Chap 23 Optical properties of metals and inelastic scattering

- Propagation of EM wave
- Plasma wave
- Optical properties
- Angle resolved photo-emission

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Attenuation of EM wave (I)

$$n = \sqrt{\varepsilon} = n_R + i n_I$$

$$n_R = \frac{1}{\sqrt{2}} \sqrt{|\varepsilon| + \varepsilon'}$$

$$n_I = \frac{1}{\sqrt{2}} \sqrt{|\varepsilon| - \varepsilon'} \cong \frac{\varepsilon''}{2\sqrt{\varepsilon'}} \quad (\text{if } \varepsilon'' \ll \varepsilon')$$

- Attenuation of plane wave due to n_I

$$\exp(i\vec{k}\cdot\vec{r}) = \exp\left(in\frac{\omega}{c}\hat{k}\cdot\vec{r} \right)$$

$$= \exp(in_R\frac{\omega}{c}\hat{k}\cdot\vec{r})\exp(-n_I\frac{\omega}{c}\hat{k}\cdot\vec{r})$$

- Reflectivity (or reflectance, normal direction)

$$R = \frac{(n_R - 1)^2 + n_I^2}{(n_R + 1)^2 + n_I^2}$$

Attenuation of EM wave (II)

- Decay of intensity (energy density)

$$I(x) \equiv \frac{n_R^2}{8\pi}|E(x)|^2 = I_0 e^{-\alpha x}$$

$$\alpha = 2n_I \frac{\omega}{c} \cong \frac{\omega}{n_R c}\varepsilon''$$

- Penetration depth

$$\delta \equiv 1/\alpha$$

- Power loss (per unit volume)

$$\left|\frac{dI}{dt}\right| = \left|\frac{dI}{dx}\frac{dx}{dt}\right| = \alpha I_0 \frac{c}{n_R} = \frac{I_0}{n_R^2}\omega\varepsilon''$$

- dielectric function for metal

$$\sigma(\omega) = \frac{\sigma_0}{1-i\omega\tau}, \qquad \sigma_0 \equiv \frac{ne^2\tau}{m}$$

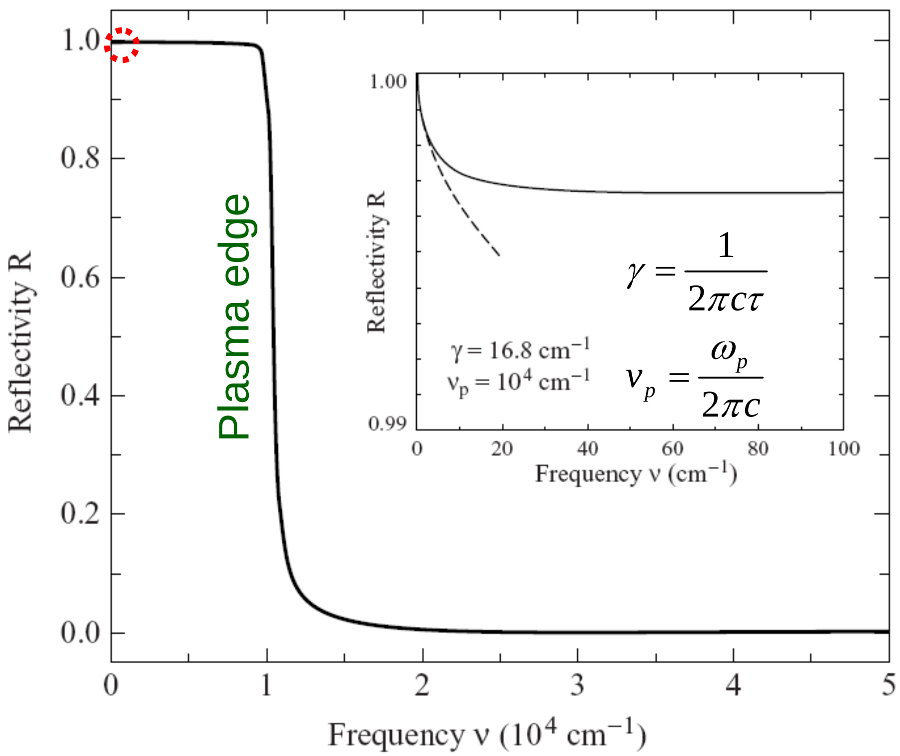
$$\varepsilon(\omega) = 1 + \frac{4\pi i\sigma_0}{\omega(1-i\omega\tau)} = \begin{cases} 1 + 4\pi i\dfrac{\sigma_0}{\omega} & \text{for } \omega\tau << 1 \\ 1 - \dfrac{\omega_p^2}{\omega^2} & \text{for } \omega\tau >> 1 \end{cases} \qquad \omega_p^2 = \frac{4\pi ne^2}{m}$$

