

4 - Deposição de Filmes por Evaporação Térmica

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Motivação

- Aplicações
 - Evaporação de metais - contatos elétricos/espelhos
 - Multicamadas ópticas / filtros interferométricos
 - Deposição de semicondutores e isolantes: dispositivos:
 - Processamento
 - Memória
 - LEDs / Lasers

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Motivação

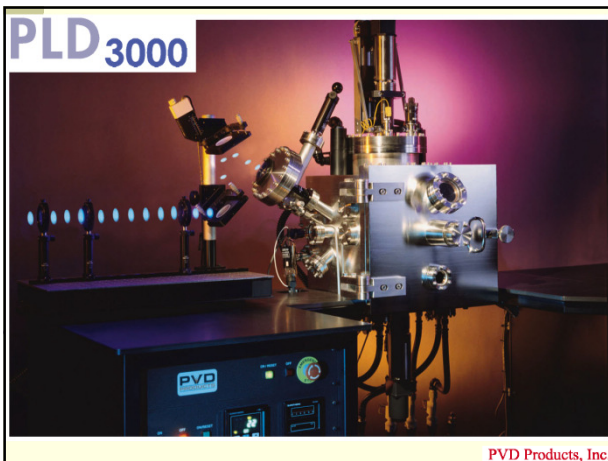
- Tecnologias / sistemas utilizados
 - Sistemas de MBE – multicamadas eletrônicas
 - Deposição por laser pulsado (PLD)
 - Deposição por feixe eletrônico (e-beam)
 - Deposição de compostos e ligas (flash)

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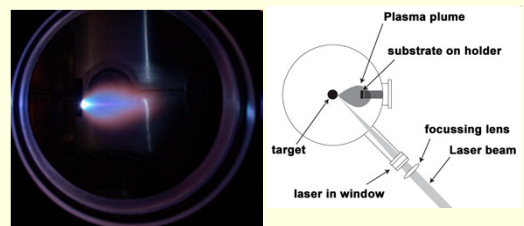
Motivação

- Sistemas de evaporação

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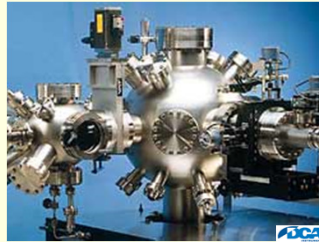
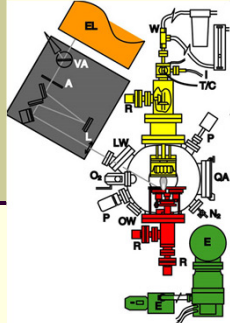
PLD – deposição por laser pulsado



Wiki - H. Perowne 2006 (UTC)

Breakthrough: 1987 - Dijkkamp / Venkatesan $\text{YBa}_2\text{Cu}_3\text{O}_7$

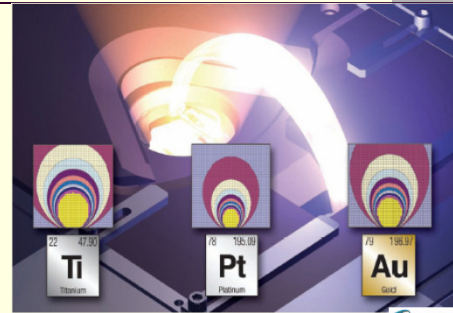
Câmara PLD



www.ik4.it/Units/AES/projects/priser/equipment.htm

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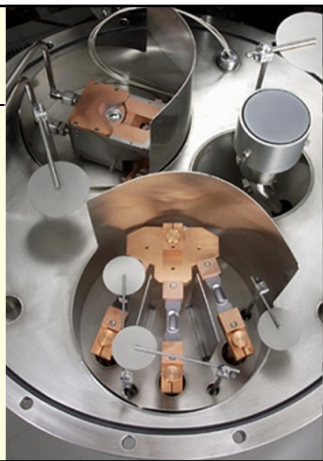
Evaporação por feixe eletrônico



