Appendix

A. Background for Material Selection and Evaporation Parameters

The EFM is a UHV evaporator and once degassed it will operate in the 10^{-10} mbar pressure range with all but the most refractory evaporants. The pressure in the atom beam of evaporant is of course much higher than this.

The rate of evaporation is a function of vapour pressure, tables of which as a function of temperature can be found in a number of vacuum handbooks etc. The vapour pressure typically required for deposition rates of monolayers per minute (the rates this evaporator is intended for) are between 10^{-2} and 10^{-4} mbar. At higher pressures the source is likely to arc-over. Another limit to the pressure is, of course, the melting point. Evaporant wires melt and can form a small blob on the end of the wire if the surface tension is sufficient. At temperatures below 800°C the evaporation from bars may not work very well.

Some materials may react with the thoriated tungsten filament.

Deposition Rates and Choice of Evaporation Source: Crucible or Rod?

The equation governing evaporation fluxes from effusive low pressure sources is:

$$\text{Deposition rate [atoms/(cm}^2\text{ s)}] \approx 8 \cdot 10^{21} \frac{p \cdot r^2}{L^2 \sqrt{M \cdot T}} .$$

As this formula does not contain a sticking coefficient it is an arrival rate.

r: radius of evaporant bar or rod (typically 1 mm)
L: distance from tip of evaporant to substrate (typically 110-150mm);
That corresponds to a distance of 10 - 50mm from the end of EFM to the sample.
M: molecular weight of evaporant (g)
T: temperature of evaporant (K)
p: vapour pressure (mbar) - which is a function of temperature for a given material. Consult appropriate tables.

The leading term in this formula is the partial presser of the material, because it can cover several orders of magnitude within the possible temperature range. Rod evaporation should be possible if a high enough pressure can be reached at the melting point or at lower temperatures. If the evaporant has to be molten to reach the deposition rates needed a crucible should be used.

The choice of evaporation rate depends upon the experimental conditions, such as background pressure, and experimental requirements of purity and duration of the experiment. In general evaporation from bars is preferred, as heating of a crucible will deliberate gas from it. Also the heat loss due to the increased surface is higher. For the selection of crucible materials the table from the Balzers AG is very helpful (see the chapter on literature)

The basic equation from which the above has been derived, can be found in:
L. Holland, W. Steckelmacher, J. Yarwood: Vacuum Manual, London 1974

Fig. A1 illustrates this formula for parameters typical for EFM as discussed in the examples below. These are theoretical results giving a good starting point for planning an experiment.

Example 1: Can aluminium give good evaporation rates in the EFM ?

First we estimate the flux at the melting point (highest temperature that a bar mounting can work at). For aluminium the parameters are: T_m = 933 K, P = $5*10^{-6}$ mbar, M = 27 g, r = 1 mm, L = 125 mm. To calculate the flux in terms of monolayers per second, we assume 10^{15} atoms per square centimetre and per layer and get a deposition rate of $2 \cdot 10^{-5}$ monolayers per second. This is a very slow almost unusable evaporation rate.

Because other values of r and L give also low evaporation rates, molten aluminium has to be used (i.e. aluminium above its melting point). At a temperature of e.g. T= 1450 K and a partial pressure of $p = 5 \cdot 10^{-2}$ mbar (and r = 1 mm, L = 125 mm) a flux of 0.1 monolayers per second is estimated. This is a useful evaporation rate and shows that for certain experiments this evaporator can be used for aluminium. As molten aluminium is very reactive, boron nitride crucibles are recommended. Heating the aluminium in a crucible must be done very slowly and carefully because it tends to give gas burst (due to its oxide coat). The aluminium must not cover the Mo-liner of the crucible because then it alloys and the purity of evaporation is degraded.

Example 2: Platinum

1) The evaporation rate (or better say arrival rate at the sample) R at the melting point of Pt (1770°C) is quite small. The calculation gives 0.1 monolayers per minute. The experiment shows that the actual rate is a little bit higher: up to 0.5 ML/minute.

If in the actual experiment this small evaporation rate is sufficient, we strongly recommend evaporation from a bar as this is the most clean evaporation method.

