Improvement directions of modern vacuum electron sources

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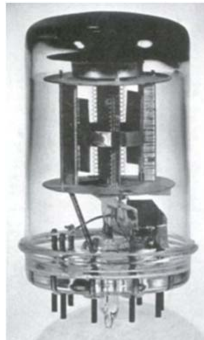
Outline:

1. Introduction: History and perspectives of Vacuum Electronics
2. Continous improvement of enabling technologies
3. Cathode requirements for future applications
4. Cathode types
   - Thoriated tungsten cathodes; Oxide cathodes
   - Impregnated cathodes
   - Scandate Cathodes
   - High brightness cathodes
   - Photo cathodes
   - Field emitters
5. Conclusions and outlook

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

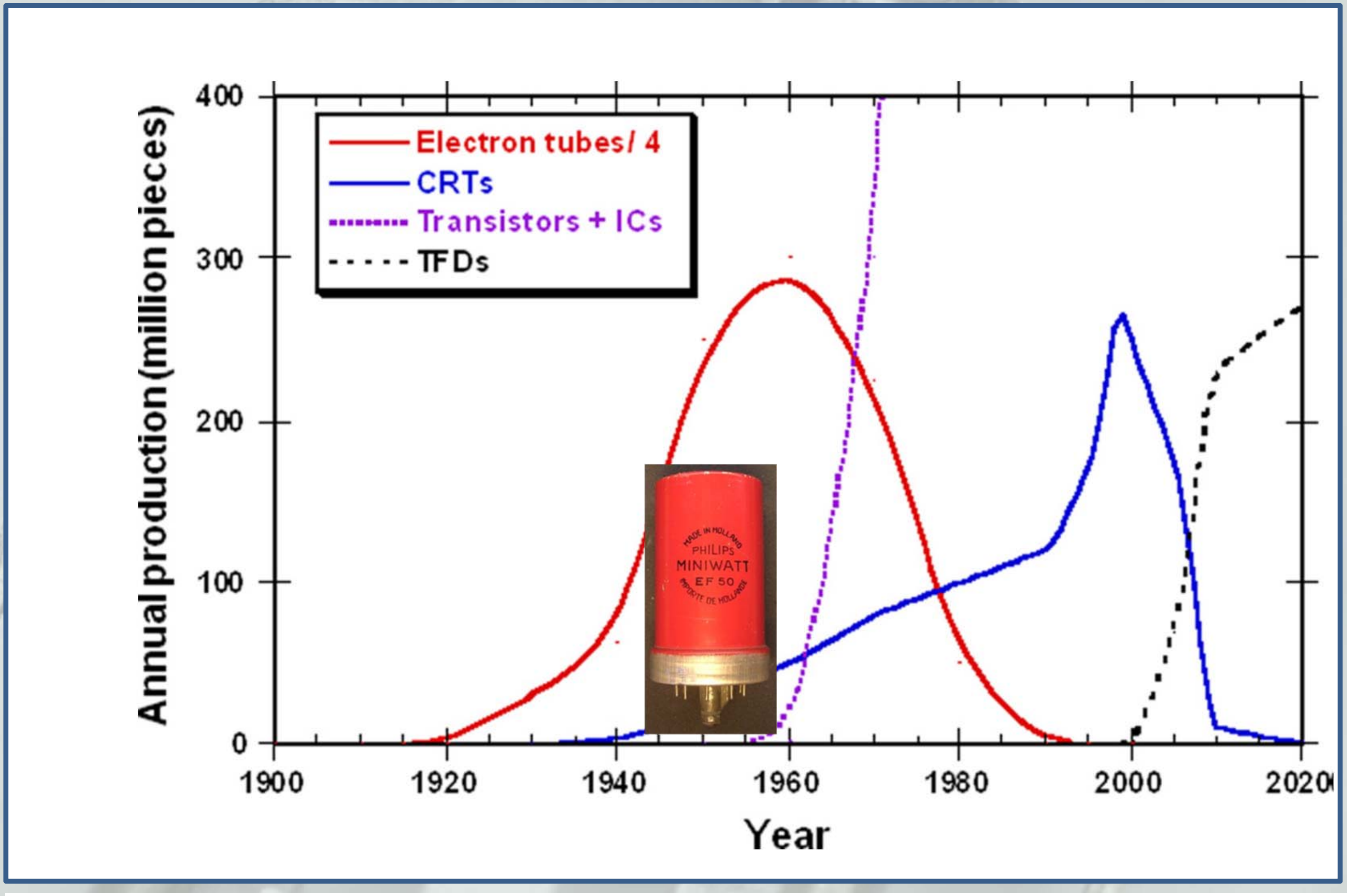
Start of incandescent lamps in 1880, first with carbon filaments, then replaced by tungsten filaments, yielding higher luminous efficacy of 10 lm/W. The era of bulb based lamps lasted till today, now being replaced by LEDs and to a lesser extent by OLEDs.

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, accompanied by a continuous improvement of vacuum techniques and cathodes.



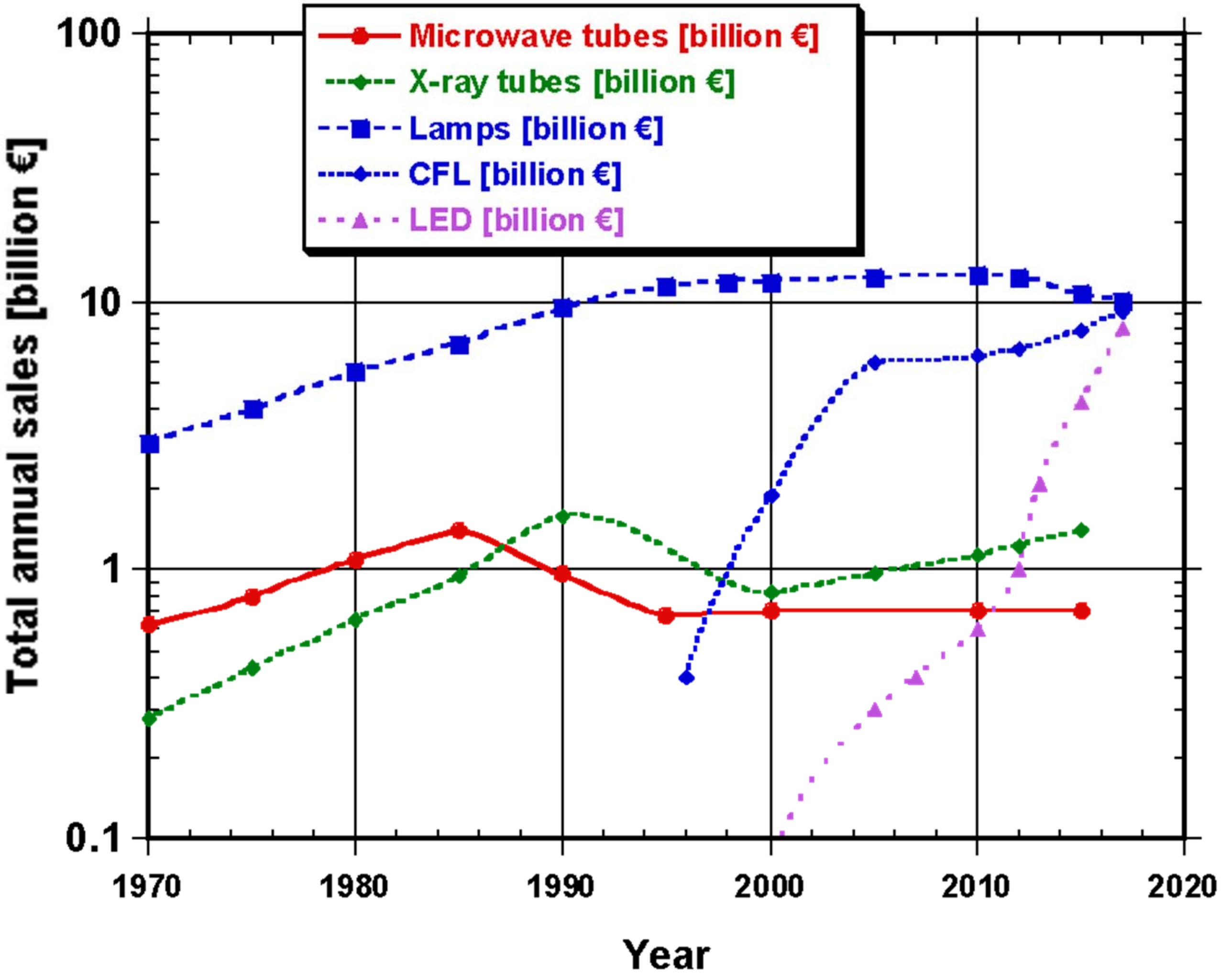
With the advent of cathode ray tubes (CRTs) a new technological cycle started, triggering further progress in the base technologies.

