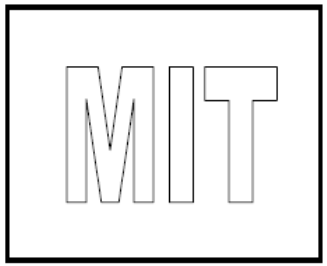
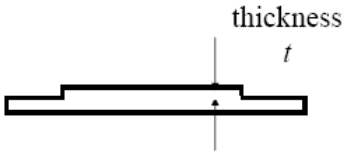
Oggetto di fase in ottica

Phase objects



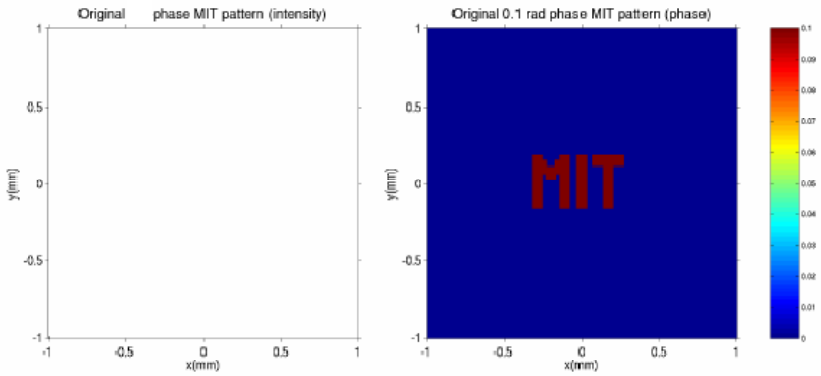
glass plate
(transparent)



protruding part
phase-shifts
coherent illumination
by amount $\varphi=2\pi(n-1)t/\lambda$

Often useful in imaging biological objects (cells, etc.)

Viewing phase objects



Intensity
(object is invisible)

Amplitude
(need interferometer)

MIT 2.71/2.710 Optics
11/08/04 wk10-a-37

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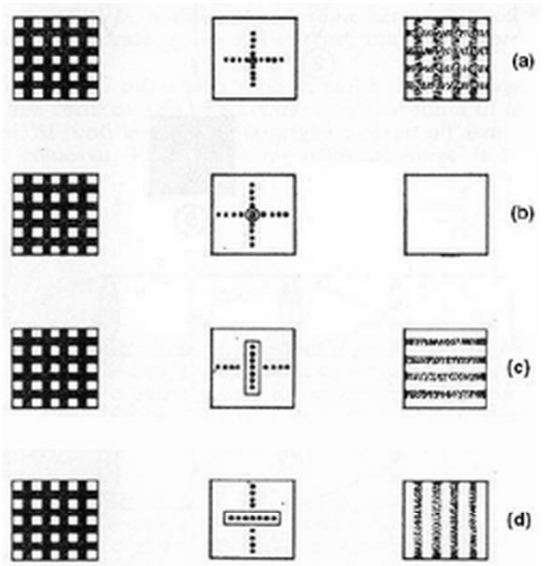
PB: Come trasformare l'informazione contenuta nella FASE dell'onda trasmessa in CONTRASTO DI INTENSITA' osservabile?

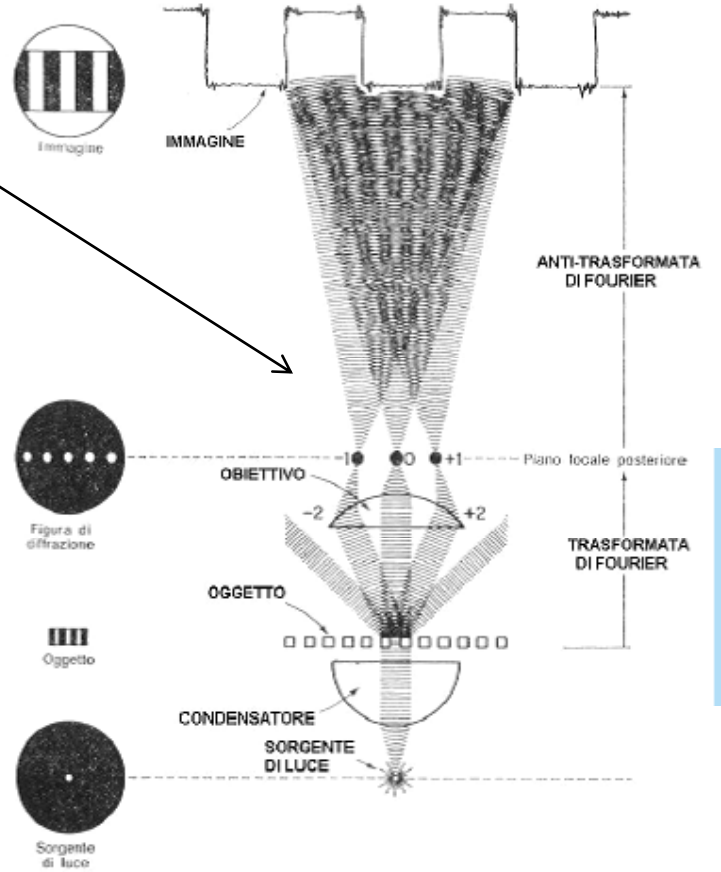
- Filtraggio spaziale
- Piatto di fase (OTTICA)
- Interferenza
- Olografia

Teoria di ABBE e filtraggio spaziale

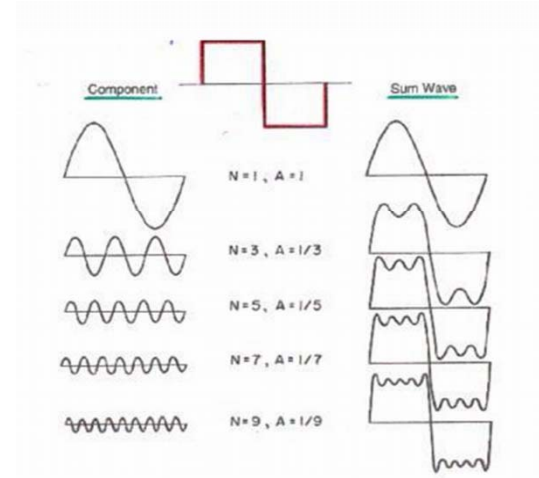
Contrasto e risoluzione

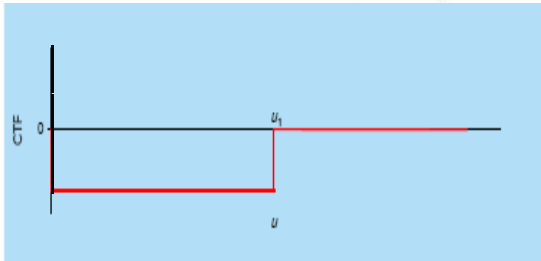


Esempio di filtraggio spaziale



(1) Formazione dell'immagine esplicata dalla teoria di Abbe





Funzione di trasferimento del contrasto di fase (ampiezza) ideale

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Coherent imaging

Thin transparency $t(x,y)$

$g_1(x,y)$ → illumination → $g_2(x,y) = g_1(x,y)\,t(x,y)$

$h(x,y) = \mathrm{sinc}\left(\frac{x'a}{\lambda f_2}\right)\mathrm{sinc}\left(\frac{y'b}{\lambda f_2}\right)$

impulse response → **convolution**

output amplitude: $g_3(x',y') = g_2(x,y) * h(x,y)$

Fourier transform ⇕

Fourier transform ⇕

(≡plane wave spectrum) $G_2(u,v)$

transfer function → **multiplication**

$G_3(u,v) = G_2(u,v)H(u,v)$

$$H(u,v) = \mathrm{rect}\left(\frac{\lambda f u}{a}\right)\mathrm{rect}\left(\frac{\lambda f v}{b}\right)$$

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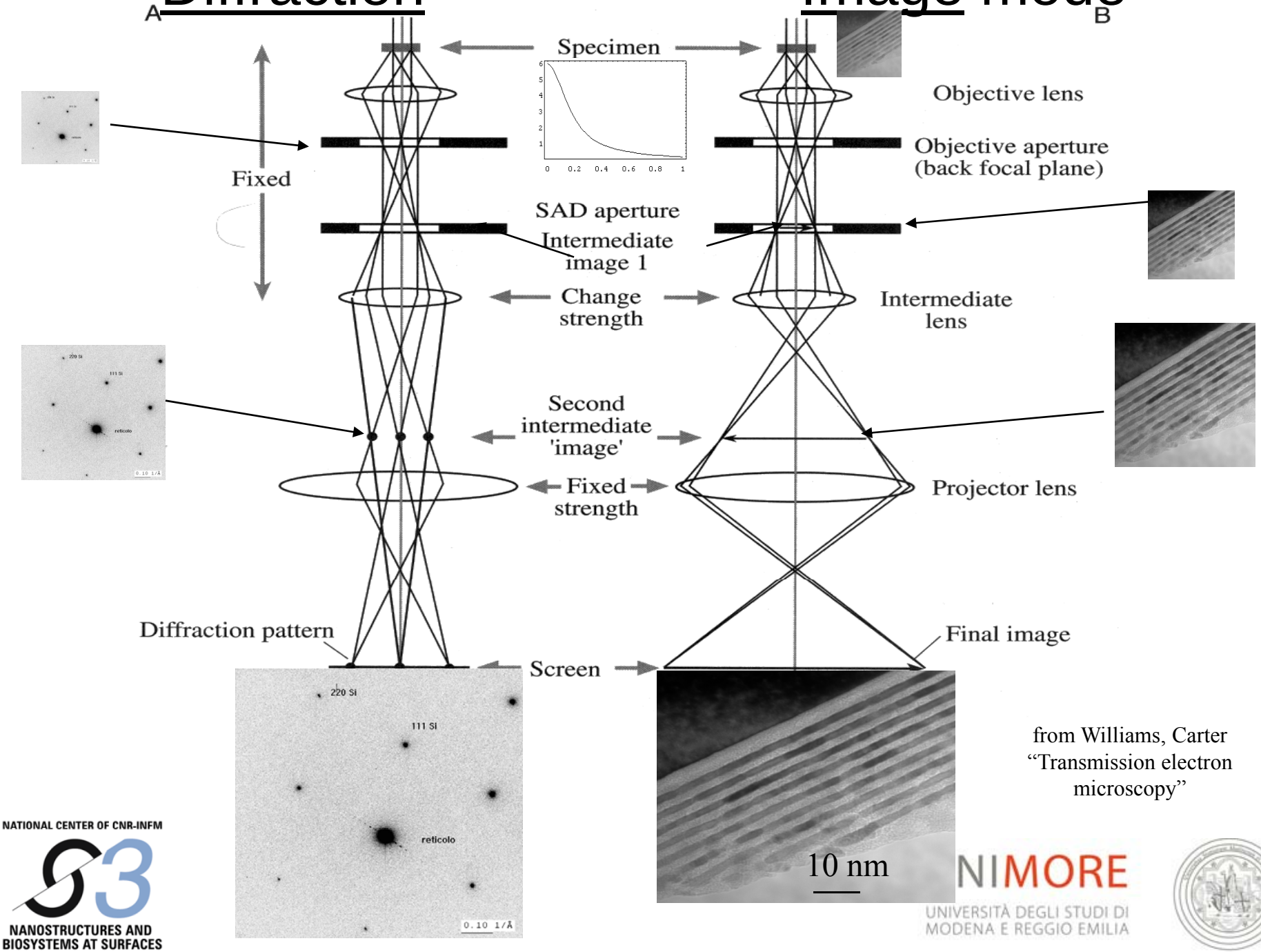
Diffraction Image mode



from Williams, Carter
"Transmission electron
microscopy"

