Enabling technologies, technological waves and future perspectives of vacuum electronics

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*retired from Philips 2014

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Outline:

1) Introduction
2) Enabling / base technologies
3) Historical development of Vacuum Electronics (=VE) and technological cycles
4) Development of cathode technology
5) Microwave tubes and advantages over SSD
6) Future applications of standard technology
7) Development and limitations of solid state electronics (=SSD)
8) Perspectives of vacuum nano electronics
9) Conclusion
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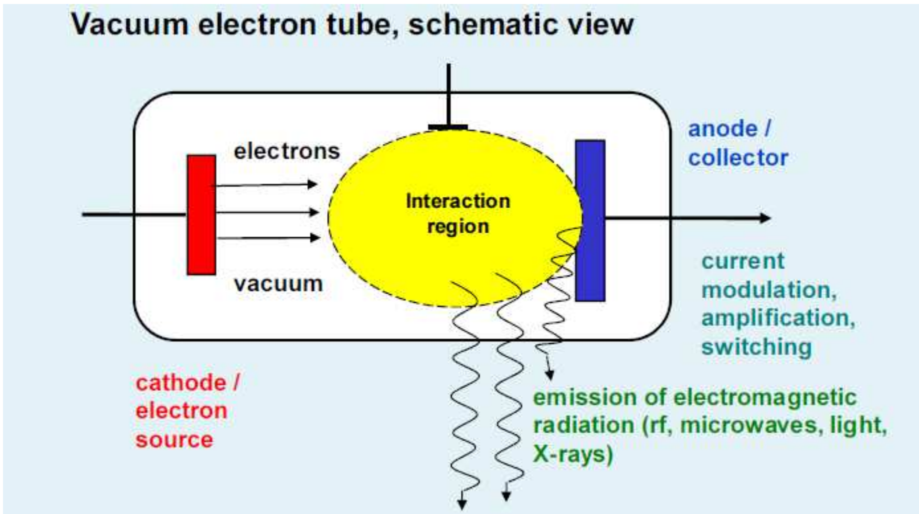
1) Introduction

For about 130 years vacuum electronics (VE) have been the motor of technical innovation in several application areas.

Only in the 1980´s solid-state electronics (SSE) took the lead and replaced tubes in several application areas, such as electronics and computing. Some of you certainly have experienced the peak and the decline of cathode-ray tubes, where thin-panel displays (e.g. LCDs) took their place. Currently incandescent and gas-discharge lamps are superseded by solid-state light-emitting diodes (LEDs). Hence one may fear, that only niche applications will remain in the future.

It is the aim of this presentation to wrap up the current application areas of VE and point out the specific advantages of VE e.g. over SSD. Based on this , future perspectives are outlined.



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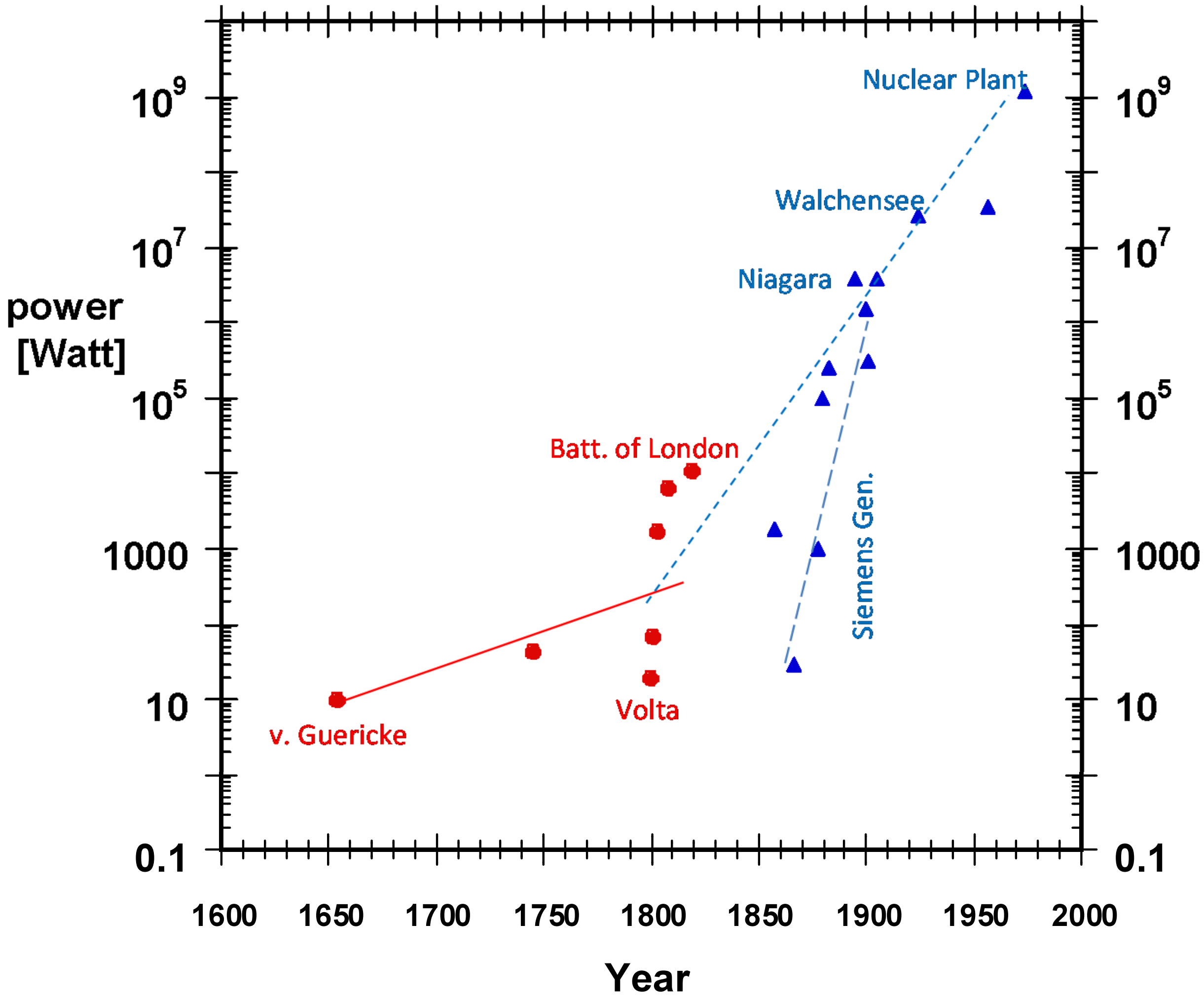
2) Enabling Technologies: Electric energy supply
a) The evolution of electric power generation



Ref.: W. E. Ayrton, “Practical Electricity”, CASSELL & Co. Ltd., London, 1891
P. Dunsheath, “A History of Electrical Power Engineering”, MIT Press, Cambridge 1962
W. Fischer (Ed.), “Die Geschichte der Stromversorgung”, VWEW Verlag , Frankfurt a. Main, 1992

585 B.C. Thales of Milet, electric and magnetic forces as a curiosity

300 B.C “battery of Bagdad”, 250 μA & 0,25 V, maybe used for electroplating

1663 electrization machine of v. Guericke, using a sulfur sphere and friction.

1745 storing charges in Kleist jar or “Leyden jar”

1800 A. Volta: pile, conversion of chemical to electric energy in a redox reaction

1810 – 1836 Great Battery of London (A. Pepys, H. Davy), 2000 cells in 200 troughs, 83 m^2 electrode surface area

1857 W. v. Siemens, dynamo-electric machine

1885 dc power grid e.g. in Berlin; Start of ac power plants
1900 Paris, 1,57 MW Generator, Siemens

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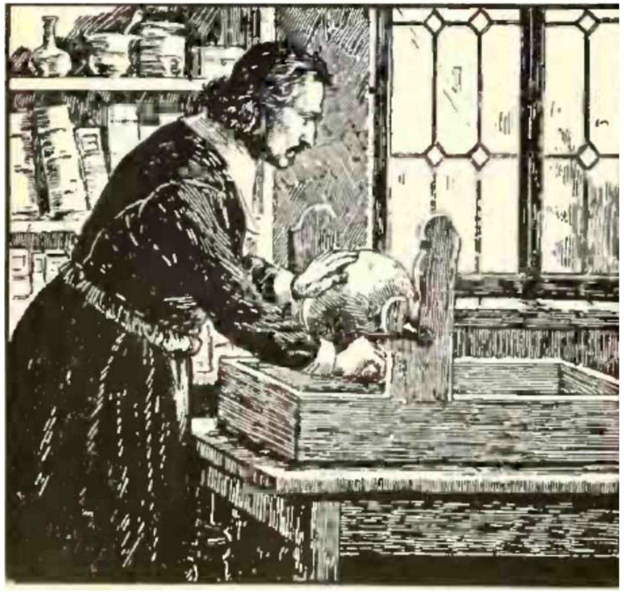
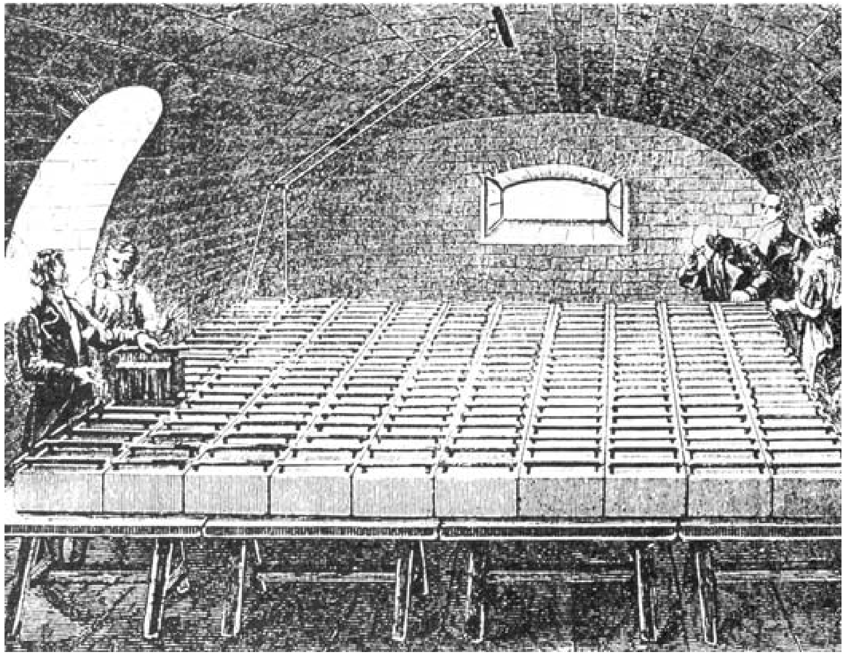


1663 electrization machine of Otto von Guericke, using a sulfur sphere and friction.