1) 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.

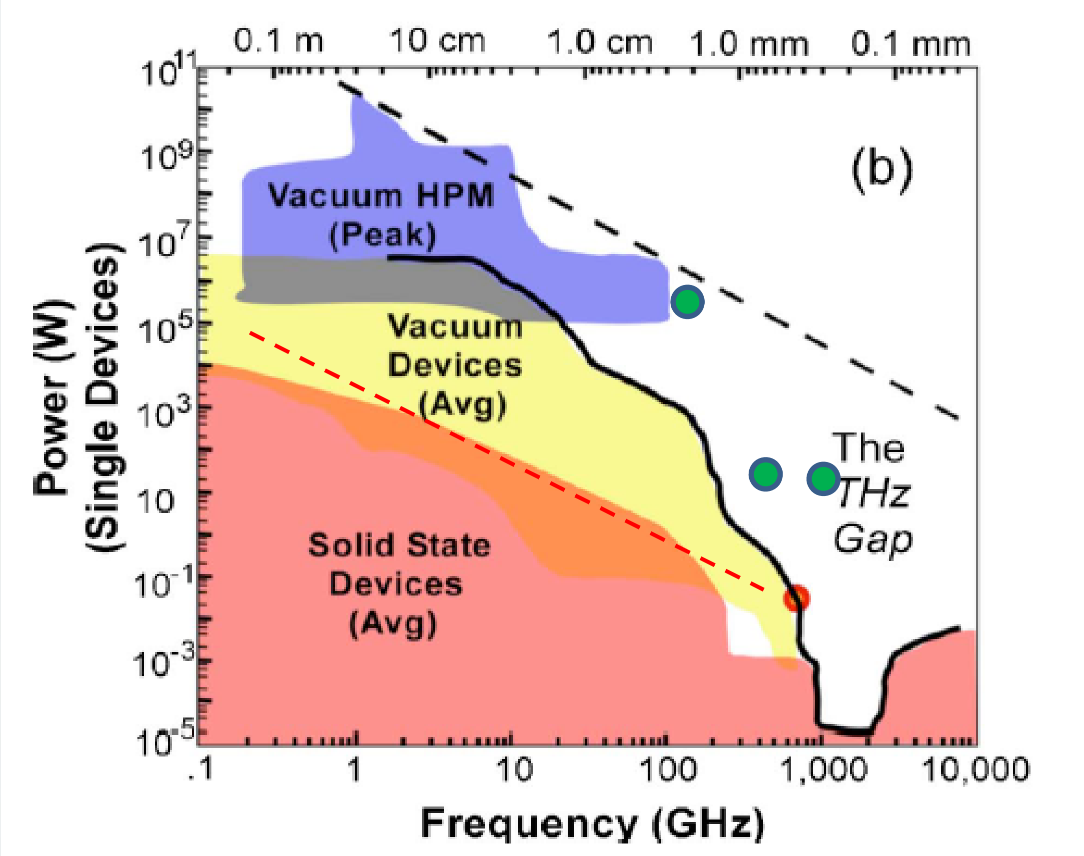
Total annual sales (in billions of €) versus time for three important vacuum tube types: microwave tubes, x-ray tubes and lamps (fluorescent/ CFL- and incandescent, see [1]).



Phasing out of incandescent lamps due to national energy savings legislation. The rise of LEDs for comparison: data without fixtures and car applications.

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

Supremacy of VEDs in the high frequency , high power domain*



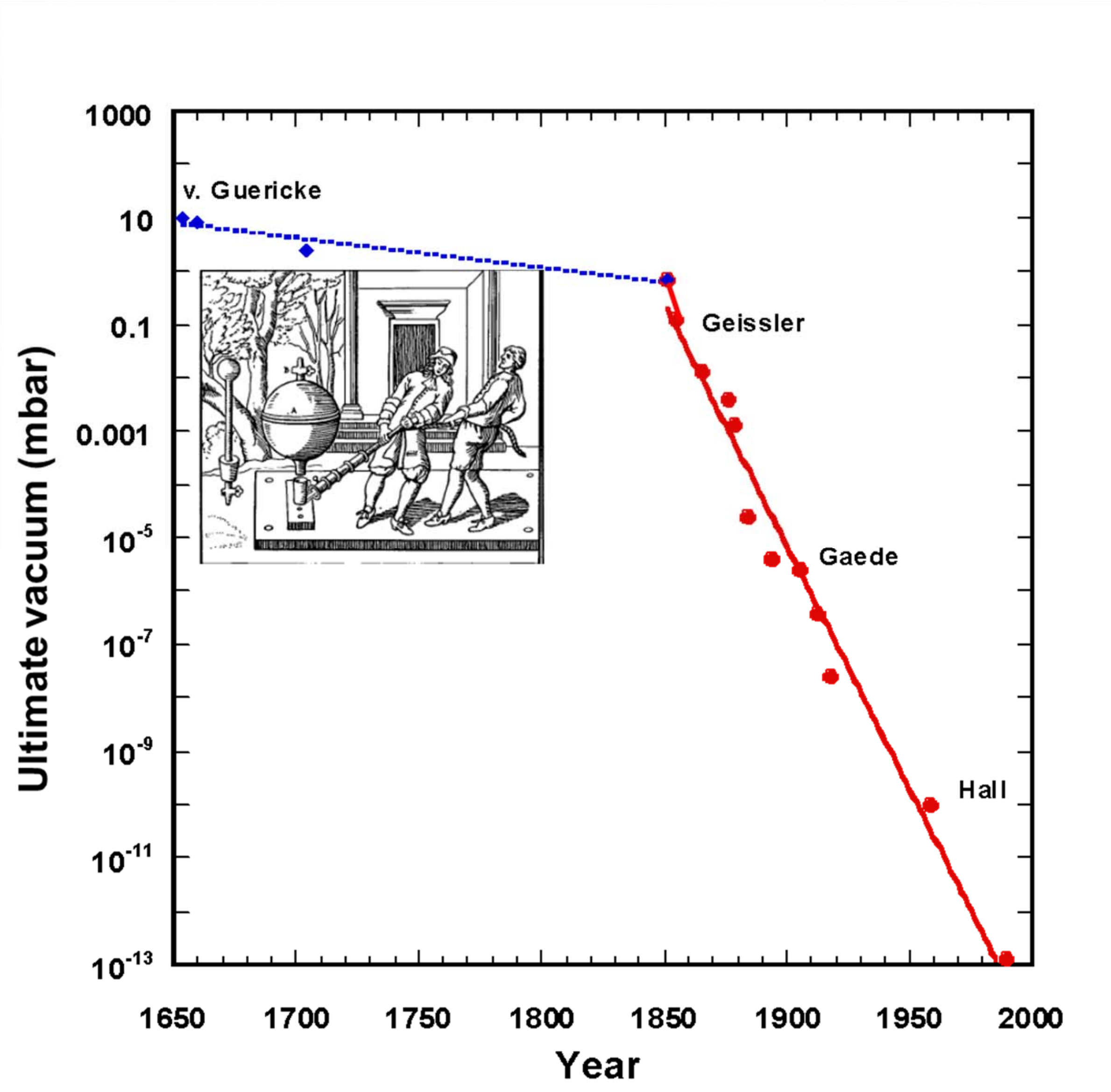
P_{cw}*f^2= 4 kW/GHz^2,
Upper limiting line for SSDs
(power per interaction area)

*three reasons:

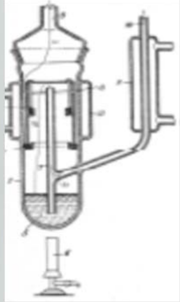
1. Electron current generates heat in SSDs via collisions
2. Breakdown voltages higher for VEDs than for SSDs
3. VEDs can be operted at higher temperatures than SSDs

(Average/CW) Power versus frequency plot of compact and mobile devices showing the TeraHertz gap.
For 100 Watt TWT operating at 200 GHz an emitter current density of 200 A/cm^2 is needed. ● cw gyrotrons
(according to J. Booske, Phys. Plasmas 15, 055502, (2008)).

