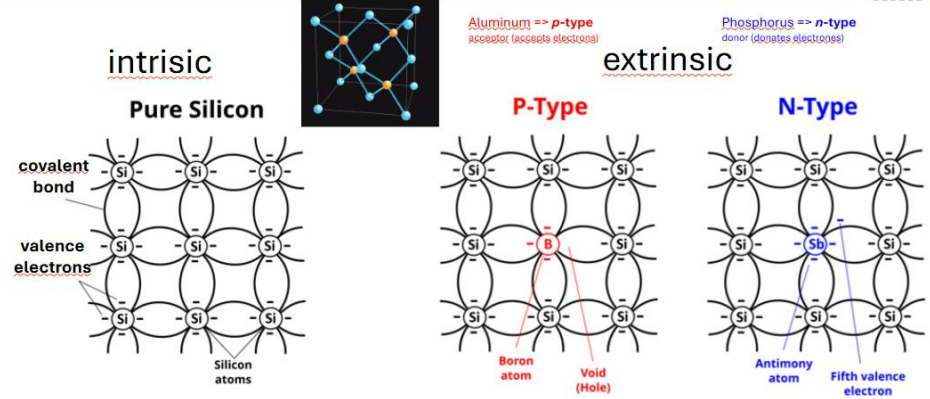
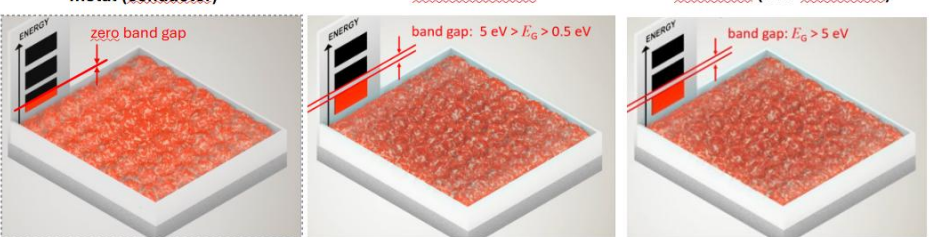
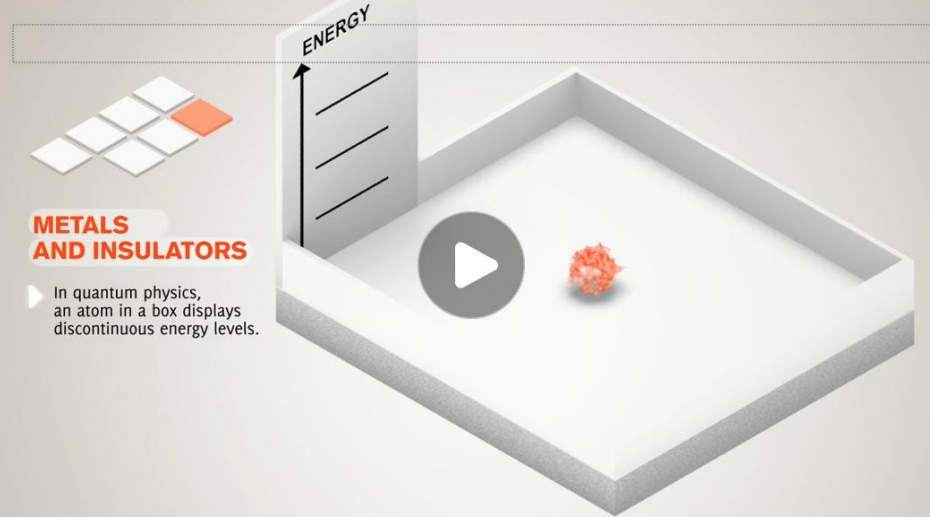
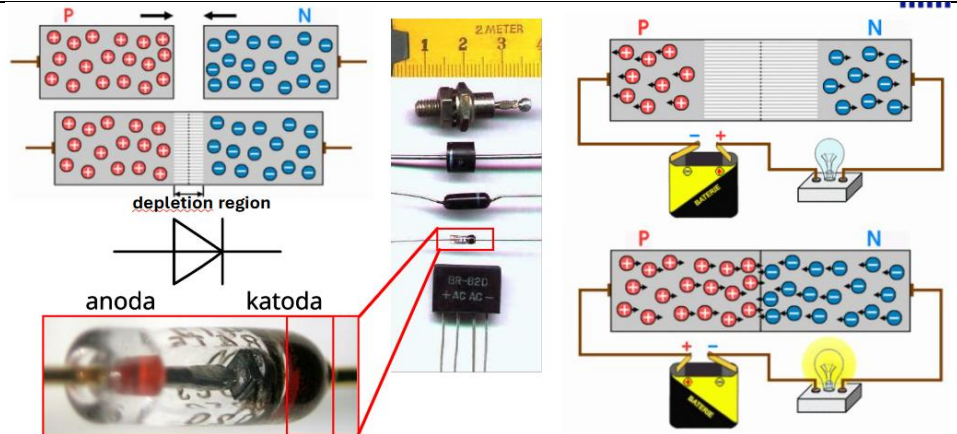
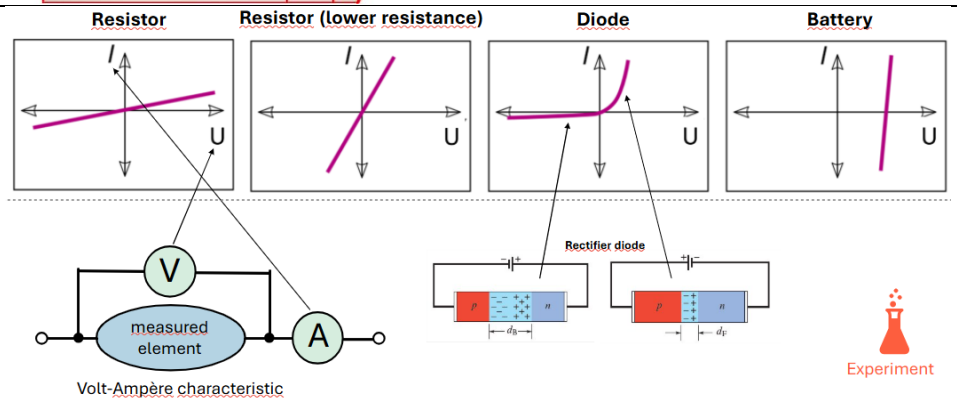