1810 – 1836 Great Battery of the Royal Society of London (A. Pepys, H. Davy), 2000 double plates of Zn and Cu in 200 troughs, 83 m^2 electrode surface area: 11,3 kW
The electrolyte : nitric acid, sulfuric acid, water

The advancement of science and technology in Europe started, when religous dogmatism had been overcome after reformation and the 30 years war, it accelerated after the french revolution and secularization and standardization of measures and increased its speed with the industrial revolution in the 19th century.

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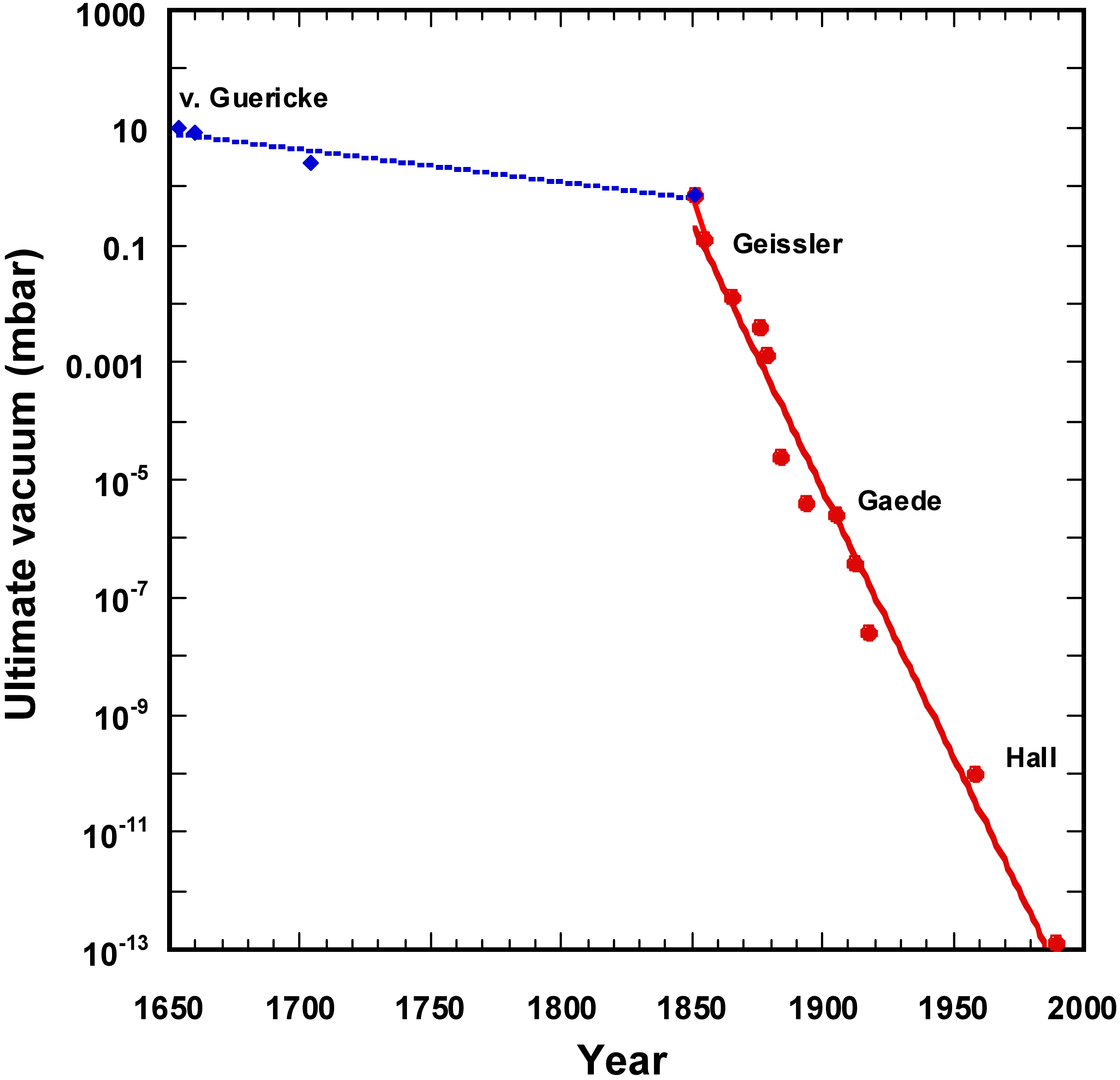
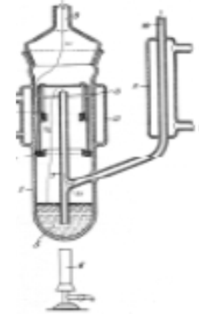
2b) Improvement of base technologies : Vacuum technology



Ultimate vacuum achieved versus time, according to P.A. Redhead and [1].

Rotary mercury sealed mechan. pump 1905

Wolfgang Gaede (1878-1945)



Mercury diffusion pump 1915

Varian ion getter pump

Balzers Turbo molecular pump

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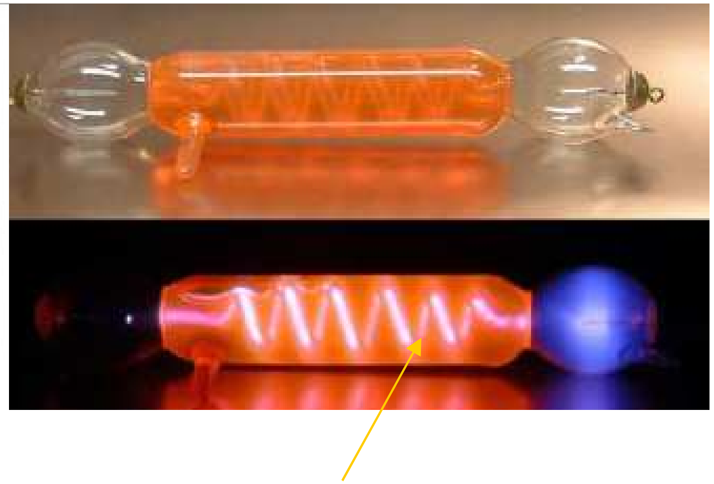
3) Historical Development

–the early days


Johann Heinrich Wilhelm Geissler 1815-1879




Thomas Alva Edison
1847-1931

1854 - The glassblower Heinrich Geissler from Bonn invents the Geissler tube, created using his Hg pump - this was the first good evacuated vacuum tube later modified by Sir William Crookes.

1859 - German mathematician and physicist, Julius Pluecker also from Bonn experiments with invisible cathode rays. Cathode rays were first identified by him.

1878 - The Englishman Sir William Crookes was the first one to confirm the existence of cathode rays by displaying them, with his invention of the Crookes tube, a crude prototype for all future CRTs.

1883 - USA: Thomas Alva Edison discovers current flow in a light bulb

1897 - Germany: Karl Ferdinand Braun invents the CRT oscilloscope - the Braun Tube was the forerunner of today's television and radar tubes.

1929 - SU: Vladimir Kosma Zworykin invents a CRT called the kinescope, a simple television system, and the iconoscope, an early television camera

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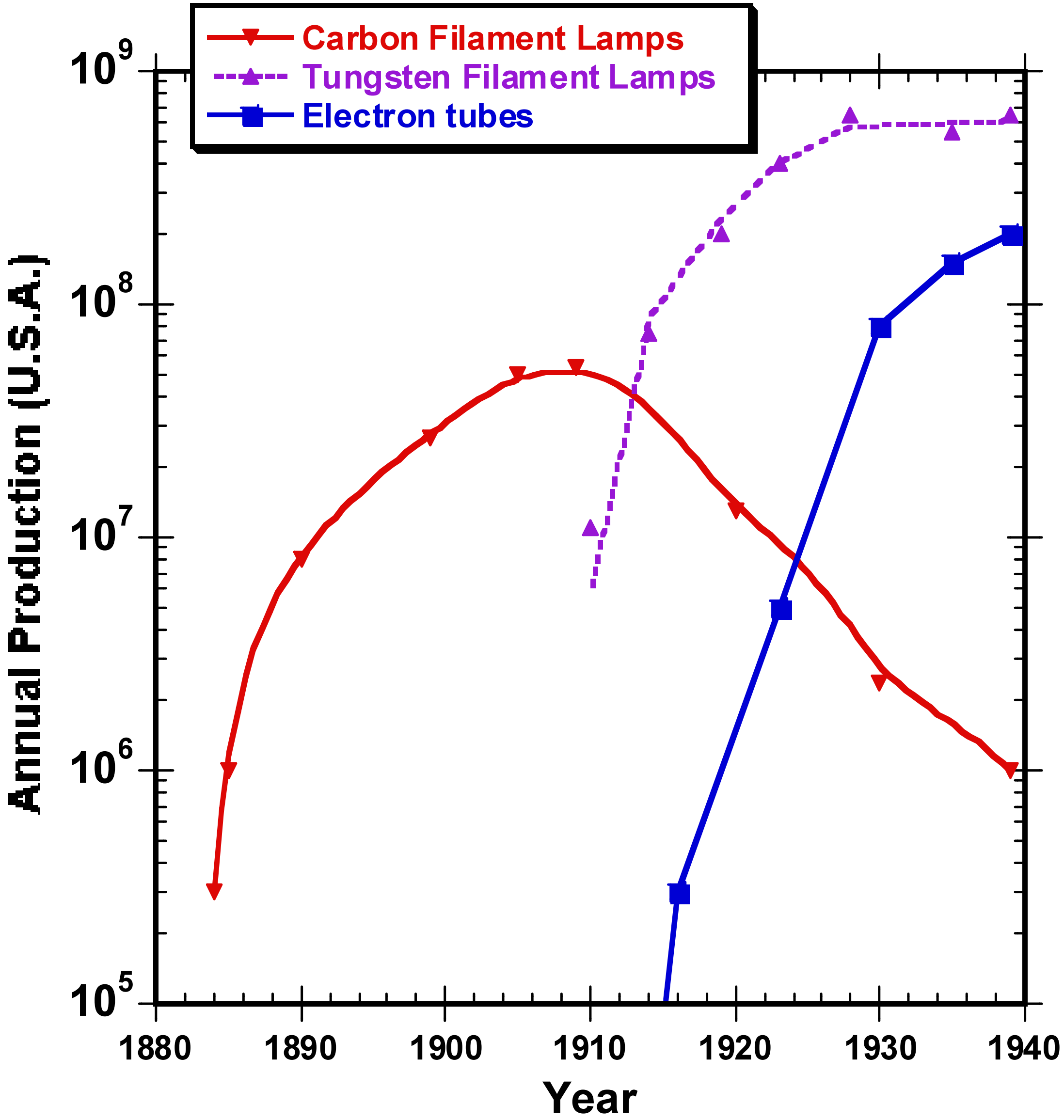
3) Historical development of Vacuum Electronics (=VE) and technological cycles