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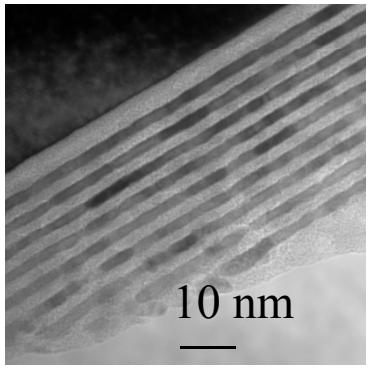
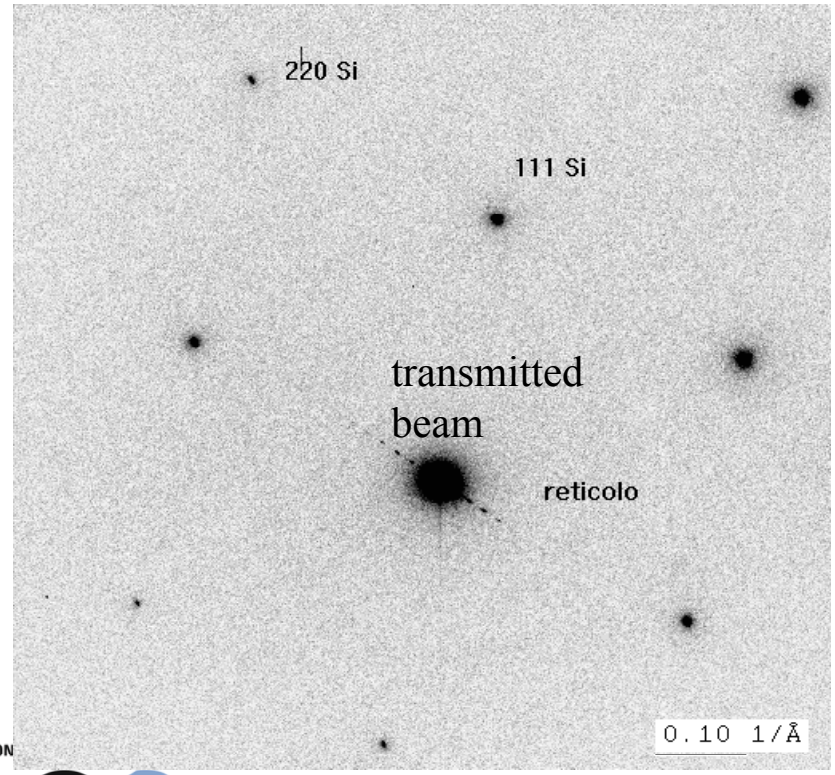
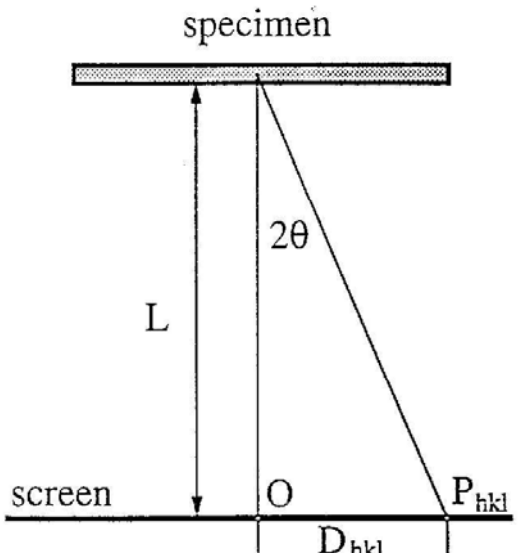
CTEM and Selected Area Electron Diffraction (SAED)







$$2d_{hkl}\sin(\theta_B) = \lambda : \text{legge di Bragg}$$

$$d_{hkl}\sin(2\theta_B) = \lambda$$

$$\sin(2\theta_B) \approx \tan(2\theta_B) \approx 2\theta_B \approx \frac{D_{hkl}}{L}$$

$$d_{hkl} = \frac{\lambda L}{D_{hkl}}\left[1 + \frac{3}{8}\left(\frac{D_{hkl}}{L}\right)^2 + ...\right]$$

$$\frac{\Delta d_{hkl}}{d_{hkl}} \approx 0.001 - 0.01$$

NATION

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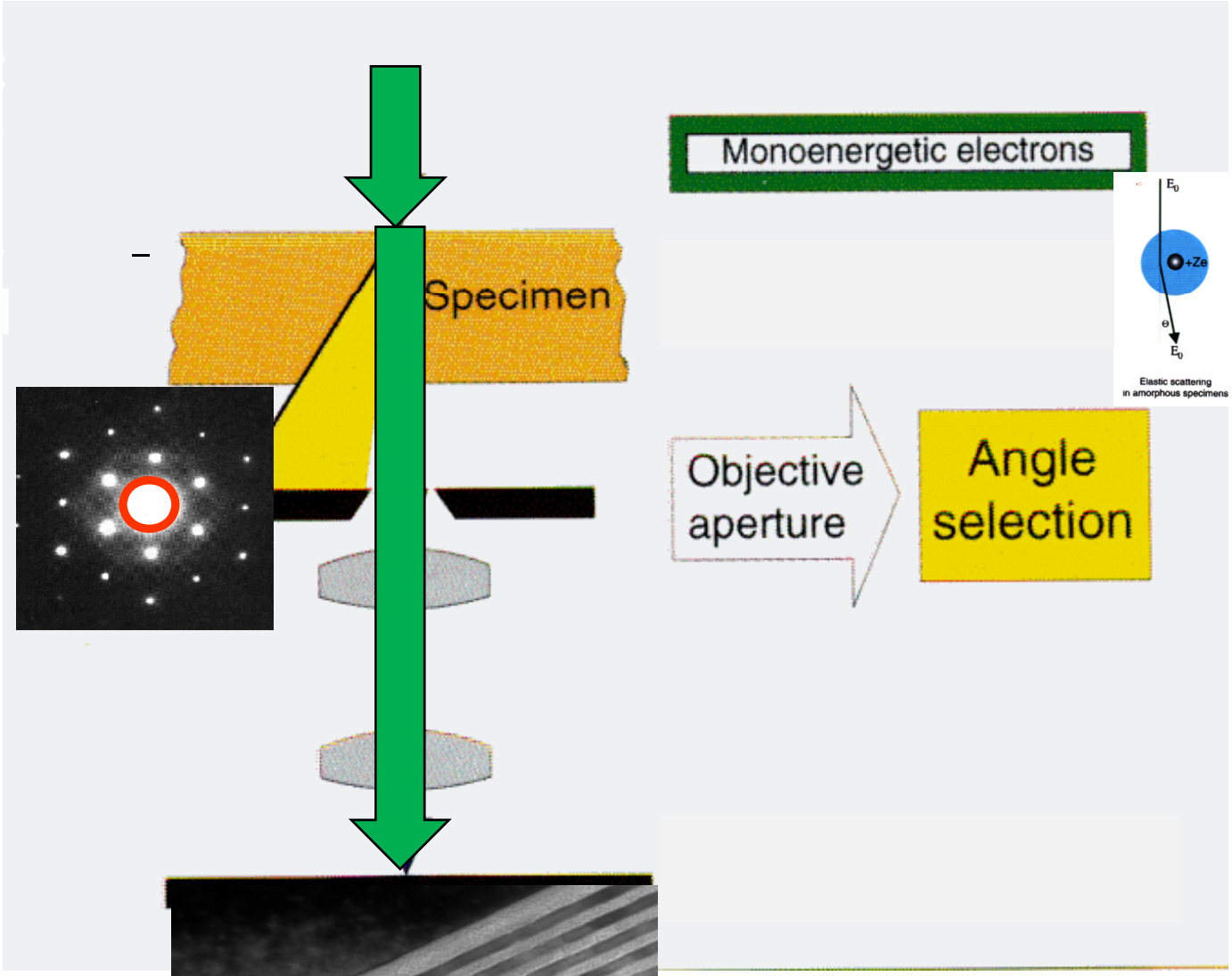

