

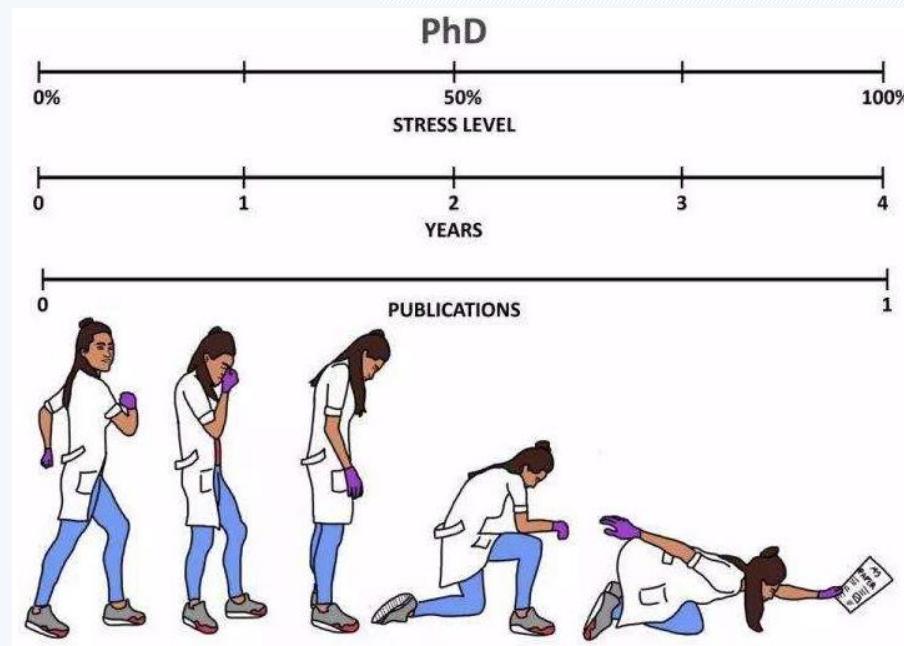
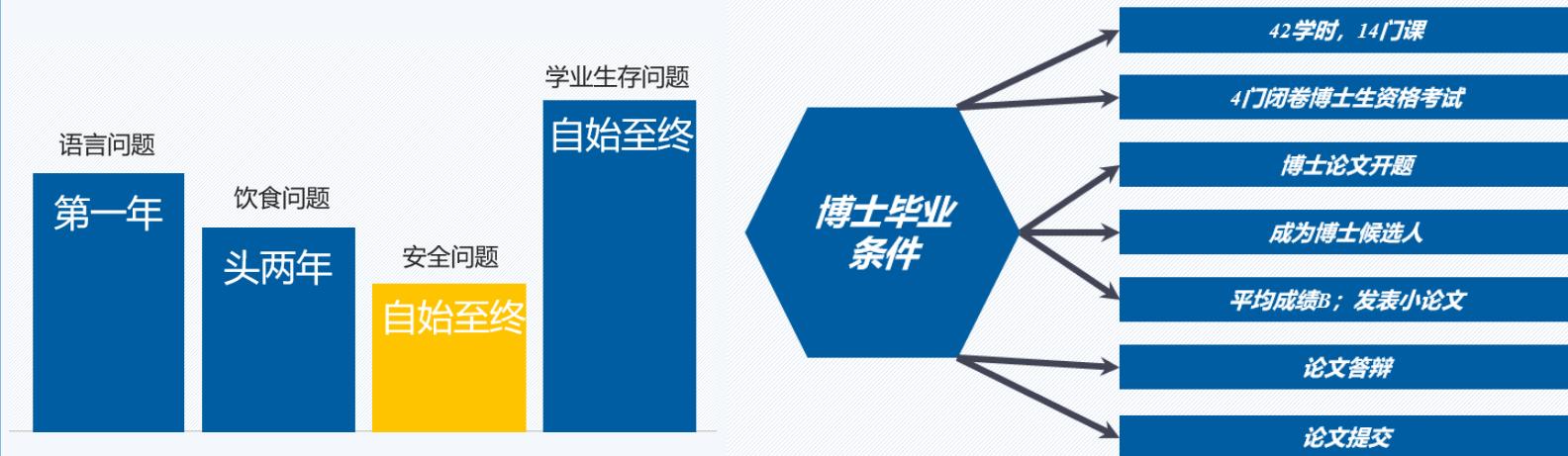
# 从“0”到“1”：研究 生道路上的劈荆斩棘

极端环境粉末冶金材料研究所

唐思危

2020年7月9日

# 研究“僧”



# 制备具有磁斯格明子相的MnSi、FeGe纳米线

如何制备？



纳米线的特殊性能？

什么是磁斯格明子？

有什么应用？

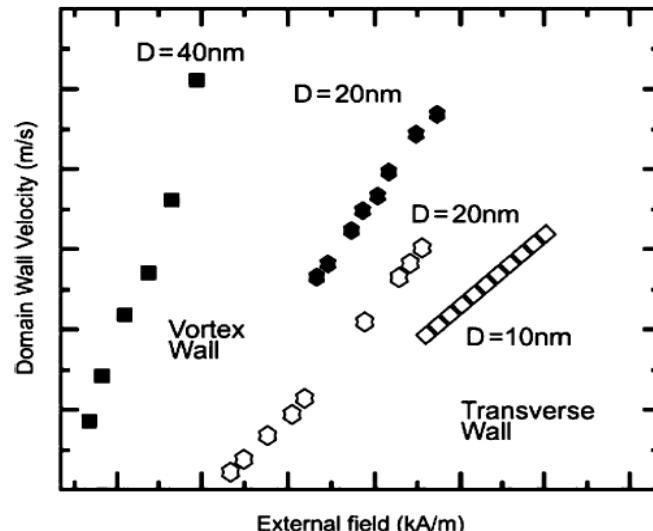
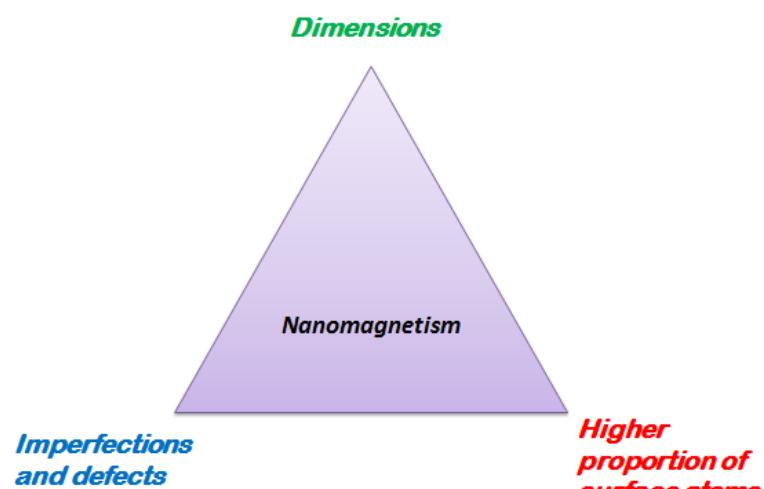
MnSi，FeGe材料特性？

## 不懂导师给的课题的时候应该怎么办？一文献调研

The screenshot shows the Web of Science search interface. At the top, there are links for Web of Science, InCites, Journal Citation Reports, Essential Science Indicators, EndNote, Publons, Kopernio, and Master Journal List. On the right, there are links for 登录 (Login), 帮助 (Help), and 简体中文 (Simplified Chinese). The main title "Web of Science" is at the top left. Below it, there's a "选择数据库" dropdown set to "所有数据库". The search bar contains the term "skyrmion". To the right of the search bar are buttons for "工具" (Tools), "检索和跟踪" (Search and Track), "检索历史" (Search History), and "标记结果列表" (Marked Result List). The Clarivate Analytics logo is in the top right corner. Below the search bar, there are tabs for "基本检索" (Basic Search), "被引参考文献检索" (Cited Reference Search), and "高级检索" (Advanced Search). The "基本检索" tab is selected. The search results page is visible below the search bar.

1. 看近期综述
2. 看高质量期刊的 introduction
3. 搜专家学术报告PPT
4. 找名校学位论文
5. 找领域专家专著

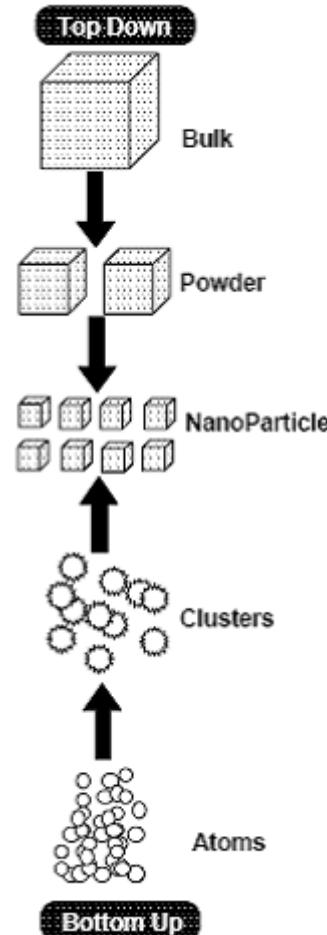
# 文献调研—磁性纳米线的特性？（相关书籍）



Symbol	Length	Typical scale (nm)
$d_a$	铁原子间距离	$2.5 \times 10^{-1}$
$d_{ex}$	交换相互作用范围	$\sim 10^{-1} - \sim 1$
$d_{RKKY}$	RKKY作用范围	$\sim 10^{-1} - \sim 10$
$d_c$	磁畴尺寸	$10 - 10^4$
$D_{cr}^{spm}$	超顺磁临界直径	$\sim 1 - \sim 10^2$
$D_{cr}$	单个磁畴尺寸	$\sim 10 - \sim 10^3$
$\delta_0$	磁畴壁宽度	$\sim 1 - \sim 10^2$
$l_{ex}$	交互长度	$\sim 1 - \sim 10^2$
$\zeta$	超导相干长度	$\sim 1 - \sim 10^3$

1. Teruya Shinjo, *Nanomagnetism and Spintronics*, Elsevier, 2014
2. Alberto P. Guimar˜aes, *Principles of Nanomagnetism*, Springer, 2009
3. D.L. Mills, J.A.C. Bland, *Nanomagnetism*, Elsevier, 2006
4. Farzad Nasirpour, Alain Nogaret, *Nanomagnetism and Spintronics*, World Scientific, 2009

## 纳米线的气-固相生长



Nanowire growth principle in vapor-solid method:  
it is commonly accepted two dimensional nucleation probability on the surface of whisker is:

$$P_N = B \exp\left(-\frac{\pi \sigma^2}{k^2 T^2 \ln \alpha}\right)$$

B-constant

$\sigma$ -surface energy of a solid whisker

k-Boltzmann constant

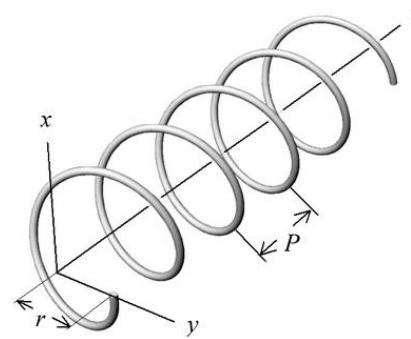
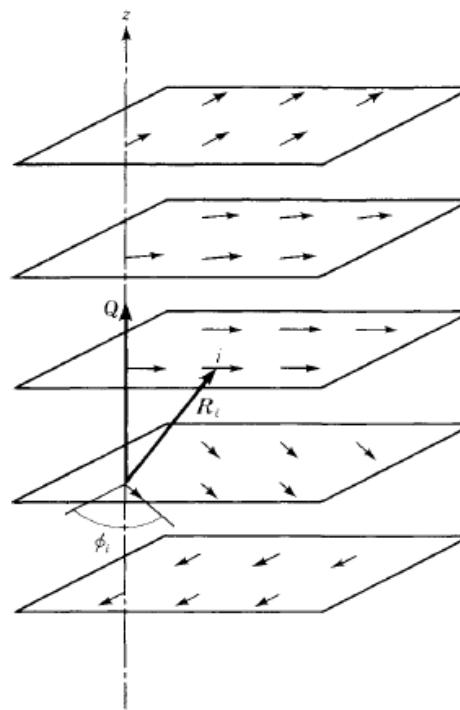
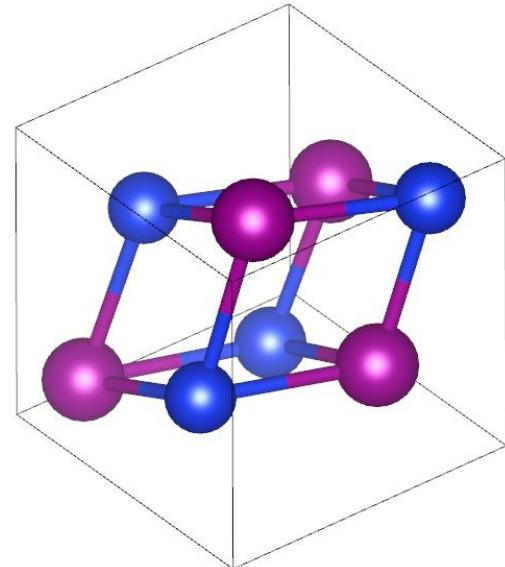
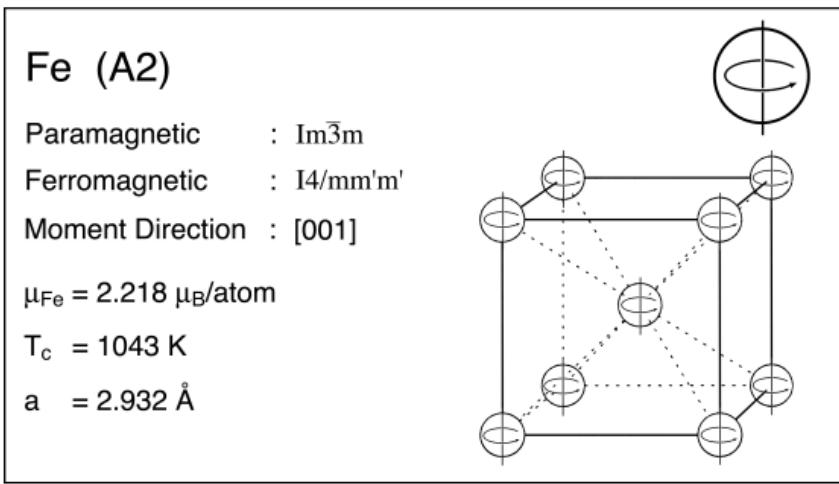
T-absolute temperature

