Fotogravação

Litografia: de máscara à gravação

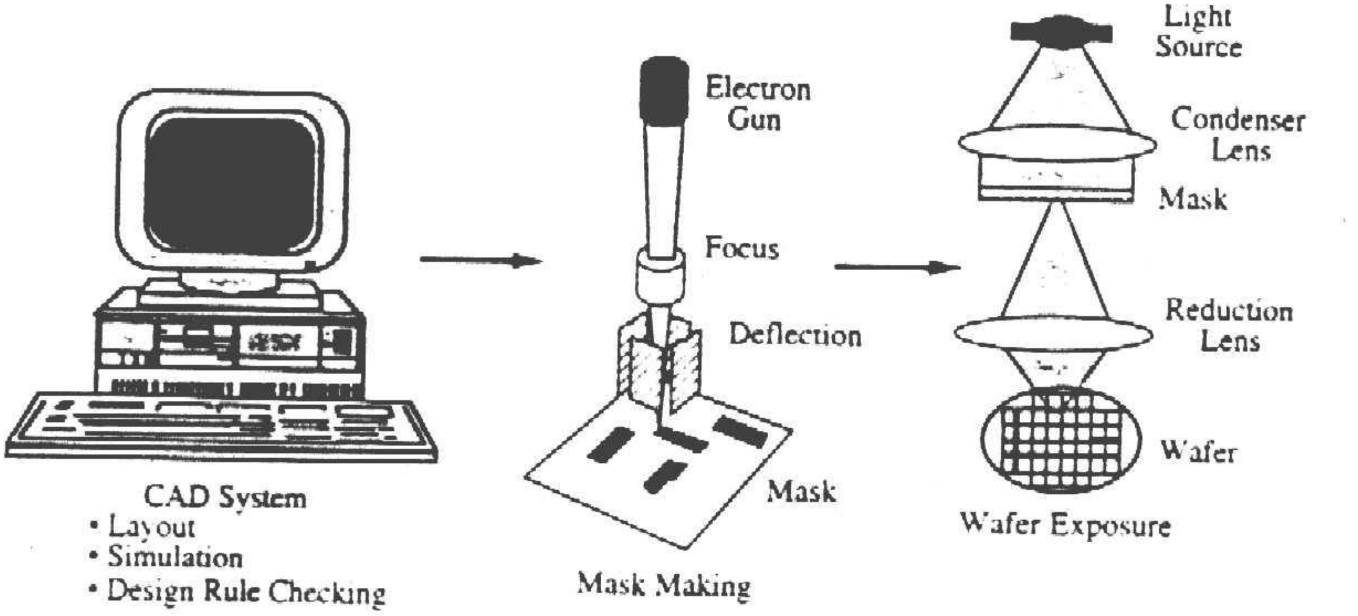


Figure 5–1 Lithography process from mask design to wafer printing.

Métodos de exposição

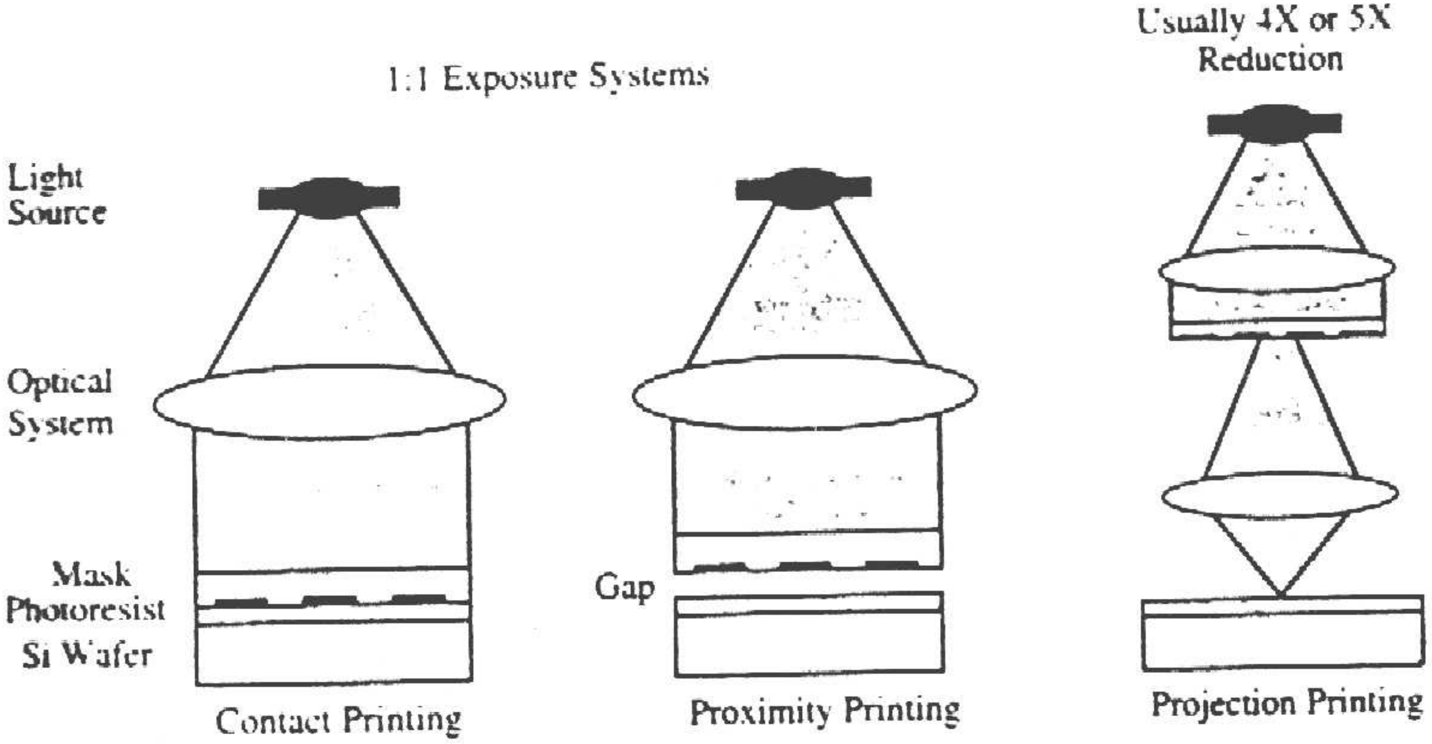


Figure 5–3 Three basic methods of wafer exposure.

Propagação de luz: efeitos de difração

a) difração Fresnel (campo próximo, *near-filed*),

b) difração Fraunhofer (campo distante, *far-field*)

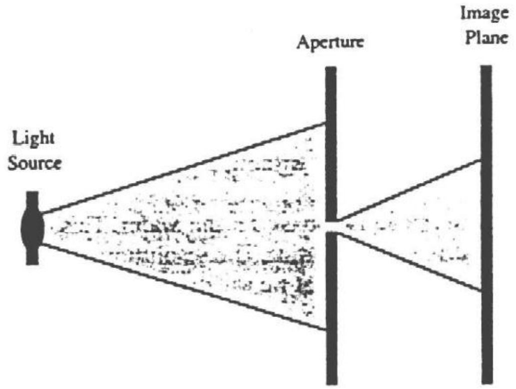


Figure 5–4 Simple example of diffraction effects. Light passes through a narrow aperture. The image formed covers a much larger area than can be explained based on simple straight line ray tracing.