|                               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
|-------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 9.                            | <b>Hvad er en halvleder?</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| Målgruppe                     | Elever, eventuelt lærere                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
| Alder, elever                 | 16–18                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Varighed                      | 1,5–2 timer                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Hvad er en halvleder          |  <p><b>intrinsic</b><br/>Pure Silicon</p> <p><b>extrinsic</b><br/><b>P-Type</b><br/>Aluminum ==&gt; <i>p-type</i> acceptor (accepts electrons)<br/>Boron atom<br/>Void (Hole)</p> <p><b>N-Type</b><br/>Phosphorus ==&gt; <i>n-type</i> donor (donates electrons)<br/>Antimony atom<br/>Fifth valence electron</p>                                                                                                                                                                                                                                                              |
| Opsummering af introduktionen |  <p><b>metal (conductor)</b><br/>zero band gap</p> <p><b>semiconductor</b><br/>band gap: <math>5 \text{ eV} &gt; E_g &gt; 0.5 \text{ eV}</math></p> <p><b>dielectric (non-conductor)</b><br/>band gap: <math>E_g &gt; 5 \text{ eV}</math></p> <p>Extrinsic semiconductors:<br/>Phosphorus ==&gt; <i>p-type</i> donor<br/>Aluminum ==&gt; <i>p-type</i> acceptor</p> <p>Electrical resistance (<math>\Omega</math>)<br/>Experiment</p> <p>CHIPS of Europe – Creating Higher-Education Industry Programmes for the Semiconductor Industry of Europe<br/>www.chips4europe.eu</p> |
| Video: Metaller og isolatorer |  <p><b>METALS AND INSULATORS</b></p> <p>In quantum physics, an atom in a box displays discontinuous energy levels.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                       |

