Nanoelectronics

Begriffe: to scatter – streuen CVD: chemical vapour deposition CNT: carbon nanotube DoS: Density of States

1 Moores Law – scaling

1. Transistormaterial: Germanium
Transistor scaling 22nm between drain and source of a MOSFET
scaling cant continue indefinitely Against Moores Law: the rising costs of fabrication, the limits of lithography, and the size of the transistor. Advantages of scaling: smaller, cheaper, and faster and to consume less power.

2 Quantenmechanik

Klassische Bewegungsgleichung: $m \frac{\mathrm{d}^2 \underline{\boldsymbol{r}}(t)}{\mathrm{d}t^2} = \underline{\boldsymbol{F}}$
Classical wave equation:
$\boxed{\frac{1}{c^2}\frac{\partial^2 \Psi}{\partial t^2} - \sum_{i=1}^{n} \frac{\partial^2 \Psi}{\partial x_i^2} = 0}$ $\boxed{\begin{matrix} c = \lambda f \\ \omega = 2\pi f \end{matrix}}$ $\boxed{k = \frac{2\pi}{\lambda}}$ Waves behave as particles. Electrons and photons are both, particles and waves.
Electron Orbits: $mvr = n\hbar \quad n\lambda = 2\pi r$
De Broglie Wavelength: $h = p\lambda \quad p = \hbar k \quad h = 2\pi\hbar$
Uncertainty principle: $\boxed{\Delta x \cdot \Delta p_x \geq \frac{\hbar}{2}}$ $\quad \Delta E \cdot \Delta t \geq \frac{\hbar}{2}$

2.1 Schroedinger Equation

$$\left(\frac{-\hbar^2}{2m}\nabla^2 + V(\underline{\boldsymbol{r}}, t)\right)\Psi(\underline{\boldsymbol{r}}, t) = \mathrm{j}\hbar\frac{\partial}{\partial t}\Psi(\underline{\boldsymbol{r}}, t) \tag{1}$$

Potential energy $V(\underline{\boldsymbol{r}}, t) \in \mathbb{R}$
Hamiltonian $\hat{H} = \left(\frac{-\hbar^2}{2m}\nabla^2 + V(\underline{\boldsymbol{r}}, t)\right)$
Probabilitydensity $P(\underline{\boldsymbol{r}}, t) = \Psi(\underline{\boldsymbol{r}}, t) \cdot \Psi^*(\underline{\boldsymbol{r}}, t) = |\Psi^2|$
Normalized: $\int |\Psi(\underline{\boldsymbol{r}})|^2 \, \mathrm{d}\underline{\boldsymbol{r}} = 1$

2.1.1 time-independent Schroedinger equation

if $V(\underline{\boldsymbol{r}}, t)$ is time-independent:
$\Psi(\underline{\boldsymbol{r}}, t) = \Psi(\underline{\boldsymbol{r}}) \exp\left(\frac{\mathrm{j}Et}{\hbar}\right) \quad \Rightarrow \quad \hat{H}\Psi(\underline{\boldsymbol{r}}) = E\Psi(\underline{\boldsymbol{r}})$

1D Confinement (infinite Quantum Well):
$\Psi_n(x) = \sqrt{\frac{2}{L_x}} \sin\left(\frac{\sqrt{2mE}}{\hbar}x\right)$
$E_n = \frac{\hbar}{2m}k_n^2 = \frac{\hbar^2\pi^2 n^2}{2mL}$

2D Confinement $\Psi(x, y) = \sqrt{\frac{4}{L_x L_y}} \sin(k_x x) \cdot \sin(k_y y)$
$E_n = \frac{\hbar}{2m}(k_x^2 k_y^2)$

δ-D Confinement wirh $\{i = x, y, \dots, \delta\}$

$\Psi(\underline{\boldsymbol{r}}) = \sqrt{\frac{2\delta}{\prod L_i}} \prod_{i=1}^{\delta} \sin(k_i \cdot i)$
$E_n = \frac{\hbar}{2m}(k_x^2 k_y^2)$

Analytical solutions are only possible for the infinite quantum well

2.2 Quantenphysik

$E_{Ph} = f \cdot h = \hbar \cdot \omega = \frac{hc}{\lambda}$ $\quad \boxed{\lambda \cdot \underline{\boldsymbol{p}} = h}$
$p = \hbar k \qquad \hbar = \frac{h}{2\pi} \qquad k = \frac{2\pi}{\lambda}$

2.3 Phonons

are quasiparticles to describe modes of vibrations of elastic structures of interacting particles. there are acoustic and optical phonons.