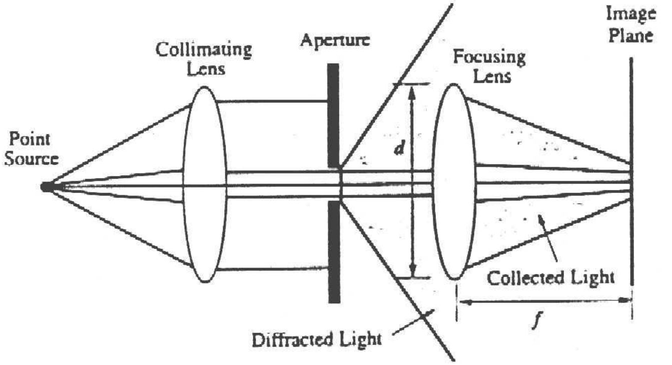


Figure 5–6 Qualitative example of a small aperture being imaged.

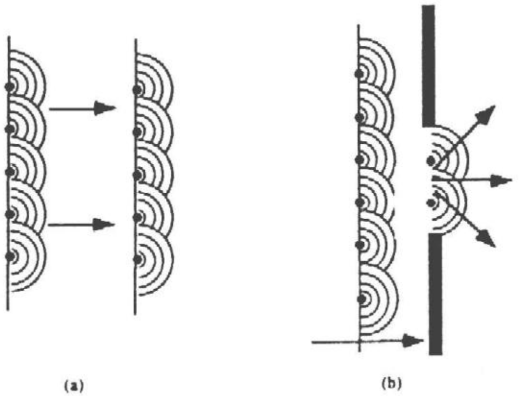


Figure 5–5 Propagation of a plane wave in (a) free space and (b) through a small aperture, illustrating the use of the Huygens-Fresnel principle to construct the wavefront as it propagates.

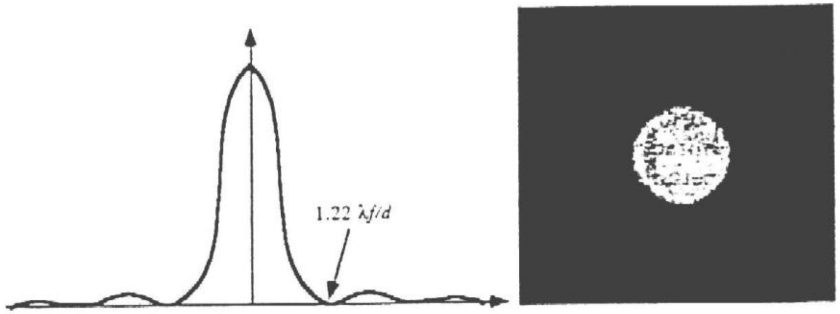


Figure 5–7 Image intensity of a circular aperture in the image plane (Fraunhofer diffraction pattern). The intensity is sketched along any diameter on the left. The pattern on the right illustrates the 2D image. Photo courtesy of J. Goodman. Reprinted with permission of McGraw-Hill [5.2].

Sistemas de exposição por projeção (difração Fraunhofer)

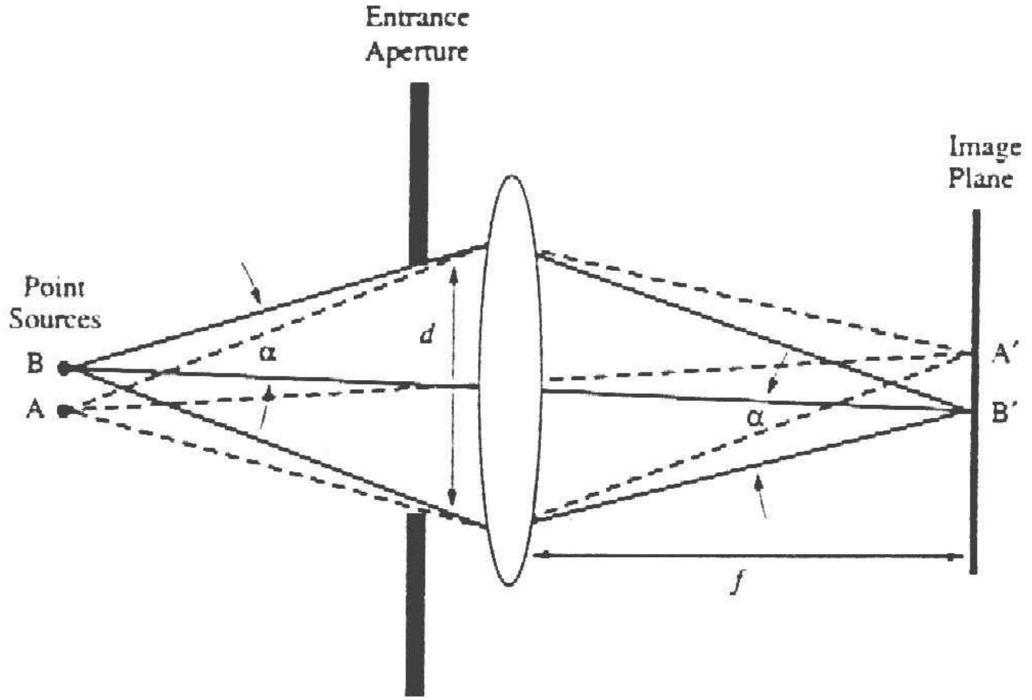


Figure 5–8 Illustration of the resolving power of a lens when two point sources are to be separated in the image.

Capacidade de resolução (*resolving power*), segundo critério Rayleigh:

$R = 1.22\ \lambda/d =$

$= 0.61\ \lambda/(n\ \mathrm{sen}\alpha)$

$d = 2f\ \mathrm{sen}\ \alpha$

$NA = n\ \mathrm{sen}\alpha$ - abertura numérica

$R = 0.61\ \lambda/NA$ ou

$R = k_1\ \lambda/NA$

onde $k_1 = 0.6 \div 0.8$

Profundidade de foco (DOF - *depth of focus*)

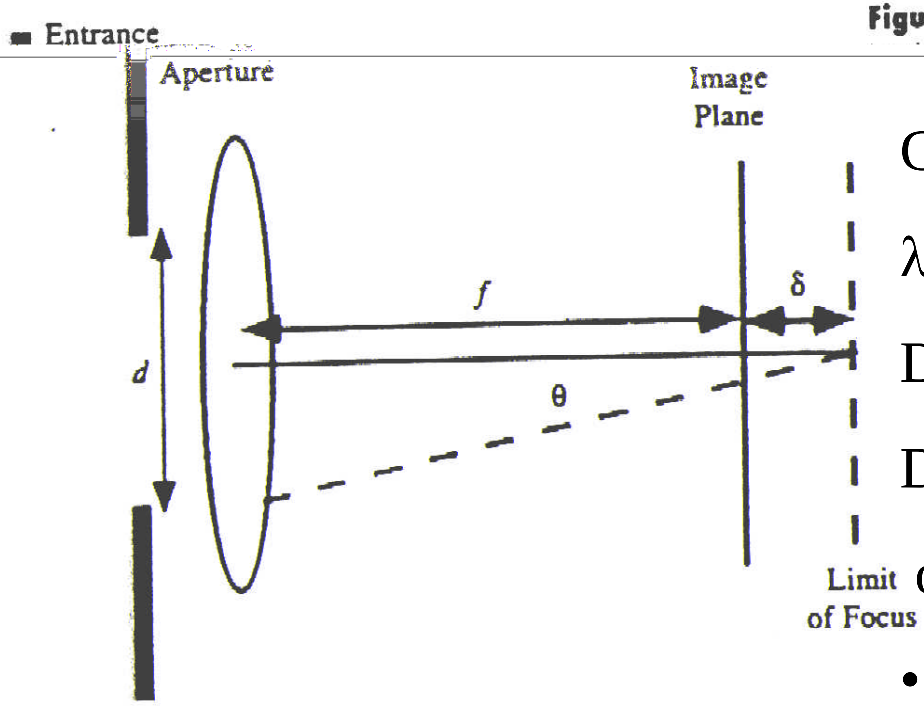


Figure 5–9 Geometry for estimating the depth of focus of an imaging system.

