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Peculiarities of Ba scandate cathodes and constituents of a model

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Peculiarities of Ba scandate cathodes and constituents of a model

Outline:

1. High emission capability of Ba Scandate cathodes
   a) anomalous behavior in „saturation“
   b) comparison with I cathodes

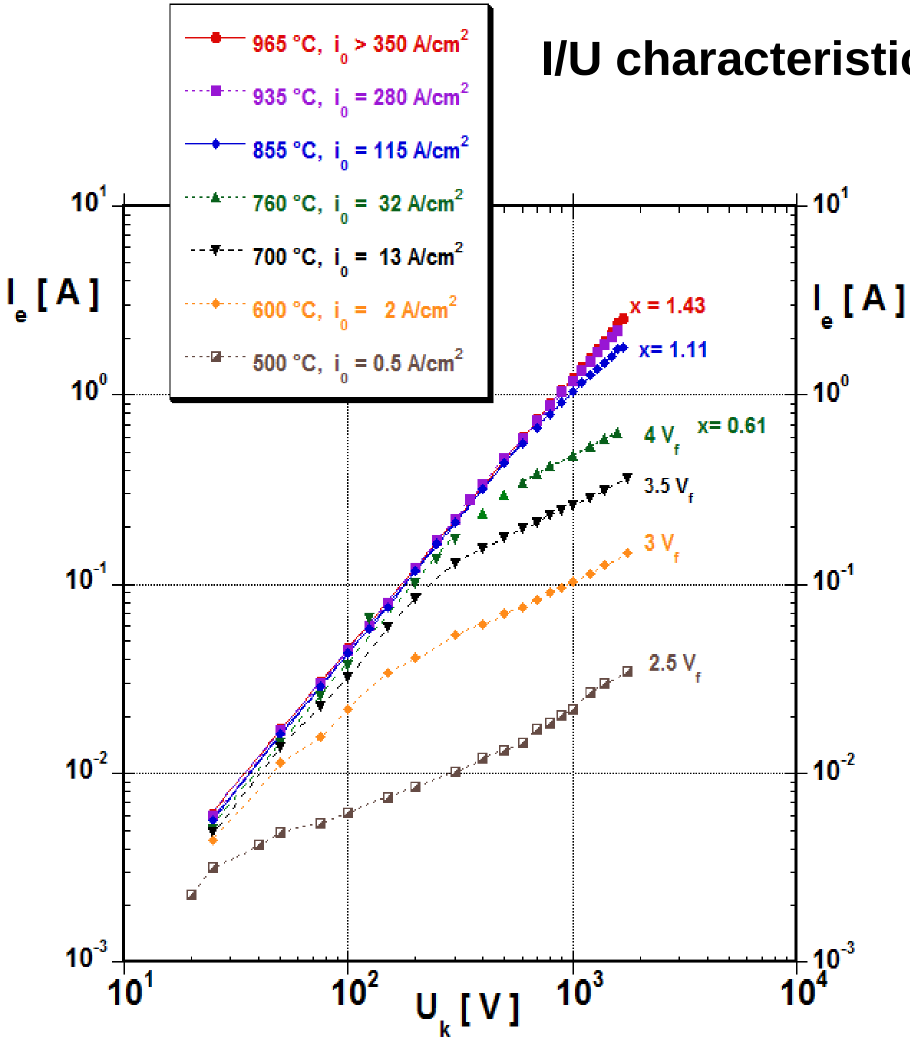
2. Surface analysis results for Scandate cathodes

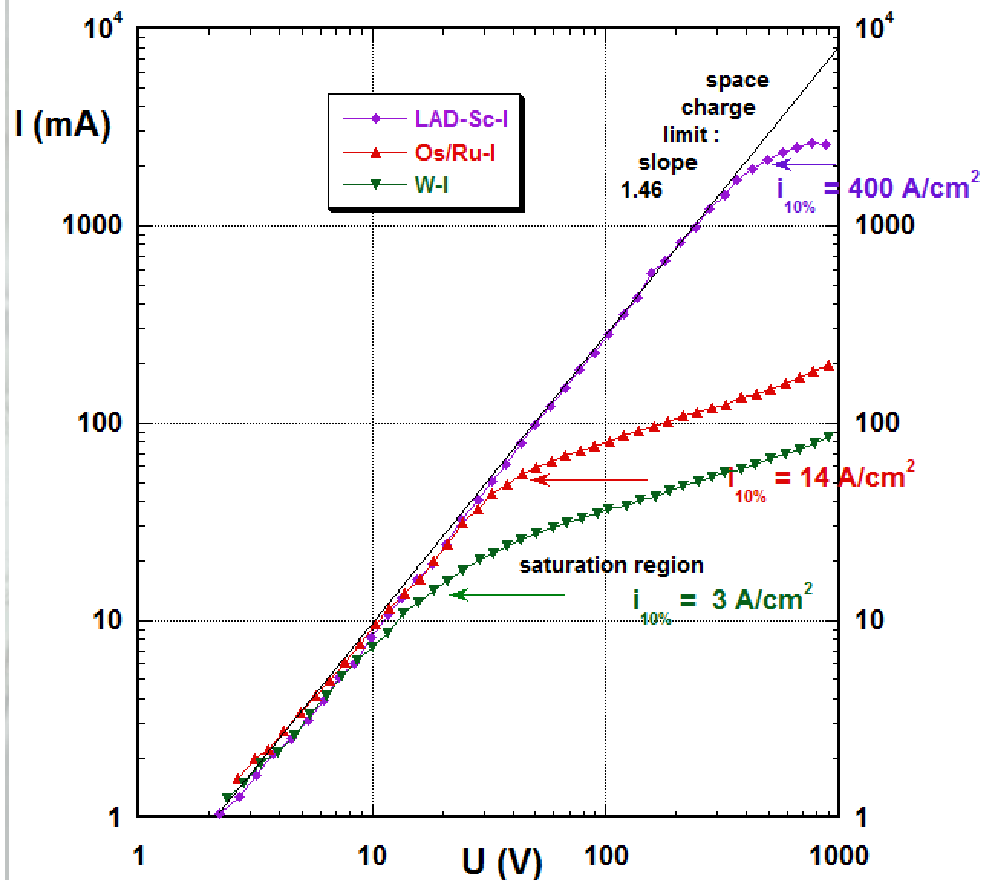
3. Evaluation of Richardson plots of I and scandate cathodes