In case a higher evaporation rate is needed the following two methods are applicable:

2) A piece of Pt-wire (some centimetres in length and some tenth of a millimetre diameter) is wound around the end of a straight carbon[1] rod of about 1 to 2 mm diameter, and 4 cm length. On heating the rod by electron bombardment, the Pt will melt and form a little droplet at the end of the bar. As it is only a small amount of material it will not drop off. Because of the surface tension it can be heated above the melting temperature of Pt. To be sure the molten Pt accumulates at the tip of the bar the EFM should point downward.

3) If it is necessary to have high evaporation rates and the EFM should point upwards, a carbon crucible should be selected.

[1] Any additional material that is heated during the evaporation, will degas itself and degrade the cleanliness of evaporation. This is especially the case with carbon. So it is best to avoid this situation. If it cannot be avoided take the minimum amount of carbon that is possible, so a rod is preferred compared to a graphite crucible.

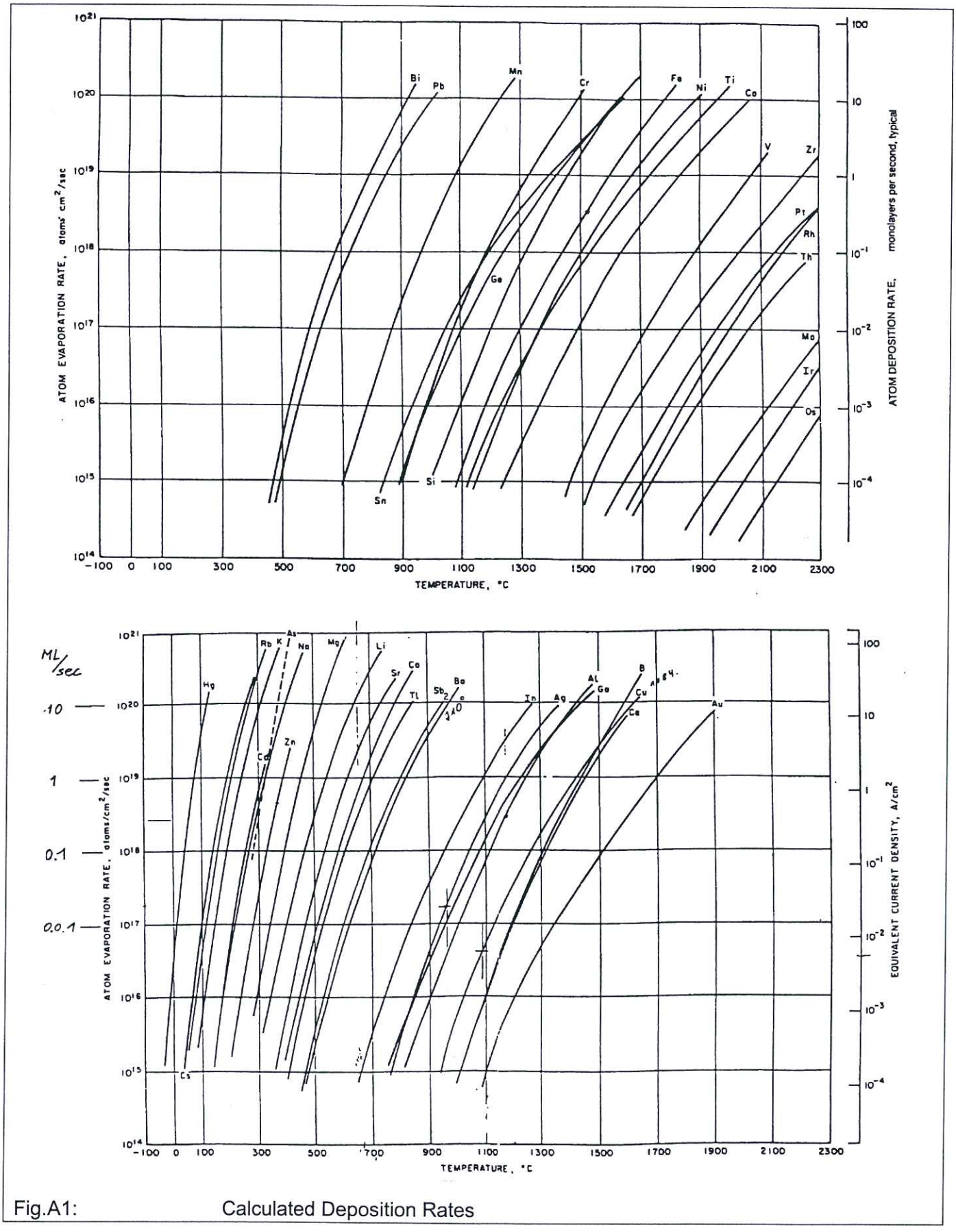


Fig.A1: Calculated Deposition Rates

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Material overview

Brief overview about material deposition techniques

Material	Symbol	Melting temp./°C	Density g/cm^3	Vapour press./torr						
				$10E^{-8}$	$10E^{-6}$	$10E^{-4}$	e-beam suitability*	Crucible	Rod evaporation possible **	Comments
Aluminum	Al	660	2.70	677	821	1010	Ex	PBN	N	Wets crucibles. Fill crucible to max. 10% to avoid creeping
