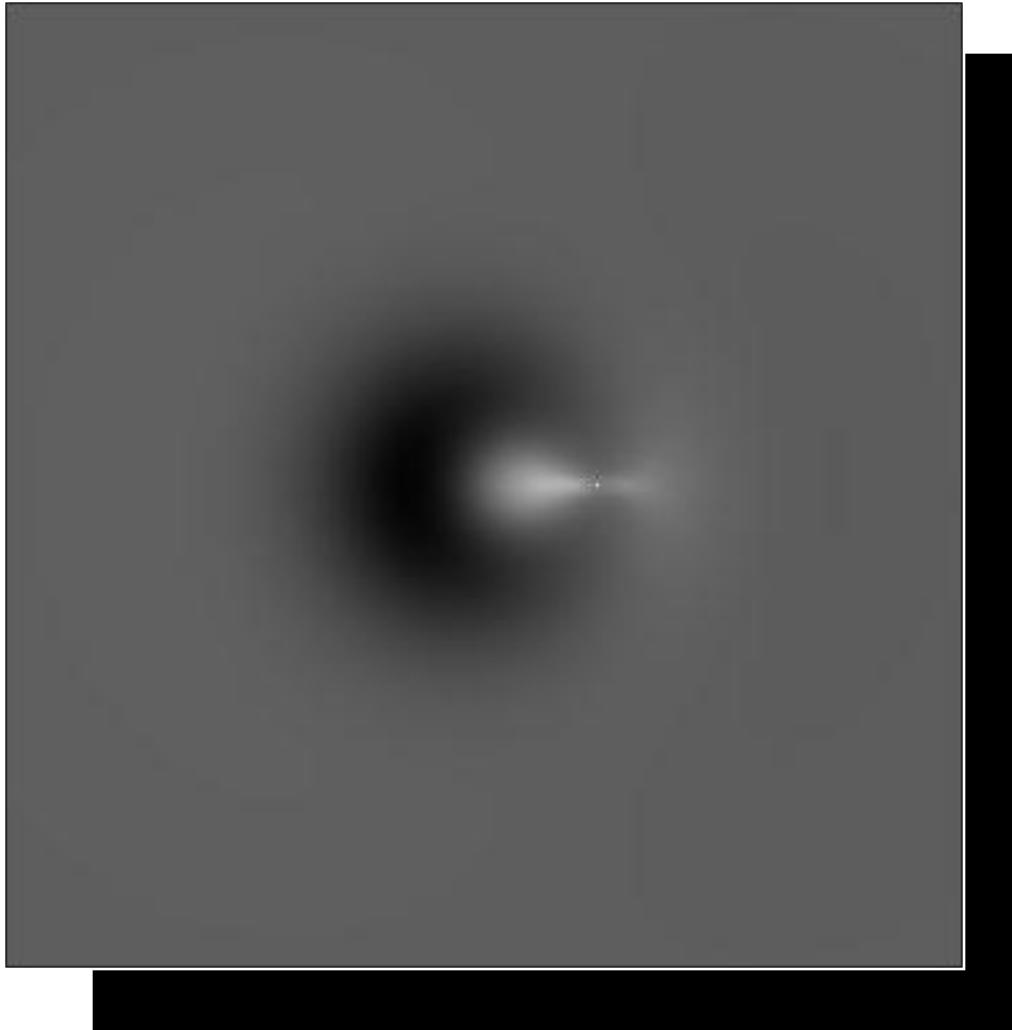
# Плоская частица во внешнем поле

$$\vec{H}$$



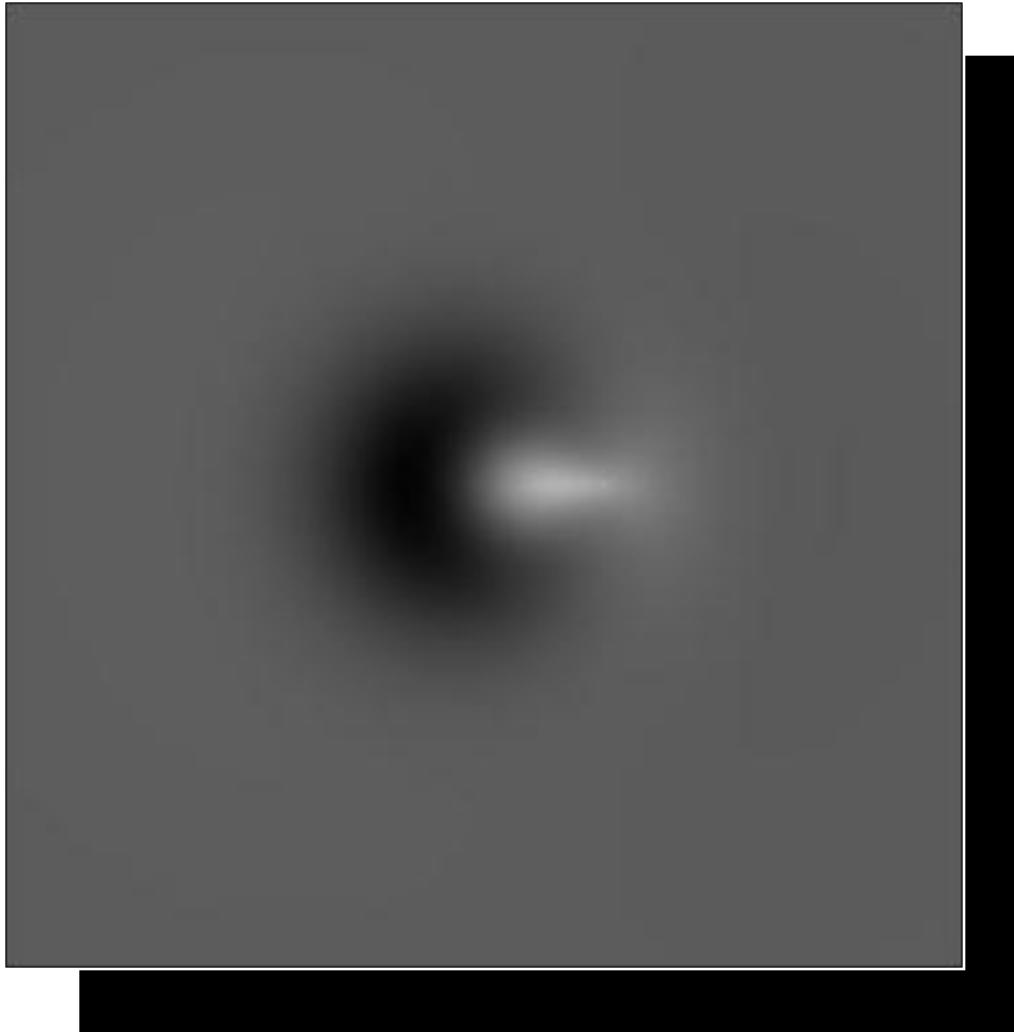
# Плоская частица во внешнем поле

$\vec{H}$



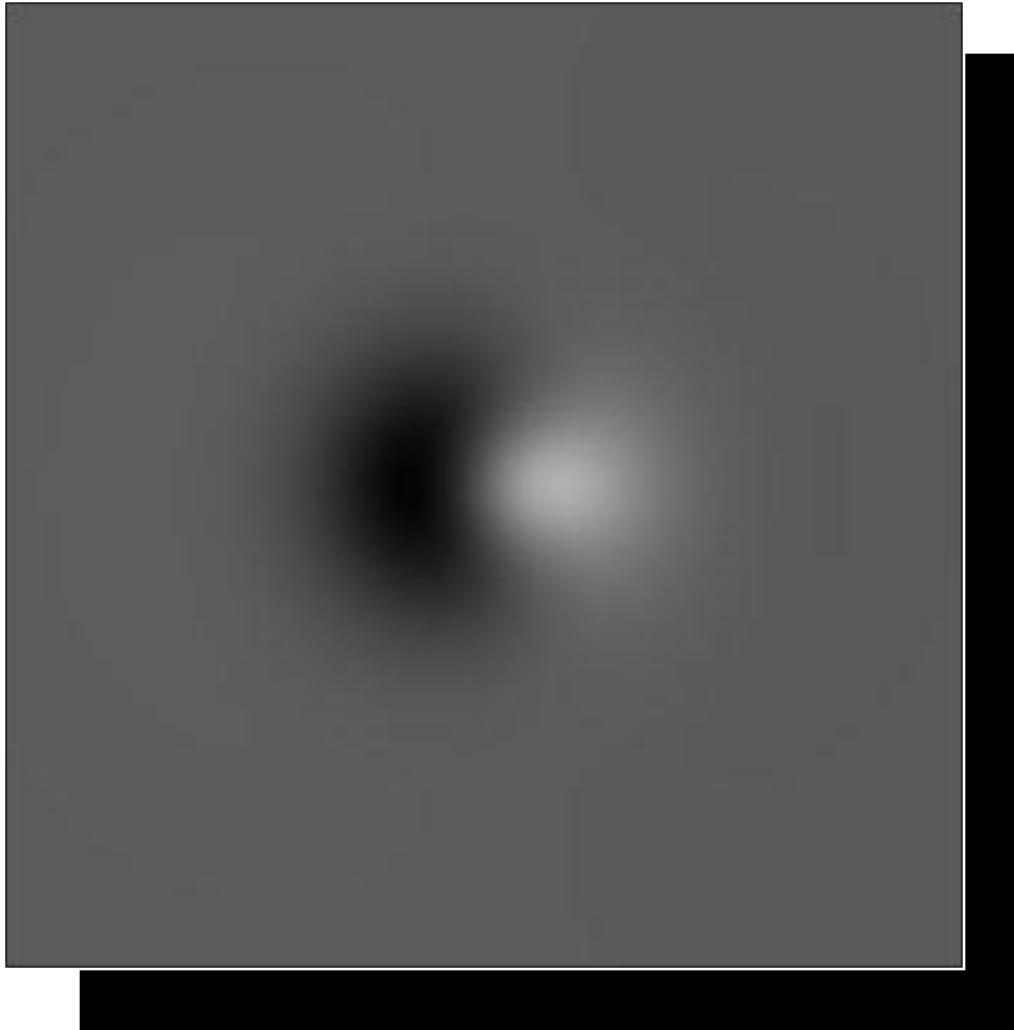
# Плоская частица во внешнем поле

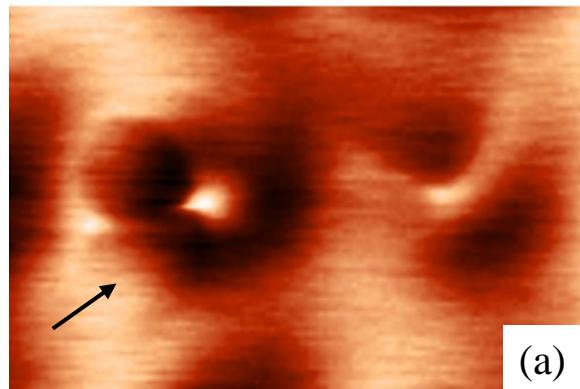