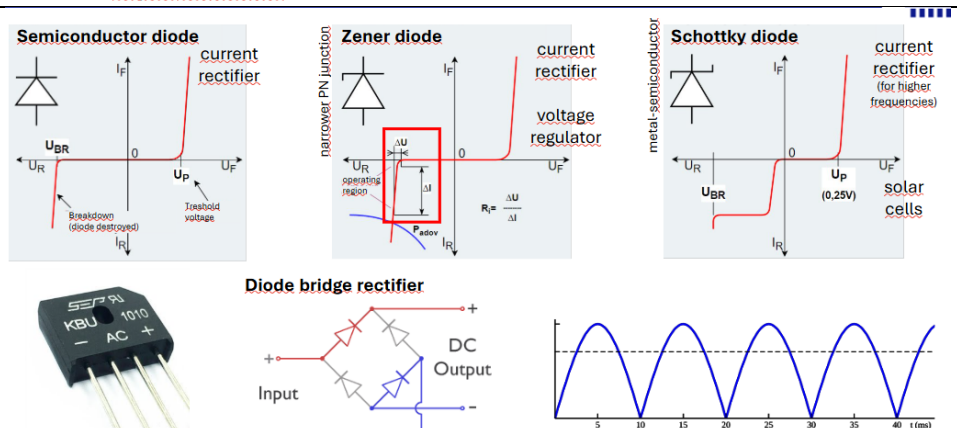
### Anvendelser: PN-overgang → Diode



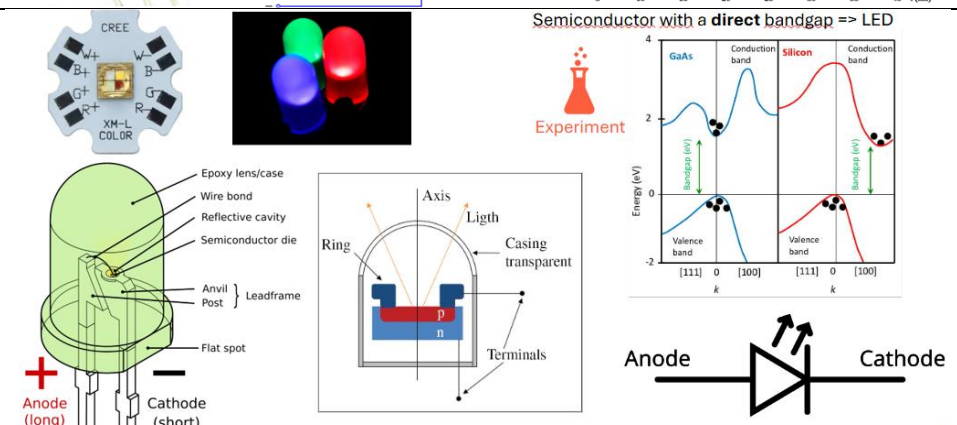
### VA-karakteristik (lineære vs. ikke-lineære elementer)



### VA-karakteristik (avanceret)



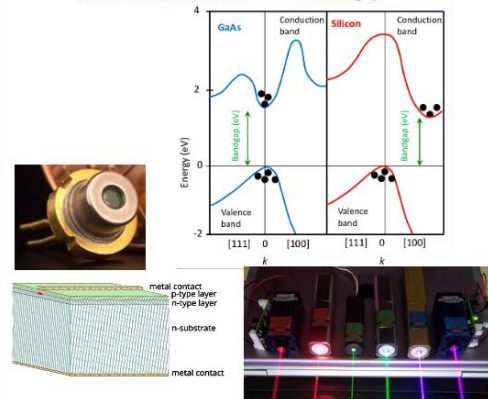
### Diode → LED (lysdiod)



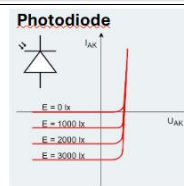
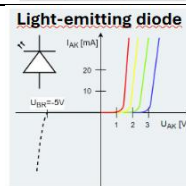
## Diode → LED → Halvlederlaser

| Color       | Wavelength (nm)       | Voltage (V)                  | Semiconductor material                                                                                                                                                                                                                           |
|-------------|-----------------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Infrared    | $\lambda > 780$       | $\Delta V < 1.9$             | Gallium arsenide (GaAs)<br>Aluminum gallium arsenide (AlGaAs)                                                                                                                                                                                    |
| Red         | $610 < \lambda < 760$ | $1.93 < \Delta V < 2.03$     | Aluminum gallium arsenide (AlGaAs)<br>Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)                                                                                                |
| Orange      | $590 < \lambda < 610$ | $2.03 < \Delta V < 2.10$     | Gallium arsenide phosphide (GaAsP)<br>Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)                                                                                                                                   |
| Yellow      | $570 < \lambda < 590$ | $2.10 < \Delta V < 2.18$     | Gallium arsenide phosphide (GaAsP)<br>Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)                                                                                                                                   |
| Green       | $500 < \lambda < 570$ | $1.9^{III} < \Delta V < 4.0$ | Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)<br>Gallium(III) phosphide (GaP) Aluminum gallium indium phosphide (AlGaInP) Aluminum gallium phosphide (AlGaP)                                                                       |
| Blue        | $450 < \lambda < 500$ | $2.48 < \Delta V < 3.7$      | Zinc selenide (ZnSe)<br>Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)                                                                                                        |
| Violet      | $420 < \lambda < 450$ | $2.76 < \Delta V < 4.0$      | Indium gallium nitride (InGaN)                                                                                                                                                                                                                   |
| Purple      | multiple types        | $2.48 < \Delta V < 3.7$      | Dual binned LEDs,<br>blue with red phosphor, or white with purple phosphor                                                                                                                                                                       |
| Ultraviolet | $\lambda < 400$       | $3.1 < \Delta V < 4.4$       | Diamond (235 nm) <sup>[12]</sup><br>Boron nitride (215 nm) <sup>[13][14]</sup> Aluminum nitride (AlN) (210 nm) <sup>[15]</sup><br>Aluminum gallium nitride (AlGaIn) Aluminum gallium indium nitride (AlGaInN) — (down to 210 nm) <sup>[16]</sup> |
| White       | broad spectrum        | $2.7 < \Delta V < 3.5$       | Blue diode with yellow phosphor or violet/IV diode with multi color phosphor                                                                                                                                                                     |

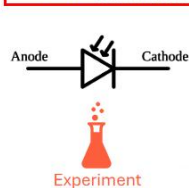
### Semiconductor with a direct bandgap => LED