4. Features of a model of scandate cathodes

5. Conclusions and outlook

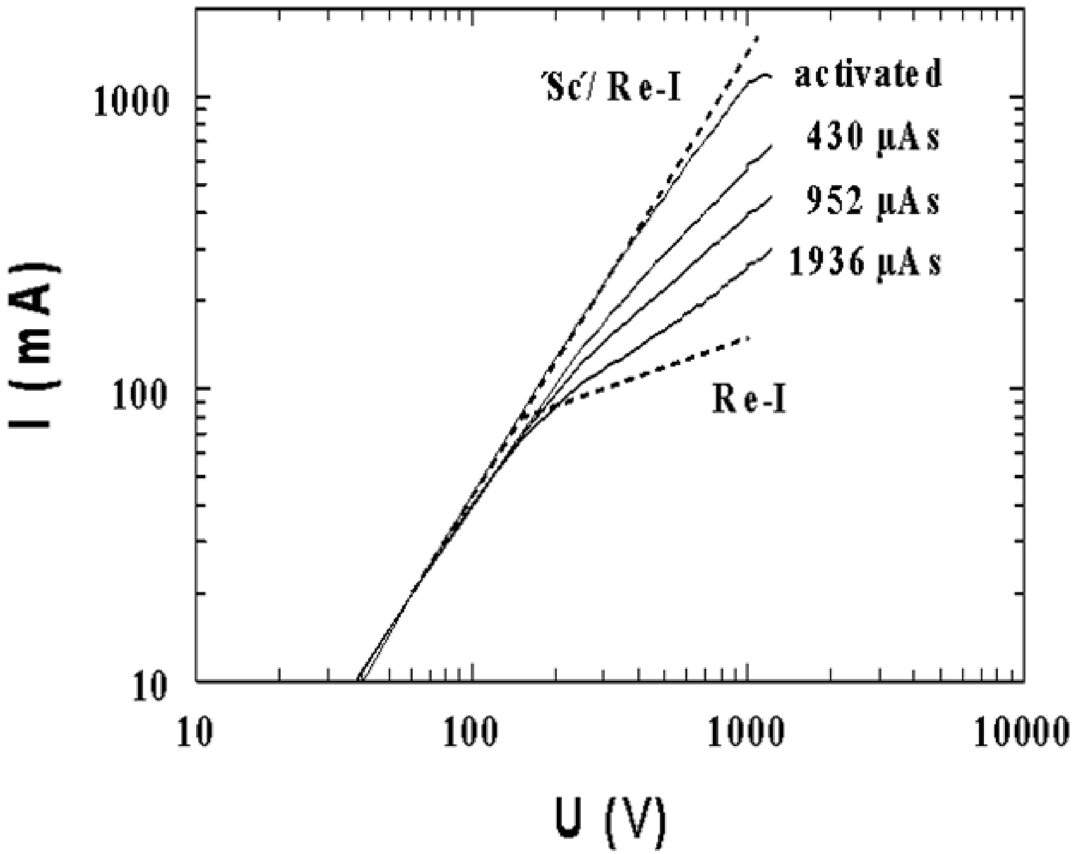
I/U characteristics of Ba dispenser + Scandate cathodes



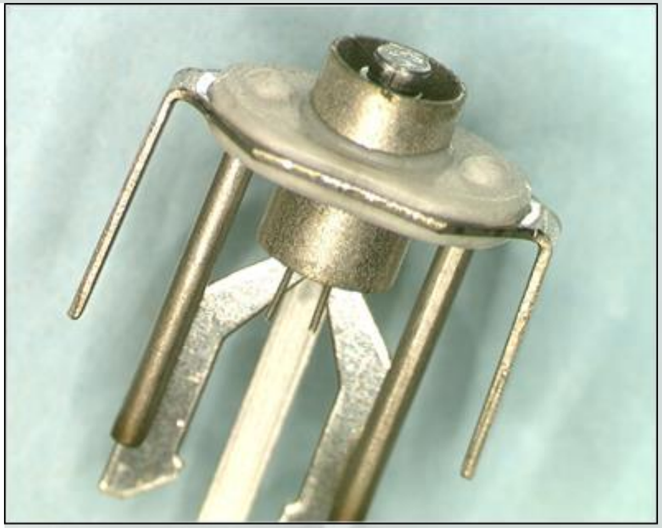


Current-voltage characteristics of LAD top-layer Scandate cathode as a function of temperature (Mo-brightness) ´measured in a closed space diode in UHV (cathode diameter 1 mm).

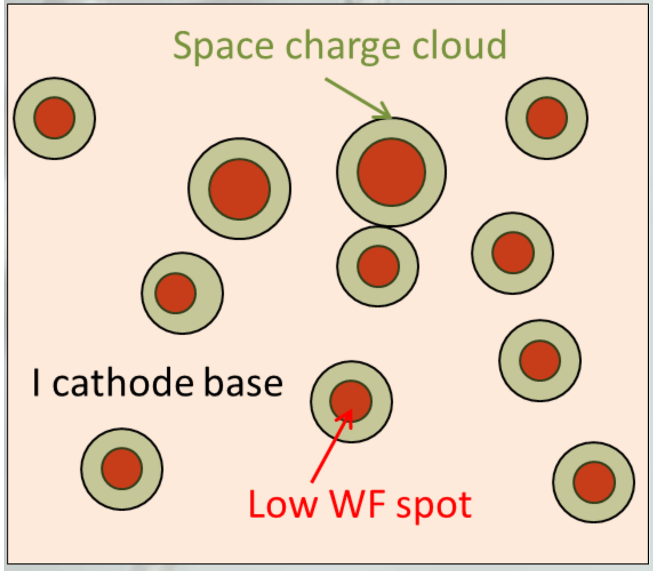
Current-voltage characteristics of:
LAD top-layer Scandate cathode (´Sc´/Re-I)
Os/Ru-I cathode and a W-I cathode
at 965°C Mo-brightness temperature (1030°C true temp.), as determined in the diode mode in an electron gun



Degradation of I/U characteristic as function of IB dose in diode with Ar ion gun (ILD = 1700 µAs): Dashed lines: perfect ´Sc´/Re-I and Re-I cathodes. Total emission is superposition of area fractions of Scandate (only space charge limited here) and Re-I. Typical is a “pseudo”-space charge behavior with a power law $I = g\,U^x$, $x < 1.4$



Philips 0.65 W I cathode unit



Schematic model: highly emitting Ba-Sc-O dots on W(Re)-I base with space charge cloud

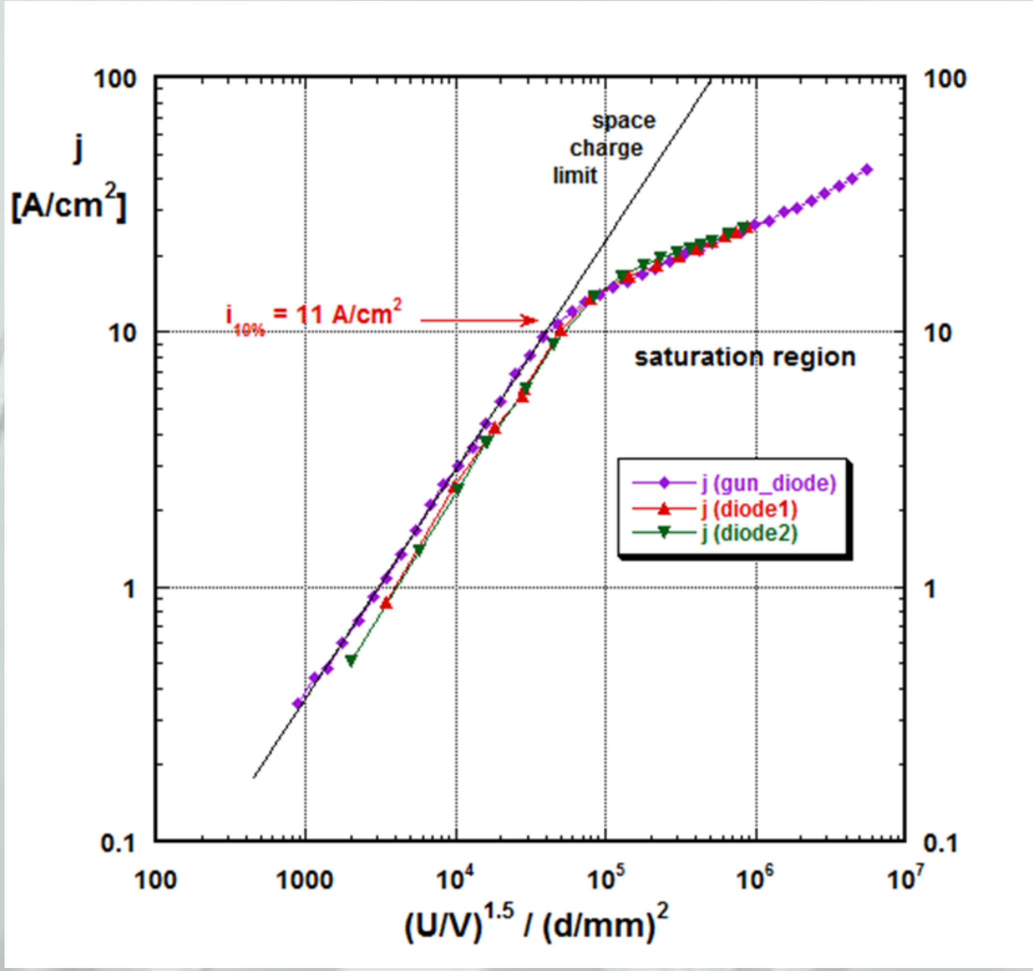
Ba Scandate I/U characteristics:

- anomalous Schottky behavior (strong increase in “saturation”) similar to oxide cathodes : the work function $e\Phi_R$ is modified to
  $e\Phi_R - e^{1.5} (4\pi\varepsilon_0)^{-0.5} (F_{el})^{0.5} - \delta\chi\ (F_{el})$
  the additional change $\delta\chi\ (F_{el})$ is caused by field penetration into the semiconductor and by space charge of ionized donors (see Raju, Wright). Wagener (p. 176) also gives a power law as heuristic dependence (see below). The image charge is also a bit smaller and dependent on ε . Further evidence by shift of Miram peak WF with increased field: semiconductor (Y. Wang 2016)

- “pseudo space charge behavior” by lg *I* versus lg *U* characteristics.
  Sc/I deviation from SCL power law $I = g\, U^x$, x $\leq$ 1.4
  observed for SDD and for LAD top-layer scandate cathodes.
  The slope x is changing during activation and life and also during ion bombardment.

- theoretical description of transition range between SCL and Schottky saturation also for I cathodes missing, which is needed for j_0 (false predictions from Schottky extrapolations, see Hasker)

- Transition region described by Scott [4] by numerical calculations and by Hasker via an approximation [3], applied by Manenschijn [5]



Electron emission current density j[A/cm^2] versus dimensionless "reduced space charge voltage coordinates" of $(U/V)^{1.5} / (d_{ca}/mm)^2$ for 3 Philips Os/Ru-I cathodes mounted in 0.65 Watt cathode units at an operating temperature of 965°$C_{Mo\text{-}br.}$; see [3].

Description of I/U emission characteristic:

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

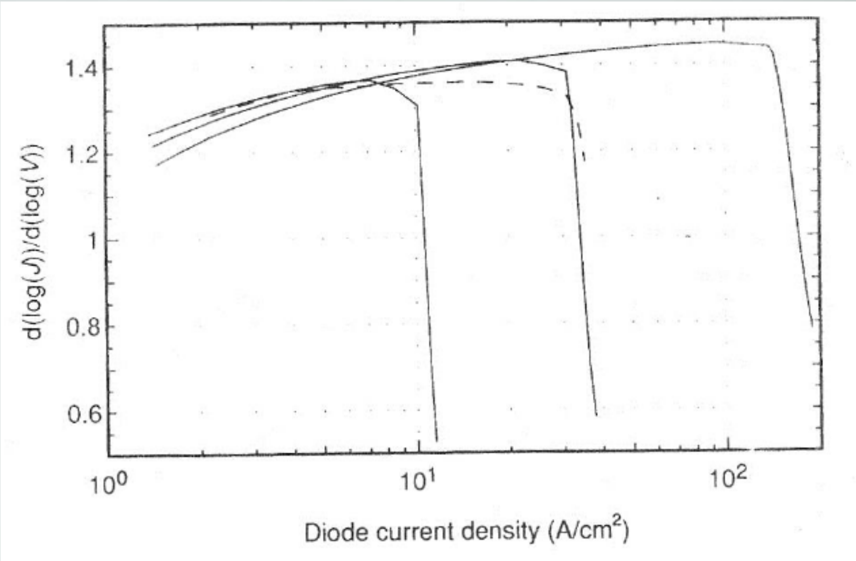
$$j_e = 4/9\ \varepsilon_0 \sqrt{(2e/m_e)}\ D^{-1/2} * (U_a/D)^{3/2} = K*U_a^{3/2}$$

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 the WF has to be further modified by $\delta\chi\ (F_{el})$ for oxide and Scandate cathodes (Wright and Woods, Raju et al. [6])

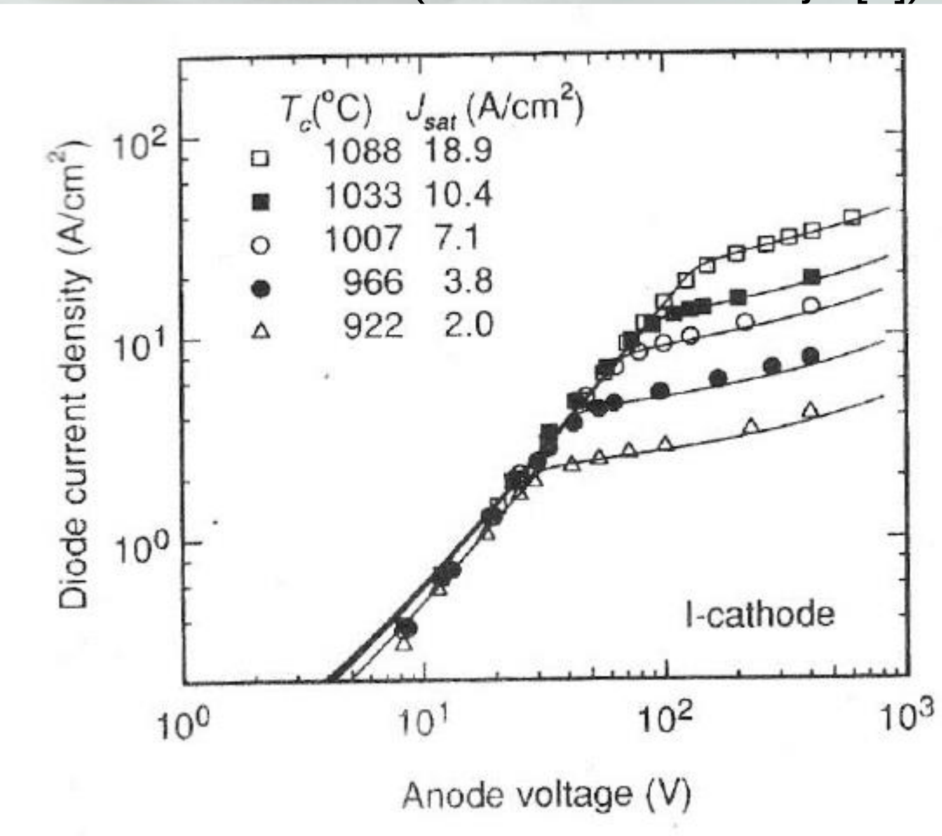
Due to the anomalous behavior, the saturated emission current density j_s cannot be determined from Schottky plots, which are also not reliable for I cathodes, but from the onset of deviation from SCL.

