



# Microscopia para Microeletrônica

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# Microscopia

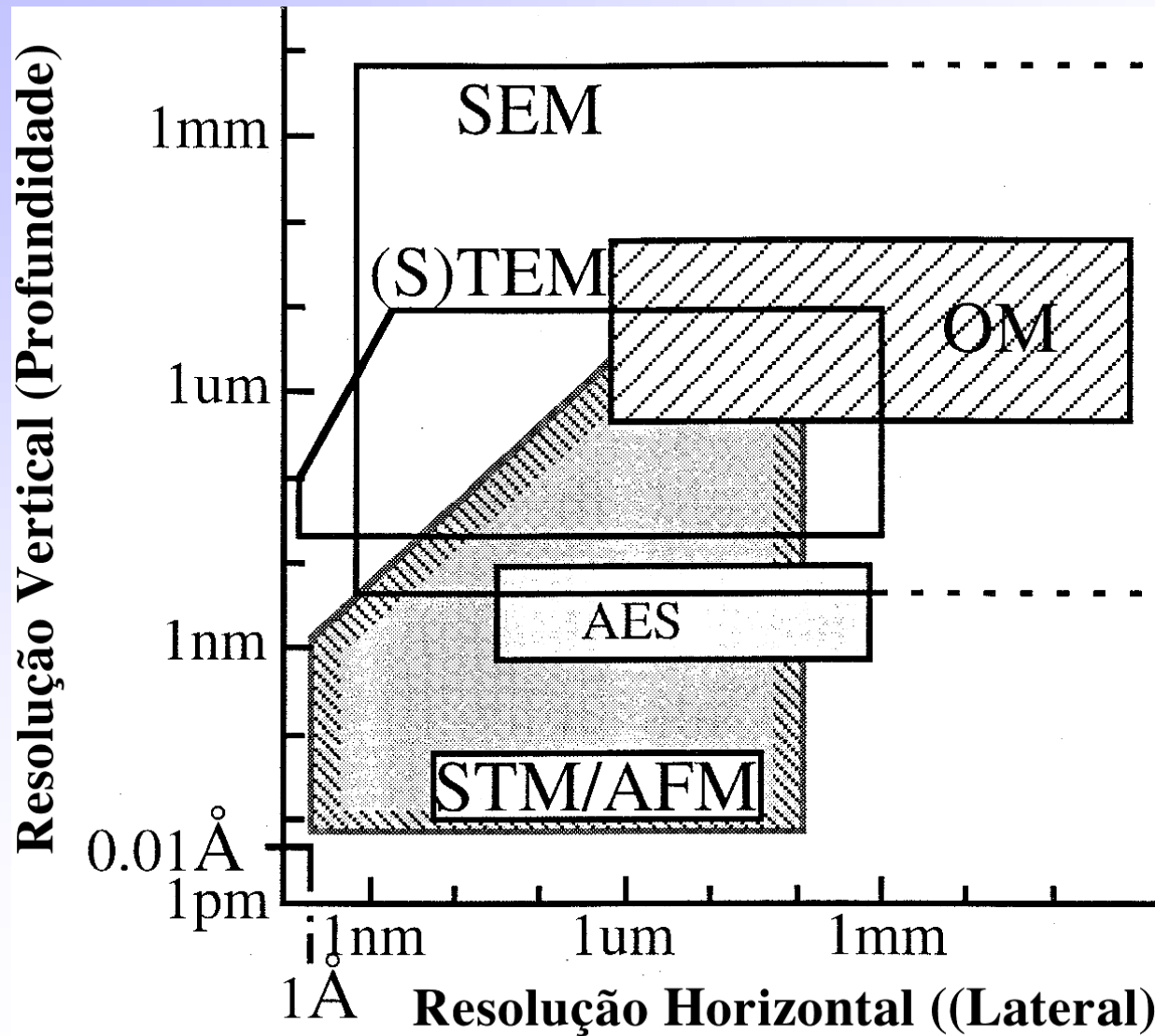
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## ◆ Tipos de análise

- Morfológica (espessura, rugosidade)
- Composição química/elementos
- Estrutura cristalográfica e Defeitos



# Comparação Geral das Técnicas Abordadas no Curso



[JEOL, 1996]



# Microscopia Eletrônica de Varredura

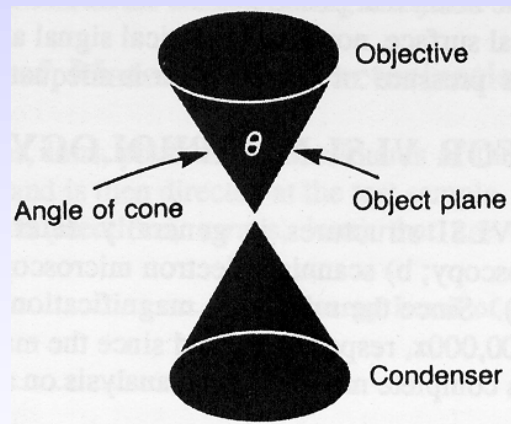
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- Óptica → (1000x ou 1 $\mu$ m)
- SEM → (100.000x ou 10nm)
- TEM → (500.000x ou 10Å)
- SPM (STM/AFM) → (átomos ou 1Å)



# Microscopia Óptica

- ◆ Resolução, Magnificação e Abertura Numérica (NA)



$$d = \frac{\lambda}{2(NA)}$$

$$NA = n \operatorname{sen}\left(\frac{\theta}{2}\right)$$

$$M_{\max} = 1000 (NA)$$

- ◆ Resolução máx.:  $\sim 0,25\mu\text{m}$

# Microscopia Óptica

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- ◆ Resolução
- ◆ Contraste
- ◆ Brilho
- ◆ Nitidez



# Iluminação

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## ◆ Campo Claro

- Luz proveniente do microscópio, através da objetiva
- Luz refletida da lâmina
- Modo “normal”

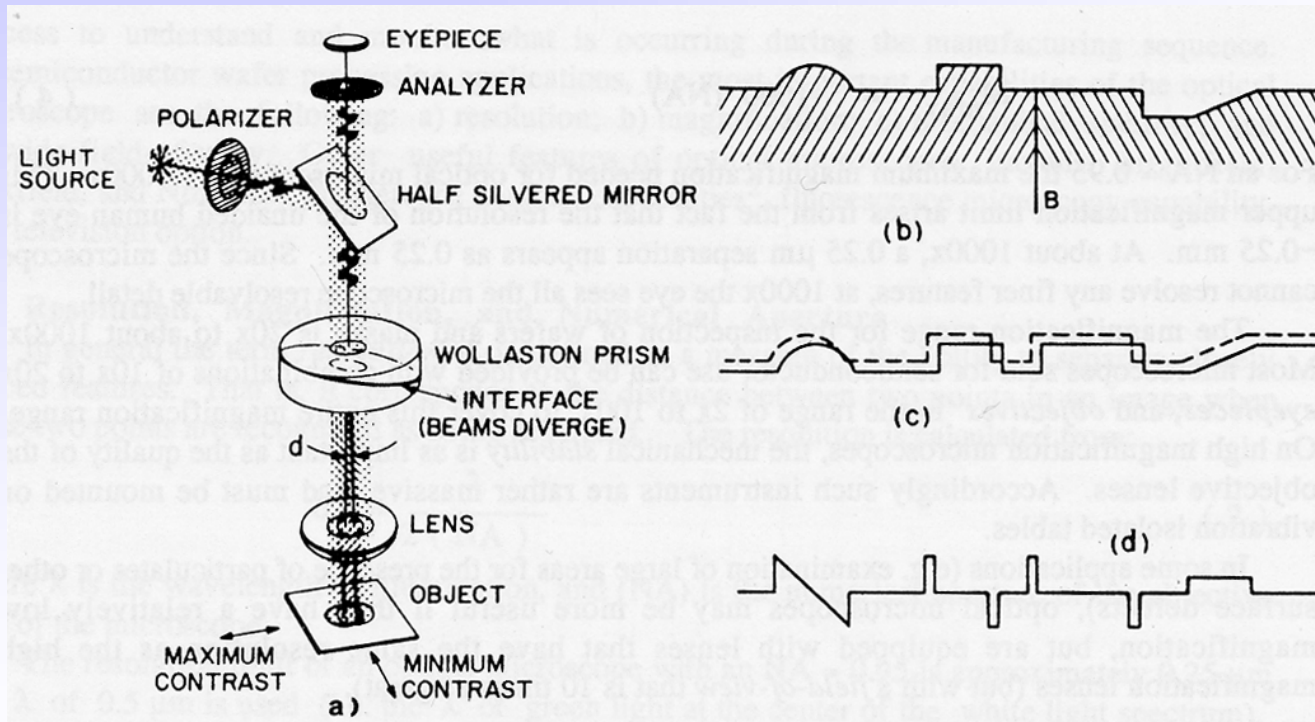
## ◆ Campo Escuro

- Luz proveniente do microscópio, porém do entorno do sistema óptico
- Luz atinge a amostra obliquamente



