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13th International Vacuum Electron Sources Conference 2020

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Enabling Technologies and Progress of Vacuum Electronics

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Outline:

1. Introduction: Enabling technologies for VE

2. Development of basic enabling technologies
   - Availability of electrical power
   - Vacuum technology

3. Link between technology development and start of VE technological waves

4. Enabling technologies (continued)
   - Materials science and chemistry
   - Surface science
   - Solid state technology
   - Lasers and optics

5. Interaction between technology progress and cathode progress; new applications (THz devices)

6. Conclusions and outlook

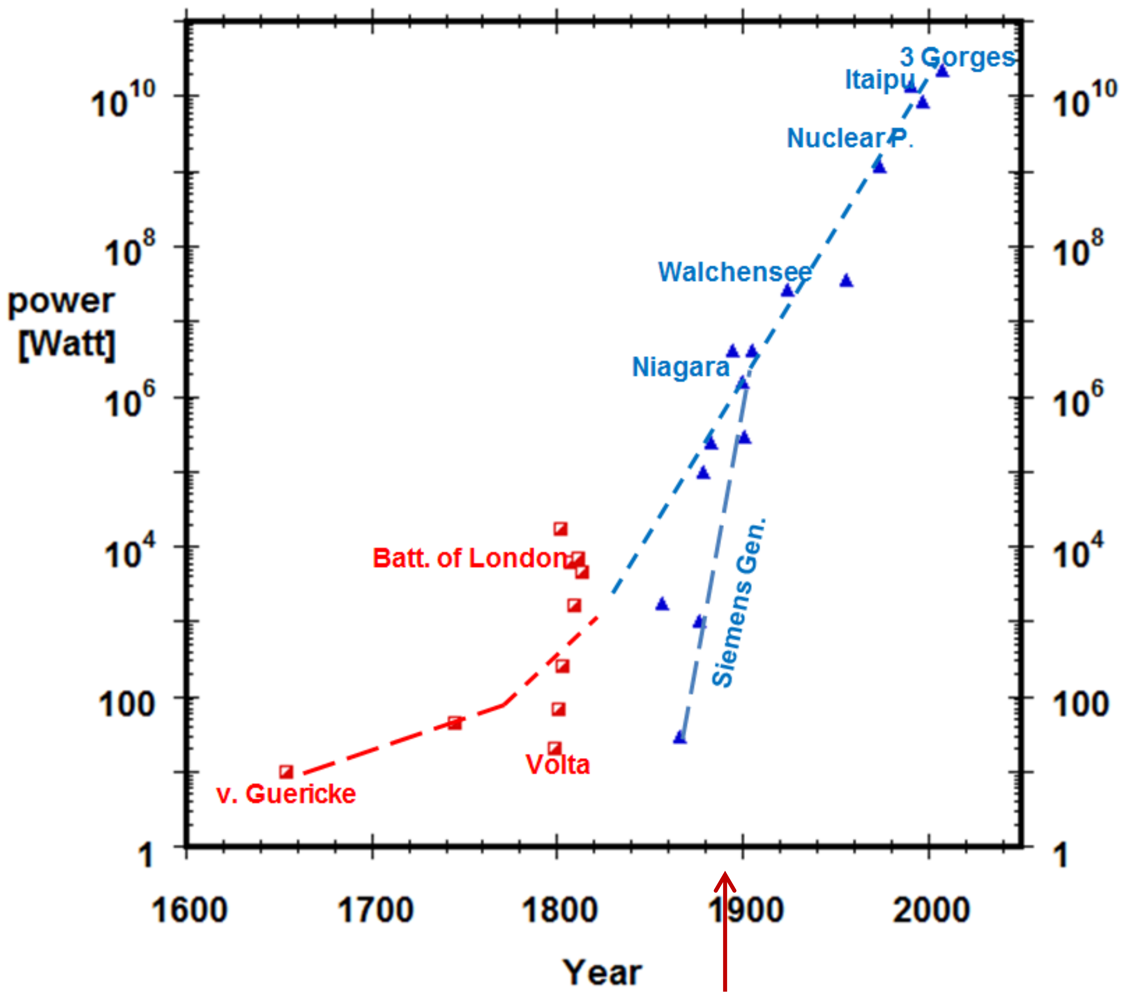
1. Introduction: Enabling technologies for VE

The historical rise of vacuum electronics (=VE) is directly linked to the availability of electrical power and to vacuum technology, but in later stages also surface science, solid state technologies and other new inventions contribute to its progress.

The development of the enabling technologies is linked to different technological waves or cycles, such as the incandescent lamp era, the radio tube era or the CRT era.

These cycles together with improvements in different sectors also trigger further cathode improvements.

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



Introduction of electrical power grids

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

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

1810 – 1836 Great Battery of London: 2000 cells in 200 troughs, 83 m² electrode surface area

1857 W. v. Siemens, dynamo-electric machine

1900 Paris, 1,57 MW Generator, Siemens

1925 Walchensee power station (D) 72 MW

1974 Nuclear power plant Biblis A (D) 1,2 GW

1997 Kashiwazaki-Kariwa nuclear power station (7 reactors, Japan) 8,2 GW

2008 Three Gorges Dam hydro power plant (China) 22,5 GW

2a) Enabling Technologies: Electric energy supply

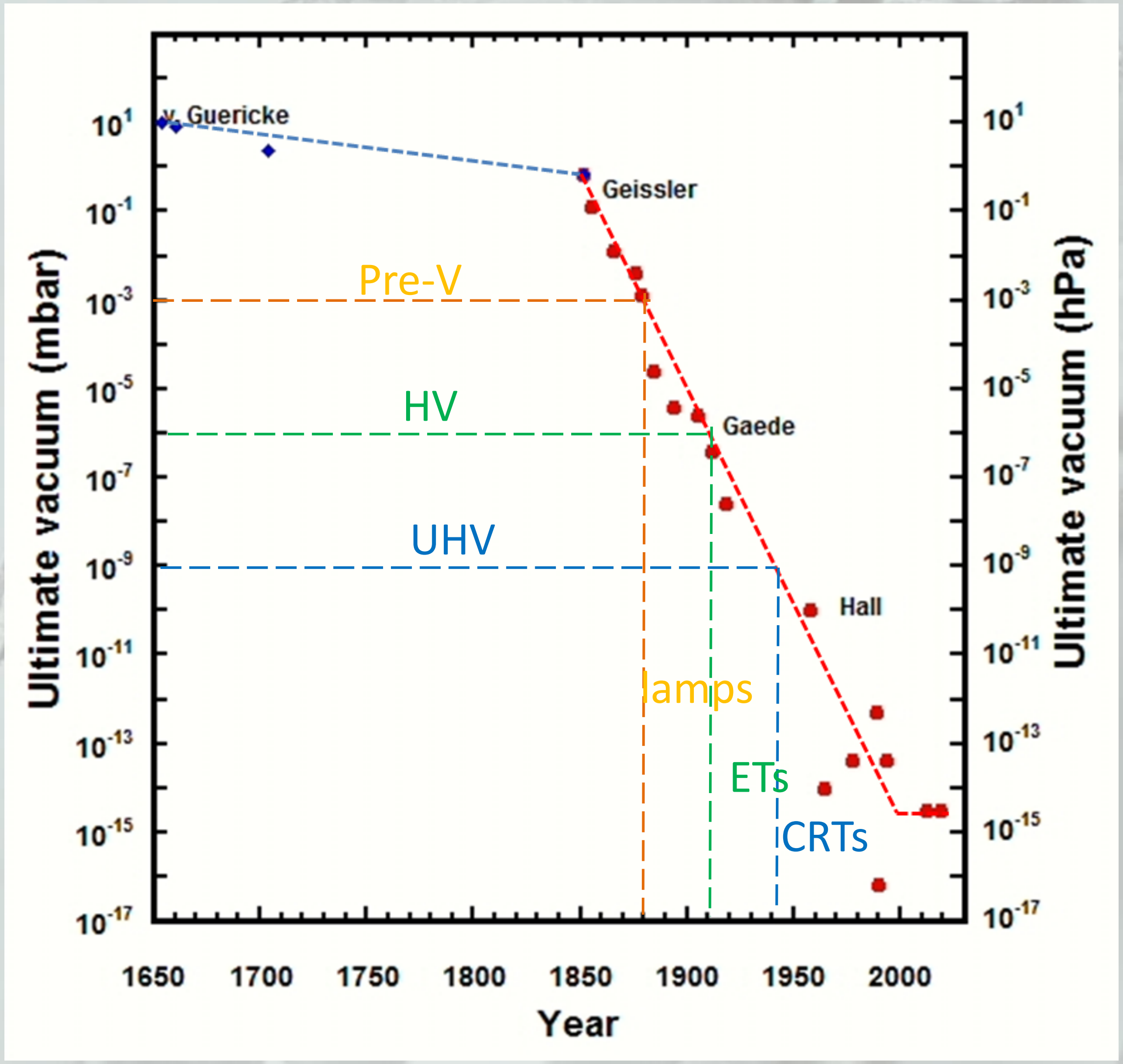
Another condition for the use of electrical energy is the introduction of an electrical power grid in the late 1890s, first as a local dc grid with high losses, then as three-phase systems, in the beginning mainly used for incandescent lamps.