$\alpha$ -supersaturation ratio ( $p/p_0$ ) where  $p$  is actual vapor pressure and  $p_0$  is equilibrium vapor pressure corresponding to T

$$\alpha_{powder}^{3D \text{ growth}} > \alpha_{thin \text{ film}}^{2D \text{ growth}} > \alpha_{nanowire}^{1D \text{ growth}}$$

Younan Xia, Peidong Yang, Yugang Sun, Yiyi Wu, Brian Mayers, Byron Gates, Yadong Yin, Franklin Kim and Haoquan Yan, One-Dimensional Nanostructures: Synthesis, Characterization and Application, Advanced Materials, 15(5), 2003:353-389 (8834)

## 非中心对称的B20晶体结构



Landau-Ginzburg free energy for non-centrosymmetric magnets (B20 structure):

$$\bullet F(\mathbf{r}) = \frac{1}{2}A(S_x^2 + S_y^2 + S_z^2) + \mathbf{b} \cdot \mathbf{S} \cdot (\nabla \times \mathbf{S}) + \frac{1}{2}B_1 [(\nabla S_x)^2 + (\nabla S_y)^2 + (\nabla S_z)^2] + \frac{1}{2}B_2 \left[ \left( \frac{\partial S_x}{\partial x} \right)^2 + \left( \frac{\partial S_y}{\partial y} \right)^2 + \left( \frac{\partial S_z}{\partial z} \right)^2 \right] + C(S_x^2 + S_y^2 + S_z^2)^2 + D(S_x^4 + S_y^4 + S_z^4)$$

Exchange interaction coupling term

Near  $T_c$ , free energy is minimized by periodic structures

$$S(r) = \frac{1}{\sqrt{2}} [S_k \exp(i\mathbf{k} \cdot \mathbf{r}) + S_k^* \exp(-i\mathbf{k} \cdot \mathbf{r})]$$

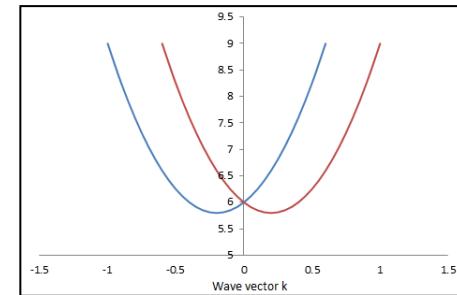
$$F(k) = \frac{1}{2}A|S_k|^2 + i\mathbf{b} \cdot (S_k \times S_k^*) + \frac{1}{2}B_1 k^2 |S_k|^2 + \frac{1}{2}B_2 (k_x^2 |S_{kx}|^2 + k_y^2 |S_{ky}|^2 + k_z^2 |S_{kz}|^2)$$

$$F(r) = \frac{1}{2}A|S_k|^2 + 2\mathbf{b} \cdot (\alpha_k \beta_k \sin(\alpha_k \cdot \beta_k)) \cos(k \cdot (\alpha_k \times \beta_k)) + \dots$$

$$F(r) = \frac{1}{2}A|S_k|^2 + i\mathbf{b} \cdot (S_k \times S_k^*) + \frac{1}{2}B_1 k^2 |S_k|^2 + \frac{1}{2}B_2 (k_x^2 |S_{kx}|^2 + k_y^2 |S_{ky}|^2 + k_z^2 |S_{kz}|^2)$$

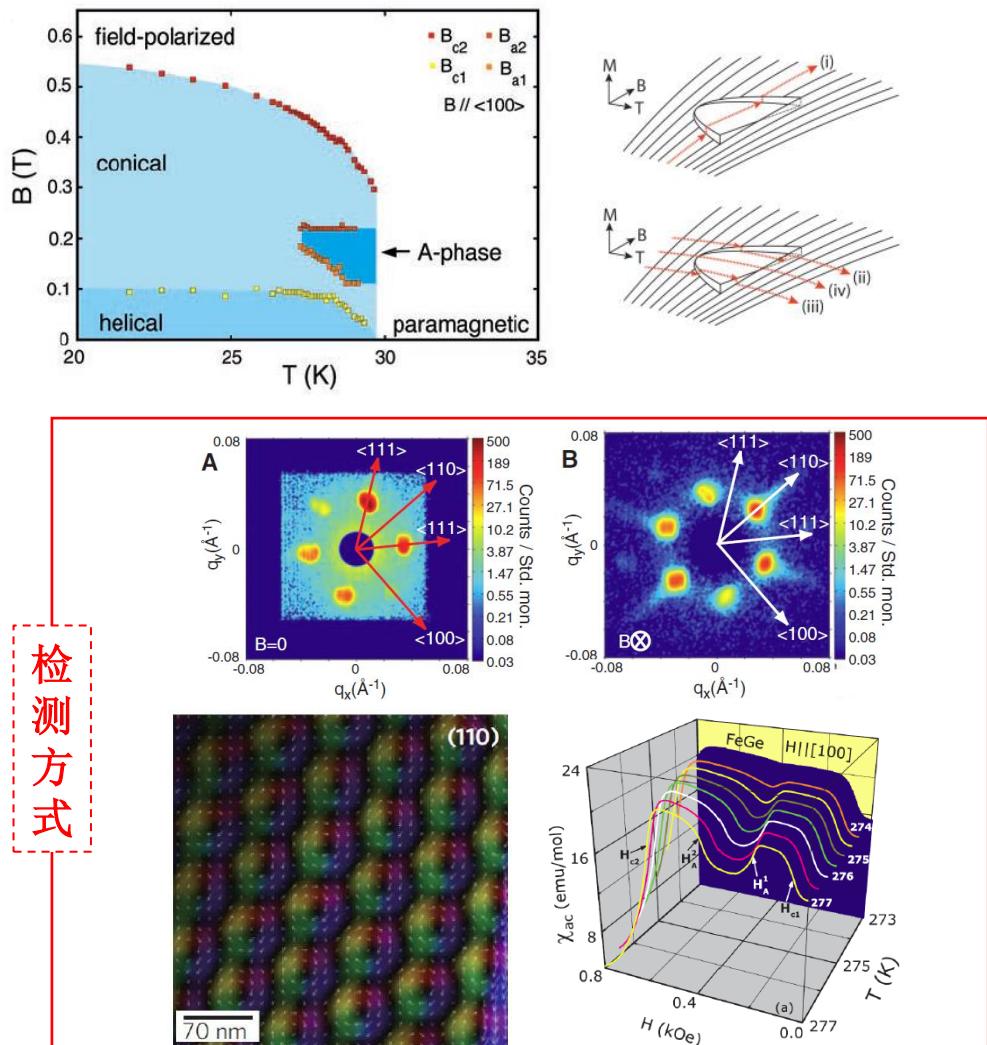
$B_2 < 0$   $\mathbf{k}$  is parallel to (111)

$B_2 > 0$   $\mathbf{k}$  is parallel to (100)



$$F = \left( \frac{1}{2}A - |\mathbf{b}|k \right) |S_k|^2 + \left( \frac{1}{2}B_1 + \frac{1}{6}B_2 \right) k^2 |S_k|^2$$

# 文献调研—追根溯源（最新的高质量物理类期刊）



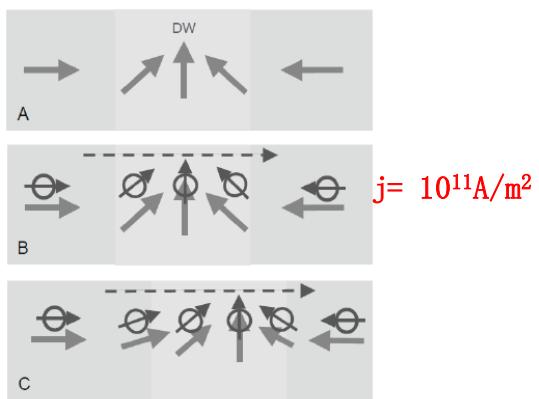
检测方式

## Journal

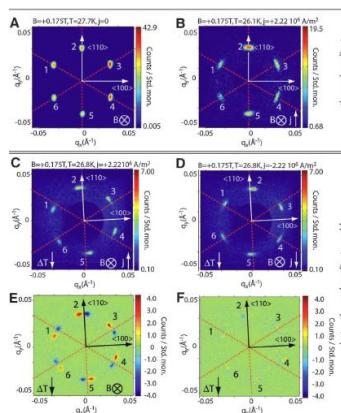
- ALL (247)
  - Rev. Mod. Phys. (247)
  - Phys. Rev. Lett.
  - Phys. Rev. X
  - Phys. Rev. A
  - Phys. Rev. B
  - Phys. Rev. C
  - Phys. Rev. D
  - Phys. Rev. E
  - Phys. Rev. Research
  - Phys. Rev. Accel. Beams
  - Phys. Rev. ST Accel. Beams
  - Phys. Rev. Applied
  - Phys. Rev. Fluids
  - Phys. Rev. Materials
  - Phys. Rev. Phys. Educ. Res.
  - Phys. Rev. ST Phys. Educ. Res.
  - Physics
  - Phys. Rev.
  - Phys. Rev. (Series I)
  - Phys. Rev. Focus
  - Physics Physique Fizika
- 2-dimensional systems (2)
  - 3-dimensional systems (5)
    - Carbon-based materials (3)
  - Applications of soft matter (2)
  - Atomic & molecular structure (2)
  - Cold atoms & matter waves (2)
    - Spin-orbit coupling (2)
  - Disordered systems (2)
  - Electronic structure (4)
    - Spin-orbit coupling (2)
  - First-principles calculations (2)
  - Interactions & forces (2)
  - Magnetic techniques (1)
  - Magnetism (7)
    - Magnetic texture (2)
    - Spintronics (4)
  - Mathematical physics methods (2)
  - Methods in magnetism
    - Micromagnetic modeling (1)
  - Phase transitions (3)
  - Quantum theory (2)
  - Resonance techniques (2)
  - Structural properties (4)
  - Superconductivity (3)
  - Topological materials (4)
  - Transport properties (3)
  - X-ray techniques (2)

斯格明子是一种量化的三维涡旋磁结构；形成于极低的温度和极窄的温度区间（ $\text{MnSi} \sim 27\text{--}30\text{K}$ ,  $\text{Fe}0.5\text{Co}0.5\text{Si} \sim 35\text{--}40\text{K}$ ）

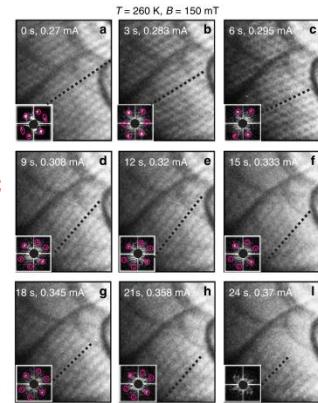
## 自旋转移力矩效应



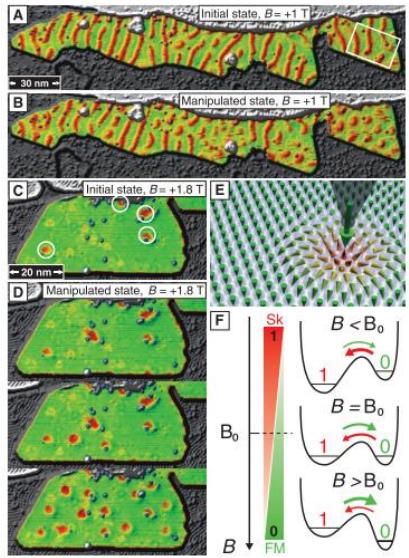
## 斯格明子的超低能耗运动



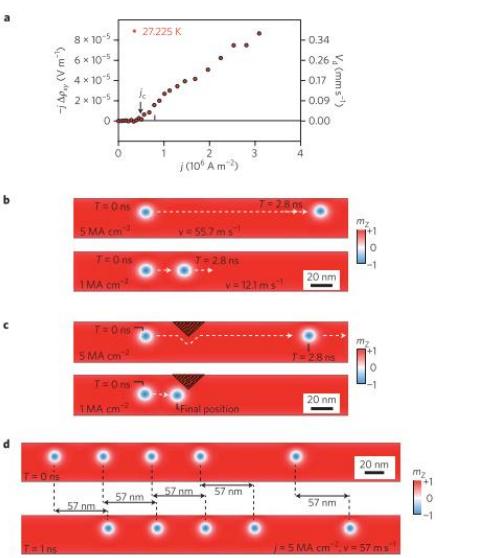
$$j = 10^6 \text{ A/m}^2$$



## 斯格明子的读和写



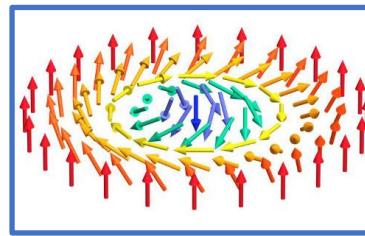
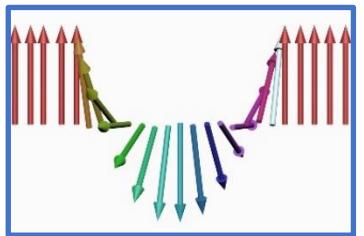
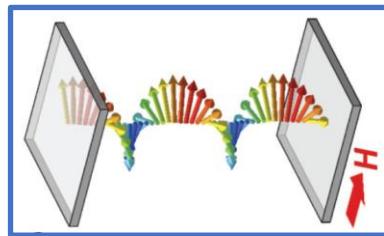
## 斯格明子纳米轨道器件



