Nano I - Nano-Elektronik: top-down

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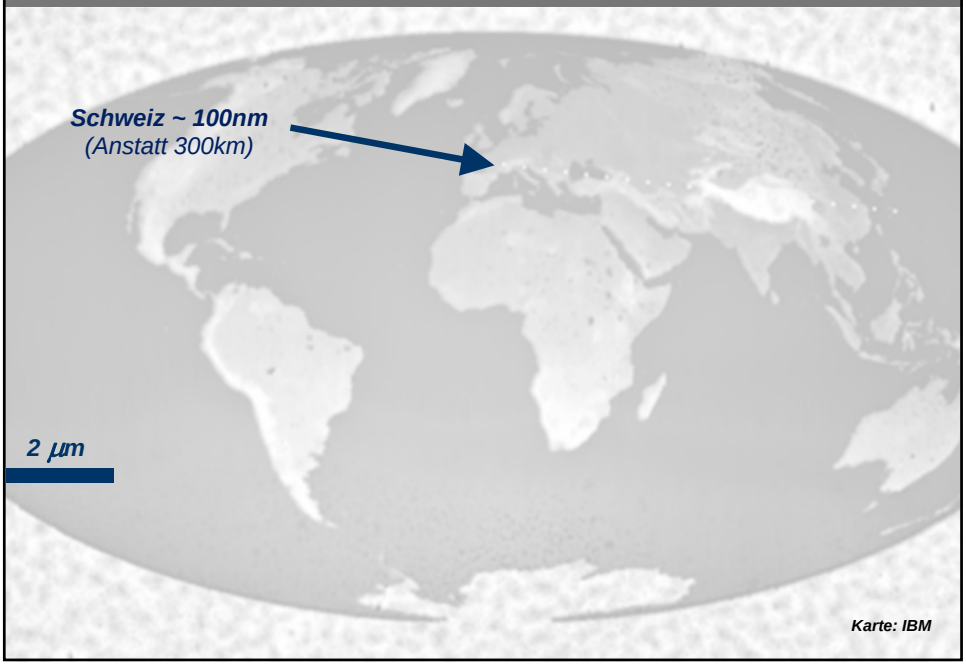
Weltkarte ... auf der nano-Skala