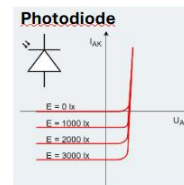
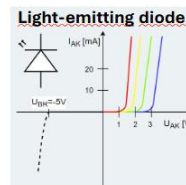
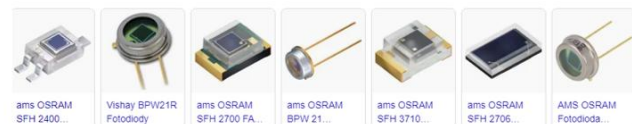
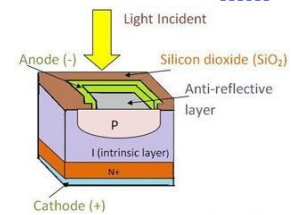
## Diode → LED → Fotodiode



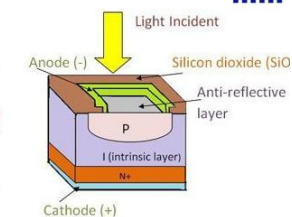
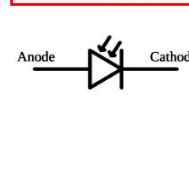
### speaker vs. microphone LED vs. photodiode



Experiment



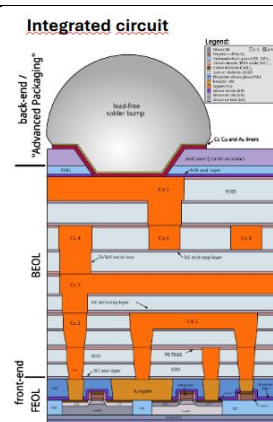
### speaker vs. microphone LED vs. photodiode



### Digital camera chip



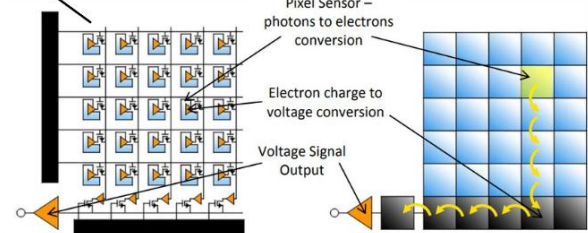
## Diode → LED → Fotodiode (CCD, CMOS)



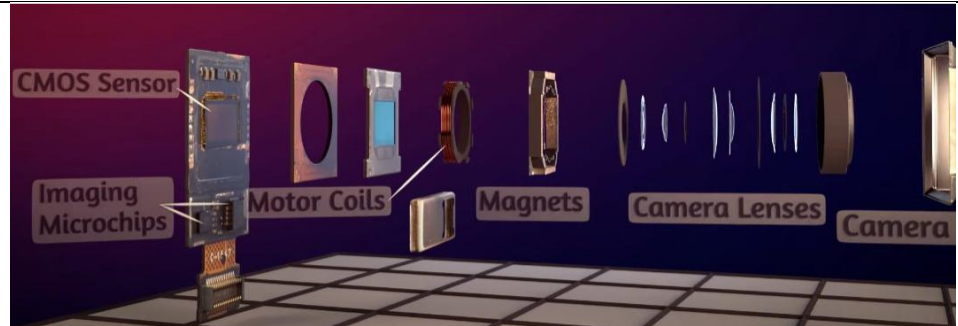
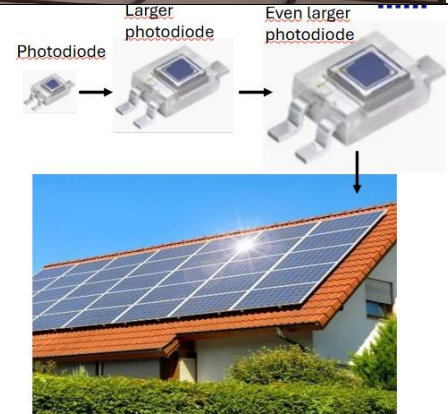
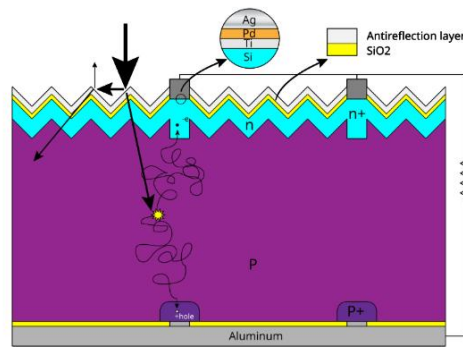
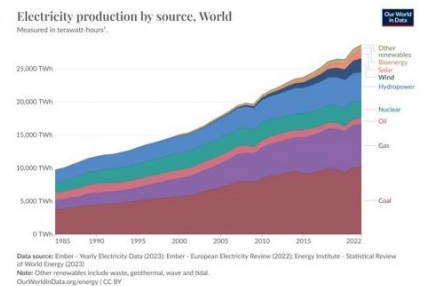
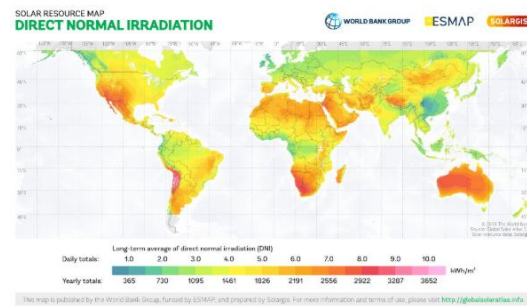
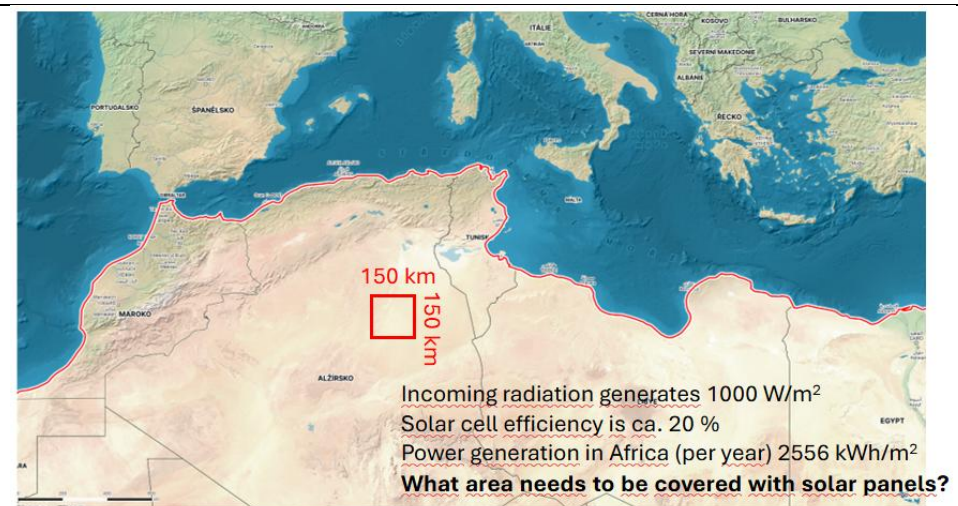
CMOS