Aluminum Oxide	Al_2O_3	2072	3.97	-	-	1550	Ex	-	Y	Sapphire excellent in E-beam; forms smooth, hard films.
Barium	Ba	725	3.51	545	627	735	F	Metals	< $10E^{-6}$ torr	Wets without alloying, reacts with ceramics.
Beryllium	Be	1278	1.85	710	878	1000	Ex	BeO, C	< $10E^{-2}$ torr	Wets W/Mo/Ta. Powder and oxides toxic. Evaporates easily.
Bismuth	Bi	271	9.80	330	410	520	Ex	Al_2O_3	N	Toxic vapor. Resistivity high.
Boron	B	2300	2.34	1278	1548	1797	Ex	-	Y	Explodes with rapid cooling. Forms carbides easily.
Boron Carbide	B_4C	2350	2.52	2500	2580	2650	Ex	C	N	
Cadmium	Cd	321	8.64	64	120	180	P	Al_2O_3	N	Bad for vacuum systems. Low sticking coefficient.
Carbon (Graphite)	C	~3652	$1.8^{-2}.1$	1657	1867	2137	Ex	-	Y	E-beam preferred. Poor film adhesion.
Cerium	Ce	798	~6.70	970	1150	1380	G	Al_2O_3, BeO, W	N	
Chromium	Cr	1857	7.20	837	977	1157	G	W	Y	Films very adherent. High rates possible.
Chromium Oxide	Cr_2O_3	2266	5.21	-	-	~2000	G	-	Y	Disproportionates to lower oxides; reoxidizes at 600°C in air.
Cobalt	Co	1495	8.9	850	990	1200	Ex	BeO	< $10E^{-2}$ torr	Alloys with refractory metals.
Copper	Cu	1083	8.92	727	857	1017	Ex	Al_2O_3, Mo, Ta	< $10E^{-4}$ torr	Adhesion poor. Use interlayer (Cr). Evaporates using any source material.
Dysprosium	Dy	1412	8.55	625	750	900	G	W	Y	-
Erbium	Er	1529	9.07	650	775	930	G	-	Y	-
Europium	Eu	822	5.24	280	360	480	F	Al_2O_3	< $10E^{-2}$ torr	Low tantalum solubility.
Gadolinium	Gd	1313	7.90	760	900	1175	Ex	Mo, W	< $10E^{-2}$ torr	High tantalum solubility.
Gallium	Ga	30	5.90	619	742	907	G	PBN	N	May condense at crucible exit.
Germanium	Ge	937	5.35	812	957	1167	Ex	W, C,	< $10E^{-6}$	Excellent films from E-beam guns.

