1. Magnetismus

Was man längst wissen sollte ...

Maßeinheiten, Diamagnet, Paramagnet,

Suszeptibilität, Magnetisierung,

Spin-Bahn Wechselwirkung, Hund'sche Regeln,

Südweiser (?), Kompass

Maschinen (Motoren, Generatoren, Kühlschränke, Lautsprecher)

Datenspeicher (Ringkern, Winchester, GMR)

verwickelt: lokal – delokal, mikro – atomar, x

1.1 Geschichtlicher Überblick

Thales von Milet, 624 – 546 v. Chr.

(Vorsokratiker)

"Alles ist voll von Göttern."

Magnetstein besitzt eine Seele,

weil er das Eisen bewegt.

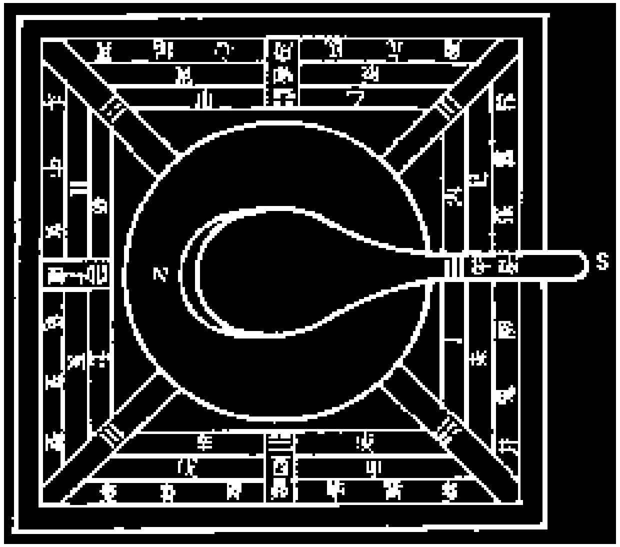
Magnetstein = Magnetit = Fe_3O_4

T_N = 871 K   Remanenz ≤ 500 nT

Hanfuzius (280 – 233 v. Chr.)

baut den Si Nan

Einsatz als Kompass: ca. 1100



William Gilbert (1544 – 1603)

Widerlegt Behauptung, Knoblauch entmagnetisiere

1600: *De Magnete, Magnetisque Corporibus, et de Magno Tellure*

Erdmagnetismus hängt mit Erddrehung zusammen

Ende des 19. und Anfang des 20. Jahrhunderts:

Mikroskopische Modelle des Magnetismus

- Elektrodynamik (Maxwell)
- Statistische Thermodynamik (Boltzmann)

Beispiel: Curie-Gesetz $X_{para} \propto T^{-1}$

Experiment: P. Curie, Ann. Chim. Phys. **5**, 289 (1895)

Theorie: P. Langevin, J. Phys. **4**, 678 (1905)

- Klassische Physik erklärt Magnetismus nicht
  - J. H. van Leeuwen, J. Phys. **2**, 361 (1921)
- Mikroskopische Theorie des Ferromagnetismus
  - P. Weiss, J. Phys. **6**, 661 (1907)
- Neue Quantenzahl ("Spin") für das Elektron nötig
  - E. Landé, Z. Phys. **15**, 189 (1923)
  - G. E. Uhlenbeck, S. Goudsmit, Nature **117**, 264 (1926)
- Heisenberg-Modell für FM und AFM
  - W. Heisenberg, Z. Phys. **38**, 441 (1926)
- W. Heitler, F. London, Z. Phys. **44**, 455 (1927)
  - H_2 – Molekül: Singulett- und Triplett-Zustand
- Itineranter Elektronenmagnetismus
  - E. C. Stoner, Proc. Roy. Soc. A **154**, 656 (1936); A **165**, 372 (1938)
- Theorie des Antiferromagnetismus
  - L. Néel, Ann. Phys. **3**, 137 (1948)

Heute:

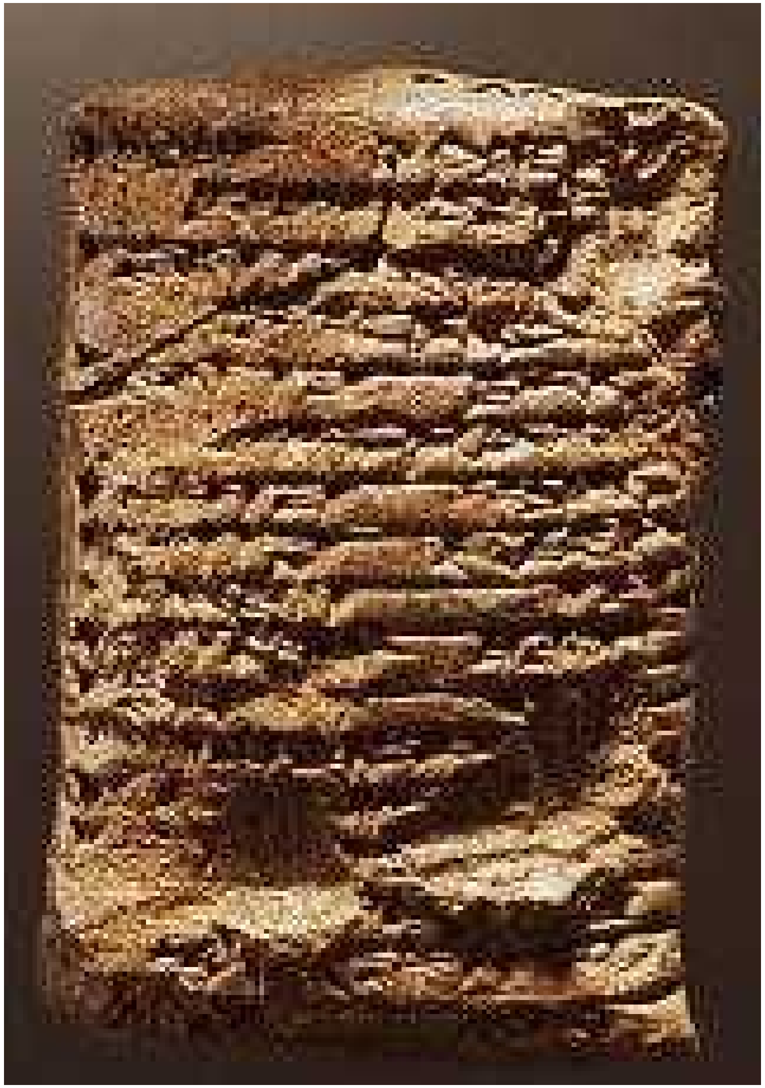
z. B. Dichte-Funktionaltheorie

P. Hohenberg, W. Kohn, Phys. Rev. **136**, 864 (1964)

Magnetismus von stark korrelierten Systemen (z.B. Hochtemperatursupraleiter) ist bislang nicht voll verstanden.

1.2 Magnetische Speichertechnologie

Datenspeicher (traditionell)



Magnetic Recording: The First 100 Years

eds. Daniel, Mee & Clark, 1999, IEEE Press

1898 Valdemar Poulsen: Telephonograph, phone answering machine

1935 AEG Magnetophon: audio recording device

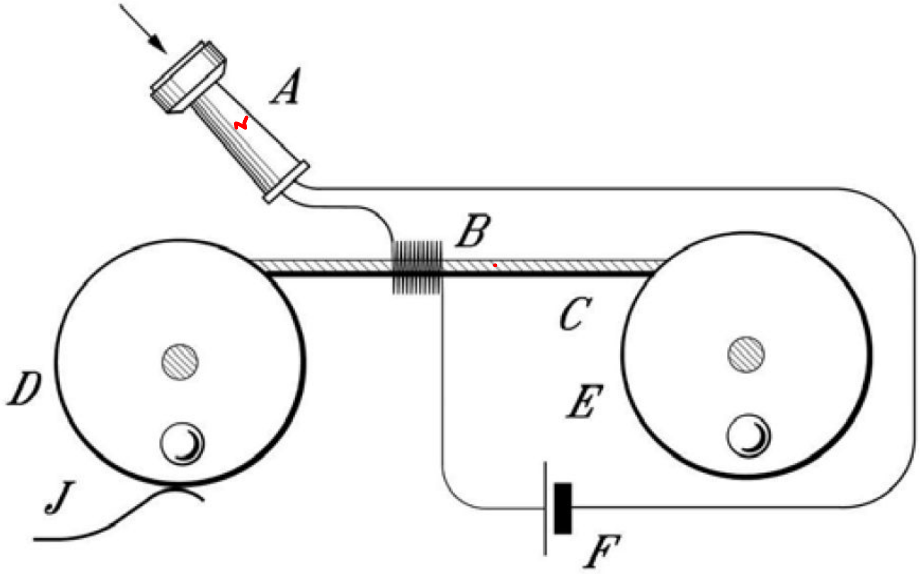
1956 IBM RAMAC: 5 MB, sized 2 large refrigerators, $10.000 per MB