2a) Improvement in vacuum techniques



Ultimate vacuum achieved versus time, see [1].



Hg diffusion pump Gaede 1915

Balzers turbomolecular pump

Varian ion getter pump

2b) Improvements in cathode performance

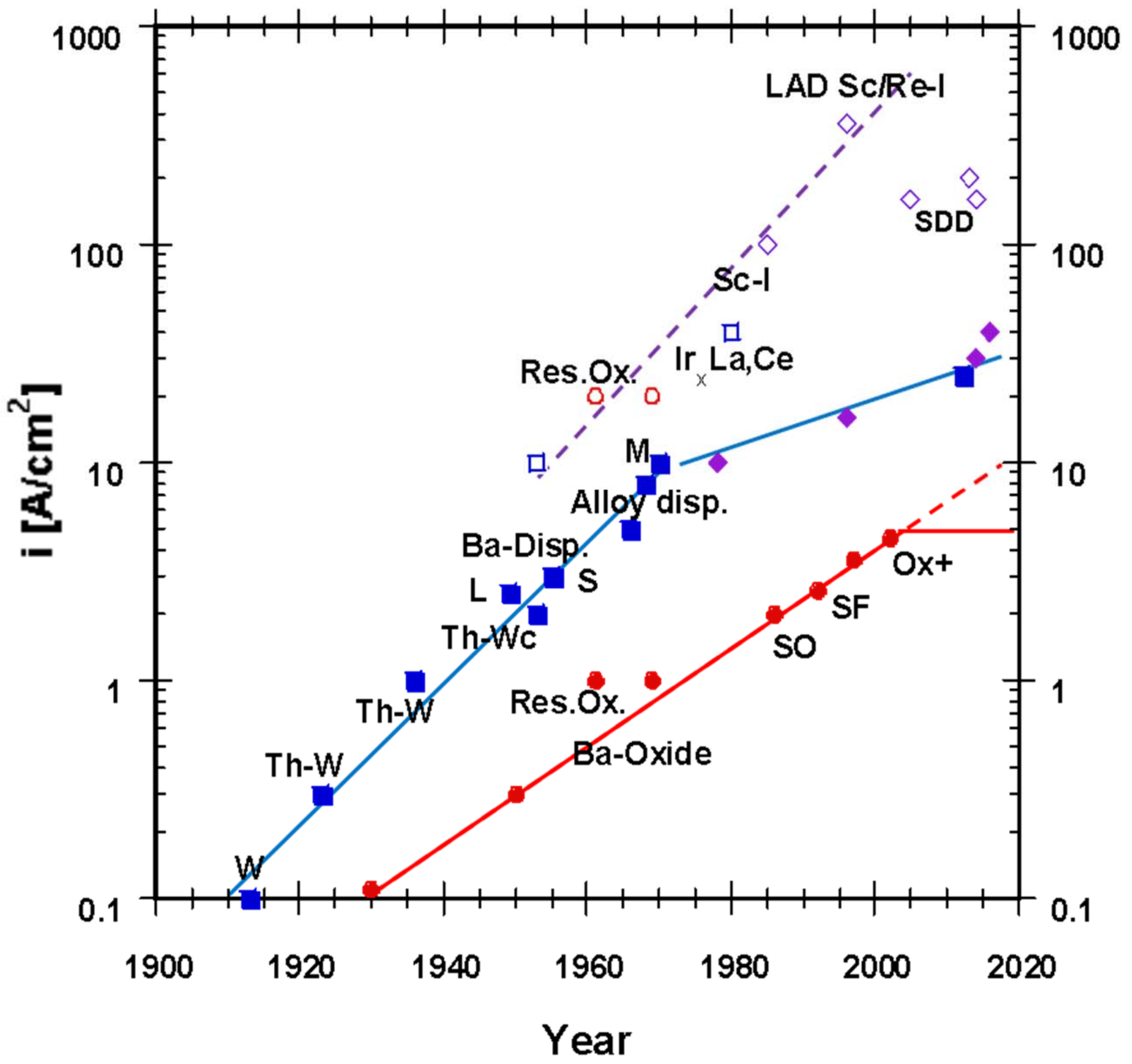


Figure :

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.

3) Thermionic cathodes – Requirements for future applications

Since till today practically all vacuum electron devices are equipped with thermionic cathodes, we will first address their general improvement directions as seen in the figure, including future requirements

(1) Higher emission current density
(2) Higher emission current (increased emitting area)
(3) Decrease of operating temperature
(4) Increase of lifetime

The first 3 trends are linked to a decrease of the work function $e\Phi$ via the Richardson equation:

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

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

3a) Thermionic cathodes

Lower WF implies higher useable space-charge limited emission as described by the Child-Langmuir equation:
(in first approximation independent of the temperature, but dependent on the Laplace field strength Ua /D

$$je = 4/9\ \varepsilon_0 \sqrt{(2e/m_e)}\ D^{-1/2} * (Ua/D)^{3/2} = K{*}Ua^{3/2}$$

The geometry factor $K = 2{,}33{*}10^{-6} /D^2$ is given in units of $A/(cm^2 * V^{3/2})$, where D is the cathode to anode distance in cm and Ua the anode voltage in V. The saturation region is described by the Schottky equation for metal and dispenser cathodes, but in general is not valid for oxide and Scandate cathodes.

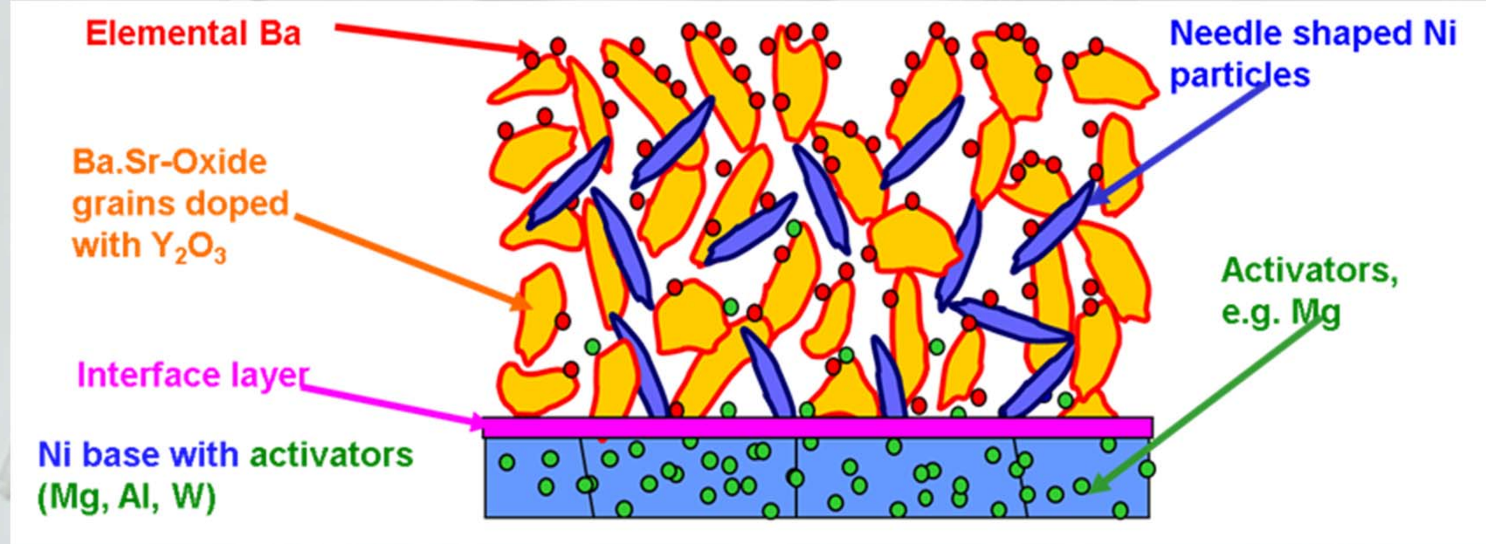
Further cathode requirements are increased robustness versus gas poisoning of emission and versus ion bombardment, usually generated by ionization of the rest gas by the electron beam.