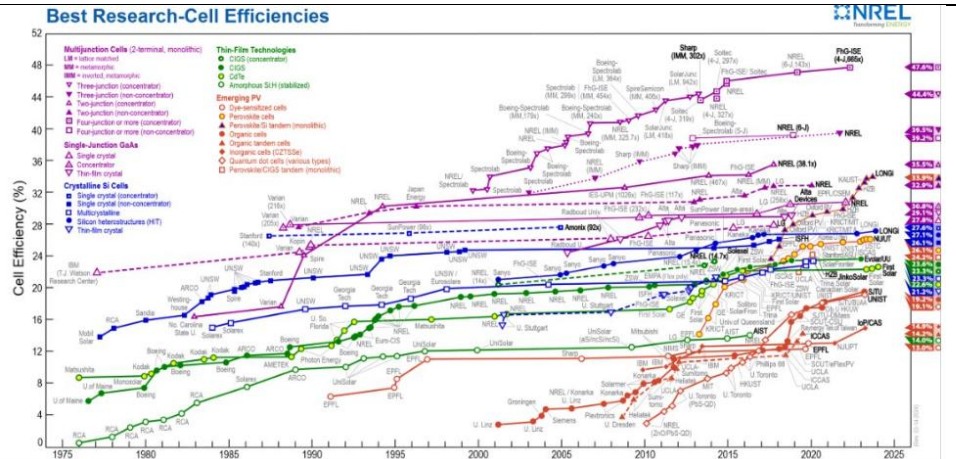
CCD



## Telefonkamera

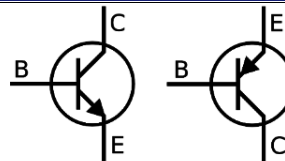

 Diode → LED →  
Fotodiode →  
Solcelle
Solindstråling vs.  
energiforbrugSolceller (hvorfor,  
hvor mange,  
hvordan..?)