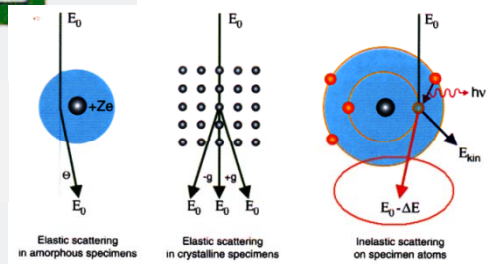

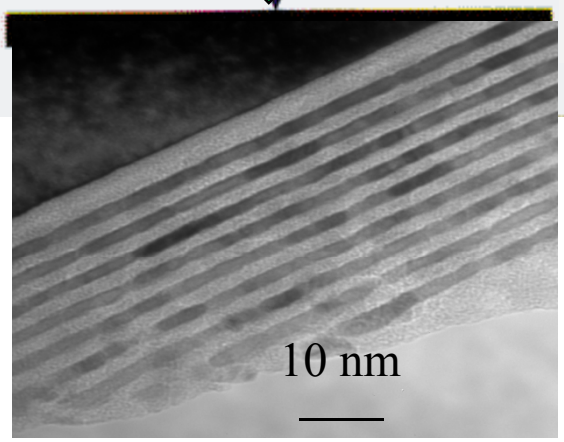

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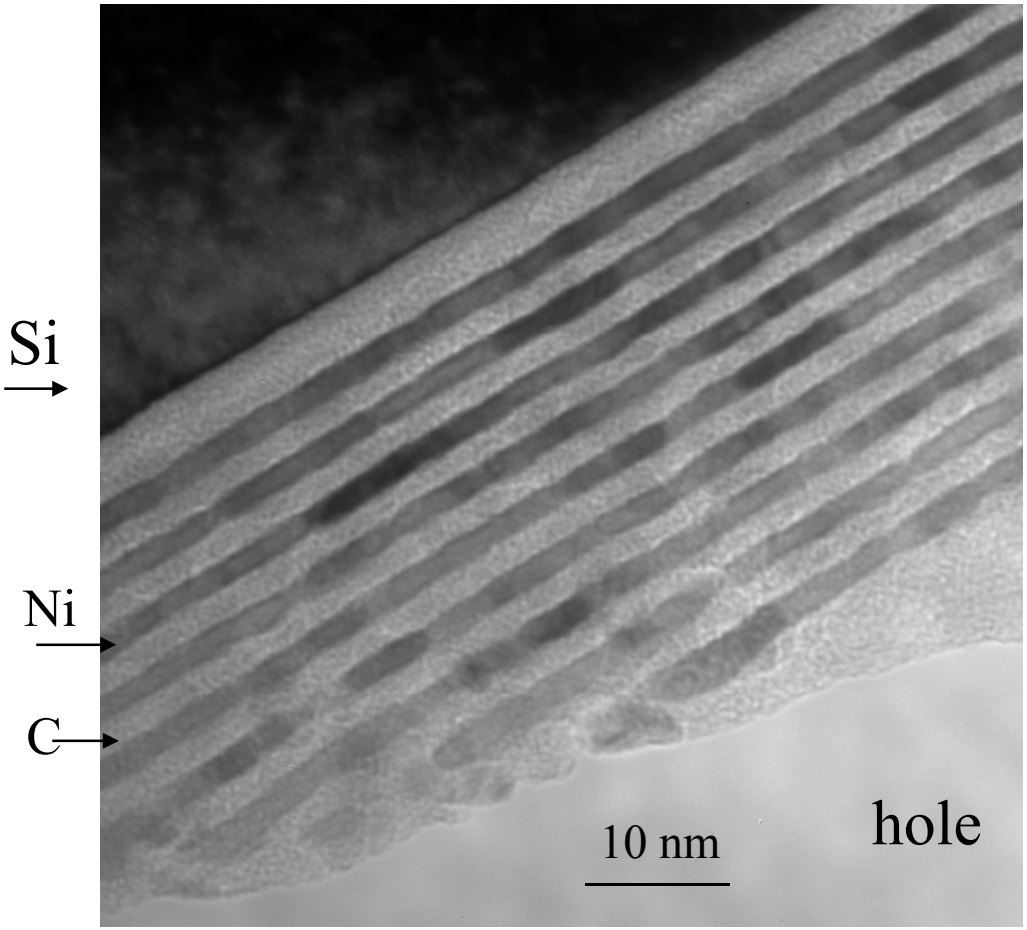
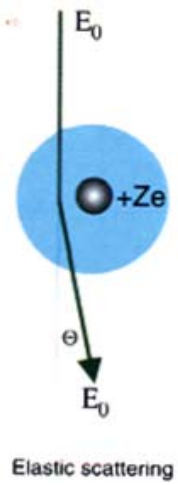
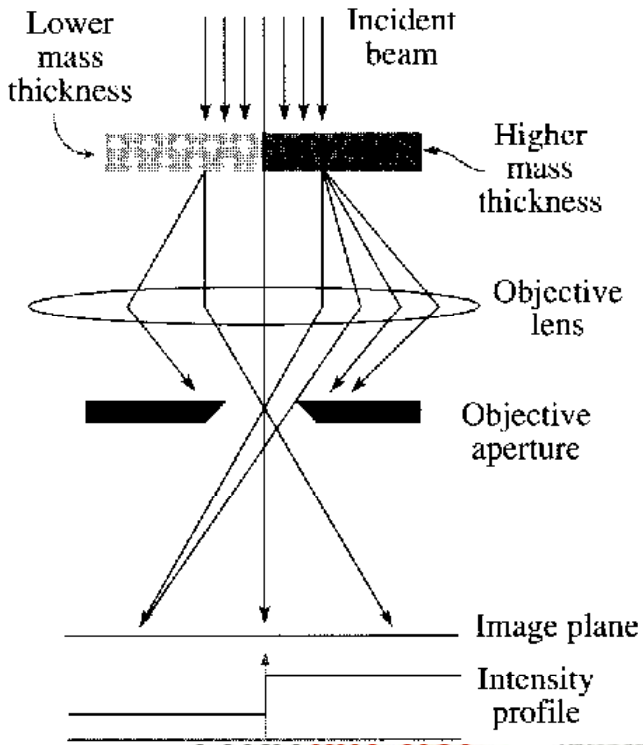
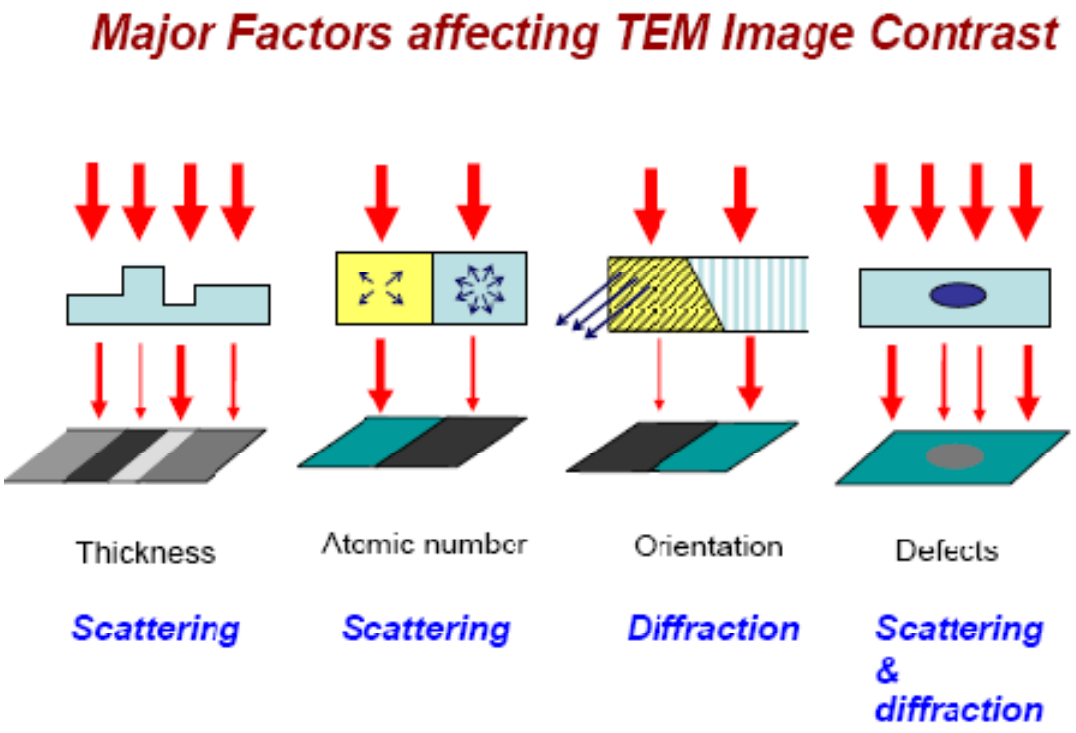
Contrasto di ampiezza prodotta dal diaframma di obiettivo







Low resolution (~1nm) imaging



Introduction to Electron Microscopy and Microanalysis
Vick Guo 1985

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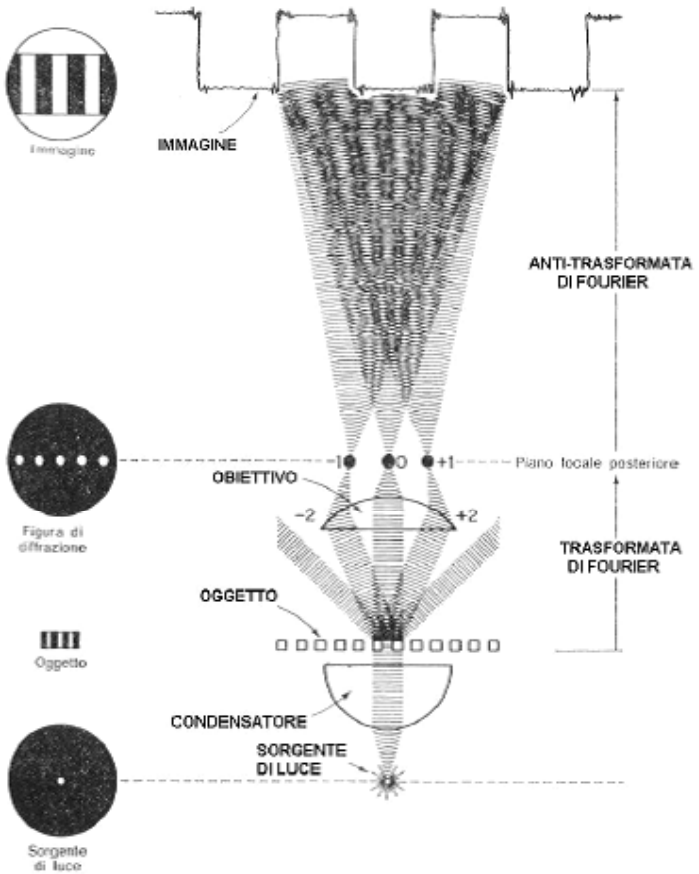
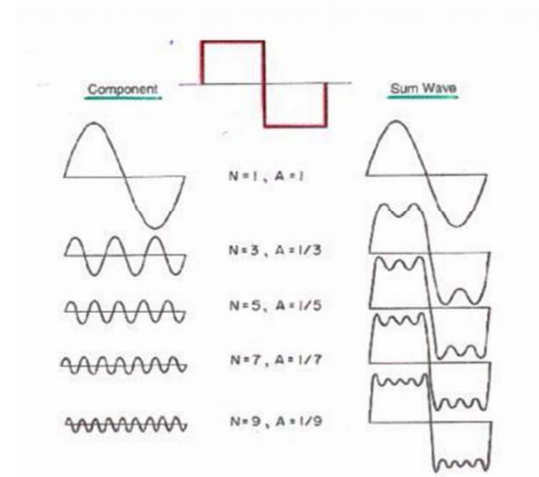
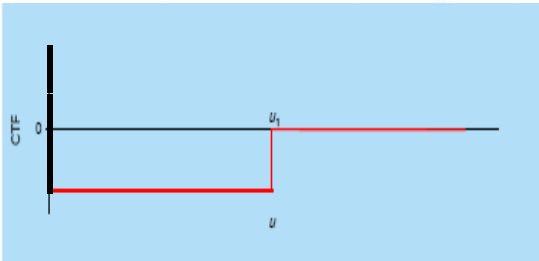
Teoria di ABBE e filtraggio spaziale



(1) Formazione dell'immagine esplicata dalla teoria di Abbe





Funzione di trasferimento del contrasto di fase ideale

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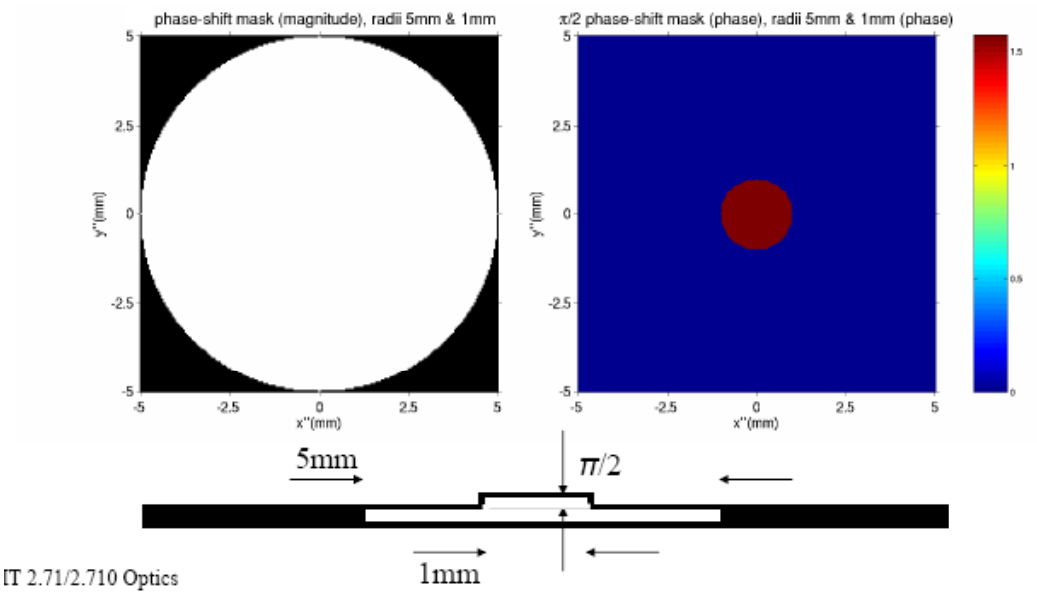
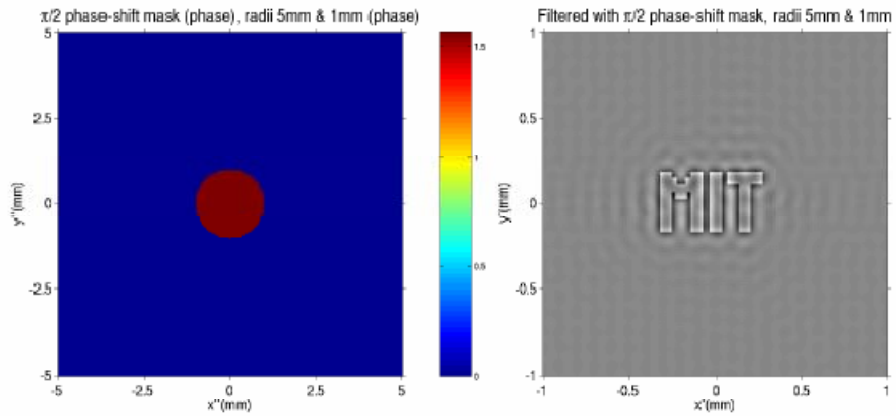
Zernicke phase-shift mask



Imaging with Zernicke mask



f_1=20cm
λ=0.5μm

Fourier filter

Intensity @ image plane

Zernike phase plate

$g(x) = e^{i\Phi(x)} \approx 1 + i\Phi(x)$ a meno di termini quadratici

$|1 + i\Phi(x)|^2 = 1 + \Phi^2(x) \approx 1$ a meno di termini quadratici

Ma se si riesce a moltiplicare per i o la parte diffratta dall'oggetto $\Phi(x)$, (o quella trasmessa) si ha :

$|1 - \Phi(x)|^2 = 1 - 2\Phi(x) + \Phi^2(x) \approx 1 - 2\Phi(x)$ a meno di termini quadratici

Nel piano FOCALE della lente obiettivo:

$$g(u) = F(g(x)) = \delta(u) + iF(\Phi(x))$$

$$g^{\otimes}(u) = \delta(u) + iiF(\Phi(x)) = \left(\delta(u) - F(\Phi(x))\right)$$