1963 Philips compact audio cassette

1971 IBM floppy disk drive

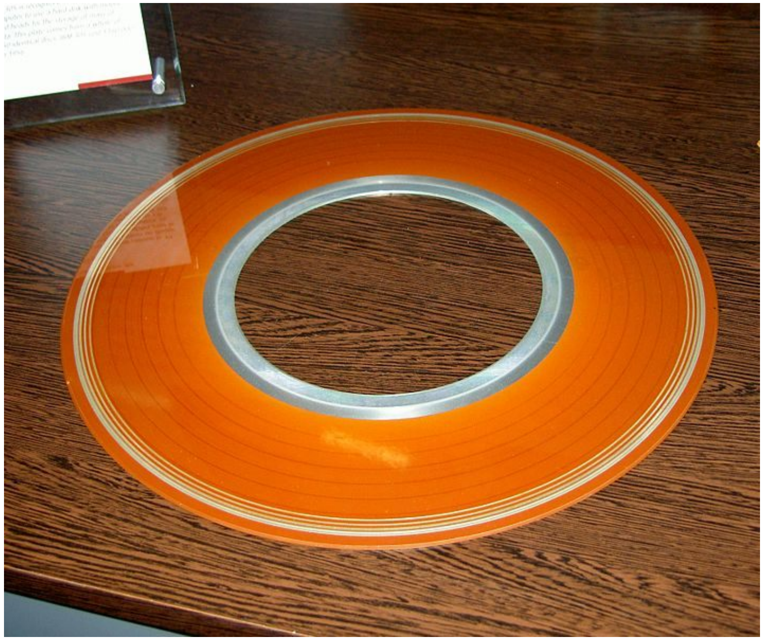
1975 Sony Betamax: home video system

1997 IBM GMR heads



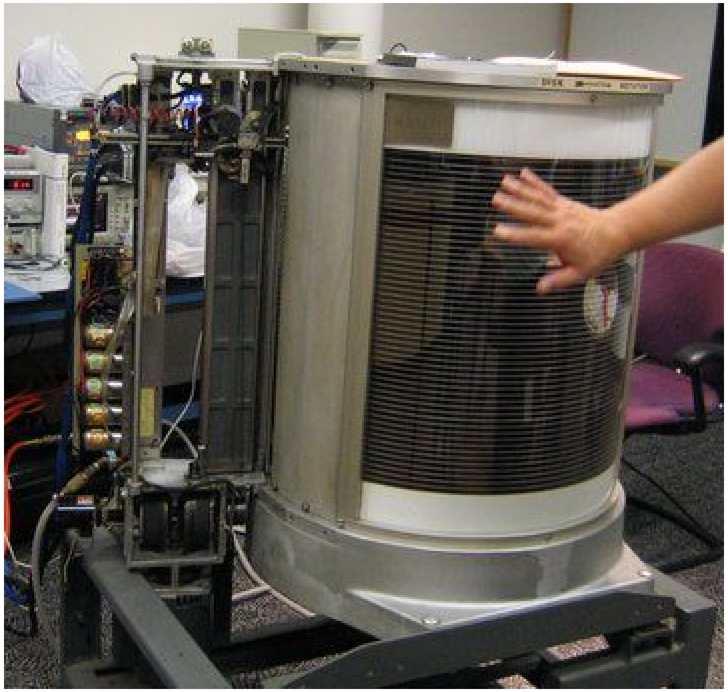
1878 Magnetic sound recording by Oberlin Smith

IBM 305 RAMAC (1956)



A storage plate

Covered with iron oxide

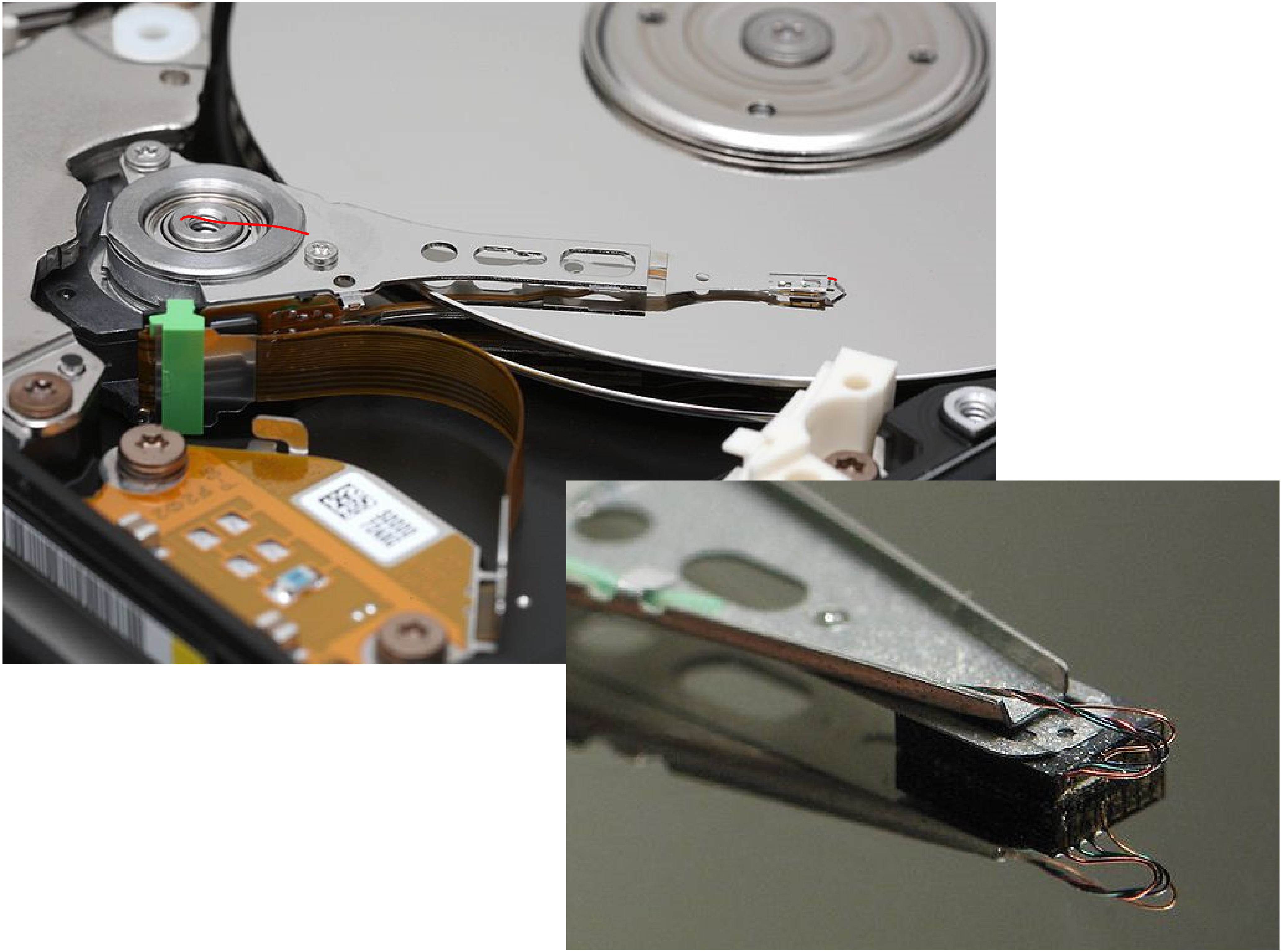


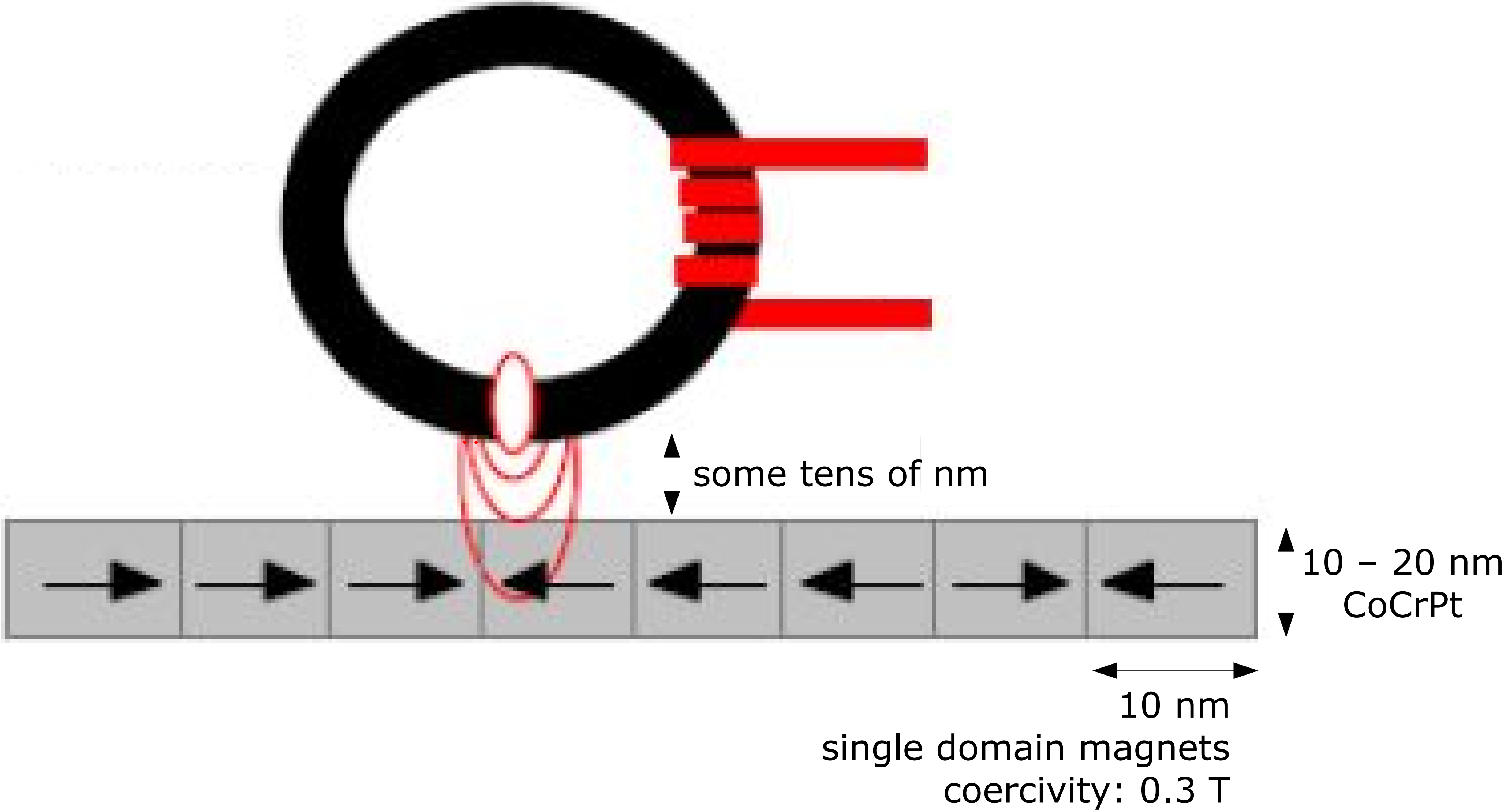
$1.5 \times 1.7 \times 0.6\ \mathrm{m}^3$