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

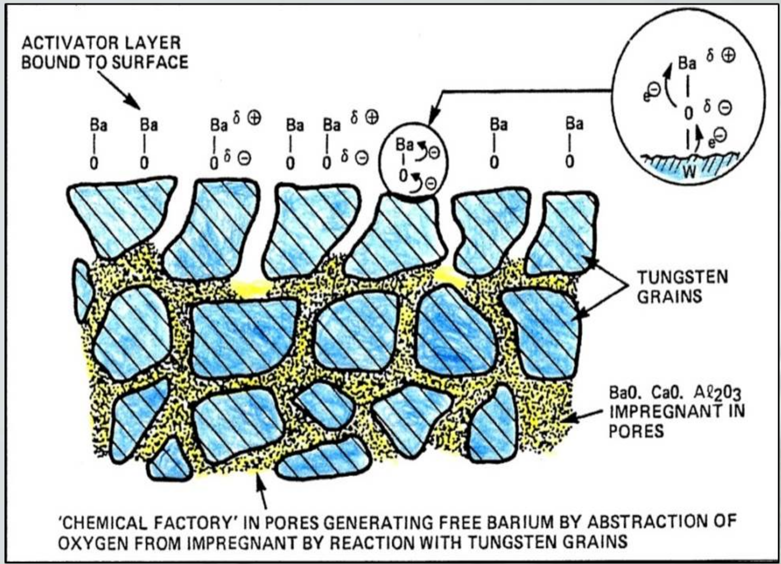
Cathode type	Abbrev.	Top [K]	Jdc [A/cm^2]	eΦ [eV]	lifetime
tungsten	W	2520	0,6	4,5	> 100 h
Thoriated tungsten	Th-W	2000	4	2,6	10 kh
Ba-oxide	Ox	1050	1 - 4	1,4	20 kh
Ba-dispenser, W-Base	W-I or A or B	1300	3	2,05	$\geq$ 20 kh
Os/Ru coating	M or Os/Ru-I	1300	10	1,85	$\geq$ 20 kh
Ba-Scandate	Imp., (TL)	1300	15	1,7 (1,45)	$\geq$ 10 kh
Ba-Scandate	SDD	1320	40	1,45	$\geq$ 4000

Ba-Oxide cathodes

Schematic view of the cross section of an oxide plus (cermet) cathode of Philips, (original by the author in 1999, [xx])



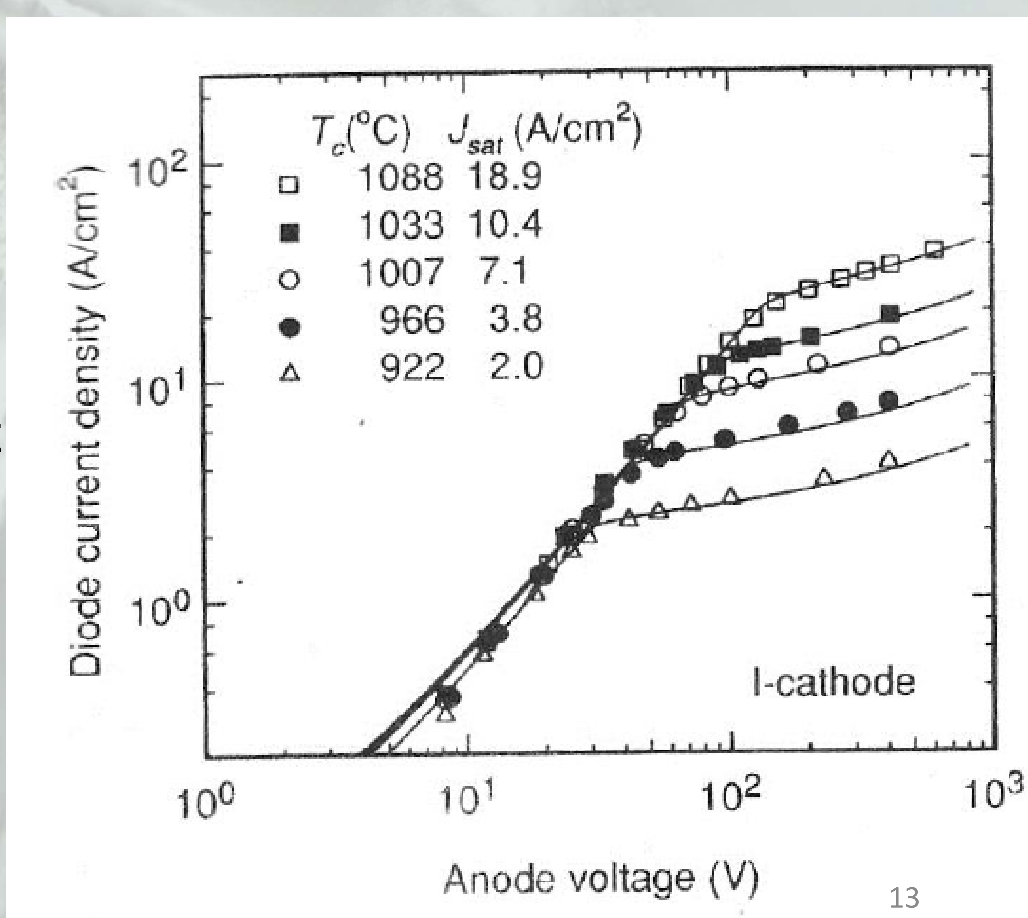
With the oxide plus cathode of Philips the oxide conductivity and dc loadability could be improved up to 4,5 A/cm^2, in lab. tests up to 10 A/cm^2 dc.
The oxide plus was used in all TV tubes of LG.Philips displays after 2002, also replacing M cathodes, which were 3 times more expensive.



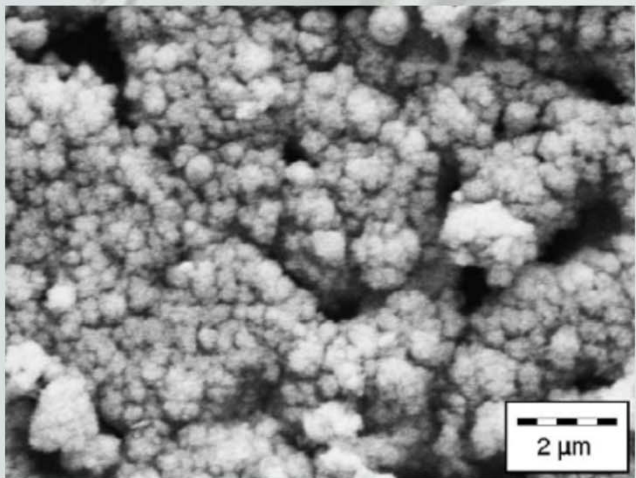
Ba dispenser or impregnated cathodes

The lg j/lgU characteristics are for a Philips Os/Ru-I cathode at different true operating temperatures. A clear Schottky behavior in saturation is seen