The rise of incandescent lamps (forerunner) and of radio tubes



Annual production rate of incandescent lamps and electron tubes in the US. till 1940 according to P. A. Redhead, J. Vac. Sci. Tech. A 23, 1252 (2005) (see [1]).
Tungsten filament lamps: luminous efficacy doubled to 10 lm/W

Below:
Edison Carbon Filament Light Bulb 1880

From: T.L. Cass, A Brief History of the Vacuum Tube Valve; The Museum of Technology 2010

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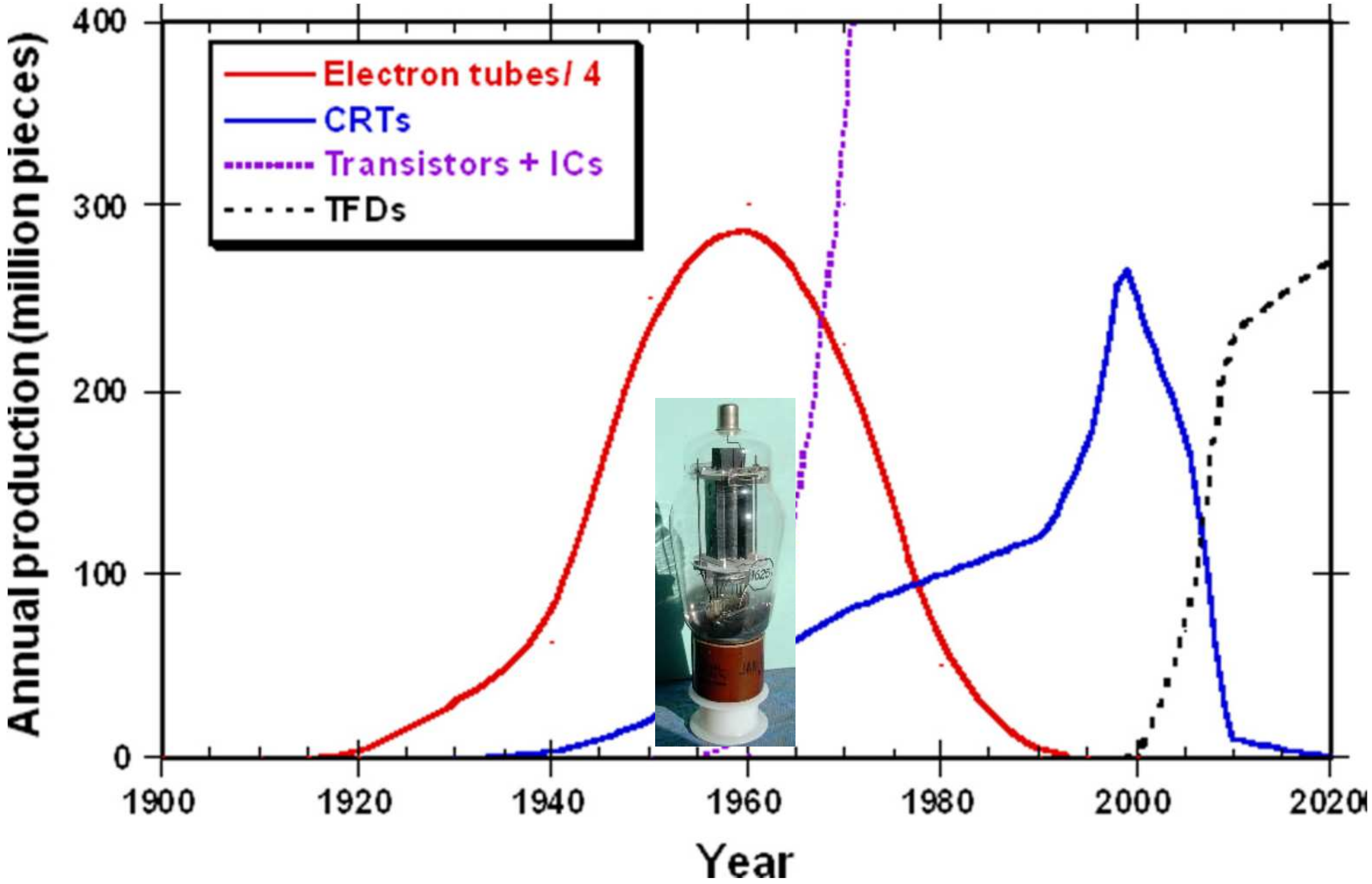
3) Historical development of Vacuum Electronics (=VE) and technological cycles-

The era of the radio tubes:



Historical trends/ technological waves in vacuum electronics and neighboring fields according to [1]. The tube shown is the type 807 or VT136 with 100 Watt at 60 MHz.

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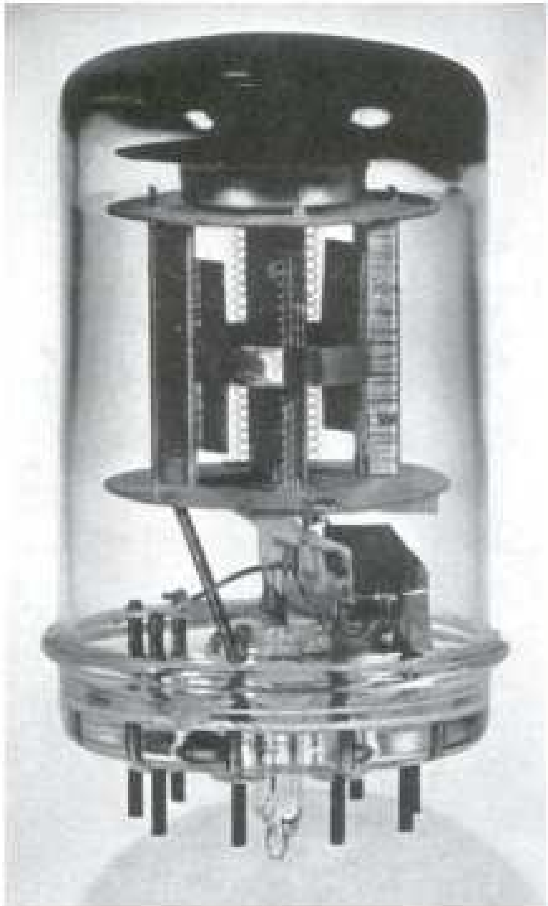
3) Historical development of Vacuum Electronics (=VE) and technological cycles



Interior and outside view with rim of the EF50 RF pentode tube manufactured by Philips, 1938-1945, (pentode, pressed glass base)
Already 1932 Philips alone had produced over 100 Millions tubes for the rising communication/radio market.

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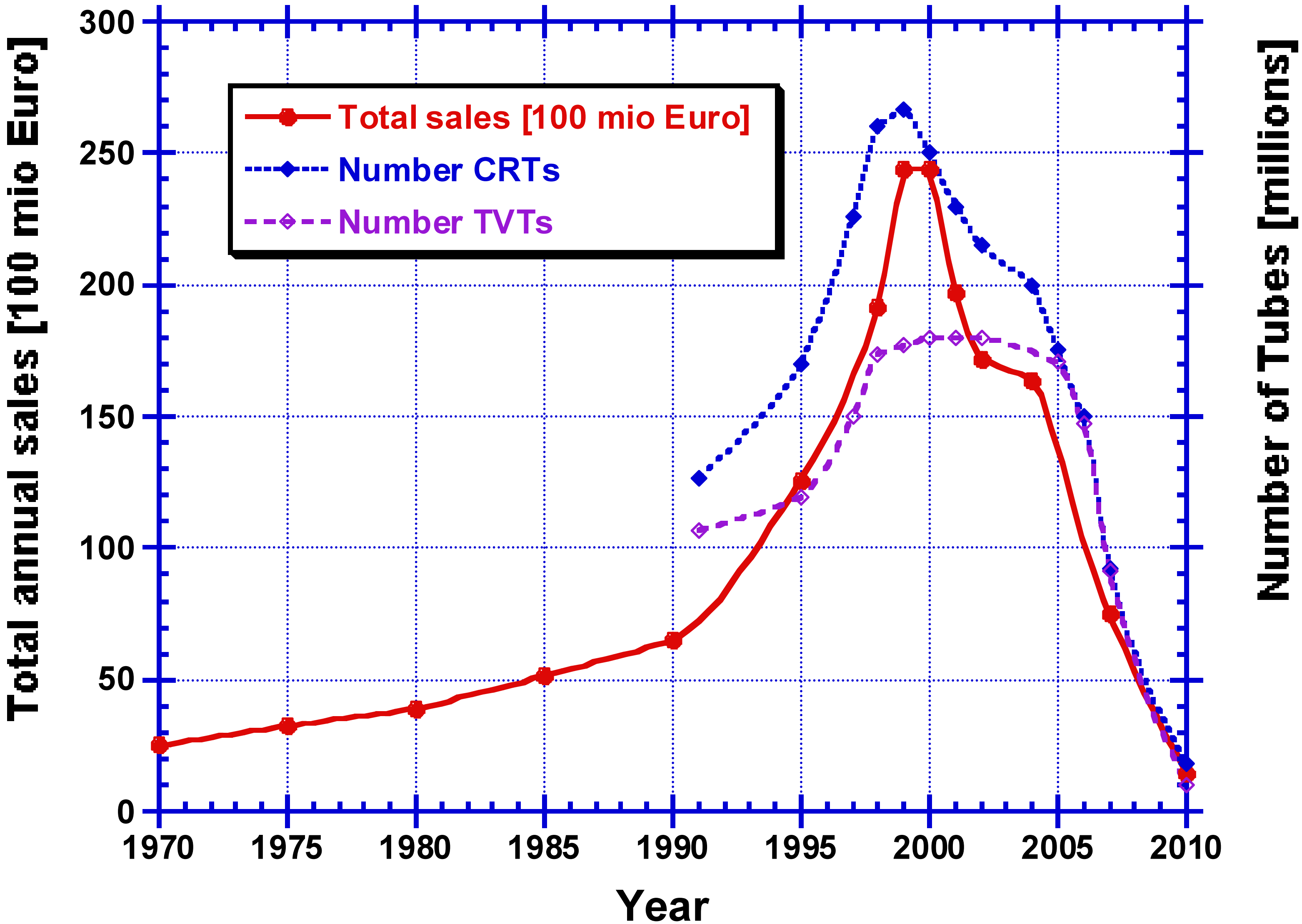
3) Technological cycles: The rise and the fall of CRTs



CRT world market versus time: The left vertical scale refers to total annual CRT sales (round dots) in units of 100 million €. On the right vertical scale, the number of tubes is given in million pieces: the solid diamonds are the total number of CRTs sold per year including color monitor tubes (CMTs), the open diamonds are the television tubes (TVT) only.