Critério Rayleigh:

$\lambda/4 = \delta - \delta \cos\theta \Rightarrow$

$\mathrm{DOF} = \delta = \pm\, 0.5\, \lambda / (\mathrm{NA})^2$ ou

$\mathrm{DOF} = \pm\, k_2\, \lambda / (\mathrm{NA})^2$

onde $k_2 \approx 0.5$

- NA ↑ ⇒ R↑ , mas δ ↓

Ex.:

$\mathrm{NA} = 0.6,\ k_1 \approx 0.75,\ k_2 = 0.5,$
$\lambda = 248\mathrm{nm}$ (KrF laser) $\Rightarrow$

$R = 0.31\ \mu\mathrm{m},\ \mathrm{DOF} = \pm\, 0.34\ \mu\mathrm{m}$

MTF: a função de transferência da modulação

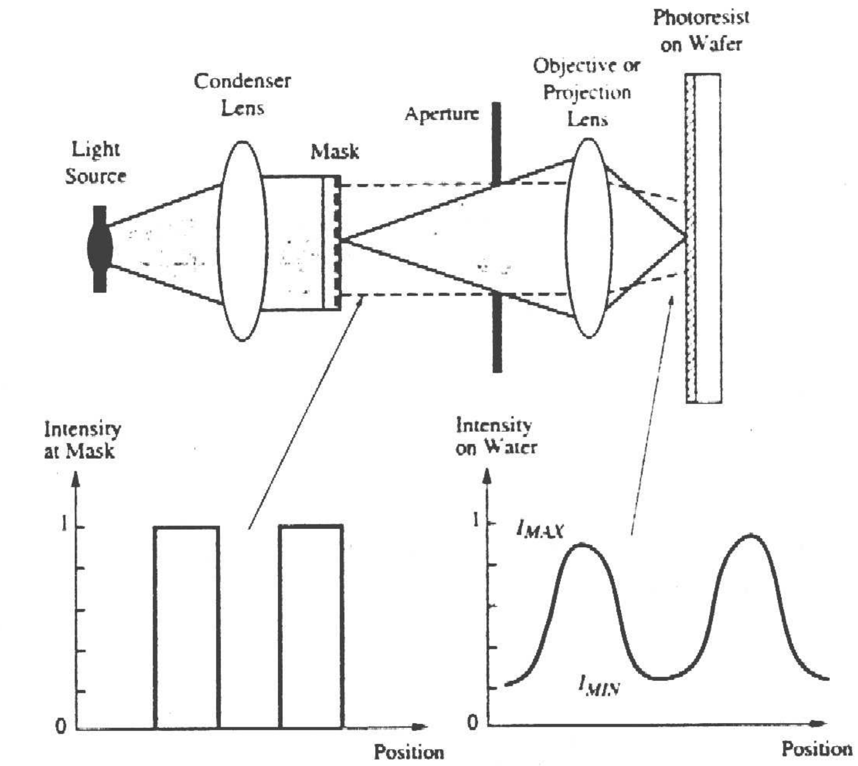


Figure 5–10 Modulation Transfer Function (*MTF*) concept. A generic lithography system is shown at the top with a mask being imaged on photoresist on a wafer. The mask *MTF* is almost ideal (*MTF* = 1) since the feature sizes are 4 – 5 X larger than those imaged in the resist and diffraction effects are minimal. The aerial image *MTF* is much lower (*MTF* ≈ 0.6) because of diffraction effects in the optical system.

$$MTF = (I_{max} - I_{max}) / (I_{max} + I_{max})$$

MTF vs. tamanho de estruturas

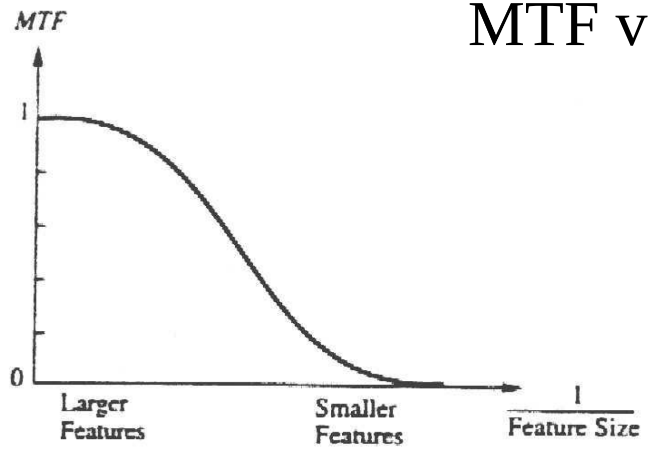


Figure 5–11 Modulation Transfer Function (*MTF*) versus feature size in the image.

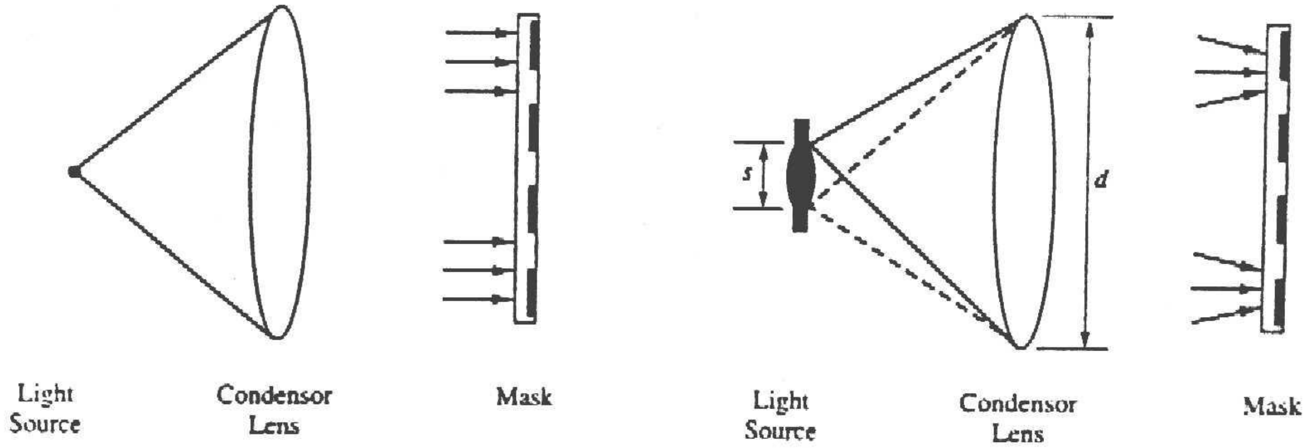


Figure 5–12 Examples of spatially coherent (left) and partially coherent (right) light sources.