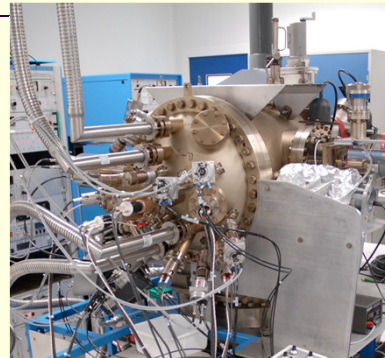
Tomcoval

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Sistemas de evaporação



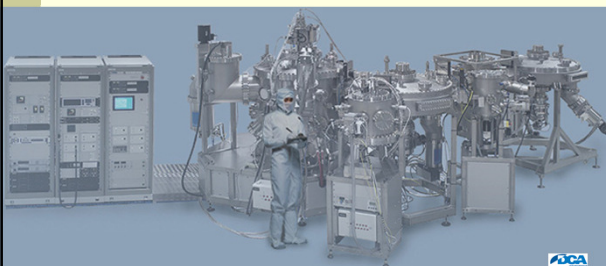
MBE – células de efusão



Molecular-beam epitaxy system at LAAS

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Micro Processadores / MQW-LEDs e LASERS:
várias etapas – em ultra-alto-vácuo



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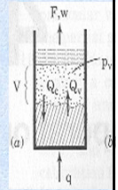
Evaporação Térmica

- 3 etapas
 - 1: Transformação de fase
sólido ou líquido => vapor
 - 2: Transporte
fonte => substrato
 - 3: Condensação e crescimento do filme

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Condição de Equilíbrio (!?)

- Como são a física e a química das transformações de fase?
- ⇒ Começaremos a abordar esse problema quando há equilíbrio de fases. (+ simples)
- ⇒ Depois veremos as condições de não equilíbrio => deposição de filmes (+ complexa)

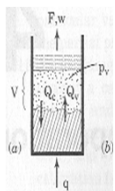


1. Transformação de fase

- Questões:
- Copo com água, Tamb. Evapora ? Por que?
 - Forma de gelo – congelador. O que acontece ?
 - Outra substância (Al, Au, Fe, Si....)

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Clausius-Clapeyron, no quadro

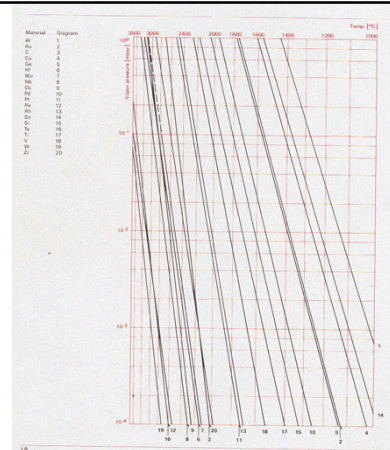


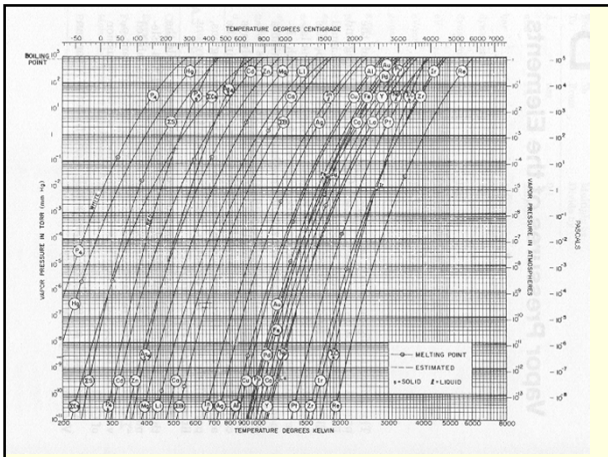
$$\frac{dp}{dT} \cong \frac{L_v}{R.T^2}$$

$$p(T) = p_o \cdot e^{-L_v/RT}$$

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Pressões de vapor – metais.
Catálogo
Balzers



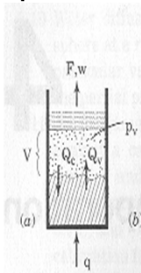


Equação de Clausius e Clapeyron

- Todas as substâncias evaporam!
(mesmo em equilíbrio há uma $\dot{e}$ dinâmica)
- Equilíbrio vs. evaporação efetiva

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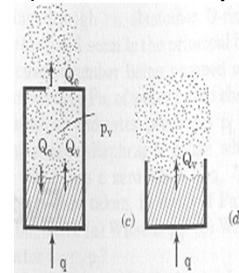
Evaporação: equilíbrio