# Iluminação

## ◆ Contraste Interferométrico





# Microscopia Eletrônica de Varredura

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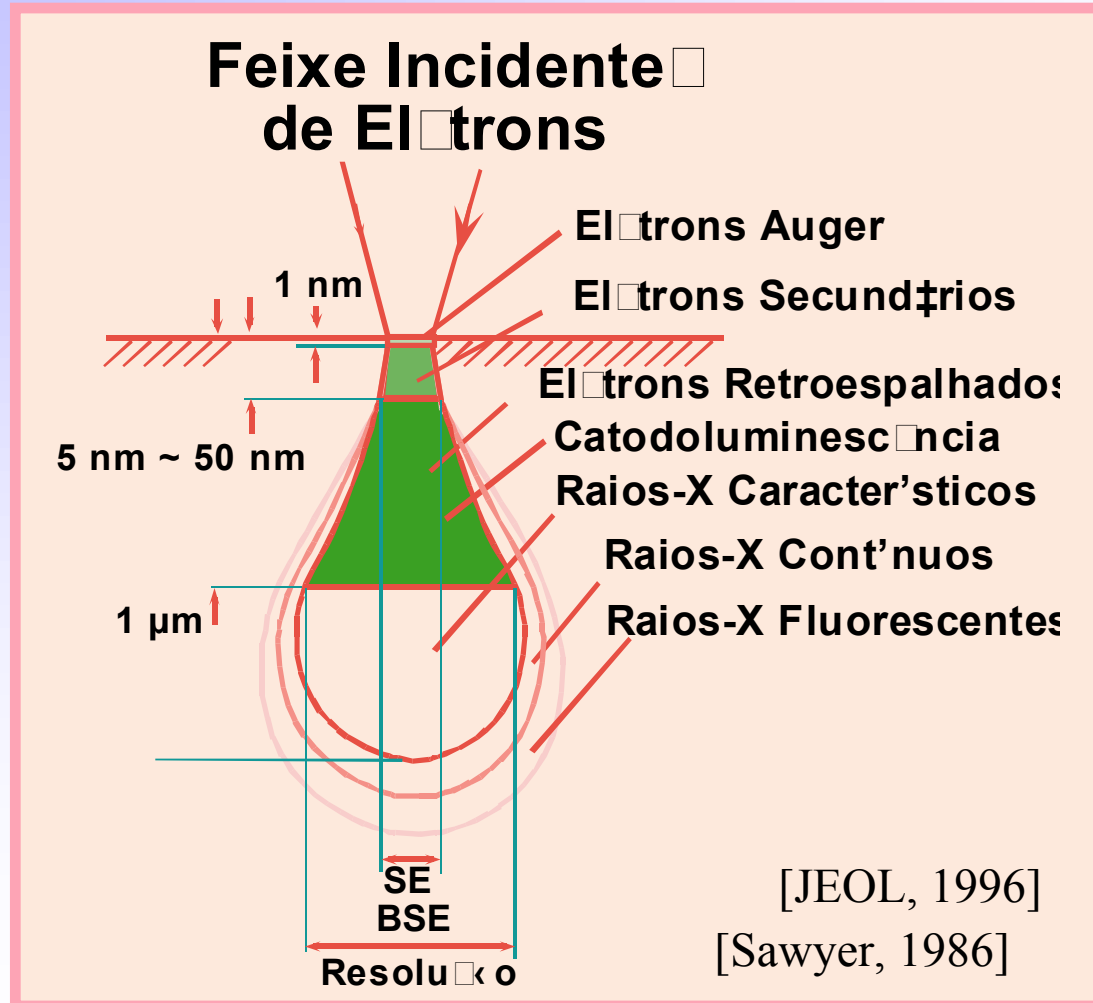
# Microscopia Eletrônica

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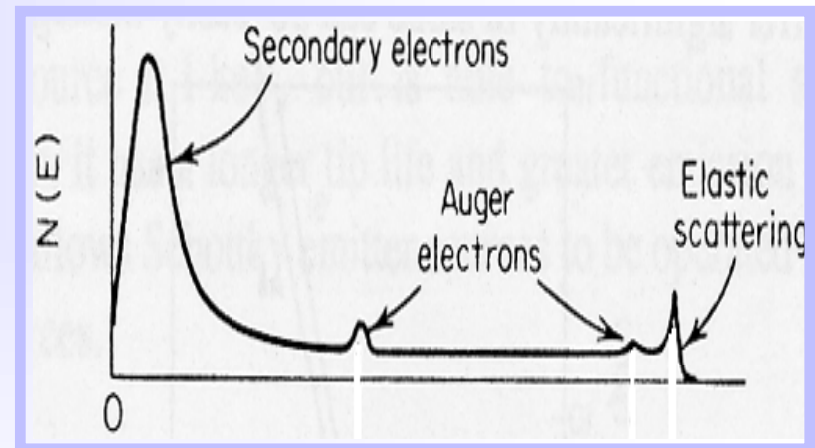
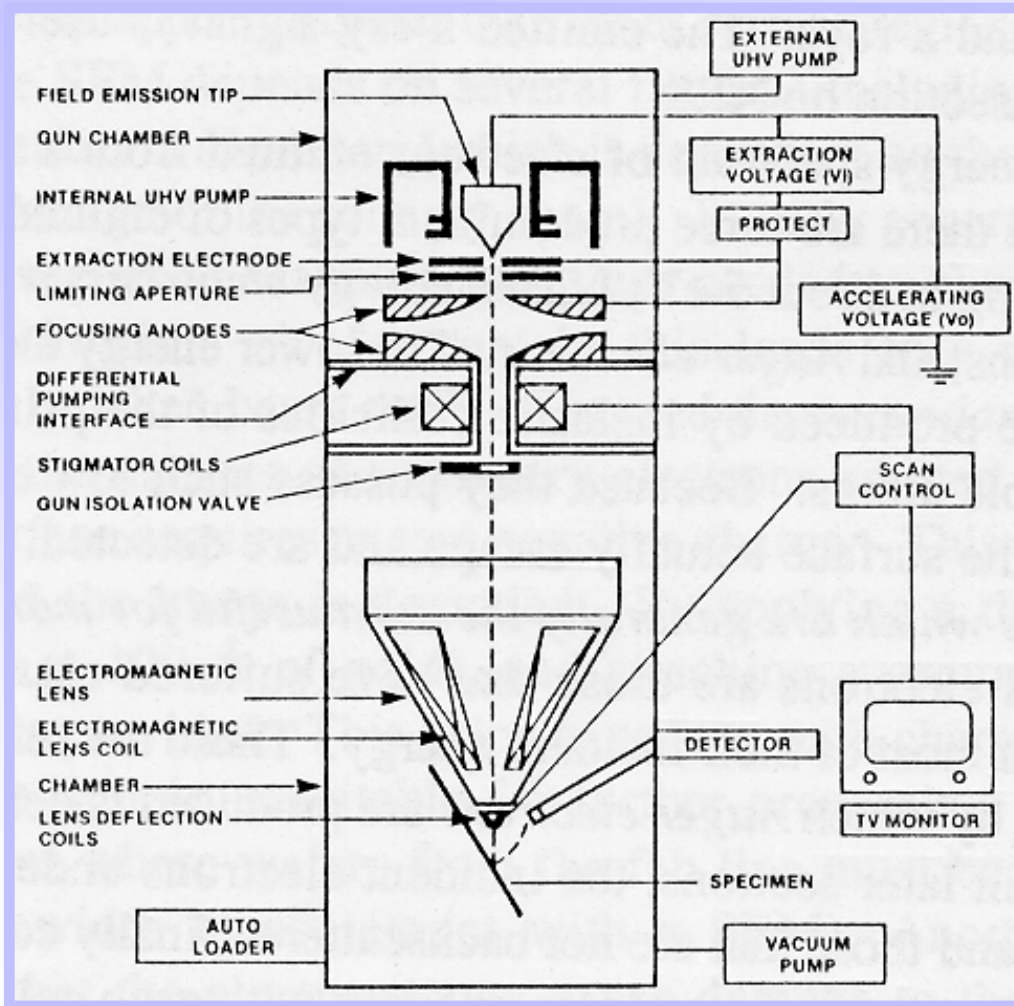
- ◆ Nitidez e contraste
- ◆ Imagens de baixa qualidade
- ◆ Ruído
- ◆ Deformação e distorção



# Interação Elétron - Amostra



# Microscopia Eletrônica



[Wolf, 1986]

# Parâmetros Importantes

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- Resolução [Murr, 1969]
  - Considerando-se a natureza ondulatória dos elétrons temos que:

$$\lambda = \frac{h}{P}$$

que no caso de elétrons torna-se:

$$\lambda = \frac{h}{m_0 v} \sqrt{1 - (v/c)^2}$$

Quando elétrons passam por um cristal eles exibem padrões de interferência e difração similares aos de raios-x tal que:

$$eV_0 = mc^2 - m_0c^2$$



- Combinando-se as duas equações anteriores temos:

$$\lambda = \sqrt{2m_0eV_0 + \frac{e^2V_0^2}{c^2}}$$

que numericamente fornece:

$$\lambda = \frac{12,27}{\sqrt{V_0(1 + 0,978 \times 10^{-6}V_0)}} \quad \square$$

Exemplos:

$$V_0 = 100\text{kV} \rightarrow \lambda = 0,037\text{\AA}$$

$$V_0 = 20\text{kV} \rightarrow \lambda = 0,086\text{\AA}$$

$$V_0 = 0,5\text{kV} \rightarrow \lambda = 0,548\text{\AA}$$

# Microscopia Eletrônica

- Considerando-se a resolução como definida pelo critério de Rayleigh e considerando  $\alpha = 0,01$  rad

$$R = \frac{0,61}{\alpha} \lambda$$

$$\left\{ \begin{array}{l} V_0 = 100\text{kV} \rightarrow \lambda = 0,037\text{\AA} \rightarrow R = 2,2\text{\AA} \\ V_0 = 20\text{kV} \rightarrow \lambda = 0,086\text{\AA} \rightarrow R = 5,2\text{\AA} \\ V_0 = 0,5\text{kV} \rightarrow \lambda = 0,548\text{\AA} \rightarrow R = 33\text{\AA} \end{array} \right.$$