1 t

5 Mbyte (8 bit per byte)

1200 rpm



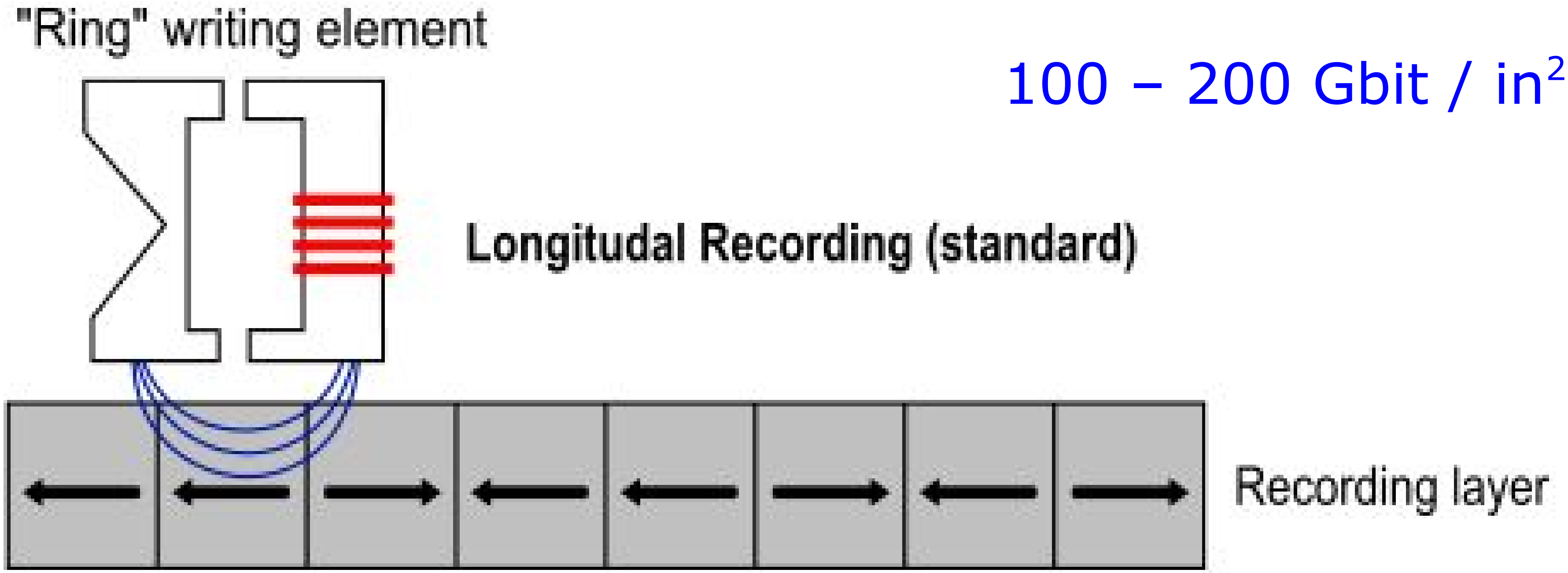


some tens of nm

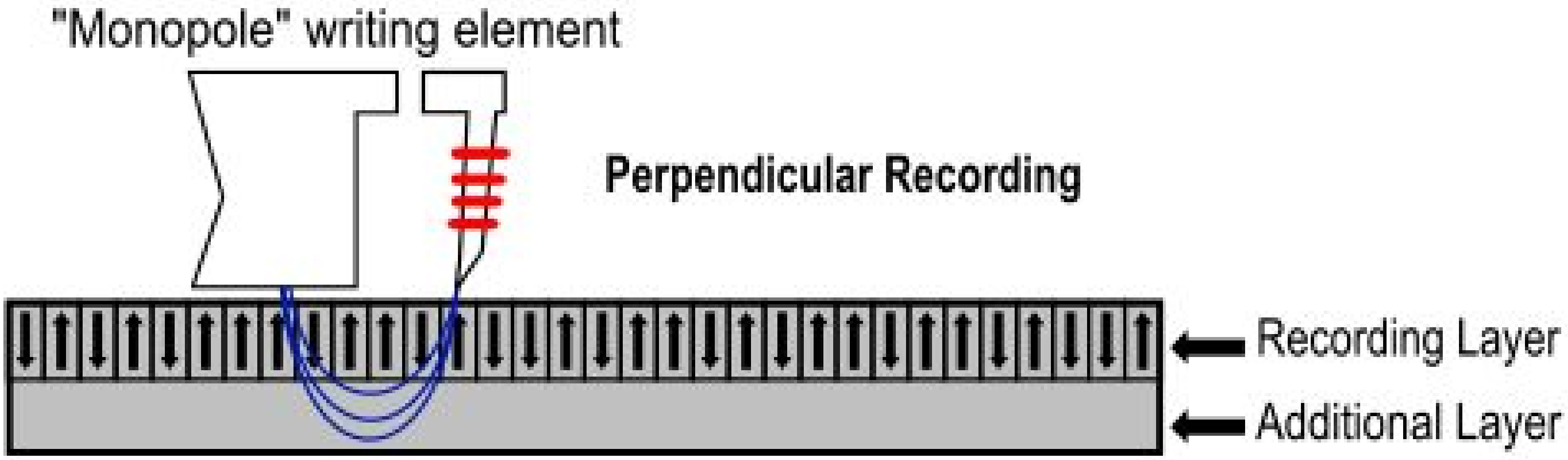
10 – 20 nm
CoCrPt

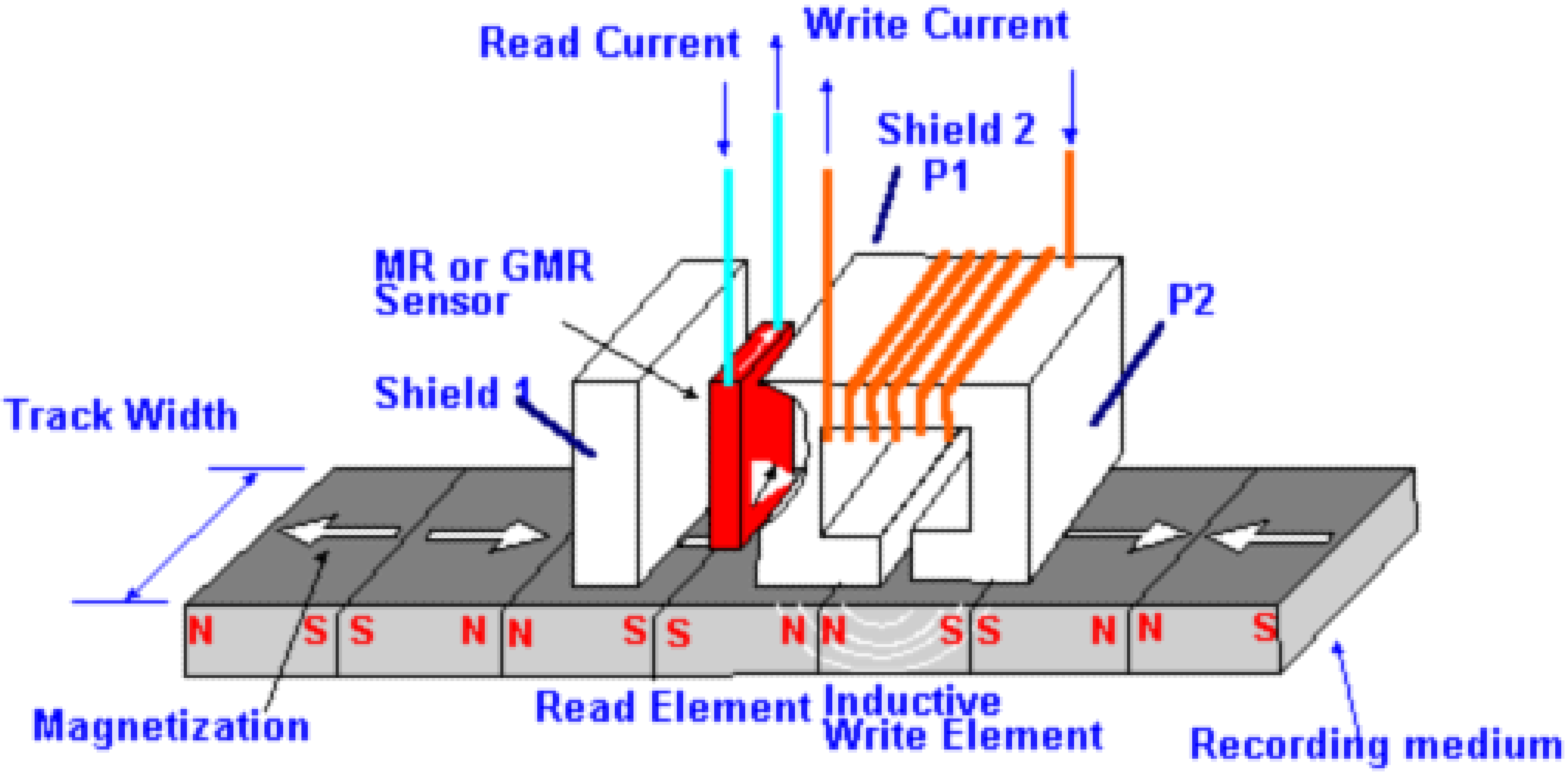
10 nm
single domain magnets
coercivity: 0.3 T

100 – 200 Gbit / in^2



≈ 1 Tbit / in^2




Read Current
Write Current
Shield 2
P1
MR or GMR Sensor
P2
Shield 1
Track Width
N
S
S
N
N
S
S
N
N
S
S
N
N
S
Magnetization
Read Element
Inductive Write Element
Recording medium

Hard disk: data in magnetization of patches of a disk surface