## Solceller: effektivitet

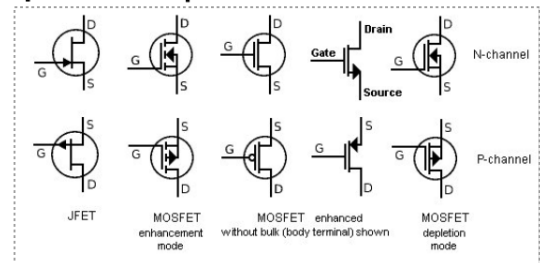


## Transistor

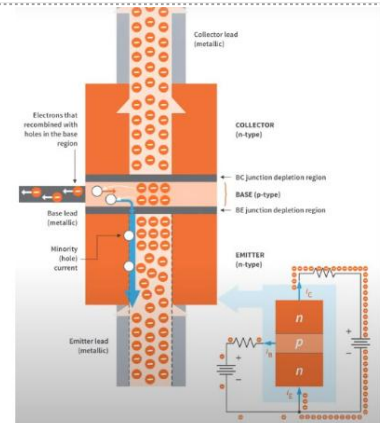
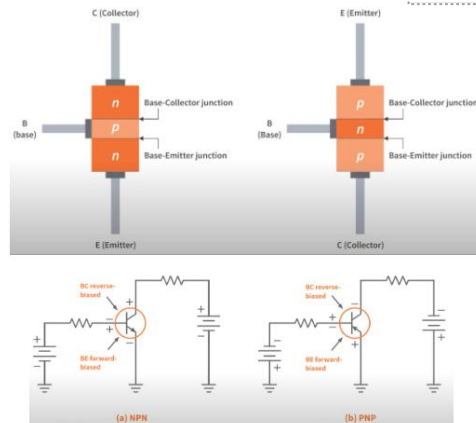
### Bipolar junction transistor (BJT)



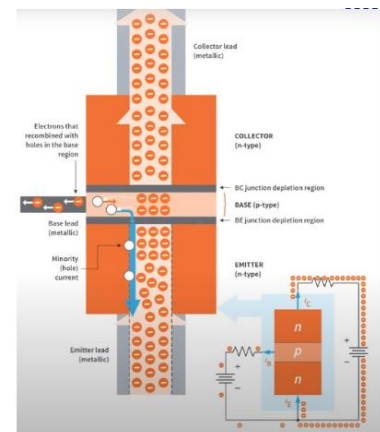
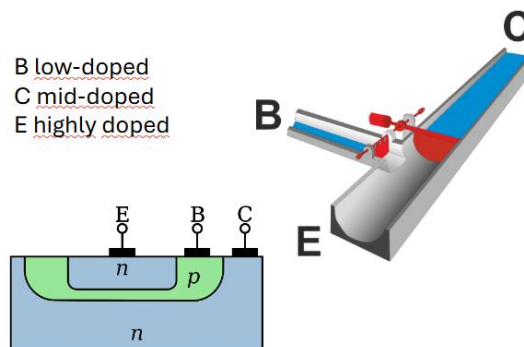
### Unipolar transistor (FET)



## Bipolar transistor (BJT)

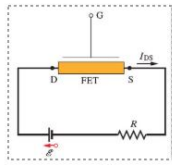


B low-doped  
C mid-doped  
E highly doped

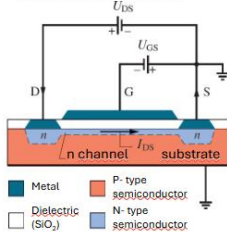


## Metal-oxid-halvleder felteffekttransistor (MOSFET)

### Field effect transistor(FET)

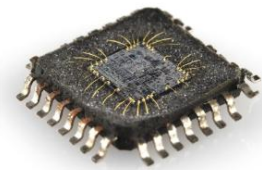
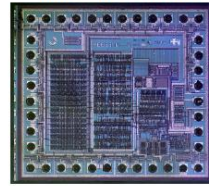


1N5200PbF Vishay N Channel Mosfet, ...  
~ 94 KΩ



S-D current flows = 1  
S-D current does not flow = 0  
Very fast switching (~1 ps)

### Integrated circuit



### Microprocessor in cross-section



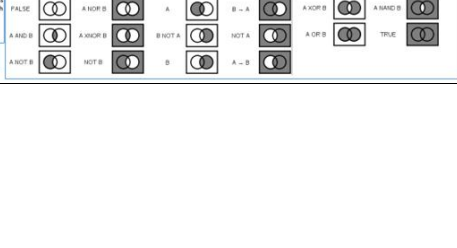
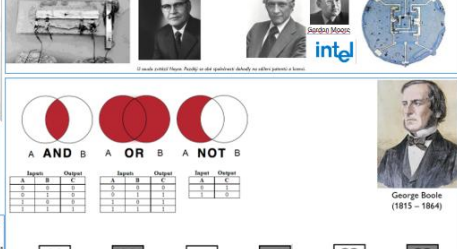
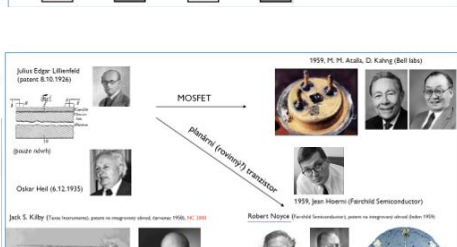
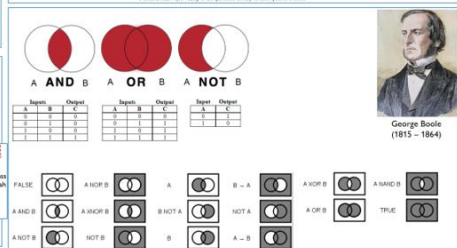
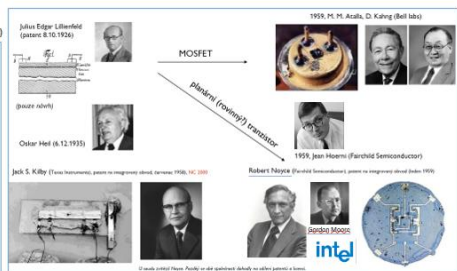
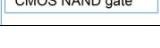
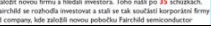
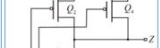
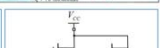
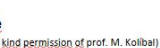
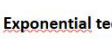
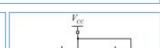
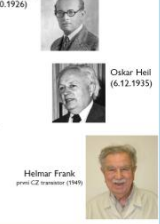
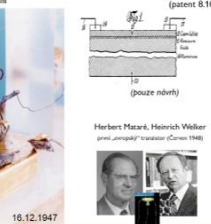
## Ekspontiel teknologi: historien om transistoren