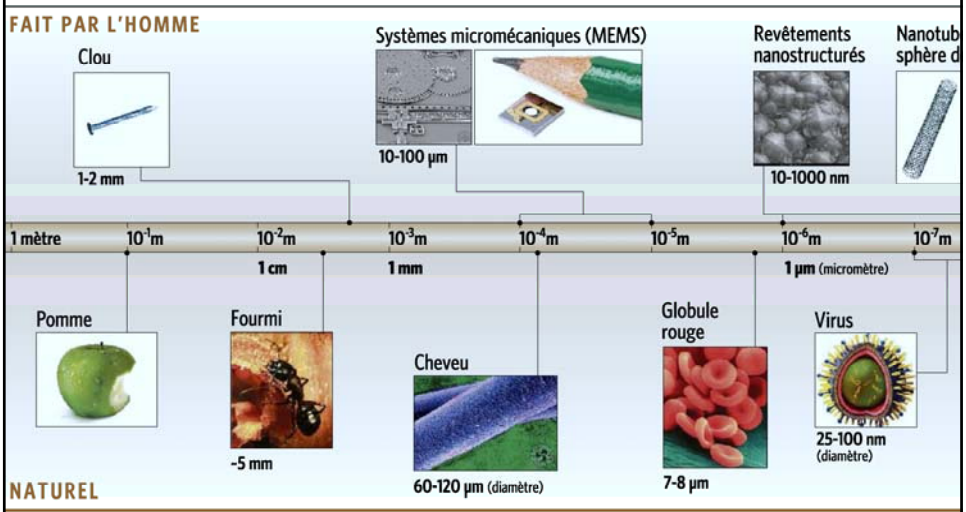


Inhalt

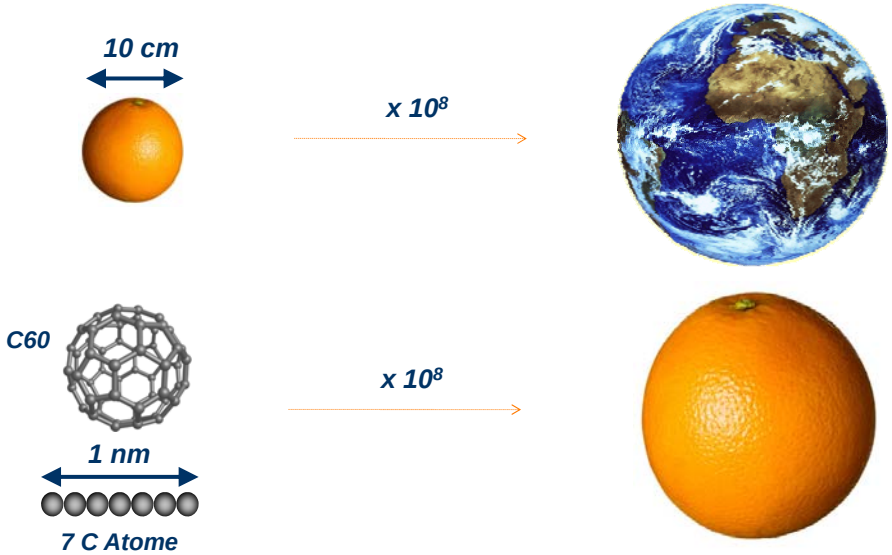
- ***nano*-Welt?**
  - eine Frage der Skala
- ***nano*-Physik – klein, aber anders**
  - etwas Nanophysik, bis zum Elektron im Potentialtopf
- ***nano-Elektronik***
  - Beispiel: Leitwert Quantisierung
  - Entwicklung der Elektronik
  - Neue Materialen

nano ?

m, dm, cm, …, nm



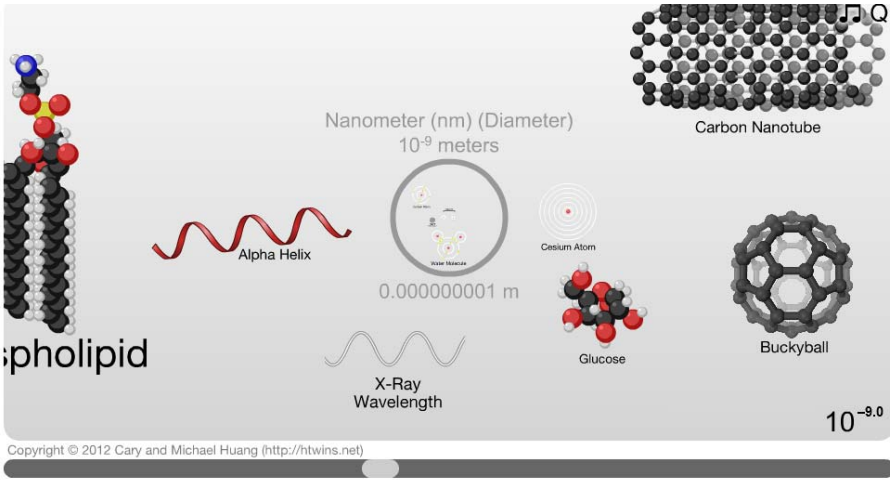
Skala



Skala

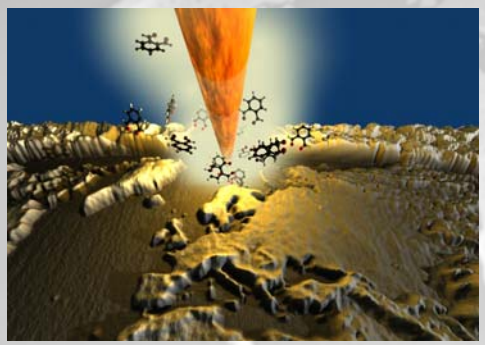
The scale of things

http://htwins.net/scale2/

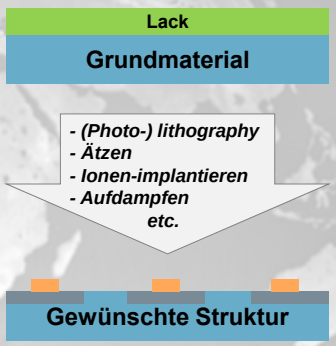


Weltkarte ... Top down

thermal Scanning Probe Lithography



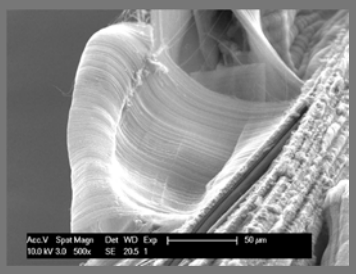
Generischer top down Prozess

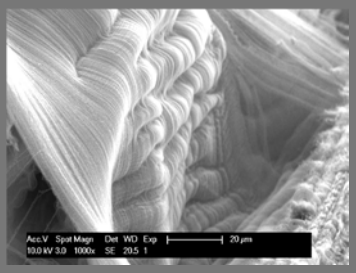


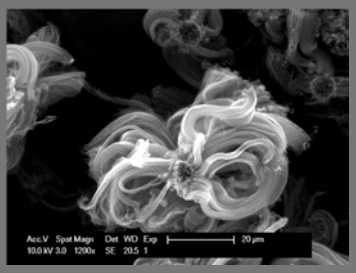
http://www.swisslitho.com
D. Pires et al. Science (2010) DOI:10.1126/science.1187851