Nel piano IMMAGINE della lente obiettivo:

$$F^{-1}(g^{\otimes}(u)) = 1 - \Phi(x)$$

$$I = |1 - \Phi(x))|^2 = (1 - 2\Phi(x) + \Phi^2(x)) \approx 1 - 2\Phi(x)$$

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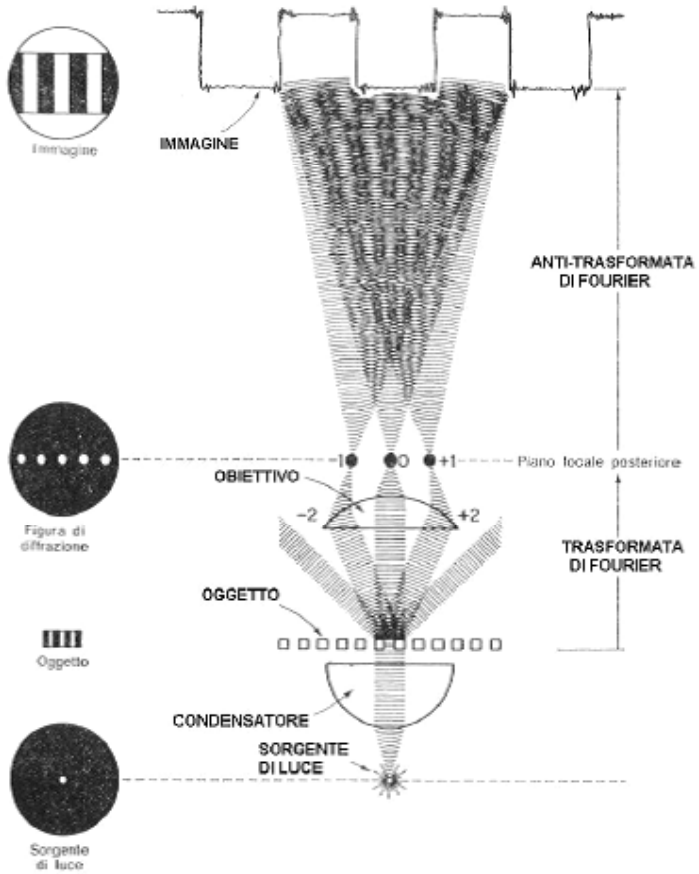
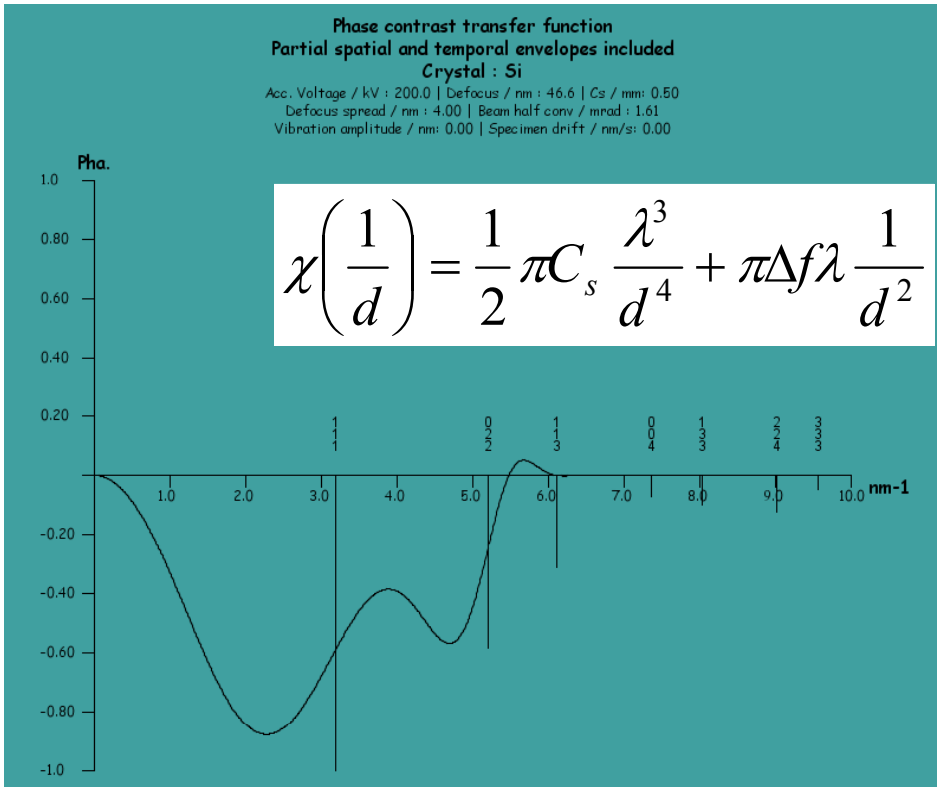
Immagini a risoluzione atomica



(1) Formazione dell'immagine esplicata dalla teoria di Abbe



$$\chi\left(\frac{1}{d}\right) = \frac{1}{2}\pi C_s \frac{\lambda^3}{d^4} + \pi \Delta f \lambda \frac{1}{d^2}$$

Optimum defocus (Scherzer defocus) Δf :

$$\Delta f = -1.2\left(\lambda C_s\right)^{1/2}$$
$$\sim 43\ nm$$

for optimum resolution

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Si monocristallino: direzione cristallografica di incidenza [110]

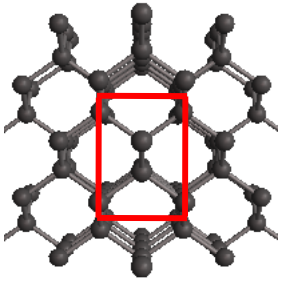
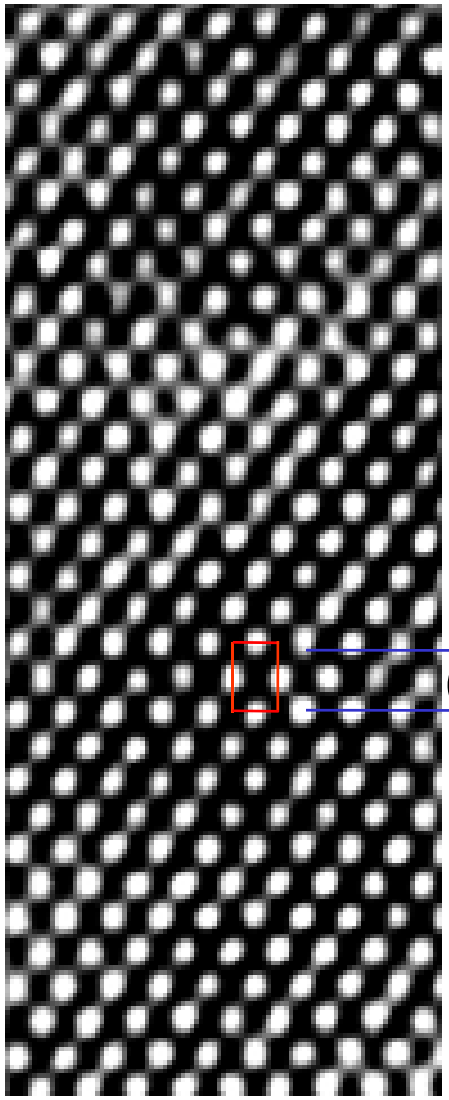


Immagine interferenziale a risoluzione atomica



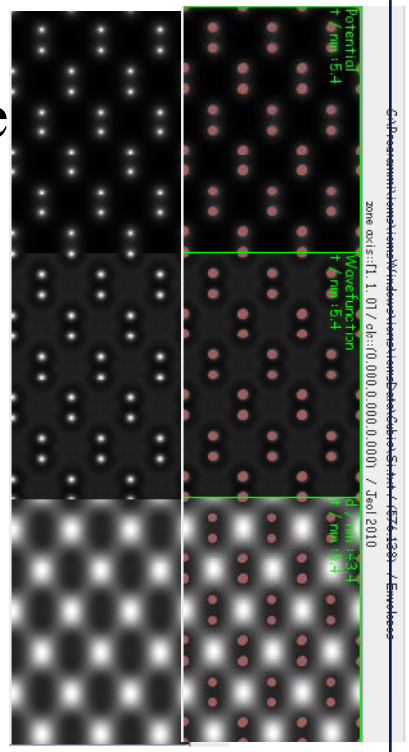
0.5431nm

Simulazione

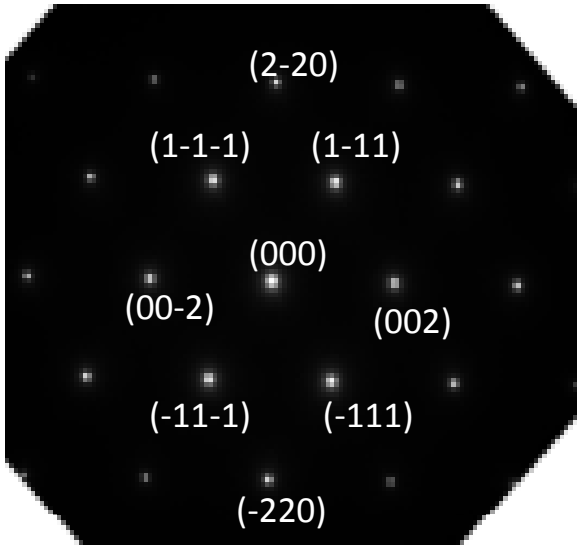
Potenziale

Funzione d'onda

Immagine



Diffrazione



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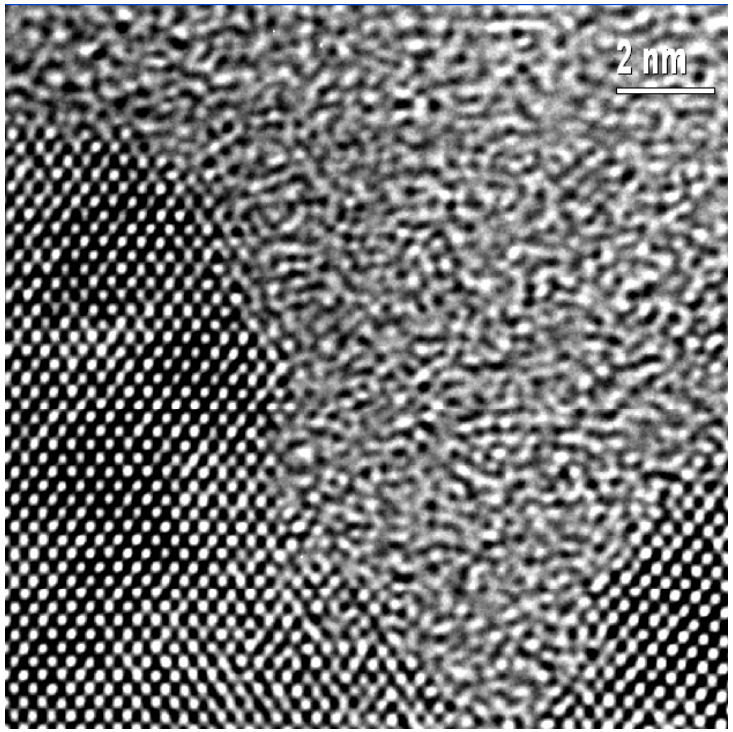
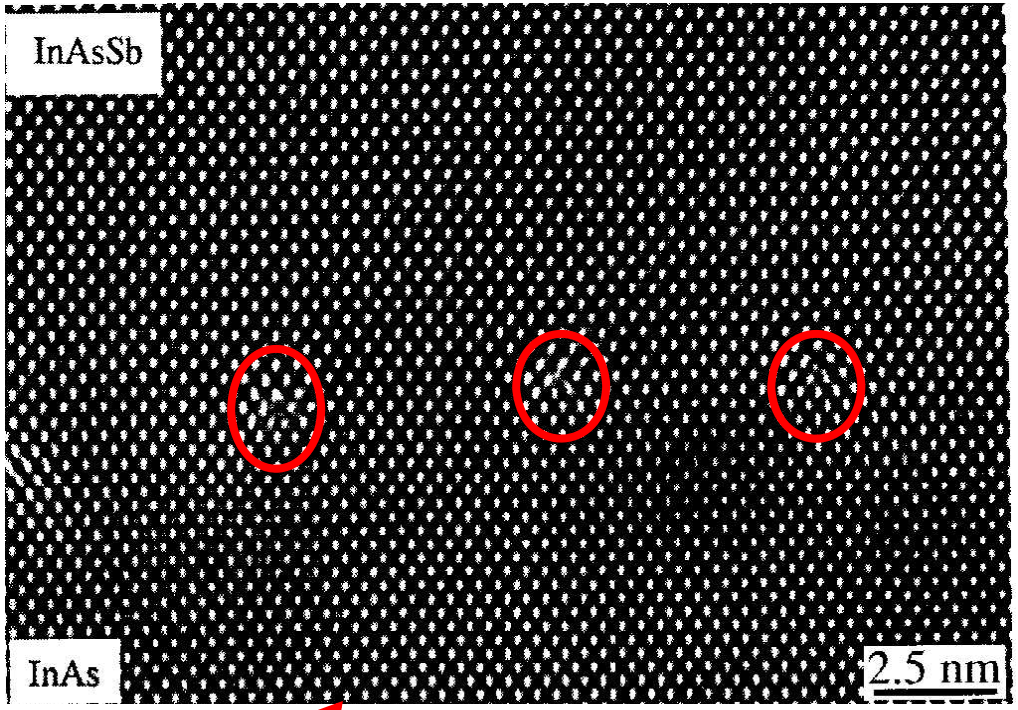
Immagini HREM direttamente interpretabili (debole oggetto di fase)