In fig. 1 the evolution of electric power generation is shown as a function of time. We see a rather step improvement within the last two centuries, which is partly due to an increase in efficiency as in case of nuclear power plants (1 g of U^{235} delivers about 2,5 * 10^6 more energy than 1 g of coal) The next step in efficiency improvement, increased safety and less waste would be fast breeder reactors (BN 800 in Belojarsk) or Th^{232} molten salt reactors, but only outside Western Europe.

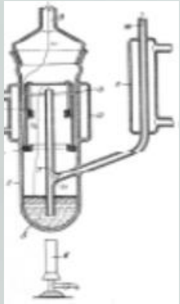
Yet nowadays this trend has changed: the use of alternate energy sources such as wind power, hydro power or solar energy implies large area consumption and a drastic loss in efficiency. This is especially dangerous for the environment in the case of wind parks: enormous area consumption*, killing of flying animals, reducing of forest area, change of the wind pattern from laminar to turbulent, and a strong drying effect of the surroundings.

*nuclear power 4.7 GW from 0,3 km^2, wind power 4,7 GW from 8000 km^2

2b) Improvement in vacuum techniques



Ultimate vacuum achieved versus time, see [1].

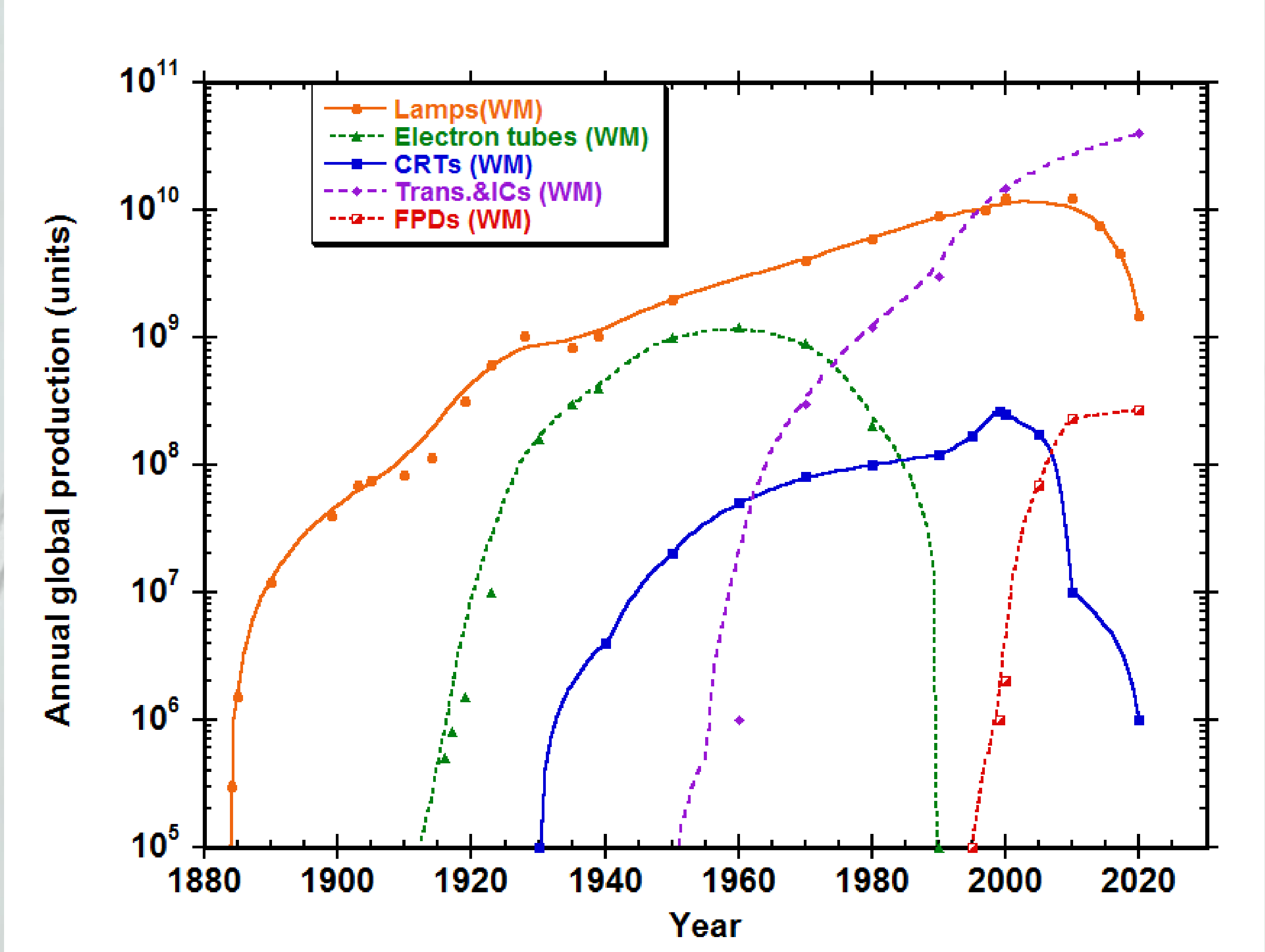


Hg diffusion pump Gaede 1915

Balzers turbomolecular pump

Varian ion getter pump

3) Historical development of Vacuum Electronics
The era of the radio tubes , of CRTs and of incandescent lamps

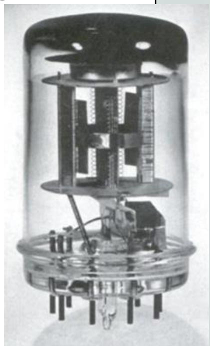


Technological waves in vacuum electronics and neighboring fields according to [1,3]. Onset of new cycle starts with improved vacuum and improved cathodes (but higher sensitivity to poisoning)