Siehe z.B. *Top-Down Fabrication of Nanostructures*
DOI: 10.1002/9783527628155.nanotech094

klein, aber anders







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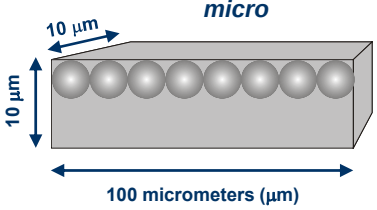
Oberfläche/Volumen

micro

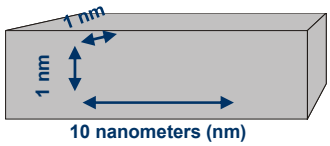


$$R = \frac{nb.\ surface\ atoms}{total\ nb.\ atoms}$$

1 atom ~ (0.1nm)x(0.1nm)x(0.1nm)

R (micro) ≈ 0.004 %

nano



R (nano) ≈ 40% !

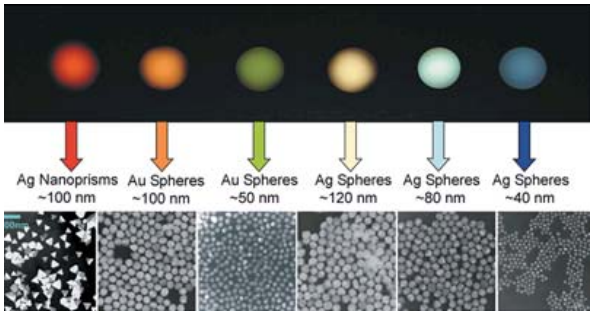
⇨ important surface effects

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

klein, aber anders

ändert sich die Farbe mit der Verkleinerung…?

klein, aber anders

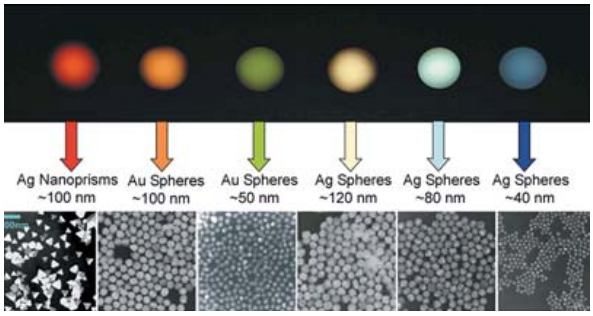


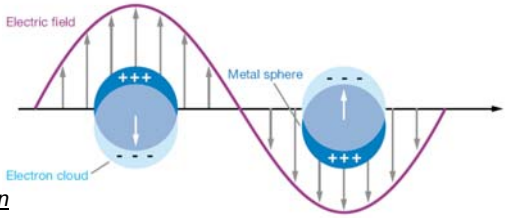
- Römischer Lycurgus-Kelch (4. Jhd. n.C.)
(Au, Ag, Cu)

- In Kirchenfenstern (teilweise)

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

klein, aber anders





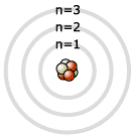
localized plasmons:
Kollektive Anregung von Elektronen

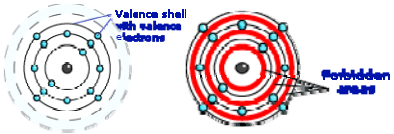
van Duyne et al., Ann. Rev. Phys. Chem. 2007

klein, aber anders

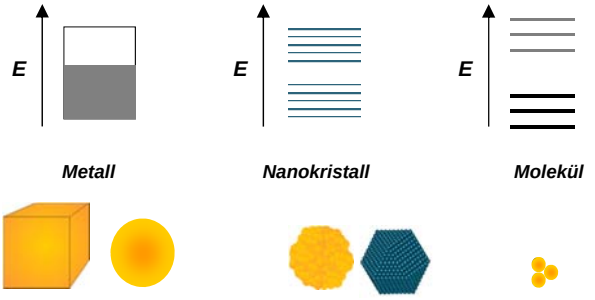
Elektronen in Festkörpern, Atomclustern & Molekülen

Atommodell: Quantisierte Energieniveaus (Bohr, Pauli, …)