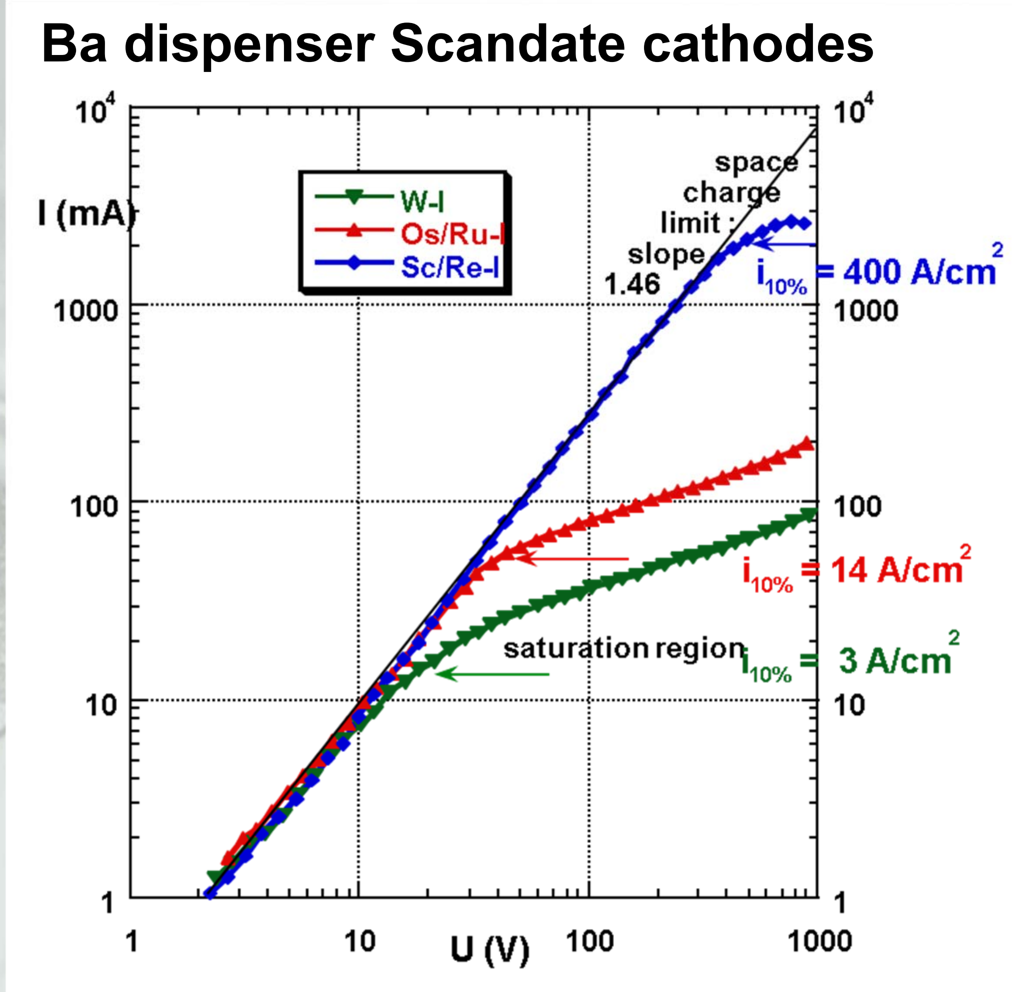
Cross sectional view of an impregnated cathode; free Ba is generated in the pores by a reaction of BaO of the impregnant with the tungsten walls



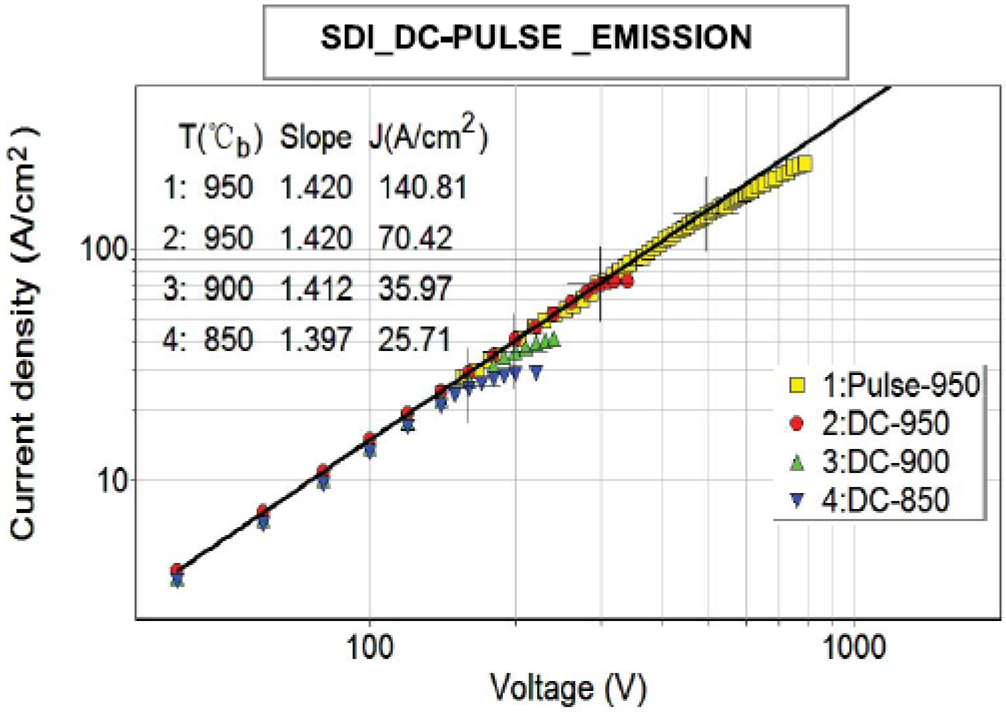
Philips 0,65 Watt I cathode unit, used as base for LAD top-layer Scandate cathode



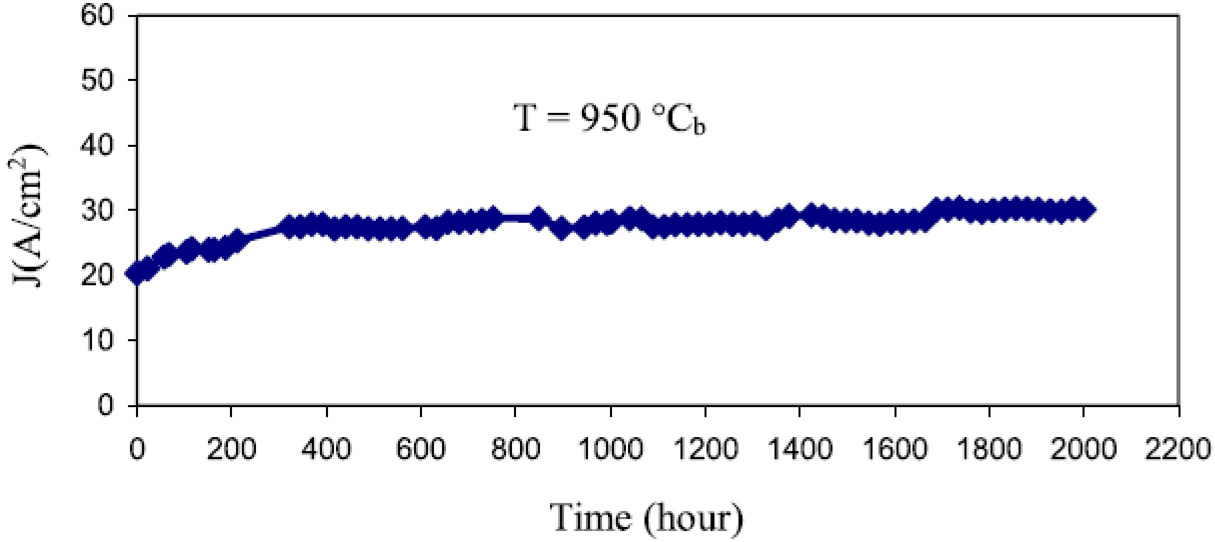
LAD coating with ultrafine particles of Re and Sc_2O_3 by Laser ablation deposition from respective targets



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



Scandia-doped impregnated (SDI) dispenser cathodes made at BJUT using nanosized-scandia-doped tungsten pellets and impregnated with Ba, Ca aluminates can provide pulsed current densities over 100 A/cm^2 at operating temperatures above 950 °C$_b$ The other variant of SDD cathodes are pressed (SDP) dispenser cathodes.