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								Ta	torr	
Gold	Au	1064	19.32	807	947	1132	Ex	PBN, Al_2O_3	< $10E^{-6}$ torr	reacts with W in e-beam guns. Films soft, not very adherent.
Hafnium	Hf	2227	13.31	2160	2250	----	G	C	< $10E^{-5}$ torr	
Holmium	Ho	1474	8.80	650	770	950	G		Y	-
Inconel	Ni/Cr/ Fe	1425	8.5	-	-	-	G		Y	Low rate required for smooth films
Indium	In	157	7.30	487	597	742	Ex	Mo, PBN	N	Wets tungsten . Use molybdenum or ceramic crucible. May condense at crucible exit.
Iridium	Ir	2410	22.42	1850	2080	2380	F	-	Y	-
Iron	Fe	1535	7.86	858	998	1180	Ex	Al_2O_3, BeO	< $10E^{-4}$ torr	Al2O3 below melting point,BeO above melting point. Films hard, smooth. Preheat gently to outgas.
Lanthanum	La	921	6.15	990	1212	1388	Ex	W, Ta	N	Films will burn in air if scraped.
Lead	Pb	328	11.34	342	427	497	Ex	W, Mo	N	Toxic.
Lead Telluride	PbTe	917	8.16	780	910	1050	-	Mo, Pt, Ta	< $10E^{-6}$ torr	Vapors toxic. Deposits are tellurium rich.
Lithium	Li	179	0.53	227	307	407	G	Al_2O_3, SS, PBN	Y	Reacting quickly in air, fill under protective atmosphere
Lutetium	Lu	1663	9.84	-	-	1300	Ex	-	Y	-
Manganese	Mn	1244	7.20	507	572	647	G	-	Y	-
Molybdenum	Mo	2610	10.2	1592	1822	2117	Ex	-	Y	Films smooth, hard. Careful degas required.
Molybdenum Oxide	MoO_3	795	4.69	-	-	~900	-	Mo, Pt	N	Slight oxygen loss.
Neodymium	Nd	1021	7.01	731	871	1062	Ex	Ta	< $10E^{-5}$ torr	Low tantalum solubility.
Nichrome IV	Ni/Cr	1395	8.50	847	987	1217	Ex	-	Y	Alloys with refractory metals.
Nickel	Ni	1455	8.90	927	1072	1262	Ex	W	< $10E^{-2}$ torr	Alloys with refractory metals. Forms smooth adherent films.
Niobium	Nb	2468	8.57	1728	1977	2287	Ex	-	Y	Attacks tungsten source.
Osmium	Os	2700	22.48	2170	2430	2760	F	-	Y	-
Palladium	Pd	1554	12.02	842	992	1192	Ex	-	< $10E^{-2}$ torr	Alloys with refractory metals. Rapid evaporation suggested.
Permalloy	Ni/Fe	1395	8.7	947	1047	1307	G	W	< $10E^{-4}$ torr	Film low in nickel.
Platinum	Pt	1772	21.45	1292	1492	1747	Ex	C	< $10E^{-4}$ torr	Alloys with metals. Films soft, poor adhesion.
Praseodymium	Pr	931	6.77	800	950	1150	G	Ta	< $10E^{-6}$ torr	-
Rhenium	Re	3180	20.53	1928	2207	2571	P	C	N	Fine wire will self-evaporate.

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Rhodium	Rh	1966	12.4	1277	1472	1707	G	-	Y	E-beam gun preferred.
Ruthenium	Ru	2310	12.3	1780	1990	2260	P	W	N	-
Samarium	Sm	1074	7.52	373	460	573	G	-	Y	-
Scandium	Sc	1541	2.99	714	837	1002	Ex	-	Y	Alloys with tantalum.
Selenium	Se	217	4,2	89	125	170	G	Mo, Ta, Al_2O_3	Y	
Silicon	Si	1410	2.32	992	1147	1337	F	Ta,G, PBN	< $10E^{-2}$ torr	-
Silver	Ag	962	10.5	847	958	1105	Ex	W, Mo, Ta	< $10E^{-4}$ torr	Rod evaporation with W-wire wound around the silver rod.
Strontium	Sr	769	2.6	239	309	403	P	W, Ta, Mo	N	Wets but does not alloy with refractory metals. May react in air.
Tantalum	Ta	2996	16.6	1960	2240	2590	Ex	-	Y	Forms good films.
Terbium	Tb	1356	8.23	800	950	1150	Ex	W	Y	-
Thorium	Th	1875	11.7	1430	1660	1925	Ex	W, Ta,Mo	Y	Toxic, radioactive.
Thulium	Tm	1545	9.32	461	554	680	G	-	Y	-
Tin	Sn	232	7.28	682	807	997	Ex	Ta, PBN	N	Wets molybdenum. Use tantalum or PBN in E-beam guns.
Titanium	Ti	1660	4.5	1067	1235	1453	Ex	-	Y	Alloys with refractory metals; outgas gently.
Tungsten	W	3410	19.35	2117	2407	2757	G	-	Y	Forms volatile oxides. Films hard and adherent.
Uranium	U	1132	19.05	1132	1327	1582	G	Mo, W	N	Films oxidize.
Vanadium	V	1890	5.96	1162	1332	1547	Ex	W	Y	Wets molybdenum. E-beam-evaporated films preferred.
Ytterbium	Yb	819	6.96	520	590	690	G	-	Y	-
Yttrium	Y	1522	4.47	830	973	1157	Ex	-	Y	High tantalum solubility.
Zirconium	Zr	1852	6.49	1477	1702	1987	Ex	C	< $10E^{-6}$ torr	Alloys with tungsten. Films oxidize readily.