Sistemas de exposição por contato ou proximidade (difração Fresnel)

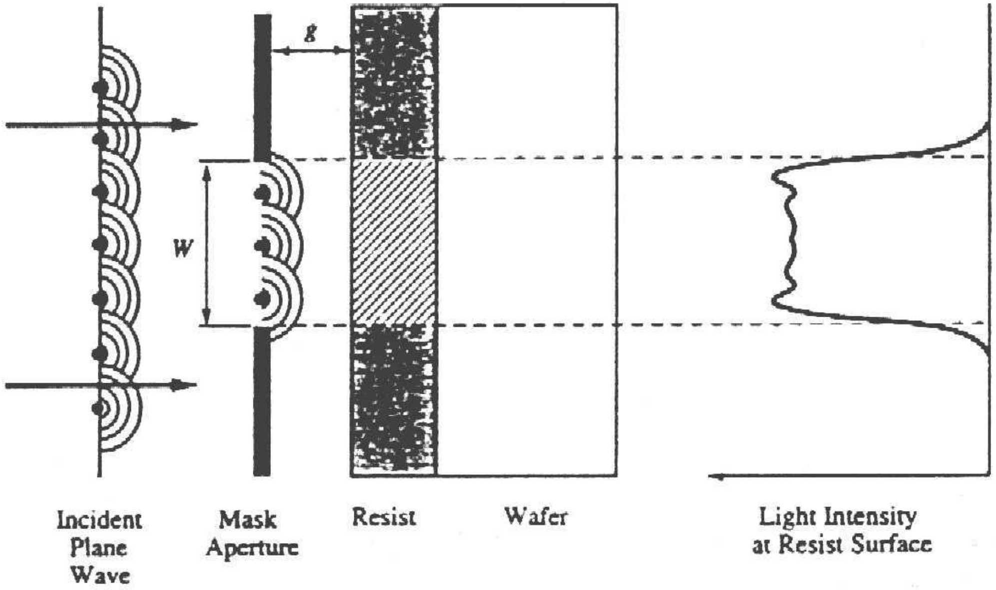


Figure 5–14 Basic contact or near field exposure system illustrating the use of Huygen's wavelets emanating from an aperture in the mask. A mask feature size of *W* is assumed, along with a mask to resist separation of *g*. The resulting light intensity distribution (aerial image) at the resist surface is shown on the right.

Difração Fresnel,
a condição para a separação (*gap*) *g* :

$\lambda < g < W^2/\lambda$

Qualidade de imagem para diferentes sistemas de projeção

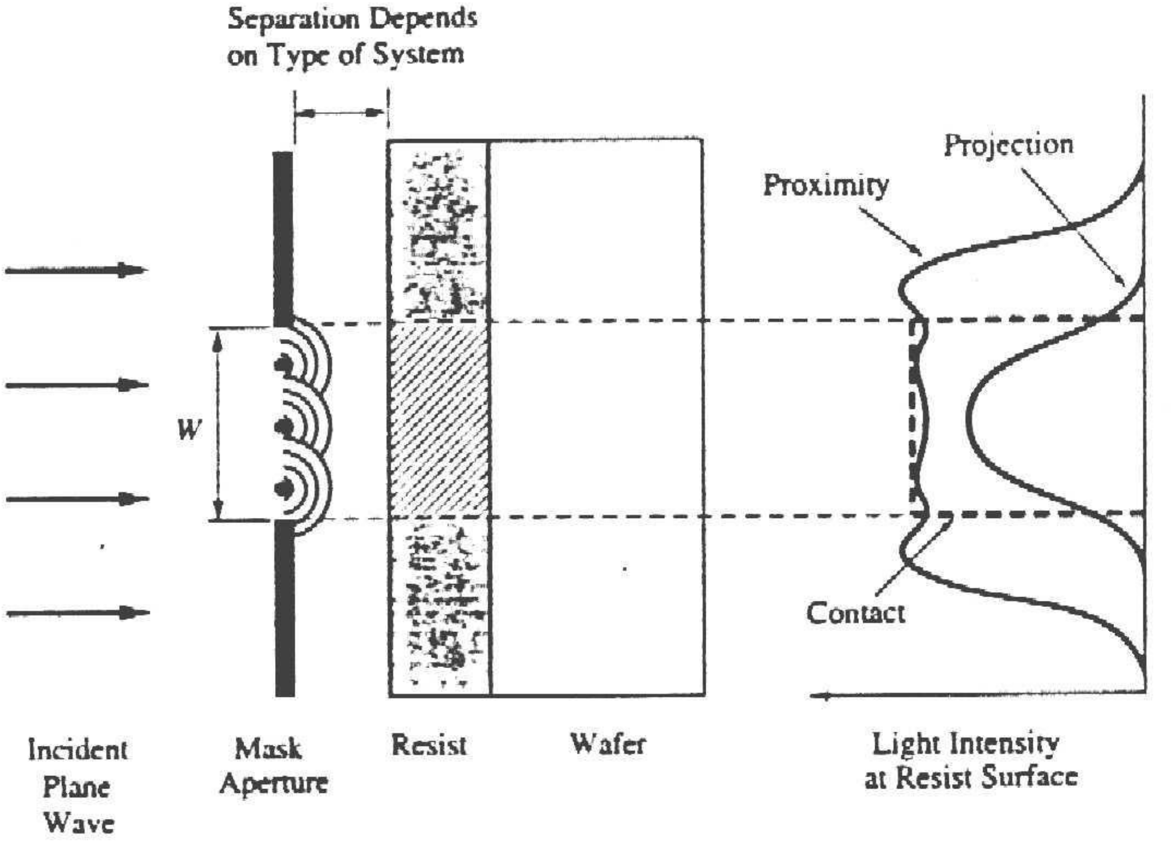


Figure 5–15 Aerial images produced by the three types of optical lithography tools. The mask and wafer would be in hard contact in a contact aligner, separated by a gap *g* in a proximity aligner, and far apart with an intervening focusing lens in a projection system.

Espectro típico de emissão das lâmpadas de Hg de alta pressão usadas para fotogravação

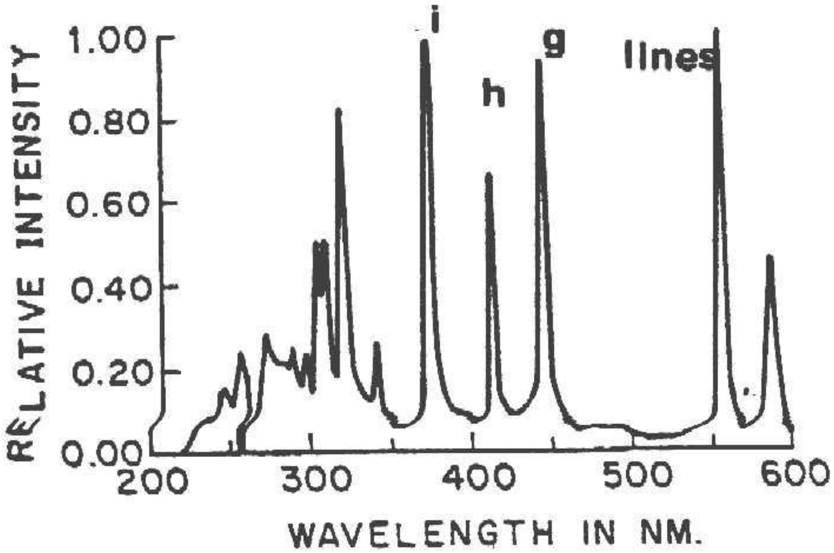


Fig. 12 Typical high pressure mercury-arc spectrum. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

Foto-resistes (linhas *g* e *i* - visível e UV) e a foto-química de processos

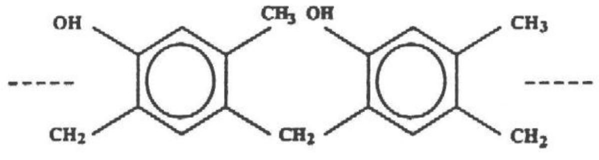


Figure 5–16 Basic structure of novolac, a thick resin used as the base material in positive photoresists.

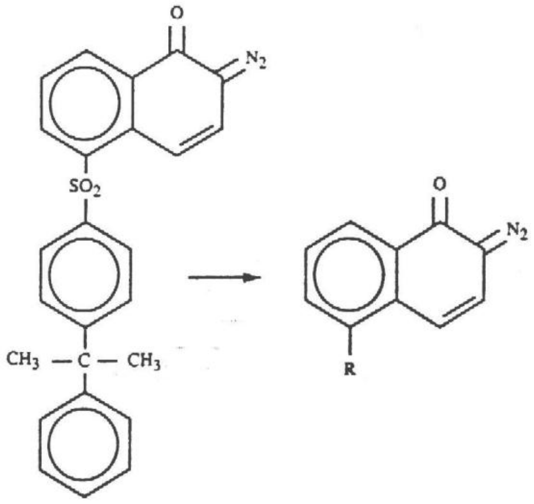


Figure 5–17 Basic structure of diazoquinone, a commonly used photoactive compound in positive photoresists. R represents the bottom part of the molecule.