- Na prática deve-se considerar ainda o efeito das aberrações do sistema óptico da coluna, notadamente as aberrações esférica e cromática, tal que:

$$R_{\text{SEM}} = \sqrt{R^2 + \frac{R_{\text{esf}}^2}{2} + \frac{R_{\text{crom}}^2}{2}} \quad (+10\%)$$



# Microscopia Eletrônica

- Essa resolução pode ser considerada como limite e na verdade deve ainda considerar o fato do feixe possuir um diâmetro finito, que é função da densidade de corrente e da tensão de aceleração da coluna:

$$d_{\text{SEM}} \cong \sqrt{\left(\frac{6I_0 kT}{\pi J_0 e V_0 \alpha^2}\right)^2 + R^2 + \frac{R_{\text{esf}}^2}{2} + \frac{R_{\text{crom}}^2}{2}}$$

- Além disso, deve-se considerar fatores práticos tais como
  - Natureza da superfície observada
  - Contraste da imagem

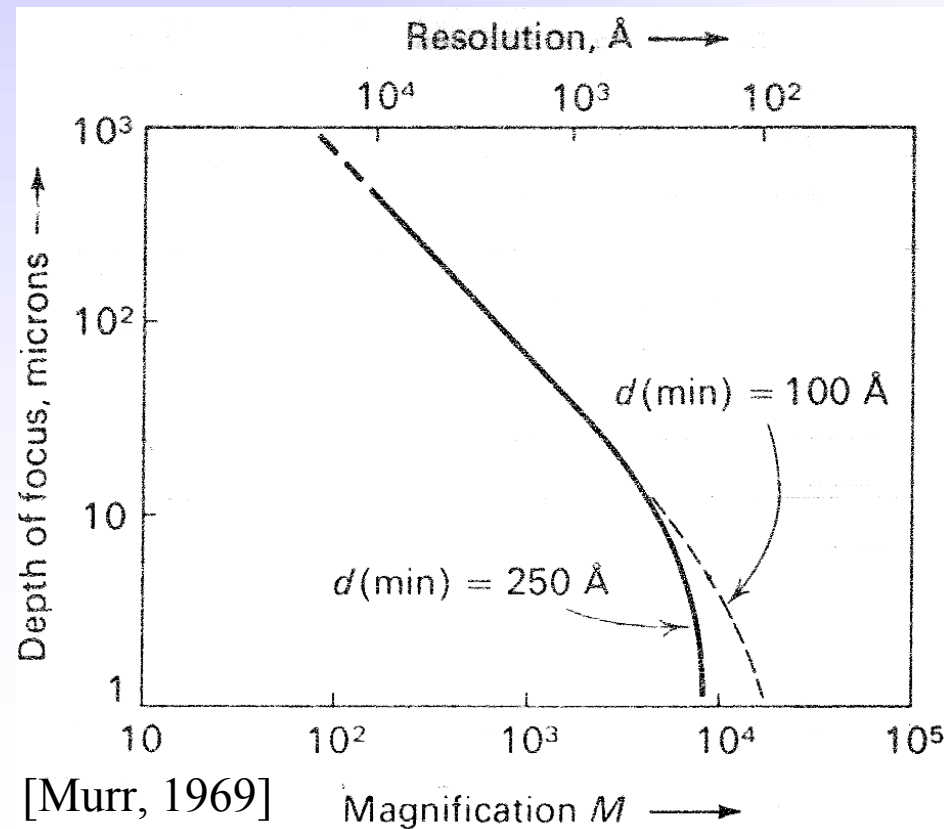




- Por fim, a profundidade de foco pode ser dada por

$$DOF = \frac{R}{\alpha} \frac{1}{M}$$

(quando  $\alpha$  pequeno)



[Murr, 1969]

Magnification  $M$  →



# Tensão de Aceleração

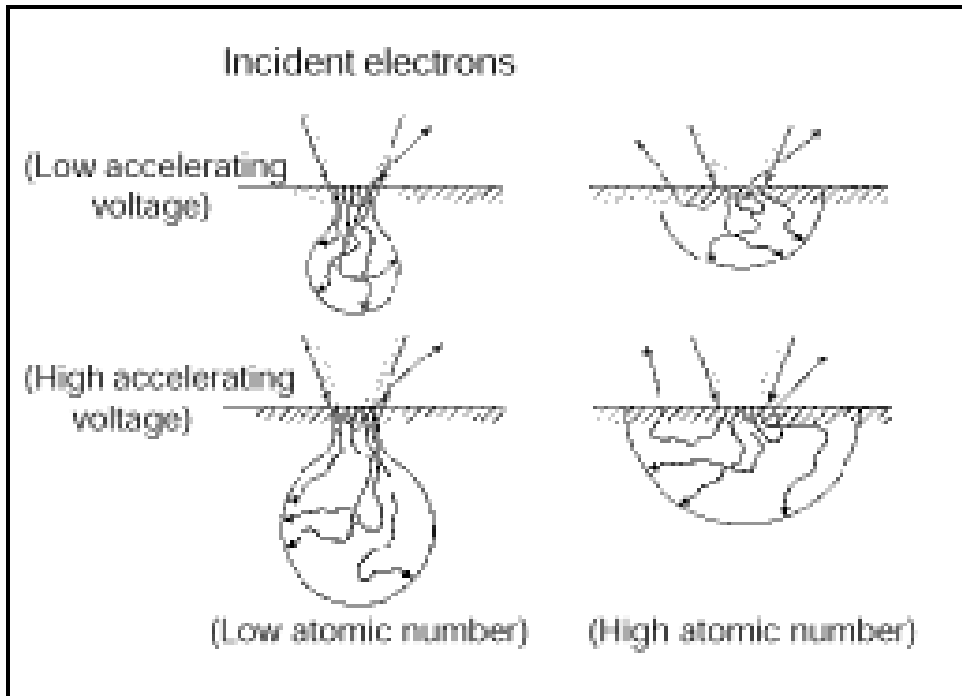
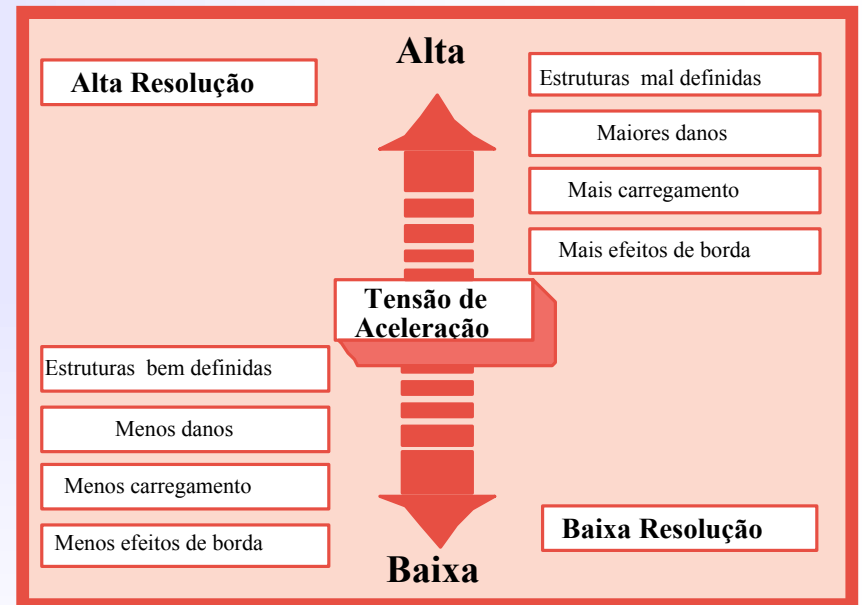
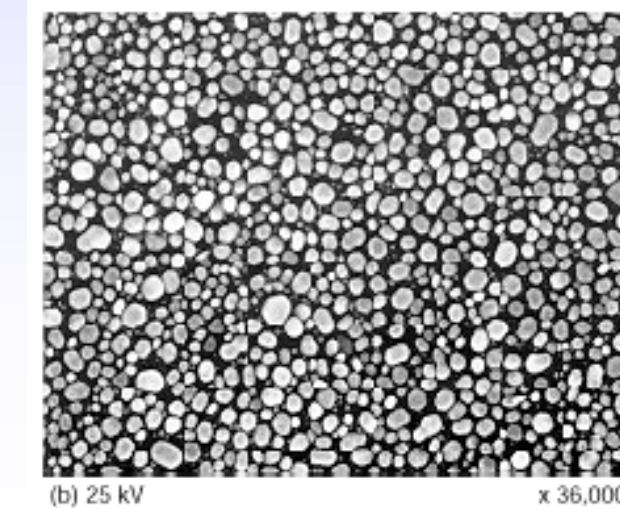
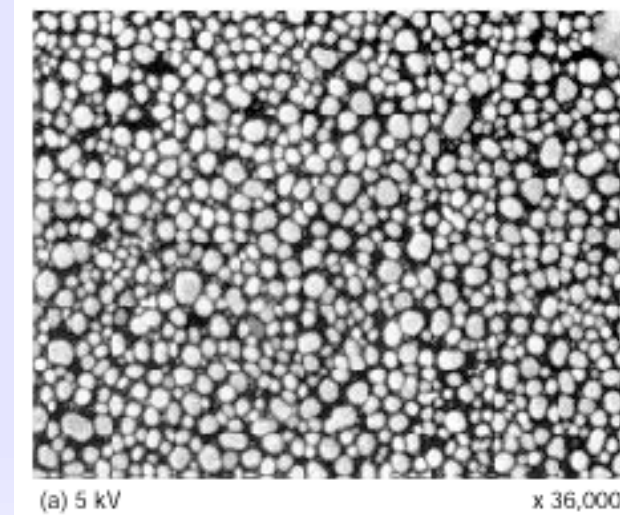
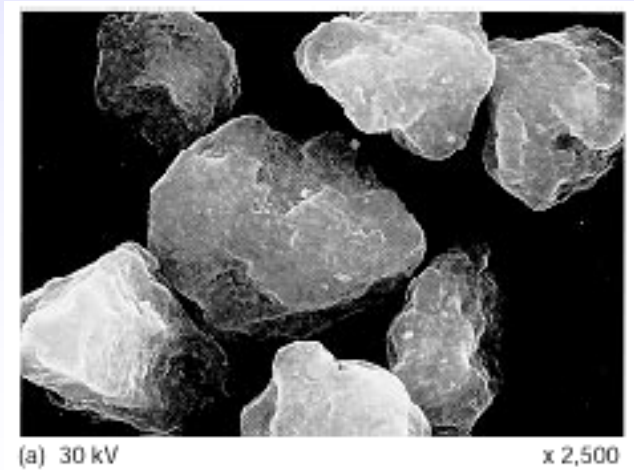
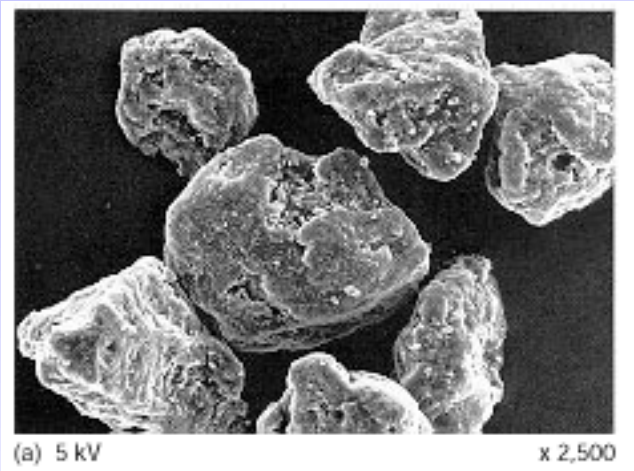