Ba dispenser or impregnated (I) 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 (see A. Manenschijn [5])



Slope x of lg I versus lg U curve for impregnated cathode for three j_{sat} = 10, 40 and 140 A/cm^2 according to Hasker, see [5]
x at high current densities 1.45



$$I_{SCL} = (4/9)\varepsilon_0\sqrt{2e/m_e}A_k(U_a-U_m)^{3/2}/(D-D_m)^2*\{1+2.66\sqrt{(kT/(eU_a-eU_m))}\}.$$

Eichkurve	H8104.EIC
Apparatur	6
Flansch	0
Fenster	0
Einbau	24.04.96
Kathode	H803 3
Verzeichnis	H8033
Operator	Lade
Kommentar	gun S49;Rot nach Aktivierung
Datum	04/29/96
Uhrzeit	14:50:44
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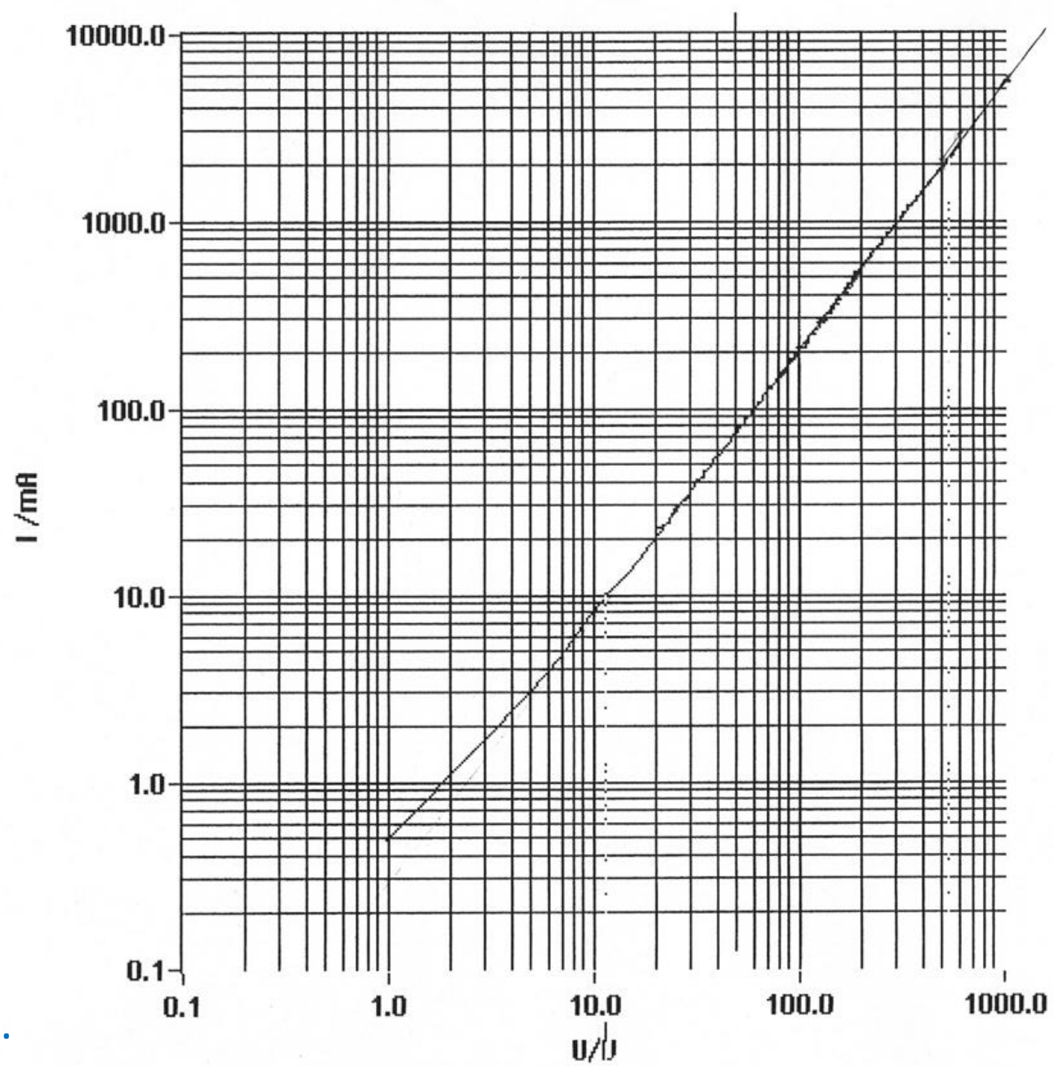
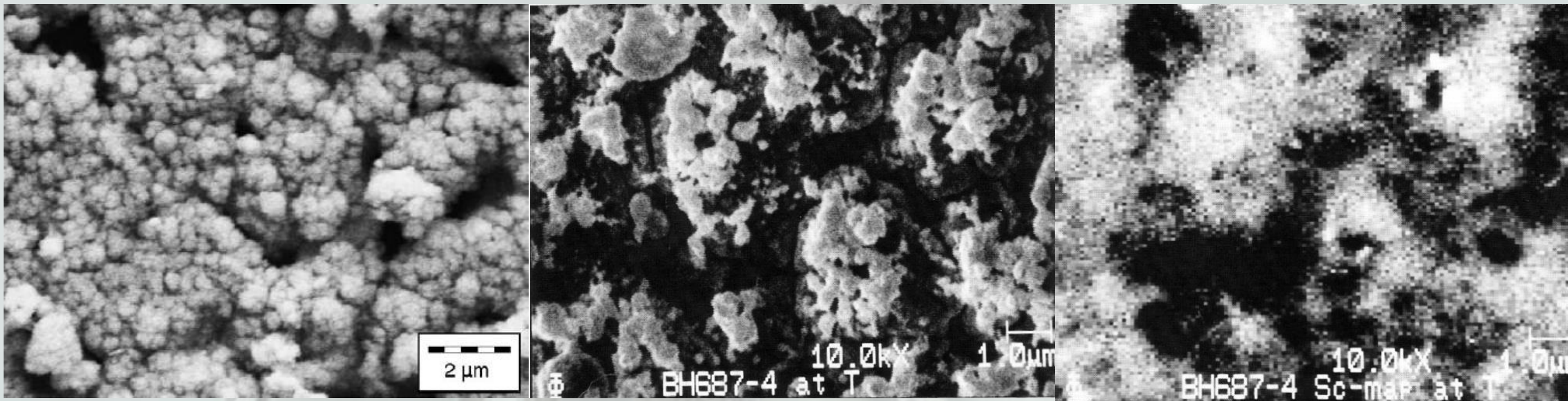