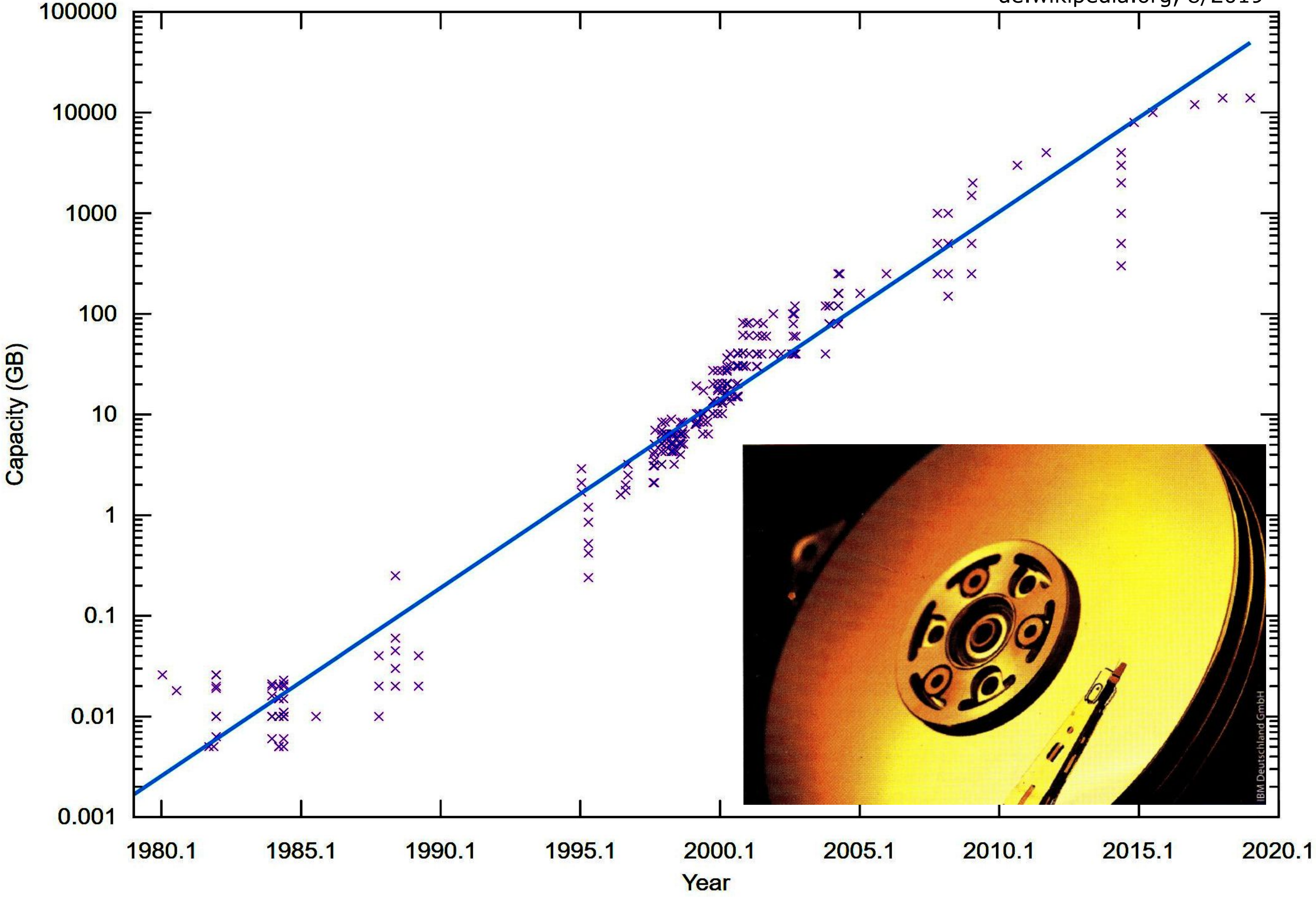
maximum areal density determined by ...

- size of magnetic particles (T matters)
- size of read/write head
- mechanical precision

1956 2000 bit/in^2 *2015* 1.34 Tbit/in^2 (factor > 600 million)

"feasible" scale > 5 Tbit/in^2 (heat-assisted and microwave-assisted magnetic recording)

Media, Write-read heads, Mechanics, ...



de.wikipedia.org, 8/2019

Limit: Superparamagnetism

For crystallites with 1 – 10 nm diameter:

$T < T_C, T_N$: Magnetic moment of particle as a whole can fluctuate

Néel-Arrhenius equation:

$$\boxed{\tau = \tau_0 \exp\left(\frac{E}{\mathrm{k_B} T}\right)}$$

τ: reversal time

τ_0: attempt period

E: magnetic anisotropy energy

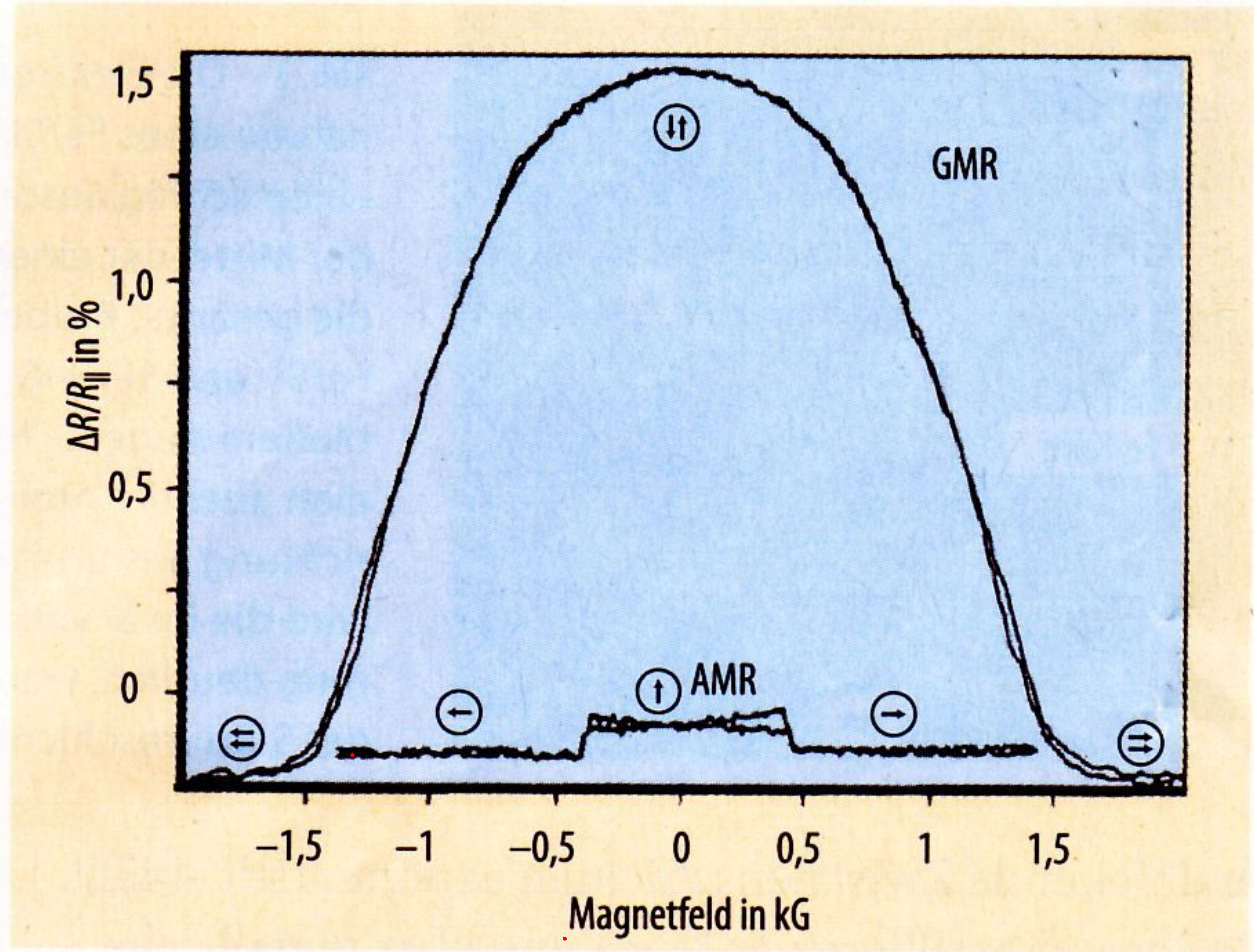
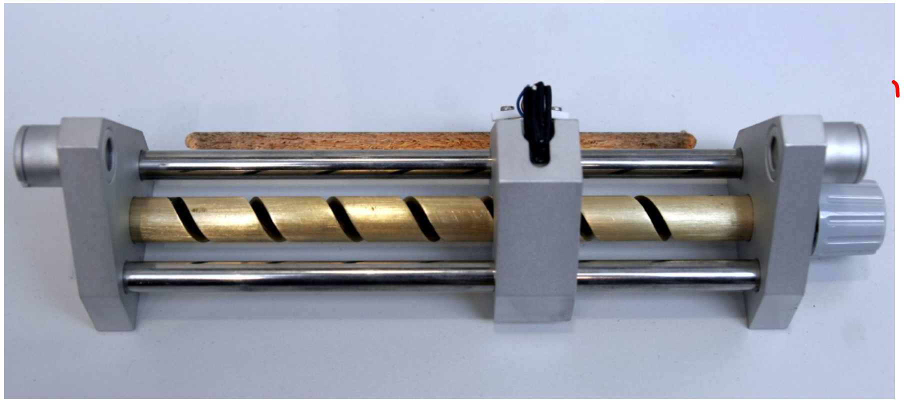
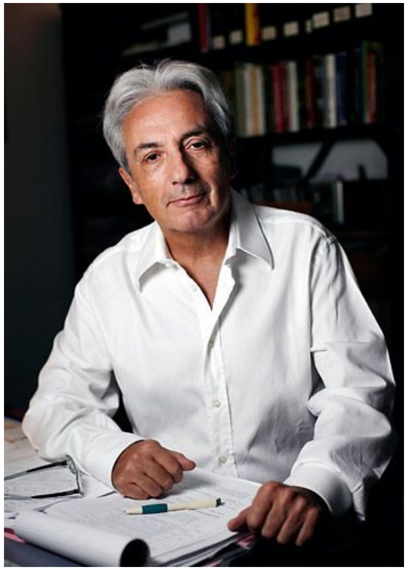


Abb. 4 Der GMR-Effekt im Dreilagensystem Fe/Cr/Fe (Schichtdicke des Eisens: 12 nm) ist im Vergleich zum AMR-Effekt eines 25 nm dicken Fe-Films deutlich ausgeprägter.

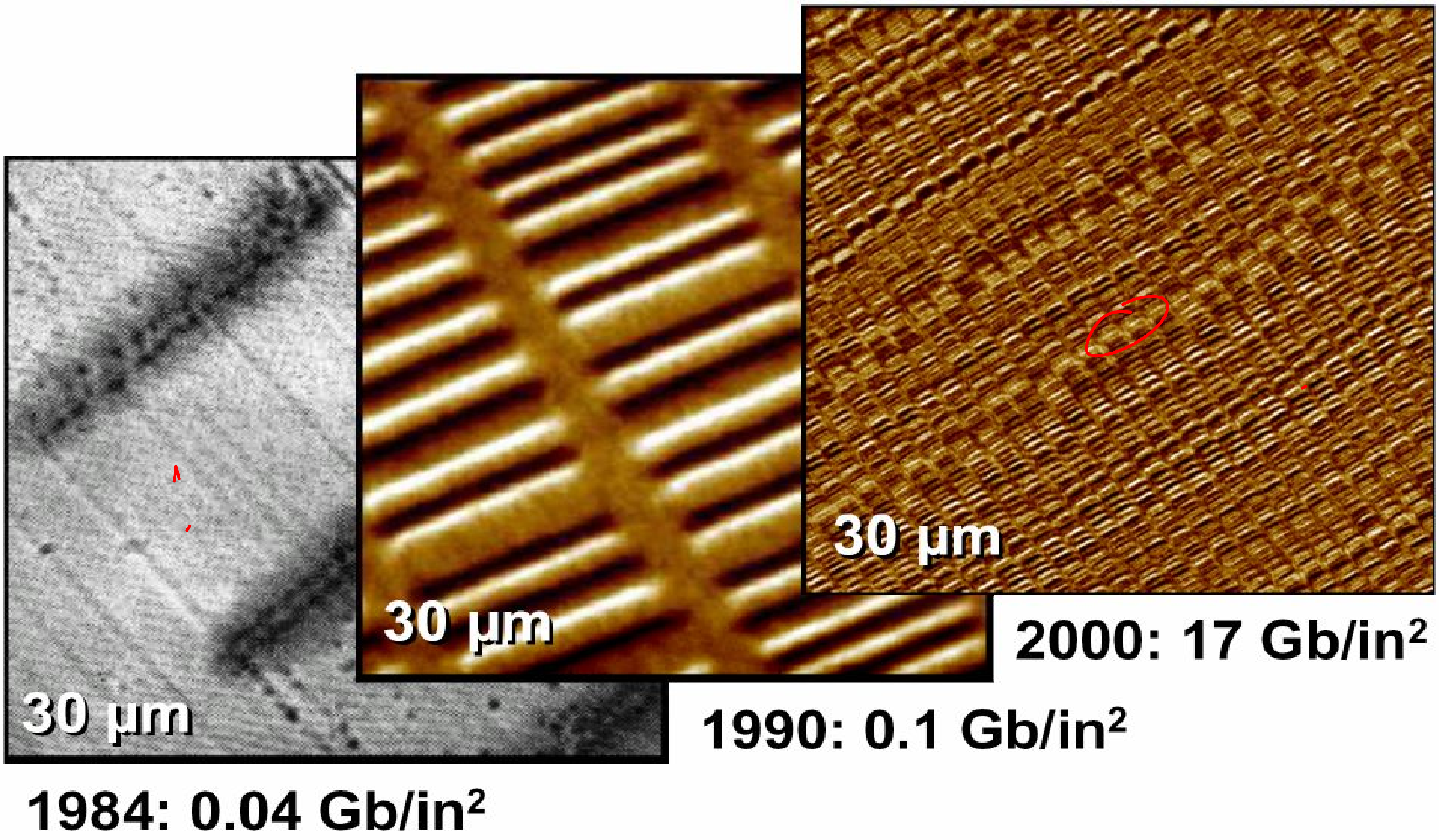


Nobel Prize in Physics
2007
Peter Grünberg 1939-2018
F'zentrum Jülich

Albert Fert 1938
Université Paris-Sud
Orsay



Physik Journal 6 (2007)