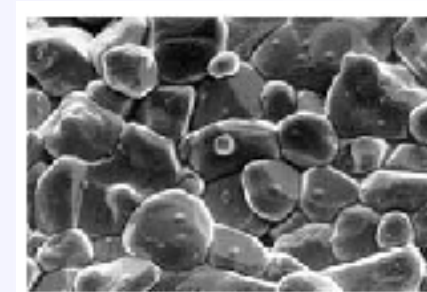
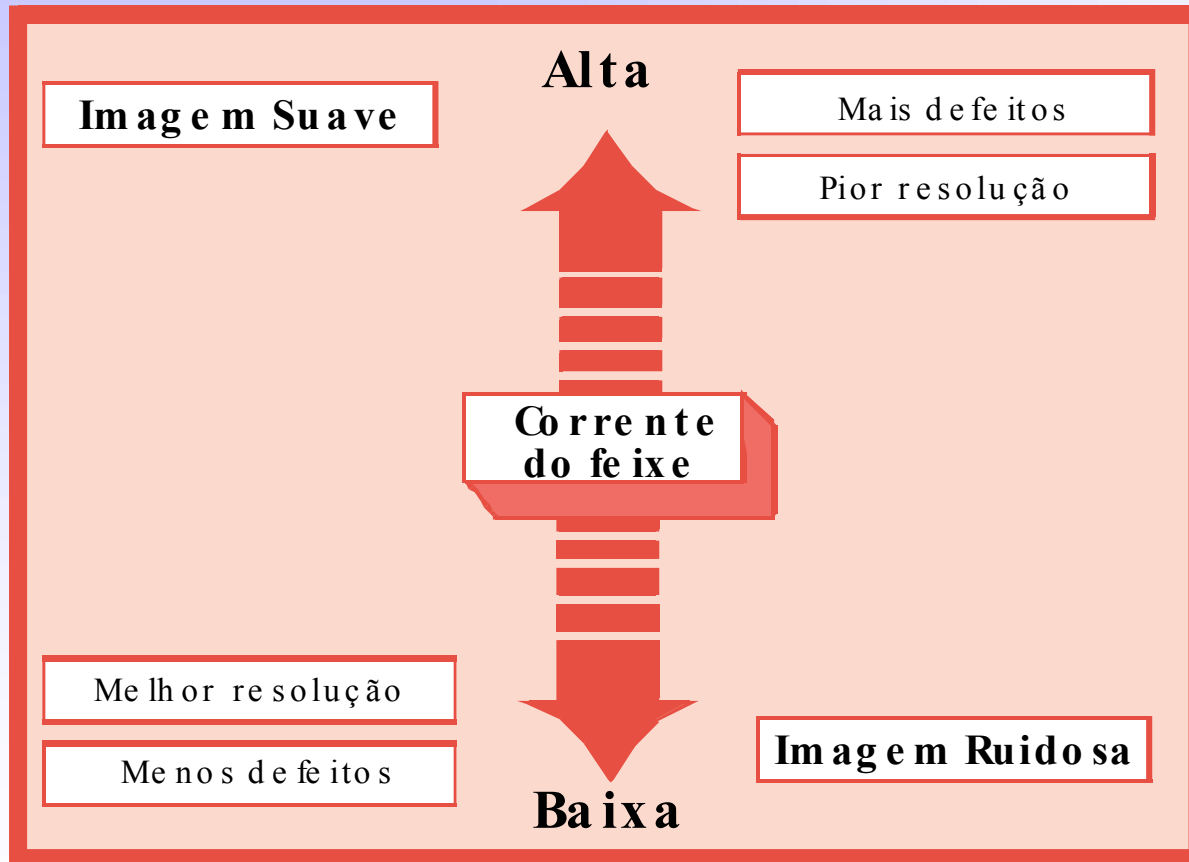
Fig.1 Diffusion of incident electrons (after Ducumb and Shields).



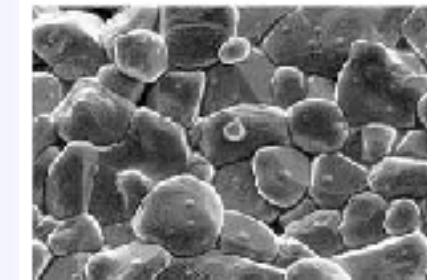
# Tensão de Aceleração



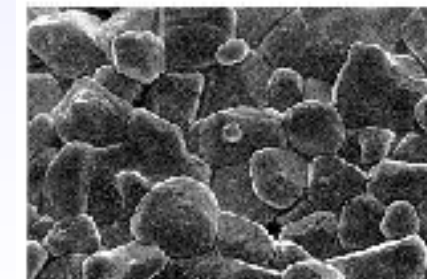
# Tipo de Feixe (I, d) & Qualidade da Imagem



(a) 1 nA



(b) 0.1 nA



(c) 10 pA

# Tipos de Microscópio

**Table 2. CHARACTERISTICS OF ELECTRON BEAM SOURCES**

Type of Emission	Tungsten Hair Pin Thermionic (Heated)	Lanthanum Hexaboride Thermionic (Heated)	Field Emission (Room Temperature)	Schottky /Extended Field (Heated)
Brightness (A /cm <sup>2</sup> /ster)	10 <sup>4</sup>	10 <sup>5</sup>	10 <sup>8</sup>	10 <sup>8</sup>
Effective Source Size (Å)	1,000,000	200,000	100	100
Energy Spread (eV)	3	3	0.2-0.3	0.28-0.38
Operating Life (hrs)	30-100	100-500	300-1000	2000-10000
Vacuum Required (torr)	10 <sup>-3</sup> -10 <sup>-5</sup>	10 <sup>-5</sup> -10 <sup>-6</sup>	10 <sup>-9</sup> -10 <sup>-11</sup>	< 10 <sup>-8</sup>