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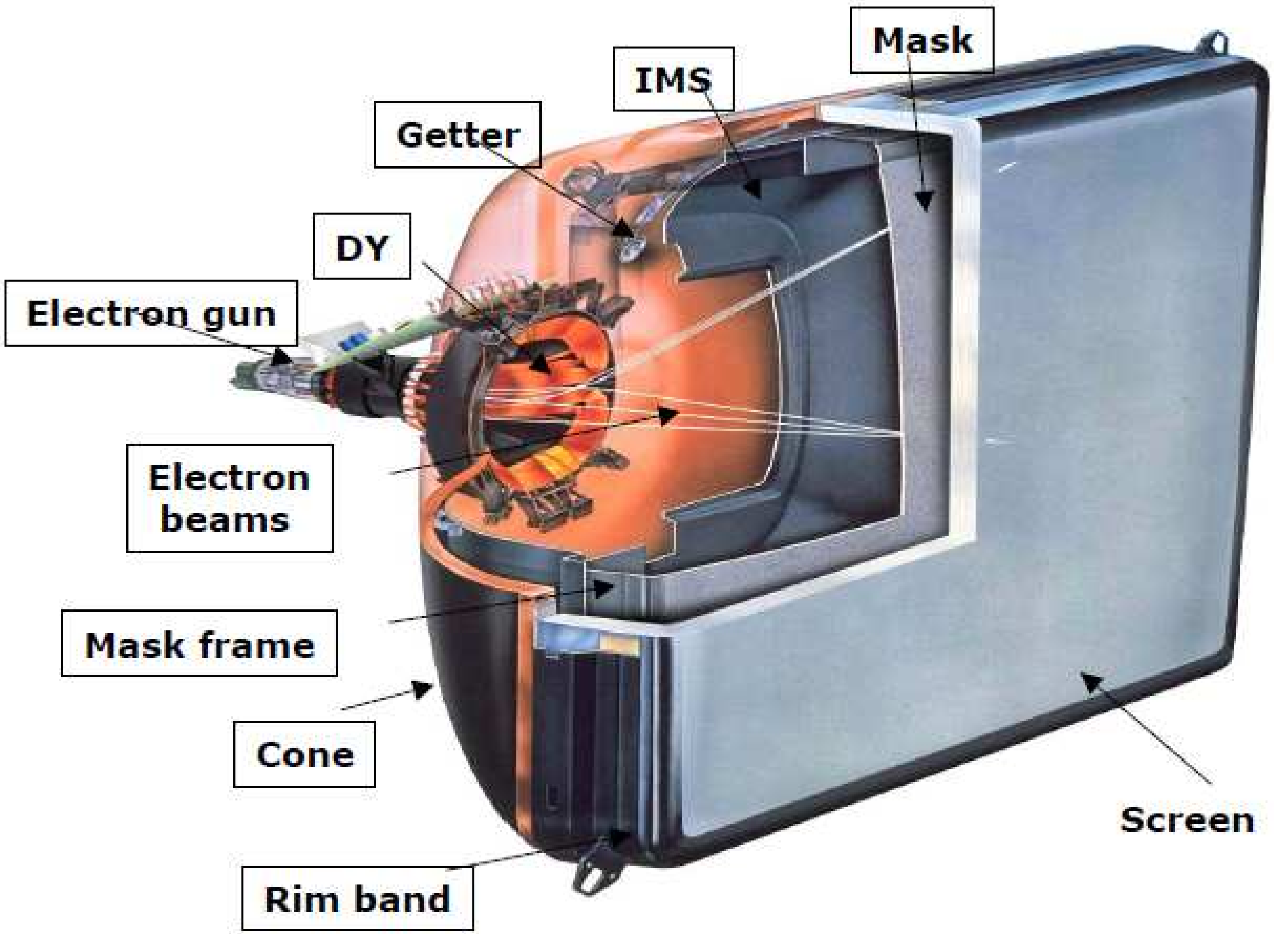
3) Technologicl cycles: The rise and the fall of CRTs



Schematic view of a television tube (Philips).

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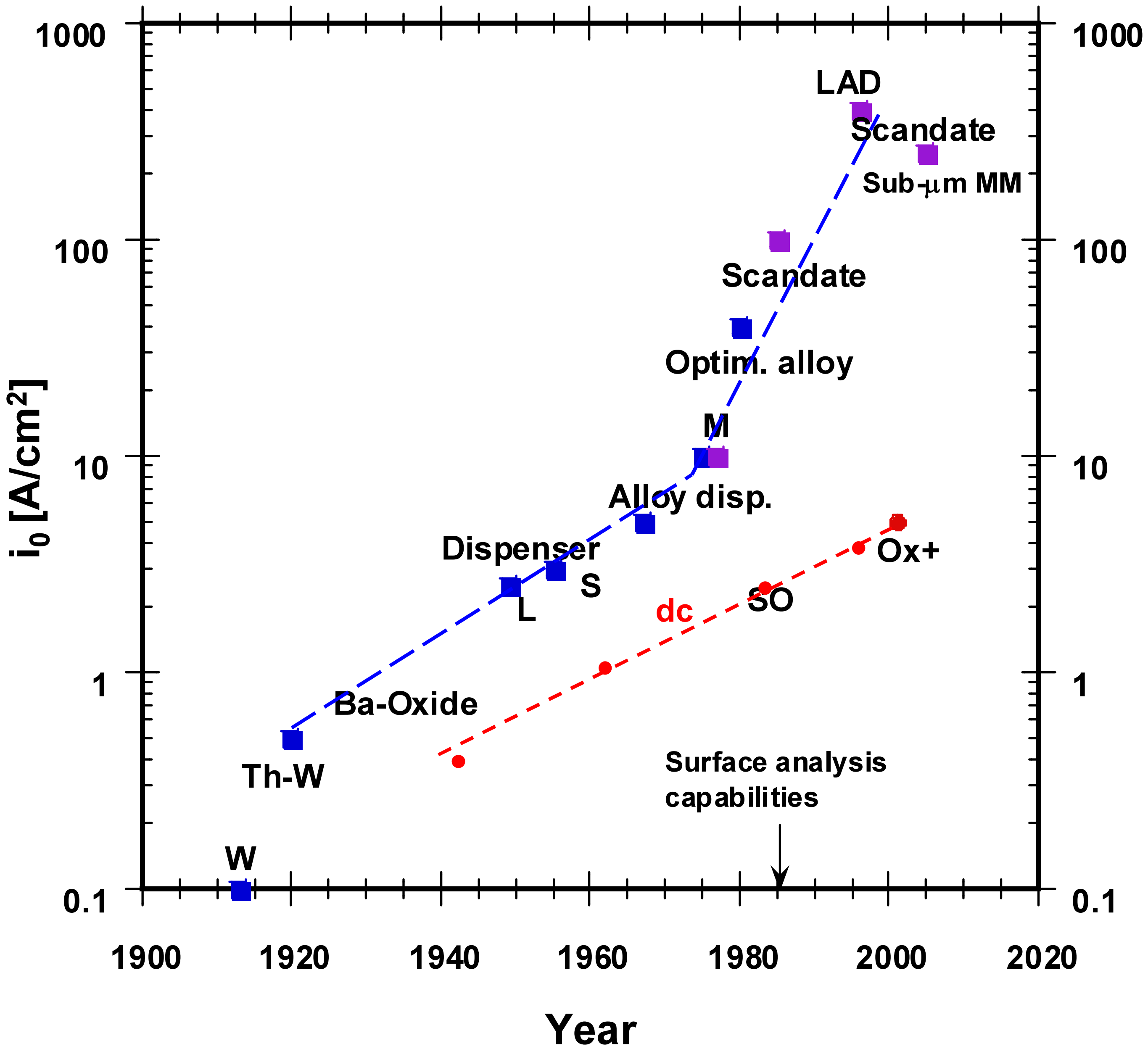
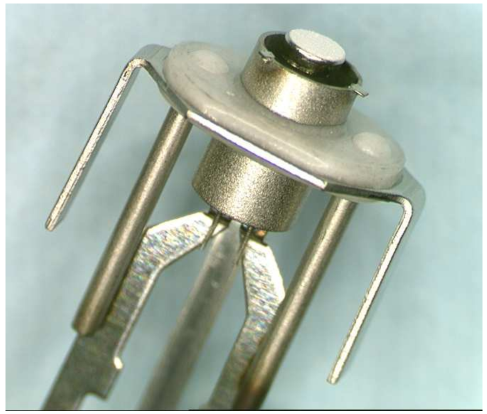
4) Improvement of base technologies : Cathode technology





Philips 0,65 Watt I cathode unit

Left: Historical development of thermionic cathodes emission capabilities (life $t_{op} \geq$ 4000 h at saturated emission current density i_0).

