



Nano I - Nano-Elektronik: top-down

Nanoelectronics and Information Technology
R. Waser ed., Wiley & Sons (3rd ed.) 2012

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From Oct. 2016

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Weltkarte ... auf der nano-Skala

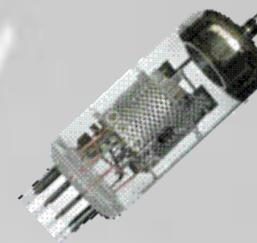
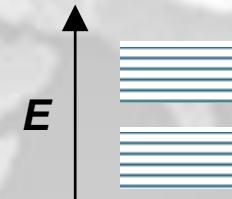
Schweiz ~ 100nm
(Anstatt 300km)



$2 \mu m$

Inhalt

- ***nano-Welt?***
 - eine Frage der Skala
- ***nano-Physik – klein, aber anders***
 - etwas Nanophysik, bis zum Elektron im Potentialtopf
- ***nano-Elektronik***
 - Beispiel: Leitwert Quantisierung
 - Entwicklung der Elektronik
 - Neue Materialen



nano ?



m, dm, cm, ..., nm

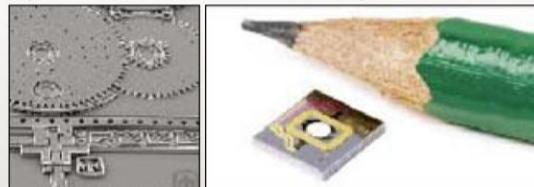
FAIT PAR L'HOMME

Clou



1-2 mm

Systèmes micromécaniques (MEMS)



10-100 µm

Revêtements nanostructurés



10-1000 nm

Nanotube sphère de



1 mètre

10^{-1} m

10^{-2} m

10^{-3} m

10^{-4} m

10^{-5} m

10^{-6} m

10^{-7} m

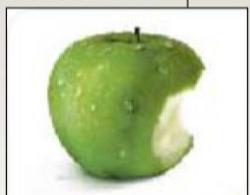
1 cm

1 mm

10^{-5} m

1 µm (micromètre)

Pomme



Fourmi



~5 mm

Cheveu



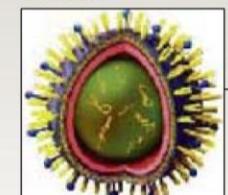
60-120 µm (diamètre)

Globule rouge



7-8 µm

Virus



25-100 nm (diamètre)

NATUREL

m, dm, cm, ..., nm

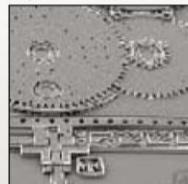
FAIT PAR L'HOMME

Clou



1-2 mm

Systèmes micromécaniques (MEMS)



10-100 µm



Revêtements nanostructurés



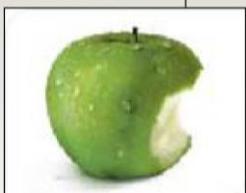
10-1000 nm

Nanotube sphère de



1 mètre 10^{-1}m 10^{-2}m 10^{-3}m 10^{-4}m 10^{-5}m 10^{-6}m 10^{-7}m

Pomme



Fourmi



~5 mm

Cheveu



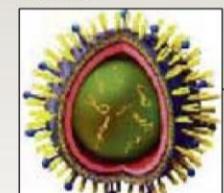
60-120 µm (diamètre)

Globule rouge



7-8 µm

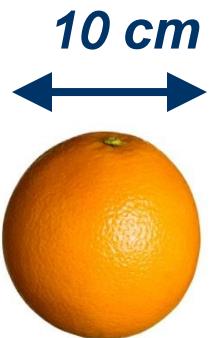
Virus



25-100 nm
(diamètre)