Dc emission life test at 950°C$_b$ and 30 A/cm^2 In the meantime also dc lifetime of 3000 h has been reached at 40 A/cm^2 and 970 °C$_b$

See Y. Wang et al. IEEE Trans. ED 61,1749(2014)

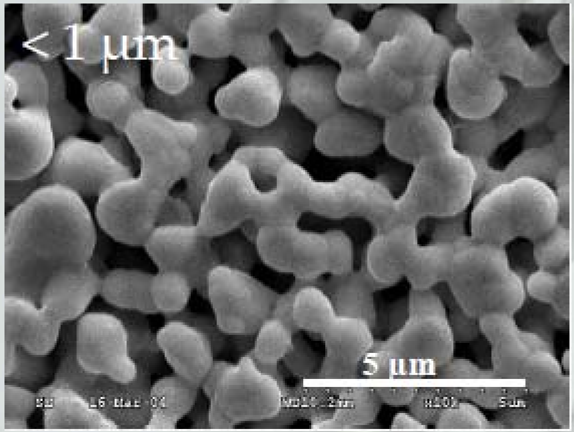
Methods to improve thermionic cathode performance:

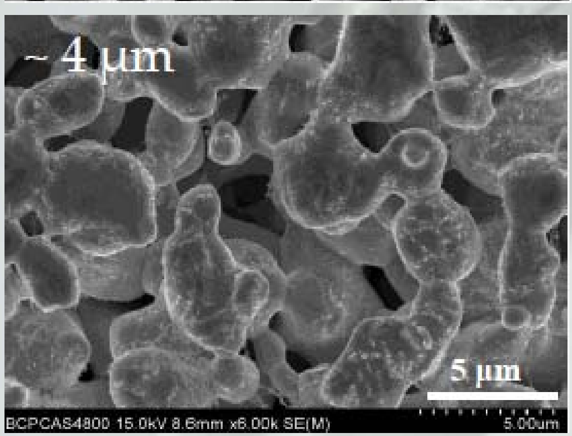
Submicron technologies, lower diffusion lengths, optimization of material combinations and structures

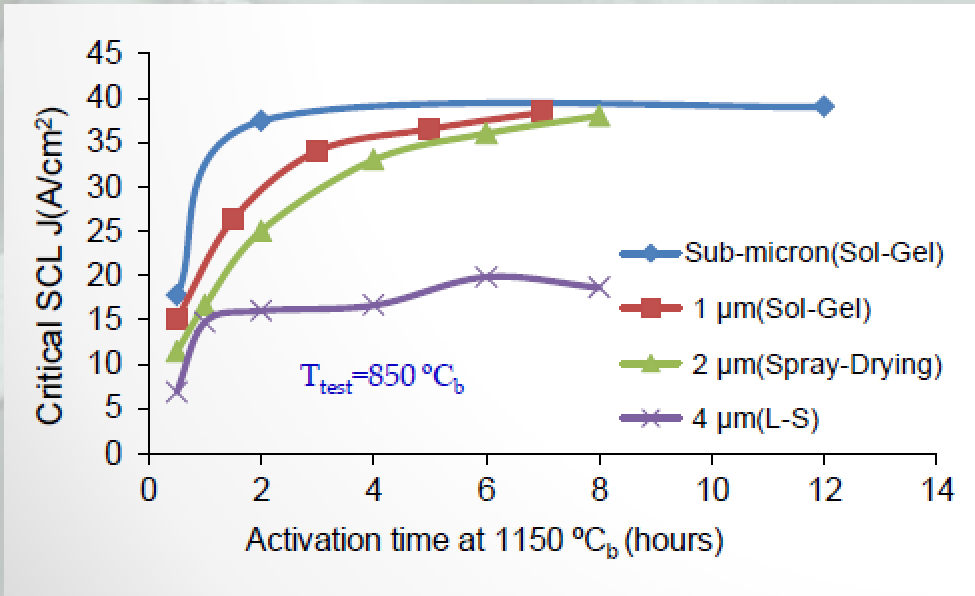
a) Laser ablation deposition surface coating with ultrafine particles (Philips)

b) Submicron particle coating of I cathodes (Toshiba)

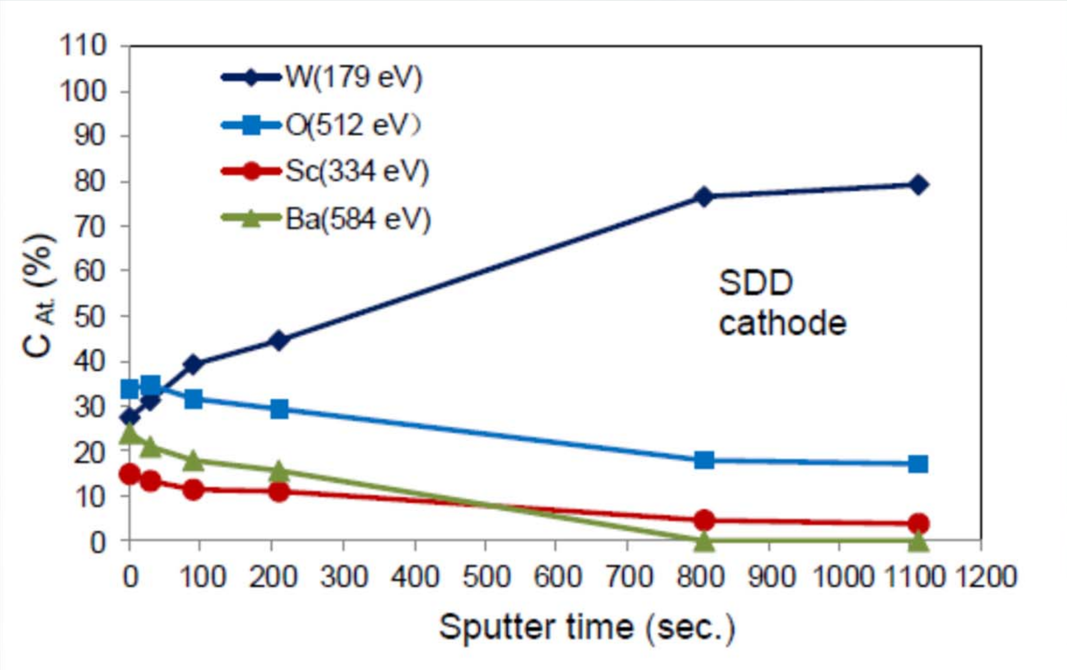
c) Submicron Scandia and μm tungsten particles (SDI and SDP; BJUT China)