* Ex = Excellent, G = Good, F = Fair, P = Poor

** Y = rod always possible, N = not recommended due to melting point or e-beam suitability. Otherwise recommeded pressure limit is given.

NOTE:	**This information has been collected to give customers a brief overview about material deposition techniques. The provider of this information is not responsible for the performance of any evaporation process which is developed based on the informations provided in this table.** **Some materials in this table are hazardous. Determine toxicity, flammability radioactivity or any other risks for health, environment or system components before using.**

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For some materials experimental hints for evaporation with the EFM evaporators are additionally given below. The provider of this information is not responsible for the performance of the described evaporation process in this table.

Pb, Cu, Ag, Au:	W or Mo crucible, Cu gives max values exceeding 10 ML/ sec., Cu wets Mo. Ag: high voltage 800V, emission 15-20 mA, flux 1-10 µA Au: I_{Fil}= 2A, I_E=20 mA, U_{HV}= 750 V flux approx. 900nA. Attention: reacts with W under high e-beam current. Films soft, not very adherent. alternatively : Au wire 1 mm diameter, supported by spiral of tungsten, wire 0.25mm dia. at 800V, 2mA
Fe, Co:	bar 2 mm ∅, 800 V, 5-10 mA, 20 nA of ion current giving about 1 ML/minute alternatively: BeO-crucible (ideal) or ZrO_2 -crucible
W:	wire 1-1.5 mm dia.: 900 V, 50-70 mA, flux up to 3 µA, above about 2 µA molten material may drop from the tip
Al:	pBN crucible, 800 V, 25 mA
C60 or other low melting point (T<500°C) materials	stainless steel crucible with nozzle, high voltage typ. 200 V
Si:	rod ∅ 2 mm or a nearly square package of wafer strips 500 V, 40-50 mA yields 20 nm in 3 h This is just one example, a much higher flux is a attainable. A supply source for rods of Si (either square or circular cross section) is: Holm, Gigerenz 1, D - 84367 Tann (Niederbayern), Tel: +49-8572/91213
Nd, Ce, Gd	Mo-crucible, fill under nitrogen atmosphere in glove box. **Note that rare earth materials (as some other materials) yield extremely high flux-monitor currents due to their anomalous high impact collision ionisation cross sections.**

B. List of Thermovoltage

Nickelchromium (NiCr) / coppernickel (CuNi), type E (steps by 10)