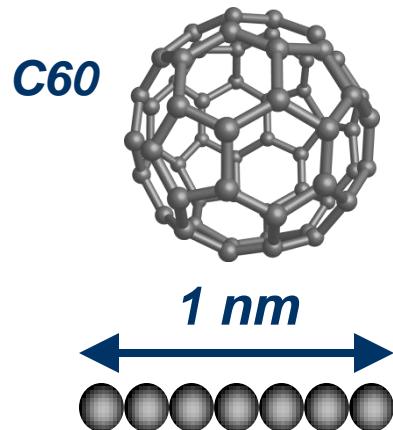
NATUREL

Skala



10 cm

$\times 10^8$



7 C Atome

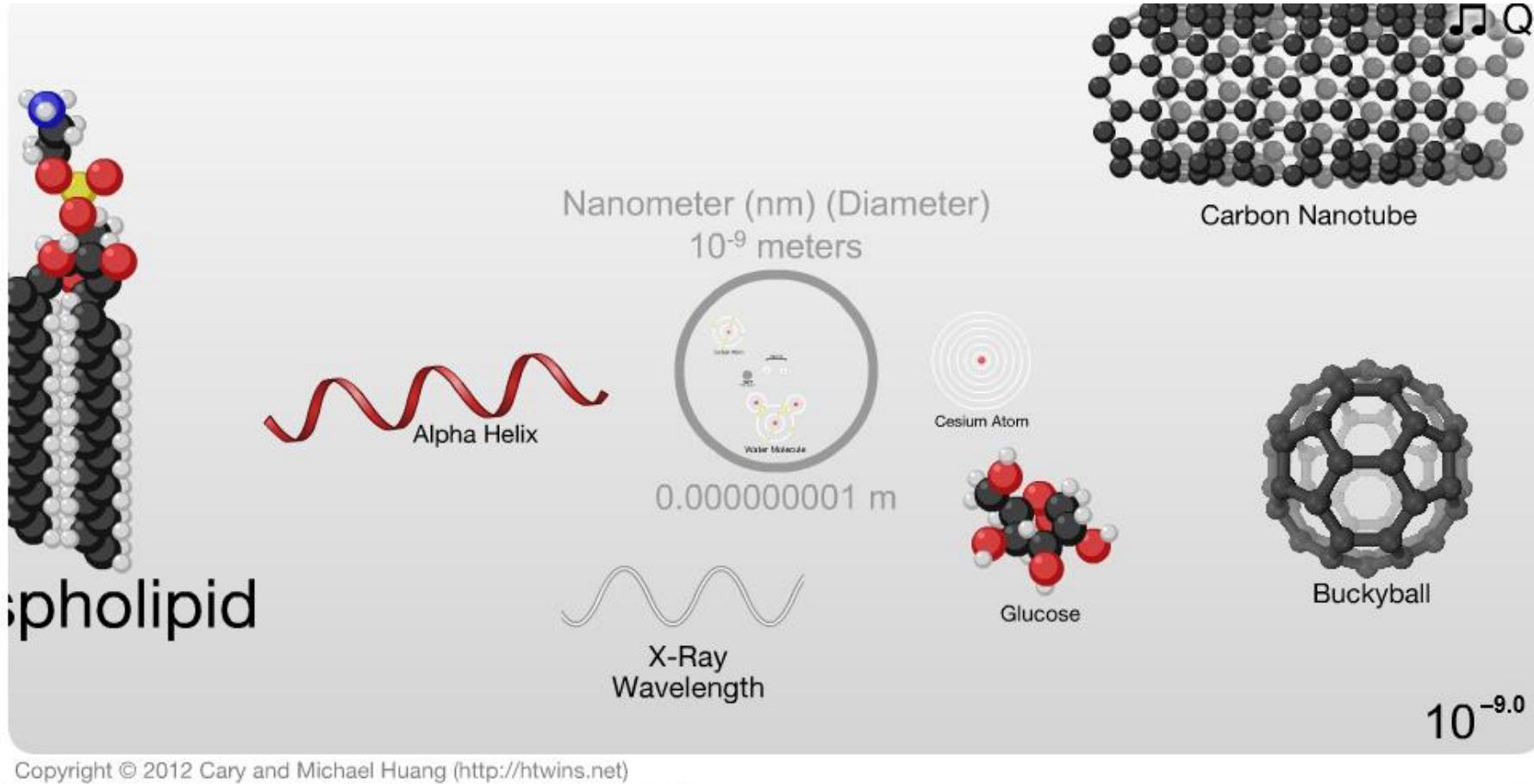
$\times 10^8$



Skala

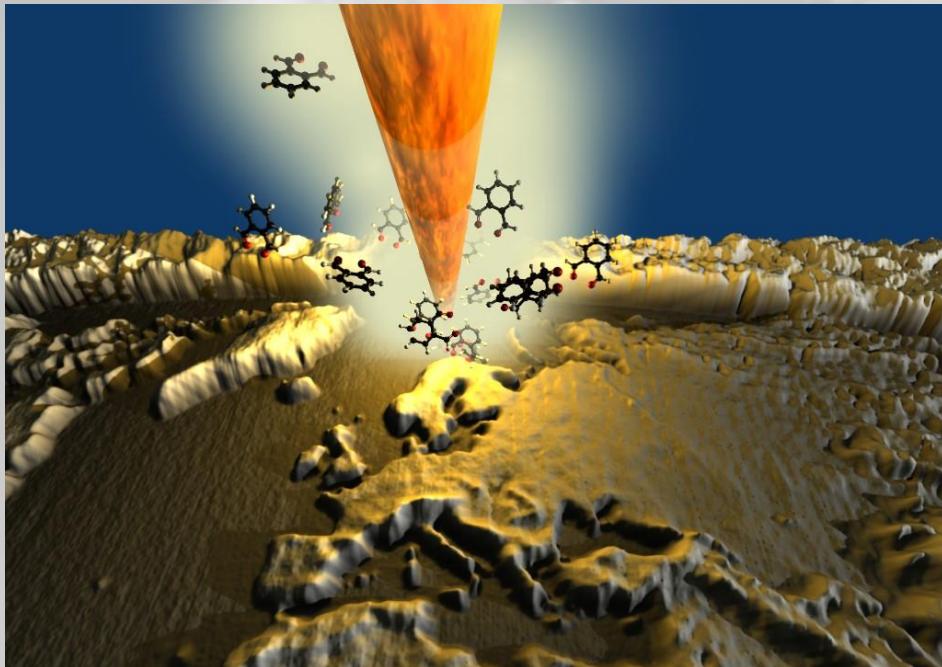
The scale of things

<http://htwins.net/scale2/>

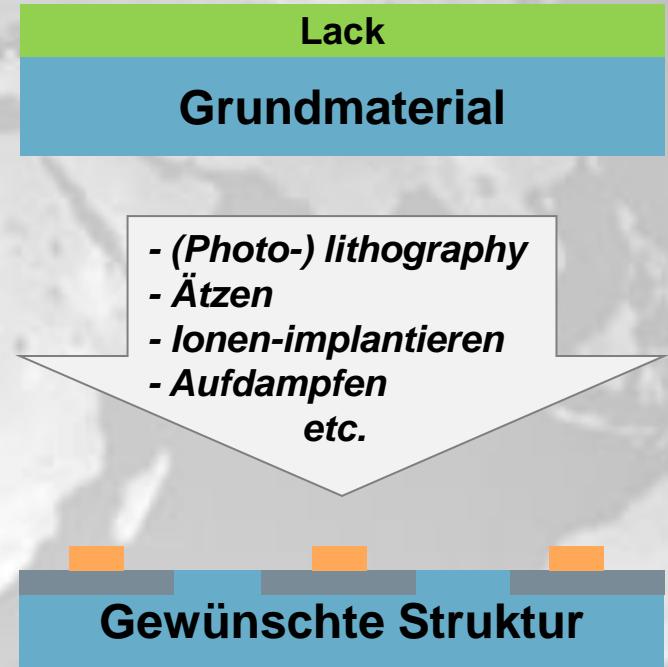


Weltkarte ... Top down

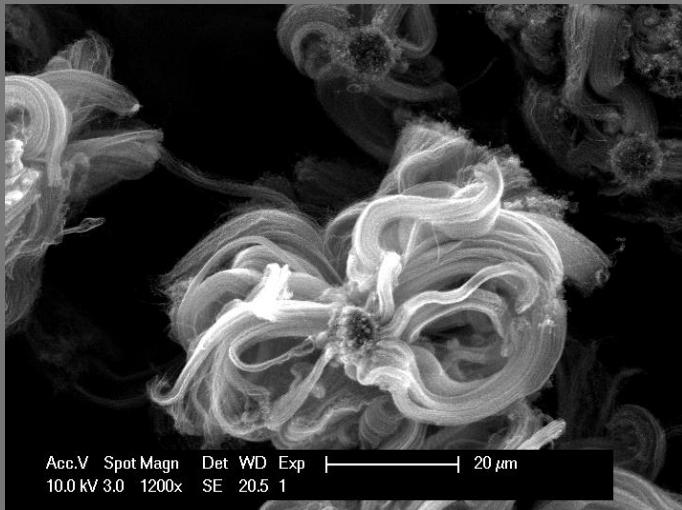
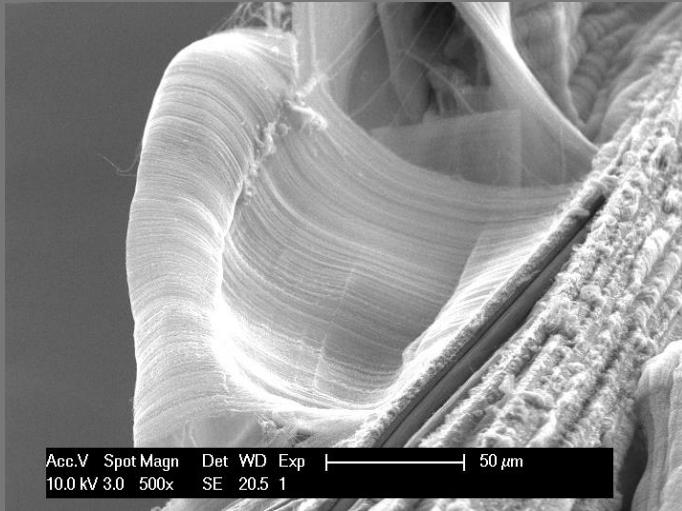
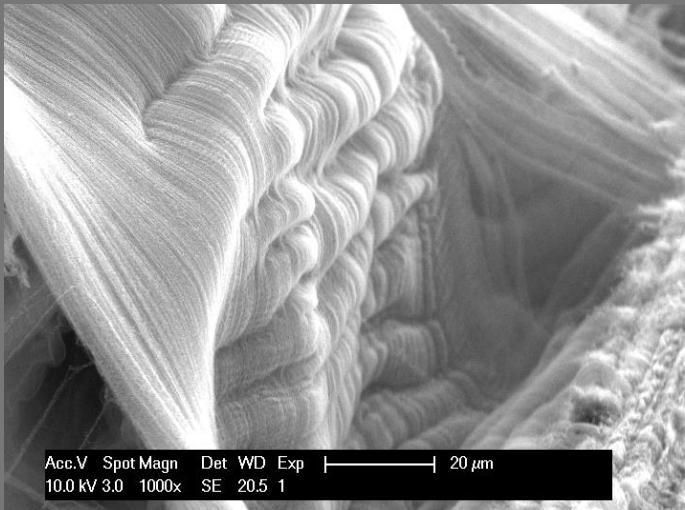
thermal Scanning Probe Lithography



Generischer top down Prozess



klein, aber anders



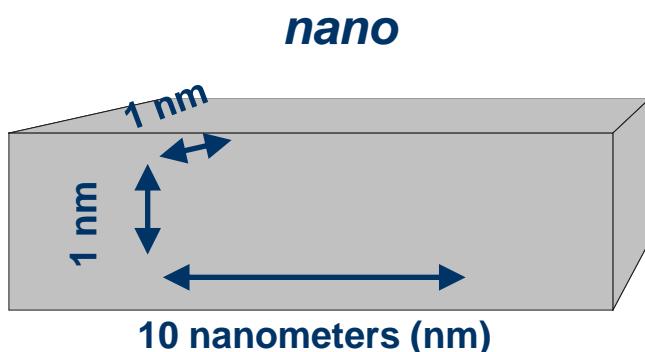
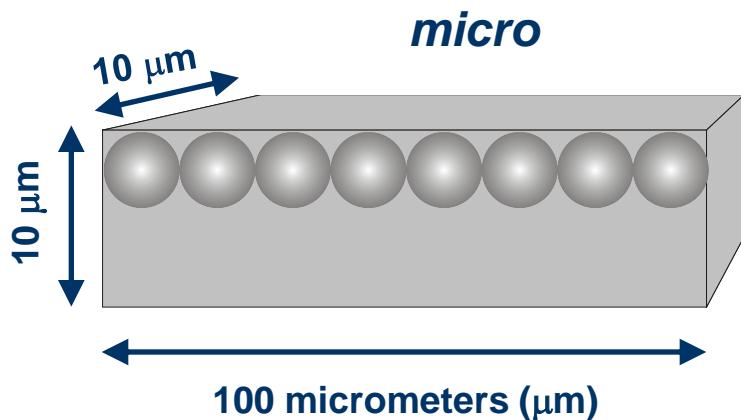
klein, aber anders



Atome an der Oberfläche oder tief in Festkörpern sind nicht "egal"

klein, aber anders

Oberfläche/Volumen



$$R = \frac{\text{nb. surface atoms}}{\text{total nb. atoms}}$$

$$1 \text{ atom} \sim (0.1\text{nm}) \times (0.1\text{nm}) \times (0.1\text{nm})$$

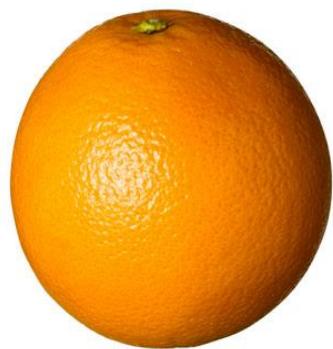
$$R (\text{micro}) \approx 0.004 \%$$

$$R (\text{nano}) \approx 40\% !$$

⇒ **important surface effects**

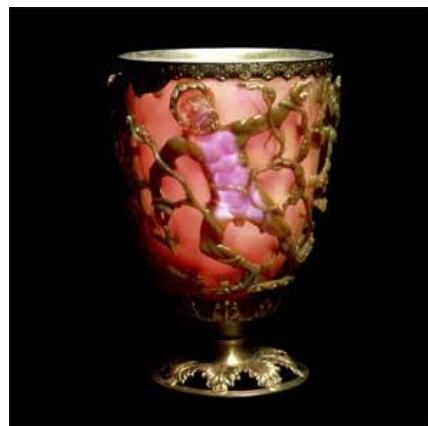
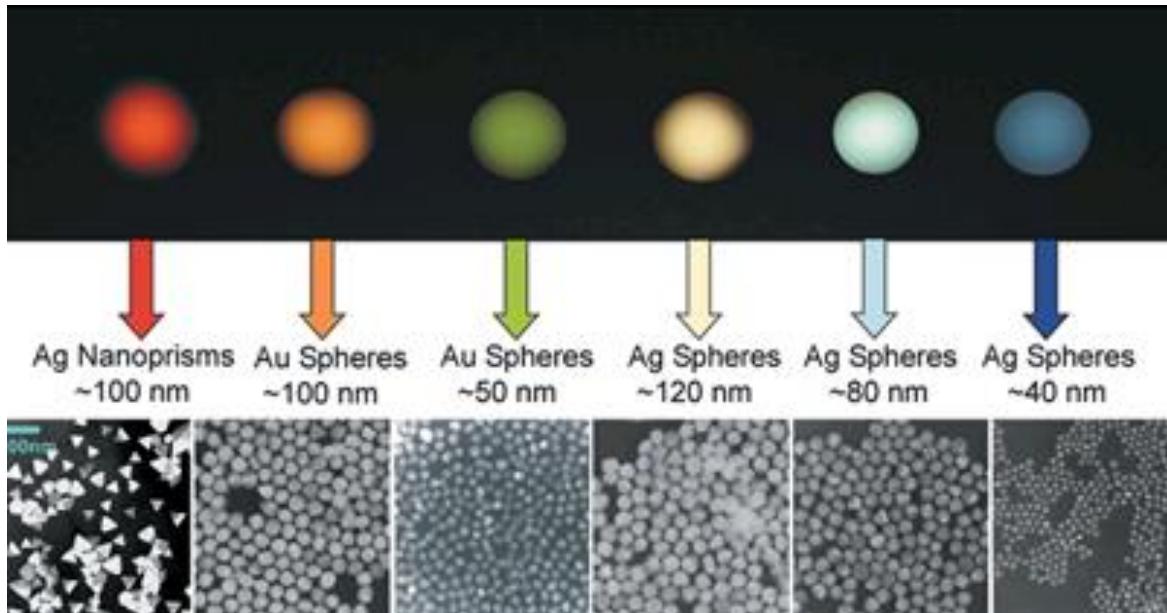
e.g.: *lower melting temperature, higher chemical reactivity*

klein, aber anders



ändert sich die Farbe mit der Verkleinerung...?

klein, aber anders



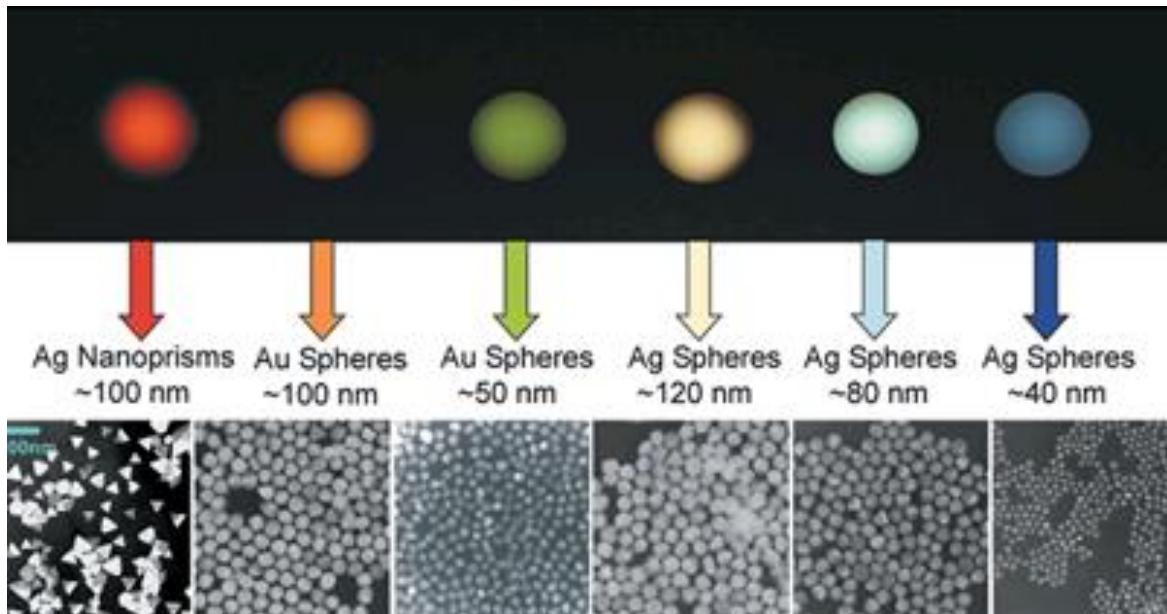
- **Römischer Lycurgus-Kelch (4. Jhd. n.C.)**
(Au, Ag, Cu)