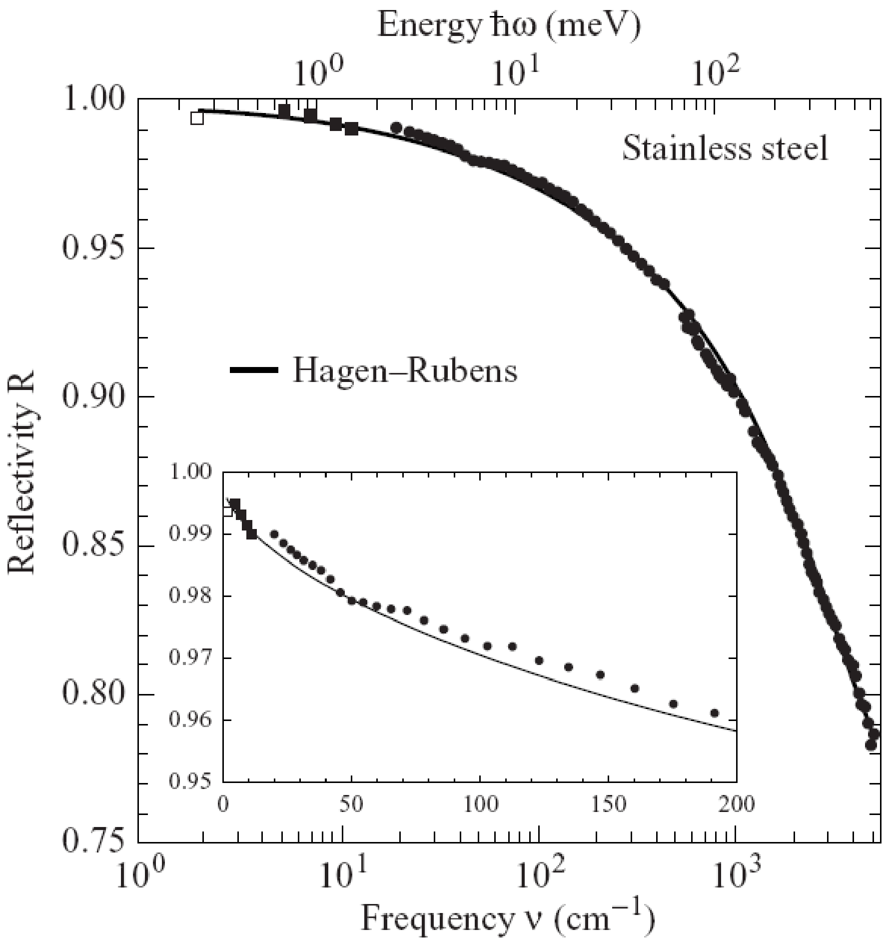
(A) Hagen-Ruben's regime

$\omega \tau \ll 1$

$\tau \sim 10^{-13} \sim 10^{-14}$

$\therefore \omega$ can be as large as 100 GHz





Dressel and Gruener, p.99, 308

$\underline{\omega\tau >> 1}$ $\varepsilon(\omega) = 1 - \omega_p^2 / \omega^2$