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

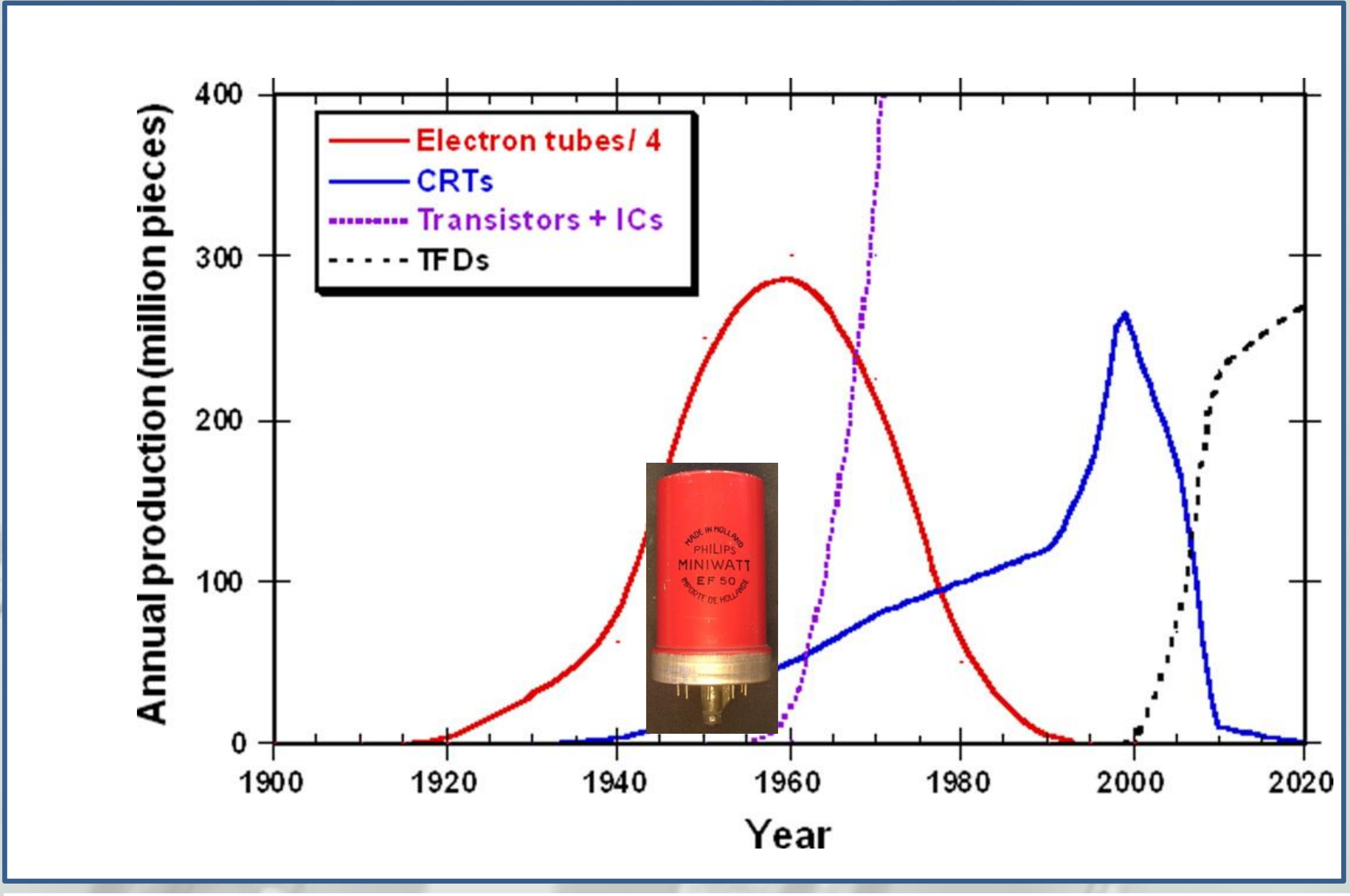
Start of incandescent lamps in 1880, first with carbon filaments, then replaced by tungsten filaments, yielding higher luminous efficacy of 10 lm/W. The era of bulb based lamps lasted till today, now being replaced mainly by LEDs.
It could start when pre-vacuum could be achieved.
Another condition is the existence of an electric power grid.

The next technological cycle based on lamp technology (start ~ 1904) was the era of the radio tubes, declining after 1960 with the rise of transistors and solid state devices.
But the progress of vacuum electronics continued.
Prerequisite here was high vacuum.



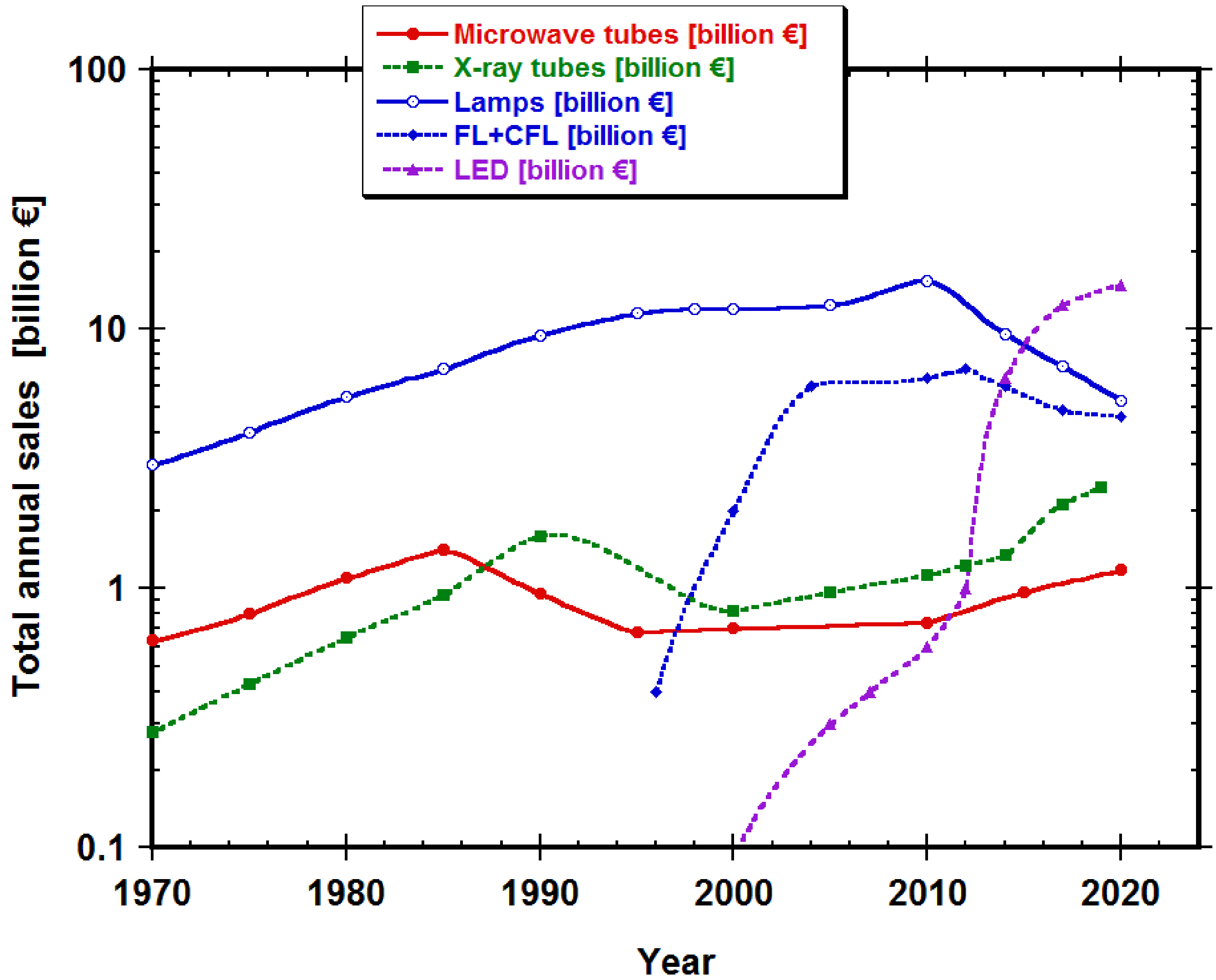
With the advent of cathode ray tubes (CRTs) a new technological cycle started, triggering further progress in the base technologies. The conditions were UHV (ultra-high vacuum) and controlled electron beams.