- **In Kirchenfenstern (teilweise)**

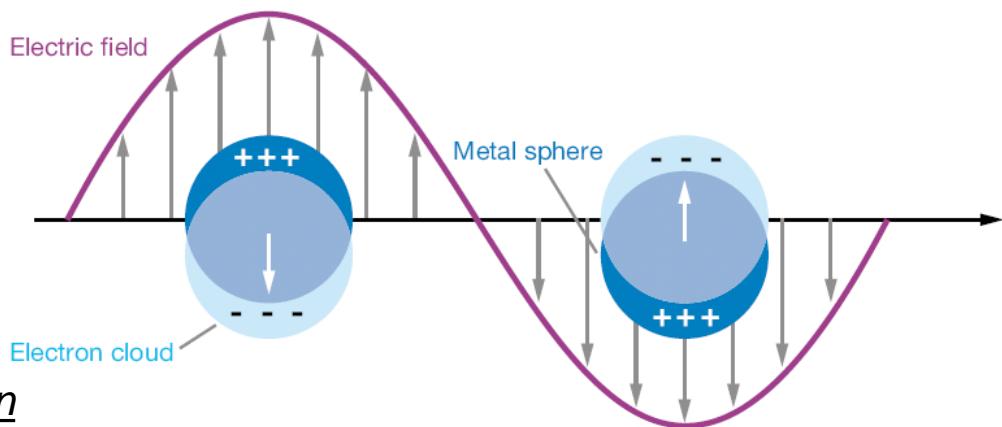


Lycurgus-Kelch, 400 A.D., British Museum; Fenster: NY Times

klein, aber anders



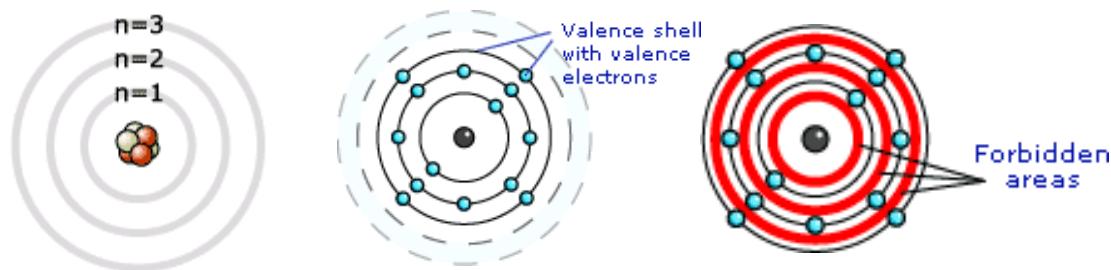
localized plasmons:
Kollektive Anregung von Elektronen



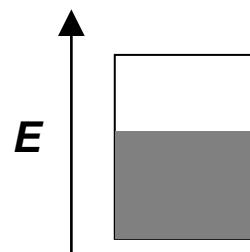
klein, aber anders

Elektronen in Festkörpern, Atomclustern & Molekülen

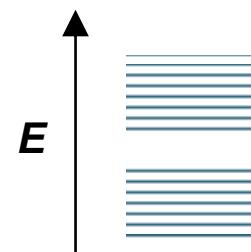
Atommodell: Quantisierte Energieniveaus (Bohr, Pauli, ...)



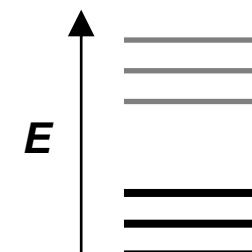
$$E_n \propto \frac{1}{L^2}$$



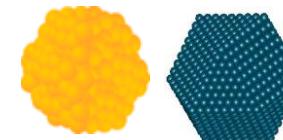
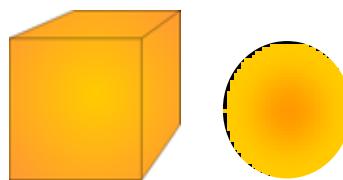
Metall



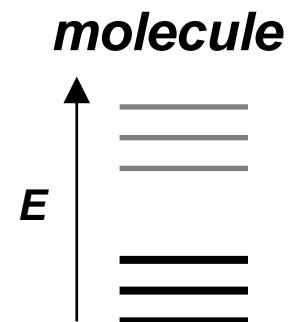
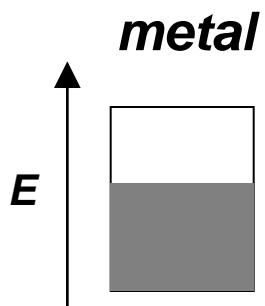
Nanokristall



Moleköl



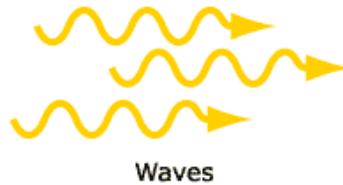
klein, aber anders



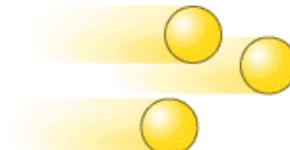
quantum confinement and energy quantization

klein, aber anders

Atome, Elektronen, ...
Teilchen oder Welle ?



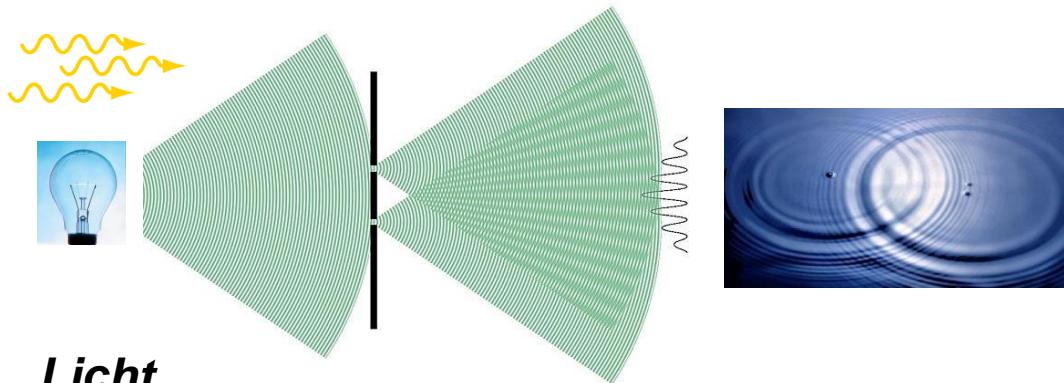
Waves



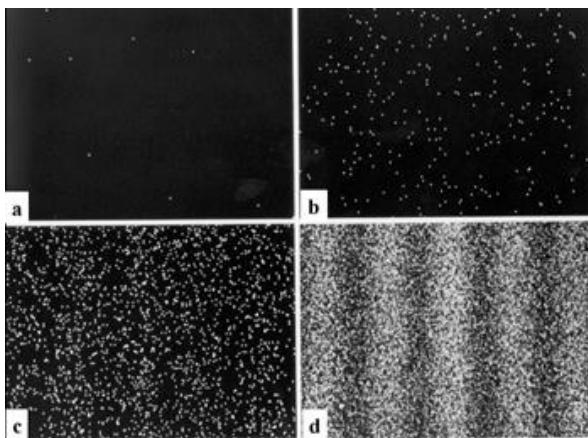
or particles?

klein, aber anders

Atome, Elektronen, ...
Teilchen oder Welle ?



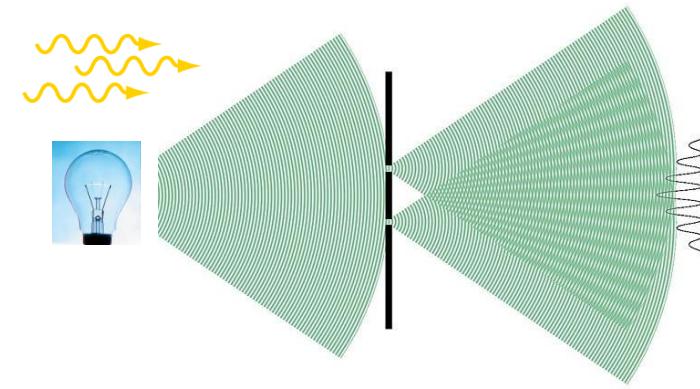
Licht



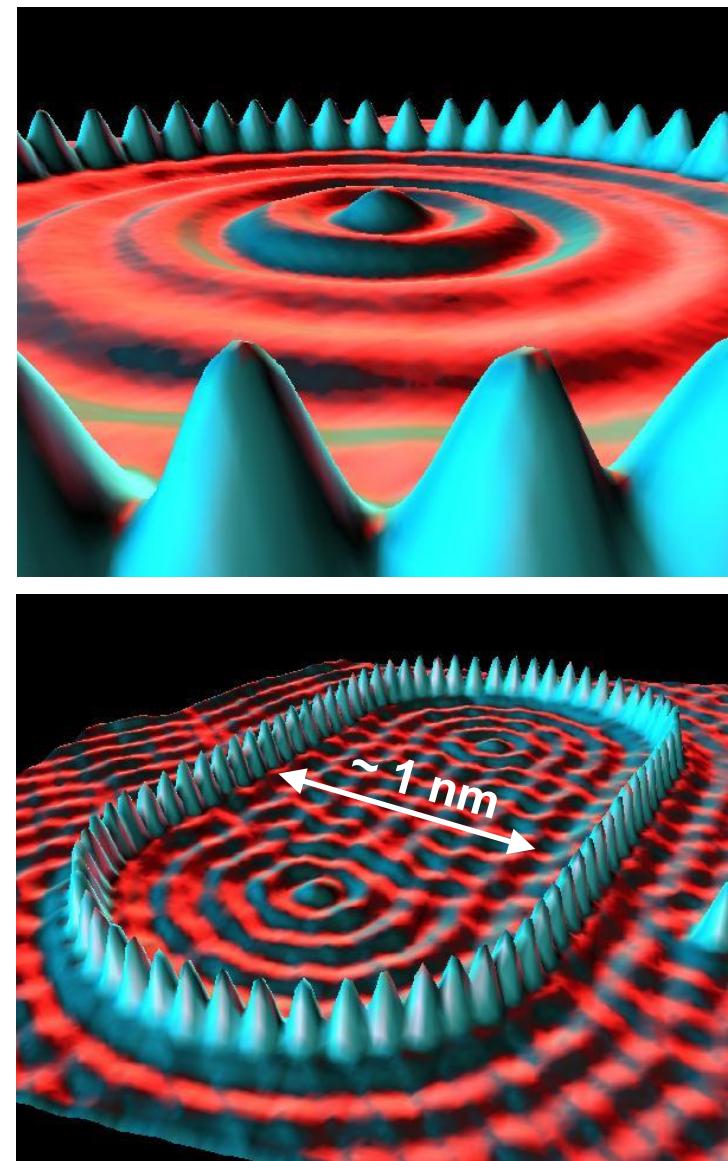
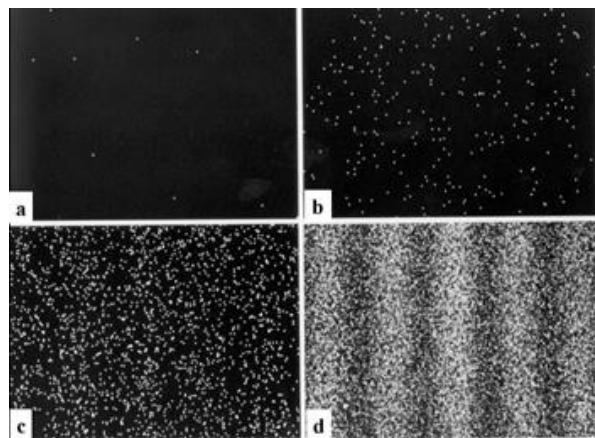
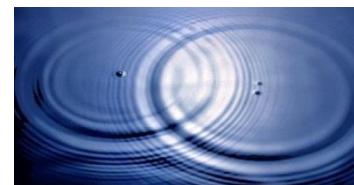
Elektronen

klein, aber anders

Atome, Elektronen, ... Teilchen oder Welle ?