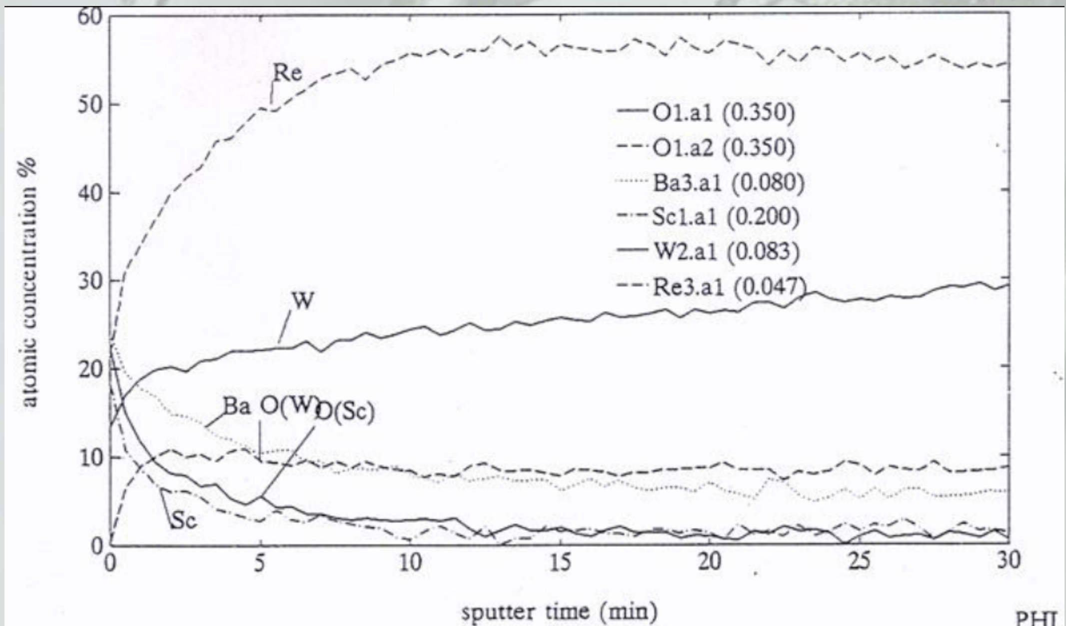




Smaller grain size favours getting higher emission in a shorter activation time.
(see Y. Wang, IVESC 2016)



Investigation of SDD surface layer and composition:
Ba,Sc,O containing layer of several 10 nm thickness, sputter rate about 20 nm/min with Ar+ ions at 4kV.
(Y. Wang et al.)
Both results are consistent with a semiconductor theory of the Scandate cathode



Investigation of LAD-TL surface layer and composition (cathode with $i_{10\%}$ = 240 A/cm^2 at 950°Cb, after several 100 h operation):
Ba,Sc,O containing layer of several 10 nm thickness.
Sputter rate about 13 nm/min with Ar+ ions at 3kV.

High brightness cathodes

For high resolution electron beams for microscope applications
Here the reduced differential brightness B_r is decisive:

$$B_r = dI / (dA_s{*}d\Omega{*}U)\ [A{*}/(m^2\ {*}sr\ {*}V)]$$

With I beam current, A_s virtual source area, Ω beam angle, U beam voltage. B_r often replaced by B. Beam arrays needed for lithography !
Larger energy spread, lower noise for higher temperatures

Cathode type	B_r [$A*/(m^2 *sr *V)$]	Lifetime	Temperature
W hairpin	$1{*}10^5$	100 h	2800 K
LaB6 hairpin tip	$2{*}10^6$	> 1000 h	1900 K
Schottky emitter Zr-O-W	$1\text{-}2\ {*}10^8$	25 kh	1800 K
Os/Ru – I cath. (+Wehnelt)	$1{*}10^6$	> 1000 h	1300 K
Scandate cath. (+Wehnelt)	$1{*}10^7$	> 1000 h ?	1200 K
W (310) FE	$5{*}10^8$	> 2000	300 K
CNTs	$5{*}10^8$		300 K

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

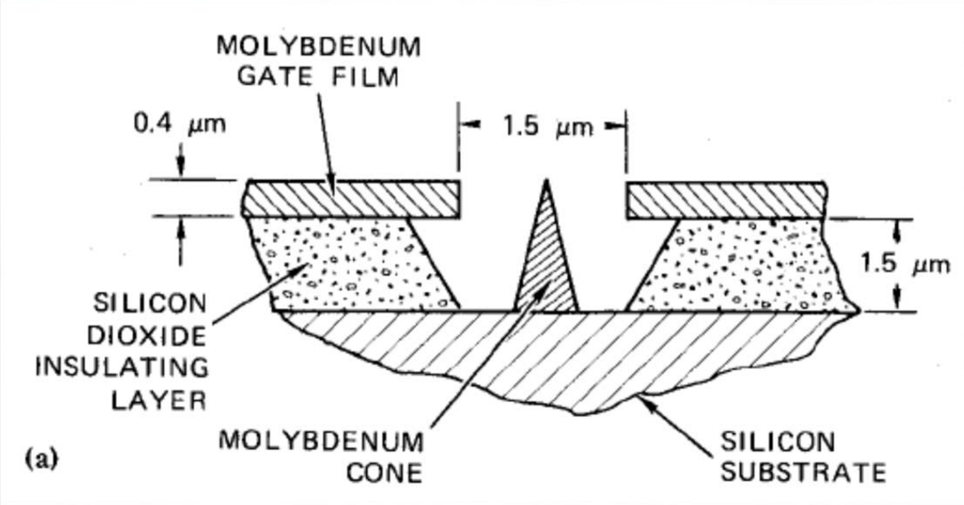
Cathode material	Quantum efficiency η	Wavelength λ	Work function
Cu	$1{,}4 \cdot 10^{-4}$	250 nm	4,6 eV
Pb	$6{,}9 \cdot 10^{-4}$	250 nm	3,6 eV
CsBr:Cu	$7 \cdot 10^{-3}$	250 nm	~2,5 eV
Cs_3Sb	0,15	432 nm	2,05 eV
K_2CsSb	0,1	534 nm	~2,0 eV

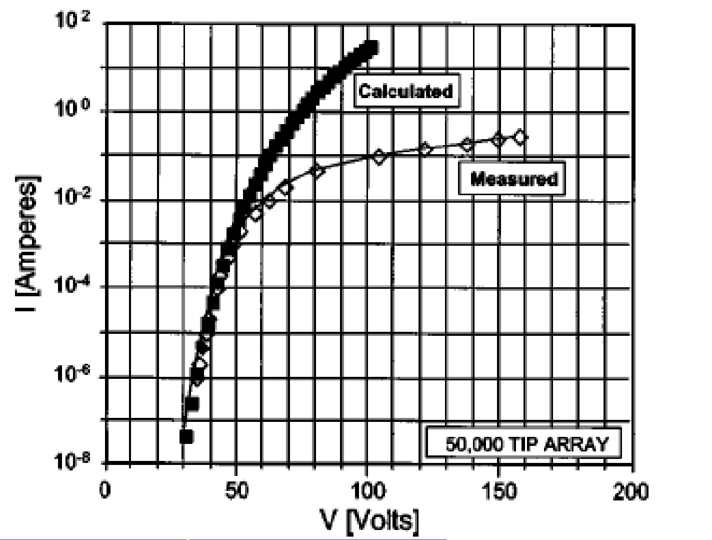
metals

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.