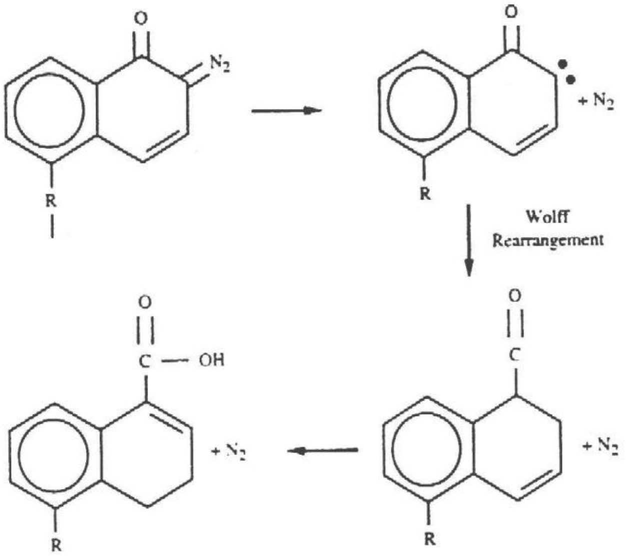


Figure 5–18 Decomposition process occurring in diazoquinones upon exposure to light.

Resistes para UV profunda (quartzo e VUV)

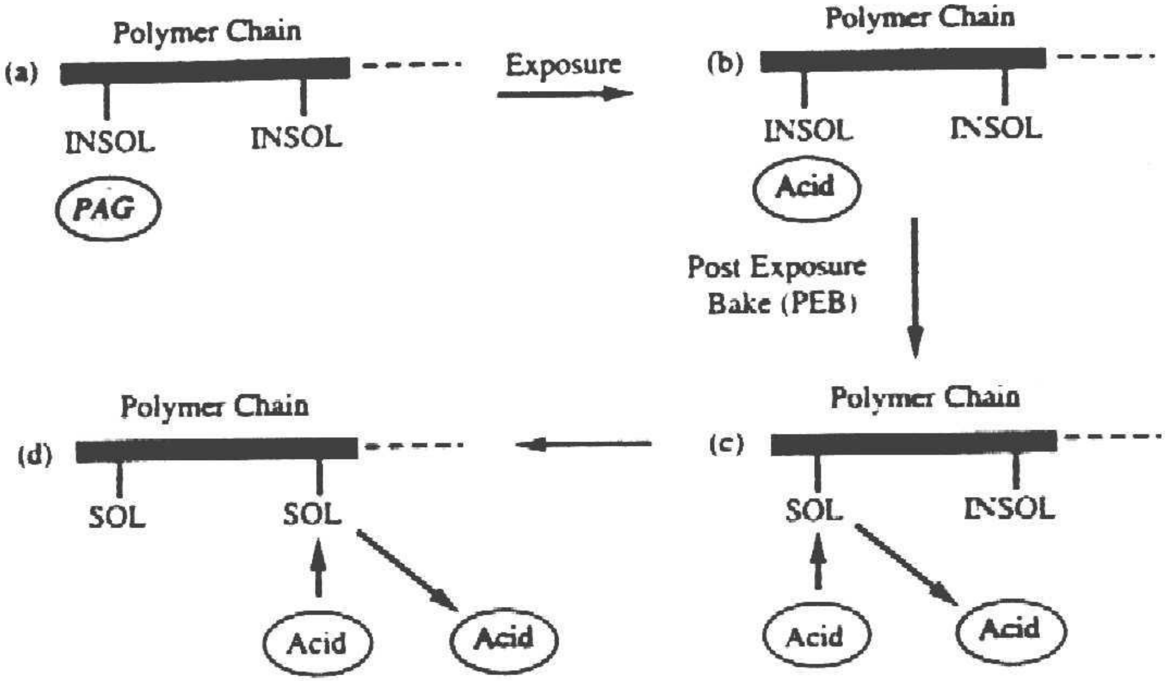


Figure 5–19 Basic operation of a Chemically Amplified (CA) resist. *PAG* is the photo-acid generator; INSOL and SOL are the insoluble and soluble portions of the polymer base. Steps (c) and (d) may repeat tens or hundreds of times during the PEB.

Resiste negativo: foto-química de processo

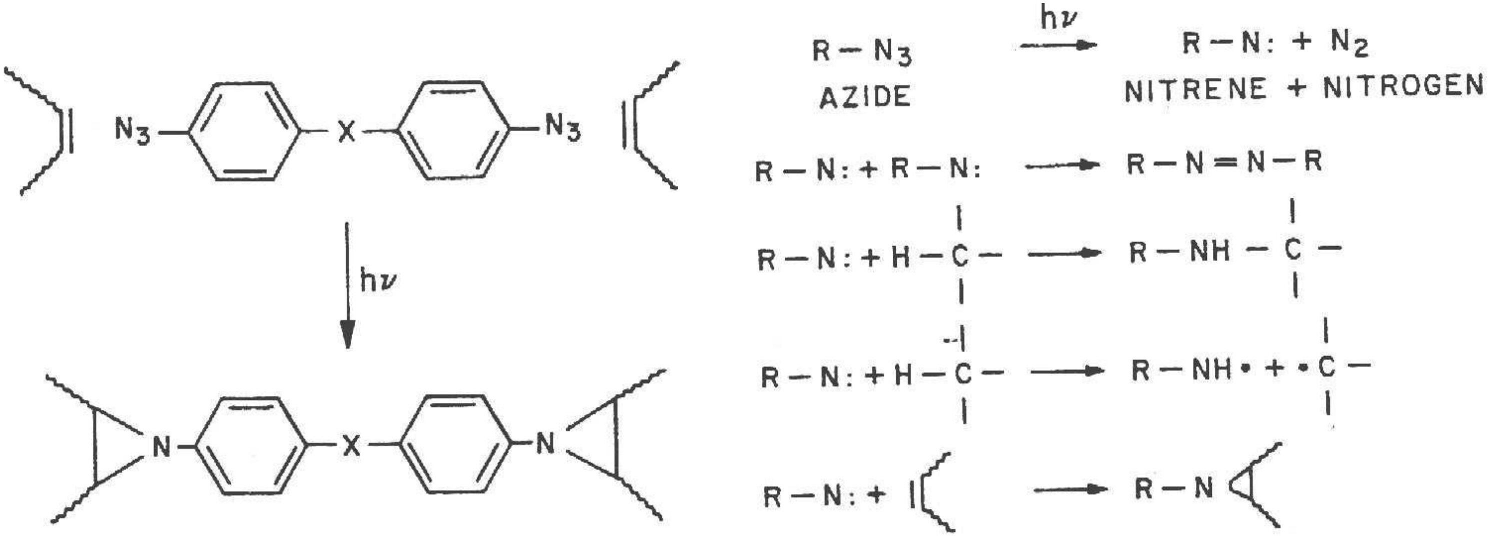


Fig. 9 Photochemical transformations of a bisazide sensitizer in negative photoresists based on cyclized polyisoprene. Reprinted from Ref. 1 with permission of the American Chemical Society.