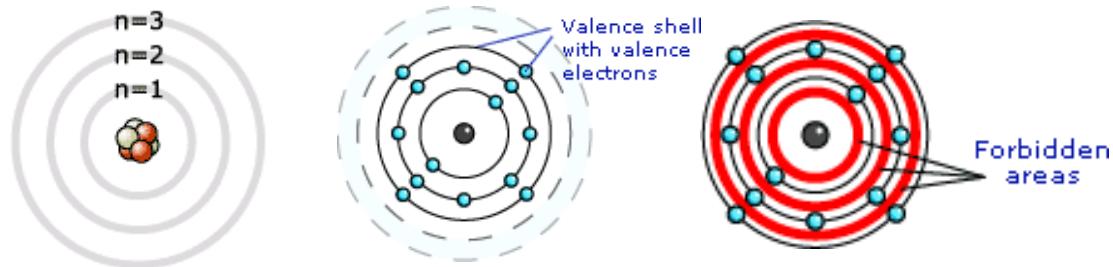


Elektronendichte Wellen
*D. Eigler et al.
IBM Almaden
Quantum corral*

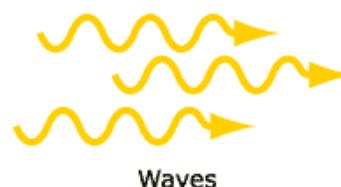


Grundlegende Eigenschaften der Materie

- Quantisierte Energieniveaus (Bohr, Pauli, ...)

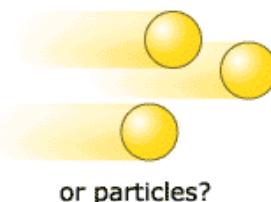


- Welle-Teilchen Dualismus (Planck, Einstein, de Broglie, Heisenberg, ...)



$$p = \frac{h}{\lambda}$$

**de Broglie
Wellenlänge
des Elektrons**



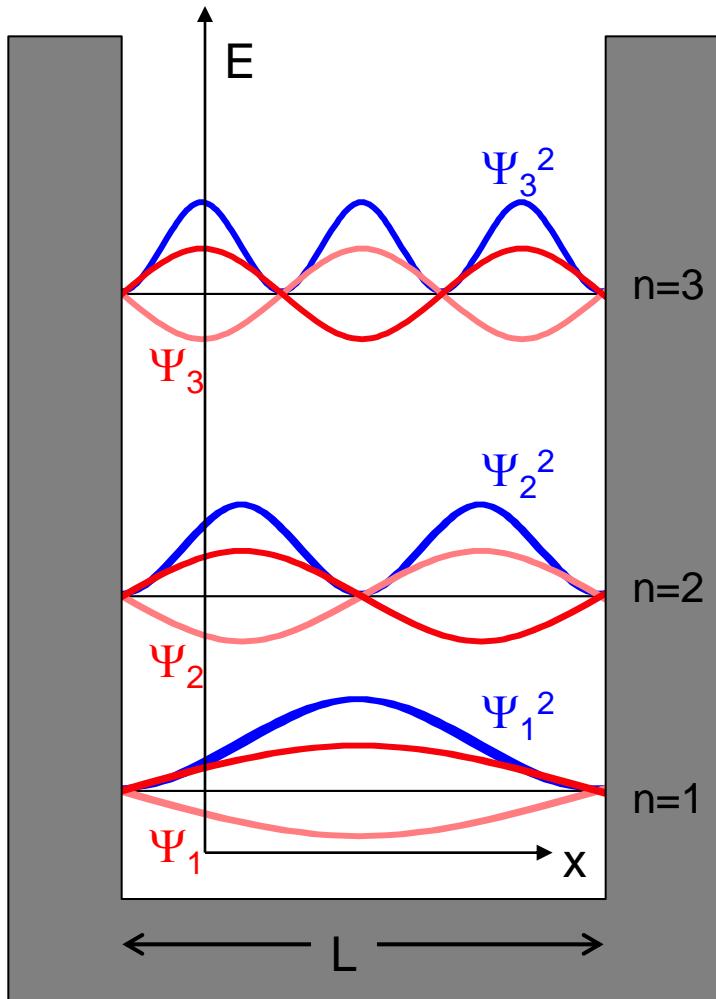
$$p = mv$$

h: Planck's constant
 $h=6.6 \cdot 10^{-34} \text{ J}\cdot\text{s}$



Institut International de Physique Solvay,
courtesy AIP Emilio Segré Visual Archives

Elektron in einem Potentialtopf (1D)



Wellenfunktion:

$$\Psi_n(x) = A \sin\left(\frac{2\pi x}{\lambda_n}\right)$$

mit $n = 1, 2, 3, \dots$

„Quantenzahlen“

nur Wellen mit
passen in den Kasten

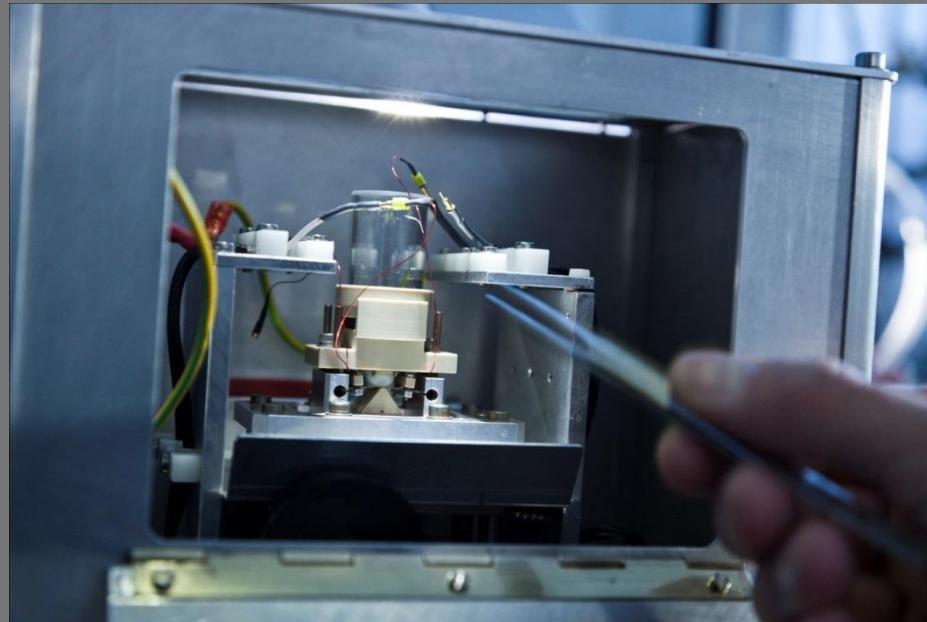
$$\lambda = 2L/n$$

Führt zu gequantelten Energiewerten
mit:

$$E_n = \frac{\hbar^2 \pi^2}{2mL^2} n^2$$

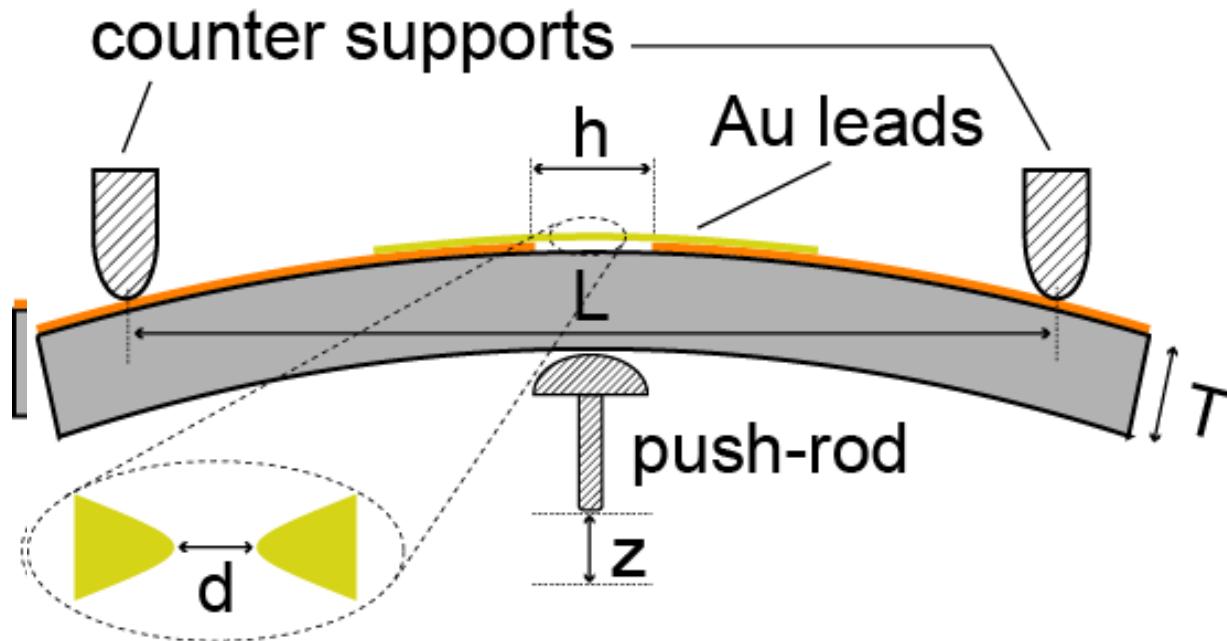
Leitwertquantisierung

als Beispiel für elektrische Effekte auf der Nanoscala



Bruchkontakte (Break Junctions)