3) Historical development of Vacuum Electronics
The era of the radio tubes and the technological cycle of CRTS



Technological waves in vacuum electronics and neighboring fields according to [1]. The tube shown is a Philips miniwatt EF50.

3) Total annual sales (in billions of €) versus time for three important vacuum tube types: microwave tubes, x-ray tubes and lamps (fluorescent/ CFL- and incandescent, see [1]).



The phasing out of incandescent lamps is due to national energy savings legislation. Tube type lamps in total (solid blue) include FL+CFL and halogen +incandescent.

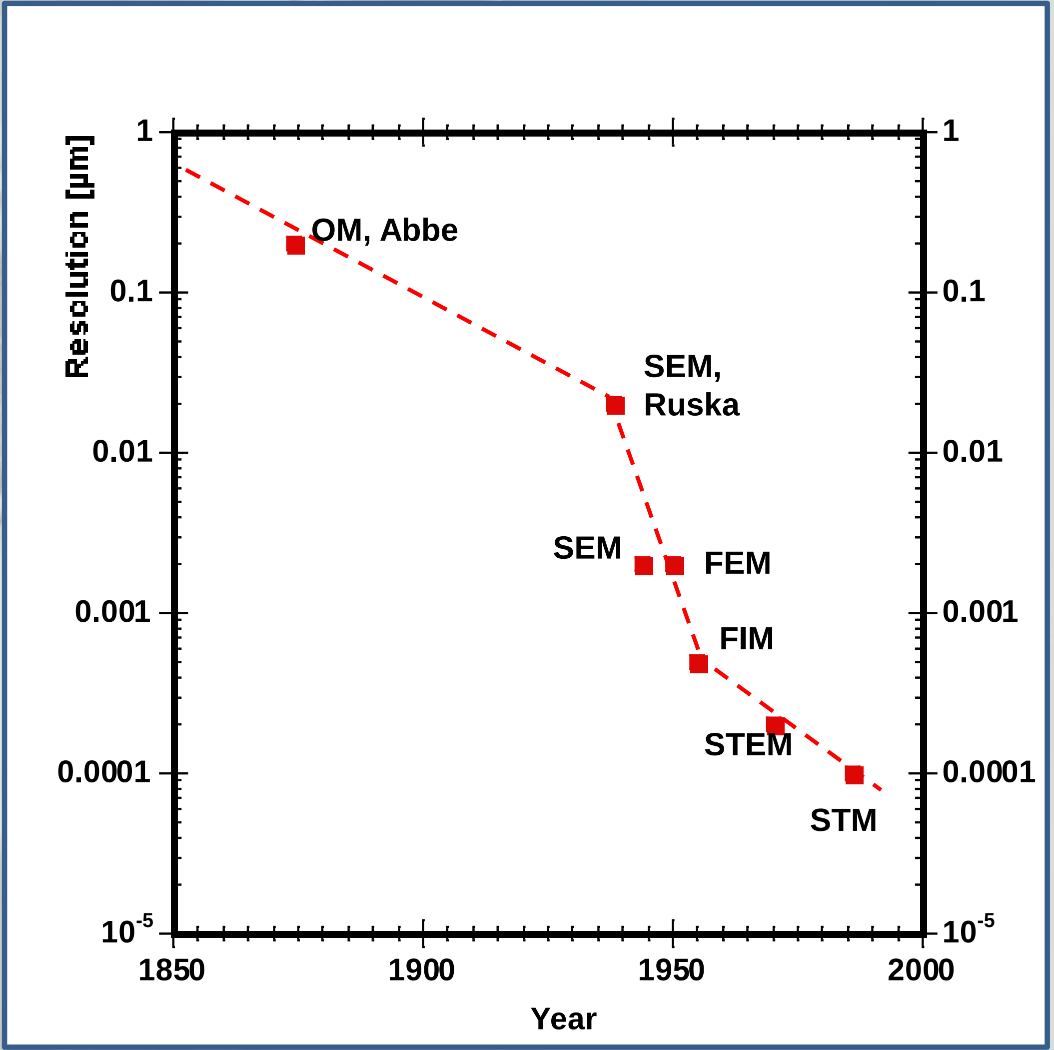
The rise of LEDs is given for comparison: data are without fixtures and car applications.

Microwave tubes and x-ray tubes are not cyclic and show a slow increase.
The figure is an update from [2,3] and a.o. based on JRC reports.

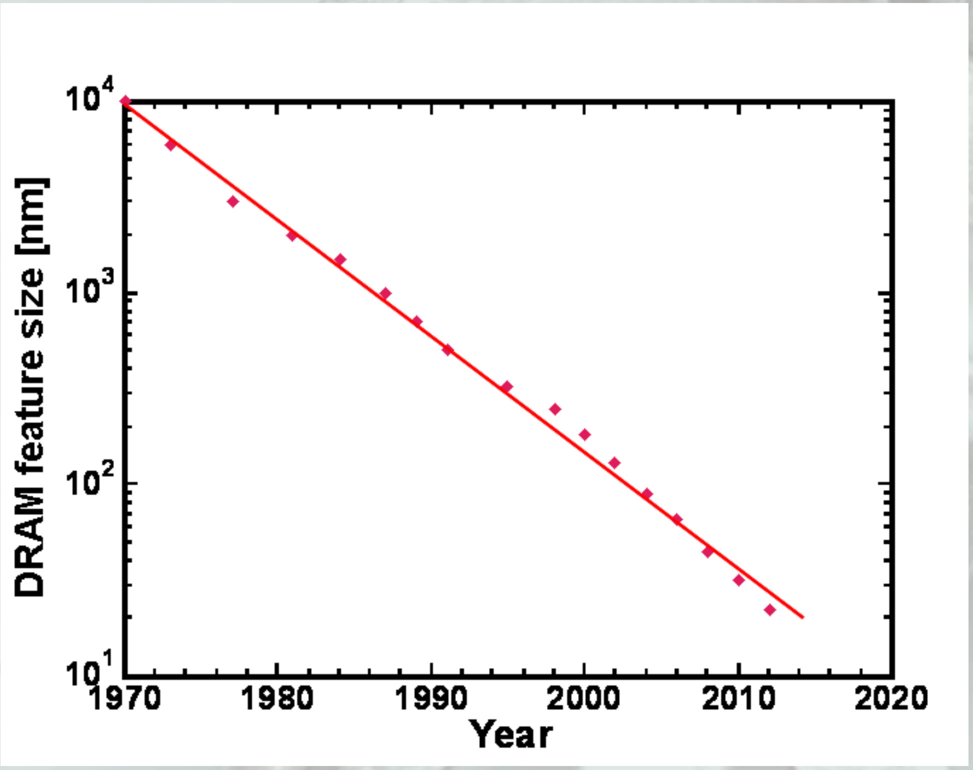
4) Progress in materials science and characterization,
comprising surface science,
with impacts on solid state technology

Surface Imaging: progress in resolution versus time;
From Optical microscopes to SEM and STM (Binnig, Rohrer 1982)