- Yu, **Nature Comm**, 3,988,2012  
 Joietz, **Science**, 330,2010  
 Niklas, **Science**, 341,2013  
 Muhlauer, **Science**, 323,2009  
 Albert Fert, **Nature Nano**, 8,2013  
 Stuart, **Science**, 320,2008

斯格明子纳米轨道存储：超紧凑，低能耗，高运算速度

未来计算机芯片、信息存储领域的全新信息载体——磁性斯格明子



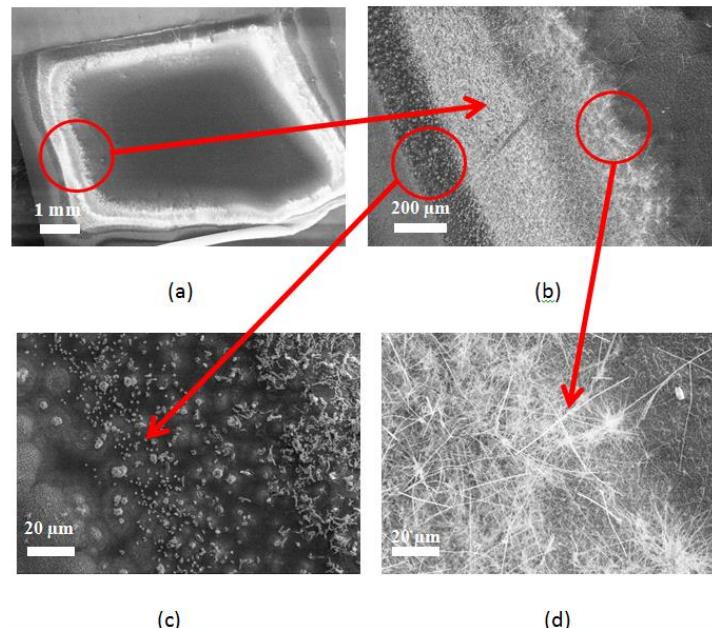
发展趋势-具有超级计算机运算功能的笔记本电脑



计算机内存的平均访问时间从10 ms缩短到5 ns；存储量提高几万倍；所需电流密度从 $10^{11} \text{ Am}^{-2}$ 降低到 $10^6 \text{ Am}^{-2}$ ；并且性能更稳定。

磁斯格明子自旋电子器件——未来计算机

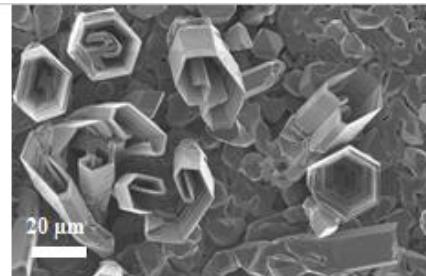
## 在漏气环境下制备纳米线



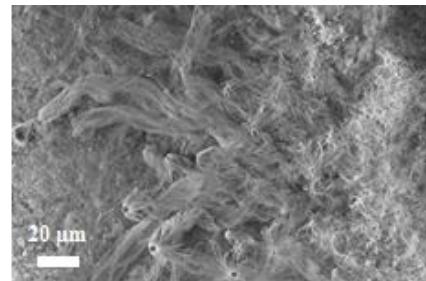
Name (from outside to inside)	Mn % (atomic)	Si % (atomic)	Relative Mn:Si composition
First band (scattered particles)	10.15	89.85	0.113:1
Second band (Nanowires plus scattered particles)	22.43	77.57	0.289:1
Third band (Nanowires)	32.2	67.8	0.475:1
Inner band (Continuous film)	30.71	69.29	0.443:1

# 问题的及时总结（失败的原因在哪儿？）

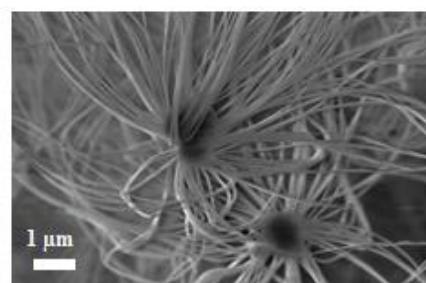
Chemical vapor deposition (Mn powder touch with substrate)



Chemical vapor deposition (System open to air)



Details of nanoctopus prepared



Nanowires favors growth near melted  $\text{SiO}_2$

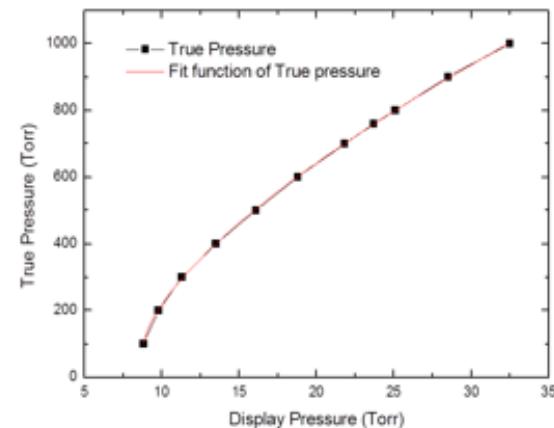
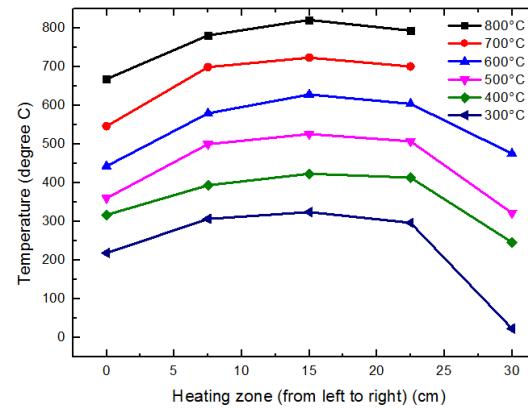
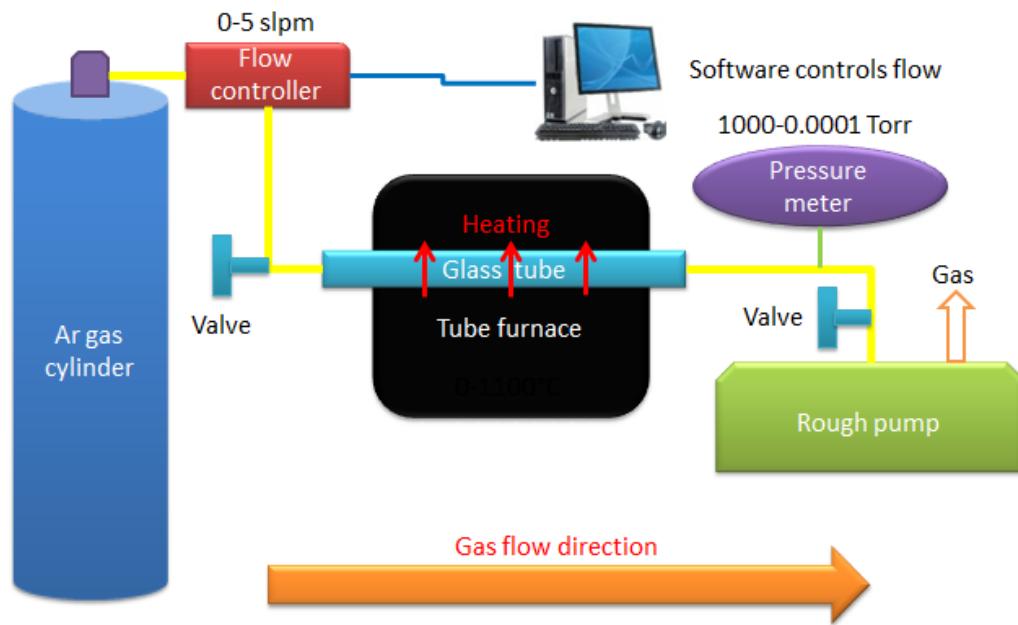


1. 及时总结
2. 寻找样品特征
3. 没有好样品和坏样品
4. 理性思考

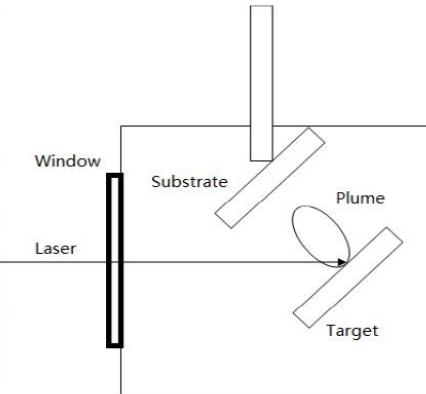
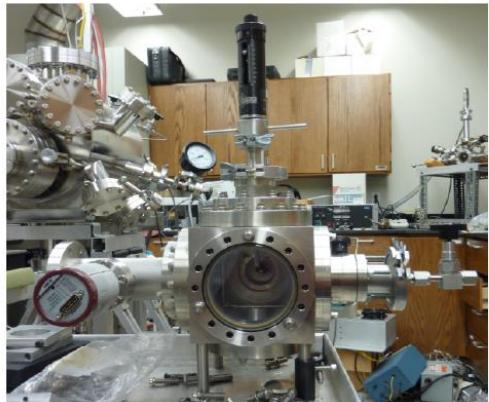
# 生长系统的升级+精确实验参数（去除不需要的氧）



Home-build tube furnace chemical vapor deposition system



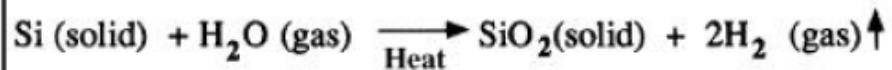
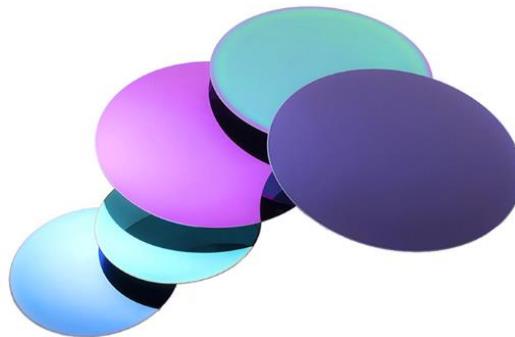
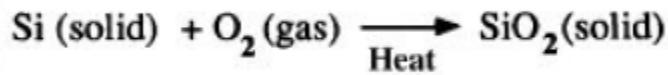
# 生长系统的升级+精确实验参数(融入自己的想法)



Condition	Thickness (nm)	Photo
60 mTorr Nitrogen plasma	307.6	
60 mTorr Nitrogen gas	77.48	
100 mTorr Nitrogen plasma	198.9	
100 mTorr Nitrogen gas	46.40	
150 mTorr Nitrogen plasma	44.52	
150 mTorr Nitrogen gas	48.07	