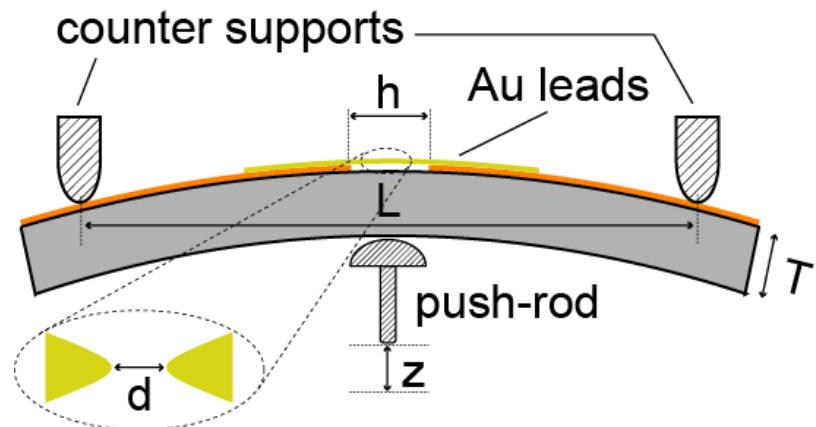
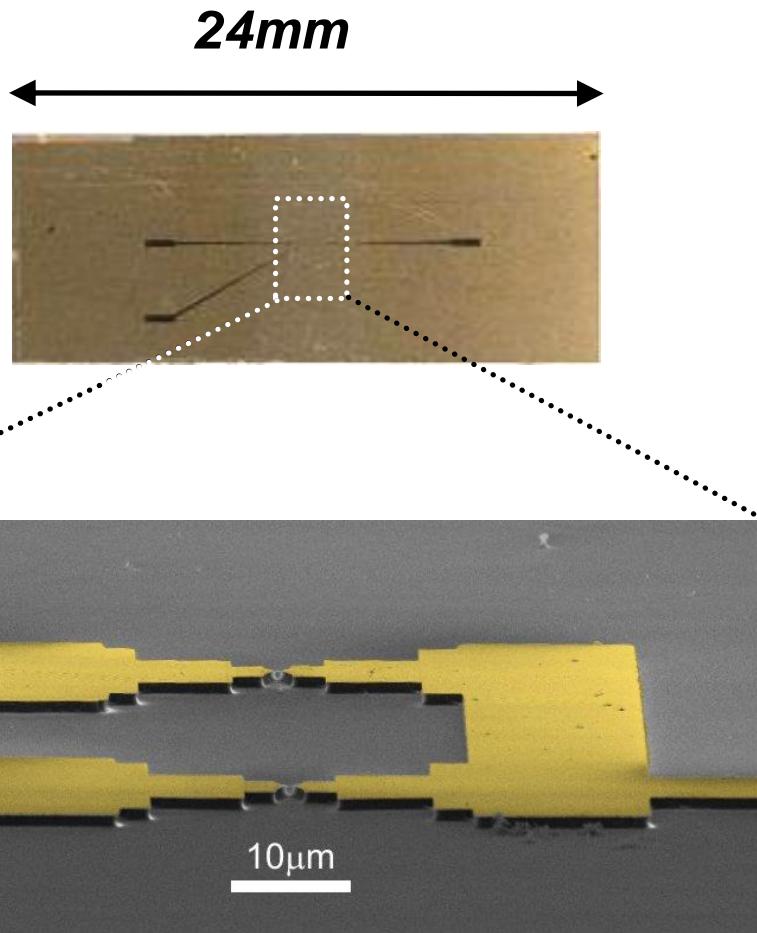
3-Punkt-Biegevorrichtung



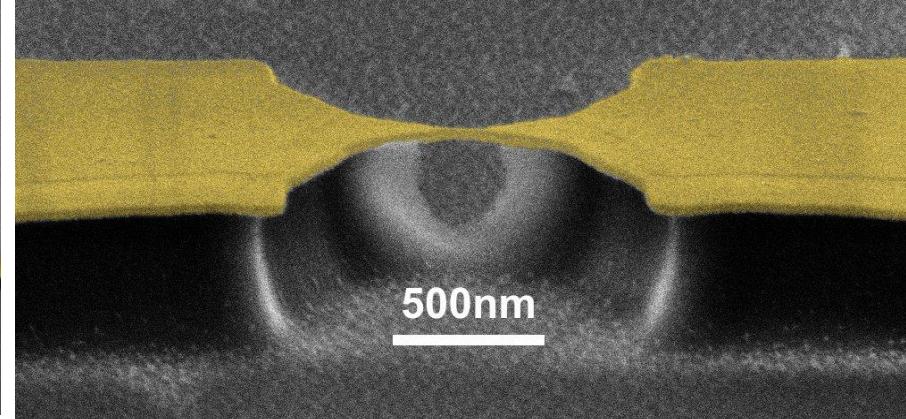
$$\Delta Z = 10\mu\text{m} \Leftrightarrow \Delta d \sim 3 \text{ \AA}$$

sehr genaue Kontrolle der Lücke, hohe mechanische Stabilität

Bruchkontakte



Herstellung «Top-Down» mittels Elektronenstrahl-Lithographie und reaktivem Ionenätzen

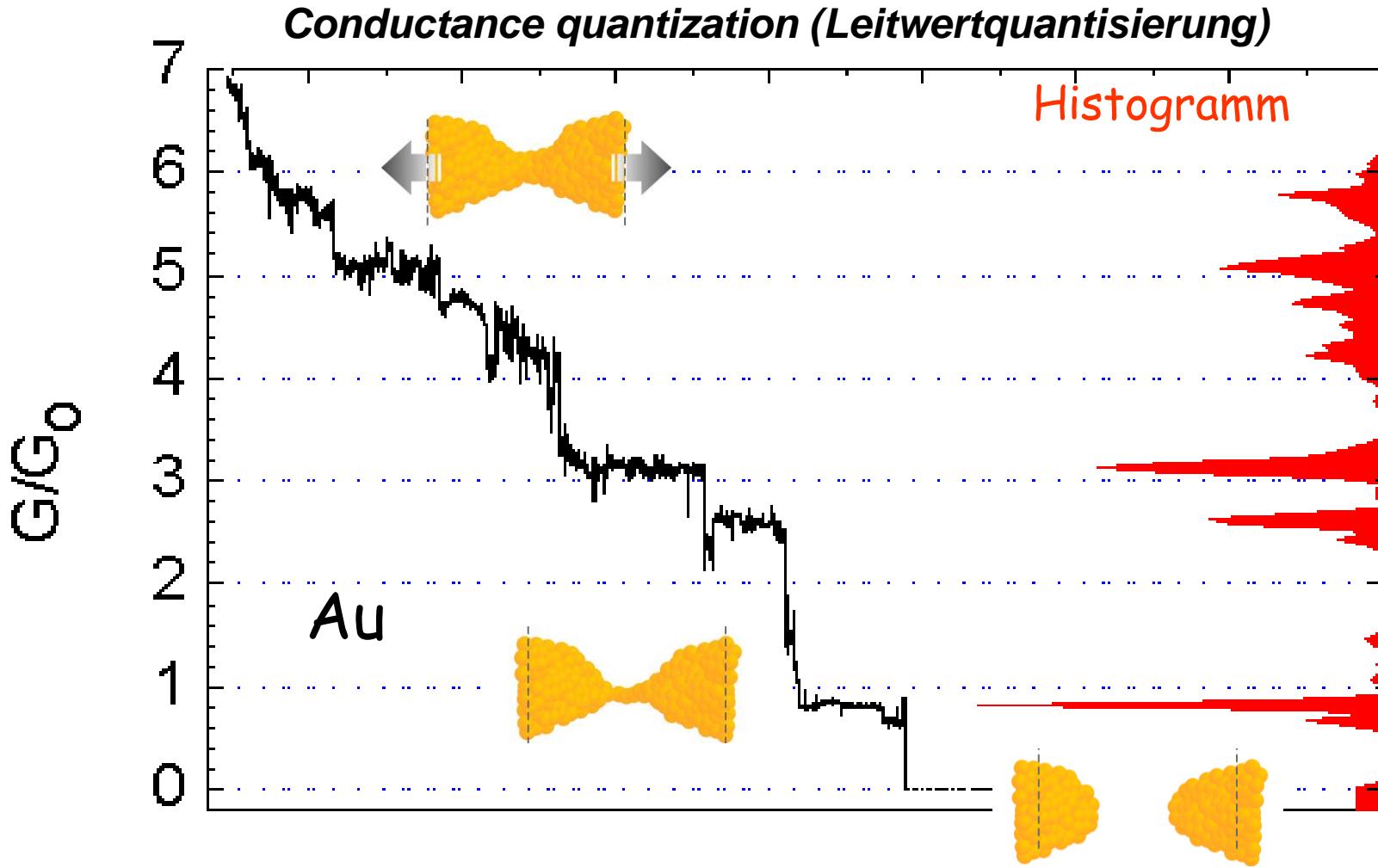


Bruchkontakte



Leitwert in atomaren Kontakt

Geschlossen \Rightarrow Offen: Von Kontakt zum Tunnelregime



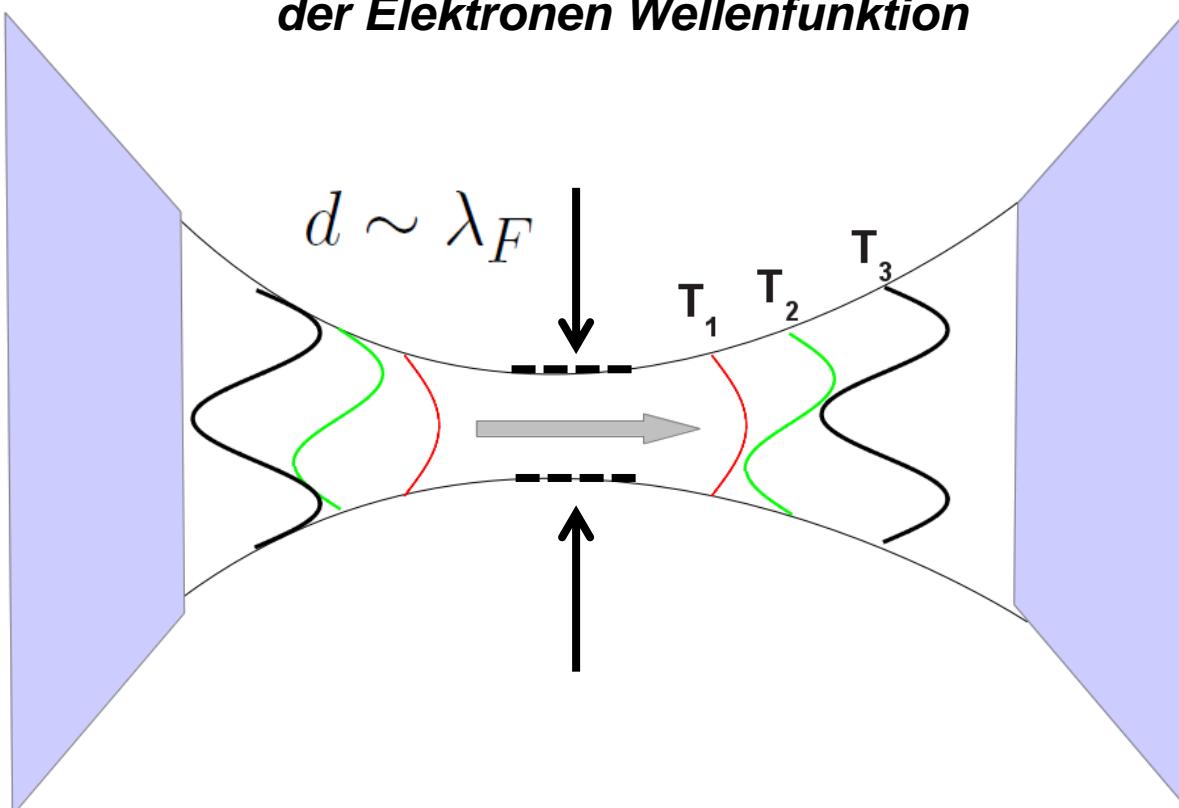
klein, aber anders



Elektronentransport auf der Nanoskala

Leitwert in atomaren Kontakten

**Leitwert : Transmission /Reflexion
der Elektronen Wellenfunktion**



**Leitfähigkeit einer Struktur mit N
Transportkanälen**

T_n : *Transmissionswahrscheinlichkeit durch Kanal n*

Fermi Wellenlänge (Au)