### Exponential technology: The transistor tale

(with kind permission of prof. M. Koilbal)



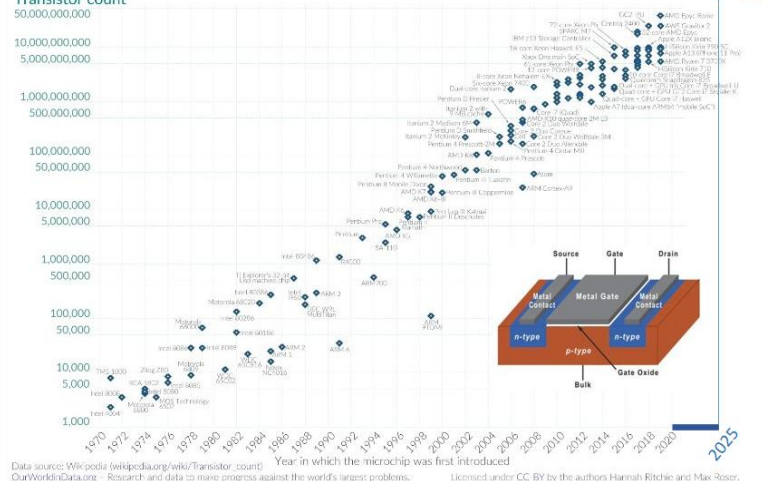
William Shockley, John Bardeen, Walter Brattain  
(Nobelprisen 1956)



## Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

### Transistor count



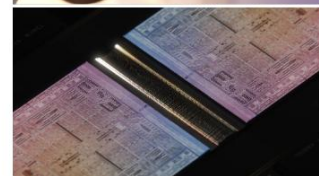
### Semiconductor device fabrication



#### MOSFET scaling (process nodes)

|        |      |
|--------|------|
| 20 μm  | 1958 |
| 10 μm  | 1971 |
| 6 μm   | 1974 |
| 3 μm   | 1977 |
| 1.5 μm | 1981 |
| 1 μm   | 1984 |
| 800 nm | 1987 |
| 600 nm | 1990 |
| 350 nm | 1993 |
| 250 nm | 1996 |
| 180 nm | 1999 |
| 130 nm | 2001 |
| 90 nm  | 2003 |
| 65 nm  | 2005 |
| 45 nm  | 2007 |
| 32 nm  | 2009 |
| 28 nm  | 2010 |
| 22 nm  | 2012 |
| 14 nm  | 2014 |
| 10 nm  | 2016 |
| 7 nm   | 2018 |
| 5 nm   | 2020 |
| 3 nm   | 2022 |
| Future |      |
| 2 nm   | 2025 |
| 1 nm   | 2027 |