# Bordas & Inclinação (tilt)

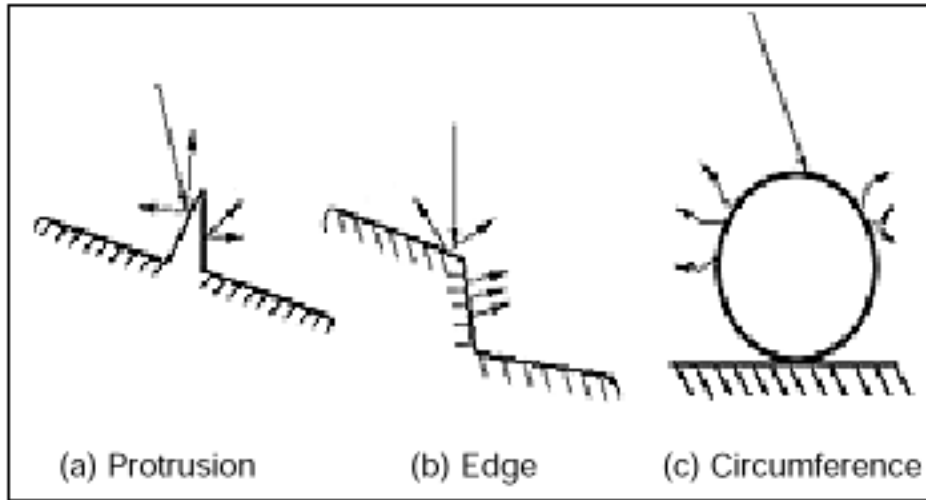
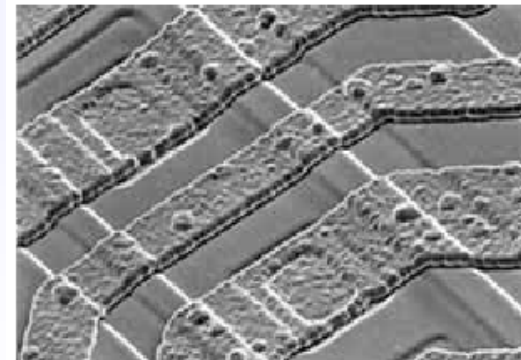
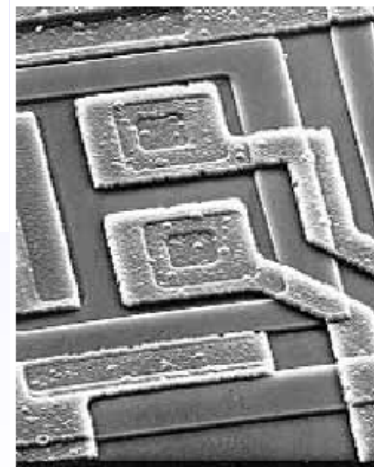
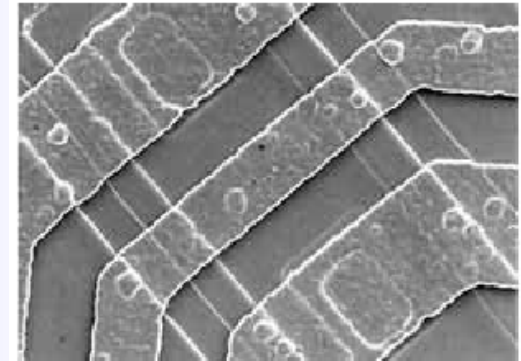
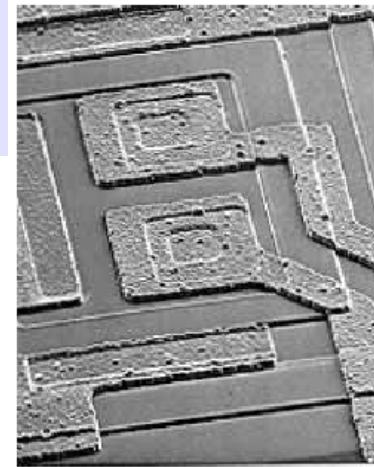


Fig. 11. Edge effect (secondary electron emission differing with surface condition).



# Posição do Detetor

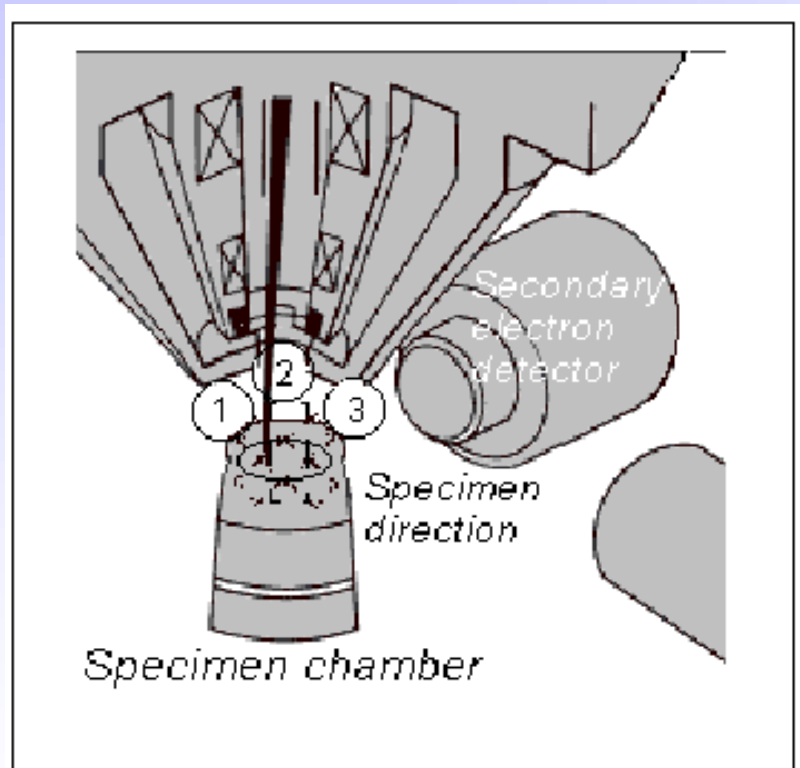
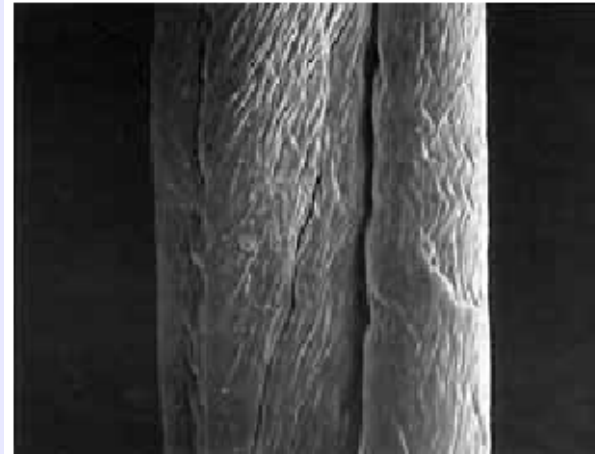
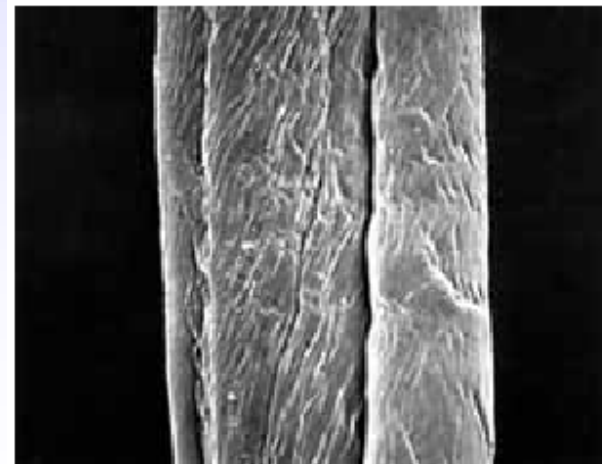


Fig. 15 Detector position and specimen direction.