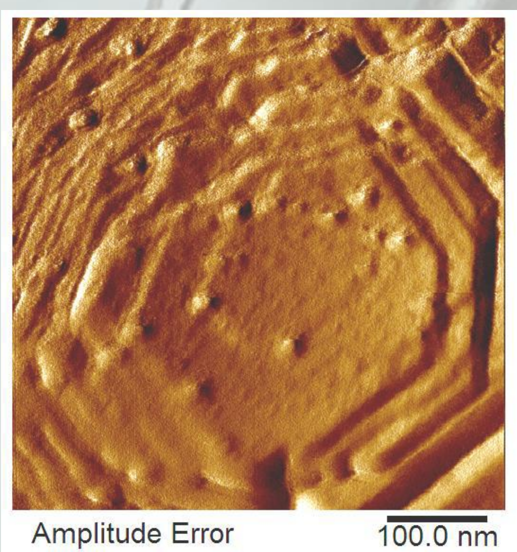
LAD Scandate cathode:
Emitting area 0.4354 mm^2,
Maximum pulsed current
density about 590 A/cm^2
Emission space charge limited.

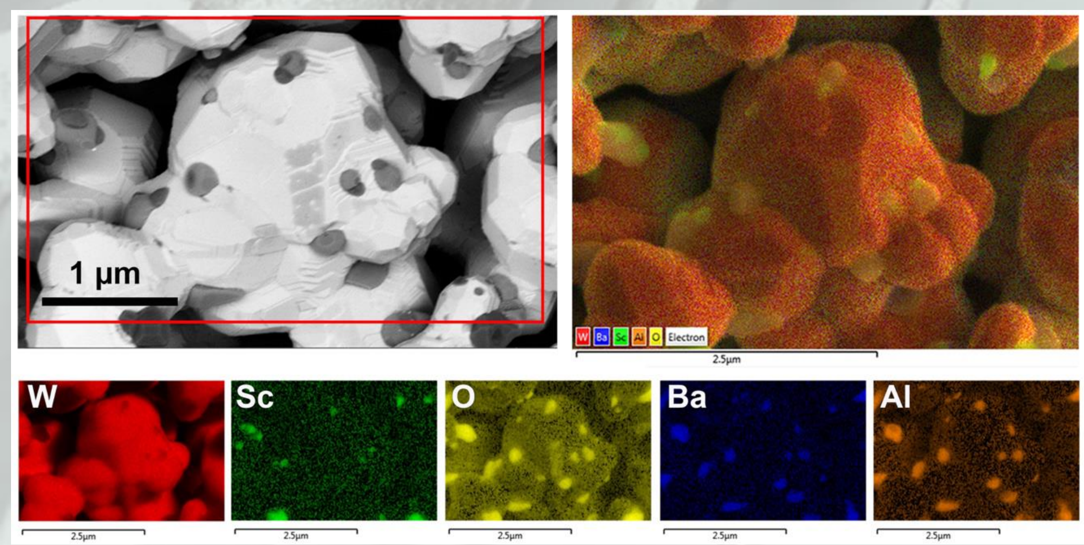
2. Surface analysis results for Scandate cathodes



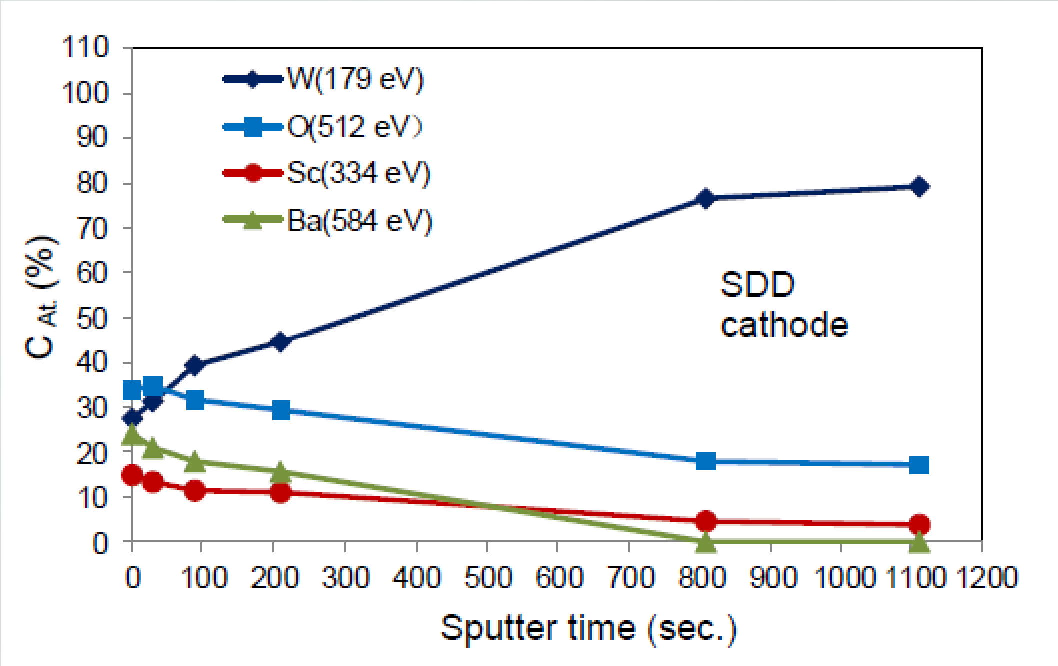
a) after LAD **b) after activation** **c) Auger Sc-mapping**

LAD Ba-scandate cathode SEM micrographs (G. Gaertner et al.)

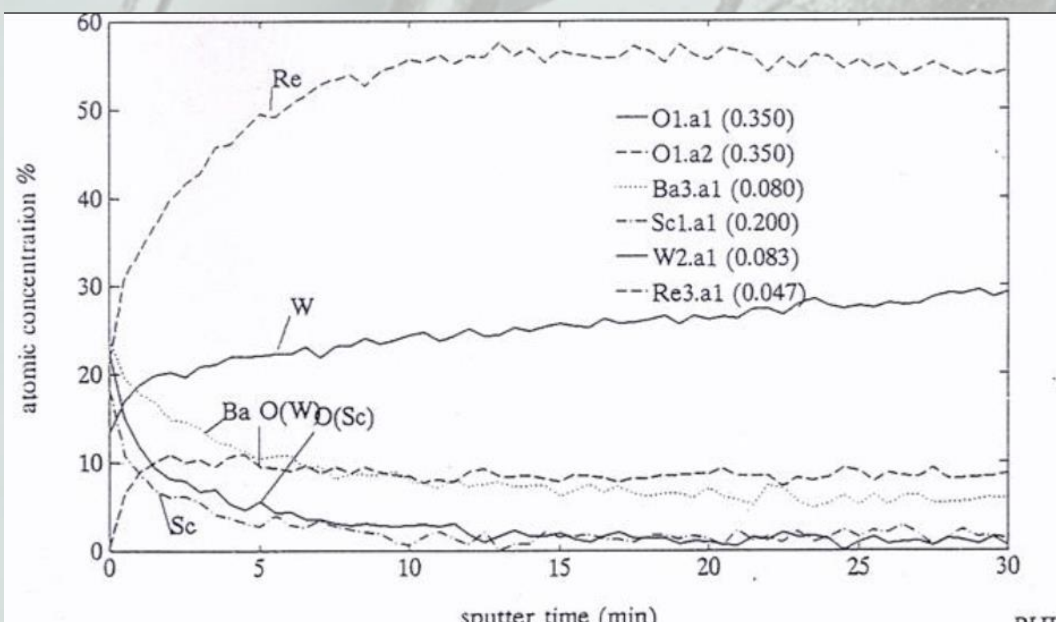




SDD Cathode (Y. Wang et al., J. Balk et al.); separate Sc containing nanoparticles; somewhat in contradiction to Auger depth profiles (next page)



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.