|                                                                                                            |                                                |      |       |                            |                       |                       |
|------------------------------------------------------------------------------------------------------------|------------------------------------------------|------|-------|----------------------------|-----------------------|-----------------------|
| Apple M3 (octa-core 64-bit ARMv8 SoC, SIMD, caches)                                                        | 25,000,000,000 <sup>[186]</sup>                | 2023 | Apple | 3 nm                       | ?                     | ?                     |
| Apple M3 Pro (dodeca-core 64-bit ARMv8 SoC, SIMD, caches)                                                  | 37,000,000,000 <sup>[186]</sup>                | 2023 | Apple | 3 nm                       | ?                     | ?                     |
| Apple M3 Max (hexadeca-core 64-bit ARMv8 SoC, SIMD, caches)                                                | 92,000,000,000 <sup>[186]</sup>                | 2023 | Apple | 3 nm                       | ?                     | ?                     |
| Apple A17                                                                                                  | 19,000,000,000 <sup>[187]</sup>                | 2023 | Apple | 3 nm                       | 103.8 mm <sup>2</sup> | 183,044,315           |
| Sapphire Rapids quad-chip module (up to 60 cores and 112.5 MB of cache) <sup>[188]</sup>                   | 44,000,000,000–48,000,000,000 <sup>[188]</sup> | 2023 | Intel | 10 nm ESB (Intel 7)        | 1,600 mm <sup>2</sup> | 27,500,000–30,000,000 |
| Apple M2 Pro (12-core 64-bit ARMv8 SoC, SIMD, caches)                                                      | 40,000,000,000 <sup>[189]</sup>                | 2023 | Apple | 5 nm                       | ?                     | ?                     |
| Apple M2 Max (12-core 64-bit ARMv8 SoC, SIMD, caches)                                                      | 67,000,000,000 <sup>[189]</sup>                | 2023 | Apple | 5 nm                       | ?                     | ?                     |
| Apple M2 Ultra (two M2 Max dies)                                                                           | 134,000,000,000 <sup>[190]</sup>               | 2023 | Apple | 5 nm                       | ?                     | ?                     |
| AMD Epyc Bergamo (4th gen/97X4 series) 8-chip module (up to 128 cores and 256 MB (L3) + 128 MB (L2) cache) | 82,000,000,000 <sup>[191]</sup>                | 2023 | AMD   | 5 nm (CCD) 6 nm (IOD)      | ?                     | ?                     |
| AMD Instinct MI300A (multi-chip module, 24 cores, 128 GB GPU memory + 256 MB (LLC/L3) cache)               | 146,000,000,000 <sup>[192][193]</sup>          | 2023 | AMD   | 5 nm (CCD, GCD) 6 nm (IOD) | 1,017 mm <sup>2</sup> | 144,000,000           |



### Graphics processing unit (GPU)

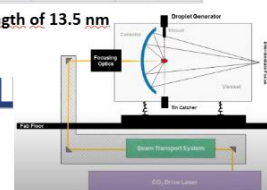
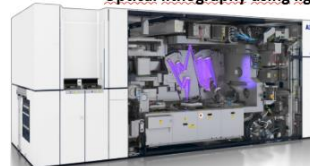
|                       |                                                                       |      |        |      |                          |                                                                                        |                                                            |
|-----------------------|-----------------------------------------------------------------------|------|--------|------|--------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------|
| GH100 Hopper          | 80,000,000,000                                                        | 2022 | Nvidia | TSMC | 4 nm                     | 814 mm <sup>2</sup>                                                                    | 98,280,000                                                 |
| AD102 Ada Lovelace    | 76,300,000,000                                                        | 2022 | Nvidia | TSMC | 4 nm                     | 608.4 mm <sup>2</sup>                                                                  | 125,411,000                                                |
| AD103 Ada Lovelace    | 45,900,000,000                                                        | 2022 | Nvidia | TSMC | 4 nm                     | 378.6 mm <sup>2</sup>                                                                  | 121,240,000                                                |
| AD104 Ada Lovelace    | 35,800,000,000                                                        | 2022 | Nvidia | TSMC | 4 nm                     | 294.5 mm <sup>2</sup>                                                                  | 121,560,000                                                |
| AD106 Ada Lovelace    | ?                                                                     | 2023 | Nvidia | TSMC | 4 nm                     | 190 mm <sup>2</sup>                                                                    | ?                                                          |
| AD107 Ada Lovelace    | ?                                                                     | 2023 | Nvidia | TSMC | 4 nm                     | 146 mm <sup>2</sup>                                                                    | ?                                                          |
| Navi 31 RDNA3         | 57,700,000,000 (MCM)<br>45,400,000,000 (GCD)<br>6+2,050,000,000 (MCD) | 2022 | AMD    | TSMC | 5 nm (GCD)<br>6 nm (MCD) | 531 mm <sup>2</sup> (MCM)<br>306 mm <sup>2</sup> (GCD)<br>6+37.5 mm <sup>2</sup> (MCD) | 109,200,000 (MCM)<br>132,400,000 (GCD)<br>54,640,000 (MCD) |
| Navi 32 RDNA3         | 28,100,000,000 (MCM)                                                  | 2023 | AMD    | TSMC | 5 nm (GCD)<br>6 nm (MCD) | 350 mm <sup>2</sup> (MCM)<br>200 mm <sup>2</sup> (GCD)<br>4+37.5 mm <sup>2</sup> (MCD) | 80,200,000 (MCM)                                           |
| Navi 33 RDNA3         | 13,300,000,000                                                        | 2023 | AMD    | TSMC | 6 nm                     | 204 mm <sup>2</sup>                                                                    | 65,200,000                                                 |
| Aqua Vanjaram CDNA3   | 153,000,000,000 (MCM)                                                 | 2023 | AMD    | TSMC | 5 nm (GCD)<br>6 nm (MCD) | ?                                                                                      | ?                                                          |
| GB200 Grace Blackwell | 208,000,000,000                                                       | 2024 | Nvidia | TSMC | 4 nm                     | ?                                                                                      | ?                                                          |



Taiwan Semiconductor Manufacturing Company Limited  
(TSMC, sometimes only Taiwan Semiconductor)



### Optical lithography using light with wavelength of 13.5 nm



Thanks to nanotechnology!

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(MOSFET)**