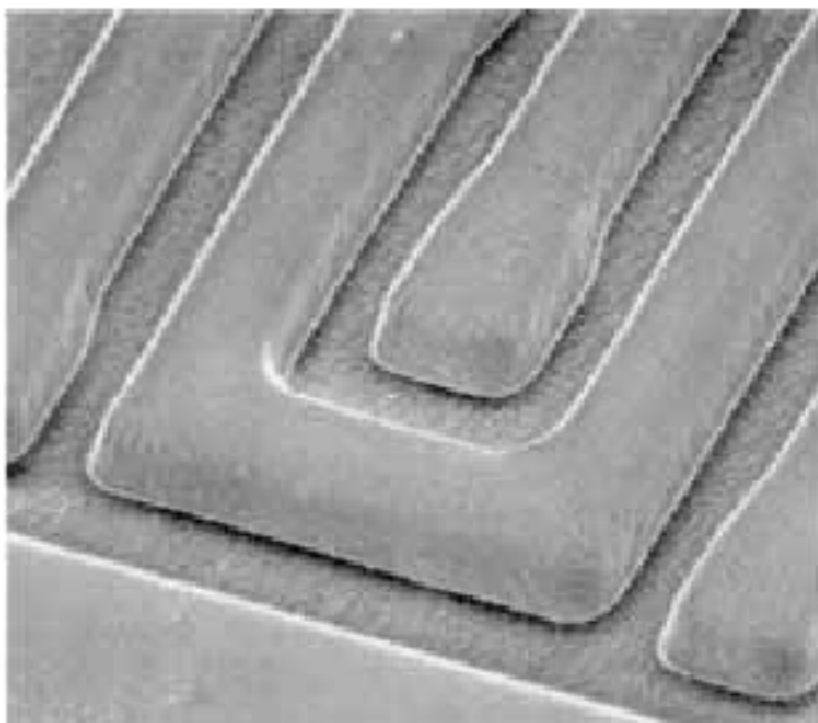
(a) Specimen directed as at 1



(c) Specimen directed as at 3

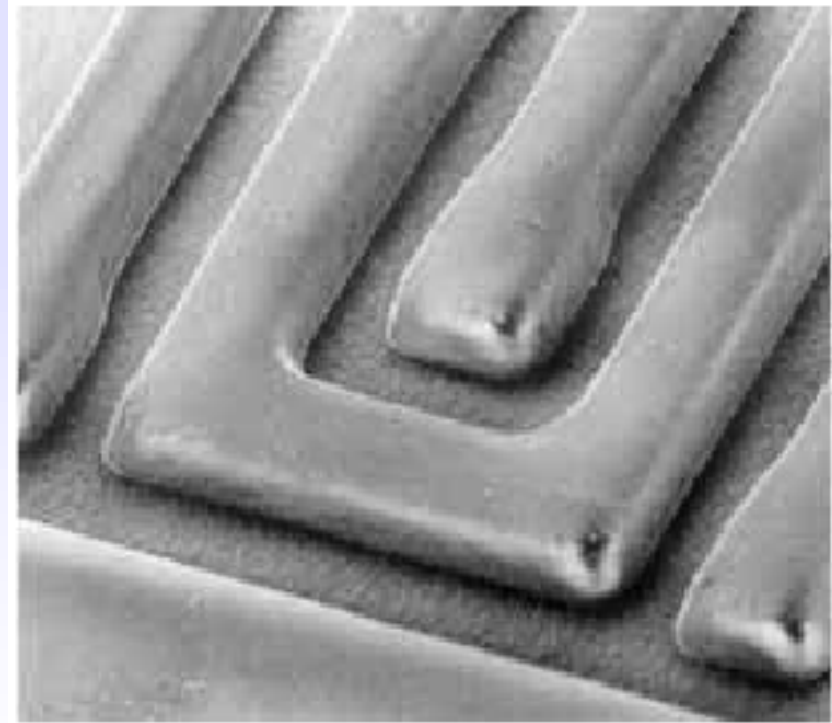
# Carregamento da Amostra

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(a) 1.0 kV

x3,200



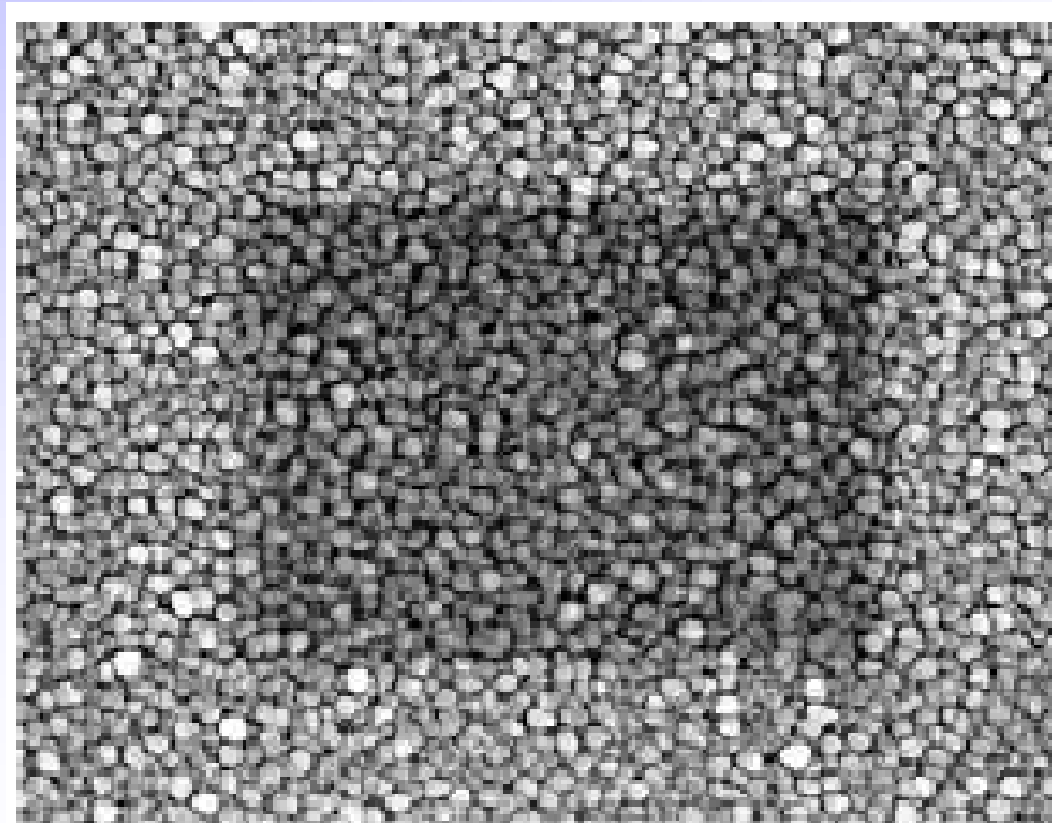
(b) 1.3 kV

x3,200



# Contaminação da Amostra

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5 kV

x18,000



# Preparação da Amostra

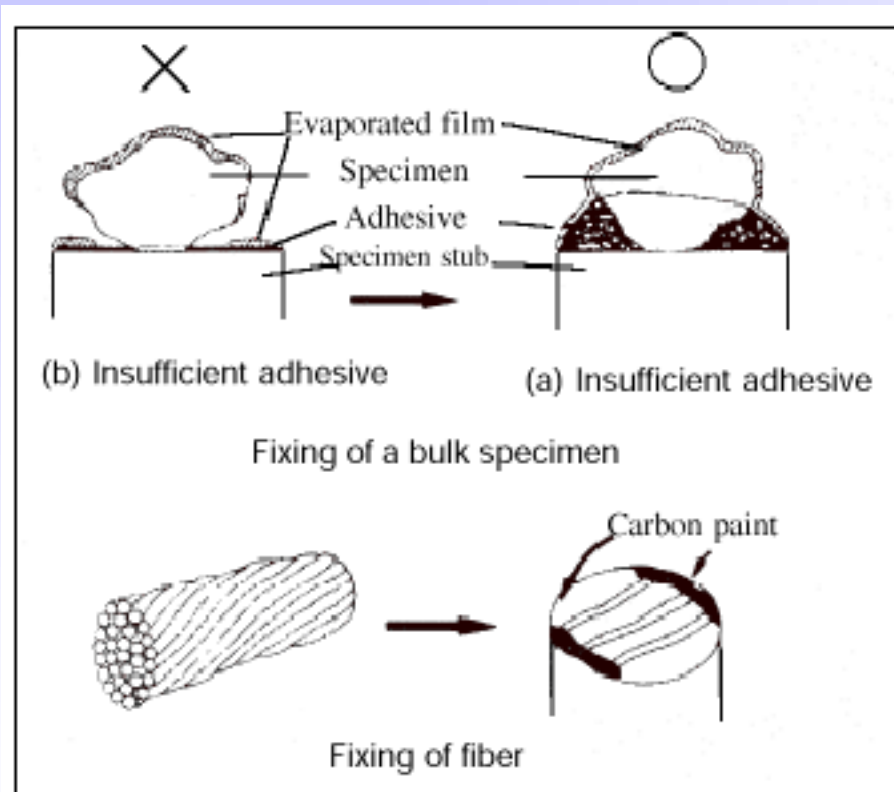


Fig. 23 Fixing the specimen.

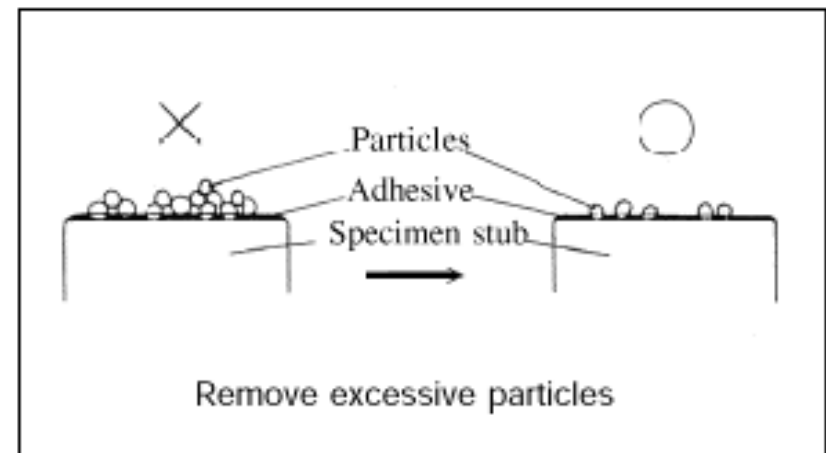
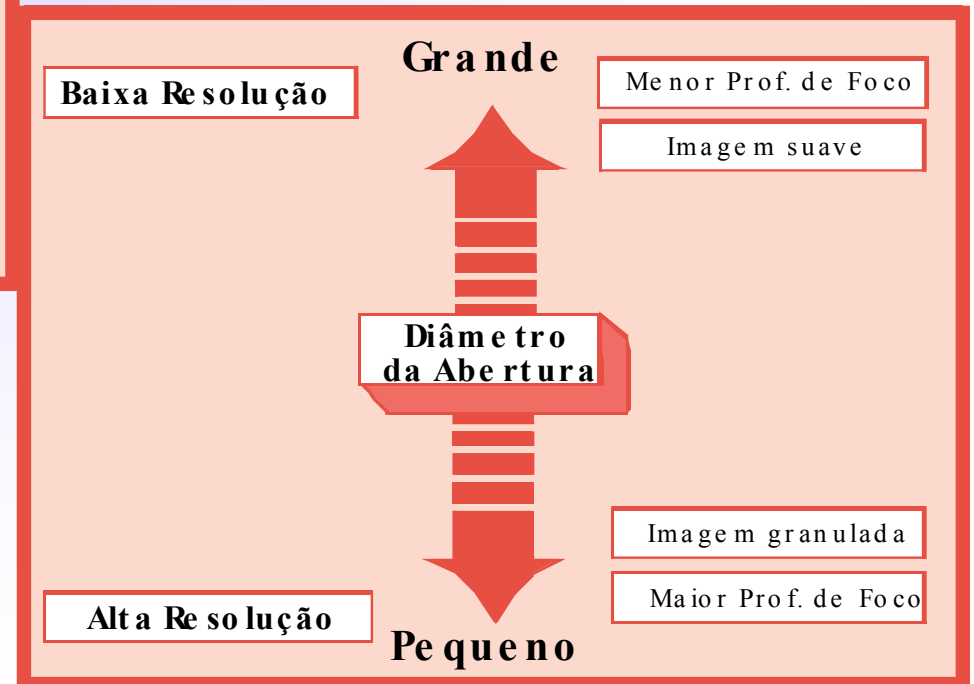
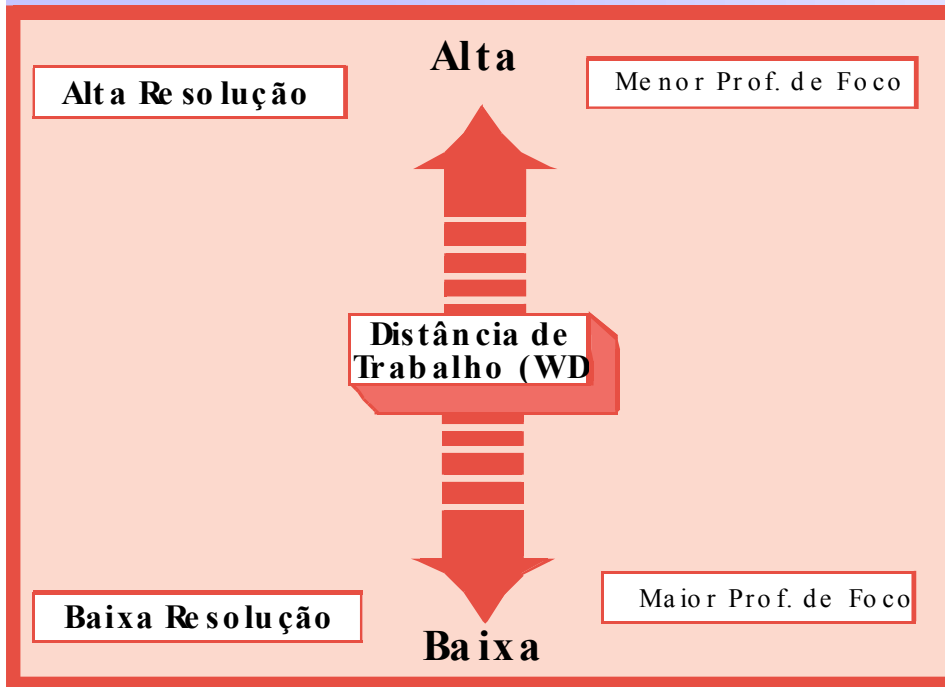