$$\vec{H}$$



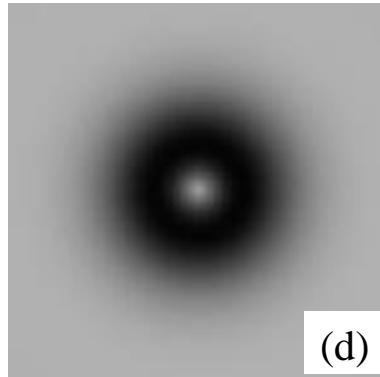
# Плоская частица во внешнем поле

$$\vec{H}$$

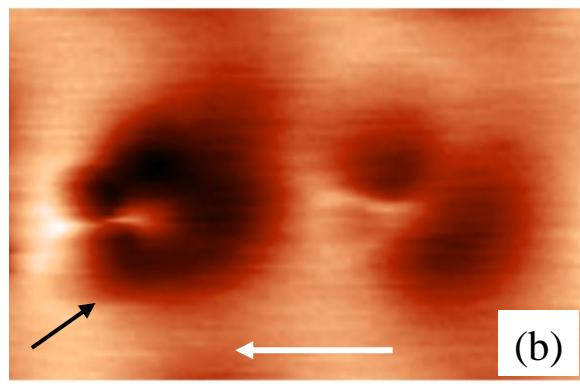




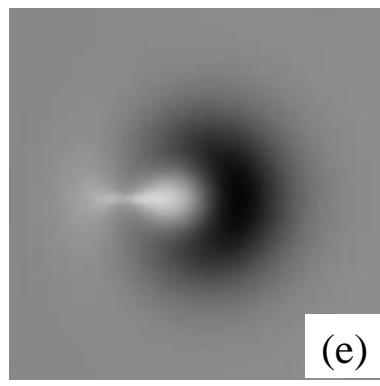
(a)



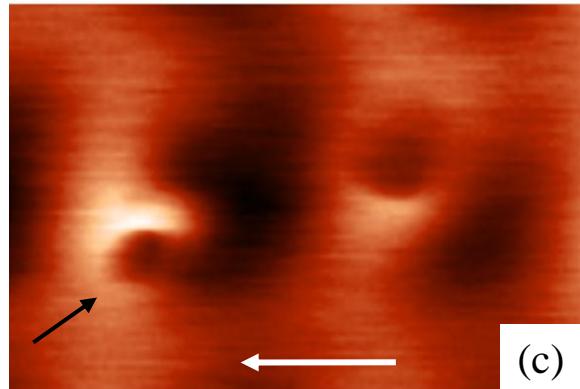
(d)



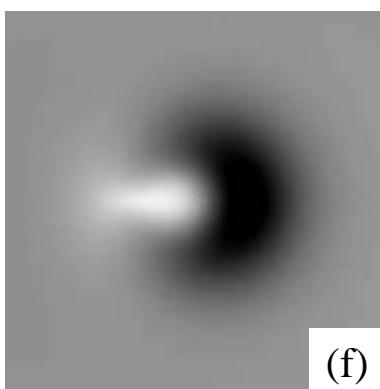
(b)



(e)



(c)



(f)

Частицы Со  
диаметр 50 нм  
толщина 20 нм

# **Заключение**

- 1. МСМ вихревых состояний в наночастицах.**
- 2. Эффекты перемагничивания частиц зондом МСМ.**
- 3. МСМ многослойных частиц на основе Со.**
- 4. МСМ слабокоэрцитивных наночастиц.**

# *Acknowledgements*