Similar improvements also in chemical analysis:
EDX (1962) sensitivity 0,1%
Spotsize 1 µm
Laser ICP MS (Gray 1985) sensitivity 100 ppm to 1ppt
Spot size 15 µm
SAM (Harris 1967) spot size 10 nm, elemental sensitivity 100 ppm



4) Progress in solid state technology



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

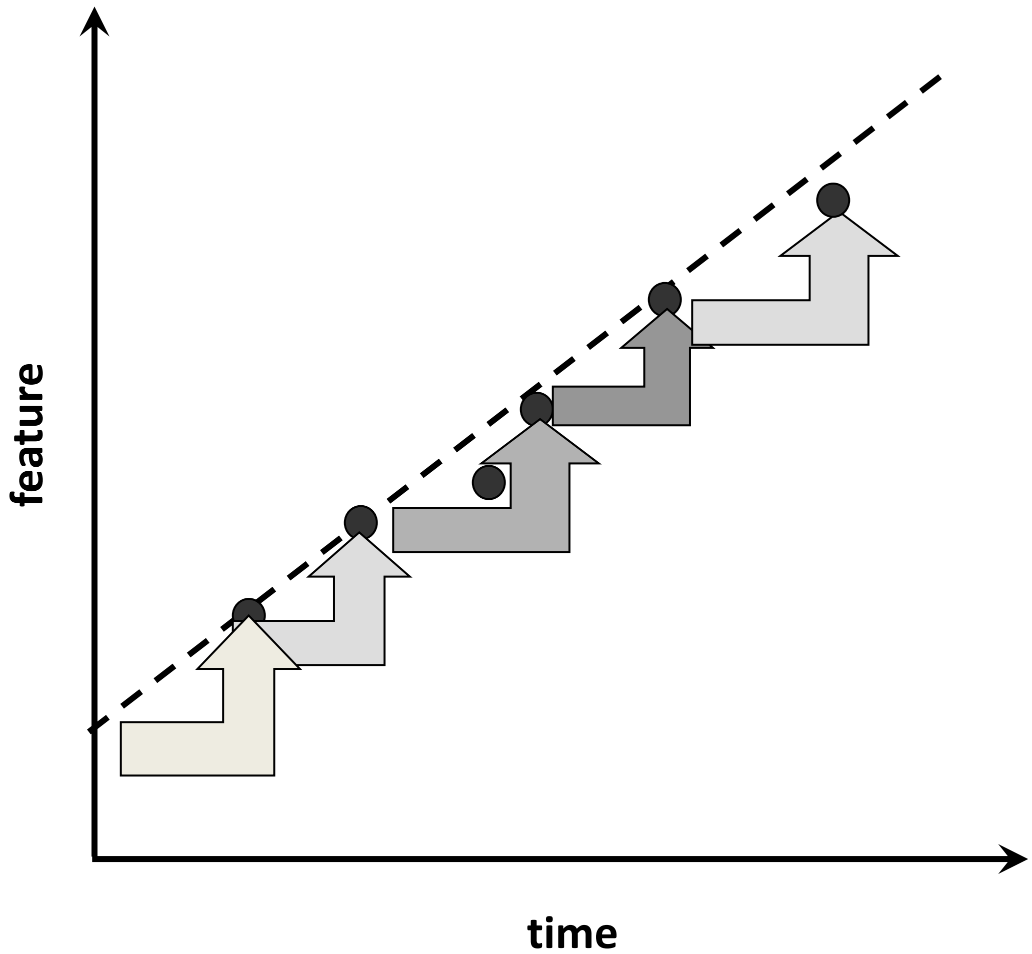
Progress in lasers and optics:
Pulsed lasers for photcathodes

The introduction of solid state technology including lithography and thin film deposition for SSDs led to the phase out of radio tubes, but also had a positive effect on cathode technology (FE).

The continous progress of SSD is illustrated by the figure, where IC feature size has continuously been scaled down.

Solid state technology also enabled the introduction of LEDs and led to the phase out of incandescent lamps now.

The progress is stepwise



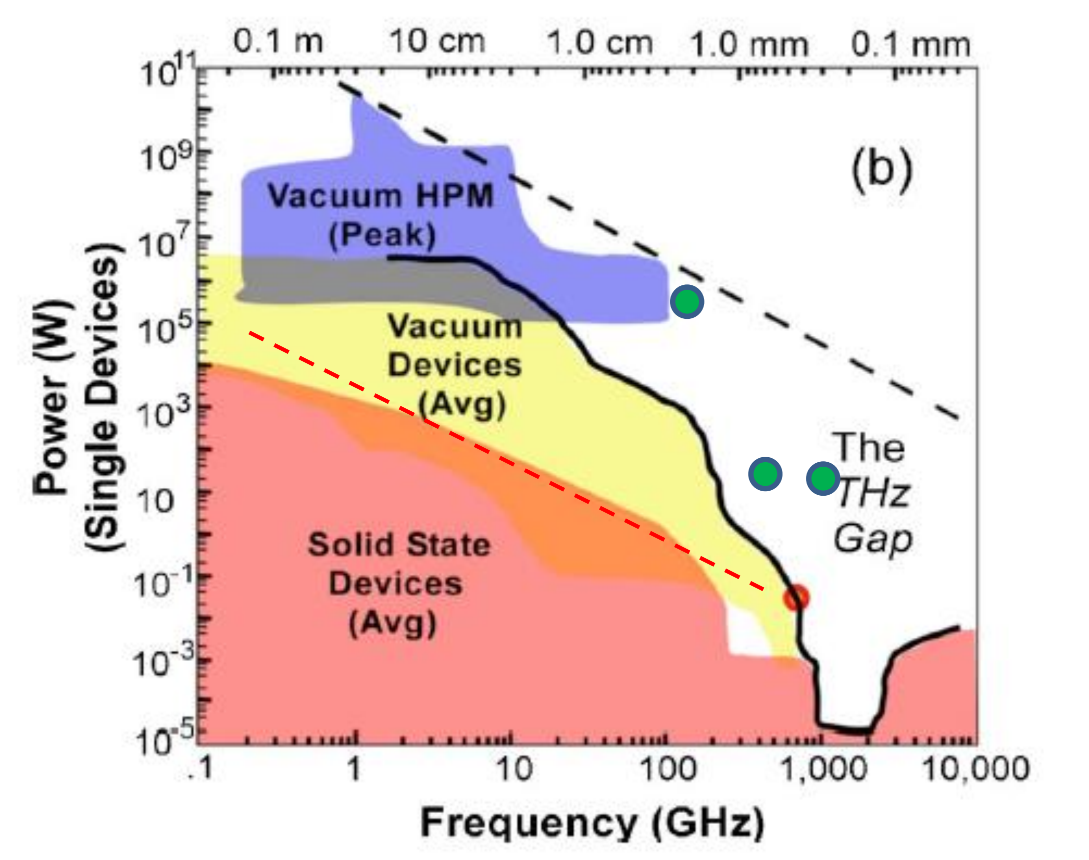
Schematic view of a development curve: Typically the time is in a linear scale and the feature in a logarithmic scale.