$$\lambda_F \approx 5.2 \text{ \AA}$$

Leitwert

$$G = G_0 \sum_{n=1}^N T_n$$

Landauer, Büttiker

Leitwertquantum

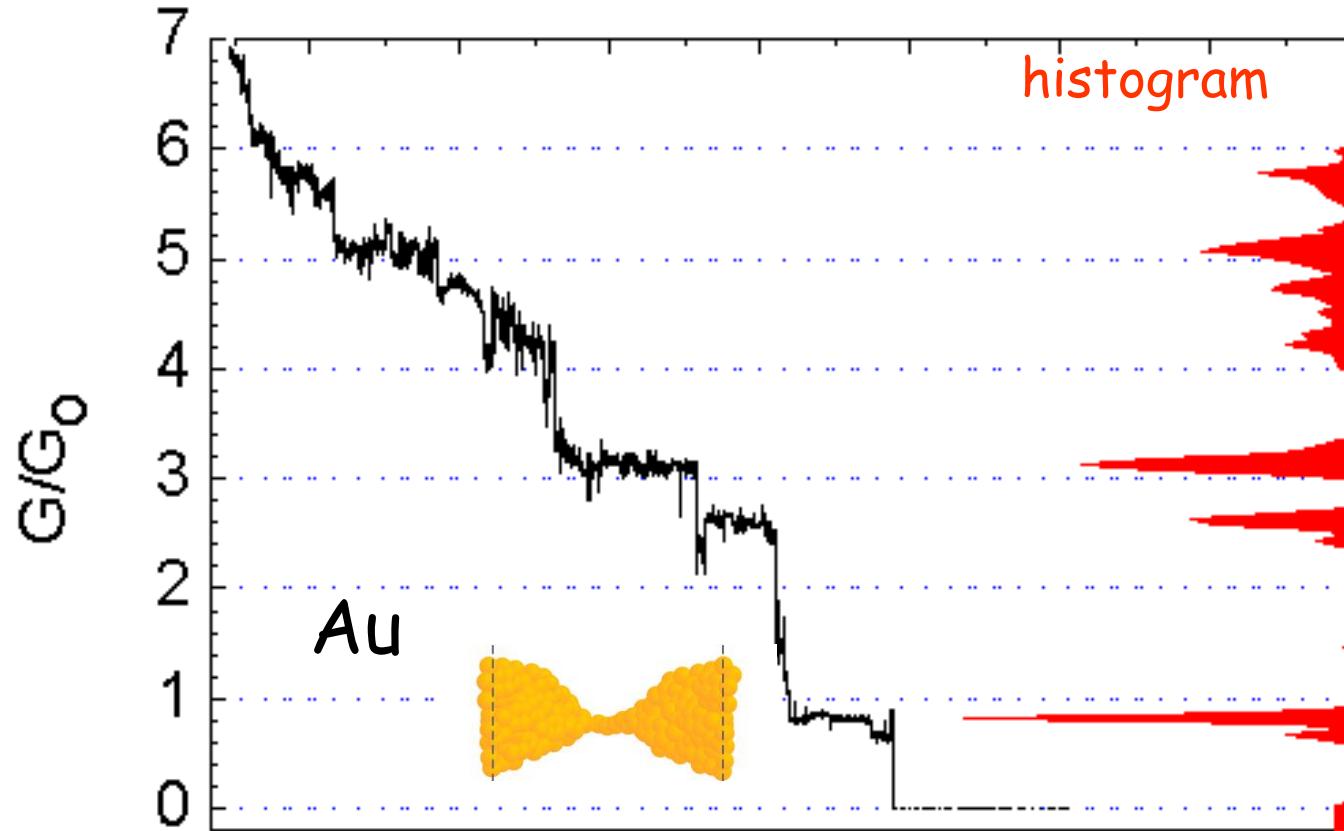
$$G_0 = \frac{2e^2}{h}$$

$$G_0 \simeq (12.9 k\Omega)^{-1}$$

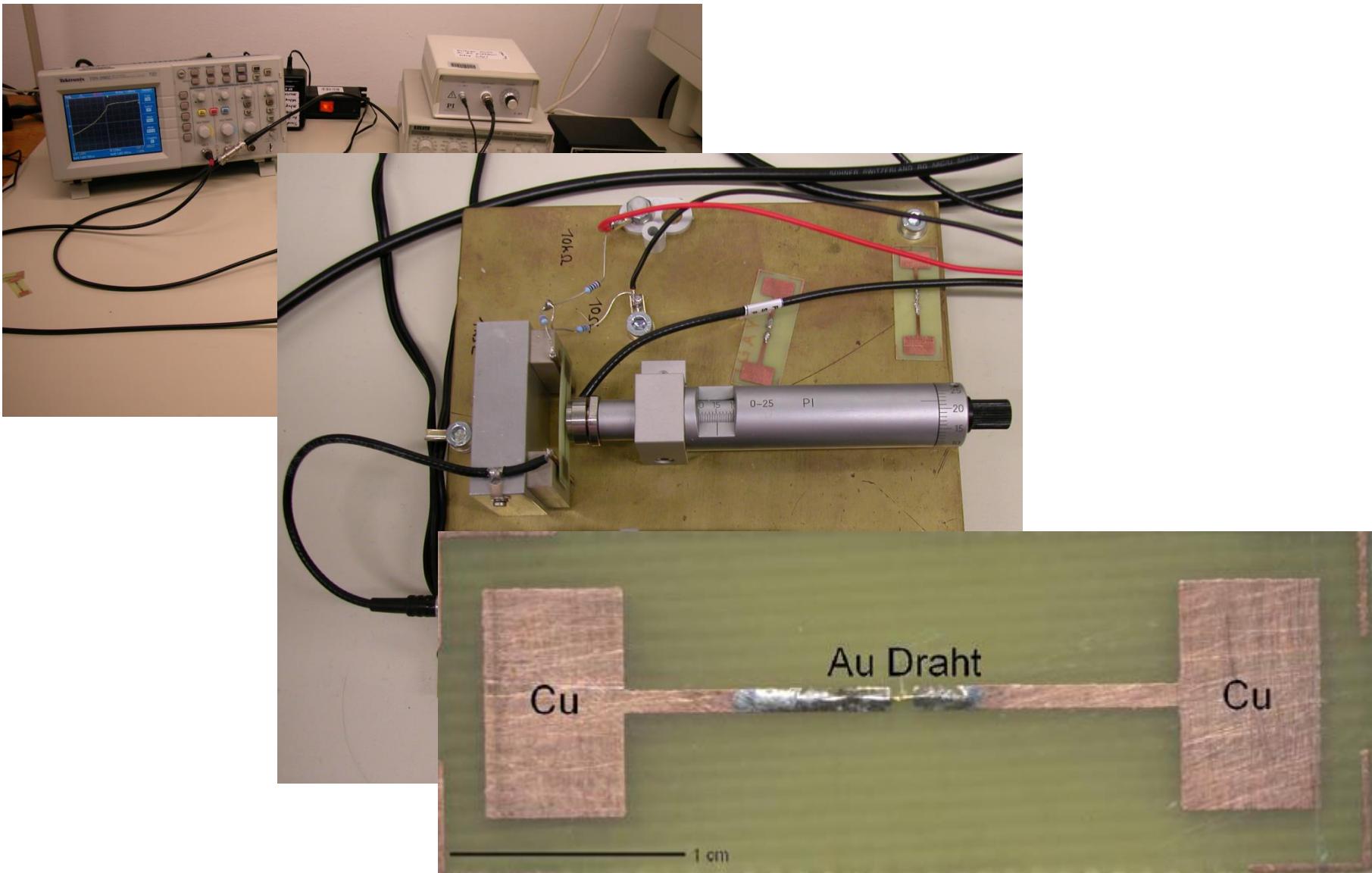
Leitwert in atomaren Kontakt

Leitwertquantisierung für Goldkontakt: $\lambda_F \approx 5.2 \text{ \AA}$

$$n = 1 \text{ with } T = 1 \Rightarrow G = \frac{2e^2}{h} \sum_n T_n = G_0 = \frac{2e^2}{h} = 77.5 \mu\text{S}$$



Simple experimentelle Realisierung atomarer Kontakte



Simple experimentelle Realisierung atomarer Kontakte

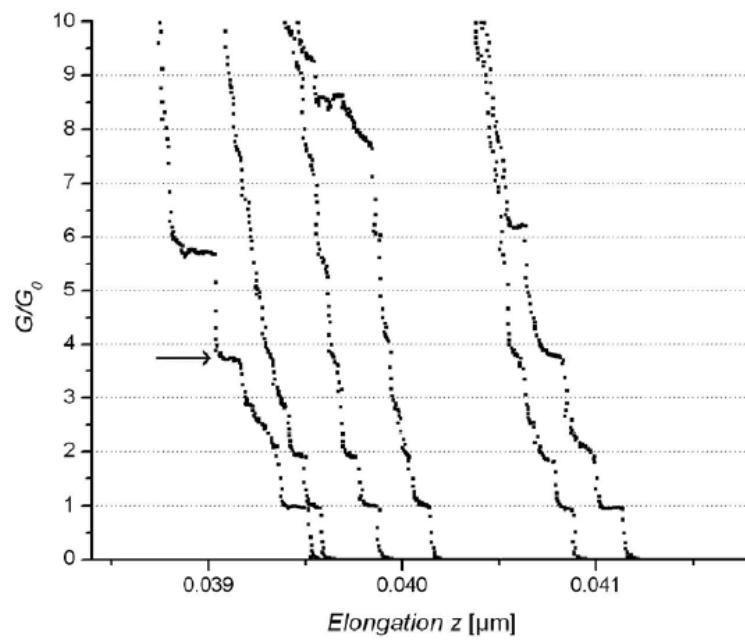


Abbildung 3.3

Graphische Darstellungen der Abhangigkeit des Quotienten G/G_0 zur vertikalen Elongation z des piezoelektrischen Elements, wobei $G_0 = 0.0775 \text{ mS}$. Graphen anhand von Resultaten verschiedener Messungen und Proben hergestellt. Gold.

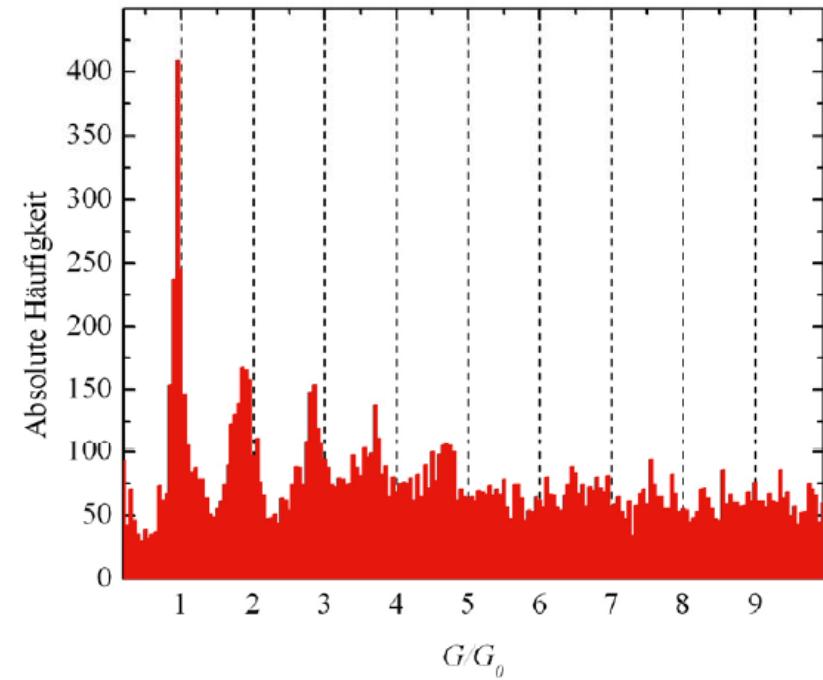
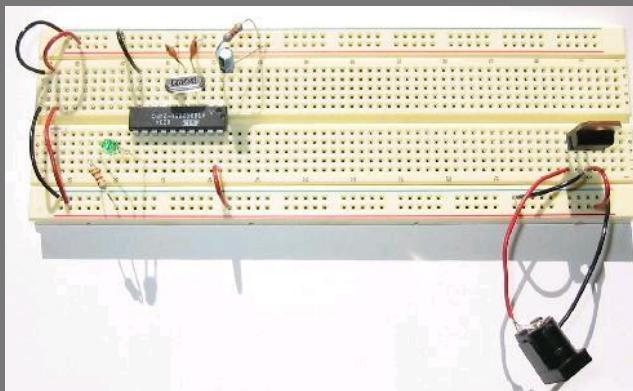


Abbildung 3.5
Histogramm von 120 verschiedenen Messungen an einer Goldprobe.