Reversão de imagem (resiste positivo)

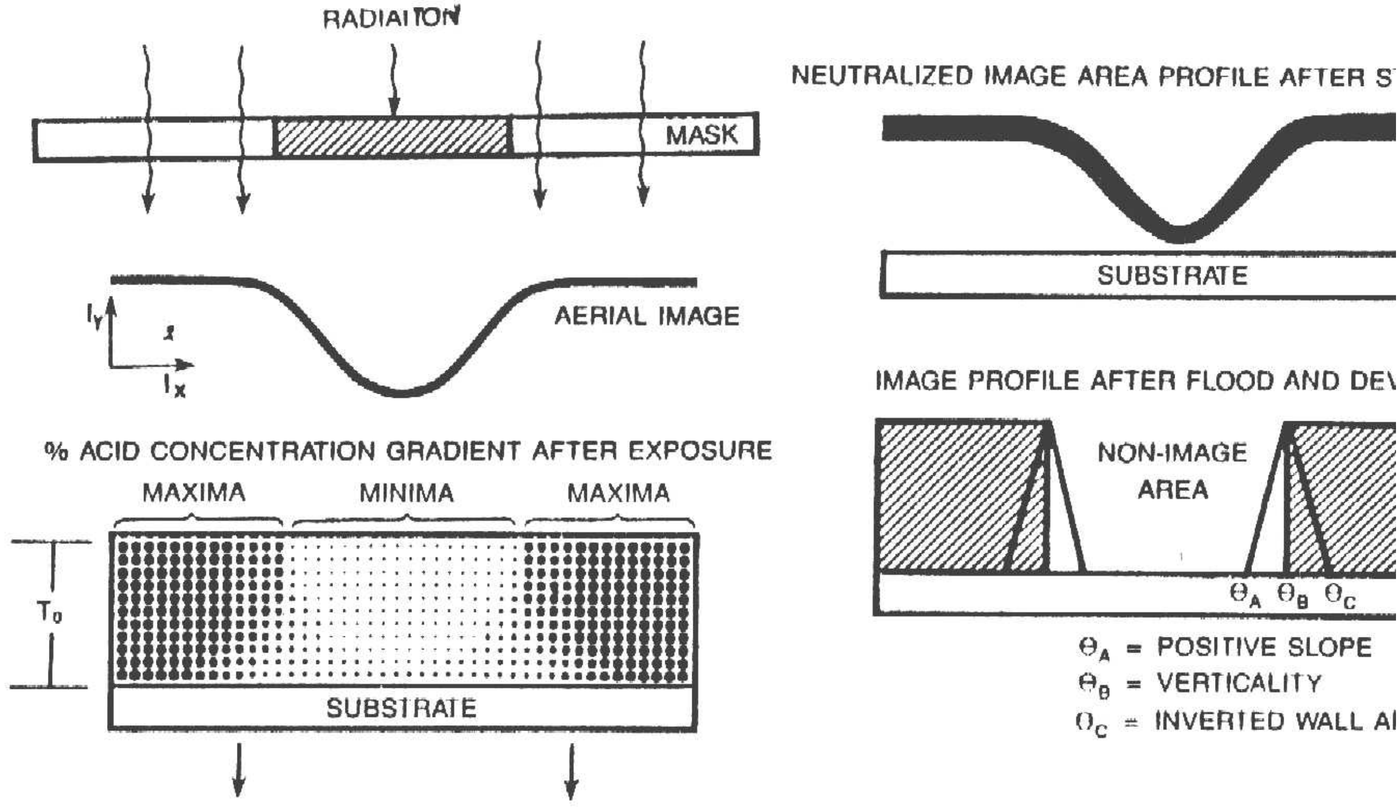


Fig. 10 Sequence of steps in an image reversal process[20]. Reprinted with permissi

Processo de 3 camadas (planarização)

enhancement layer (CEL) . The penalties incurred for obtaining

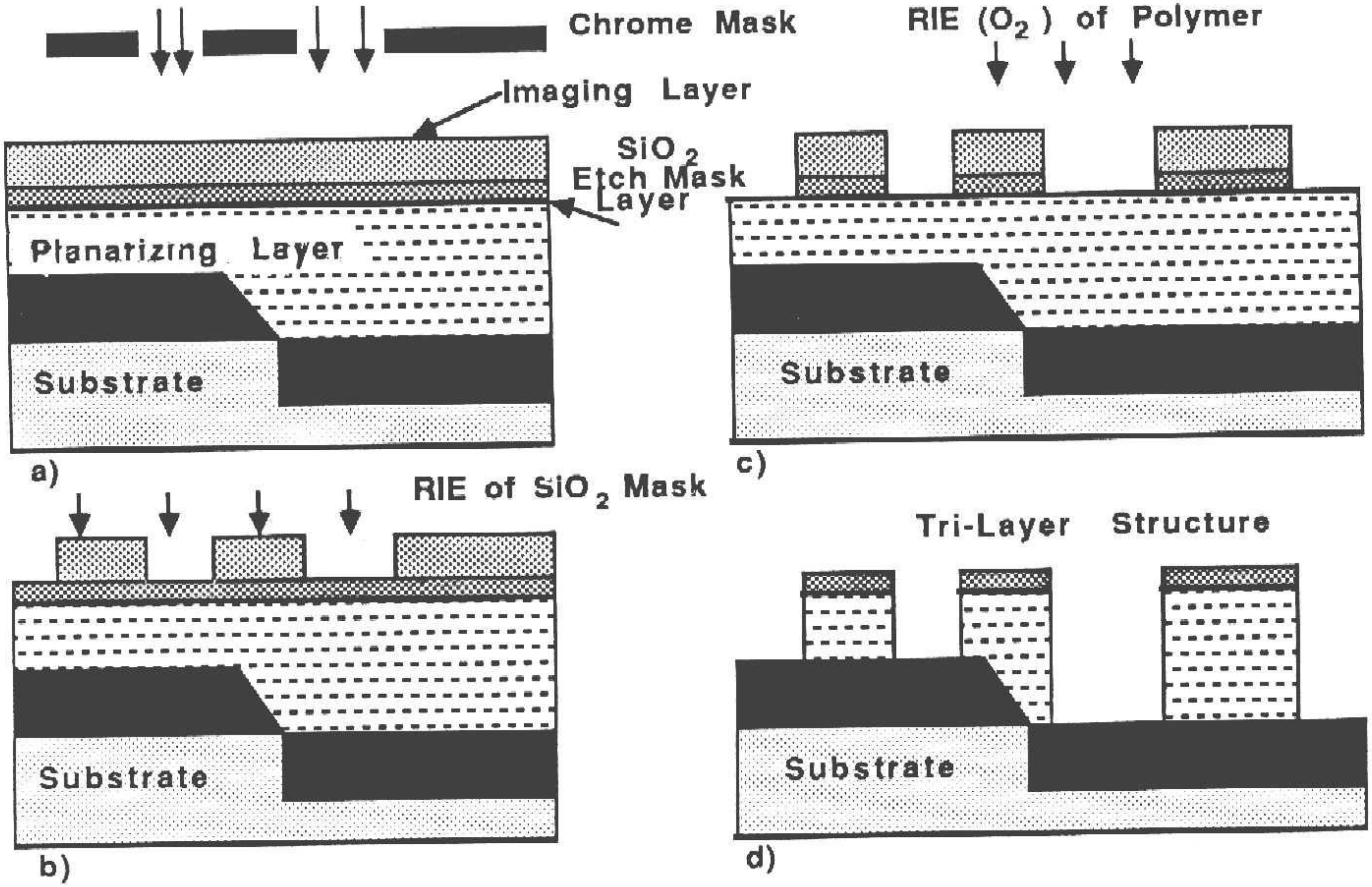


Fig. 11 Schematic of the tri-layer process[21]. Reprinted with permission of Solid St Technology, published by Technical Publishing, a company of Dun & Bradstreet.