3 Semiconductors

3.1 bandstructure

Fermienergie F_E: Höchste Energie eines Elektrons bei $T = 0K$ Isolator: große Bandlücke $E_G > 3\text{eV}$ Halbleiter: kleine Bandlücke $1eV < E_G < 3eV$ kann durch thermische Energie überwunden werden
Materials in columns:
IV: Si,Ge, III-V(GaAs, InP, GaN(BluRay), InSB),II-VI(CdSe, CsTe) IV-VI(PbS,PbSe)
Silicon in crystal structure: 5 per Cube
Chemical band structure: energylevels of diffrent atoms moving close together
At finite temperature some electrons can move around. $n \propto \exp(Tb_{gap})$
At $300K : n = 1.5 \times 10^10 cm^3$
doping with donors(P,As) or acceptors(B,In) to lower the energy for emission or capture an electron
atoms: 10^23 per cm^3, dopants: 10^15 per cm^3

$E_{kin} = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} \qquad \frac{\mathrm{d}^2 E}{\mathrm{d}p^2} = \frac{1}{m}$
Effektiv mass: $\frac{1}{m^*_{eff}} = \frac{1}{\hbar} \cdot \frac{\mathrm{d}^2 E}{\mathrm{d}k^2}$

Resistorequation: $R_{Mat} = \rho_{Mat}\frac{l}{wt}$
conductivity: $\sigma = \frac{1}{\rho} = q\mu_n n_i$
resistivity: ρ

uncrtainity for electron: $\Delta x \geq \frac{0.5 \cdot 10^{-4}}{\Delta v}$

v_{sat} for Si: $2 \cdot 10^7 \frac{cm}{s}$
$I_{DS} = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{DD} - V_T)^2$
$P = V_{DD}^2 C_{ox} f_{max}$

4 Transistors

$I_D = \frac{1}{2}\mu_n C'_{ox}\frac{W}{L} \cdot (V_{GS} - V_{th})^2$
$\mu_n \approx 250 \cdot 10^{-4} \frac{m^2}{Vs}$, $\mu_p \approx 100 \cdot 10^{-4} \frac{m^2}{Vs}$

$P_{cap} = \alpha_{01} f C_{ox} V_{DD}^2$
$f_{max} = \frac{I_{sat}}{V_{DD} C_{ox}}$

4.1 scaling with factor $S < 1$

reduce area $A = W \cdot L \quad A' = A \cdot S^2$
increase speed $\tau = \frac{L}{v} \quad \tau' = \tau \cdot S$
reduce power $P = VI\tau \quad P' = P \cdot S^3$

Transistorscaling in nm: 90(2003), 65(2005), 45(2007), 32(2009), 22(2011)

4.1.1 Problem of scaling

1. Tunneling across the oxide
2. Need for new lithographic techniques
3. Parasitic effects due to inteconnects
4. Melting interconnects due to voids
5. High field and breakdown effects

$\Rightarrow$ new materials, processes and technologies needed!
High-K Material (high dielectric ε) as Gate isolator: $\Rightarrow 1,6 \cdot C_G$, $0.01 \cdot I_{leak}$

Example Intels 45nm MOSFET: High-K with silicon gaten: Problems: uneven
Form: Normalgate, Dualgate, Trigate
Best: Surrounding Gate: CNT – high-K – metal-gate

4.2 Silicon Nanowire

Fabrication: growth on a gold(Au) particle

4.3 GaN - Transistors

Why GaN?