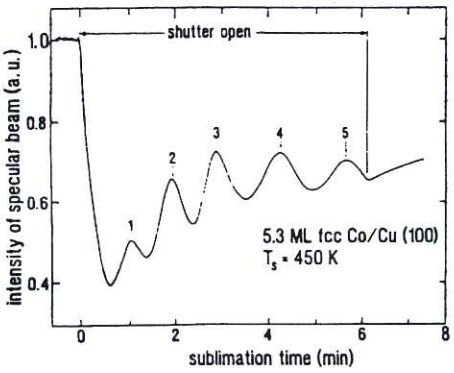
Reference temperature 0°C

°C	µV	°C	µV	°C	µV
-270	-9835	160	10501	590	44278
-260	-9797	170	11222	600	45085
-250	-9719	180	11949	610	45891
-240	-9604	190	12681	620	46697
-230	-9455	200	13419	630	47502
-220	-9274	210	14161	640	48306
-210	-9063	220	14909	650	49109
-200	-8824	230	15661	660	49911
-190	-8561	240	16417	670	50713
-180	-8273	250	17178	680	51513
-170	-7963	260	17942	690	52312
-160	-7631	270	18710	700	53110
-150	-7279	280	19481	710	53907
-140	-6907	290	20256	720	54703
-130	-6516	300	21033	730	55498
-120	-6107	310	21814	740	56291
-110	-5680	320	22597	750	57083
-100	-5237	330	23383	760	57873
-90	-4777	340	24171	770	58663
-80	-4301	350	24961	780	59451
-70	-3811	360	25754	790	60237
-60	-3306	370	26549	800	61022
-50	-2787	380	27345	810	61806
-40	-2254	390	28143	820	62588
-30	-1709	400	28943	830	63368
-20	-1151	410	29744	840	64147
-10	-581	420	30546	850	64924
0	0	430	31350	860	65700
10	591	440	32155	870	66473
20	1192	450	32960	880	67245
30	1801	460	33767	890	68015
40	2419	470	34574	900	68783
50	3047	480	35382	910	69549
60	3683	490	36190	920	70313
70	4329	500	36999	930	71075
80	4983	510	37808	940	71835
90	5646	520	38617	950	72593
100	6317	530	39426	960	73350
110	6996	540	40236	970	74104
120	7683	550	41045	980	74857
130	8377	560	41853	990	75608
140	9078	570	42662	1000	76358
150	9787	580	43470		

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C. Calibration of Flux Monitor

a) MEED assembly:



MEED (Medium Energy Electron Diffraction) curve measured for the epitaxial system cobalt on copper (100). Specular (0,0) beam at grazing incidence as a function of evaporation time. The equidistant oscillations indicate layer-by-layer growth. The evaporation rate was kept constant using the flux monitor.

Ref.: C.M. Schneider, J.J. de Miguel, P. Bressler, J. Garbe, S. Ferrer, R. Miranda and J. Kirschner, Journal de Physique C8, 1657 (1988)

b) Quartz thickness monitor

c) RHEED

d) SPA-RHEED (= Spot Profile-Analysis Rheed)

e) Conductivity measurement

see M. Henzler, W Göpel: Oberflächenphysik des Festkörpers, Stuttgart 1991, p.535

f) Hall Effect

see W.D. King et al, J. Vac. Sci. Technol. B9 (1991) 2771

g) Ellipsometry

Meyer, F.: Ellipsometric Study of Adsorption Complexes on Silicon Surf.Sci. 27 (1971) 107

Habraken, F. et.al.: Ellipsometry of Clean Surfaces, Submonolayers and Monolayer Films, Surf.Sci. 96 (1980) 482

h) Dynamic Optical Reflectivity In Situ (DORIS)

III - Vs Review, Val 5, p. 40:
Real-time monitoring of the growth of AlGaAs layers by dynamic optical reflectivity

T. Farrell, J.V. Armstrong, P. Kightley: Dynamic Optical Reflectivity, Appl.Phys.Lett. 59 (10) 1991, 1203 - 1205

J.V. Armstrong et.al., Appl.Phys.Lett 61 (23) (1992) 2770

for details on instrumentation contact Omicron

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D. Literature

General literature

[1] S. Schiller, U. Heisig: Bedampfungstechnik, Berlin 1975

[2] M.v. Ardenne, Tabelle zur Angewandten Physik Bd II B, Berlin 1975[3]

[3] S. Dushman: Scientific Foundations of Vacuum Technique; New York, London 1962

[4] Balzers AG: Aufdampf- und Zerstäubungs- Materialen, Verdampfungsquellen, Lichtenstein, 1990

[5] Balzers AG: Coating Materials and Sources Selector Guide.

[6] Jeffrey Y. Tsao: Materials Fundamentals of Molecular Beam Epitaxy, Academic Press 1992

IBAD evaporation with EFM 3i

[7] J. Kirschner, H. Engelhard and D. Hartung, Rev. Sci. Intrum., Vol. 73, No. 11, Nov. 2002.
(Description of EFM 3i)

and references therein.