Fig. 24. Preparation of powder specimen.

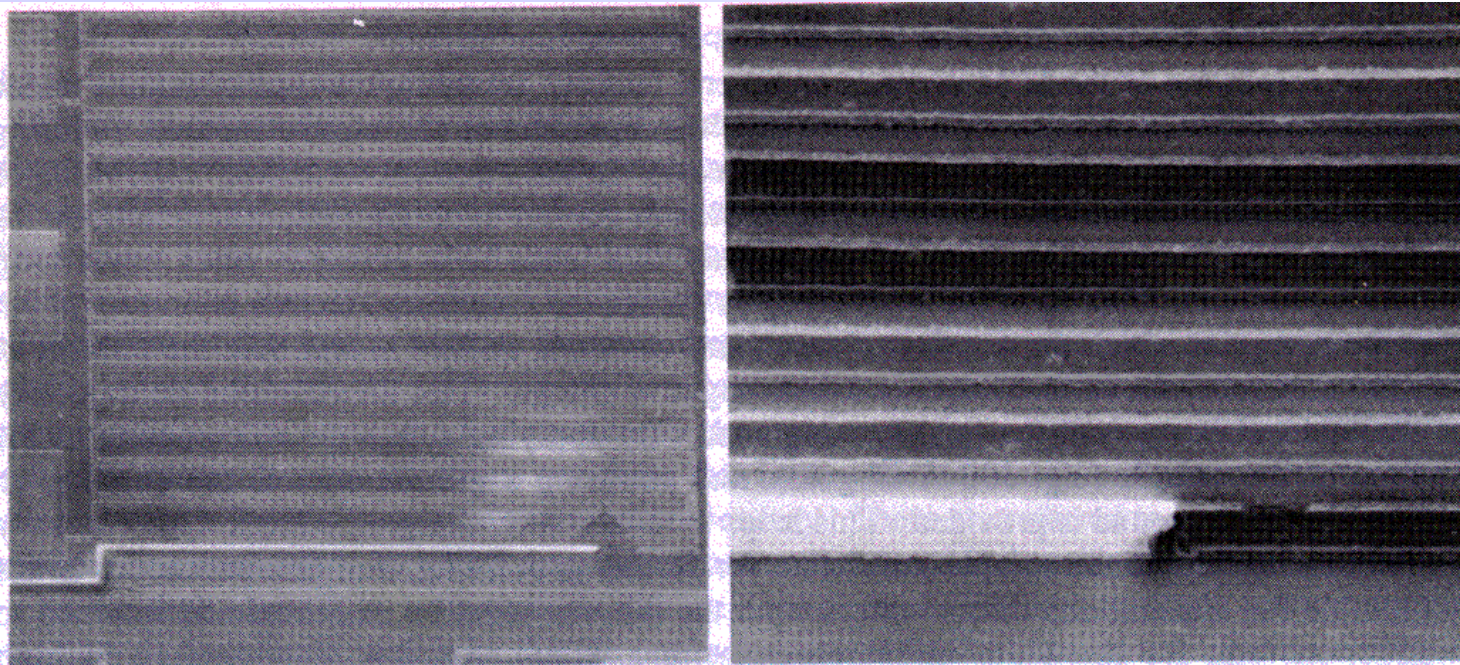
# Questões Operacionais



# Análises com o SEM

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## ◆ Microscopia por Contraste de Tensão



**Fig. 7** Example of using the SEM voltage contrast mode to locate an open circuit in a long metal stripe. Courtesy of TRW.

# Espectroscopia por Emissão de Raios-X

## ◆ EDX

## ◆ WDX

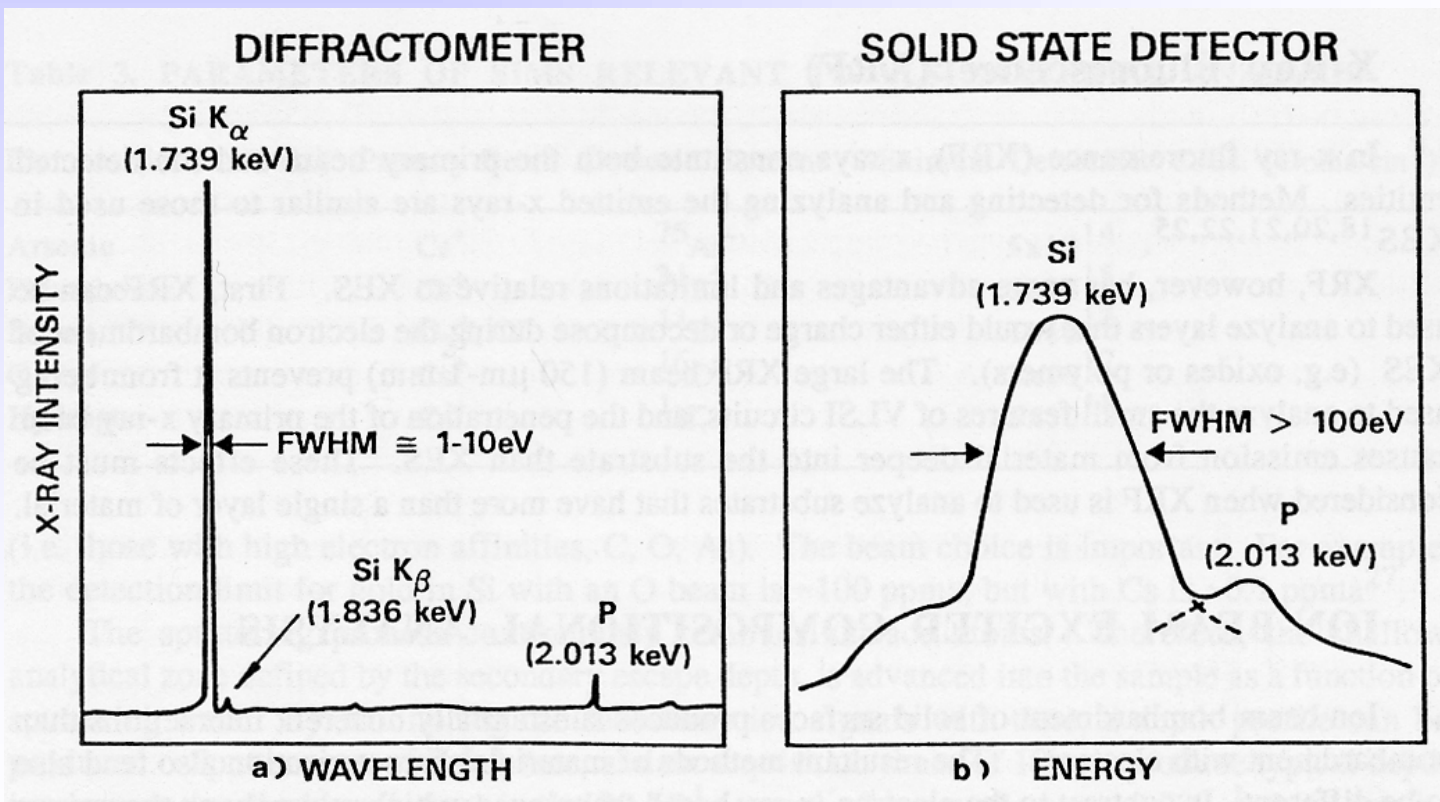
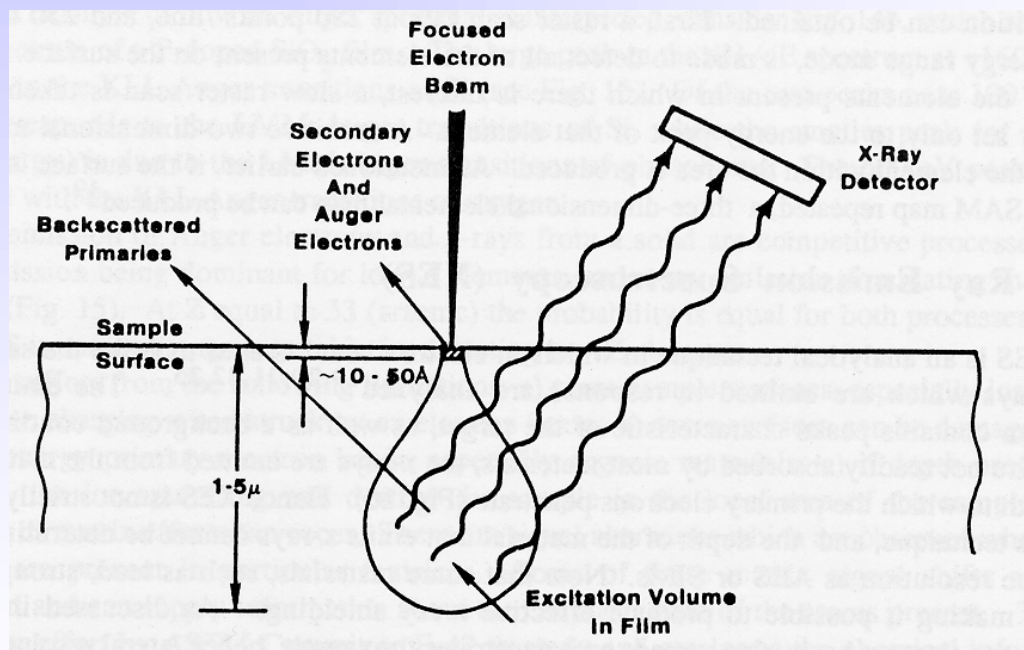