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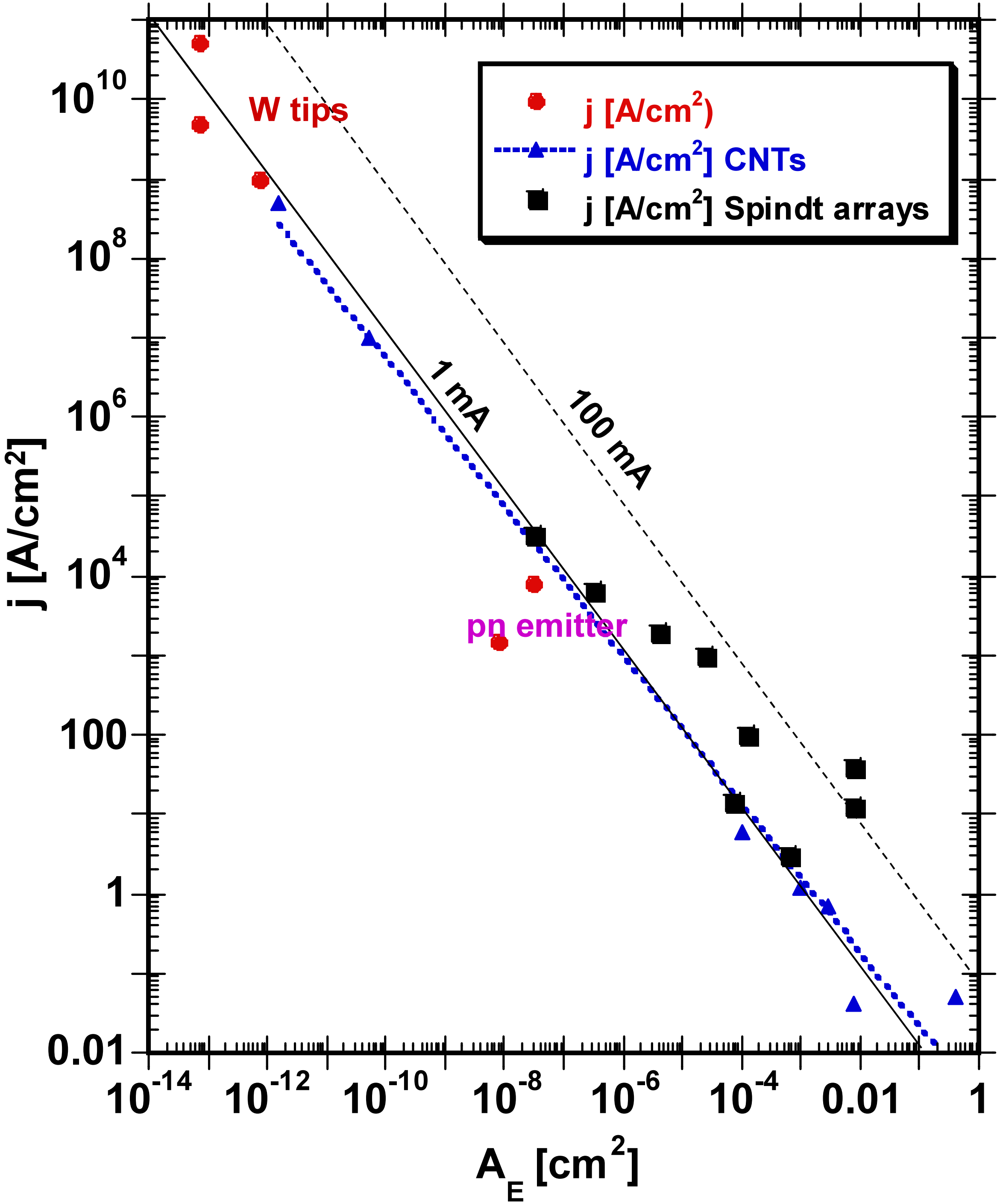
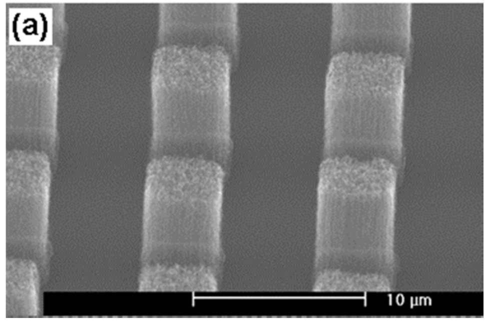
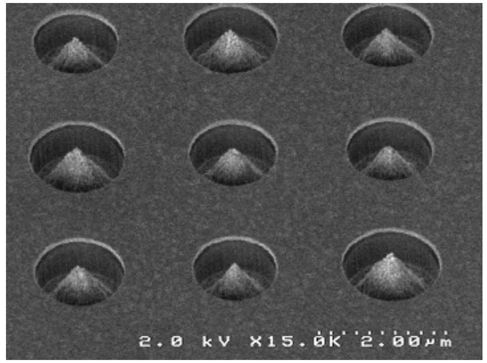


Plot of field emission (cold emission) current density versus emitter area (including passive parts) based on literature data for CNTs (a), W tips, pn emitters, and Spindt arrays (b). Lines of equal current are shown for 1 mA and 100 mA.
Direction of improvement to higher current!



(a)



(b)

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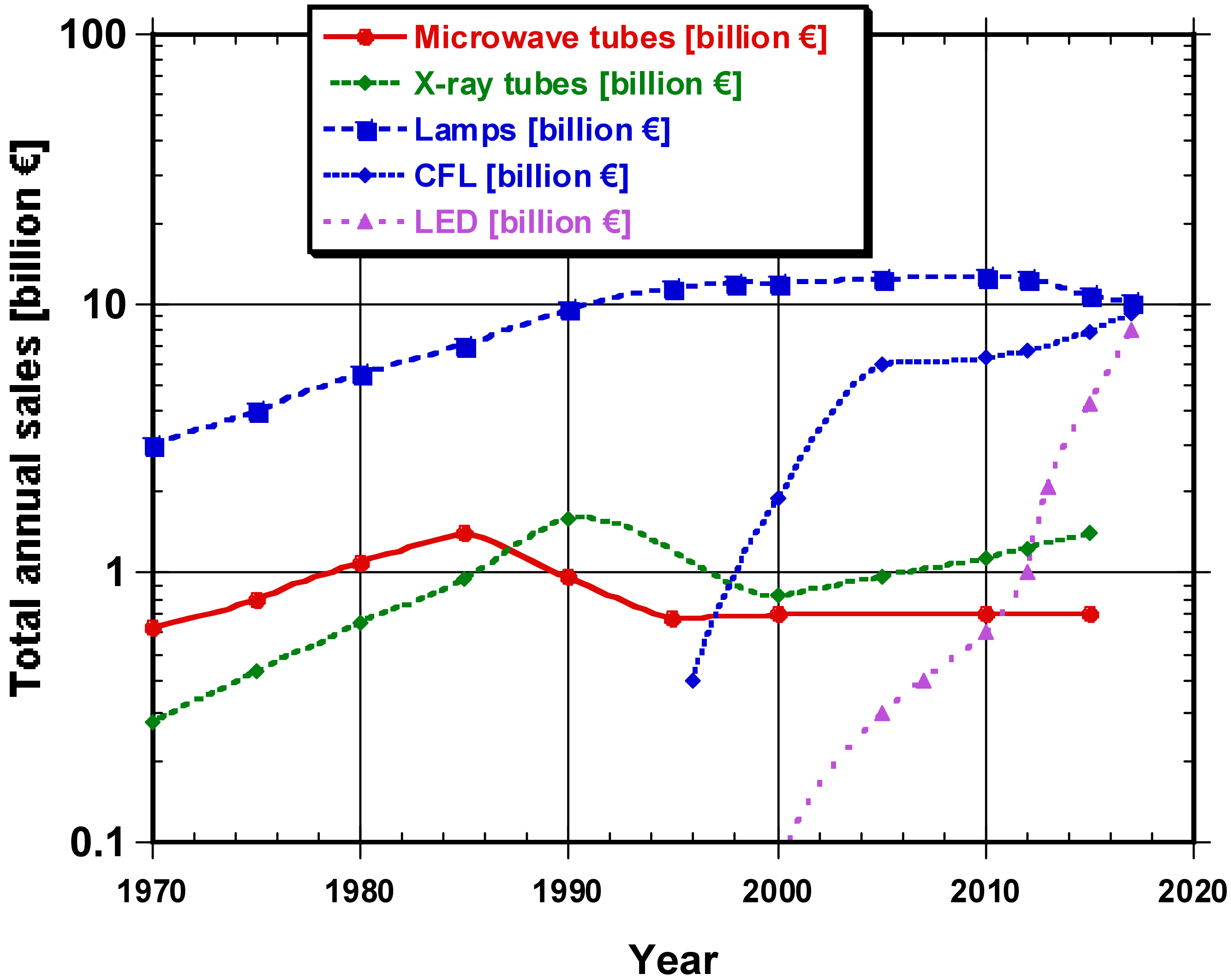
5) Microwave tubes and advantages over SSD



Total annual sales (in billions of €) versus time for three important vacuum tube types, namely microwave tubes, x-ray tubes and lamps (fluorescent/ CFL- and incandescent, see [1]). Phasing out of incandescent lamps has started due to national energy savings legislation. The rise of LEDs is also shown, data here are without fixtures and without car applications.

(lighting world market see: van Schooten, Sustainable value creation in lamps, ppt-pres. 2011 and: Frost &Sullivan, The LED revolution, 2011)

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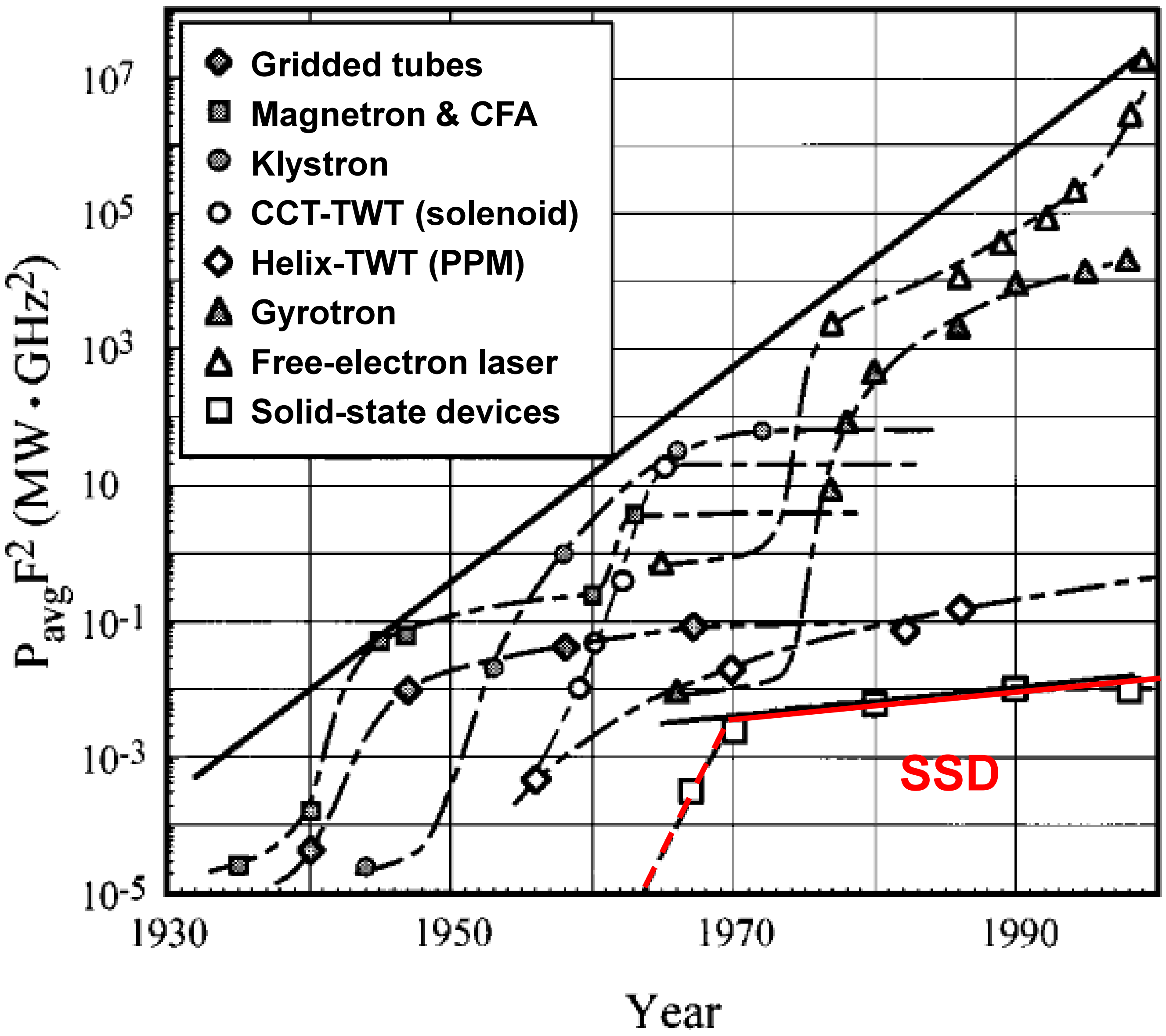
5) Microwave tubes and advantages over SSD



Progression of device power density $\mathbf{P_{av}*f^2}$ for major device types according to V. Granatstein et al., see [1]. Solid state devices (in red) are in the right lower part.