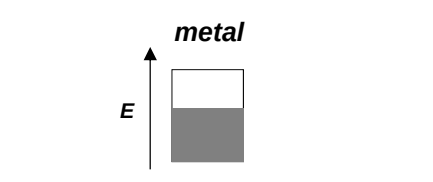


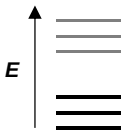


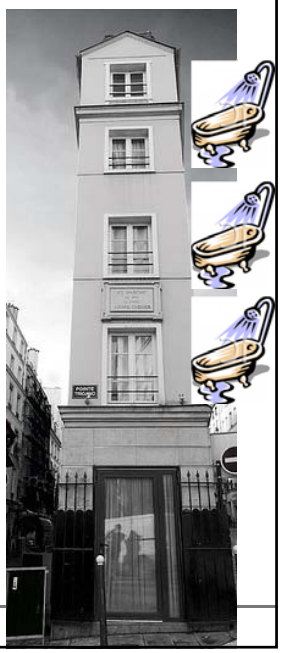
$$E_n \propto \frac{1}{L^2}$$



klein, aber anders



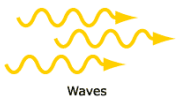


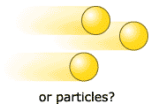


quantum confinement and energy quantization

klein, aber anders

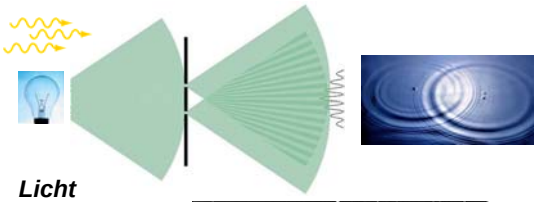
Atome, Elektronen, …
Teilchen oder Welle ?





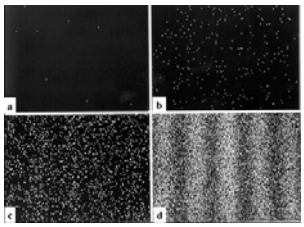
klein, aber anders

Atome, Elektronen, …
Teilchen oder Welle ?



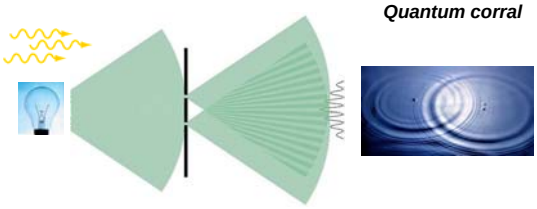
Licht

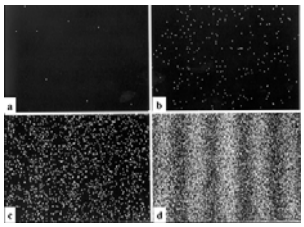
Elektronen



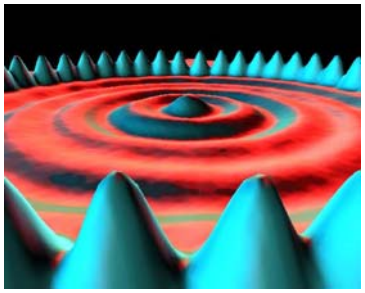
klein, aber anders

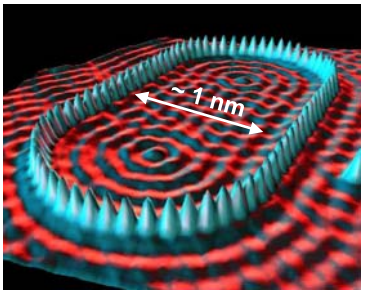
Atome, Elektronen, …
Teilchen oder Welle ?





Elektronen-dichte Wellen
D. Eigler et al.
IBM Almaden
Quantum corral



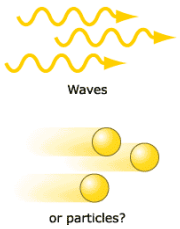


http://www.almaden.ibm.com/vis/stm/corral.html

Grundlegende Eigenschaften der Materie

- Quantisierte Energieniveaus (Bohr, Pauli, …)

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



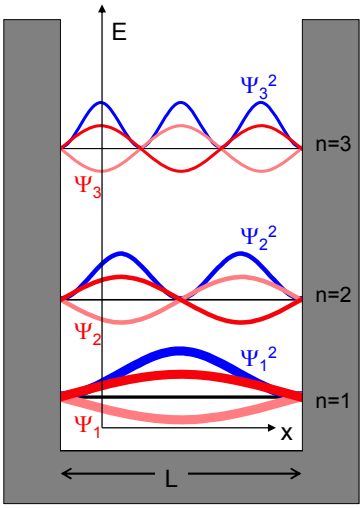
$$p = \frac{h}{\lambda}$$ ***de Broglie Wellenlänge des Elektrons***

$$p = mv$$

h: Planck's constant
h=6.6 10^{-34} J·s

5. Solvay Konferenz über Elektronen & Photonen, 1927 **nobelprize.org**

Elektron in einem Potentialtopf (1D)



Wellenfunktion:

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

mit **n** = 1, 2, 3, ...