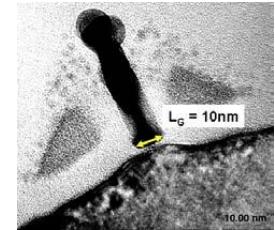
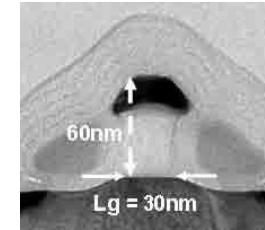
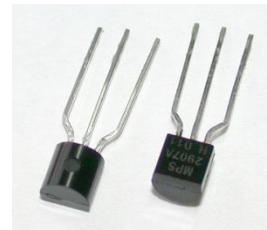
nano-Elektronik



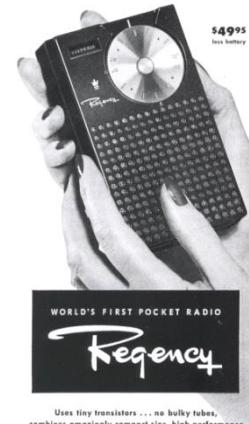
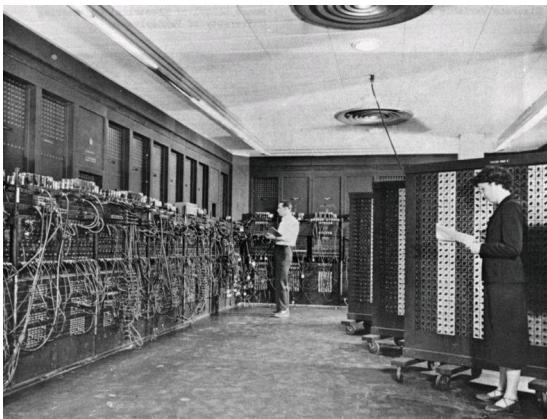
Entwicklung der Elektronik



**Bardeen,
Brattain,
Shockley**



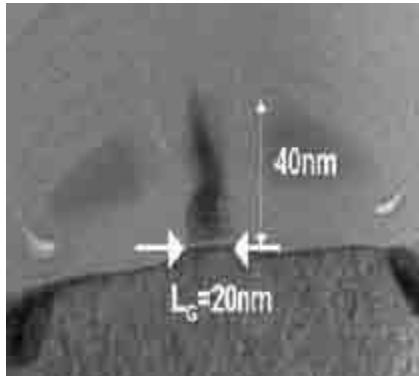
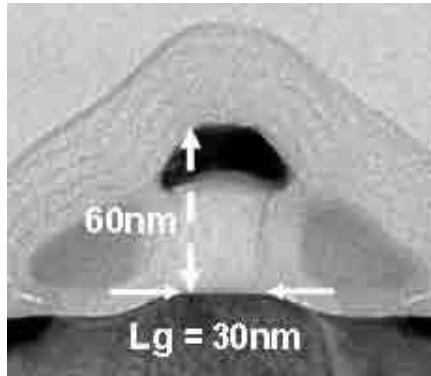
1947 ... today



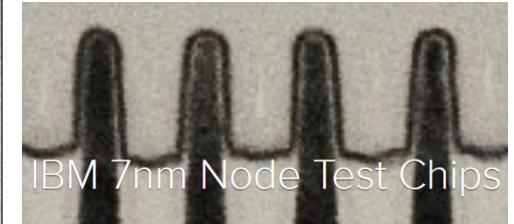
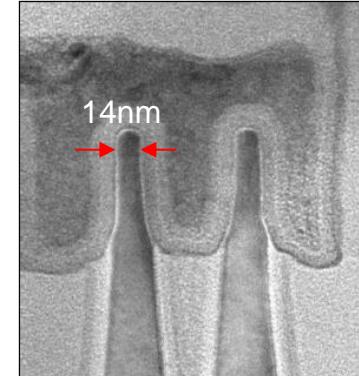
⇒ **Building blocks (transistors) at nm scale**
Volume reduced by 10^{12}

heutige Technologie: < 50nm

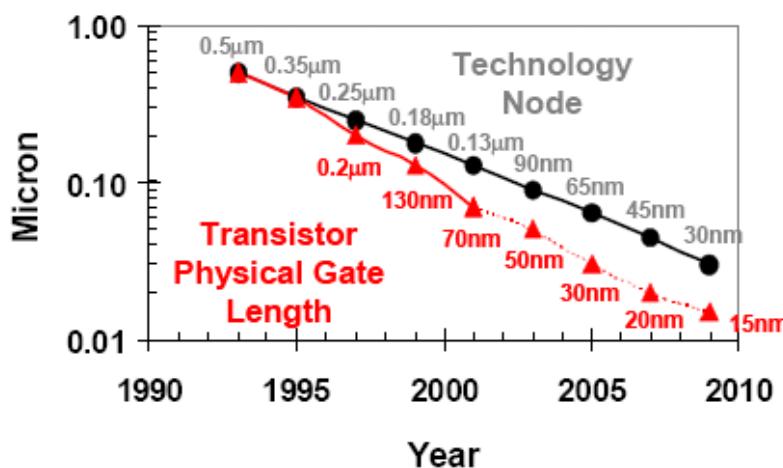
TEM cross-sections (Chau et al., Intel, 2004)



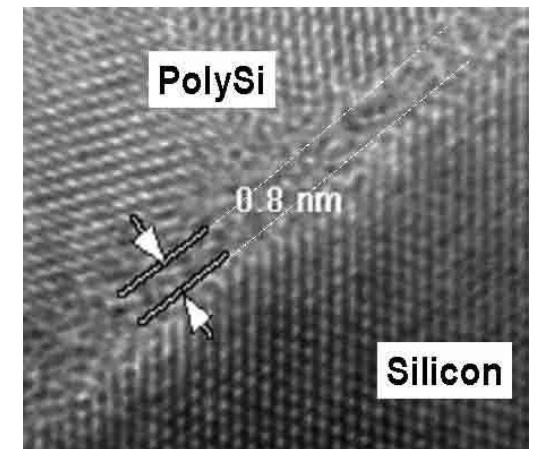
*Current Intel Broadwell
14nm node*



IBM, 9.7.2015

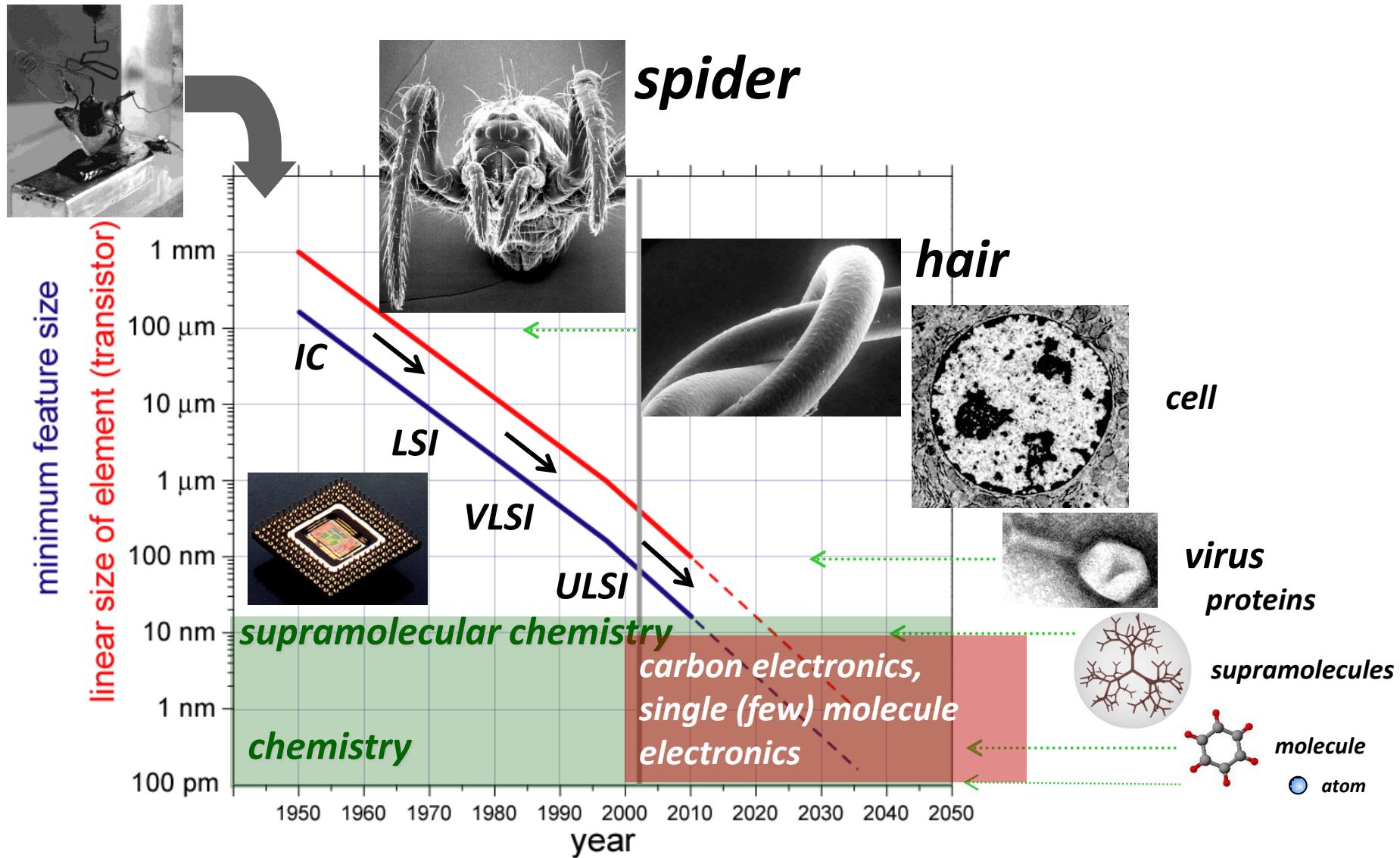


gate dielectric

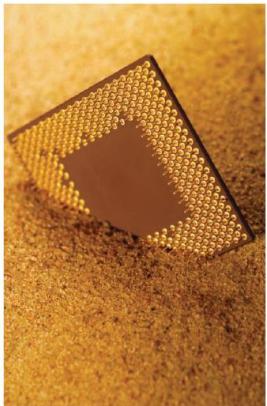


Wie geht es weiter ...?

Entwicklung der Elektronik



emerging materials



INTRODUCTION

Looking Beyond Silicon

Science 2010 special issue

AAAS 2015 ANNUAL MEETING
INNOVATIONS, INFORMATION, AND IMAGING

SAN JOSE, CA

Beyond Silicon: New Materials for 21st Century Electronics

Saturday, 14 February 2015: 8:00 AM-9:30 AM

physicstoday

Industrial Physics Forum 2013: The future of electronics

What technologies will extend silicon's reign as the preeminent material for electronics? What materials will ultimately supplant silicon?