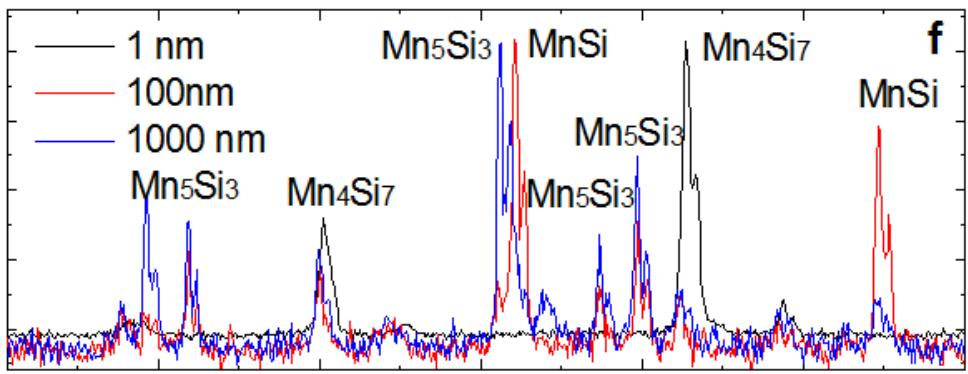
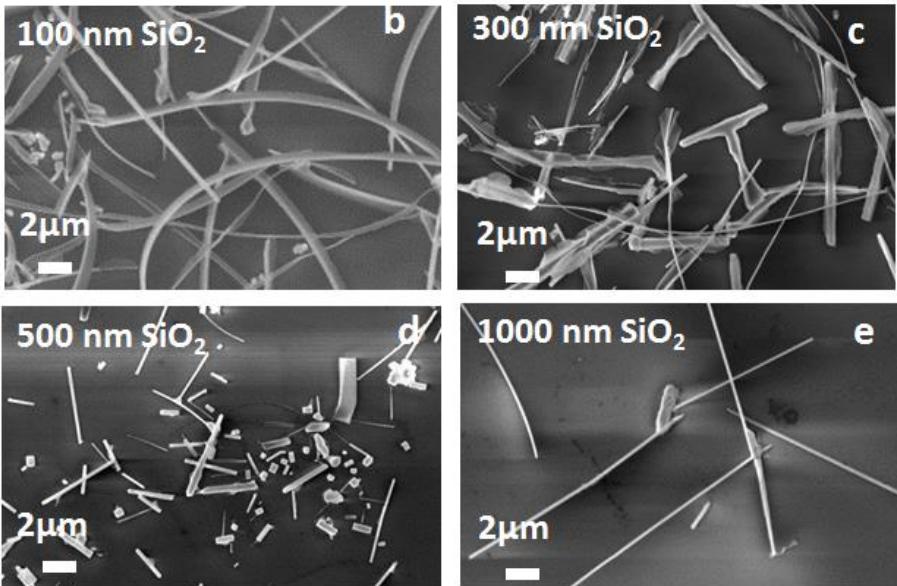
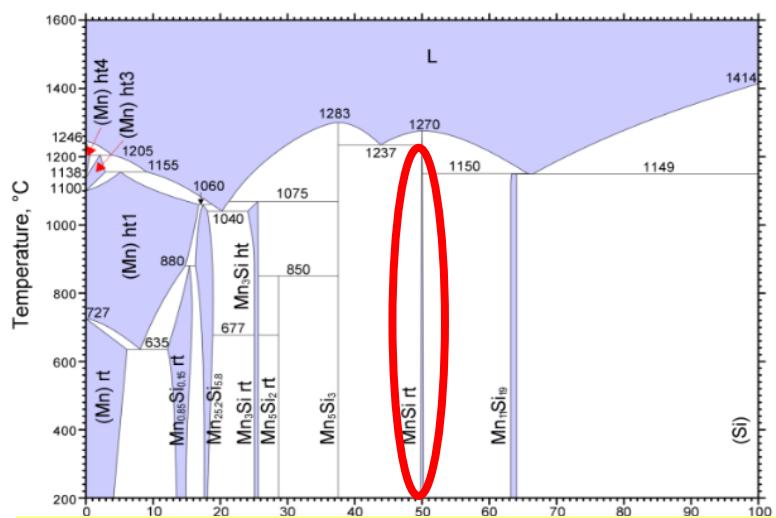
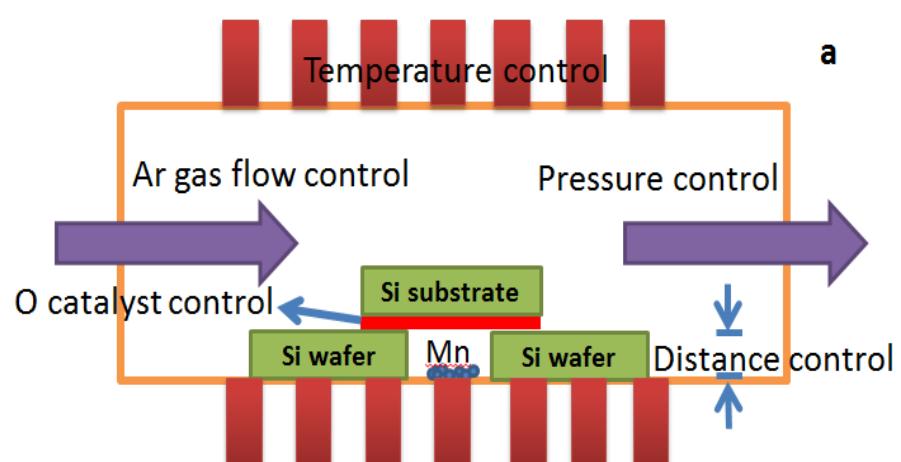
# 基板的选择（引入精确控制的氧）

Silicone Dioxide Thickness, Å	Application
10–100	Tunneling gates
150–500	Gate oxides, capacitor dielectrics
200–500	LOCOS pad oxide
2000–5000	Masking oxides, surface passivation
3000–10,000	Field oxides