Bits auf Festplatten

Bildkanten jeweils 30µm

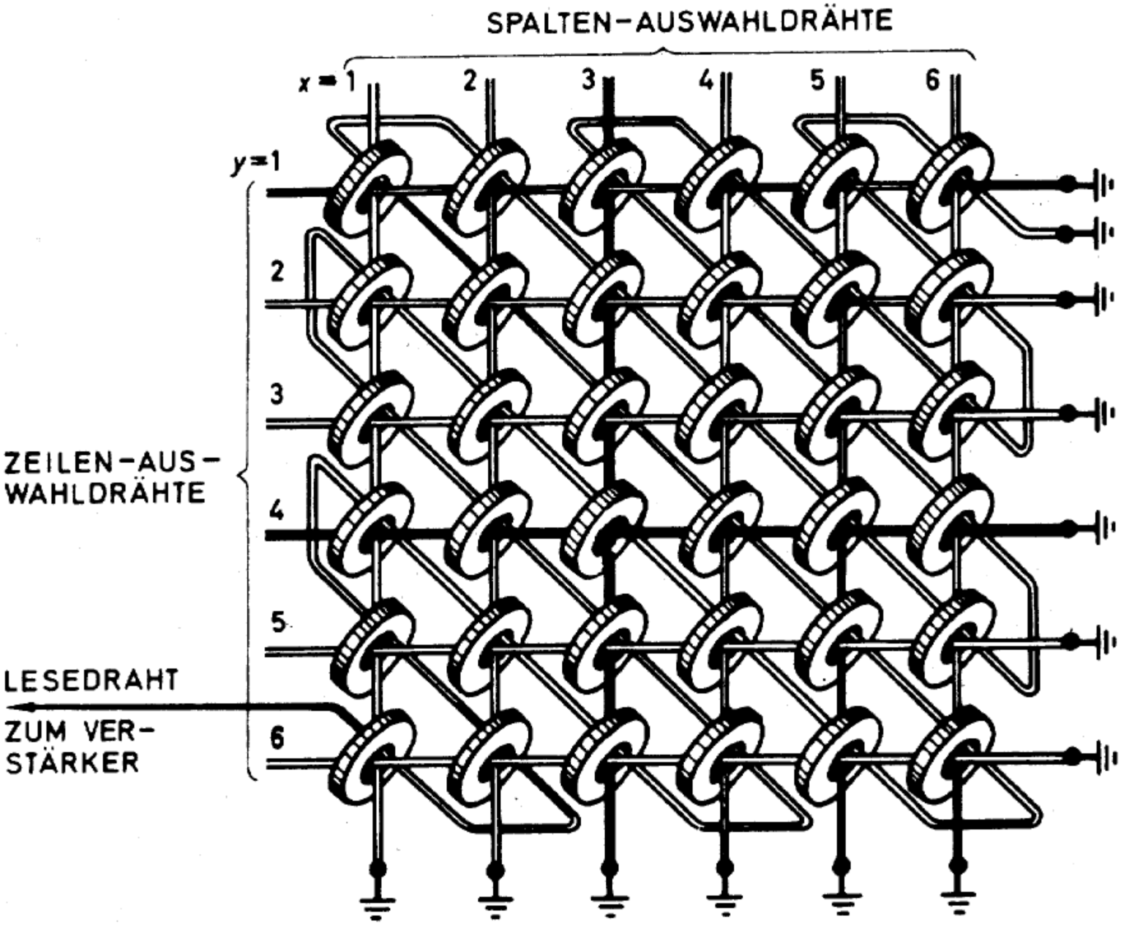
Jedes Bit = Hunderte Partikel

(Quelle: IBM Deutschland)

c’t 2020, Heft 22

“Festplatten sind wohl das beste Mittel, Daten für längere Zeit zu sichern.”

"MRAM" Ringkernspeicher

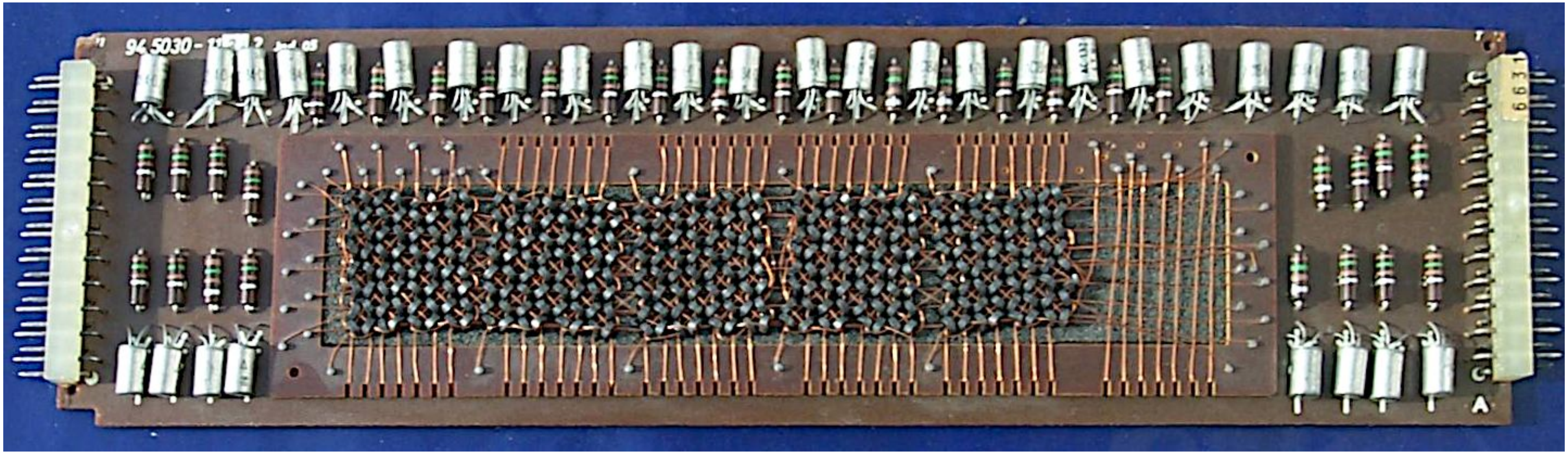


Lese- & Schreibzyklus gleichzeitig.

Lesen: mit X- & Y-Drähten gewünschten Kern zur '0' hin magnetisieren

- falls zuvor '0': keine Änderung, kein Spannungspuls auf Lesedraht
- falls zuvor '1': Änderung, Spannungspuls auf Lesedraht

Kernspeicherplatine einer Olympia Rechenmaschine, ca. 1968



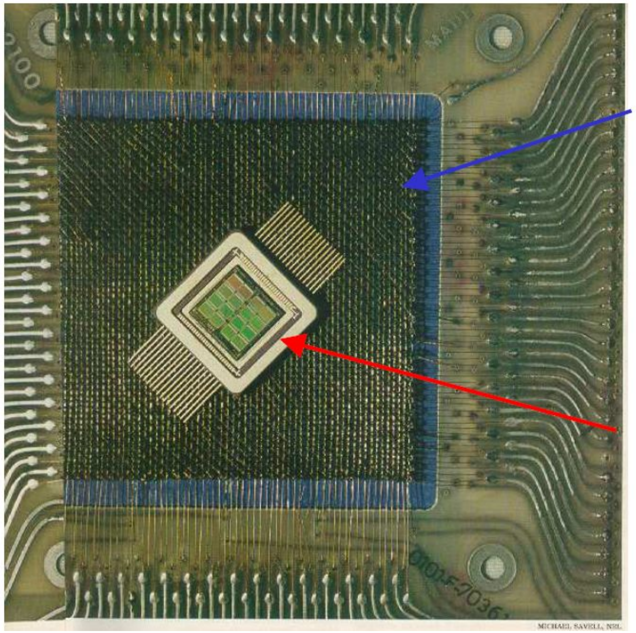
32 Bit Wort - 32 Ebenen (!)

Takt bis 3 MHz

Nicht flüchtig

core dump: (wikipedia)

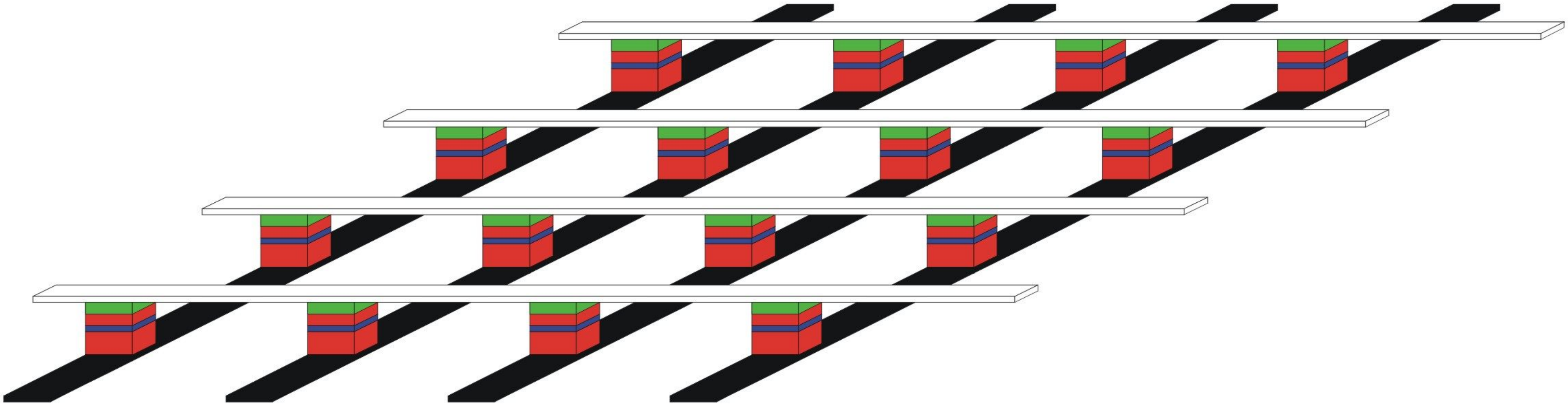
Momentaufnahme des Kernspeichers

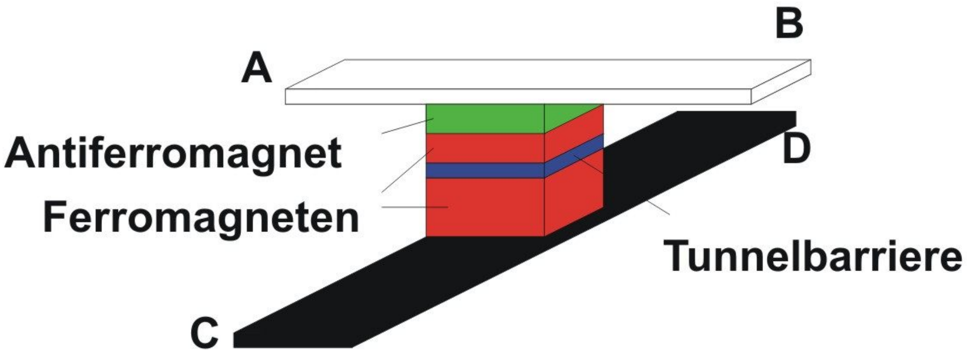


1 kBit Ringkern-speicher

16 kBit Dünnschicht-Speicher (Honeywell)