interfaccia amorfo-cristallo



interfaccia eterostruttura semiconduttore



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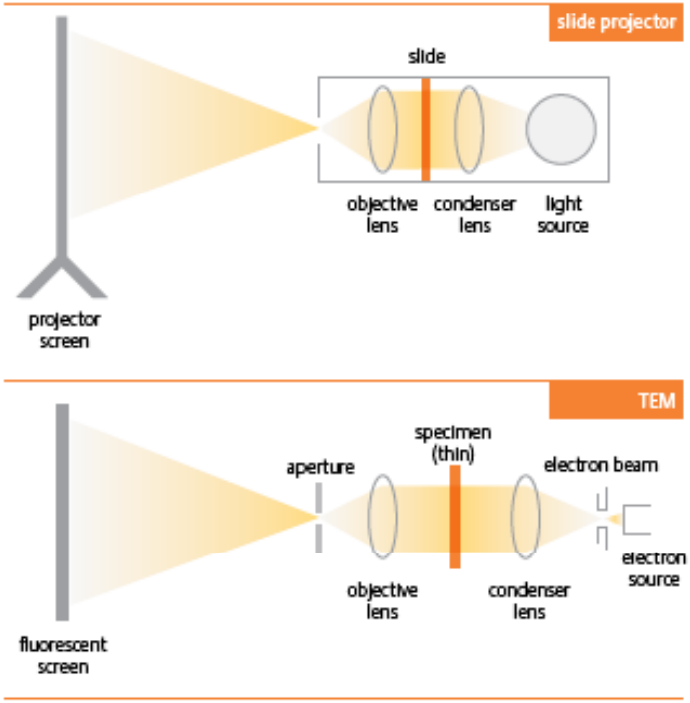
Parte lab:
Il microscopio ottico a proiezione come modello per introdurre la microscopia elettronica in trasmissione



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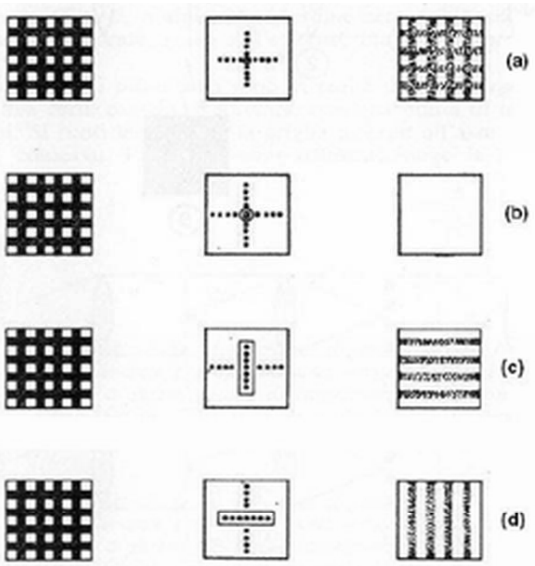
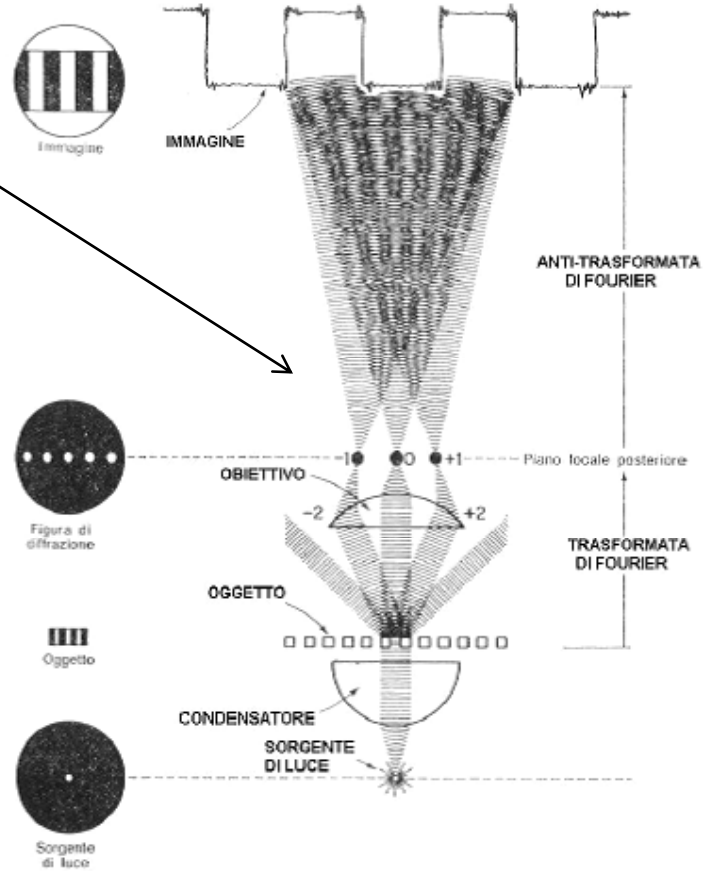
Teoria di ABBE e filtraggio spaziale

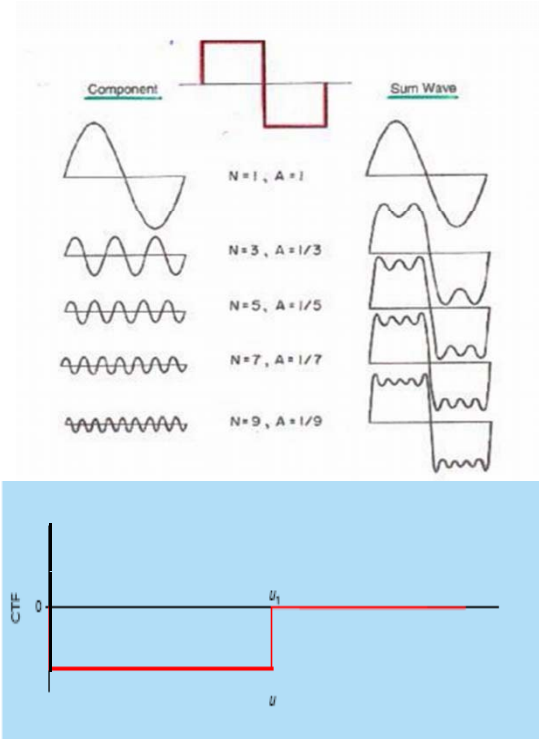
Contrasto e risoluzione



Esempio di filtraggio spaziale



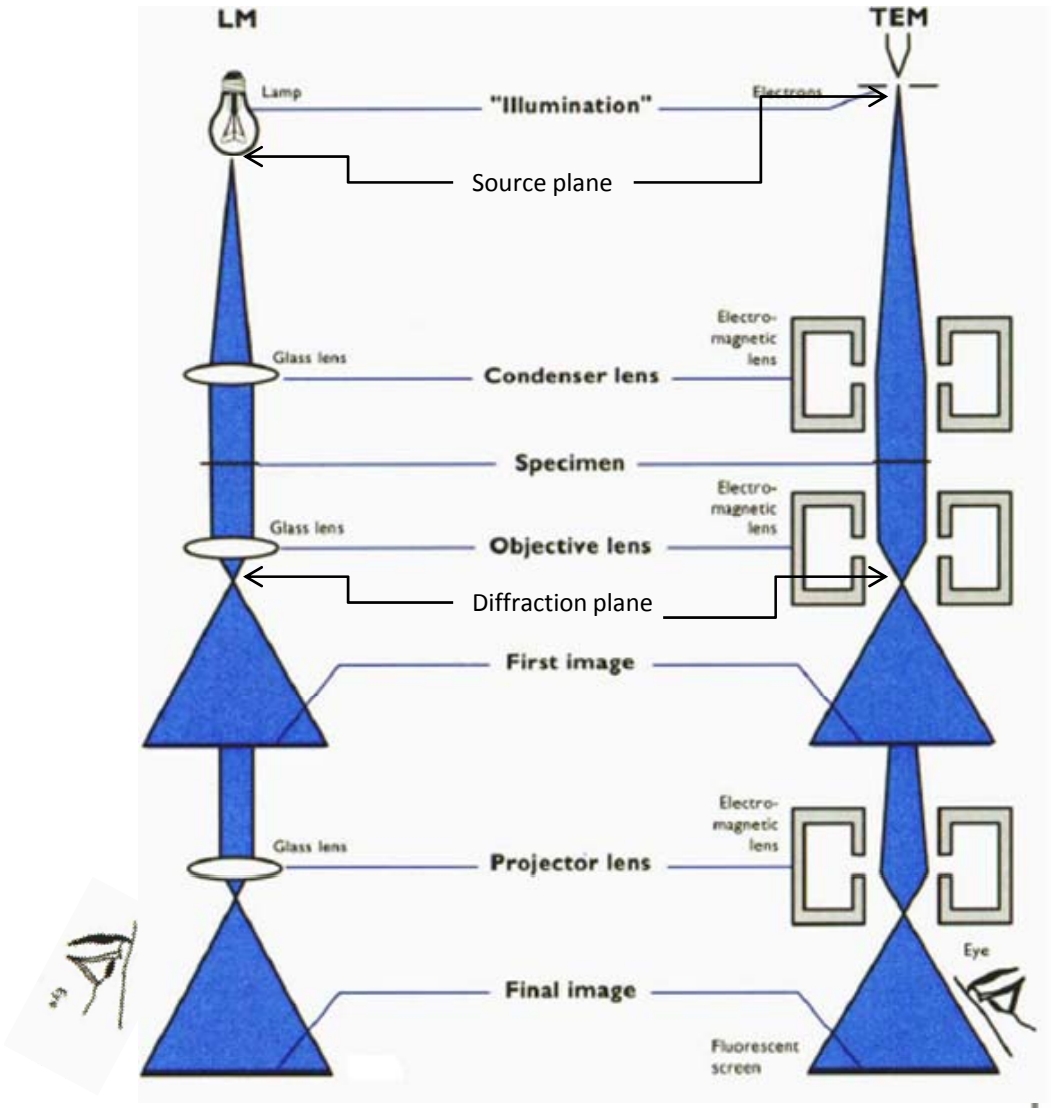
(1) Formazione dell'immagine esplicata dalla teoria di Abbe