# 问题的解决—新的调控方式

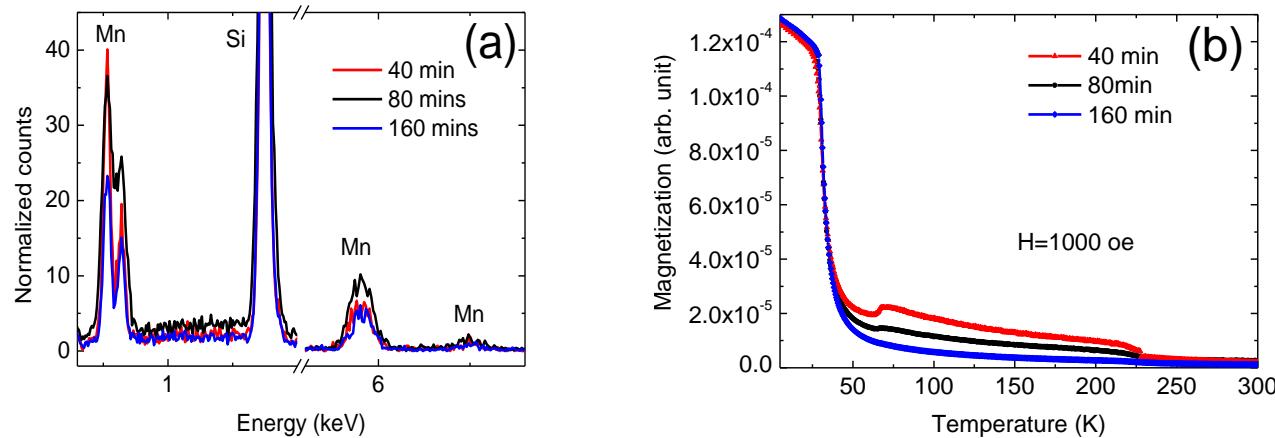
## 氧化膜辅助斯格明子相MnSi纳米线生长



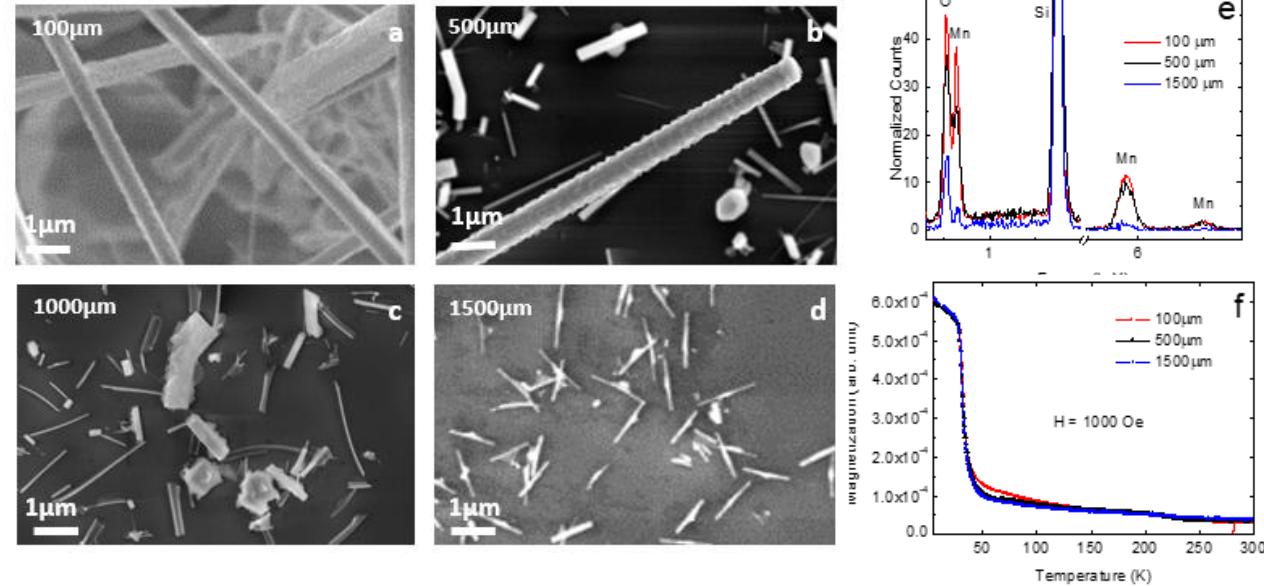
调节氧化膜厚度可以控制纳米线的形貌，晶体结构

# 问题的解决—新的调控方式

生长时间  
对纳米线  
的影响



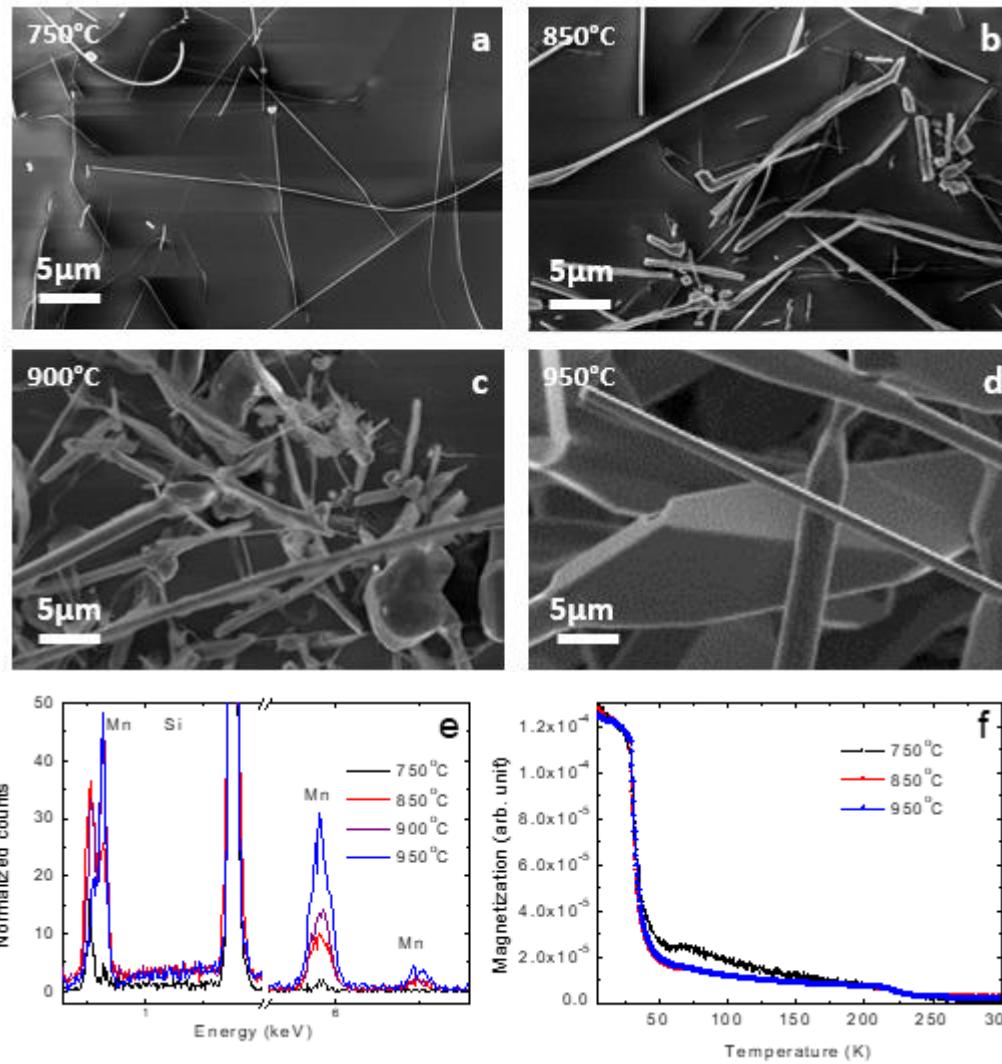
基体-前驱  
体距离对纳  
米线的影响



生长时间和基体-粉源距离可以调节纳米线的形貌，成分和磁性能

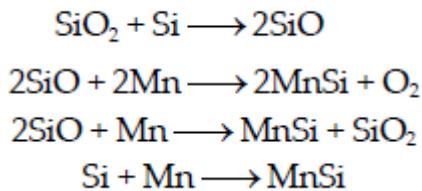
# 问题的解决—新的调控方式

生长温度对纳米线的影响



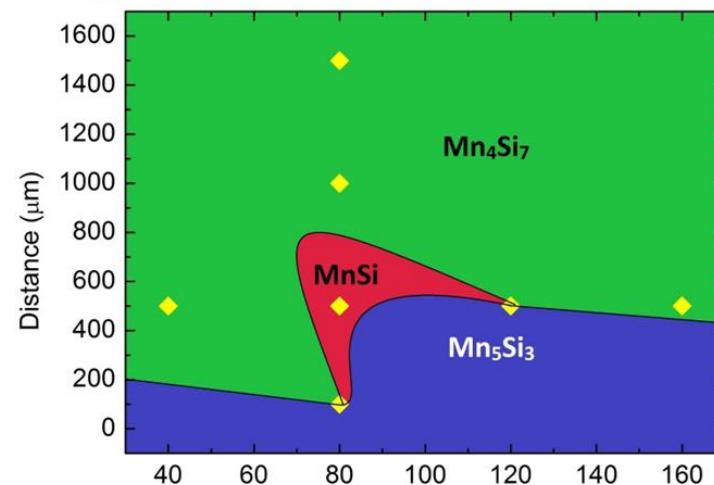
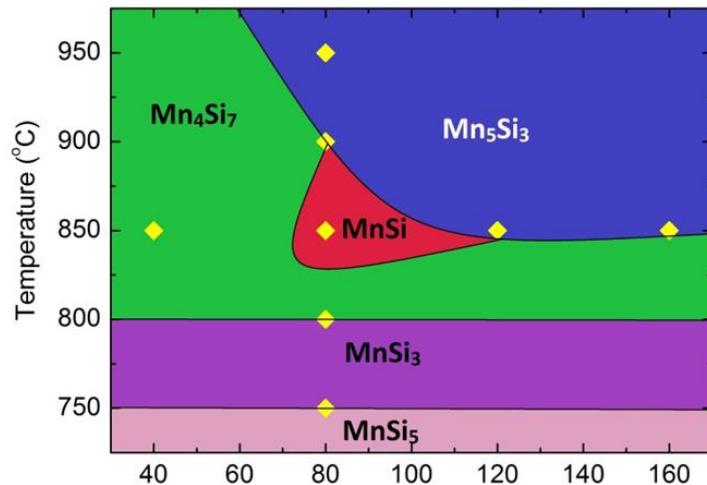
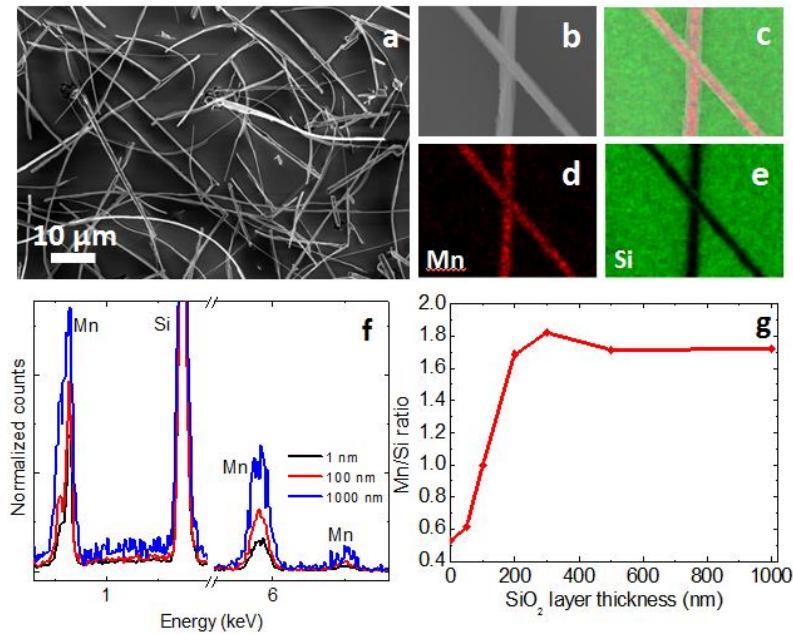
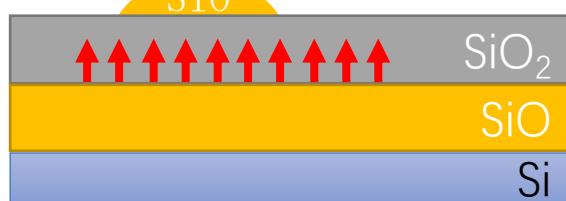
生长温度也能调节纳米线的成分和磁性能

# 新的调控方式—新的生长机制（依据？）



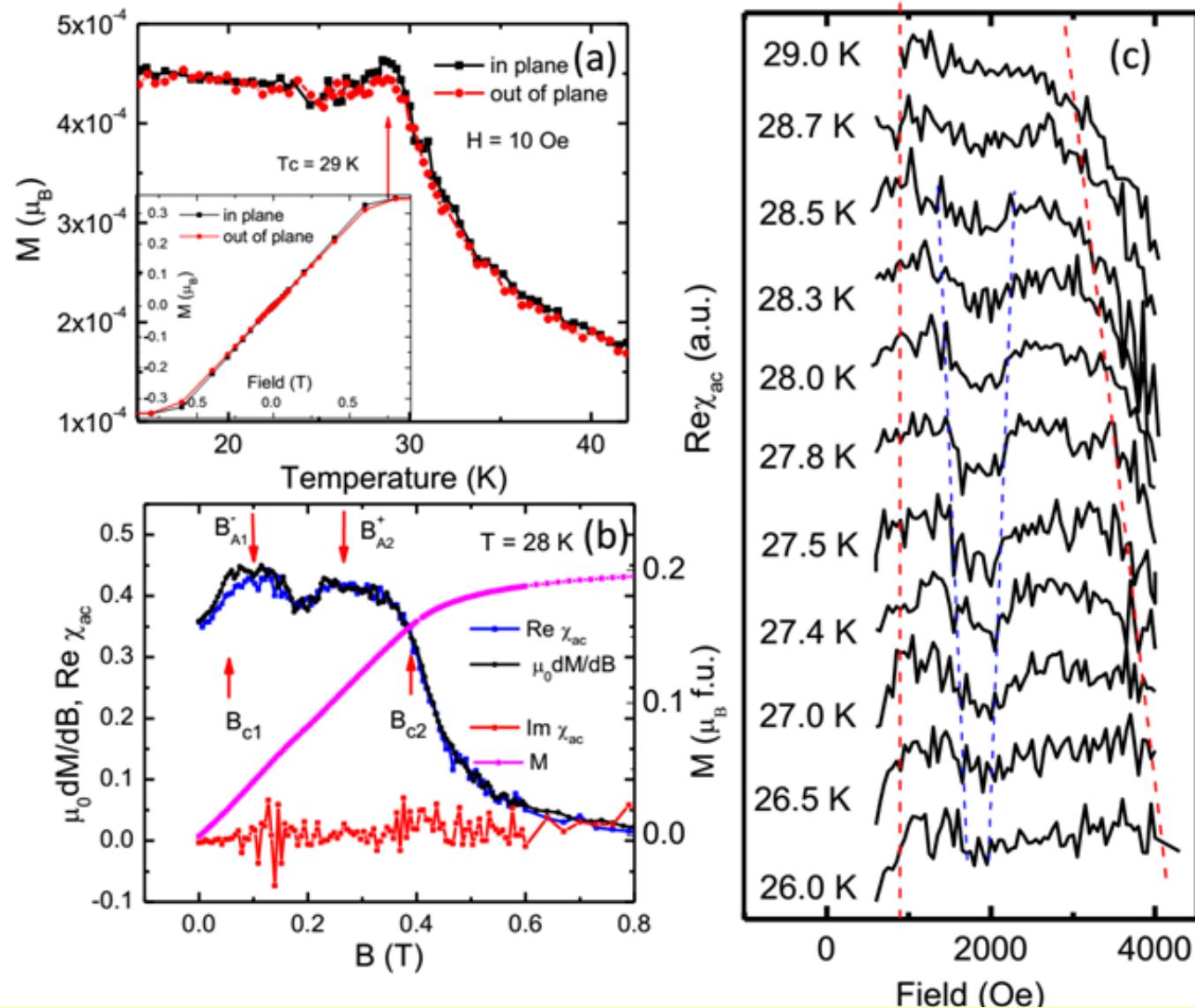
Mn

$$P_N = B \exp \left( -\frac{\pi \sigma^2}{k^2 T^2 \ln \alpha} \right)$$



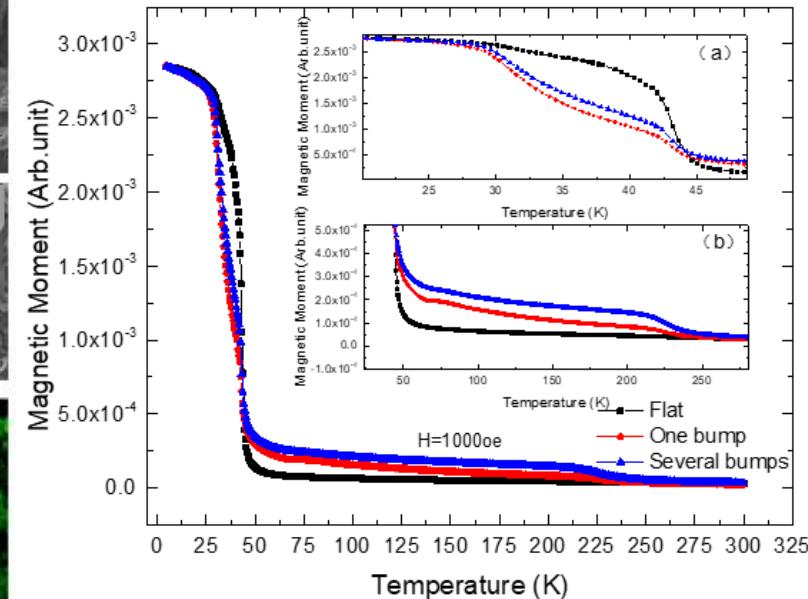
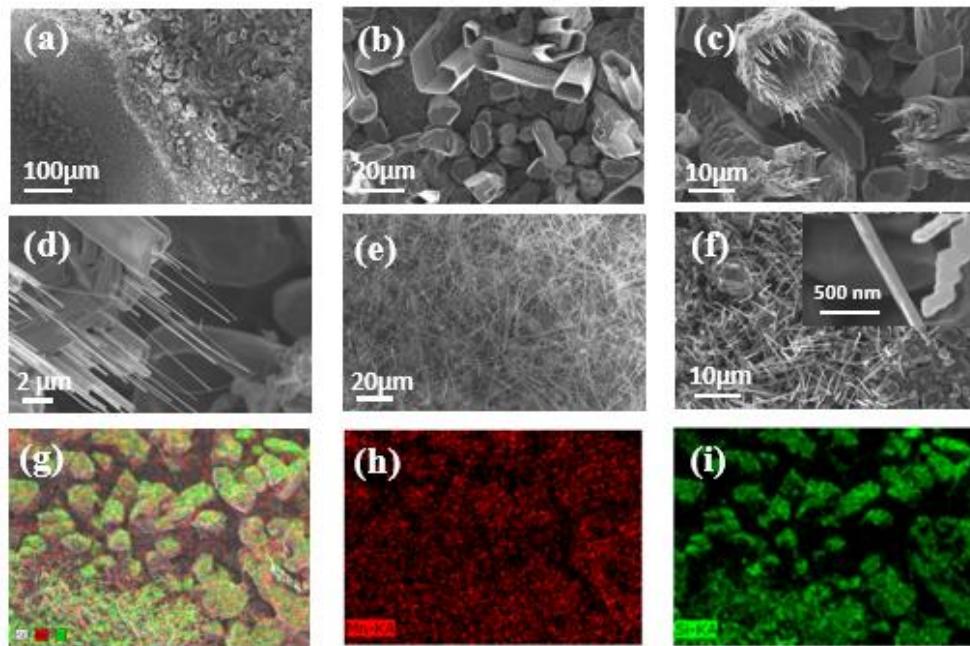
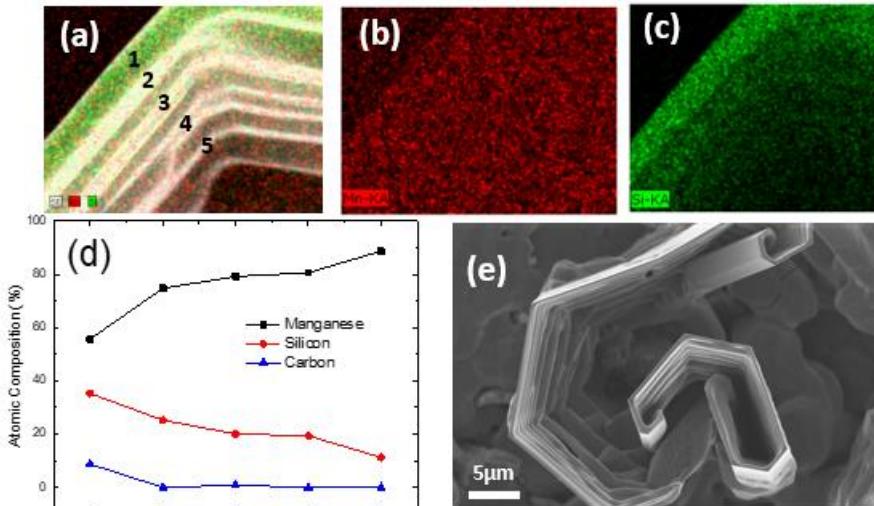
氧化物辅助化学气相沉积MnSi纳米线的生长相图构筑