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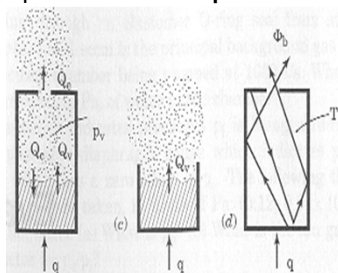
Evaporação:

| fora do equilíbrio



Evaporação:

| fora do equilíbrio

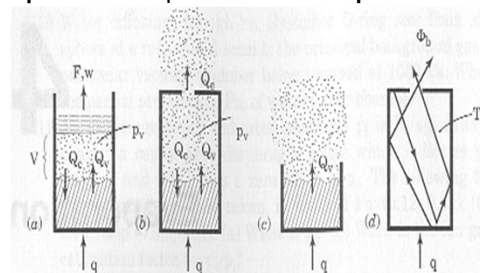


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radiação cavidade

Evaporação:

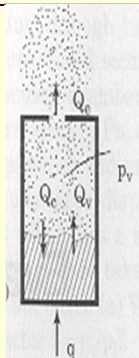
equilíbrio | fora do equilíbrio



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radiação cavidade

Evaporação – célula de Knudsen



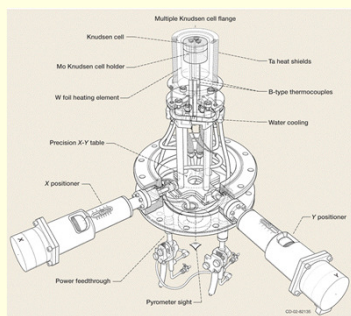
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Célula de Knudsen