„Quanten-zahlen"

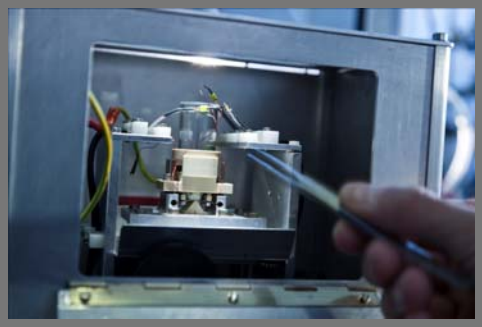
nur Wellen mit $\lambda = 2L/n$ passen in den Kasten

Führt zu gequantelten Energiewerten mit:

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

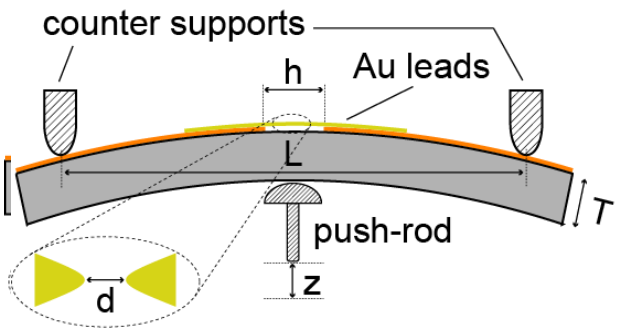
Leitwertquantisierung

als Beispiel für elektrische Effekte auf der Nanoscala



Bruchkontakte (Break Junctions)

3-Punkt-Biegevorrichtung

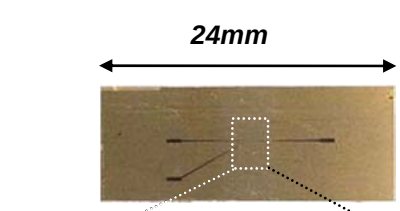


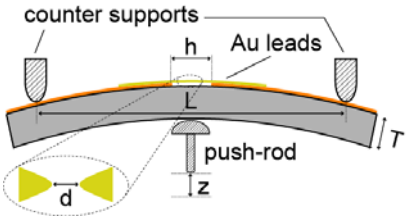
ΔZ = 10 μm ⇔ Δd ~ 3 Å

sehr genaue Kontrolle der Lücke, hohe mechanische Stabilität

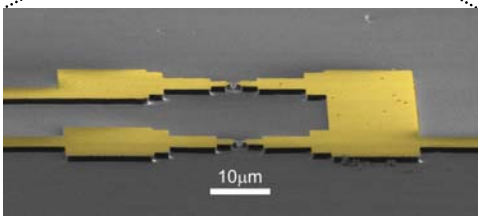
Moreland & Ekin, J. Appl. Phys, (1985); Ruitenbeek et al., Phys. C (1992); Reed et al., APL (1995)

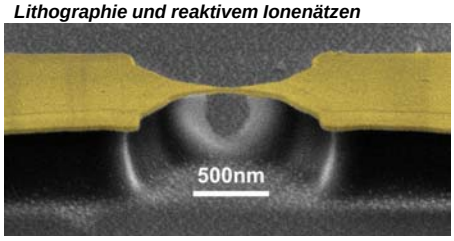
Bruchkontakte





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





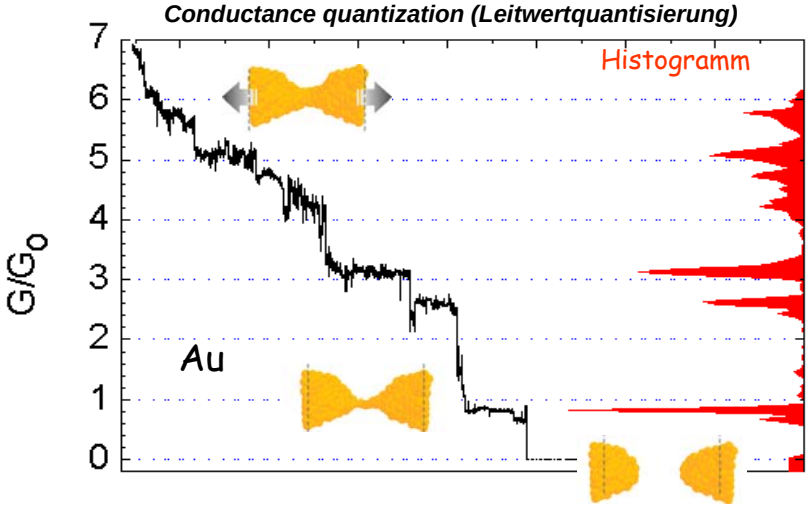
L. Grüter et al., Small (2005); M.T. Gonzalez, et al., Nano Letters (2006); R. Huber et al., JACS (2008)