# 新的调控方式—特性验证



磁性测量证明MnSi纳米线在26–29K下存在斯格明子相

# 解决问题之后的反哺—新形态纳米材料的生长



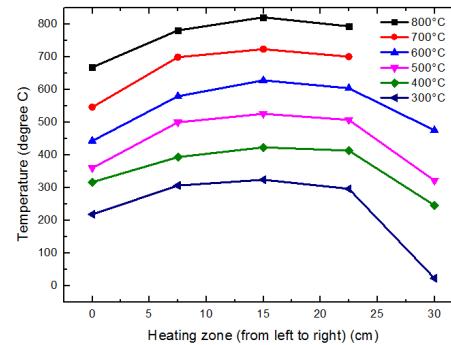
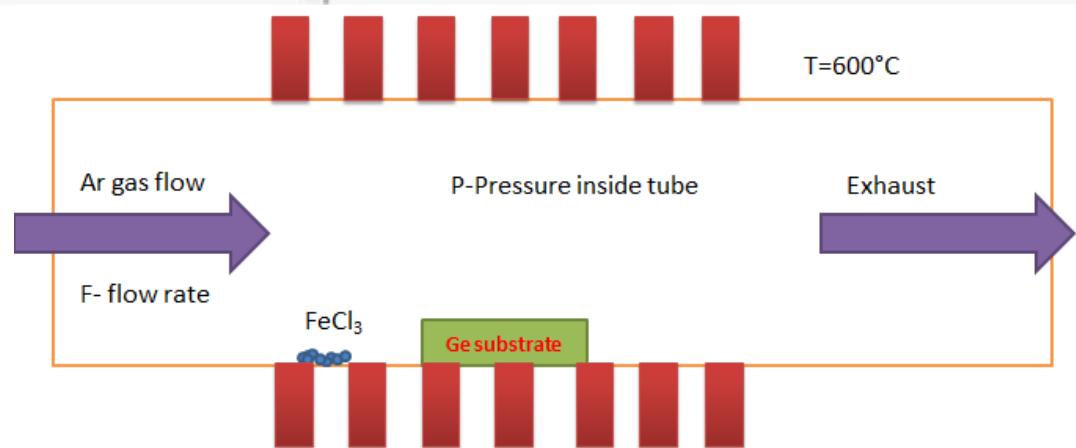
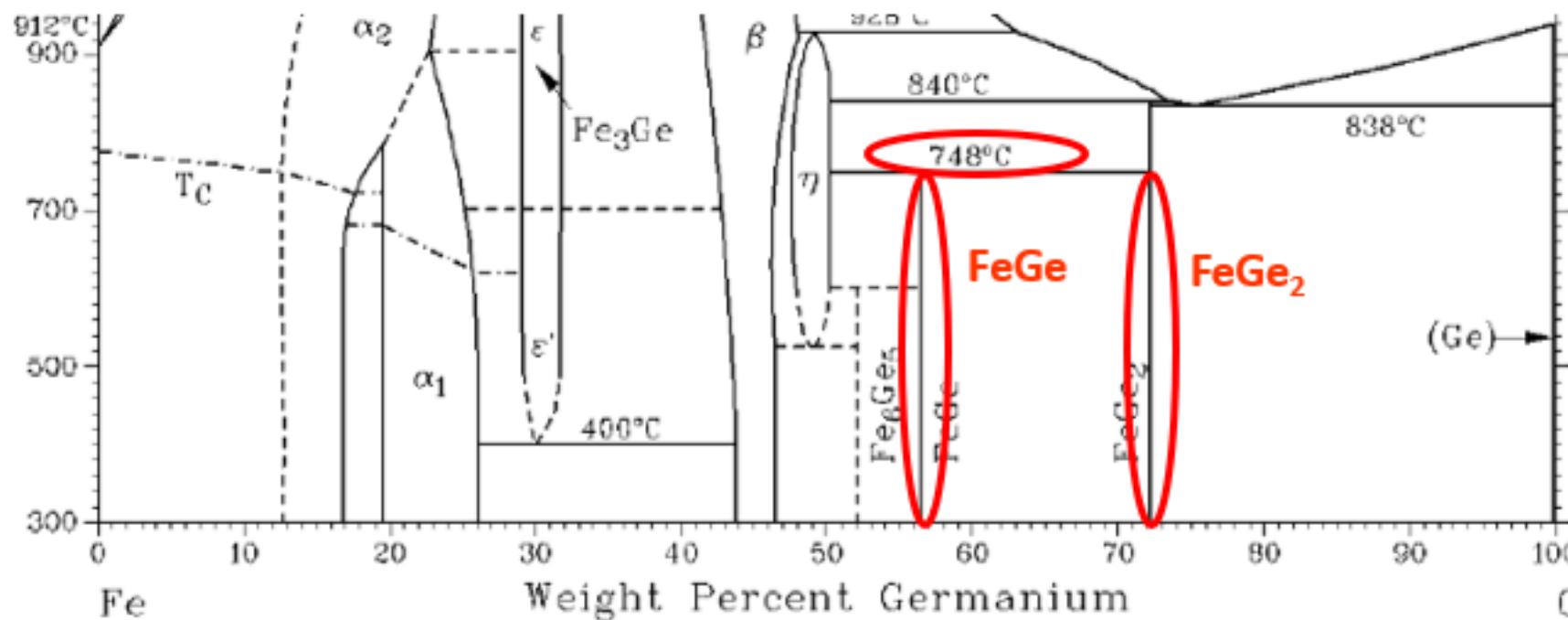
采用不同源-基板距离方式生长具有MnSi成分梯度的纳米结构

# 经验借鉴—FeGe纳米线生长



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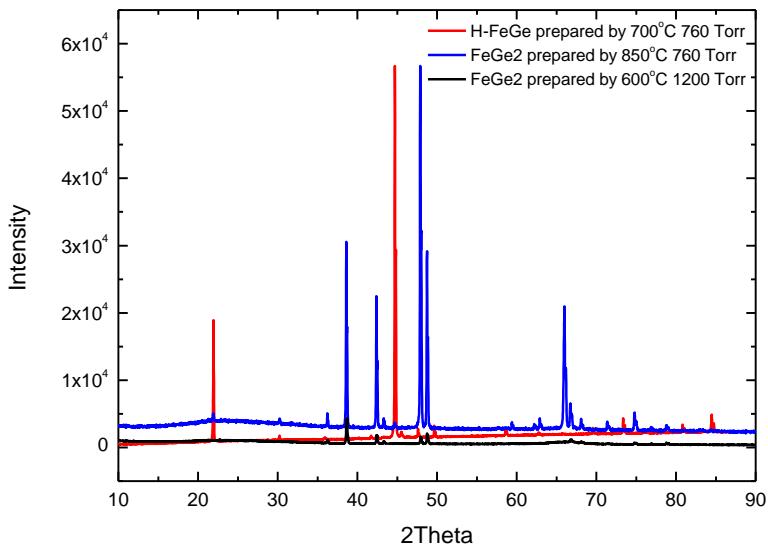
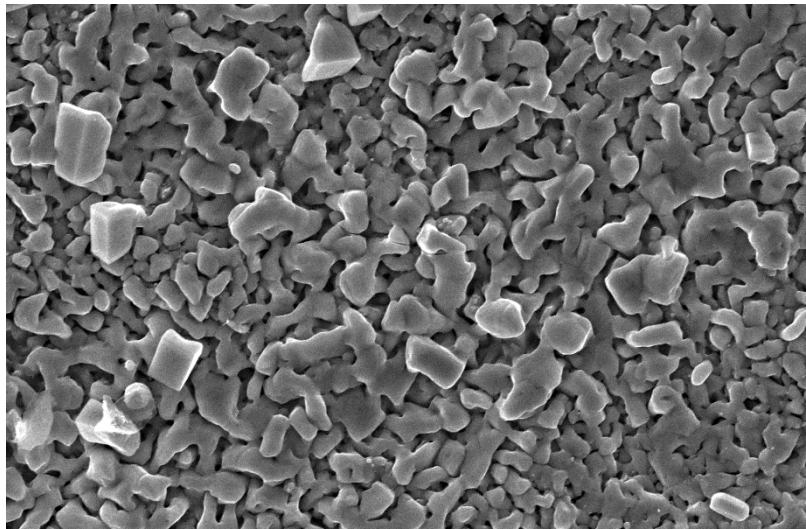
OAK RIDGE  
National Laboratory



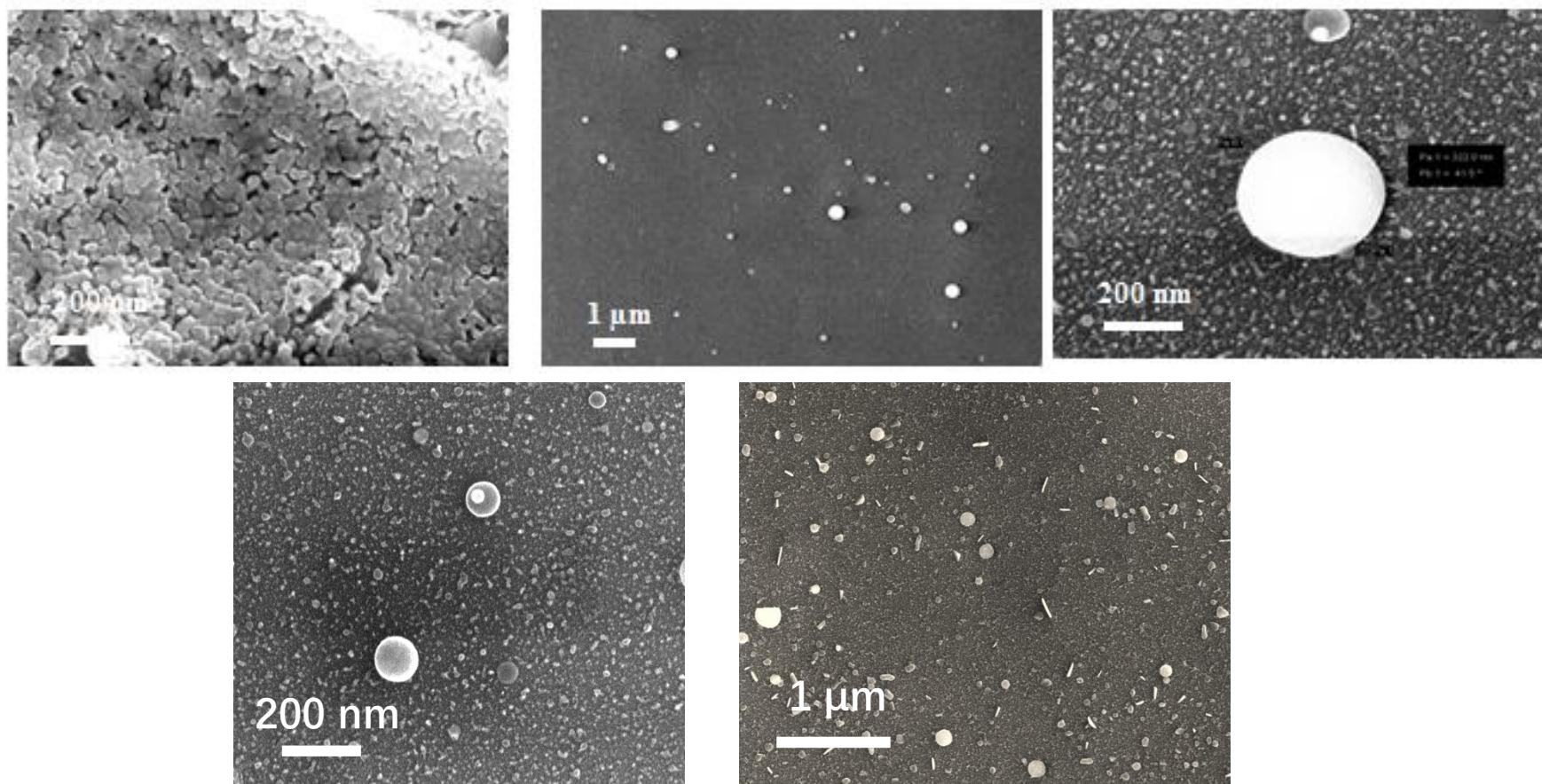
# 经验借鉴—FeGe纳米线生长



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CENTRAL SOUTH UNIVERSITY



This layer could transform from  $\text{FeGe}_2$  to hexagonal  $\text{FeGe}$  as reaction temperature decreasing from 850°C to 700°C with pressure around 760 Torr.



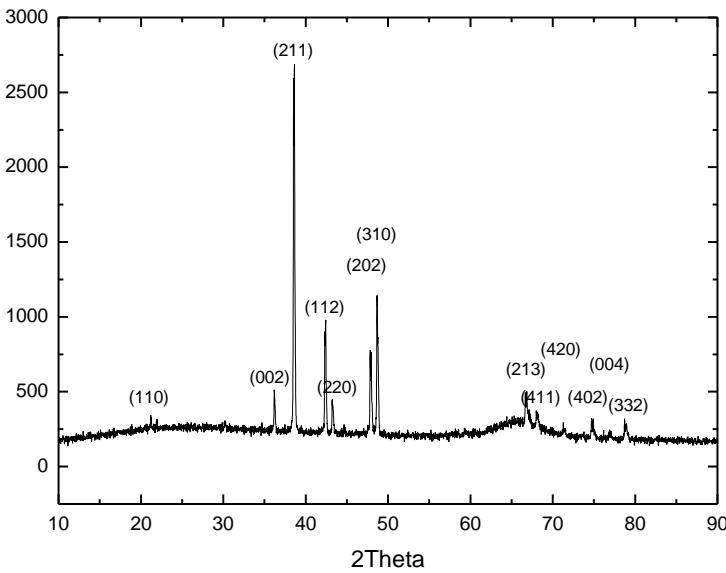
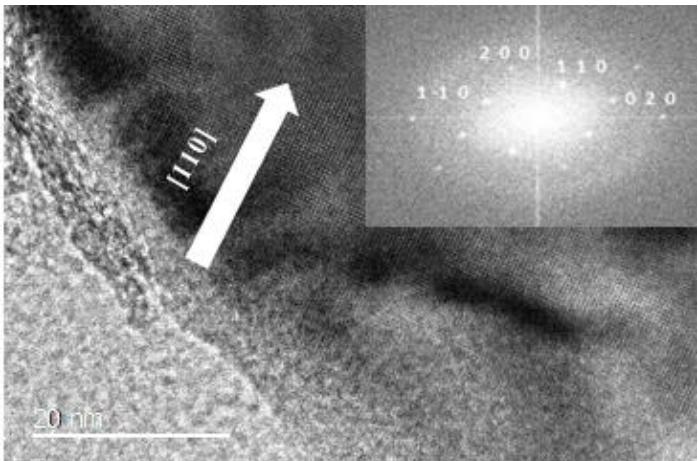
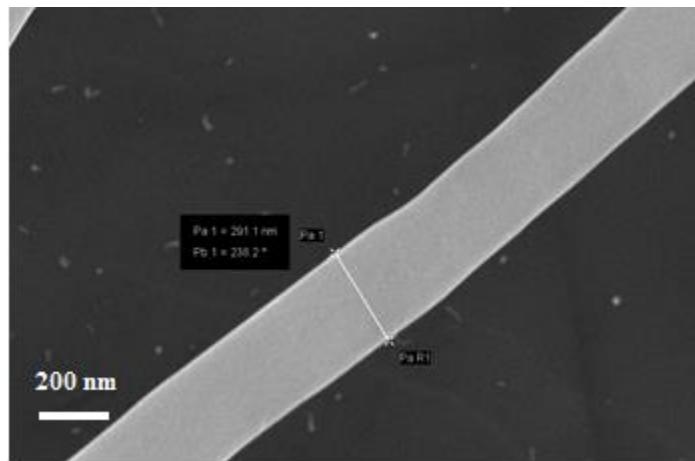
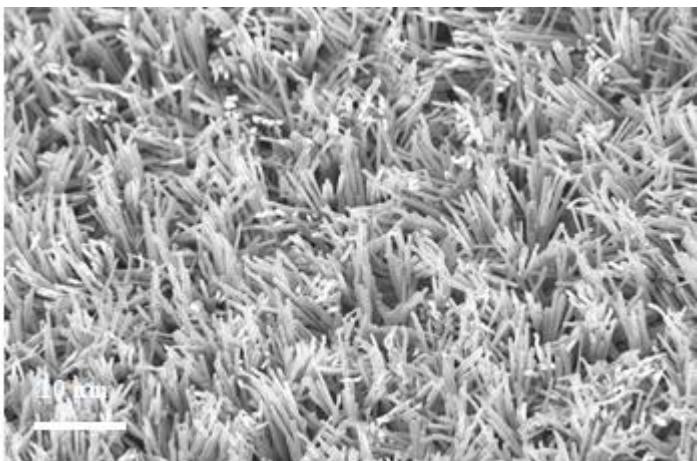
Substrate control:  
Cr layers and laser ablation particles as surfactant