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Célula de Knudsen - esquema



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Dimensions in mm, volume V in cm ³		$\frac{V}{m^3}$	Fig. No.
(mm)	(in)		
Thickness 0.1	125	50	80 482 000.1
Thickness 0.1	250	100	80 482 001.1
Thickness 0.1	380	150	80 482 002.1
Thickness 0.1	500	200	80 482 003.1
Thickness 0.1	625	250	80 482 004.1
Thickness 0.1	750	300	80 482 005.1
Thickness 0.1	875	350	80 482 006.1
Thickness 0.1	1000	400	80 482 007.1
Thickness 0.1	1125	450	80 482 008.1
Thickness 0.1	1250	500	80 482 009.1
Thickness 0.1	1375	550	80 482 010.1
Thickness 0.1	1500	600	80 482 011.1
Thickness 0.1	1625	650	80 482 012.1
Thickness 0.1	1750	700	80 482 013.1
Thickness 0.1	1875	750	80 482 014.1
Thickness 0.1	2000	800	80 482 015.1
Thickness 0.1	2125	850	80 482 016.1
Thickness 0.1	2250	900	80 482 017.1
Thickness 0.1	2375	950	80 482 018.1
Thickness 0.1	2500	1000	80 482 019.1
Thickness 0.1	2625	1050	80 482 020.1
Thickness 0.1	2750	1100	80 482 021.1
Thickness 0.1	2875	1150	80 482 022.1
Thickness 0.1	3000	1200	80 482 023.1
Thickness 0.1	3125	1250	80 482 024.1
Thickness 0.1	3250	1300	80 482 025.1
Thickness 0.1	3375	1350	80 482 026.1
Thickness 0.1	3500	1400	80 482 027.1
Thickness 0.1	3625	1450	80 482 028.1
Thickness 0.1	3750	1500	80 482 029.1
Thickness 0.1	3875	1550	80 482 030.1
Thickness 0.1	4000	1600	80 482 031.1
Thickness 0.1	4125	1650	80 482 032.1
Thickness 0.1	4250	1700	80 482 033.1
Thickness 0.1	4375	1750	80 482 034.1
Thickness 0.1	4500	1800	80 482 035.1
Thickness 0.1	4625	1850	80 482 036.1
Thickness 0.1	4750	1900	80 482 037.1
Thickness 0.1	4875	1950	80 482 038.1
Thickness 0.1	5000	2000	80 482 039.1
Thickness 0.1	5125	2050	80 482 040.1
Thickness 0.1	5250	2100	80 482 041.1
Thickness 0.1	5375	2150	80 482 042.1
Thickness 0.1	5500	2200	80 482 043.1
Thickness 0.1	5625	2250	80 482 044.1
Thickness 0.1	5750	2300	80 482 045.1
Thickness 0.1	5875	2350	80 482 046.1
Thickness 0.1	6000	2400	80 482 047.1
Thickness 0.1	6125	2450	80 482 048.1
Thickness 0.1	6250	2500	80 482 049.1
Thickness 0.1	6375	2550	80 482 050.1
Thickness 0.1	6500	2600	80 482 051.1
Thickness 0.1	6625	2650	80 482 052.1
Thickness 0.1	6750	2700	80 482 053.1
Thickness 0.1	6875	2750	80 482 054.1
Thickness 0.1	7000	2800	80 482 055.1
Thickness 0.1	7125	2850	80 482 056.1
Thickness 0.1	7250	2900	80 482 057.1
Thickness 0.1	7375	2950	80 482 058.1
Thickness 0.1	7500	3000	80 482 059.1
Thickness 0.1	7625	3050	80 482 060.1
Thickness 0.1	7750	3100	80 482 061.1
Thickness 0.1	7875	3150	80 482 062.1
Thickness 0.1	8000	3200	80 482 063.1
Thickness 0.1	8125	3250	80 482 064.1
Thickness 0.1	8250	3300	80 482 065.1
Thickness 0.1	8375	3350	80 482 066.1
Thickness 0.1	8500	3400	80 482 067.1
Thickness 0.1	8625	3450	80 482 068.1
Thickness 0.1	8750	3500	80 482 069.1
Thickness 0.1	8875	3550	80 482 070.1
Thickness 0.1	9000	3600	80 482 071.1
Thickness 0.1	9125	3650	80 482 072.1
Thickness 0.1	9250	3700	80 482 073.1
Thickness 0.1	9375	3750	80 482 074.1
Thickness 0.1	9500	3800	80 482 075.1
Thickness 0.1	9625	3850	80 482 076.1
Thickness 0.1	9750	3900	80 482 077.1
Thickness 0.1	9875	3950	80 482 078.1
Thickness 0.1	10000	4000	80 482 079.1
Thickness 0.1	10125	4050	80 482 080.1
Thickness 0.1	10250	4100	80 482 081.1
Thickness 0.1	10375	4150	80 482 082.1
Thickness 0.1	10500	4200	80 482 083.1
Thickness 0.1	10625	4250	80 482 084.1
Thickness 0.1	10750	4300	80 482 085.1
Thickness 0.1	10875	4350	80 482 086.1
Thickness 0.1	11000	4400	80 482 087.1
Thickness 0.1	11125	4450	80 482 088.1
Thickness 0.1	11250	4500	80 482 089.1
Thickness 0.1	11375	4550	80 482 090.1
Thickness 0.1	11500	4600	80 482 091.1
Thickness 0.1	11625	4650	80 482 092.1
Thickness 0.1	11750	4700	80 482 093.1
Thickness 0.1	11875	4750	80 482 094.1
Thickness 0.1	12000	4800	80 482 095.1
Thickness 0.1	12125	4850	80 482 096.1
Thickness 0.1	12250	4900	80 482 097.1