Bruchkontakte

Leitwert in atomaren Kontakten

Geschlossen ⇨ Offen: Von Kontakt zum Tunnelregime

Conductance quantization (Leitwertquantisierung)

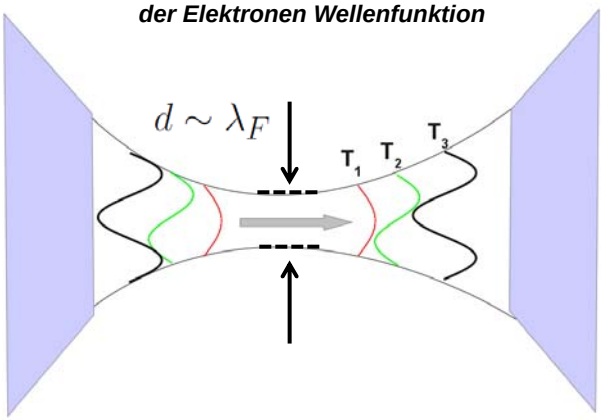


klein, aber anders

Elektronentransport auf der Nanoskala

Leitwert in atomaren Kontakten

Leitwert : Transmission /Reflexion der Elektronen Wellenfunktion



Leitfähigkeit einer Struktur mit N Transportkanälen

Tn: Transmissionswahrscheinlichkeit durch Kanal n

Fermi Wellenlänge (Au)

$$\lambda_F \approx 5.2\mathring{A}$$

Leitwert

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

Landauer, Büttiker

Leitwertquantum

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

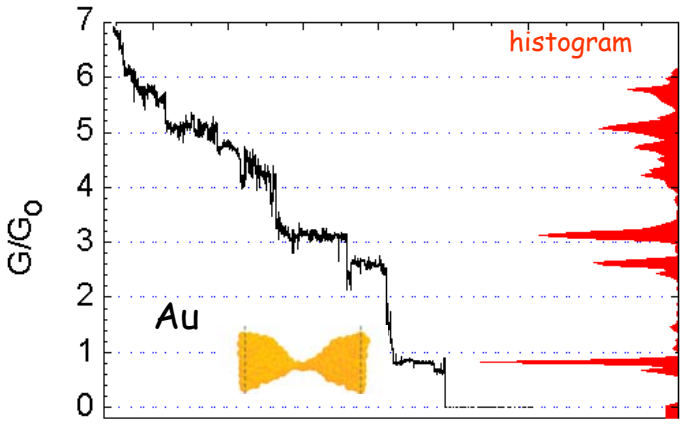
$$G_0 \simeq (12.9k\Omega)^{-1}$$

siehe z.B. Agrait, van Ruitenbeek, Phys. Rep. (2003)

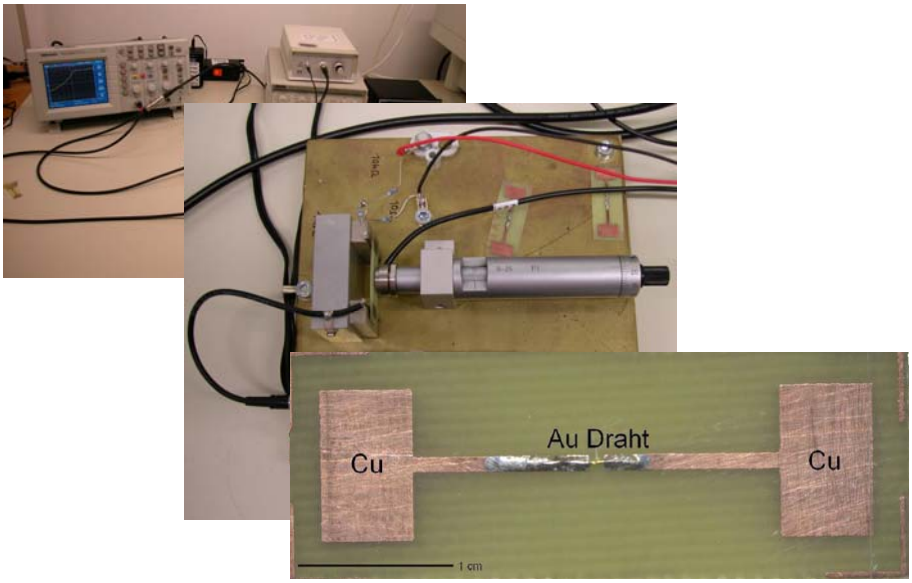
Leitwert in atomaren Kontakten

Leitwertquantisierung für Goldkontakt: $\lambda_F \approx 5.2\mathring{A}$

n = 1 with T = 1 ⇨ $G = \frac{2e^2}{h} \sum_n T_n = G_0 = \frac{2e^2}{h}$ = 77.5 μS