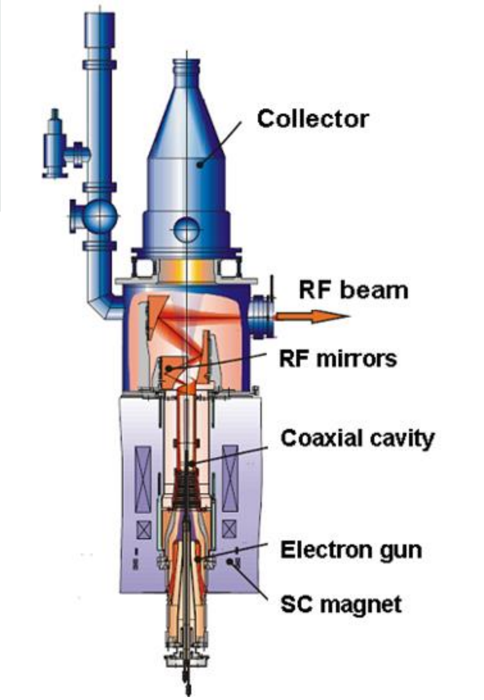
It is not a continuous, but a limiting mathematical curve. Progress goes stepwise!

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

5) Current and future applications of VE and cathodes, new tube types





THz generators:
Gyrotrons (KIT), FELs

Particle Accelerators (photocathodes)

Electron beam lithography machines (multiple electron beams)

Vacuum channel transistors

5) Thermionic cathodes – Requirements for future applications

Since till today practically all vacuum electron devices are equipped with thermionic cathodes, future requirements are:

(1) Higher emission current density (up to 200 A/cm^2 needed)
(2) Higher emission current (increased emitting area)
(3) Decrease of operating temperature
(4) Increase of lifetime

The first three trends are linked to a decrease of the work function $e\Phi$ via the Richardson equation:

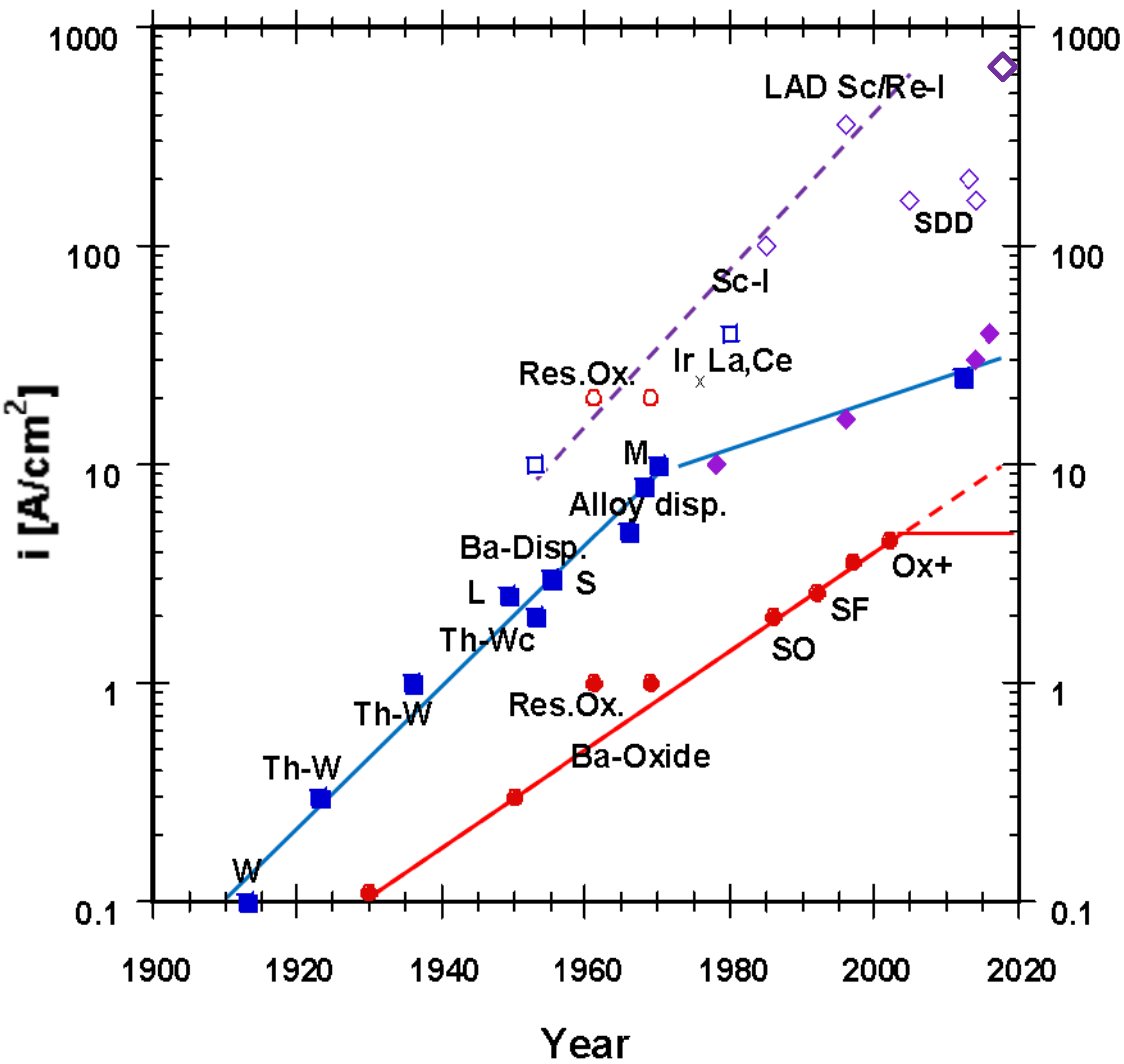
$$j_s = A_R * T^2 \exp(- e\Phi / kT)$$

with j_s the saturated emission current density and
$A_R = A_{Th} = 120.4\ Acm^{-2}K^{-2}$ the thermionic constant for uniform $e\Phi$, e.g. a pure metal

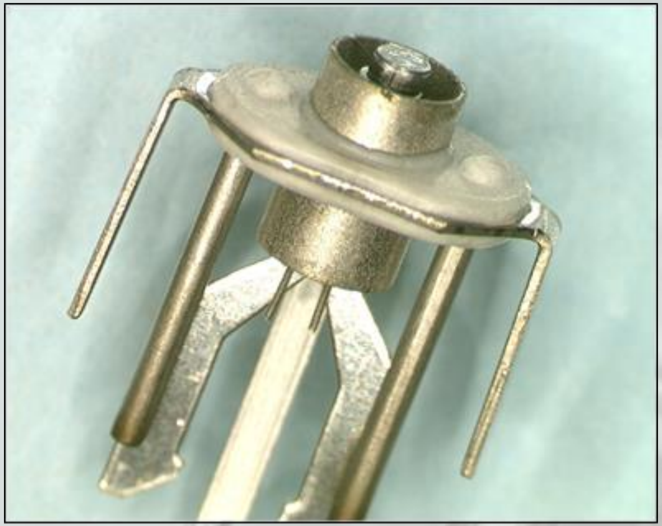
5) Types of thermionic cathodes in commercial tubes, sequence of introduction

Cathode type	Abbrev.	T_{op} [K]	J_{dc} [A/cm²]	eΦ [eV]	lifetime
Tungsten (flat)	W	2520	1 - 4	4,5	> 1000 h
Thoriated tungsten	Th-W	2000	4	2,6	10 kh
Ba-oxide	Ox	1050	1 - 4	1,4	20 kh
Ba-dispenser, W-Base	W-I or A or B	1300	3	2,05	≥ 20 kh
Os/Ru coating	M or Os/Ru-I	1300	10	1,85	≥ 20 kh
Ba-Scandate	Imp., (TL)	1300	15	1,7 (1,45)	≥ 10 kh
Ba-Scandate	SDD	1320	40	1,45	≥ 4000