3. Evaluation of Richardson plots of I and scandate cathodes

For saturated (zero field) thermionic emission current density the as a function of true temperature T the Richardson equation holds:

$$j_s = A_{th} * T^2 \exp(- e\Phi / kT)$$

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

In its more heuristic practical form it is written as

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

With A_R the fitted Richardson constant and $e\Phi_R$ the Richardson WF;

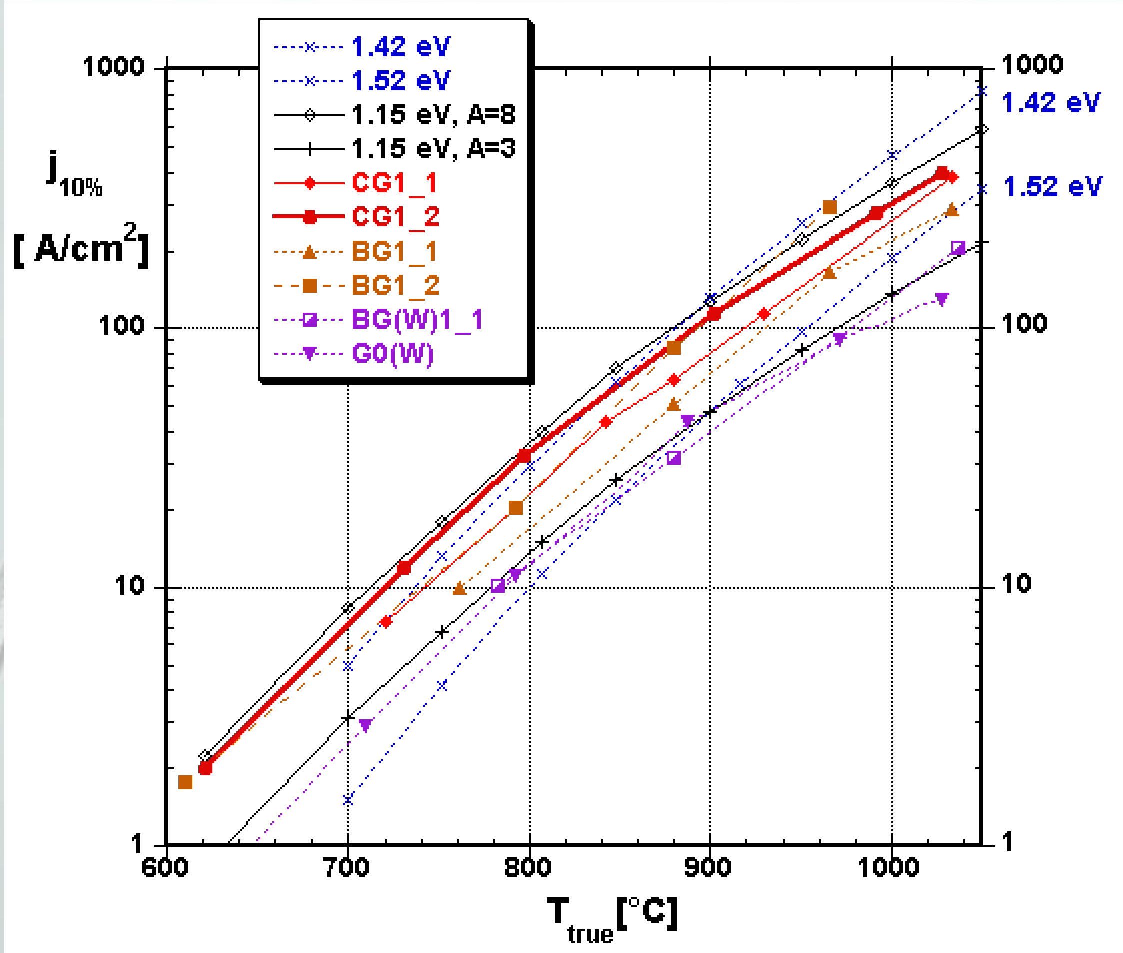
They can be obtained from a Richardson plot of $\lg(j_s / T^2)$ versus $1/T$

$$\lg(j_s / T^2) = \lg A_R - e\Phi / (k * \ln 10) * 1/T$$

The Richardson constant A_R can also be expressed as a temperature dependence of work function $\boldsymbol{e\Phi = e\Phi_R + \alpha * T}$, with the coefficient $\boldsymbol{\alpha = k * \ln(A_{th} / A_R)}$. This of course only makes sense for uniform surfaces.

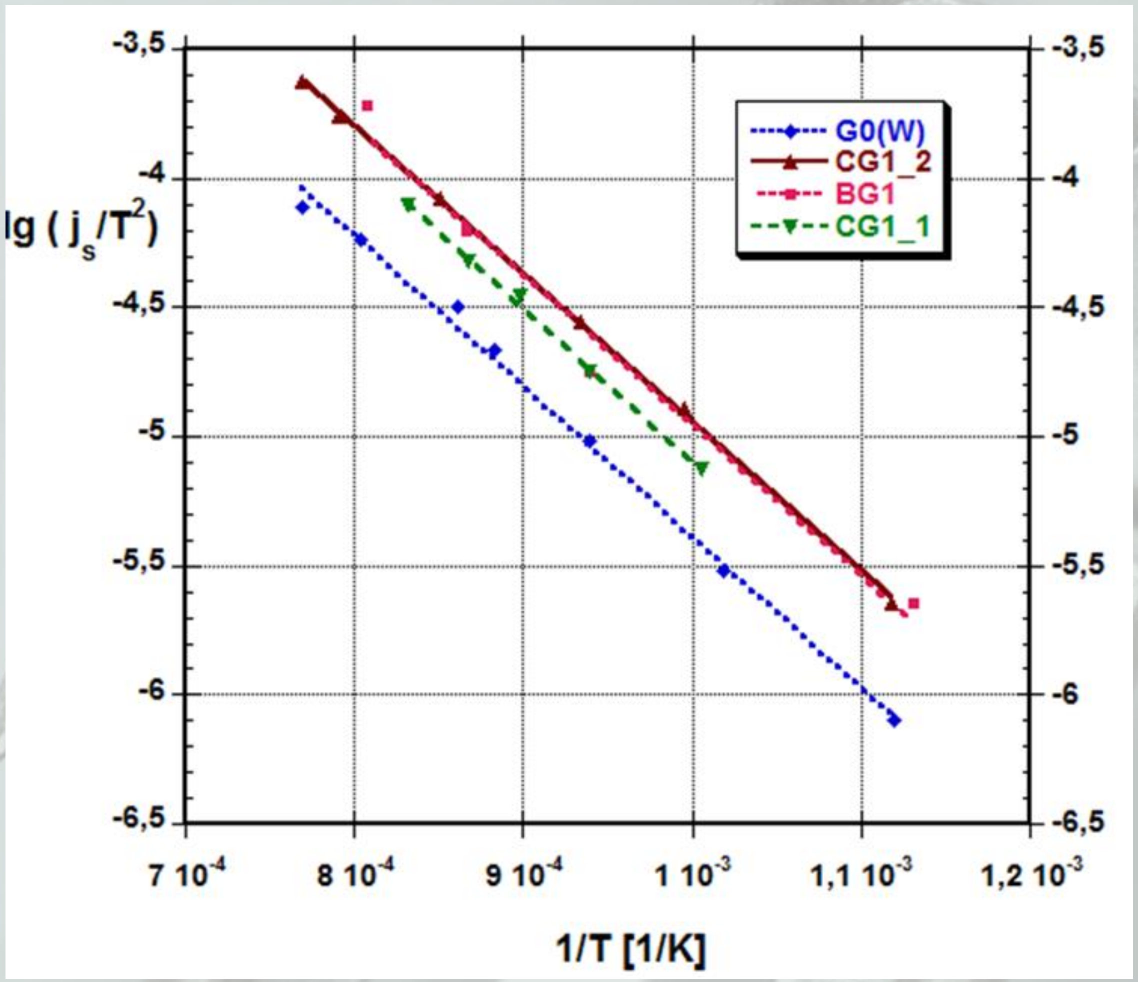
Langer has proposed an additive model for α, namely