Funzione di trasferimento del contrasto

Il microscopio ottico a proiezione

Il microscopio elettronico in trasmissione



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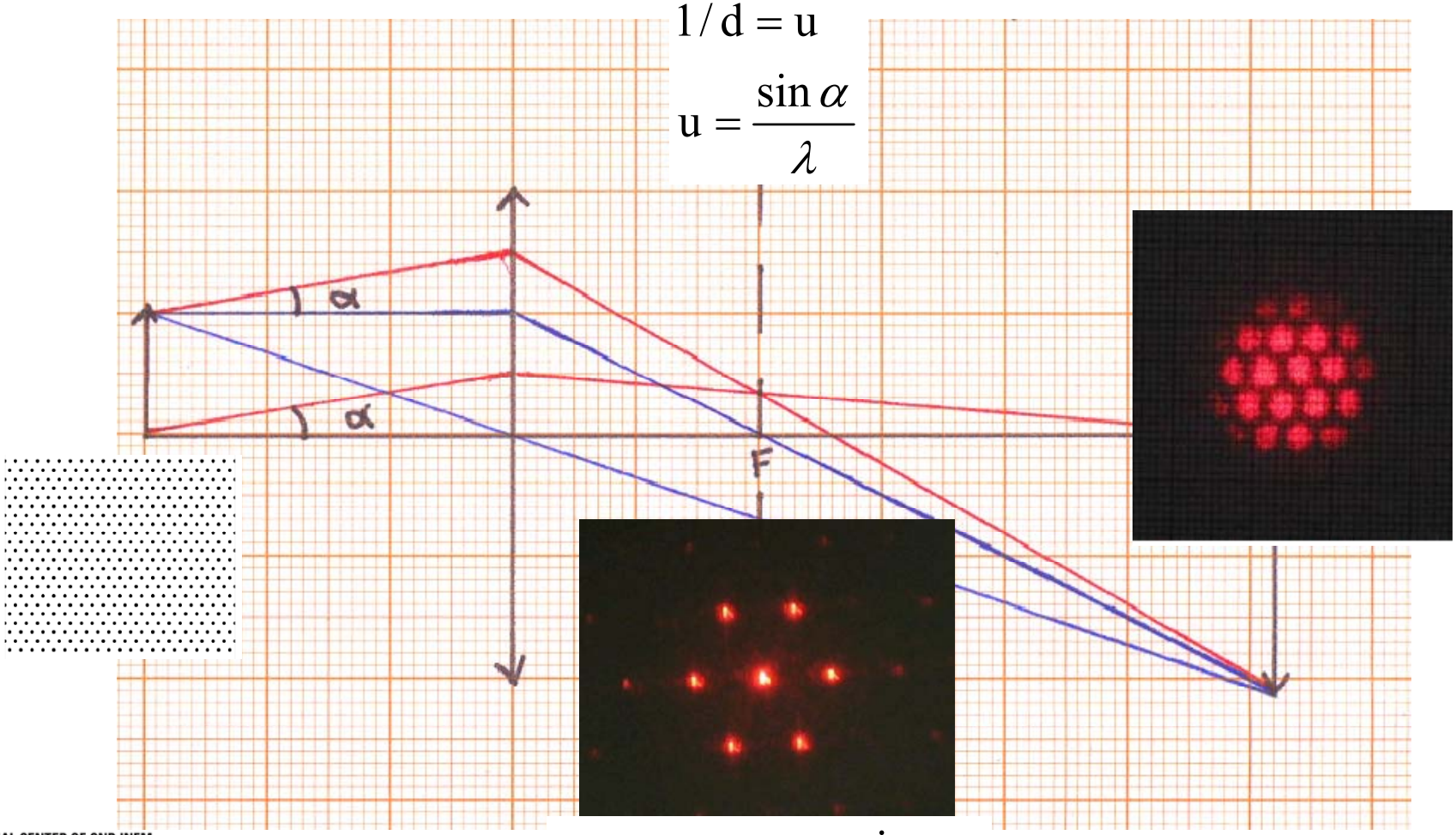
Lente sottile: piano focale e piano immagine

$$1/d = u$$

$$u = \frac{\sin\alpha}{\lambda}$$



$$u = \frac{\sin\alpha_x}{\lambda}, v = \frac{\sin\alpha_y}{\lambda}$$

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MICROSCOPIO OTTICO A PROIEZIONE:
Filtraggio spaziale

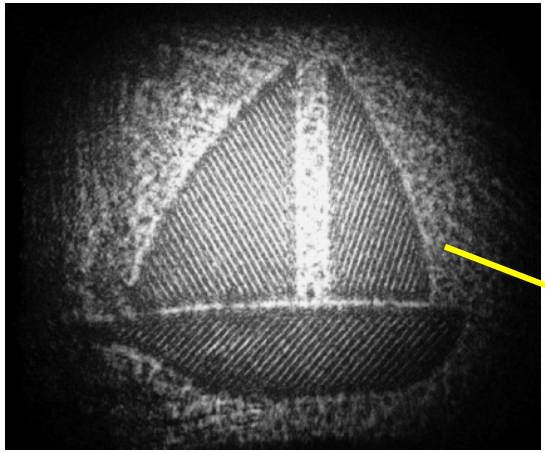
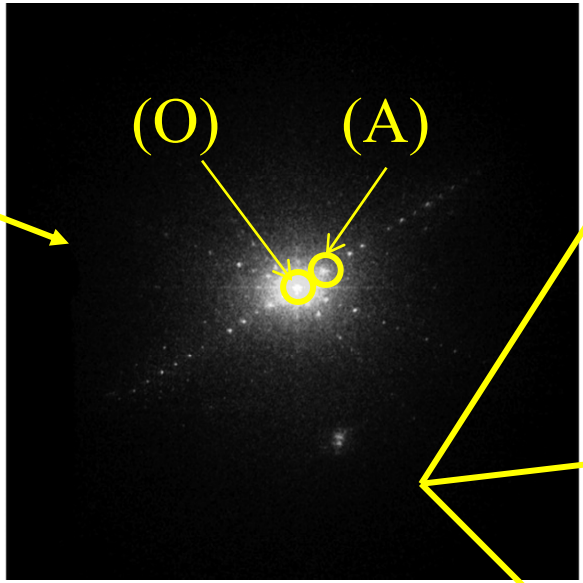
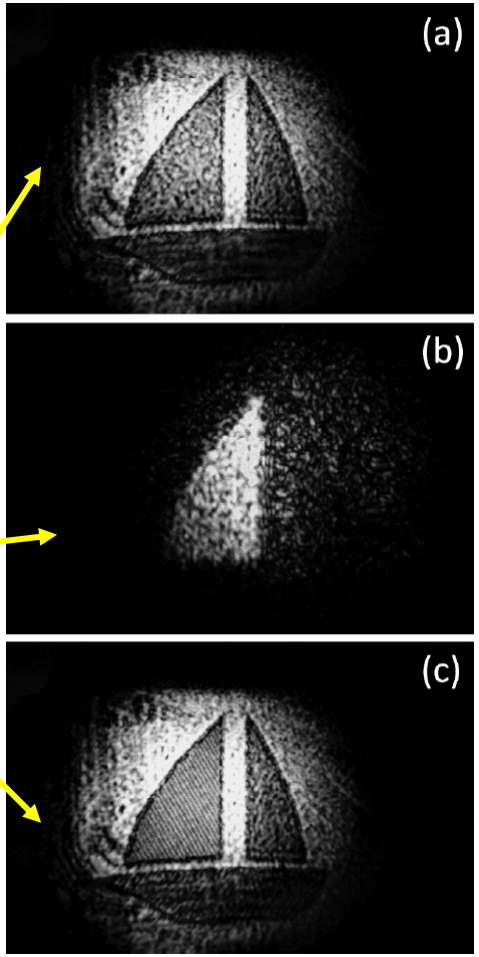


Figura di diffrazione





a) Immagine ottenuta selezionando solo il massimo centrale (O)
b) Immagine ottenuta selezionando solo un massimo secondario
c) Immagine ottenuta con il massimo centrale (O) e il massimo A.

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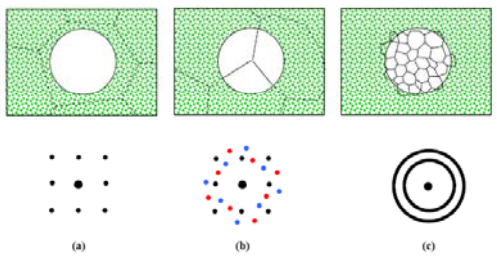
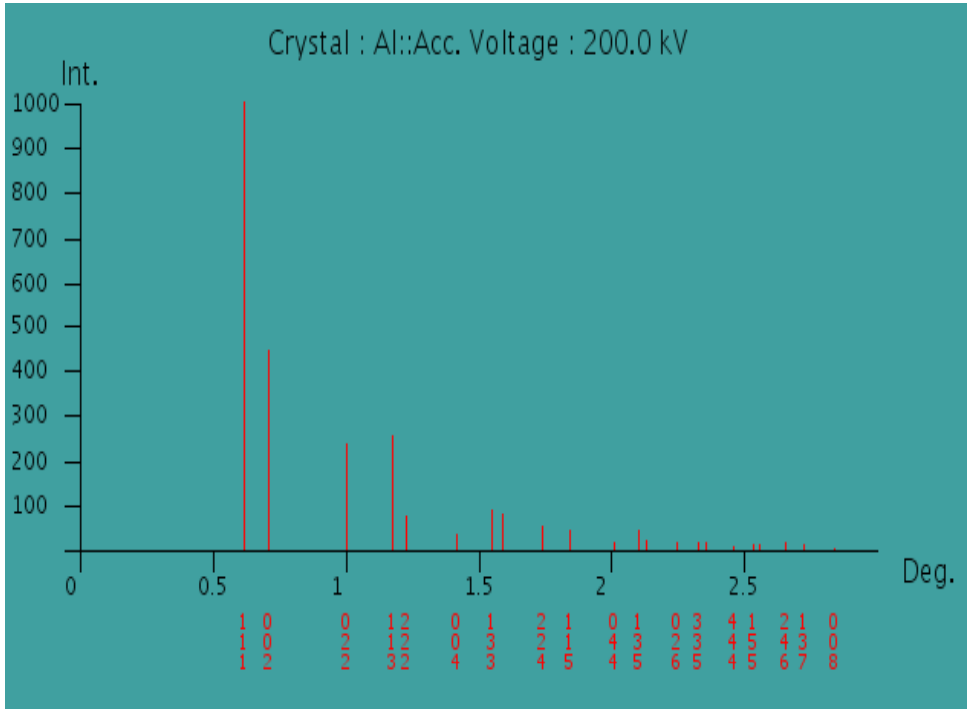
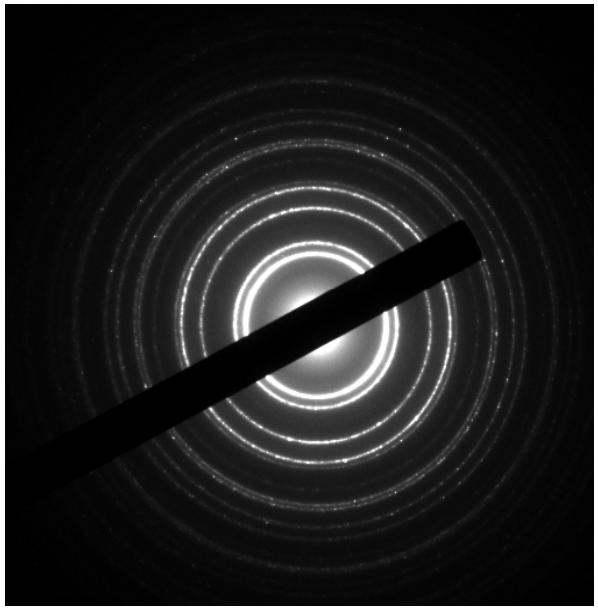
Electron Diffraction Pattern--Spot to Ring







$$I_{hkl} = j_s \frac{2\pi^2 m^2 e^2}{h^4} KNVcp_{hkl} \left|V_g\right|^2 \lambda^2 d_{hkl}$$

j_s densità di corrente, K: numero di cristalli con N celle unitarie, V_e volume di una cella unitaria, p_{hkl}: molteplicità del piano hkl, Vg: fattore di struttura, λ lunghezza d'onda, d_{hkl} spaziatura dei piani.