- Wide bandgaps of GaN and AlGaN (high breakdown volt.)
- high drift velocity(hf)
- strong piezoelectric effekt
- High temperature operation

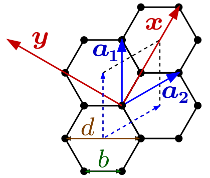
HEMT-Transistor: Two substrate materials, doped and undoped
$\Rightarrow$ electrons move on a 2D-Sheet
Cut-Off-Frquency $f_T = \frac{v_{sat}}{2\pi L_g}$: $g_m = 1$ (no amplification anymore)
Oxide-Capacitance $C_{ox} = \frac{\varepsilon_0 \varepsilon_r}{t_{ox}}$
T-Gate: smooth electric field in the channel.

4.4 Quantum Wire

Ideal: just one subband in two dimensions But for good conductance(mobility, drift velocity) one need $20nm$ Fabrication Methods: Stressor, Etching, Ion implantation, Vicinal Growth
Split Gate Transistor: 1D tunnel in the gate between source and drain. electron wave transistor:

4.5 Graphene

2D Network of 3D Carbon Atoms.
Stacked Layers of Graphene form Graphite.
carbon nanotubes are curled graphene layers



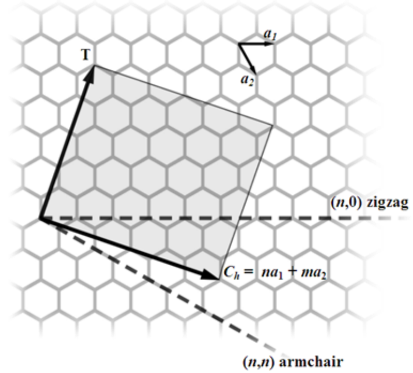
$b \approx 0.14\,\text{nm}$
$d = 2b$
$\underline{\boldsymbol{a}}_1 = \frac{3}{2}b\underline{\boldsymbol{x}} + \frac{\sqrt{3}}{2}b\underline{\boldsymbol{y}} = \frac{\sqrt{3}}{2}a\underline{\boldsymbol{x}} + \frac{1}{2}a\underline{\boldsymbol{y}}$
$\underline{\boldsymbol{a}}_2 = \frac{3}{2}b\underline{\boldsymbol{x}} - \frac{\sqrt{3}}{2}b\underline{\boldsymbol{y}} = \frac{\sqrt{3}}{2}a\underline{\boldsymbol{x}} - \frac{1}{2}a\underline{\boldsymbol{y}}$
$\|\underline{\boldsymbol{a}}_1\| = \|\underline{\boldsymbol{a}}_2\| = a = \sqrt{3}b$
$\|\underline{\boldsymbol{x}}\| = \|\underline{\boldsymbol{y}}\| = 3b$

4.5.1 Properties

thinnest material sheet imagineable
extremly strong (5 times stronger than steel)
semimetall: better conduction than metal, can switched ON and OFF
very light, good head conductor size of one cell: edge $d \approx 0.14nm$, edge2edge $a = \sqrt{3}d$

4.6 Carbon-Nano-Tubes CNT

Propertys: diameter: $d \approx 1\text{nm}$ Application: wires, transitors, seperation membranes, sensors, capacitors Single Walled and Multiwalled: SWCNT: single layer of graphite(graphene) rolled up as cilynder



Kind of curls: zig-zag $(n, 0)$, armchair (n, n), quiral (n, m)
chiral vector (tube circumfence): $\underline{\boldsymbol{C}}_h = n\underline{\boldsymbol{a}}_1 + m\underline{\boldsymbol{a}}_2$
translation vector $\underline{\boldsymbol{T}} = [(2m + n)\underline{\boldsymbol{a}}_1 - (2n + m)\underline{\boldsymbol{a}}_2] / \gcd(n, m)$
Tube-Diameter: $d_T = \frac{\|\underline{\boldsymbol{c}}_h\|}{\pi} = \frac{a}{\pi}\sqrt{n^2 + nm + m^2}$ with $a = 0.246\text{nm}$

Kind of Nanotube: $\begin{cases} \text{metalic} & \text{if}(n - m)/3 \in \mathbb{N}_0 \\ \text{semiconductor} & \text{else} \end{cases}$