$\boldsymbol{\alpha = \alpha_E}$ **(em. Area) +** $\boldsymbol{\alpha_S}$ **(Semicond.) +** $\boldsymbol{\alpha_T}$ **(true temp. dependence)**

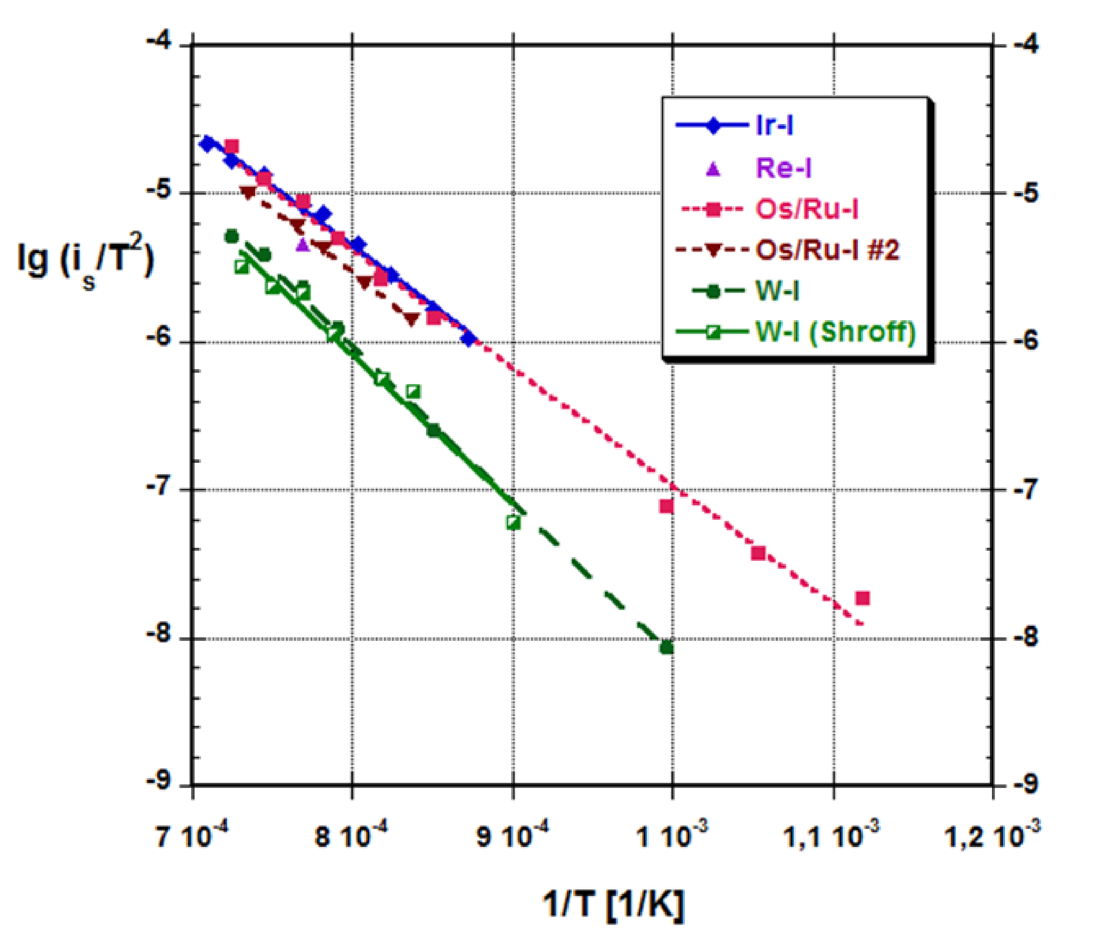


Red and orange curves: LAD with Re
Violett curves: LAD with W

Saturation current density versus true temperature. A general feature of all Ba-scandate cathodes prepared by LAD is the work function of about 1.15 eV, whereas the Richardson constant A_R is varying between 3 and 8 $A/(cm^2K^2)$. For comparison also the saturated emission density curves for work functions of 1,52 eV and 1,42 eV with the Richardson constant being the thermionic constant are shown.



Richardson Plot of LAD top-layer scandate cathodes G_0 (without 411x layer), CG_1_1 (x=1/4), CG_1_2 (x=1/4), and BG_1 (x=1/2);



Richardson plots of different Ba dispenser cathodes

From the measured dependence of j_s on true temperature T one can determine work function and Richardson constant from a so-called Richardson plot [48] of log (j_s /T²) versus 1/T:

$$\lg(j_s /T^2) = \lg A_R - e\Phi/(k*\ln 10) * 1/T$$

Fitted results of Richardson plots for LAD Scandate cathodes and Ba dispenser cathodes

Ba dispenser cathode type	Reference	Richardson work function $e\Phi_R$ [eV]	Richardson constant A_R [A/(cm^2*K^2)]
LAD Scandate BG_1 ('Sc'/Re-I) LAD Scandate Sc/W-I	G. Gaertner et al., [59,61]	1.15 1.16	7.0 2.8
Os/Ru-I (M)	G. Gaertner et al., [59,61]	1.58	10.5
Os/Ru-I (M), #2	A. Manenschijn et al. [39], [36]	1.71	22.1
Ir-I (M)	P. Geittner et al., [61,62]	1.60	13.0
W-I (S)	G. Gaertner et al., [59,61]	2.08	178
W-I (S)	A. Shroff et al., 1980*	2.01	102.6

4. Superposition model of highly emitting scandate cathode (semiconductor) patches, surrounded by W - I or Re - I cathode emission [1].

- explains deterioration with t_{op} and by IB, decreasing the size / number of patches by ablation [1].
  power law $I = g\,U^x$ remains valid, but with x decreasing with increasing IB / t_{op}

- **$e\Phi_R = 1.15$ eV $\pm$ 0.05 eV for all types of scandate cathodes** also during deterioration, namely the WF of the highly emitting patches.