# 调控促进FeGe纳米线生长



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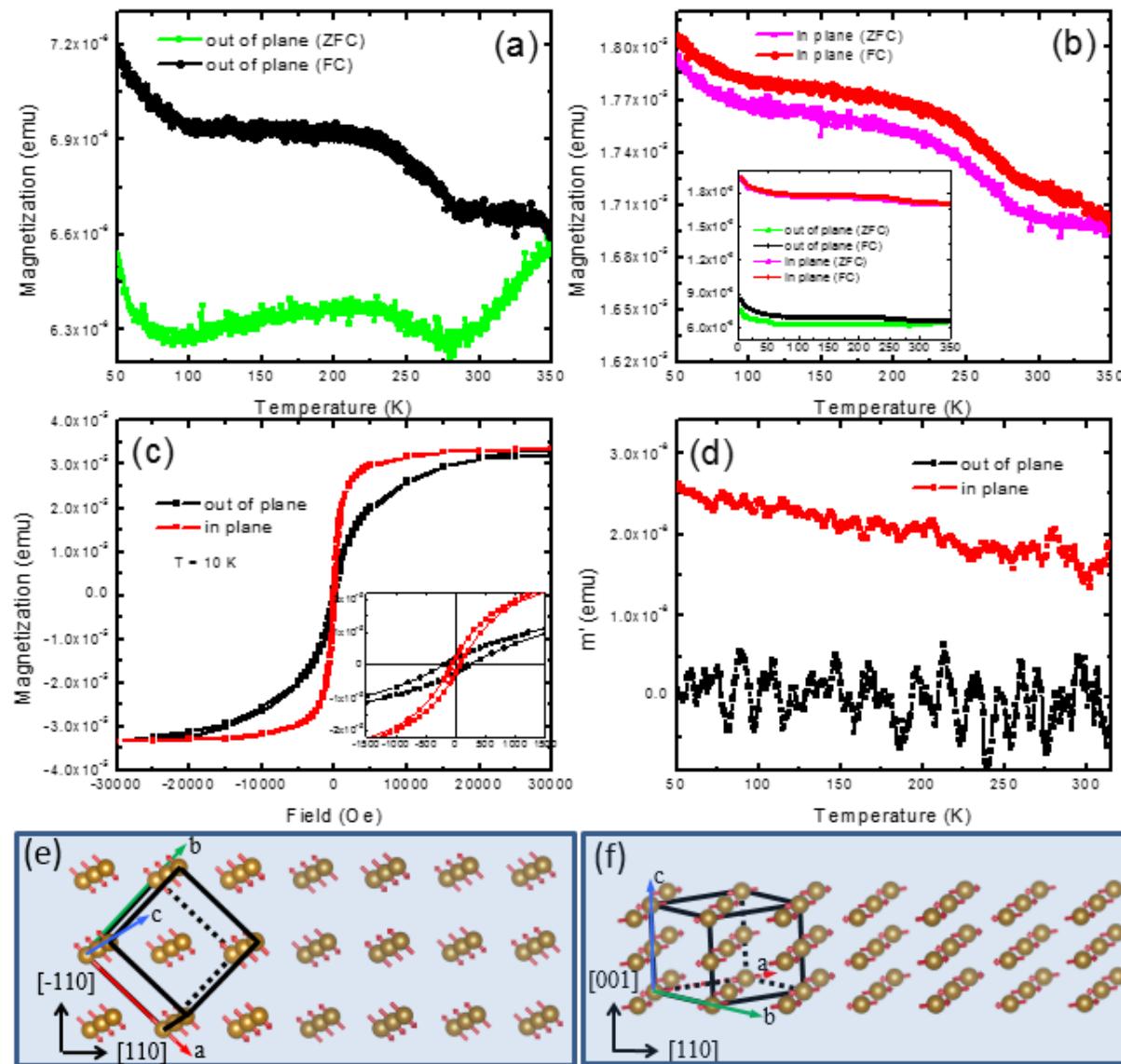


# 纳米线的奇异磁性能



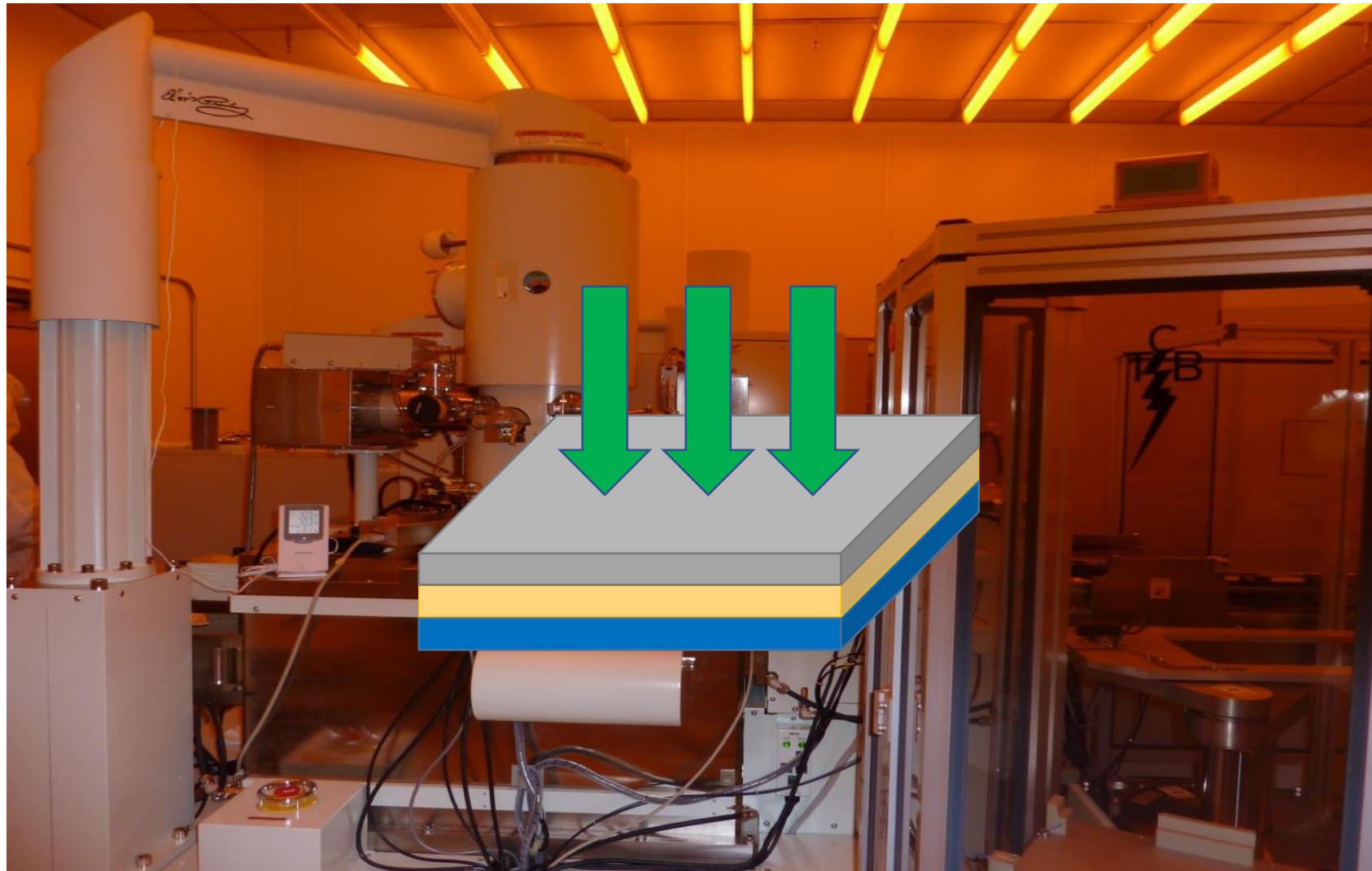
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National Laboratory



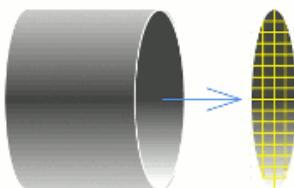
铁原子自旋的排列方向引起了 $\text{FeGe}_2$ 纳米线具有强烈的磁各向异性

## Four probe nanowire device fabrication

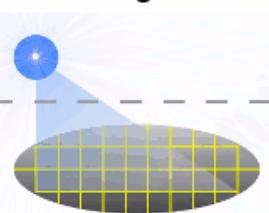


# Making a microchip - in six steps

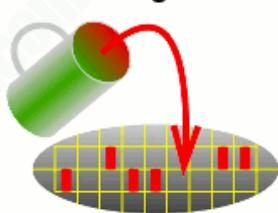
## 1. Making wafers



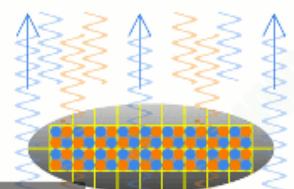
## 2. Masking



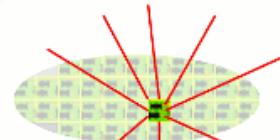
## 3. Etching



## 4. Doping



## 5. Testing



## 6. Packaging



### PROCESS STEP

1. Surface preparation

### PURPOSE

Clean and dry wafer surface

2. Photoresist apply

Spin coat a thin layer of photoresist on surface

3. Soft bake

Partial evaporation of photoresist solvents by heating

4. Alignment and Exposure

Precise alignment of mask/reticle to wafer and exposure of photoresist. Negative resist is polymerized

5. Development

Removal of unpolymerized resist

6. Hard bake

Additional evaporation of solvents

7. Develop inspect

Inspect surface for alignment and defects

8. Etch

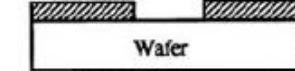
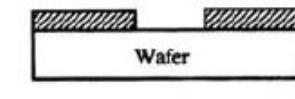
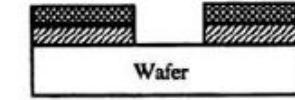
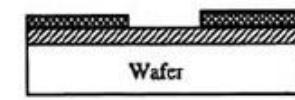
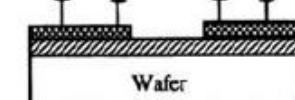
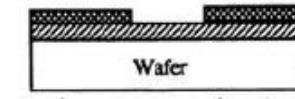
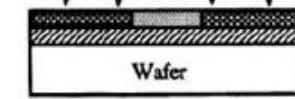
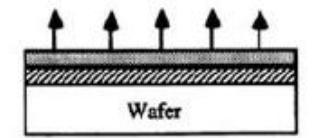
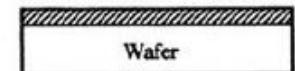
Top layer of wafer is removed through opening in resist layer