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5) Microwave tubes and advantages over SSD

Microwave tubes are superior to solid state microwave amplifiers / generators in the high frequency, high power range (see previous slide) , also w.r.t. reliability and life

In [4] J. H. Booske gives a limiting line with respect to cost and reliability between commercial solid state amplifiers and vacuum electronic amplifiers of

$$P_{cw} = 4kW/ f^2[GHz^2],$$

Above this line vacuum-electronic devices (VEDs) are superior in the high frequency, high-power region. There are three reasons for it:

1. **In SSDs the electron current generates heat via collisions in the solid, which is not the case for an electron beam in vacuum.**
2. **Second, voltages in a SSD are limited to avoid breakdown. These voltage limits are much higher for VEDs.**
3. **Third, VEDs can be operated at higher temperatures than SSDs.**

6) Future applications of standard technology :

(1) X-ray tubes

Philips X-ray tube

(2) Microwave tubes

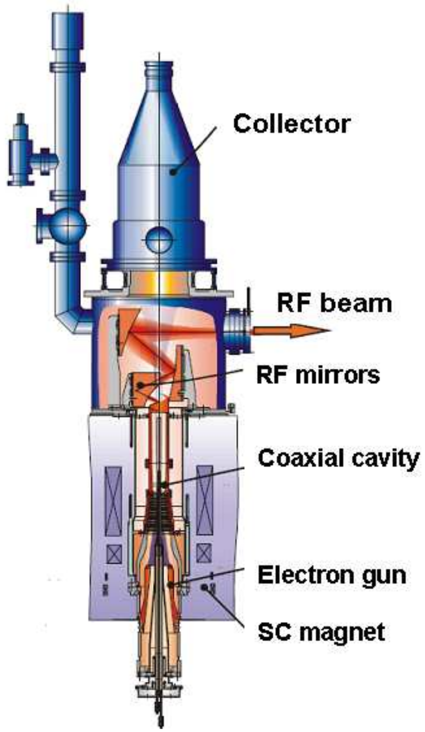
e.g. for space applications,

3 times longer life than SSD

TH 2132 Klystron: Highest peak power 45 MW for 4.5 µs. (Thales)

Ultrahigh power applications:
(3) Gyrotrons

Schematic view of 170 GHz gyrotron of 2.2 megawatt power of Karlsruhe Institute of Technology (KIT, courtesy of M. Thumm)



(4) Free electron Lasers (FELs)

(5) Combination of SSD and VE: MPM = mm-wave power module: TWT amplifier

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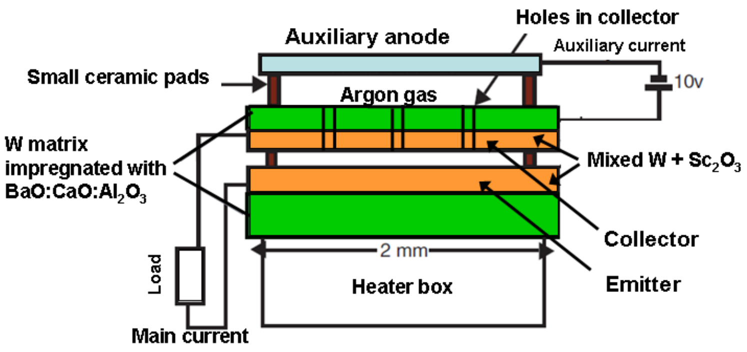
6) Future applications of standard technology :

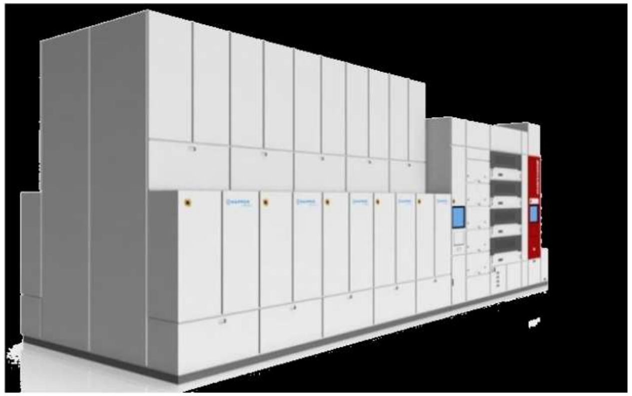
(6) Thermionic Energy Converters

(increase of efficiency of power plants, vehicles, photocells,..)



Concept of a thermionic converter (Thanner et al.)

(7) Electron beam lithography

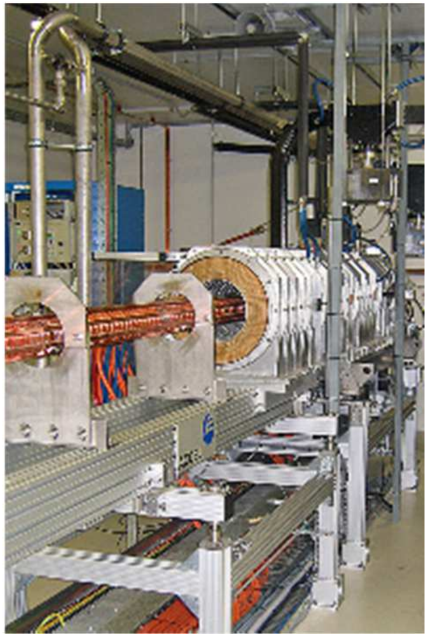


Maskless electron beam lithography (Mapper) :

Multibeams, 10 clustered modules – 1 module 10 Wafers/h

L. Pain (LETI / Mapper)

(8) Particle accelerators



Linear particle accelerator = Linac of Australian Synchrotron:

Rf cavities for acceleration of electron beam (Wikipedia)

(9) Ion thrusters for space propulsion

(10) Vacuum interrupters

(11f) Electron and ion beam devices for materials processing and characterization, e.g. : SEM, TEM, SAM

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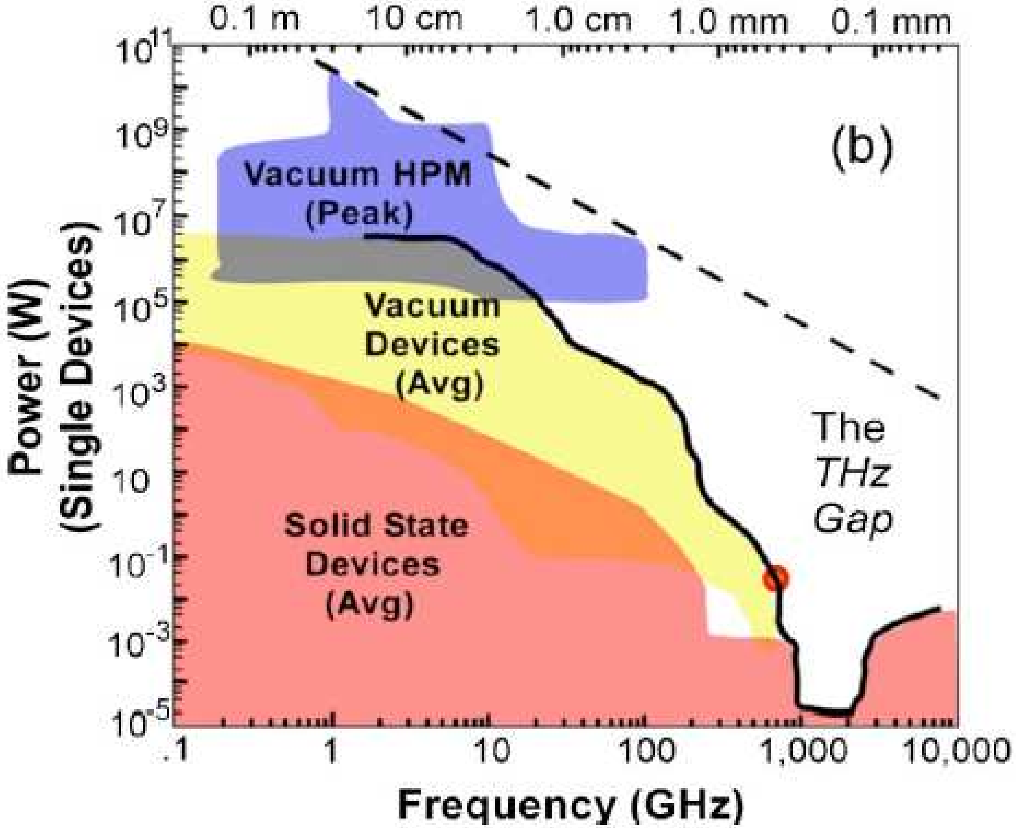
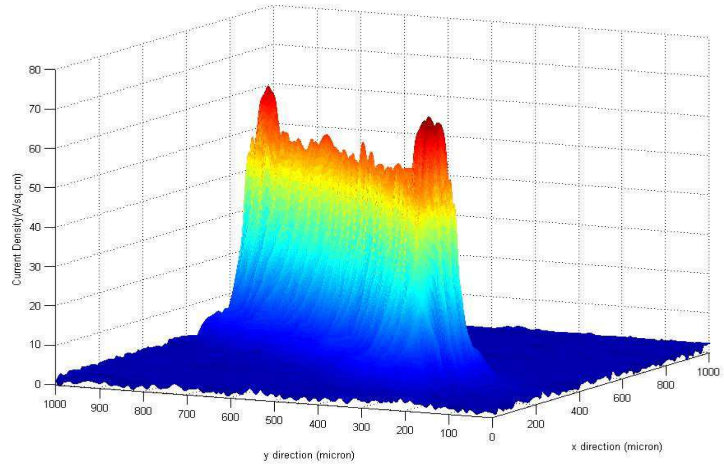
6) Future applications of standard VE : terahertz imaging



(Average) Power versus frequency plot of compact and mobile devices showing the TeraHertz gap.