- **figure of merit** of improved scandate cathodes is **increase of Richardson constant**, i.e. the growing patch area or number (or decreasing "temperature dependence" α).

- **transition to saturation** (deviation from SCL) governed by the **space charge coupling length d_m**, if d_m is smaller than distance of highly emitting patches; second saturation after the transition zone.

5. Conclusion:

Further **high resolution surface investigations** of scandate cathodes also as a function of time needed;
Accompanied by **model calculations for highly emitting patches/dots** including space charge around them.

Thank you for your attention

References:

1. G. Gaertner, P. Geittner, H. Lydtin, A. Ritz, “Emission properties of top-layer Scandate cathodes prepared by LAD”, Appl. Surf. Sci. 111, 11-17 (1997)

2. Y. Wang, J. Wang, W. Liu, K. Zhang, Ji Li,“ Development of High Current-Density Cathodes with Scandia-Doped Tungsten Powders”, IEEE Transact. ED 54/5, 1061 - 1070 (2007)

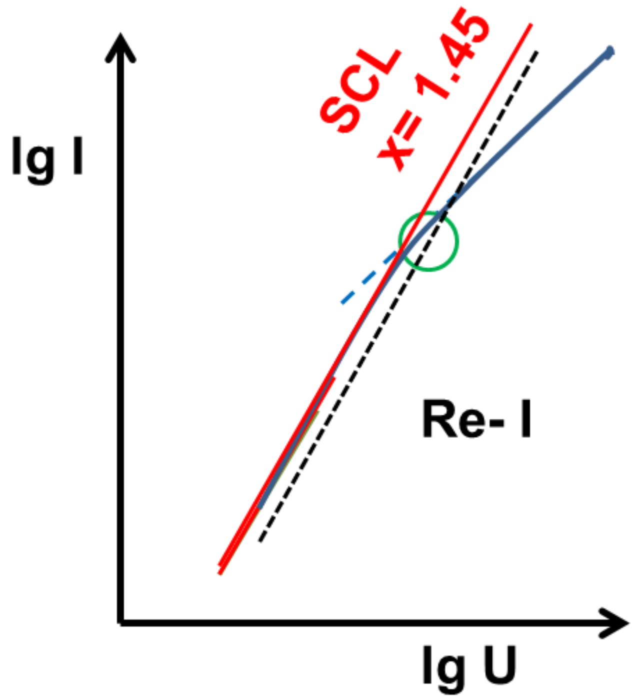
3. J. Hasker, “Calculation of diode characteristics and proposed characterization of cathode emission probability”, Appl. Surf. Sci.16, 220 – 237 (1983)

4. J.B. Scott, “Extension of Langmuir space charge theory into the accelerating field range”, J. Appl. Phys. 52, 4406 – 4410 (1981)

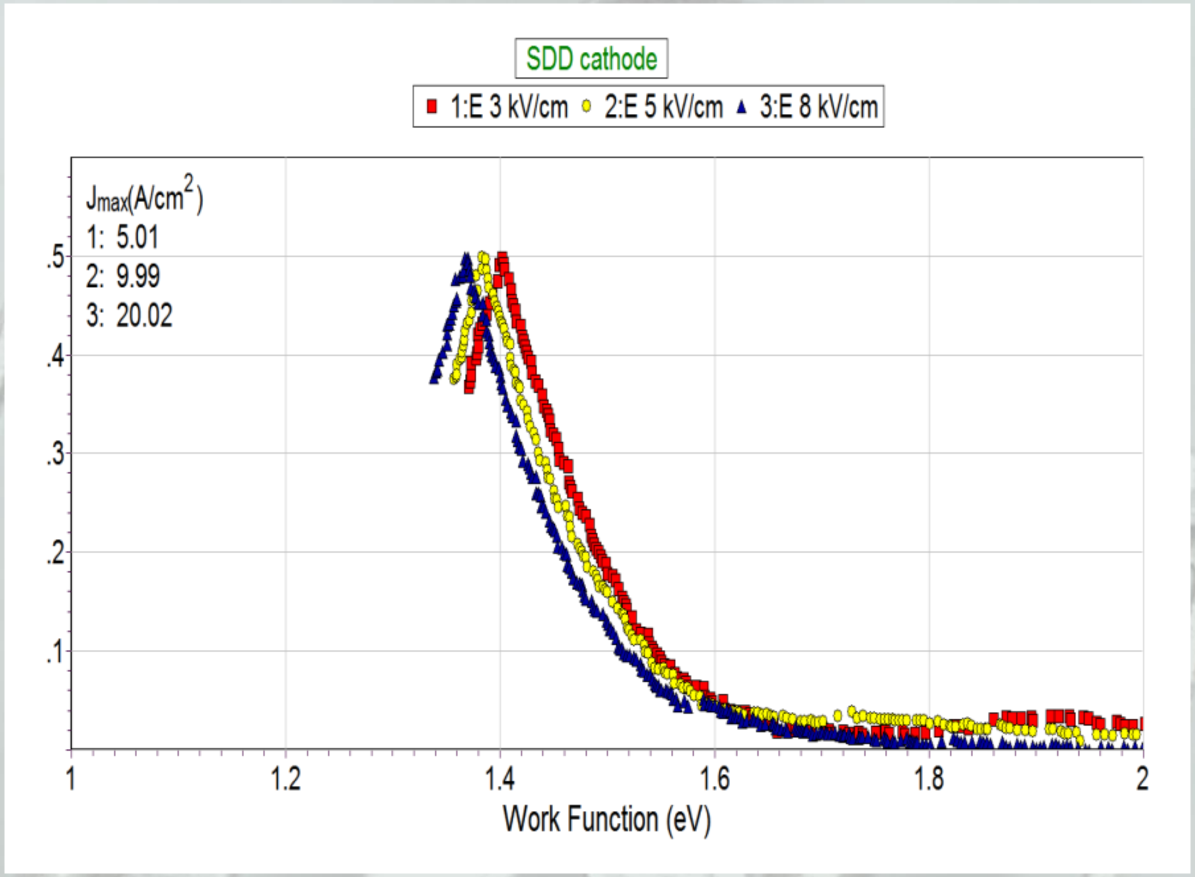
5. A. Manenschijn et al., “Emission characterization of impregnated cathodes and Scandate cathodes”, Conference record of 1992 TRI-Service/ NASA Cathode Workshop, Greenbelt/Md, USA, 67-71 (1992)

6. R. Raju, C. Maloney, “Characterization of an impregnated Scandate cathode using a semiconductor model, IEEE Transact. ED 41/12, 2460 – 2467 (1994)

Determination of zero field emission current density



In the space charge limited (SCL) regime electrons have to overcome the **space charge barrier**; when the electric field is further increased, at some point the **space charge is compensated by the external electric field**: this is the point of **zero field emission current density** (or saturated emission current density). In case of anomalous Schottky behavior the practical determination of j_0 is by **onset of deviation from SCL** / or -10% value of Philips / or intersection of SCL and power law line.



Miram Plot of SDD cathode at different field strengths;
Shift of peak WF is typical for a semiconductor:
Plot of Y. Wang, IVESC 2016