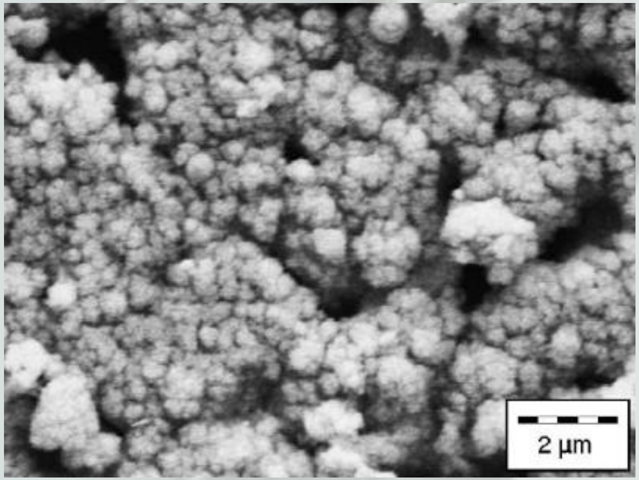
5) Improvements in cathode performance



Historical development of thermionic cathode emission capabilities - an update. The lower red line : dc emission of oxide cathodes (red circles). The upper blue line: metal matrix based (including Ba dispenser) cathodes; Scandate cathodes: violet diamonds. Open symbols + dashed line: pulsed emission data including Scandate cathodes.

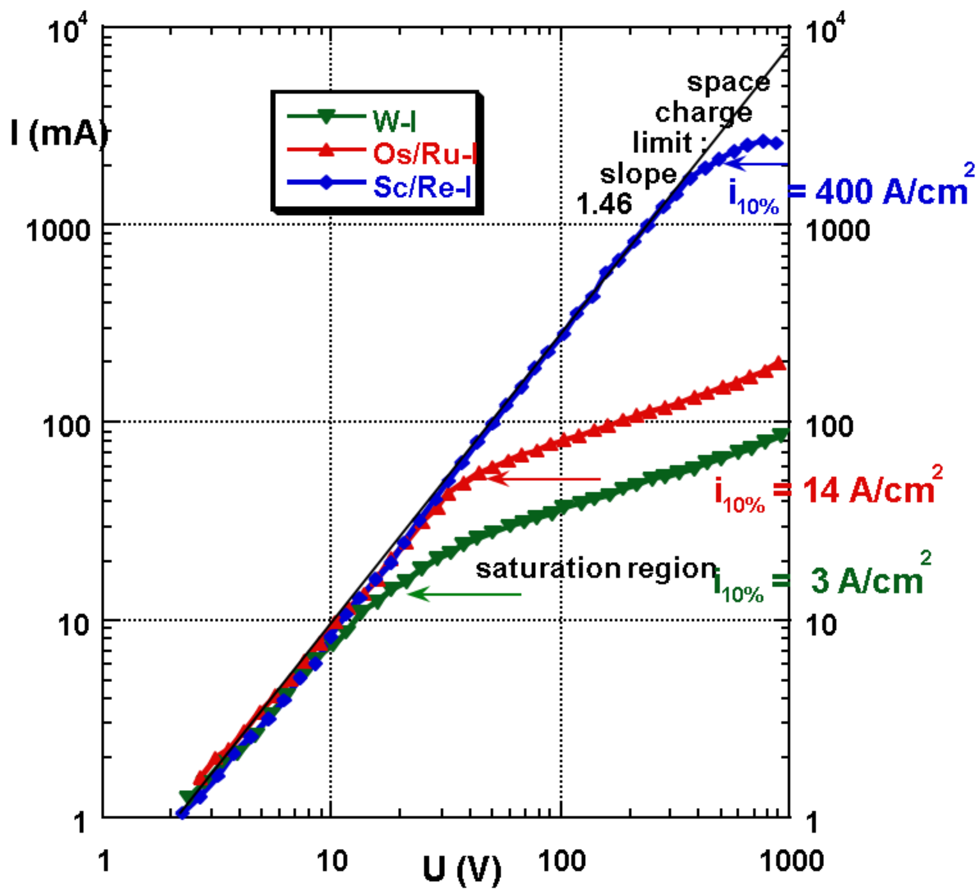


Philips 0,65 Watt I cathode unit, used as base for LAD top-layer Scandate cathode



LAD coating with ultrafine particles of Re and Sc_2O_3 by Laser ablation deposition from respective targets

Ba dispenser Scandate cathodes



Current-voltage characteristics of:
LAD top-layer Scandate cathode (´Sc´/Re-I)
Os/Ru-I cathode and a W-I cathode
at 965°C Mo-brightness temperature (1030°C true temp.), as determined in the diode mode in an electron gun

Photo-cathodes

The generation of electrons is based on the photo-electric effect
$E_{kin} = h\nu - e\Phi$;
the quantum efficiency η is the number of electrons per photon

Applications: photo detectors (night vision), photo multipliers, Electron injectors for accelerators and FELs

Improvement directions: Higher quantum efficiency via lower work function and surface coatings; for laser exited photocathodes : fast response times; high brightness

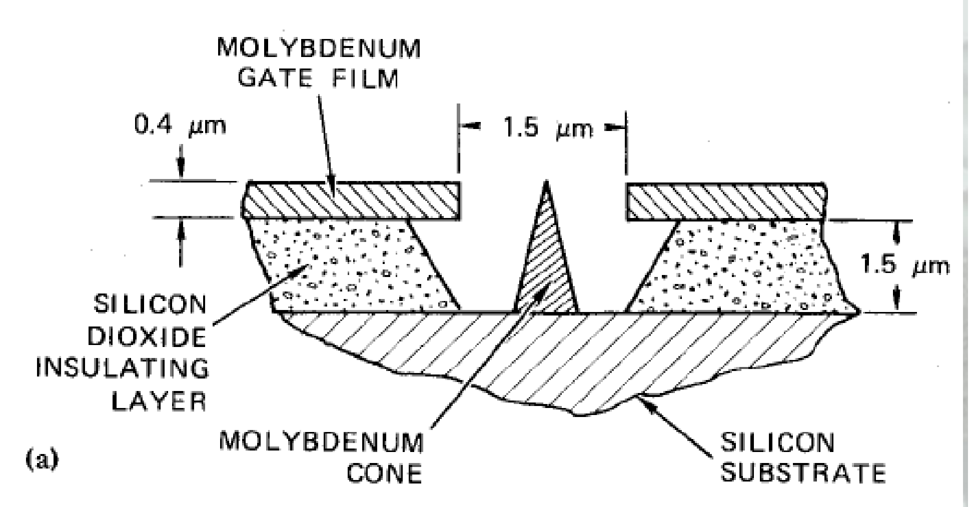
Cathode material	Quantum efficiency η	Wavelength λ	Work function
Cu	$1,4 \cdot 10^{-4}$	250 nm	4,6 eV
Pb	$6,9 \cdot 10^{-4}$	250 nm	3,6 eV
CsBr:Cu	$7 \cdot 10^{-3}$	250 nm	~2,5 eV
Cs_3Sb	0,15	432 nm	2,05 eV
K_2CsSb	0,1	534 nm	~2,0 eV

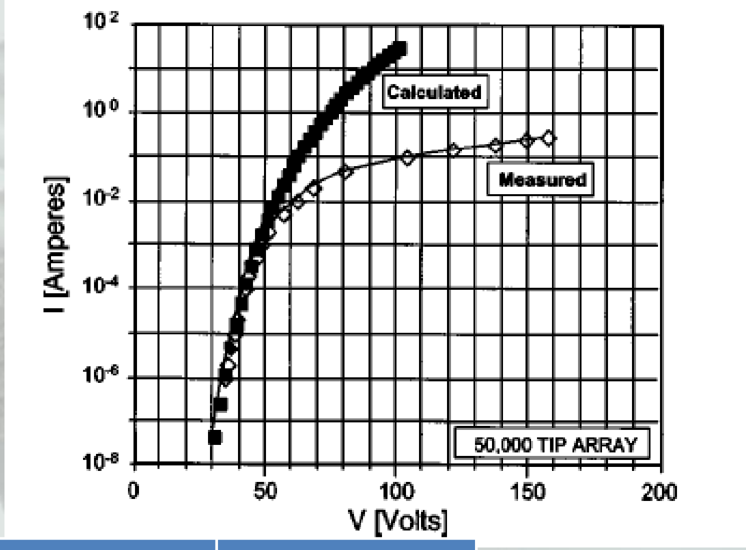
metals

semicon-ductors

Spindt field emitter arrays

In the 1970s C.A. Spindt and his colleagues at SRI developed methods for fabricating arrays of minute field emitter cones by using thin-film technology and electron beam microlithography.