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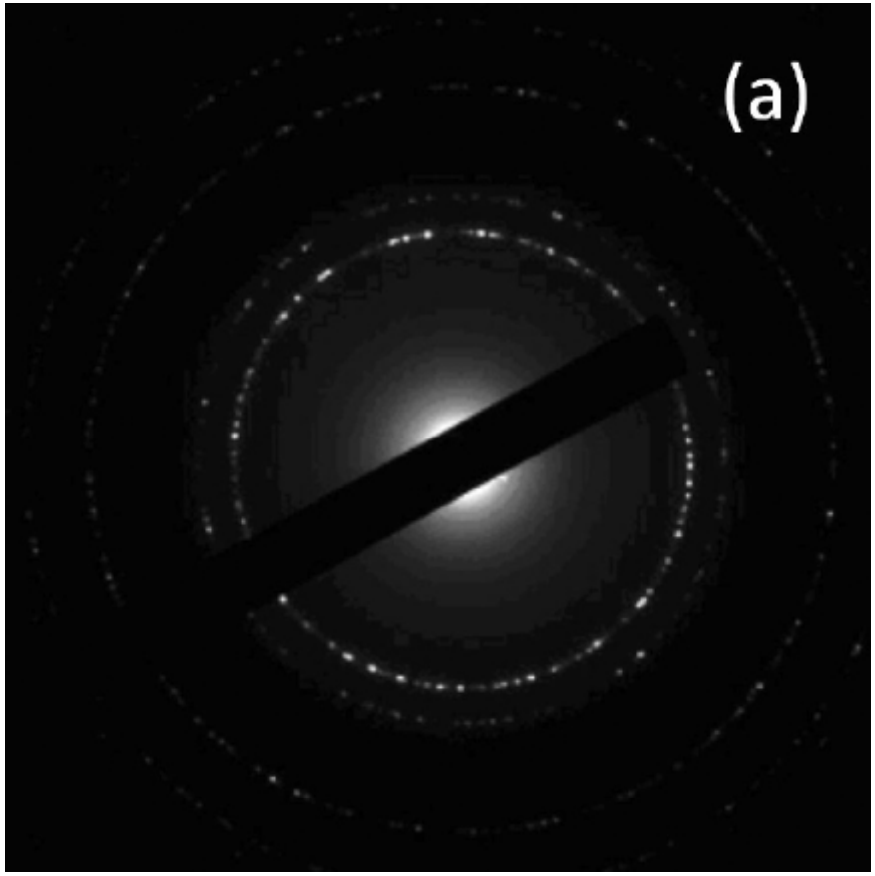
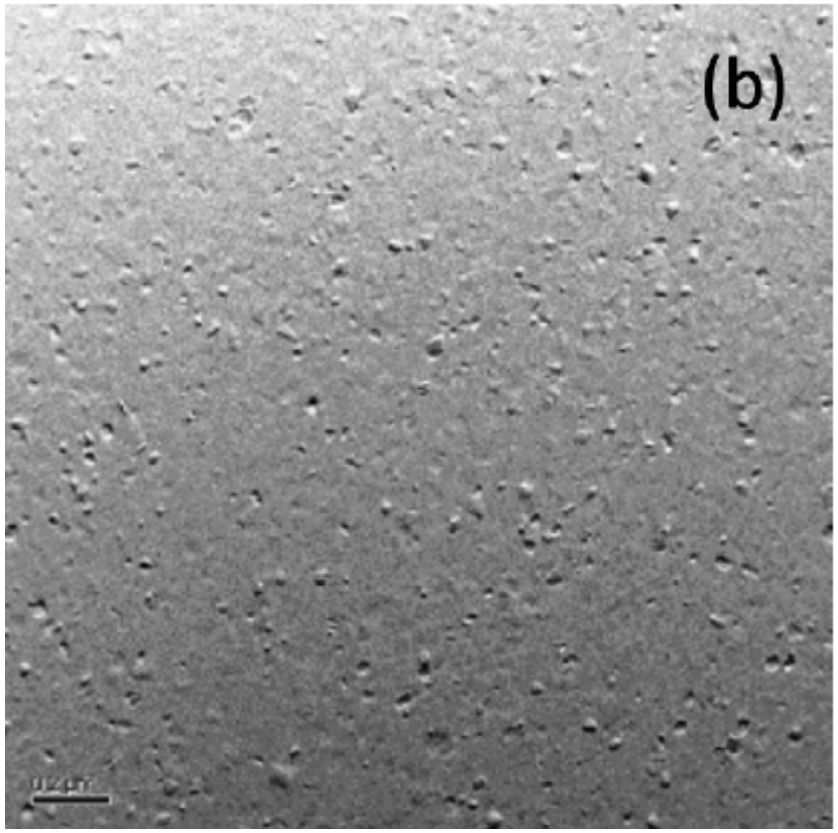
IMMAGINI **TEM** DI *Al* POLICRISTALLINO: DIFFRAZIONE

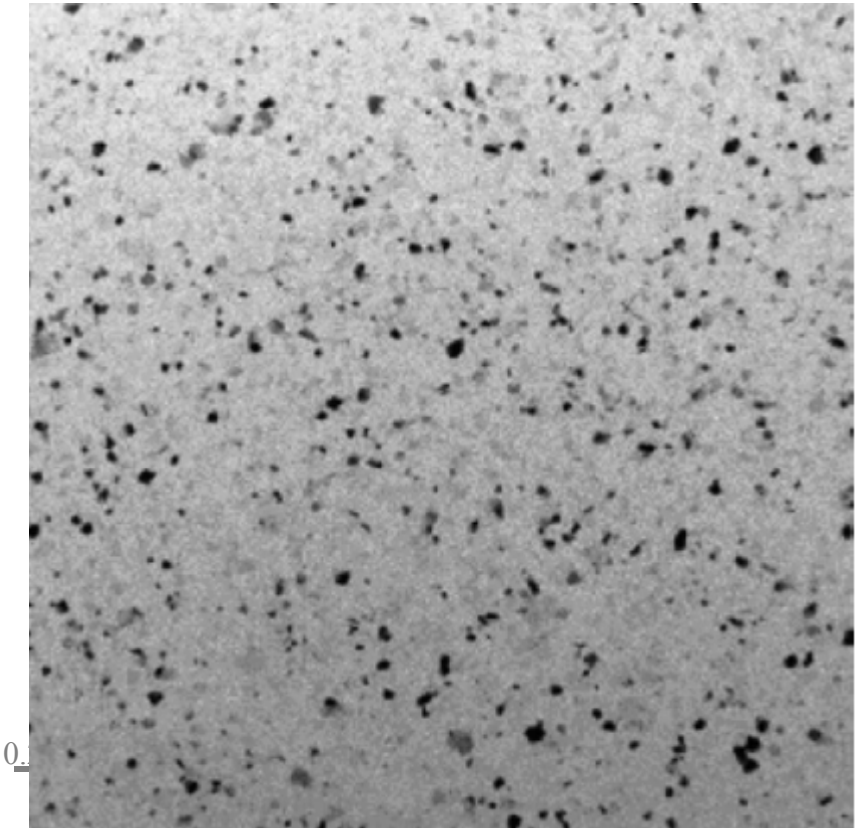


IMMAGINI **TEM** DI *Al* POLICRISTALLINO:campo chiaro

senza diaframma di obj.



con diaframma di obj. sul centrale



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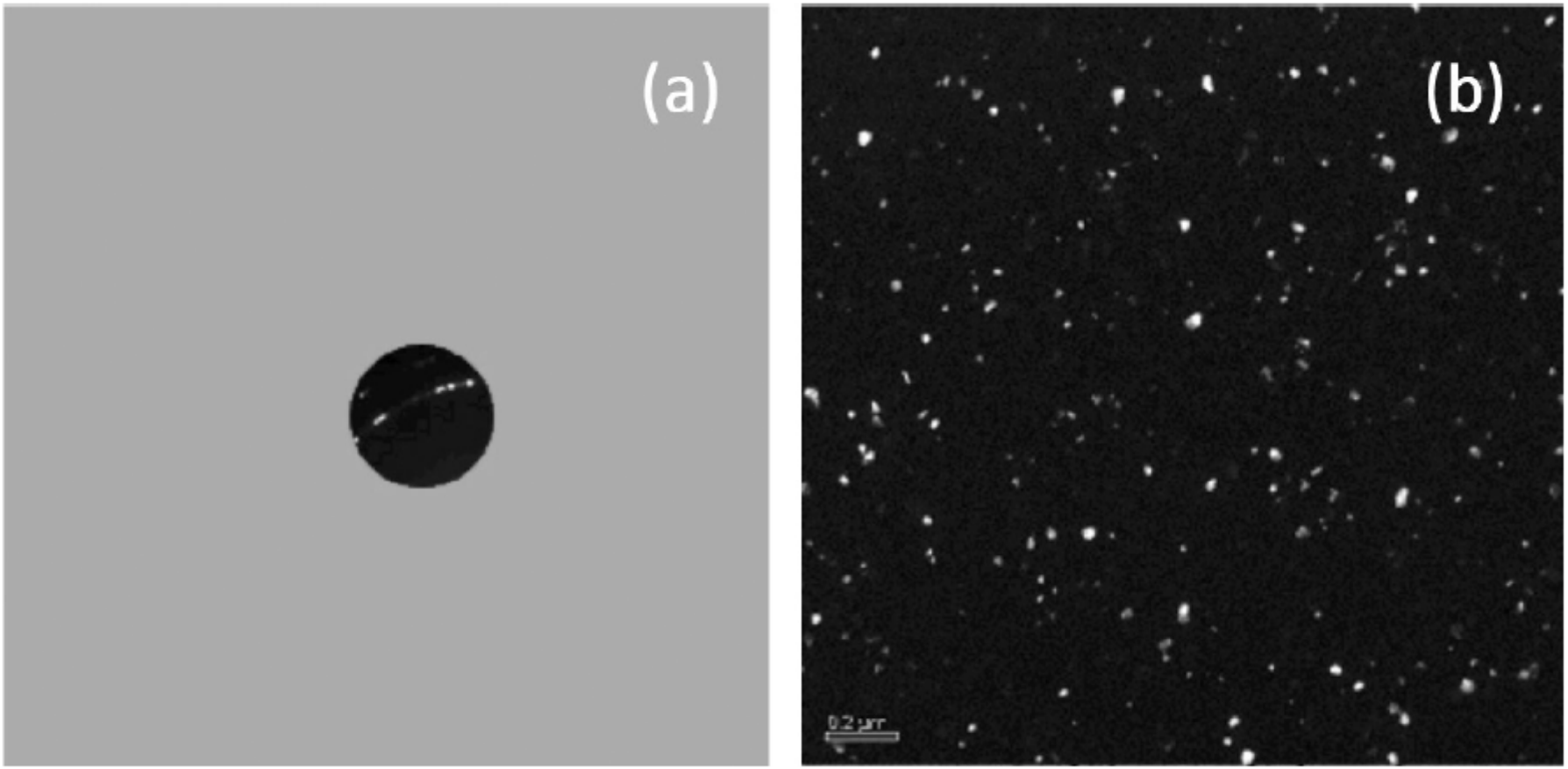

Figura 12. (**a**) Selezione dei punti dalla figura di diffrazione e (**b**) corrispondete immagine in modalità *dark field* del campione di alluminio policristallino.