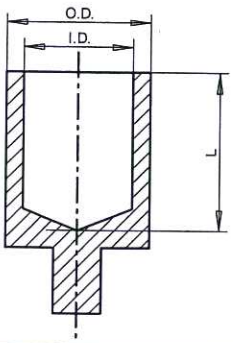
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E. Options

E 1. Crucibles

Dimensions of crucibles

* can be used with EFM 3T and EFM 3i



	I.D./mm	O.D./mm	L / mm	capacity / mm^3	T_{max} (°C) @10^{-4} Torr vapor pressure	order code
Tungsten*, small	4,0	6.0	6.5	75	2750	C W S
Tungsten*, medium	6.0	8.0	9.0	250	2750	C W M
Tungsten, large	8.0	10.0	12.0	600	2750	C W L
Mo small*	4.0	6.0	6.5	75	2120	C Mo S
Mo medium*	6.0	8.0	9.0	250	2120	C Mo M
Mo large(esp. for EFM 4)	8.0	10.0	12.0	600	2120	C Mo L
Ta small*	4.0	6.0	6.5	75	2590	C Ta S
Ta medium*	6.0	8.0	9.0	250	2590	C Ta M
Ta large	8.0	10.0	12.0	600	2590	C Ta L
Al_2O_3 small*	3.0	7.5	5.5	60	1320	C HA S
Al_2O_3 medium	5.0	9.0	8.0	150	1320	C HA M
Al_2O_3 large	6	10	10	280	1320	C HA L
Al_2O_3 x-large	10	11	13	650	1320	C HA XL
Silica s,m,l on request					1025	C Q xx
Silica x-large	8	11	15	630	1025	C Q XL
Pyrolytic BN medium for 3T/I *	5.5	8.0	8.0	190	1600	C BN S
Pyrolytic BN medium	5.5	8.5	8.0	190	1600	C BN M
Pyrolytic BN large	8	11	12	600	1600	C BN L

Graphite small*	4.0	6.0	6.5	75	>1800	C Gr S
Graphite medium*	4.5	6.0	8.0	125	>1800	C Gr M
Graphite large*	6.0	8.0	9.0	300	>1800	C Gr L
Graphite x-large	9.0	11.0	12.0	700	>1800	C Gr XL
Stainless Steel (St/St)* with removeable nozzle (i.d. 1mm)	5.0	7.0	8.0	150	800	C SS
Beryllium Oxide (BeO) small*	4.0	8.0	7	85	1900	C BO S
Beryllium Oxide (BeO), medium	6.0	10.0	7	190	1900	C BO M
Zirconium Oxide (ZrO_2)*	4.5	8.0	7.6	110	n.a.	C ZrO

Notes:

PBN-crucibles: For temperatures above 1300° the heating of the PBN results in a raising N_2 background pressure

BeO-crucibles: **WARNING! Safety precautions must be followed**

Beryllium oxide ceramics are harmless as supplied but should be handled with care. A potential health hazard may exist if secondary operations which can generate dust or fumes are carried out. It is recommended not to machine the beryllium oxide crucibles.

Ceramic crucibles: The ceramic crucibles consists of a ceramic insert with a Mo-liner. This must be considered for evaporation of materials with a tendency to react or alloy with molybdenum. Then the crucible should not be heated too fast and must not be filled to a large extend.

E 5. Barrel connectors for larger rods

Different barrel connectors are availbel to support the use of crucibles and rods with different diameter. The evaporators EFM2/3/3s/4, EFM 3i and EFM 3T use different models, please refer to the table:

Order Code	maximum rod diameter	material	use with	comment
EFM BC Mo1.5	1.5 mm	molybden with molybden screws	EFM2/3/3s/4 EFM 3i	standard barrel connector; it is supplied with the spare kit box
EFM BC Mo2.0	2.0 mm	molybden with molybden screws	EFM2/3/3s/4 EFM 3i	
EFM BC Mo4.0	4.0 mm	molybden with molybden screws	EFM2/3/3s/4 EFM 3i	
EFM BC Mo6.0	6.0 mm	molybden with molybden screws	EFM2/3/3s/4	
EFM BC SS1.5	1.5 mm	non magnetic stainless steel	EFM2/3/3s/4 EFM 3i	
EFM BC3T	1.5 mm	molybden with stainless steel screws	EFM 3T	standard barrel connector of EFM 3T; one mounted per cell

E 6. Quick-lock water hose connectors

To facilitate the connection and de-connection of the water hose for e.g. baking the system.

Order Code: EFM QWC