Thickness 0.1	12375	4950	80 482 098.1
Thickness 0.1	12500	5000	80 482 099.1
Thickness 0.1	12625	5050	80 482 100.1
Thickness 0.1	12750	5100	80 482 101.1
Thickness 0.1	12875	5150	80 482 102.1
Thickness 0.1	13000	5200	80 482 103.1
Thickness 0.1	13125	5250	80 482 104.1
Thickness 0.1	13250	5300	80 482 105.1
Thickness 0.1	13375	5350	80 482 106.1
Thickness 0.1	13500	5400	80 482 107.1
Thickness 0.1	13625	5450	80 482 108.1
Thickness 0.1	13750	5500	80 482 109.1
Thickness 0.1	13875	5550	80 482 110.1
Thickness 0.1	14000	5600	80 482 111.1
Thickness 0.1	14125	5650	80 482 112.1
Thickness 0.1	14250	5700	80 482 113.1
Thickness 0.1	14375	5750	80 482 114.1
Thickness 0.1	14500	5800	80 482 115.1
Thickness 0.1	14625	5850	80 482 116.1
Thickness 0.1	14750	5900	80 482 117.1
Thickness 0.1	14875	5950	80 482 118.1
Thickness 0.1	15000	6000	80 482 119.1
Thickness 0.1	15125	6050	80 482 120.1
Thickness 0.1	15250	6100	80 482 121.1
Thickness 0.1	15375	6150	80 482 122.1
Thickness 0.1	15500	6200	80 482 123.1
Thickness 0.1	15625	6250	80 482 124.1
Thickness 0.1	15750	6300	80 482 125.1
Thickness 0.1	15875	6350	80 482 126.1
Thickness 0.1	16000	6400	80 482 127.1
Thickness 0.1	16125	6450	80 482 128.1
Thickness 0.1	16250	6500	80 482 129.1
Thickness 0.1	16375	6550	80 482 130.1
Thickness 0.1	16500	6600	80 482 131.1
Thickness 0.1	16625	6650	80 482 132.1
Thickness 0.1	16750	6700	80 482 133.1
Thickness 0.1	16875	6750	80 482 134.1
Thickness 0.1	17000	6800	80 482 135.1
Thickness 0.1	17125	6850	80 482 136.1
Thickness 0.1	17250	6900	80 482 137.1
Thickness 0.1	17375	6950	80 482 138.1
Thickness 0.1	17500	7000	80 482 139.1
Thickness 0.1	17625	7050	80 482 140.1
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Thickness 0.1	19500	7800	80 482 155.1
Thickness 0.1	19625	7850	80 482 156.1
Thickness 0.1	19750	7900	80 482 157.1
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Thickness 0.1	20000	8000	80 482 159.1
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Thickness 0.1	21250	8500	80 482 169.1
Thickness 0.1	21375	8550	80 482 170.1
Thickness 0.1	21500	8600	80 482 171.1
Thickness 0.1	21625	8650	80 482 172.1
Thickness 0.1	21750	8700	80 482 173.1
Thickness 0.1	21875	8750	80 482 174.1
Thickness 0.1	22000	8800	80 482 175.1
Thickness 0.1	22125	8850	80 482 176.1
Thickness 0.1	22250	8900	80 482 177.1
Thickness 0.1	22375	8950	80 482 178.1
Thickness 0.1	22500	9000	80 482 179.1
Thickness 0.1	22625	9050	80 482 180.1
Thickness 0.1	22750	9100	80 482 181.1
Thickness 0.1	22875	9150	80 482 182.1
Thickness 0.1	23000	9200	80 482 183.1
Thickness 0.1	23125	9250	80 482 184.1
Thickness 0.1	23250	9300	80 482 185.1
Thickness 0.1	23375	9350	80 482 186.1
Thickness 0.1	23500	9400	80 482 187.1
Thickness 0.1	23625	9450	80 482 188.1
Thickness 0.1	23750	9500	80 482 189.1
Thickness 0.1	23875	9550	80 482 190.1
Thickness 0.1	24000	9600	80 482 191.1
Thickness 0.1	24125	9650	80 482 192.1
Thickness 0.1	24250	9700	80 482 193.1
Thickness 0.1	24375	9750	80 482 194.1
Thickness 0.1	24500	9800	80 482 195.1
Thickness 0.1	24625	9850	80 482 196.1
Thickness 0.1	24750	9900	80 482 197.1
Thickness 0.1	24875	9950	80 482 198.1
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Thickness 0.1	25125	10050	80 482 200.1
Thickness 0.1	25250	10100	80 482 201.1
Thickness 0.1	25375	10150	80 482 202.1
Thickness 0.1	25500	10200	80 482 203.1
Thickness 0.1	25625	10250	80 482 204.1
Thickness 0.1	25750	10300	80 482 205.1
Thickness 0.1	25875	10350	80 482 206.1
Thickness 0.1	26000	10400	80 482 207.1
Thickness 0.1	26125	10450	80 482 208.1
Thickness 0.1	26250	10500	80 482 209.1
Thickness 0.1	26375	10550	80 482 210.1
Thickness 0.1	26500	10600	80 482 211.1
Thickness 0.1	26625	10650	80 482 212.1
Thickness 0.1	26750	10700	80 482 213.1
Thickness 0.1	26875	10750	80 482 214.1
Thickness 0.1	27000	10800	80 482 215.1
Thickness 0.1	27125	10850	80 482 216.1