Fig. 17 Comparing energy resolution achievable with energy vs wavelength dispersive analysis.



# Espectroscopia por Emissão de Raios-X

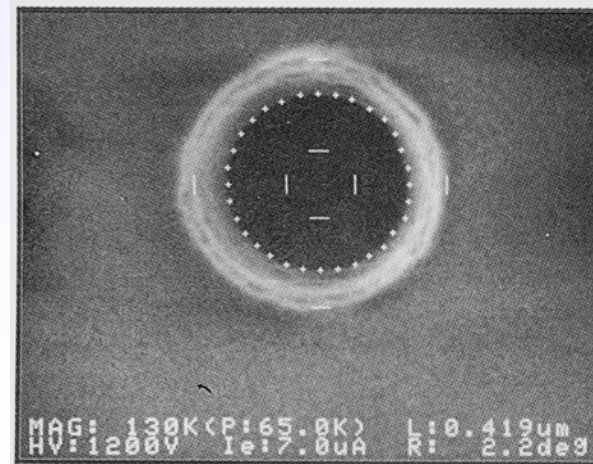
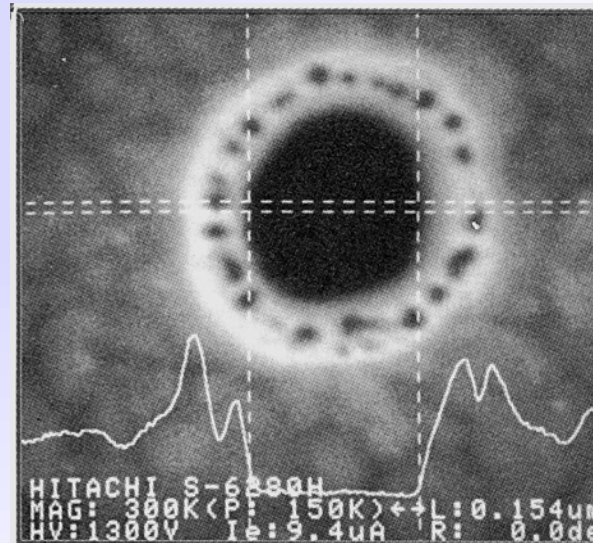
Limite: 0,3% a 1%



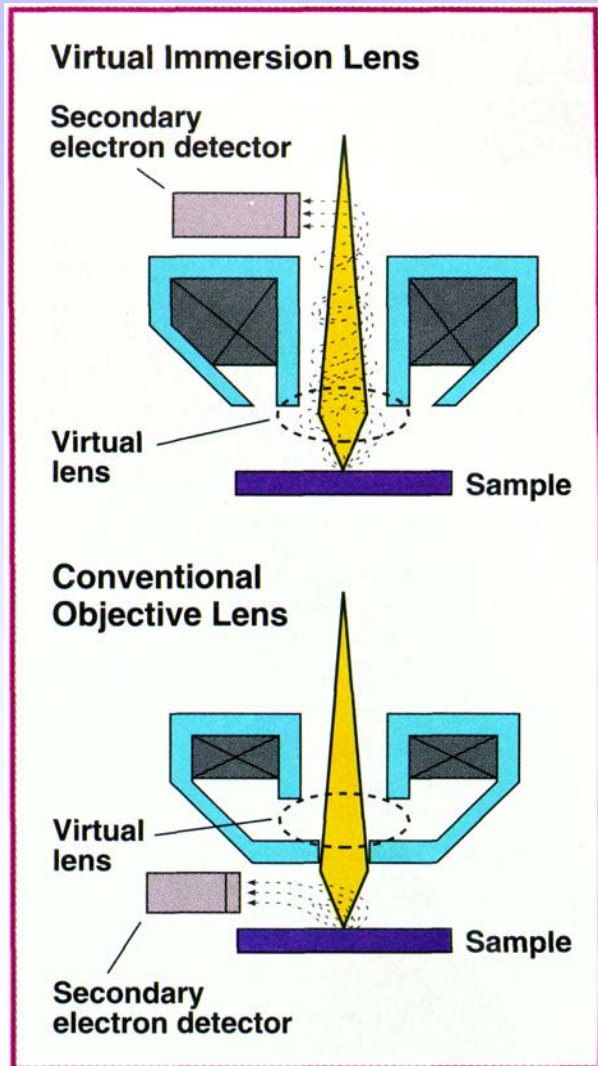
# Tendências em SEM para Microdispositivos

- Filamento de Emissão por Campo e Baixa Tensão (LV-FESEM)

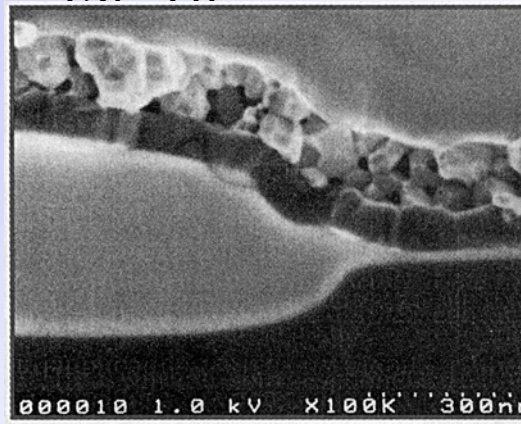
- Medidas de CD em linha de produção



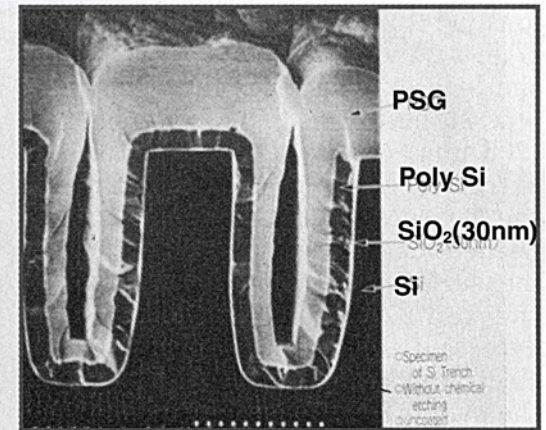
# Tendências em SEM para Microdispositivos



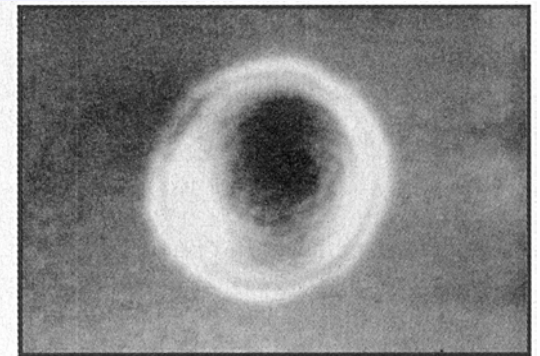
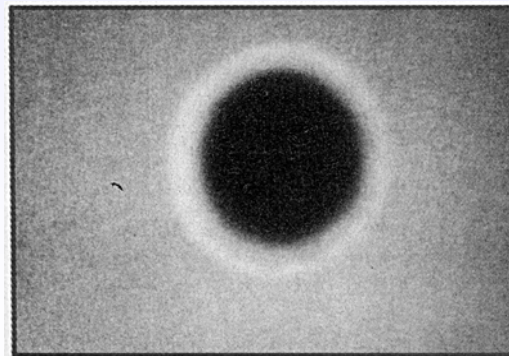
- Lentes de imersão (in-line)
  - Alta resolução (10Å) em baixa tensão



LOCOS com Porta  $WSi_2$



Distinção entre PSG, Poli e 30nm de  $SiO_2$



Imagens de Baixa (direita) e Alta (esquerda) resolução