Simple experimentelle Realisierung atomarer Kontakte



R. Huber et al., Schweizer Jugend Forscht, M. Karalic, Matura Arbeit

Simple experimentelle Realisierung atomarer Kontakte

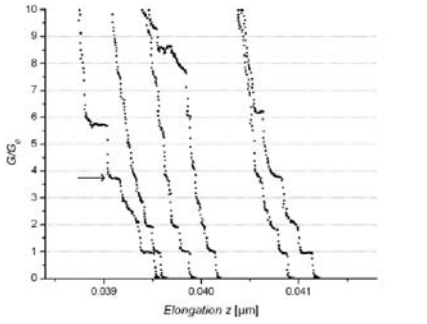


Abbildung 3.3
Graphische Darstellungen der Abhängigkeit des Quotienten G/G_0 zur vertik Elongation z des piezoelektrischen Elements, wobei $G_0 = 0.0775\,mS$. Graphen anh von Resultaten verschiedener Messungen und Proben hergestellt. Gold.

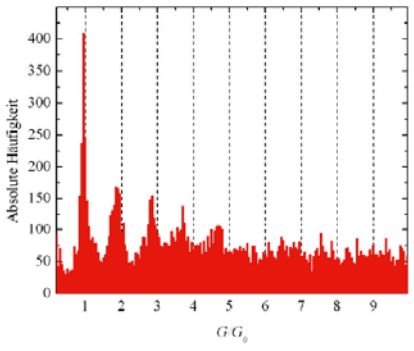
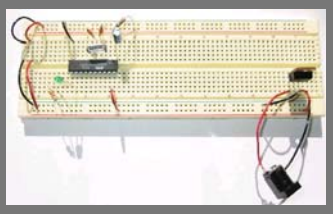


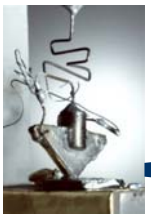
Abbildung 3.5
Histogramm von 120 verschiedenen Messungen an einer Goldlprobe.