Magnetic RAM





Lesen: Strom A->D
Schreiben: Strom A->B; C->D

Status (en.wikipedia, 2019)

2010 Hitachi and Tohoku Univ announced Multi-level SPRAM
2011 PTB, Germany, announces having achieved a below 500 ps (2GBit/s) write cycle
2012 Chandler, AZ, USA, Everspin debuts 64Mb ST-MRAM

Currently:

- diverse MRAM products available from Everspin Technol., www.everspin.com
- products planned by Samsung and Hynix
- main applications: high reliability industry apps, aviation, spacecrafts

All of the information ... in all the books in the world can be written … in a cube of material 1/200 inch [0.13 mm] wide.

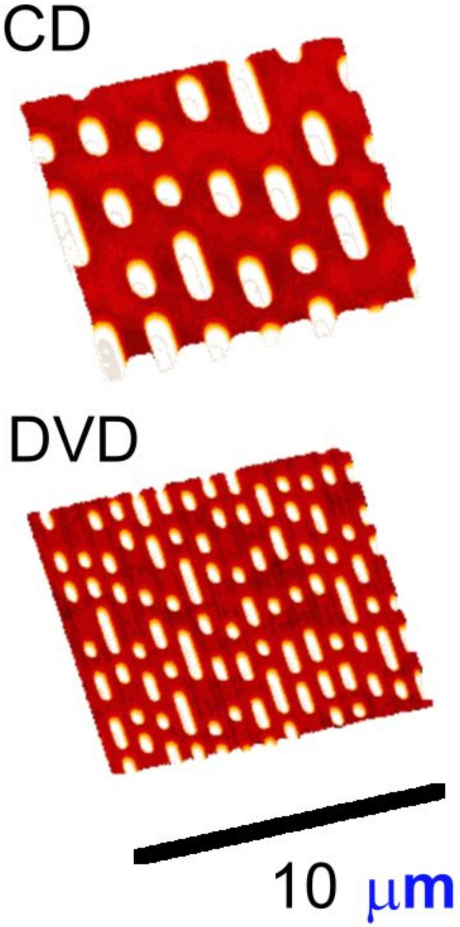
Use 125 atoms to store one bit.

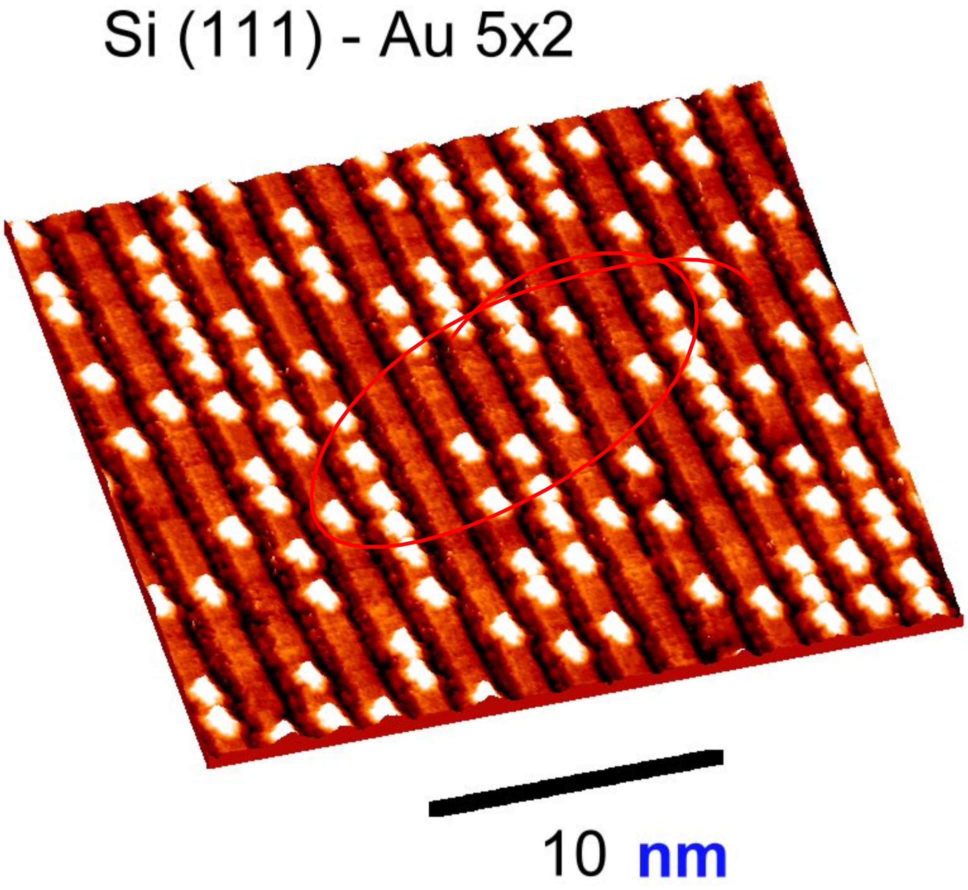
R. Feynman, Caltech, December 29th, 1959

Quelle: Prof. Franz Himpsel, UW-Madison

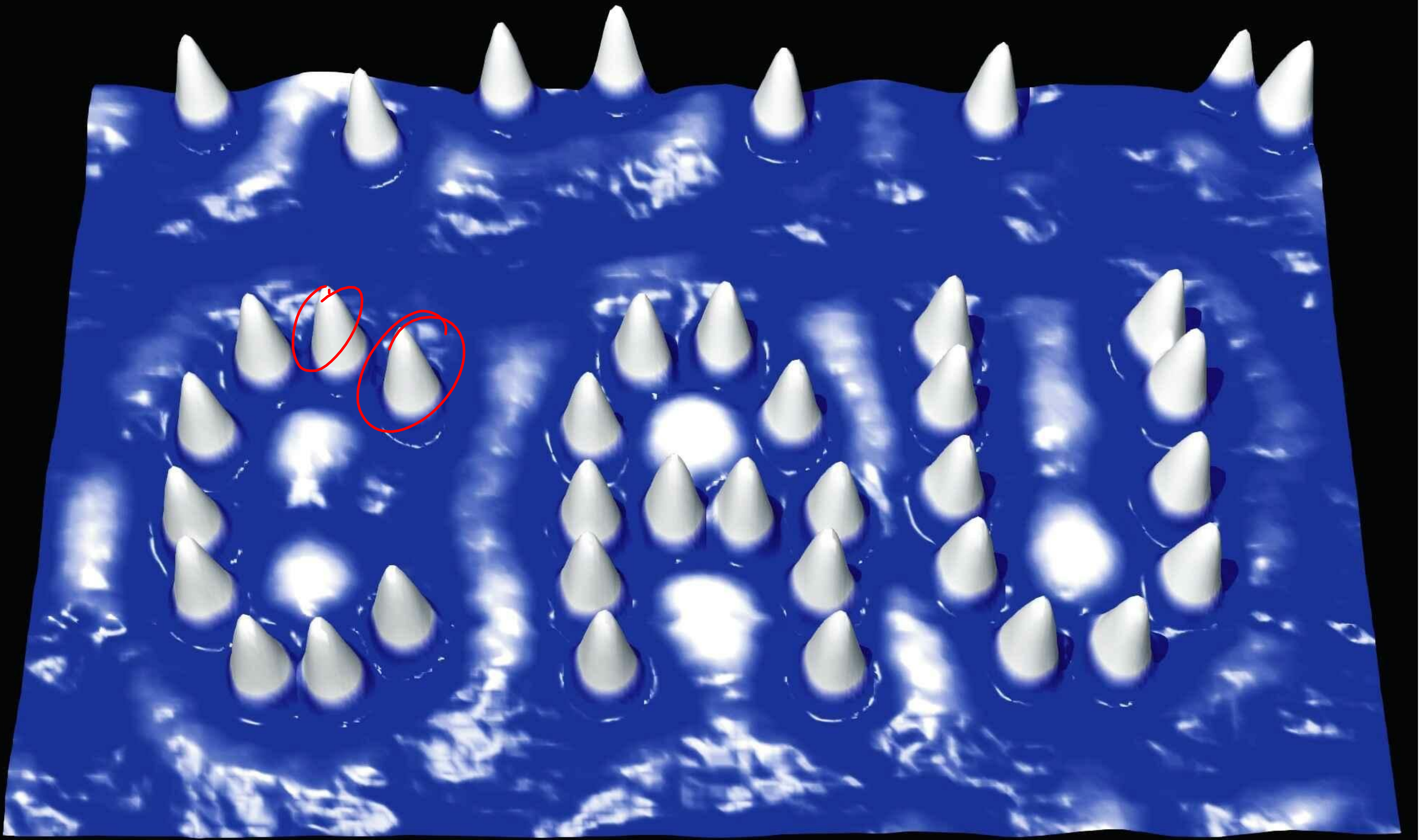
In pursuit of the ultimate storage medium