9. Photoresist removal (strip)

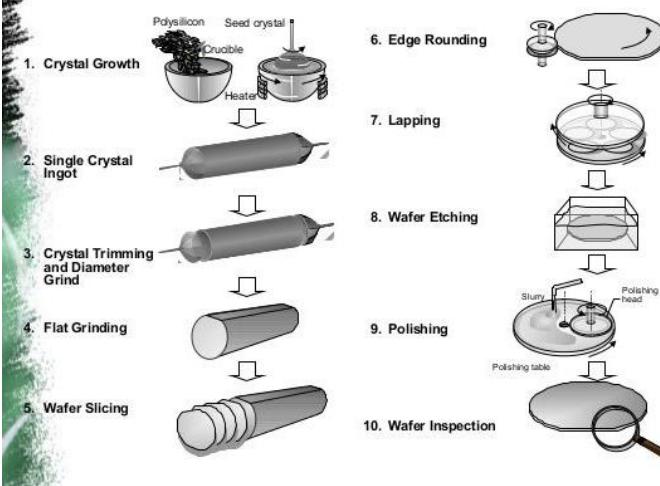
Remove photoresist layer from wafer

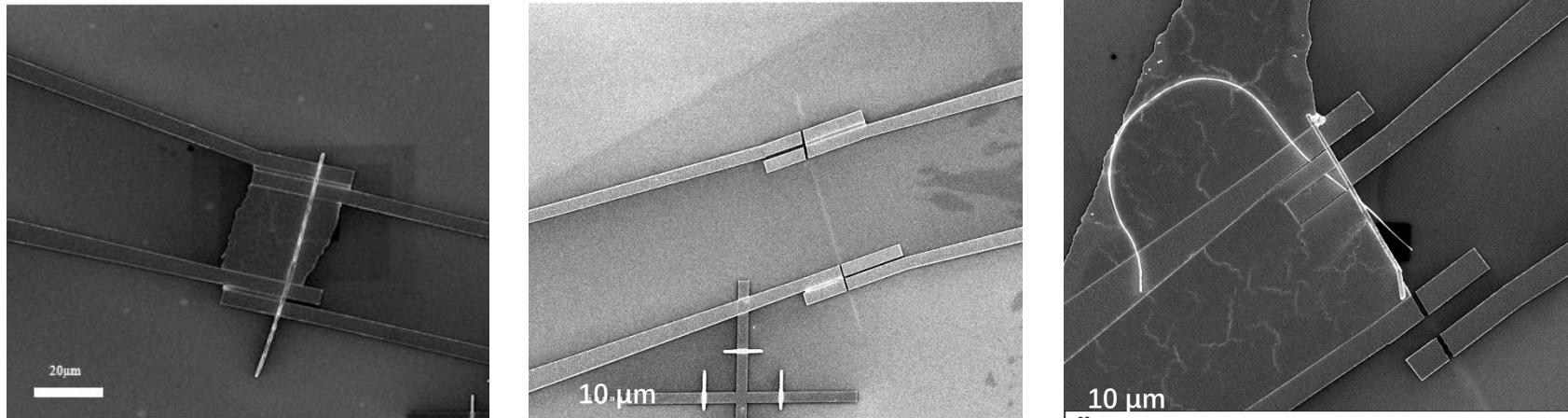
10. Final inspection

Surface inspection for etch irregularities and other problems

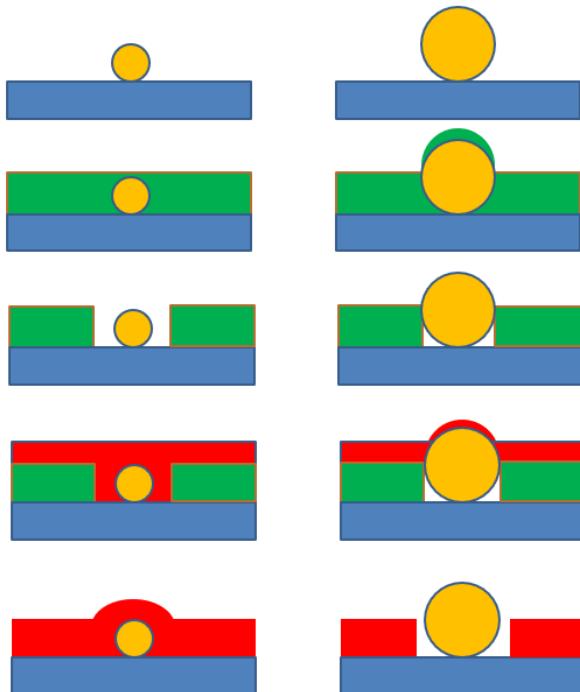


## Preparation of Silicon Wafer

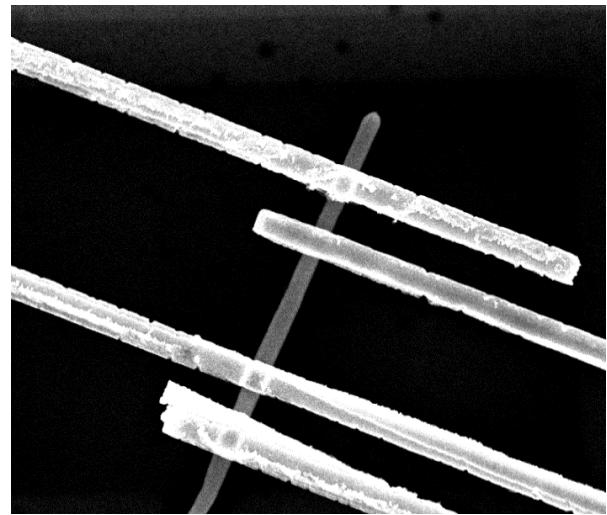




Why there is a liftoff issue?



冷静分析，多交流。  
心态很重要



电子束刻蚀参数优化:

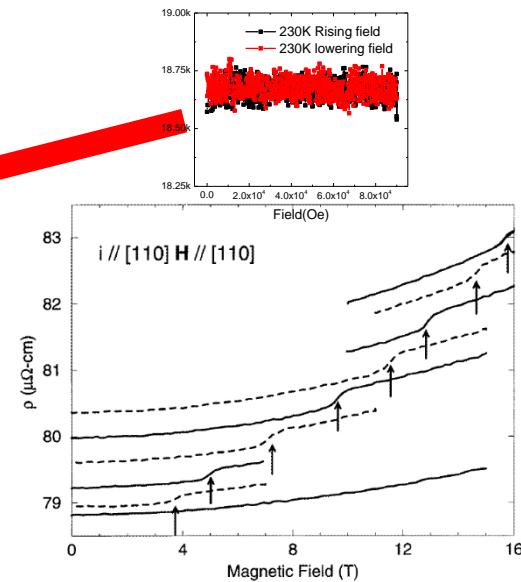
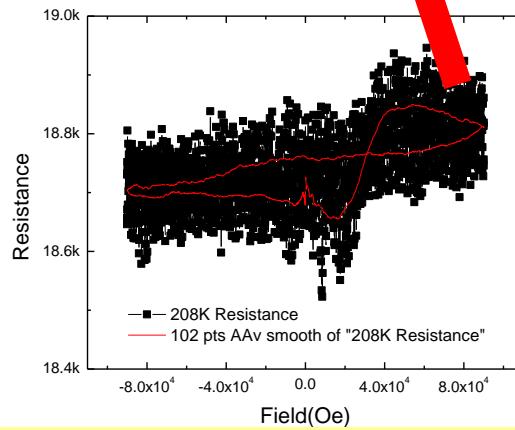
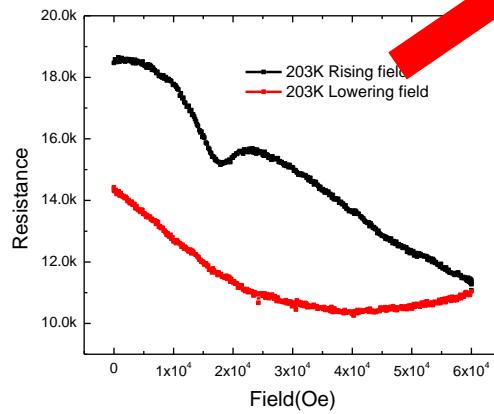
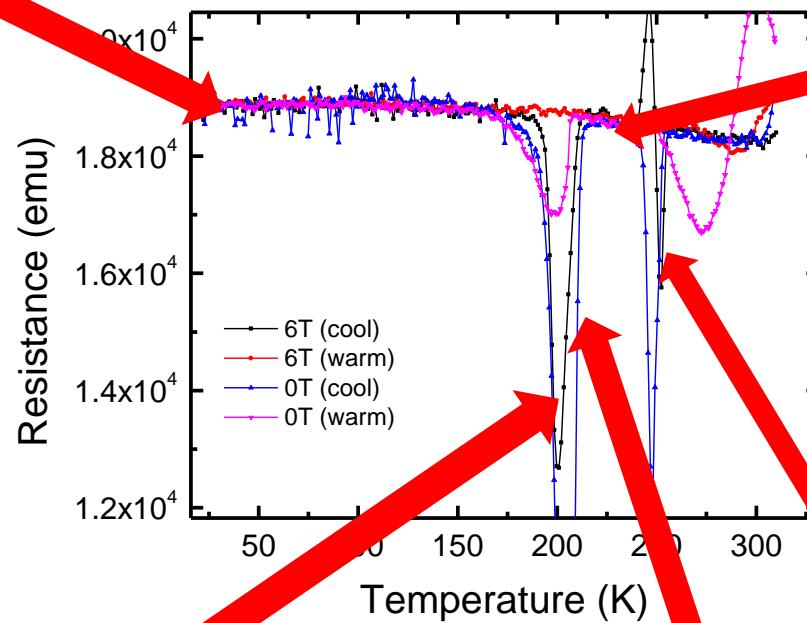
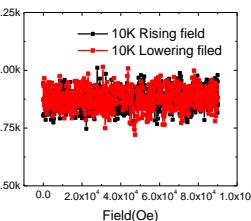
1. 烘烤: PMMA 1min, Copolymer 1min
2. 电子束剂量: 1300 coulombs/cm<sup>2</sup>
3. 显影: 35 sec
4. Cr/Au 电极厚度: 10nm/200nm

# 奇异输运行为

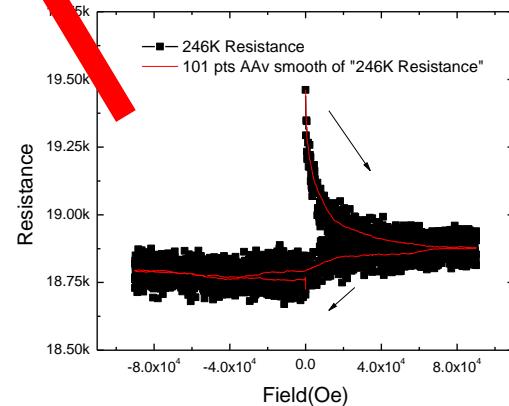


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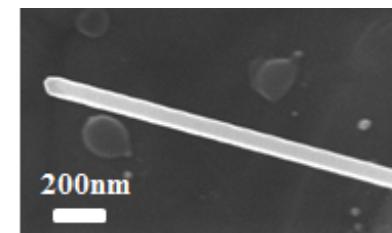
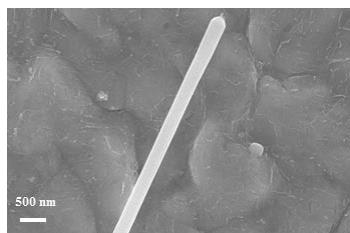
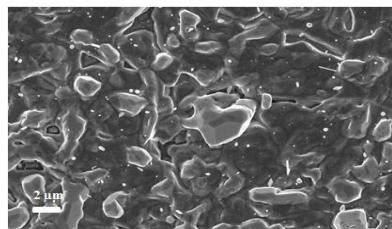
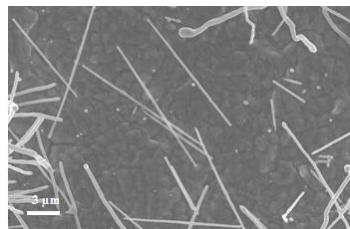


C. P. Adams, J. Physics-  
Condensed Matter 9, (1997)

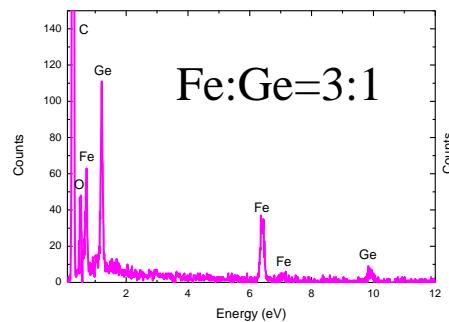


FeGe<sub>2</sub>纳米线的反常输运特性

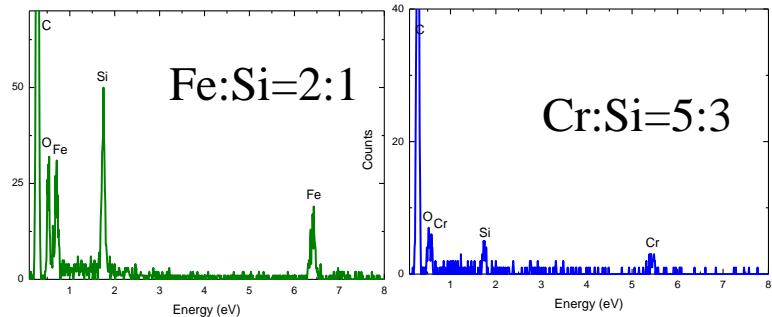
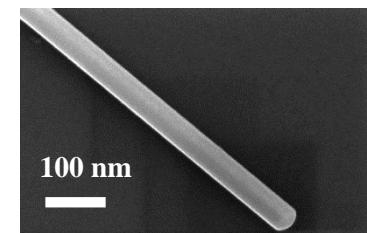
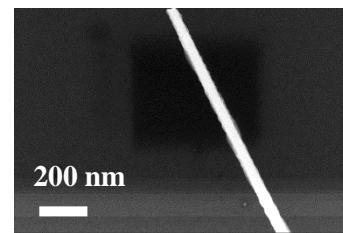
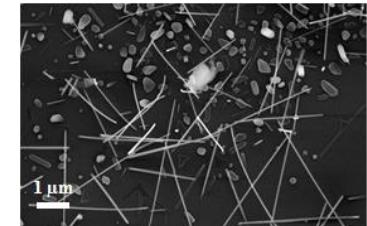
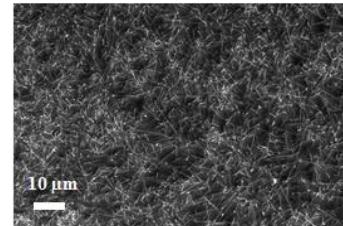
## Fe<sub>2.5</sub>Ge nanowires and Fe<sub>3</sub>Ge nanowires



Fe:Ge=2.5:1



## Fe<sub>2</sub>Si and Cr<sub>5</sub>Si<sub>3</sub> nanowires



1. 兴趣是最好的老师
2. 深思熟虑，下定决心，勇往直前，无怨无悔
3. 保持自信，乐观，积极的心态
4. 面对失败要学会自我调节，学会放松，缓解负面情绪

A person's character isn't determined by how he or she enjoys victory but rather how he or she endures defeat. Nothing can help us endure dark times better than our faith.



# HOUSE of CARDS

一个人的品质，不在于他或她如何去享受胜利（的喜悦），而在于这人如何忍受失败（的痛苦）。只有信仰（理想）才能帮我们度过生命中的那些艰难的日子。

——《纸牌屋》



感谢您的聆听！

感谢您的聆听！