Foto-resistes positivos e negativos: contraste

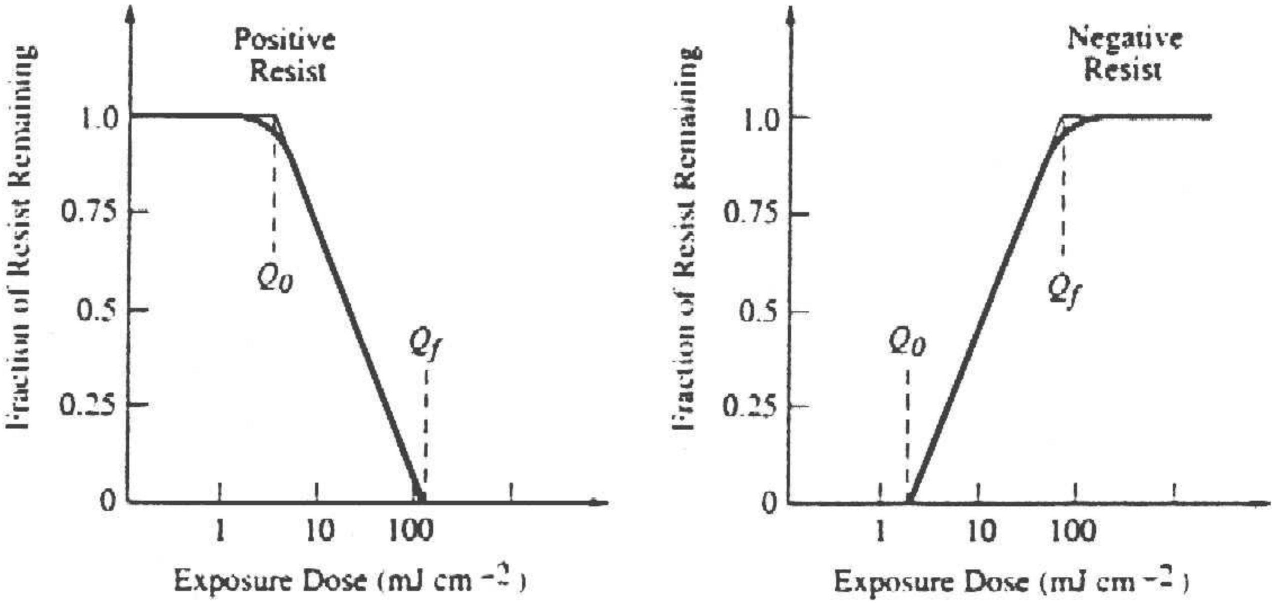


Figure 5–20 Idealized contrast curves for positive and negative resists.

Contraste: $\gamma = [\lg Q_f / Q_o]$

Aumento de contraste usando uma camada adicional com propriedades não-lineares (*contrast enhancement layer* - CEL)

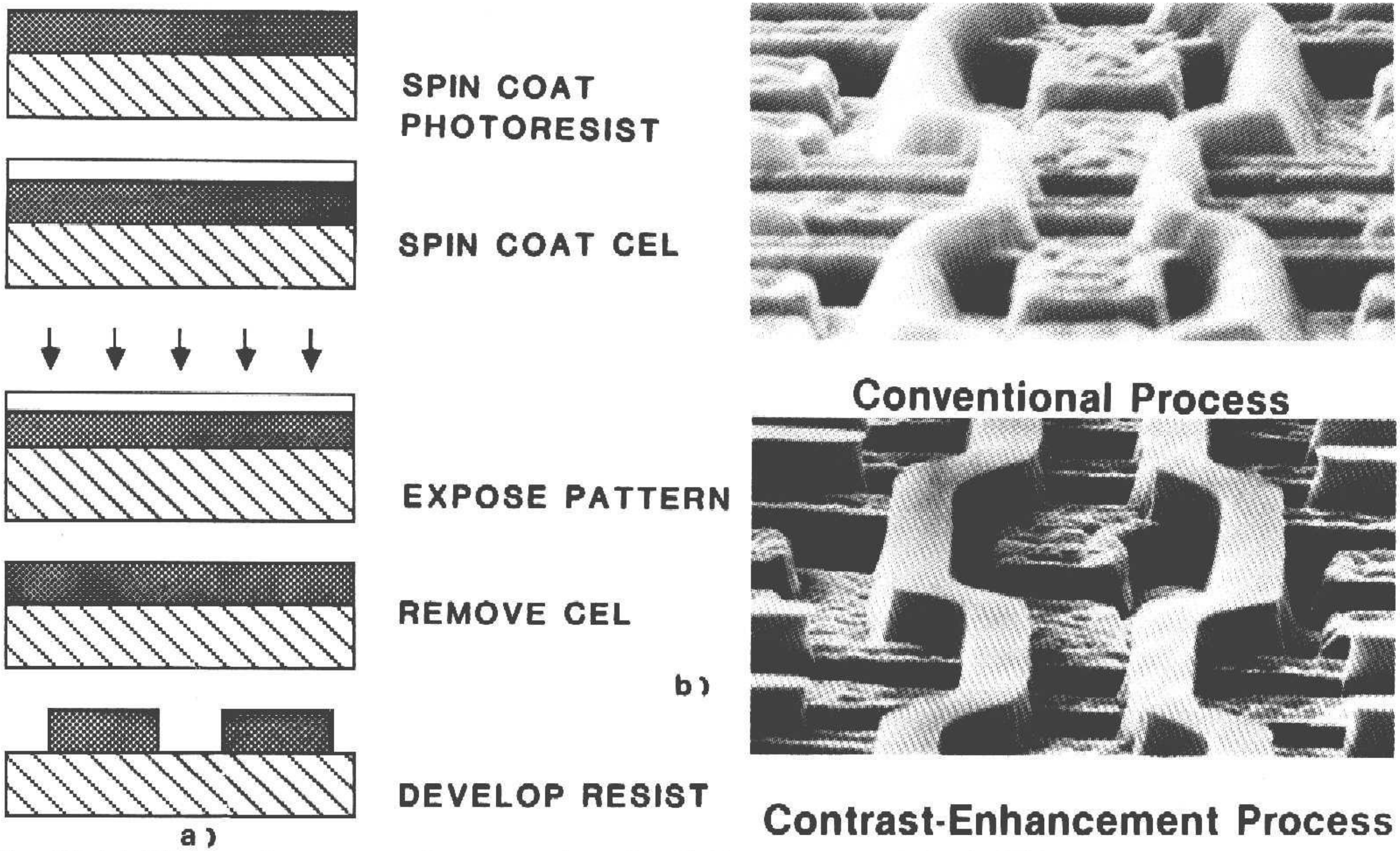


Fig. 12 (a) Photoresist process incorporating the CEL concept. Added CEL steps are outlined in boxes. (b) SEMs (8000X) of identical microcircuits produced with and without a CEL. Courtesy of the General Electric Research and Development Center.