1 Atom per Bit





Quantum Laboratory



Christian-Albrechts-Universität zu Kiel

Smaller Bits ⇒ Less Energy Stored ⇒ Slower Readout

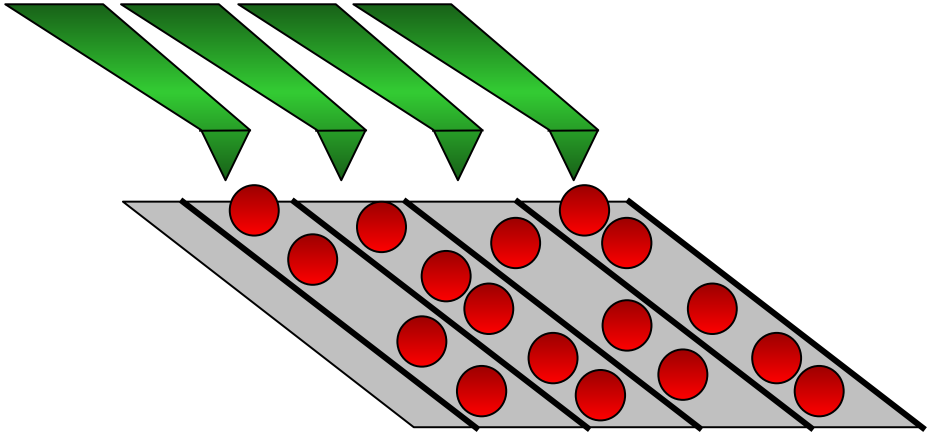
Use Highly-Parallel Readout

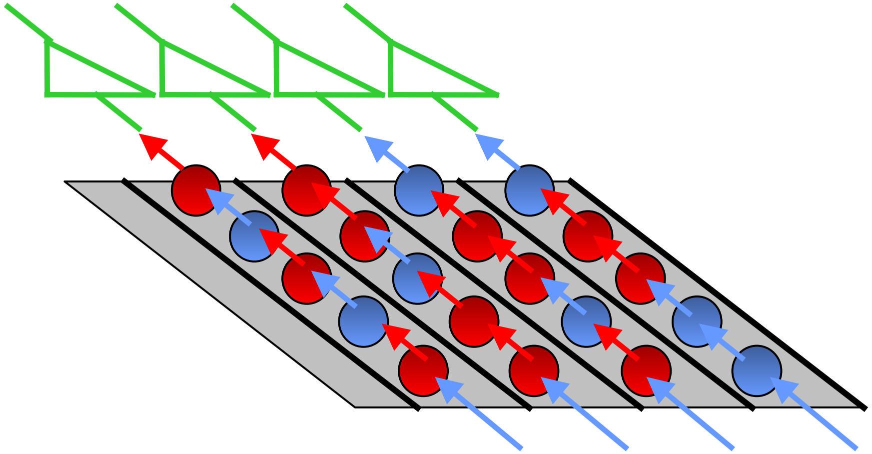
Array of Scanning Probes

(Millipede, IBM Zürich)

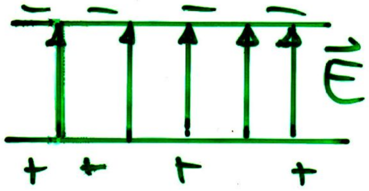
Array of Shift Registers

(nm ⇒ µm)

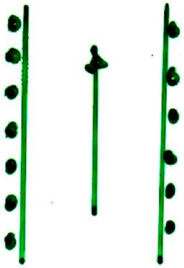




Gegenüberstellung: elektr. & magn. Größen



LEER



$B = \mu_0 H$

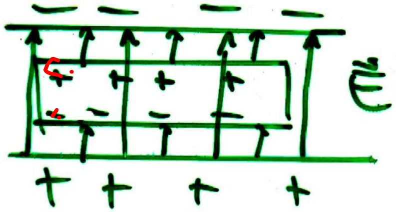
LEER

$E \longleftrightarrow B$

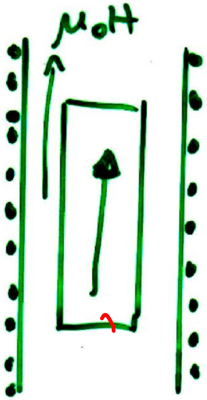
$\epsilon_0 \qquad 1/\mu_0$

$P \qquad -M$

$P = \chi_{el} E$ aber $M = \chi_m H$



$\vec{E} = \vec{E}_{leer} - \frac{1}{\epsilon_0}\vec{P}$



$B = B_{leer} + \mu_0 M$

MIT MATERIE

Suszeptibilität χ

kleine B: $M \sim B$ $\qquad \cancel{(M = \chi B)}$

$$M = \chi H$$

$$B = \mu_0 (H + M) = \mu_0 \mu H$$

Permeabilität $\mu = 1 + \frac{M}{H} = 1 + \chi$

magnet. Polarisation:

$$J_{pol} = \mu_0 M, \qquad [J] = T$$

Dipol $\vec{\mu}$

$E = -\vec{\mu}\vec{B}$ $\qquad$ $\vec{F} = \vec{\nabla}(\vec{\mu}\vec{B})$

$T = \vec{\mu} \times \vec{B}$

$$\vec{B}(\vec{r}) = \mu_0 \left(\frac{3(\vec{\mu}\vec{r})\vec{r}}{r^5} - \frac{\vec{\mu}}{r^3} \right)$$

$$E_{dipol-dipol} = \mu_0 \left(\frac{\vec{\mu}_1 \cdot \vec{\mu}_2}{r^3} - 3\frac{(\vec{\mu}_1\vec{r})(\vec{\mu}_2\vec{r})}{r^5} \right)$$

$\vec{r} = \vec{r}_1 - \vec{r}_2$

$$\vec{\mu} = I\vec{A}$$

Kreisbahn: $\vec{\mu} = -e\frac{\omega}{2\pi}\pi r^2\vec{n} = -\frac{1}{2}e\omega r^2\vec{n}$

Vergl. Drehimpuls: $\vec{J} = \vec{r} \times m_e\vec{v} = m_e\omega r^2\vec{n}$

$$\Rightarrow \vec{\mu} = -\frac{|e|}{2m_e}\vec{J}$$

$$\mu_B = \frac{|e|\hbar}{2m_e} = 9{,}2740 \cdot 10^{-24}\,\frac{J}{T}$$

$\approx 58\,\frac{\mu eV}{T}$ | k_BT bei 300 K

$\frac{1}{40}\,eV = 25\,meV$

magn. Moment des e^-

Bahn: $\vec{\mu}_e = -\frac{e}{2m_e}\vec{\ell}$

Spin: $\vec{\mu}_s = -\underbrace{g_s\frac{e}{2m_e}}\vec{s}$

gyromagn. Verhältnis

$$\vec{\mu}_j = \vec{\mu}_e + \vec{\mu}_s = -\frac{e}{2m_e}(\vec{\ell} + g_s\vec{s}) \overset{!}{=} -\frac{e}{2m_e}g_j\vec{j}$$

$$\Rightarrow g_j = 1 + \frac{j(j+1) + s(s+1) - \ell(\ell+1)}{2j(j+1)}$$

Spezialfall: $l=0,\ s=\frac{1}{2} \Rightarrow j=\frac{1}{2}$

$m_j = \pm 1 \quad ; g = 2$

$$E = -\vec{\mu}\vec{B} = \overset{\uparrow\downarrow}{\underset{\uparrow\uparrow}{\pm}} \mu_B B$$

Aufspaltungen atomarer Niveaus

① Zentralfeld (Kern $\Leftrightarrow e^-$, Zentralanteil von $e^- - e^-$)

→ Grobstruktur "Konfigurationen"

n, L ; typ. $\approx$ 1–4 eV

(Schale ≙ fester n
K, L, M)

② nicht-zentrale Anteile von $e^- - e^-$ – WW

n, L, S "Terme"

typ. $\approx$ 0,4 eV

Entartung: $(2L+1)(2S+1)$

③ Spin-Bahn-WW
"Feinstruktur"
Niveaus: festen n, L, S, J
Abstand $10^{-4} \ldots 10^{-1}$ eV
Entartung $2J+1$

④ Ext. B-Feld: Zeemaneffekt
→ J_z-Entartung aufgehoben
für $B = 5\,T$: 10^{-4} eV

⑤ WW Kernspin-Hülle: Hyperfeinstruktur
$10^{-7} \ldots 10^{-4}$ eV