Modeling shows, that for 100 Watt TWT operating at 200 G
an emitter current density of 200 A/cm^2 is needed (accordi
to J. Booske, Phys. Plasmas 15, 055502, (2008)).

One way to use Smith-Purcell radiation (SPR) effect from electrons moving over metal grating structures and improve radiation intensity is by increasing the current density of the electron beam for stimulation of the backward surface wave. Typical sheet beam structures are then needed (Y. Wang, IVESC 2008):



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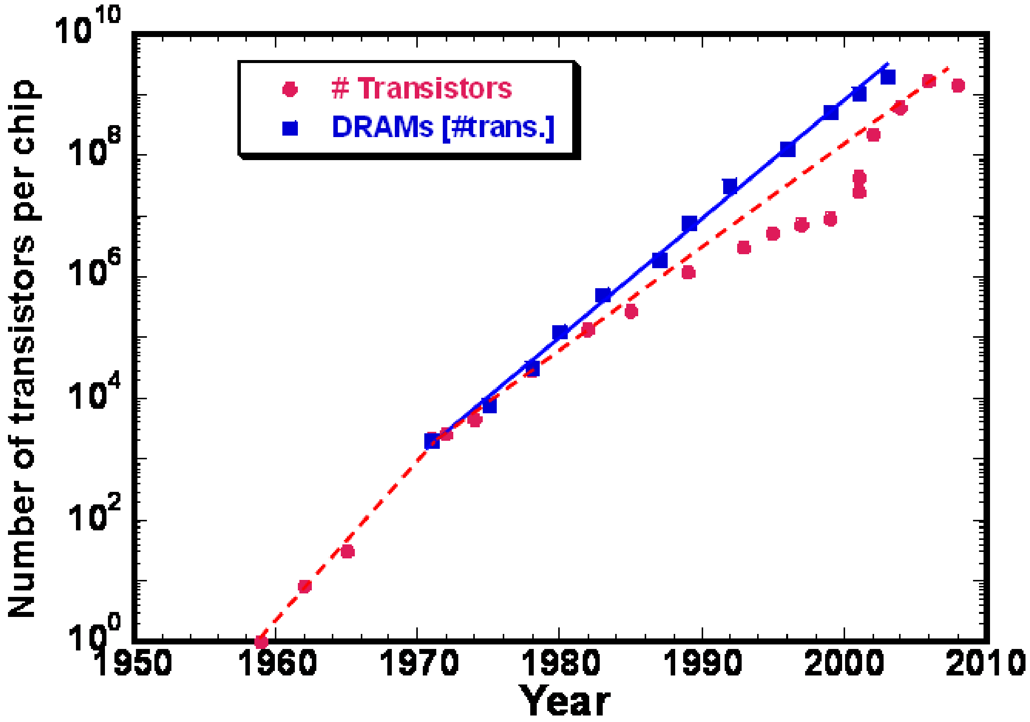
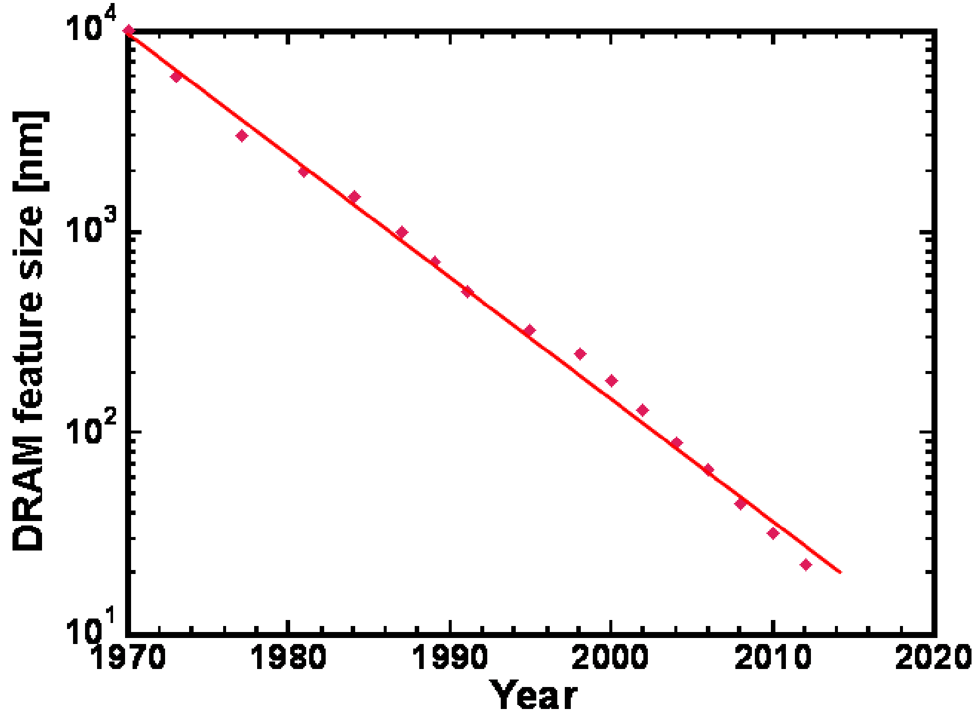
7) Development of solid state electronics and it´s limitations



Moore´s Law: the number of transistors per chip are shown for Intel micro processors (starting in 1971) and for DRAM memories versus time. The data before 1970 are from Gordon Moore [see1].



IC feature gate size versus year according to Borsuk et al. and Intel [see1].

Moore´s laws:

- Number of transistors on a chip will double every two years
- The cost of fabrication increases linearly with complexity /exponentially with time

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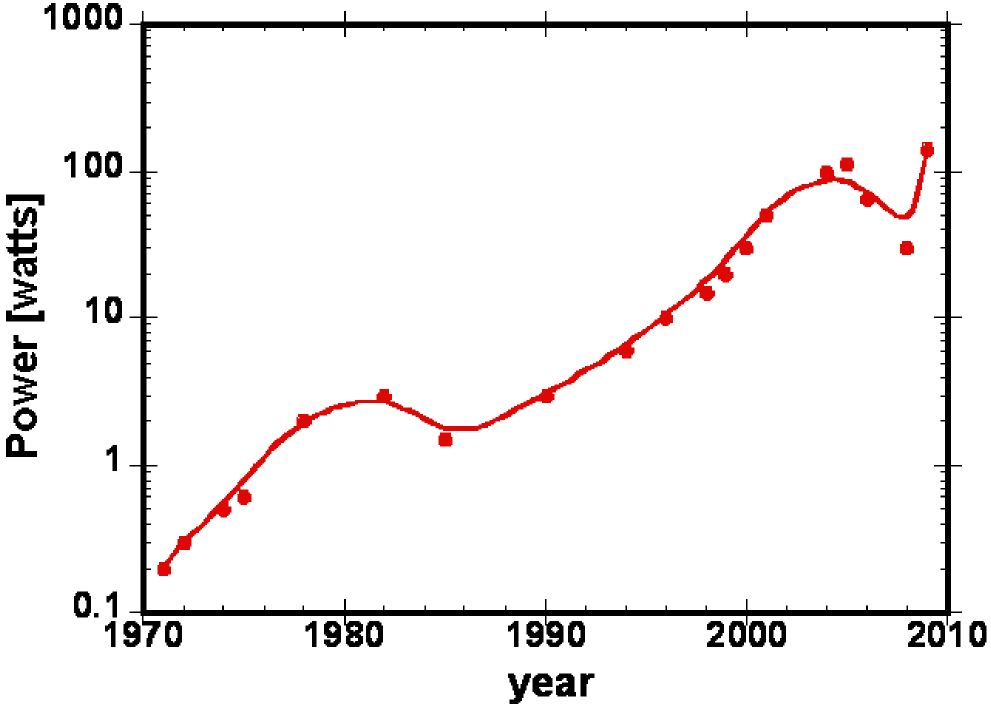
7) Development of solid state electronics and it´s limitations:



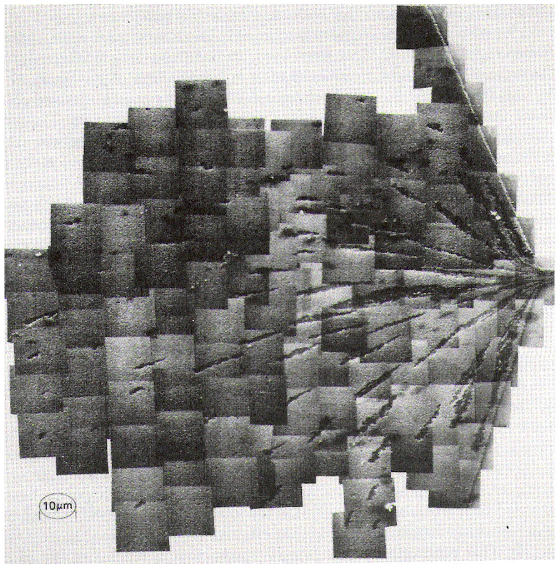
Power consumption in Watt from successive generations of Intel processors versus time according to Borsuk et al. and data from Intel [see 1].

Possible flattening of Moore´s law due to approaching physical limits. These limitations are:

(1) The cost and the physical limitations of further downsizing

(2) Increasing power dissipation with scaling down

(3) Limited solid state electron mobility, void formation



Scanning electron microscope picture of voids formed by electro-migration in the negative terminal of a single-crystal Al-3wt % Mg film.