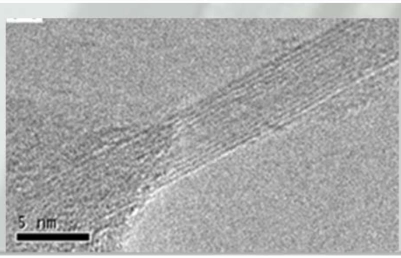


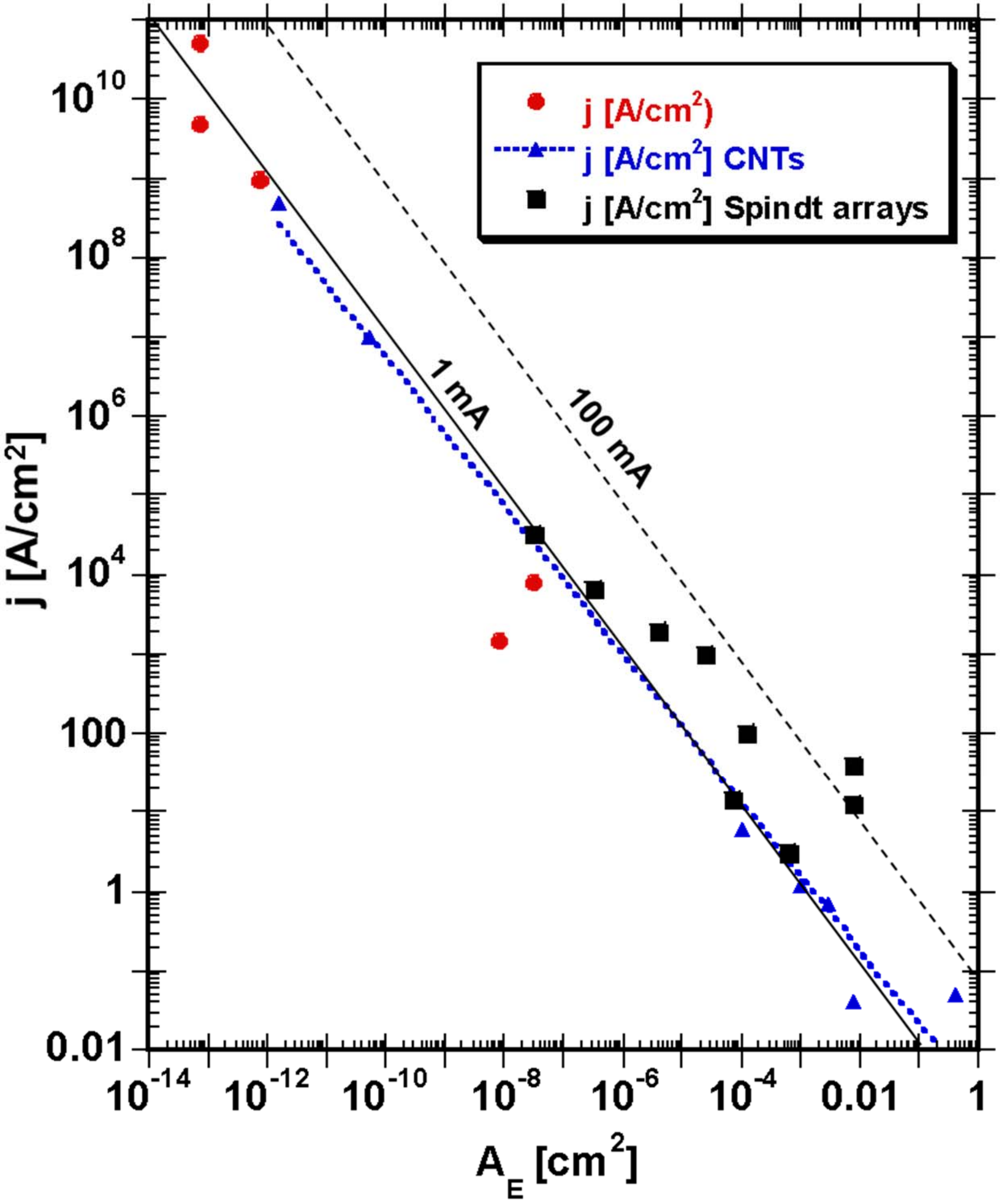
Number of tips	I	I/tip	F	Year
1	0,2 μA	0,2 μA	156 μm^2	1976
100	30 μA	0,3 μA	0,0156 mm^2	1976
5000	1 mA	0,2 μA	0,78 mm^2	1976
625	25 mA	40 μA	0,0025 mm^2	1993
50000	300 mA	6 μA	0,75 mm^2	2005

Carbon nano tubes (CNTs)

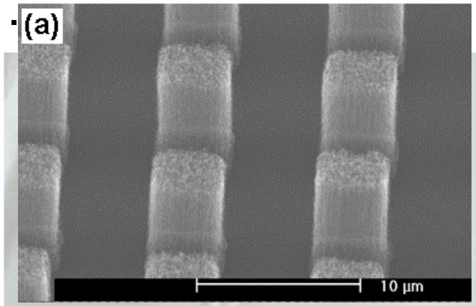
In the 1990s different groups started to investigate the preparation of CNTs via screen printing or PCVD with Fe, Ni catalyst nano particles for FE applications. Since a single wall CNT (SWNT) and multi wall CNT (MWNT) are limited in total current, lawns of CNTs and additional arrays have been prepared and tested. Some results are listed in the following table. Applications are FE displays, microwave tubes and miniature x-ray tubes, but no real commercial impact

Number of tips	Current I	j [A/cm2]	F	Year	
1 MWNT	10 µA	$3*10^6$	$3,3\ 10^{-12}\ cm^2$	2002/4	De Jonge
Circ.spot	300 µA	6	$3,85\ 10^{-3}\ mm^2$	2005	Chen
Array 10^6 dots	20 mA	0,05	$25\ mm^2$	2008	Chen
Mini X-ray tube	617 µA	0,123	$0,785\ mm^2$	2012	Hwan

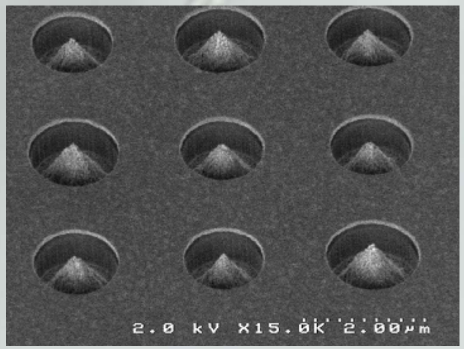




Plot of field emission (cold emission) current density versus emitter area (including passive parts) based on literature data for CNTs (a), W tips, pn emitters, and Spindt arrays (b). Lines of equal current are shown for 1 mA and 100 mA.
Direction of improvement to higher current!



(a)



(b)

5) 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

Vielen Dank für Ihre Aufmerksamkeit

References:

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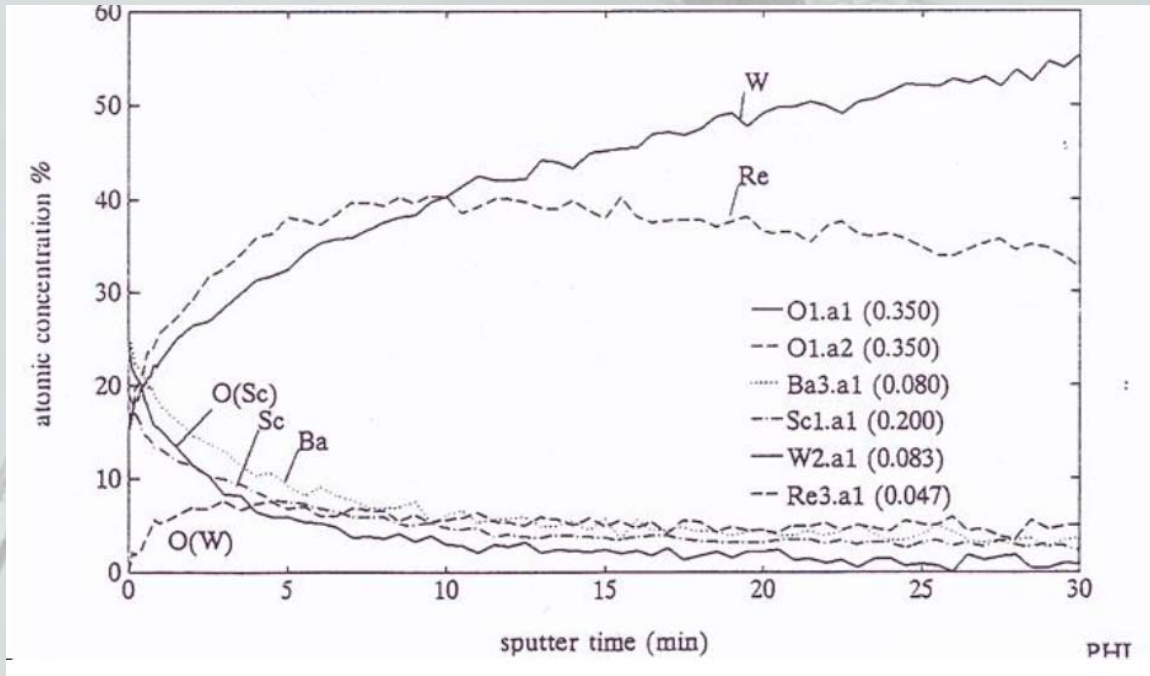
3. Y. Wang et al. (BJUT = Beijing University of Technology), Terahertz Sci. Technol. 4, 50 – 58 (2011)



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