Charles Day, December 2013

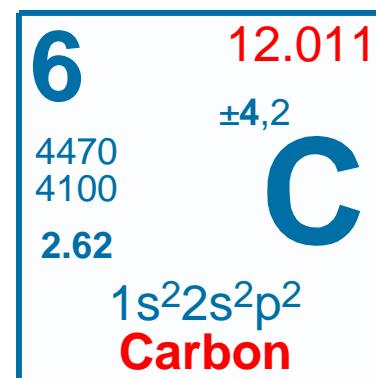
**Beyond Silicon:
Carbon-Based
Nanotechnology**

Nathan P. Guisinger and Michael S. Arnold,
Guest Editors

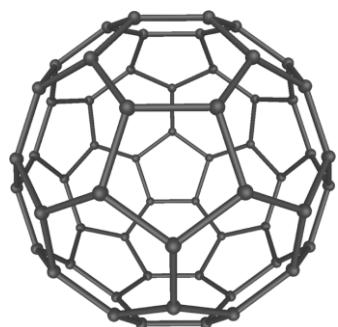
MRS Bulleting 2010 special issue

Kohlenstoff

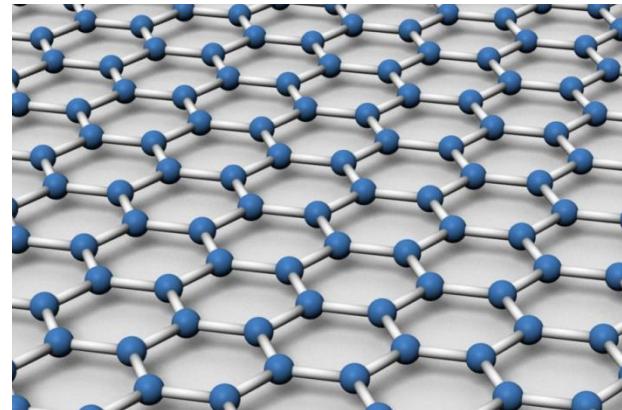
3D – Graphite and diamond



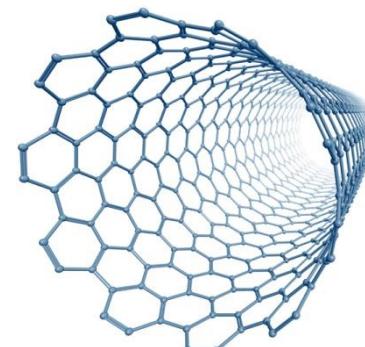
Fullerene – "0D"



Graphene – "2D"

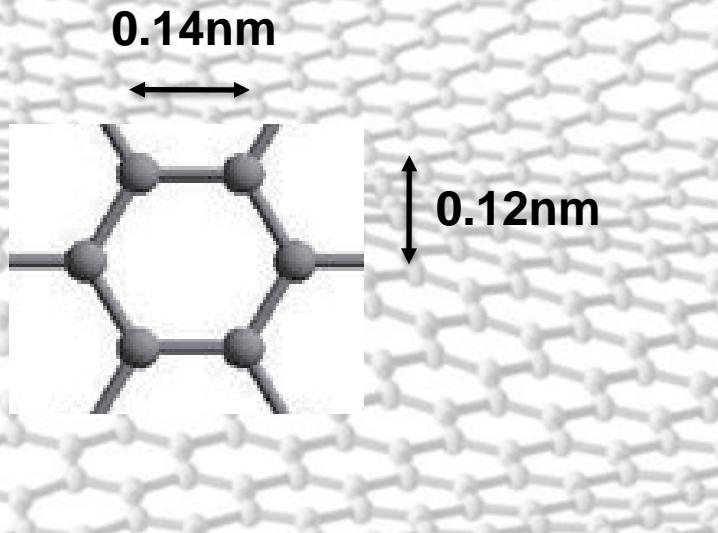


Nanotube – "1D"

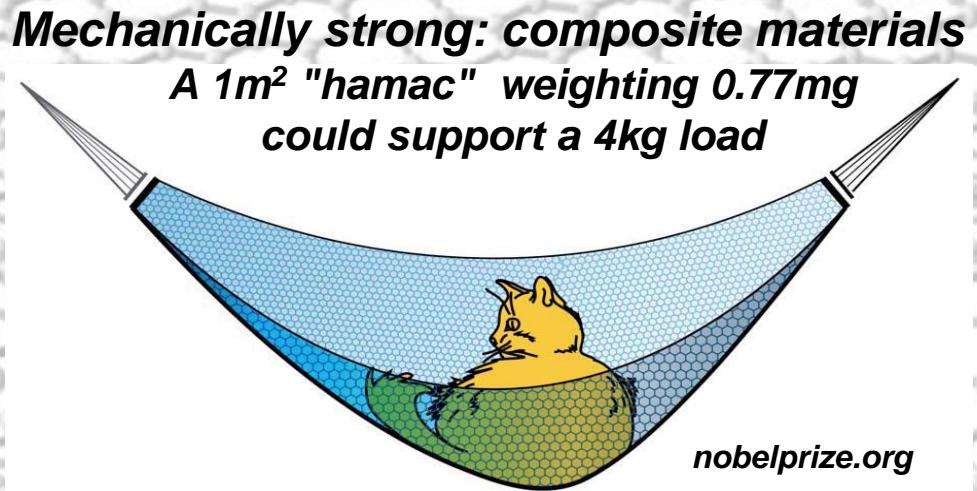
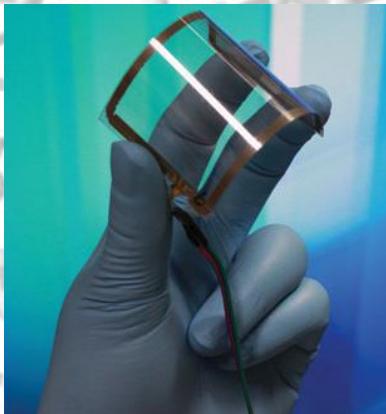


Graphen Anwendungen?

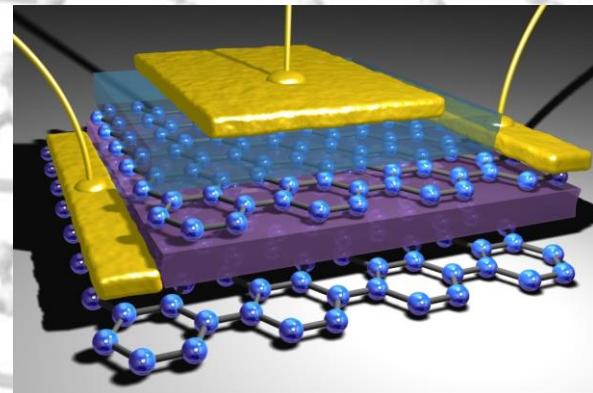
electronics



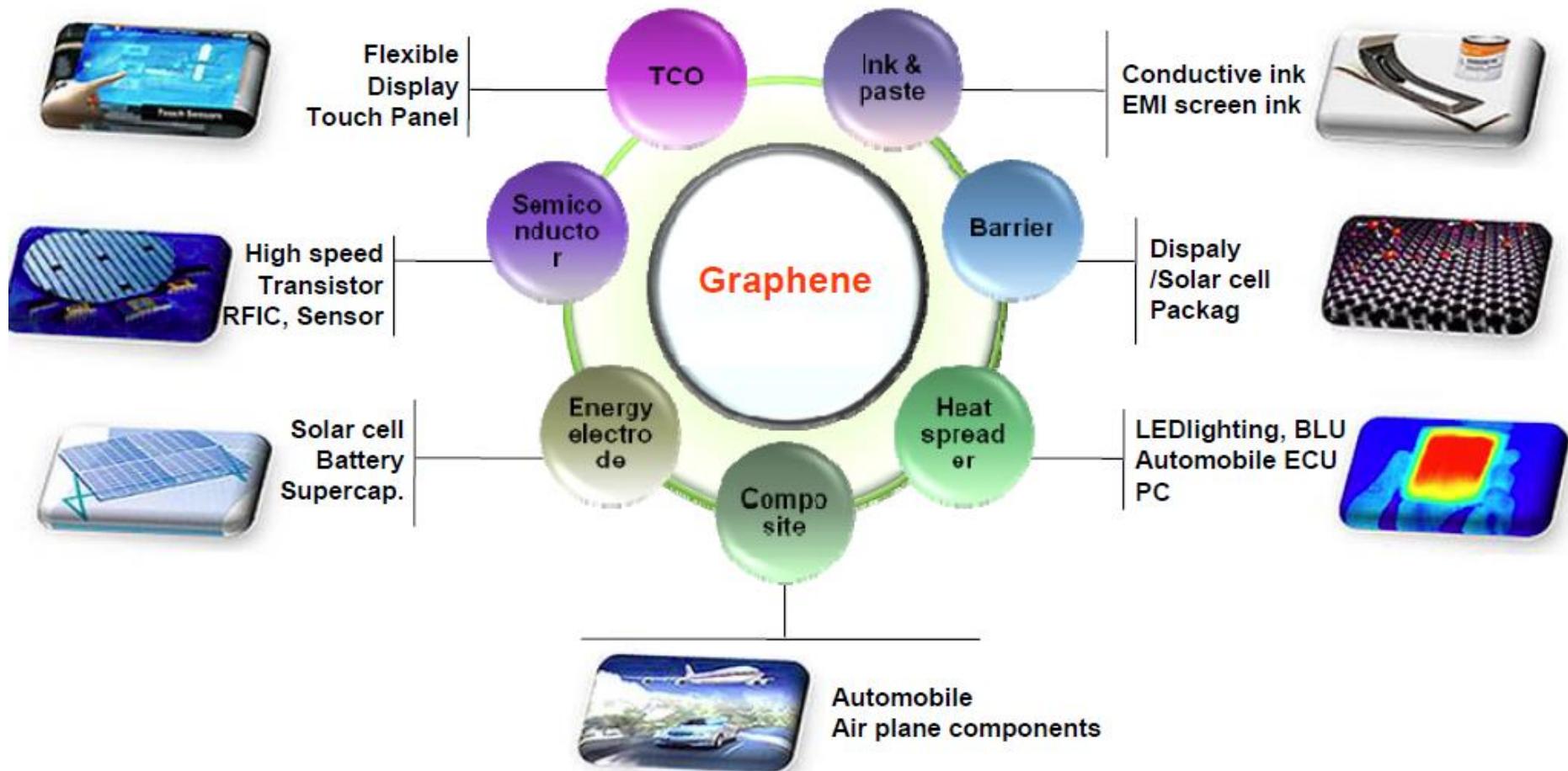
**Flexible conductor
may replace ITO**



**High charge mobility:
electrical applications**



Graphen Roadmap



Zusammenfassung

Elektronen und Elektronik auf der Nanoskala

- **Nano-Physik anders als in der alltäglichen Erfahrung**
Teilchen als Wellen, quantisierte Energie, tunnelnde Elektronen, quantisierter Leitwert
- **Fabrikations- und Skalenaspekte**
Blindleistung (power dissipation), Geschwindigkeit (Ladungsträgermobilität, Schaltkreisgröße) & Zuverlässigkeit
- Alternative Routen mit anderen Materialien als Silizium
Kohlenstoffbasierte Materialien; Moleküle; 2D Materialien (Graphen, MoS₂, HBN,...)

Weitere Informationen

www.calame.unibas.ch

www.nanoscience.ch



Danke