Filtraggio spaziale e alta risoluzione

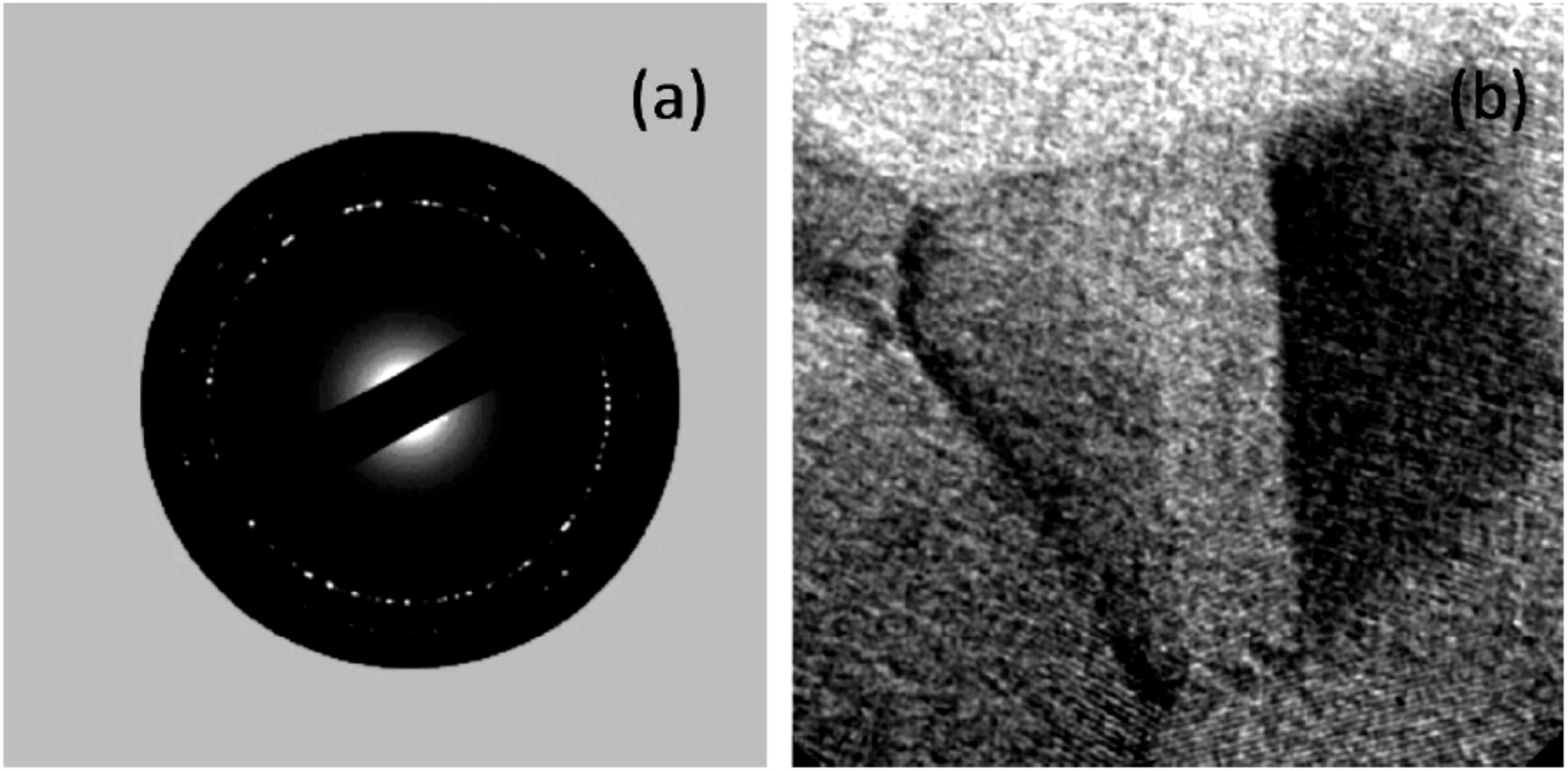

Figura 13. (a) Selezione del massimo centrale e dei punti del primo ordine di diffrazione e (b) corrispondete immagine in modalità *bright field* alta risoluzione del campione di alluminio policristallino.

Grazie per l’attenzione

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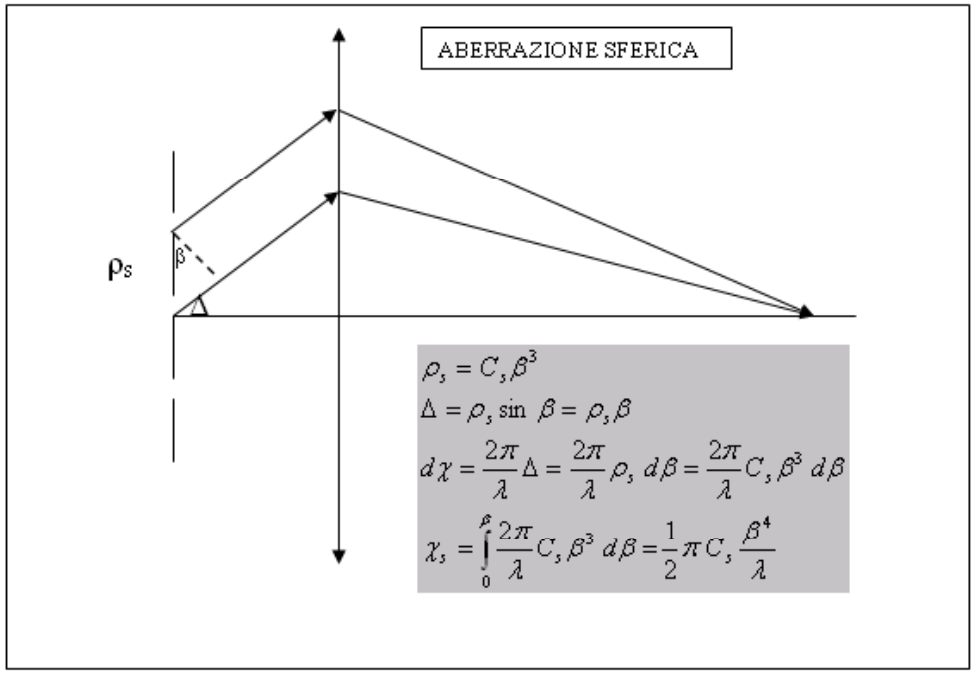
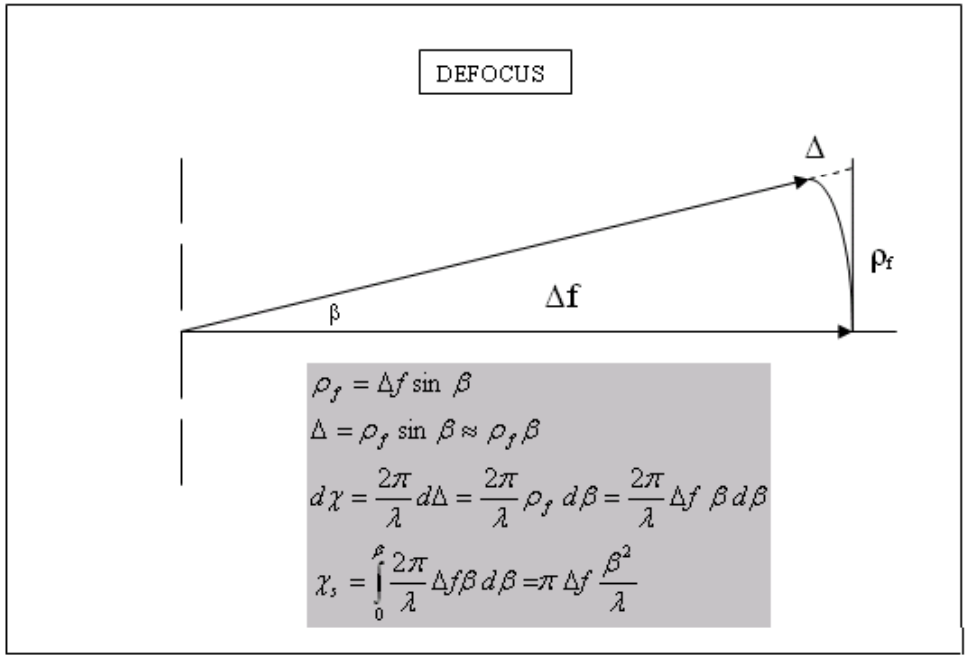
Aberrations and phase shifts



$$H(\mathbf{u}) = \exp(i\chi(\mathbf{u}))$$

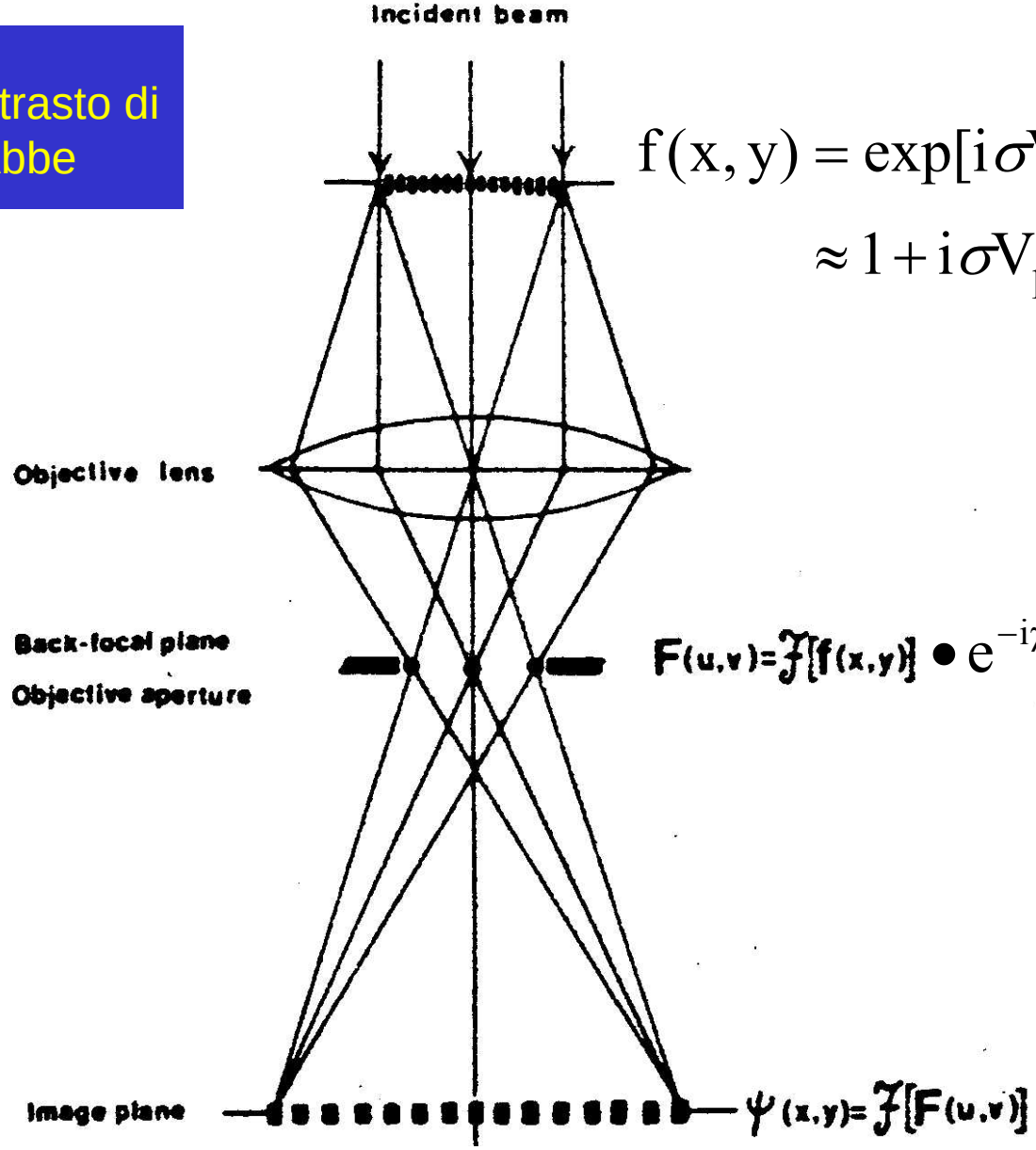
dove

$$\chi(\mathbf{u}) = \pi\lambda u^2 \Delta f + \frac{1}{2}\pi C_s \lambda^3 u^4$$



Formazione dell'immagine in contrasto di fase: Teoria di Abbe

HREM



$$f(x,y) = \exp[i\sigma V_p(x,y)]$$
$$\approx 1 + i\sigma V_p(x,y)$$

$$F(u,v)=\mathcal{F}[f(x,y)] \bullet e^{-i\chi(u,v)} \bullet A(u,v)$$

$$I(x,y) = 1 + 2\sigma V_p^{ab}(x,y)$$

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