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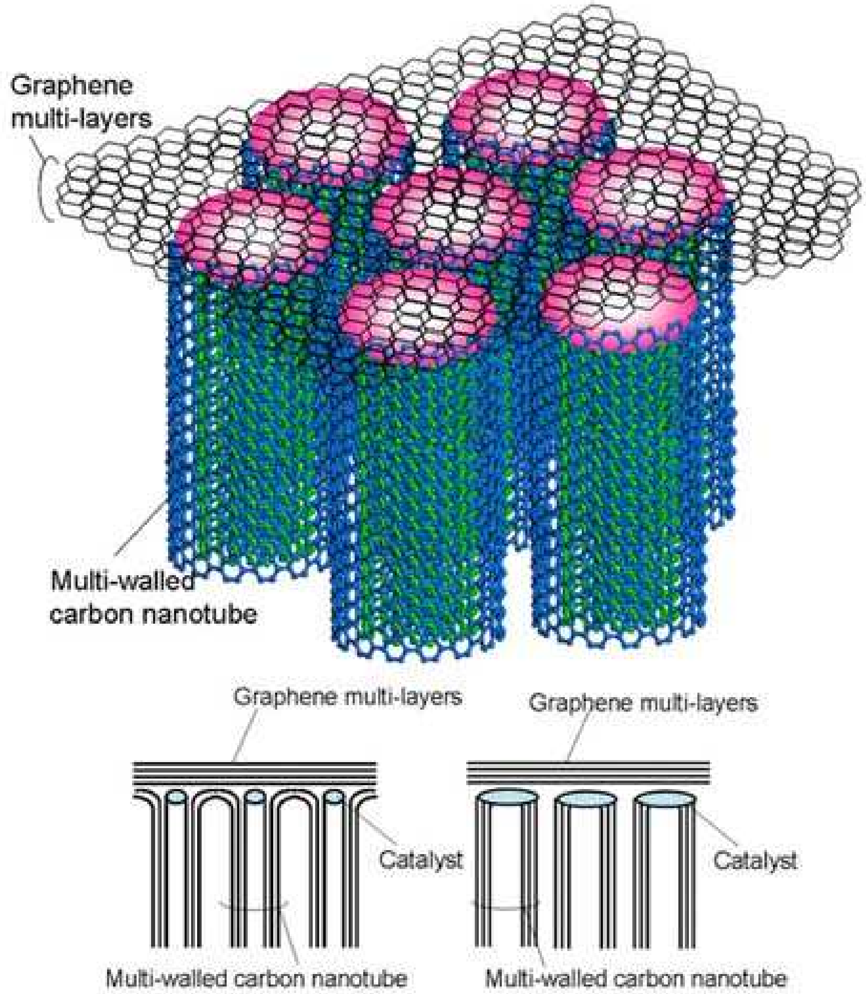
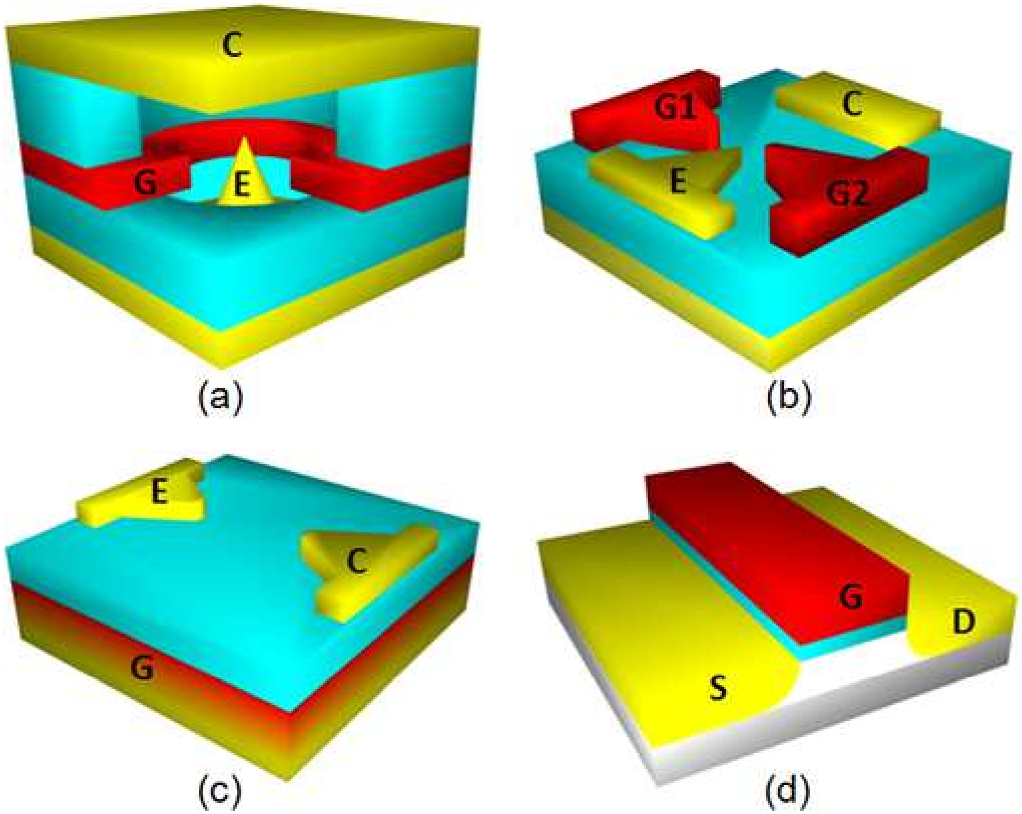
8) Perspectives of vacuum nano electronics:

To overcome the current limitations, next generation transistors need higher k gate dielectrics; also new nano materials with higher conductivity are investigated, such as nano wires, carbon nano tubes and graphene are currently developed, see example by Fujitsu (right)



Fujitsu nanoscale carbon composite
(courtesy of I. Kawai, Fujitsu, see [1])

8f) Perspectives of vacuum nano electronics:



Structures of vacuum devices and analogues to conventional MOSFET.

(a) Vertical field-emitter, (b) planar lateral field-emitter, (c) MOSFET,

and (d) gate-insulated air channel transistor according to

Jin-Woo Han, Jae Sub Oh, and M. Meyyappan, „Vacuum nanoelectronics: Back to the future?—Gate insulated nanoscale vacuum channel transistor“, APPLIED PHYSICS LETTERS 100, 213505 (2012)

See also: Introducing the Vacuum Transistor: A Device Made of Nothing, spectrum.IEEE.org, 27.6.2014, same authors (1+3)

Exploiting the following features: field electron emission, distance source/emitter – collector/ drain smaller than mean free path of electrons: 200 nm for 1 bar (in He), electron velocity not limited to ≤ $5*10^7$ cm/s, no collision loss; currently voltage still 10V. Possible to operate at TeraHertz frequencies!

9) Conclusions:

The continuous improvement of the base technologies vacuum technology and electron source technology was not only triggered by long term generic applications (lamps, x-ray tubes, microwave tubes), but also the technological waves of the radio tubes and later of the CRT era pushed the further advancement of the base technologies. These typical dynamic life-cycles are similar to life cycles of biological or sociological systems. The existing generic technologies of radio tubes / CRTs were replaced by superior SSE / TFD, which also enabled new applications.

Yet there are inherent advantages of VE over SSE showing up in the high frequency, high power range of microwave tubes e.g. due to electron collision power dissipation in SSD. Similar problems have to be overcome in ULSI and beyond. In this respect nano VE can help to overcome these SSE problems, as shown e.g. by the vacuum channel transistor.

Thank you for your attention!

10) Some references :

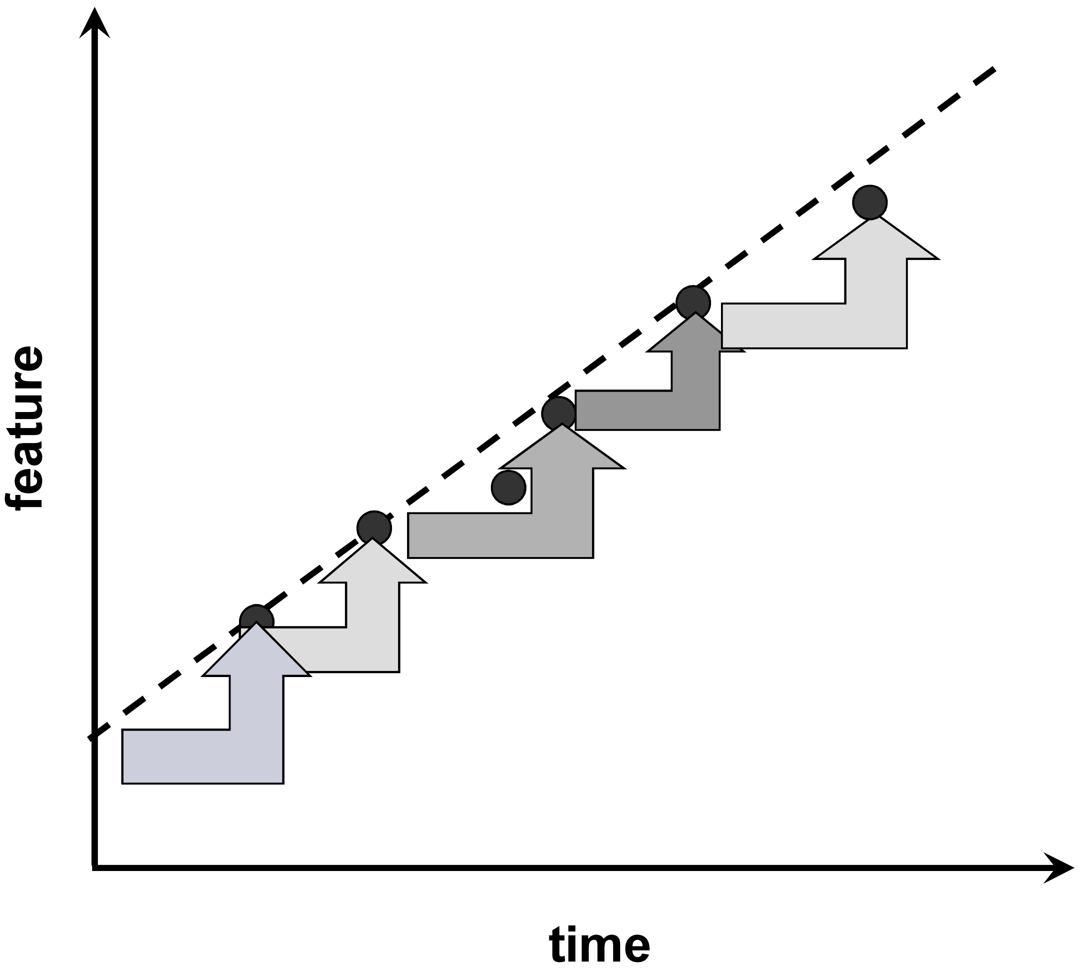
[1] G. Gaertner: Historical development and future trends of vacuum electronics J. Vac. Sci. & Technol. B 30(6) 2012, 060801-1 -14

[2] G. Gaertner, H.W.P. Koops: „Vacuum Electron Sources and their Materials and Technologies“, chapter 10 of „Vacuum Electronics, Components and Devices”, Ed. J. Eichmeier, M. Thumm, Springer 2008 (and other chapters)

[3] R. K. Parker, R. H. Abrams, B. G. Danly, and B. Levush, IEEE Trans. Microwave Theory Tech. 50, 835 (2002).

[4] Modern Microwave and Millimeter-Wave Power Electronics, edited by R. J. Barker, J. H. Booske, N. C. Luhmann, and G. S. Nusinovich, (IEEE Press, John Wiley & Sons, 2005).

Thank you for your attention



Schematic view of a development curve: Typically the time is in a linear scale and the feature in a logarithmic scale.

It is not a continuous, but a limiting mathematical curve.

The achievement of improved performance is dependent on the effort, the technological starting level, and the physical limitations.

The skills built up for the preceding point are a prerequisite for the next one

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