Number of tips	I	I/tip	F	Year
1	0,2 μA	0,2 μA	156 μm^2	1976
100	30 μA	0,3 μA	0,0156 mm^2	1976
5000	1 mA	0,2 μA	0,78 mm^2	1976
625	25 mA	40 μA	0,0025 mm^2	1993
50000	300 mA	6 μA	0,75 mm^2	2005

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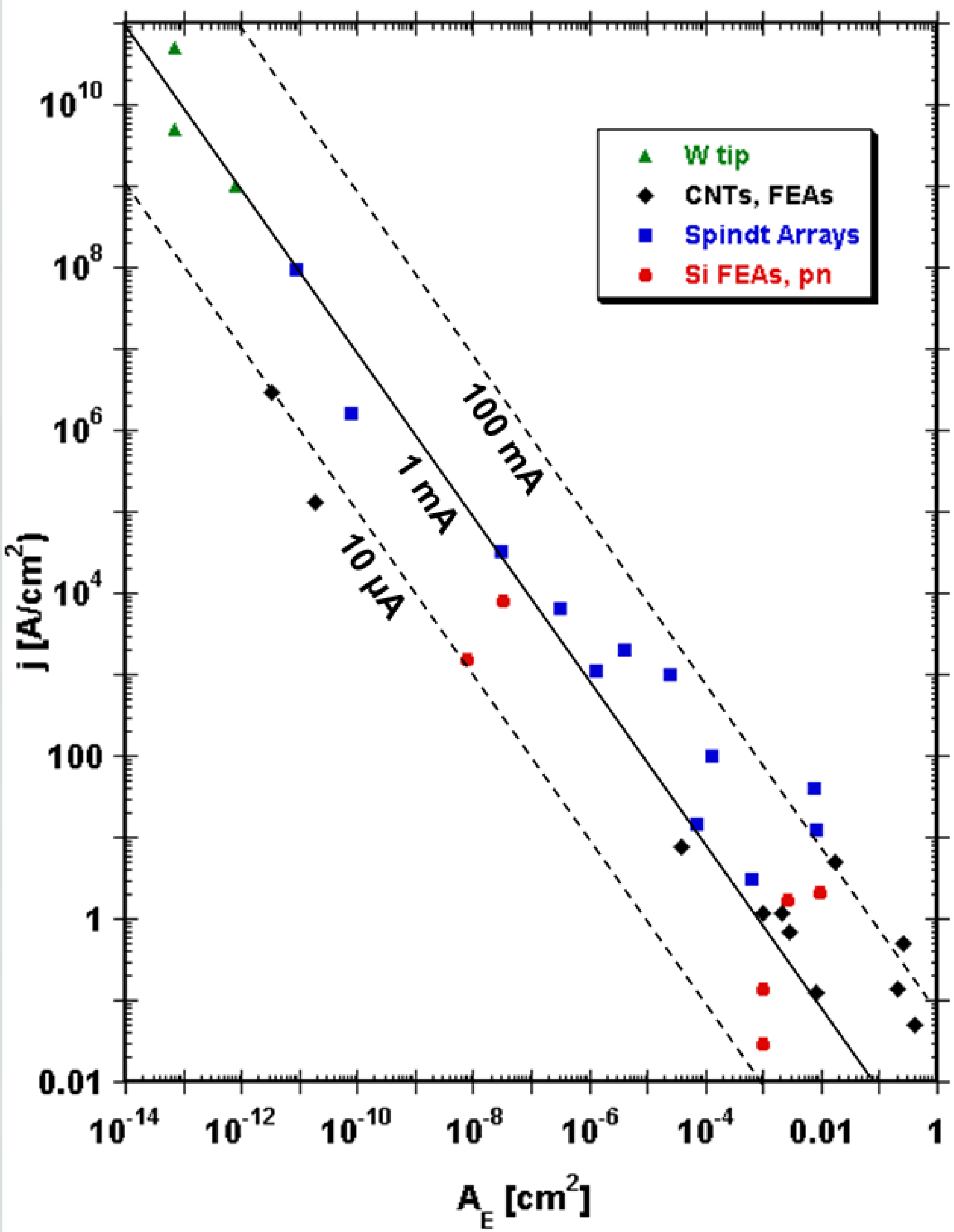
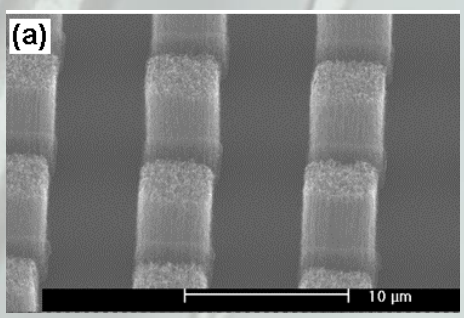
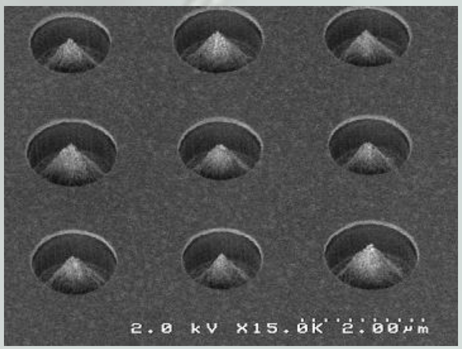


Plot of field emission (cold emission) current density versus emitter area (including passive parts) based on literature data for CNTs (a), W tips, pn emitters, and Spindt arrays (b). Lines of equal current are shown for 1 µA, 1 mA and 100 mA. Direction of improvement to higher current!



(a)



(b)

6) Conclusions and Outlook

The rise of vacuum electronics (VE) was enabled by the improvement of **vacuum techniques and cathode technology** during several **technological cycles**, (incandescent lamps - radio tube era - cathode ray tubes). Despite their decline **VE is still alive** (X-ray tubes, microwave tubes, e-beam devices, etc.).

VE is **dominant in the high power, high frequency domain**, with new applications e.g. in **TeraHertz** imaging, FELs and particle accelerators. This also implies **higher requirements for the cathodes**, which can be met by adanced new preparation and characterization techniques.

Thank you for your attention !

(That´s what we have missed; next (physical) ITG-IVEW workshop probably will take place here in 2022)

References:

1. 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

2. G. Gaertner: „Historical development and future trends of vacuum electronics“, J. Vac. Sci. Technol. B, Vol. **30**, No. 6, 060801 (2012)

3. G. Gaertner, W. Knapp, R. Forbes (Editors), “Modern Developments in Vacuum Electron Sources”, Springer 2020

View over the river Rhine to the „Siebengebirge“ (Seven Mountains)