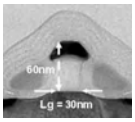
M. Karalic, Matura Arbeit

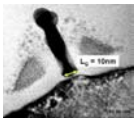
nano-Elektronik

Entwicklung der Elektronik





Bardeen, Brattain, Shockley

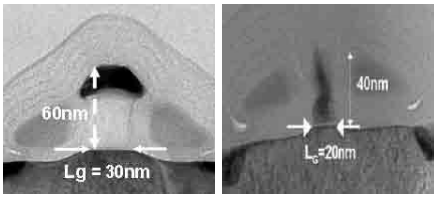
1947 … today



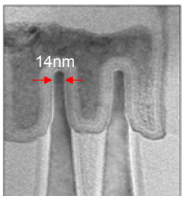

⇨ ***Building blocks (transistors) at nm scale***
Volume reduced by 10^{12}

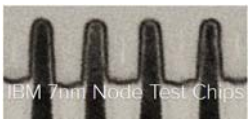
heutige Technologie: < 50nm

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

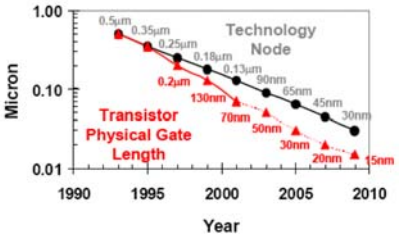


Current Intel Broadwell 14nm node

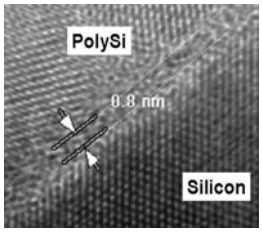




IBM, 9.7.2015



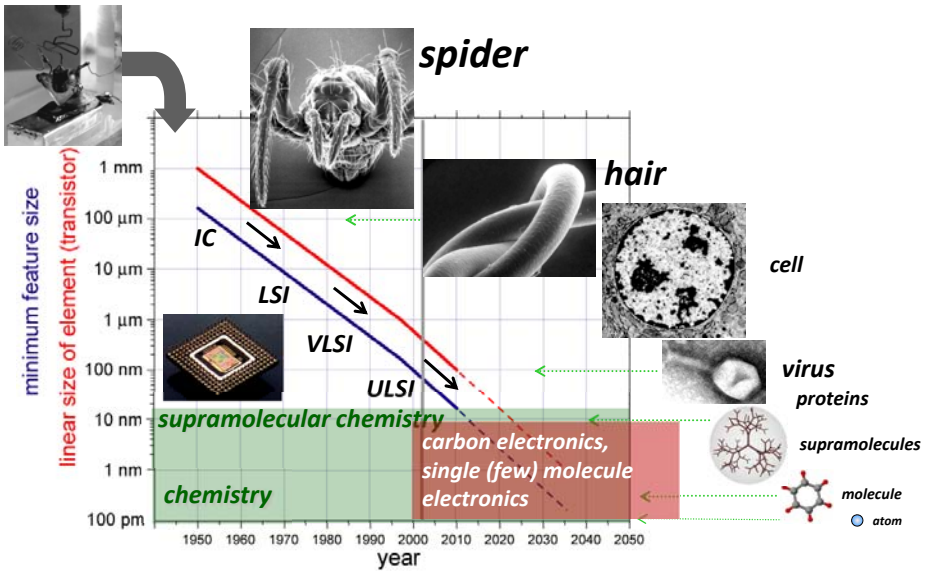
gate dielectric



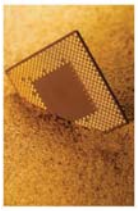
Wie geht es weiter ...?

http://www.intel.com/content/www/us/en/foundry/our-technology.html

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

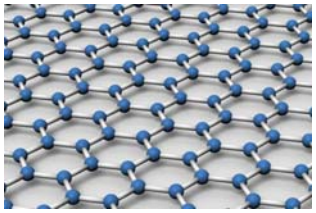
Nathan P. Guisinger and Michael S. Arnold, Guest Editors

MRS Bulleting 2010 special issue

Kohlenstoff

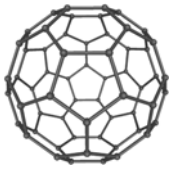
3D – Graphite and diamond

Graphene – ”2D”

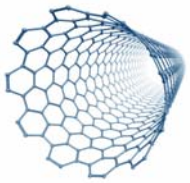


6
12.011
±4,2
4470
4100
2.62
C
$1s^2 2s^2 p^2$
Carbon

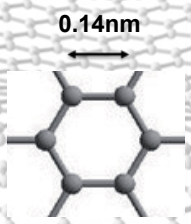
Fullerene – ”0D”



Nanotube – ”1D”

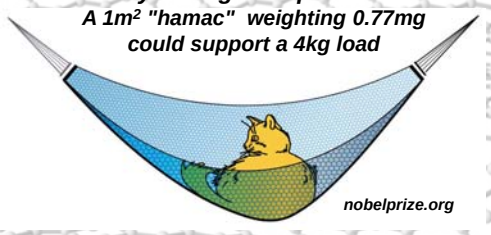


Graphen Anwendungen?



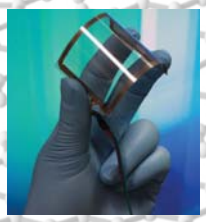
Mechanically strong: composite materials

A 1m² "hamac" weighting 0.77mg could support a 4kg load

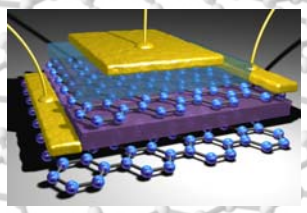


electronics

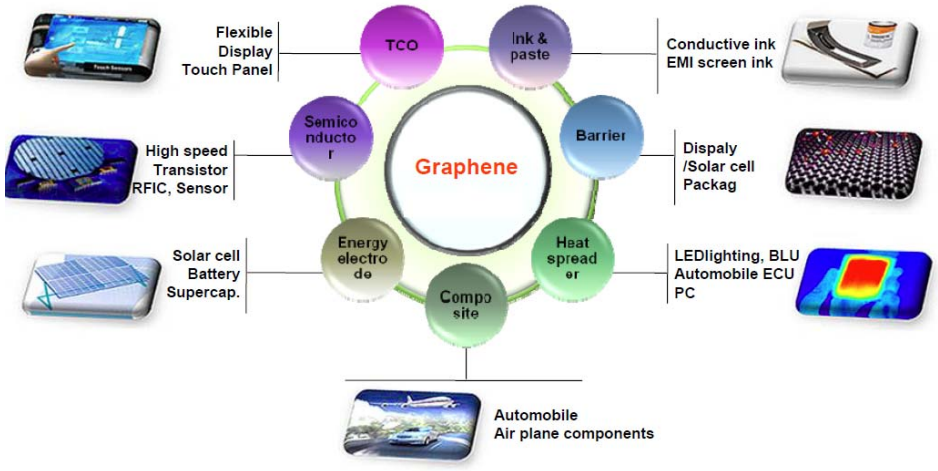
Flexible conductor may replace ITO



High charge mobility: electrical applications



Graphen Roadmap



A. Ferrari, 2011

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, MoS_2, HBN,…)

Weitere Informationen

www.calame.unibas.ch

www.nanoscience.ch