Frentes de deposição (r fixo)

$$J_{\theta} = J_o = \frac{Q}{4\pi r^2}$$

(Fonte esférica)

$$Q = \frac{J_v}{A}$$

(Taxa total de evap de uma fonte de área A, emitindo fluxo J_v)

$$J_{\theta} = J_o \cos(\theta)$$

(Disco, distribuição cossenoidal de fluxo)

Fluxo no substrato

$$J_s = J_{\theta} \cos^2(\theta)$$

$$J_T = J_o \cos^4(\theta) = \frac{Q \cos^4(\theta)}{\pi r_o^2}$$

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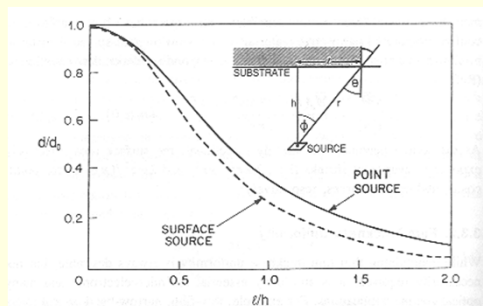


Figure 3-5. Film thickness uniformity for point and surface sources. (Insert) Geometry of evaporation onto parallel plane substrate.

3. Material => alvo formação do filme

- Monitoramento da espessura
- Morfologia/estruturação do filme

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Monitoramento da taxa de deposição

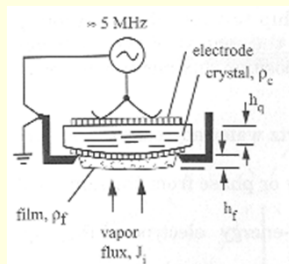


Figure 4.15 Quartz-crystal deposition monitor in cross section.

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Refletância no filme

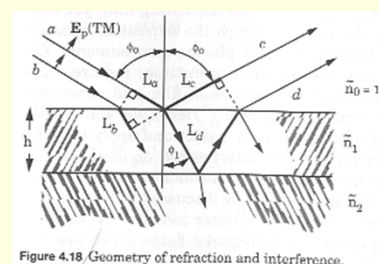


Figure 4.18 Geometry of refraction and interference.

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Conclusões

- Equação de Clausius-Clapeyron (p_v)
- Equação de Knudsen ($J_i(p, M, T)$)
- Evap. aberta $\Rightarrow J_v \sim J_{v\text{-eq}}$
- Compostos – ligas (Flash)
- Transporte (disco – $\cos^4\theta$)

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Adendo:

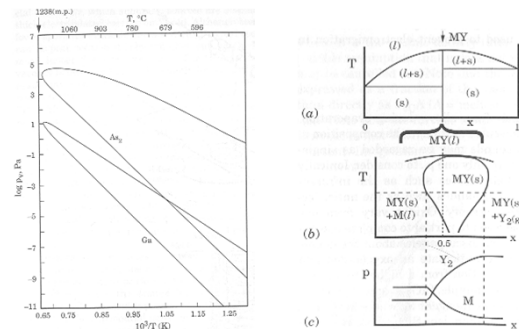
- Evaporação de compostos

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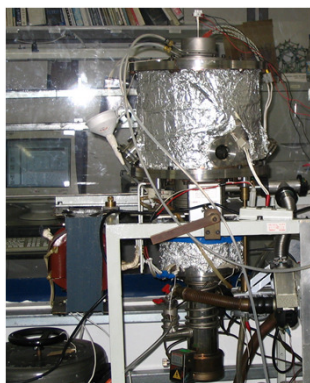
Evaporação de compostos

- Compostos que mantêm a estequiometria
- Compostos que evaporam fora da estequiometria

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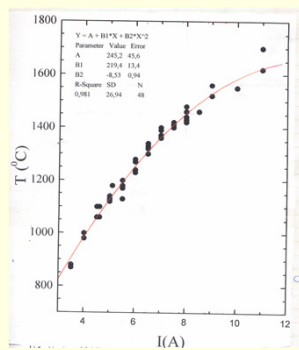
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Na prática:
(Ex: manual Balzers)

- Calibração (corrente no primário vs temperatura) – cadinho BD 482009-T



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