MTF crítica: característica de fororresiste (MTF mínima necessária para resolver a estrutura no resiste)

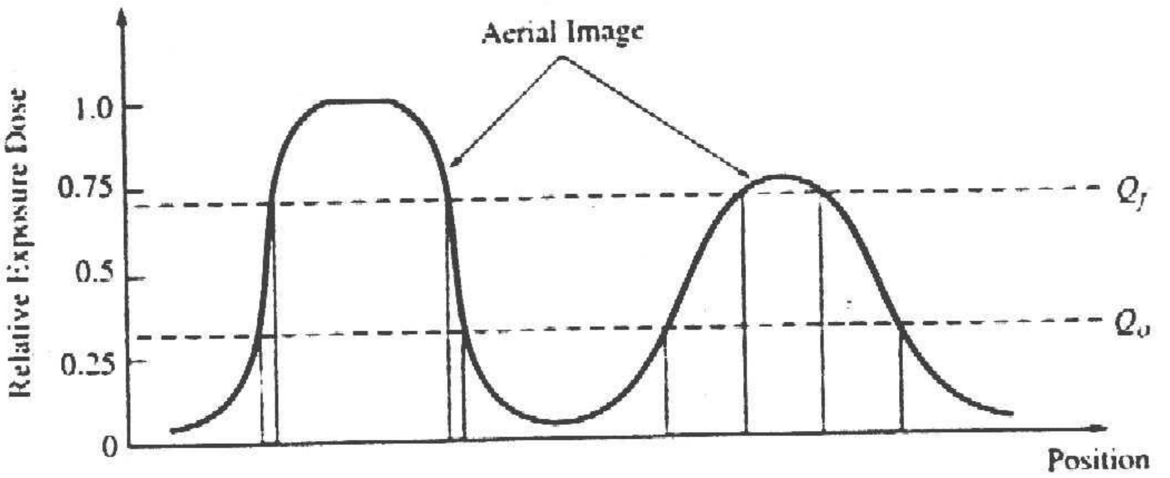


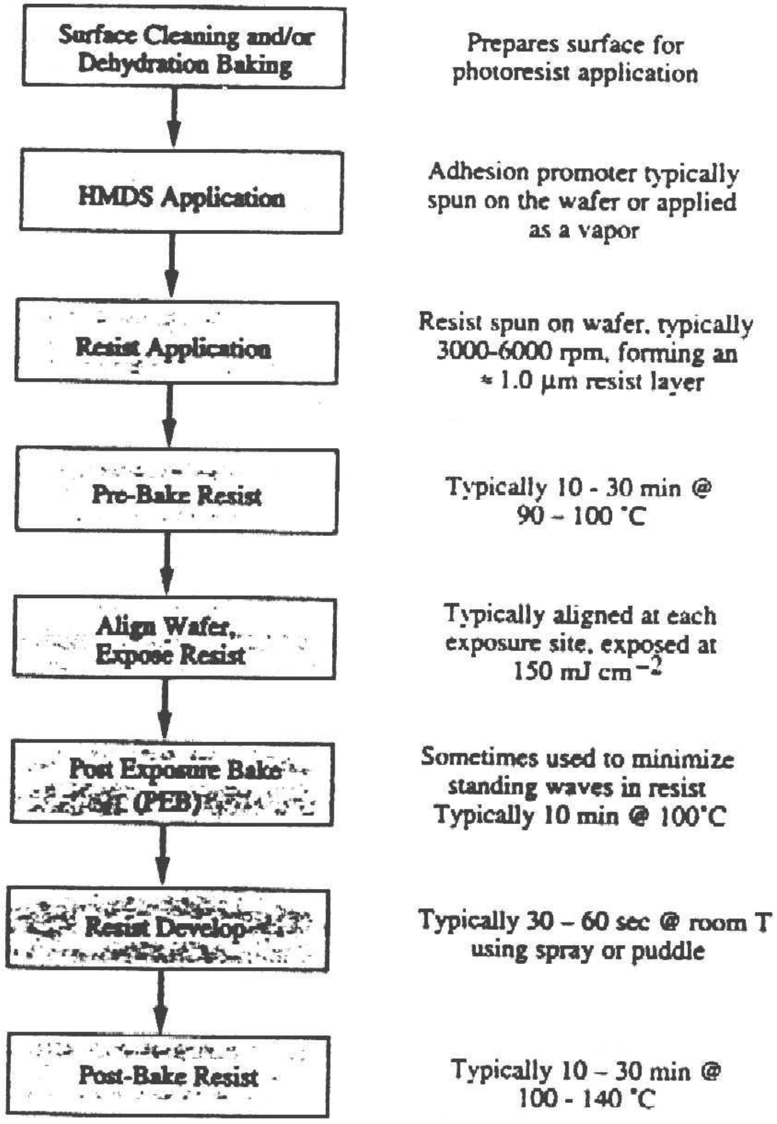
Figure 5–21 Example of how the quality of the aerial image and the resist contrast combine to produce the resist edge profile. The left side shows a sharp aerial image and steep resist edges (gray area). The example on the right shows a poorer aerial image and the resulting gradual edges on the resist profile.

MTF crítica : *CMTF*=$(Q_f - Q_o)/(Q_f + Q_o)$

CMTF ~ 0.4 para *g* e *i* linhas.

Para DUV resistes (contaste maior) , *CMTF* ~ 0.1-0.2

Seqüência típica do processamento de resistes



Surface Cleaning and/or Dehydration Baking	Prepares surface for photoresist application
HMDS Application	Adhesion promoter typically spun on the wafer or applied as a vapor
Resist Application	Resist spun on wafer, typically 3000-6000 rpm, forming an ≈ 1.0 μm resist layer
Pre-Bake Resist	Typically 10 - 30 min @ 90 – 100 °C
Align Wafer, Expose Resist	Typically aligned at each exposure site, exposed at 150 mJ cm^{-2}
Post Exposure Bake (PEB)	Sometimes used to minimize standing waves in resist Typically 10 min @ 100°C
Resist Develop	Typically 30 – 60 sec @ room T using spray or puddle
Post-Bake Resist	Typically 10 – 30 min @ 100 - 140 °C

Figure 5–31 Typical photoresist process flow for DNQ g-line and i-line positive resists.

Mecanismo de melhoria na aderência com superfícies de óxido usando HMDS

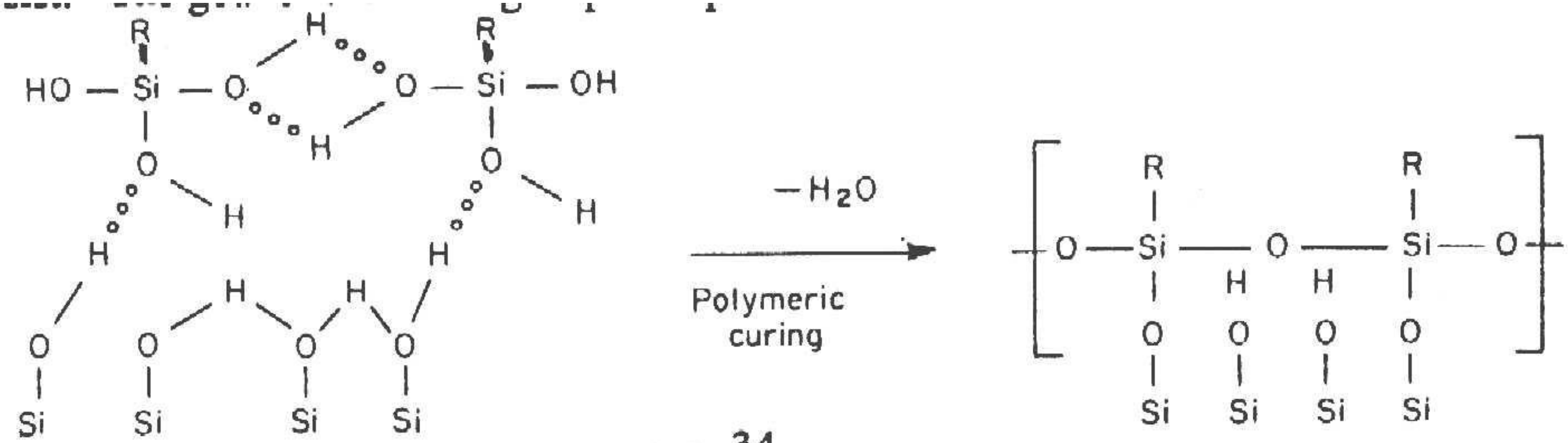


Fig. 15 HMDS bonding mechanism with SiO_2[34].