$(B)\ \omega < \omega_p \rightarrow \varepsilon(\omega) < 0$

EM wave is damped

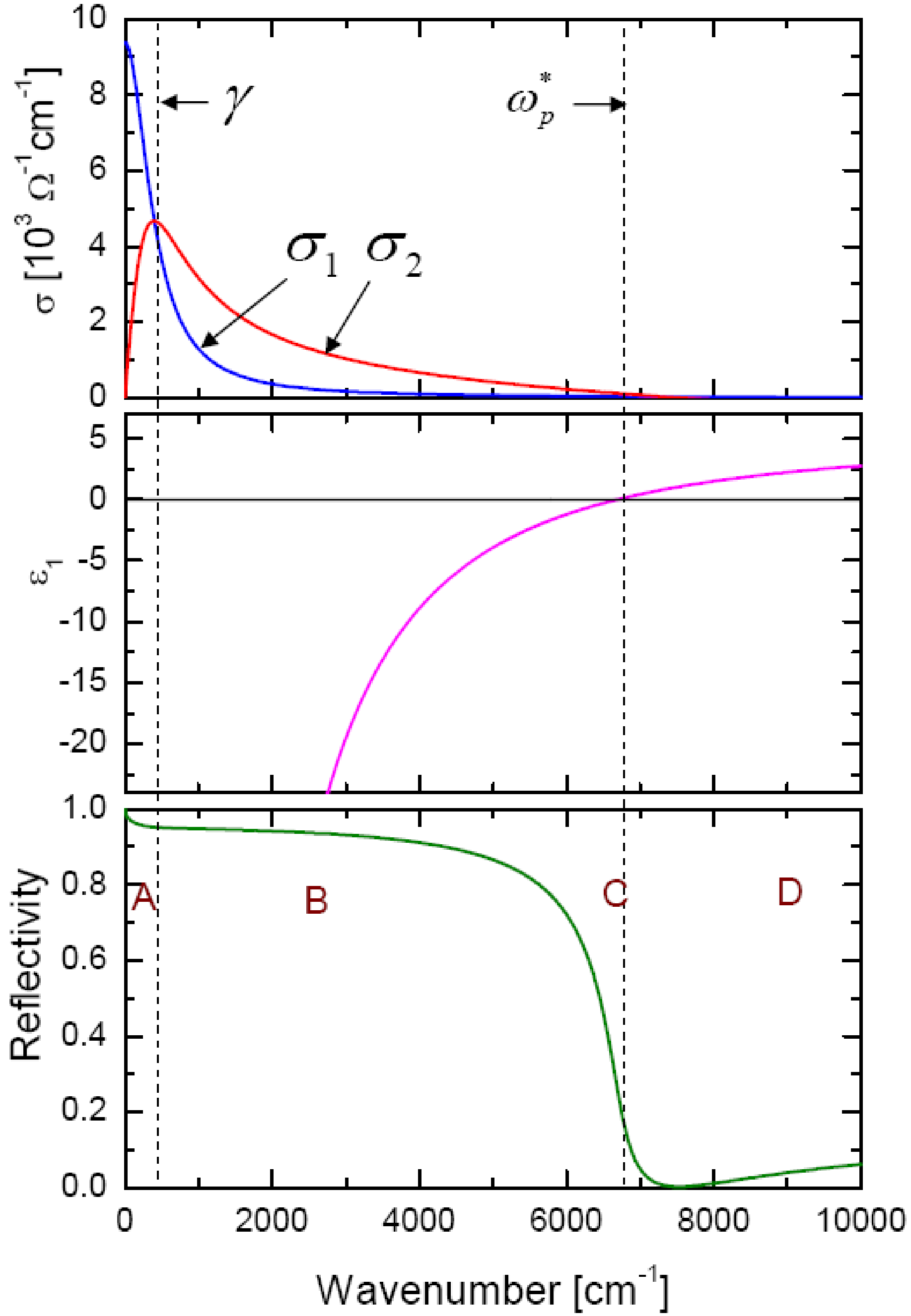
Signal blocked

$(C)\ \omega = \omega_p \rightarrow \varepsilon(\omega) = 0$

Longitudinal EM wave (plasma)

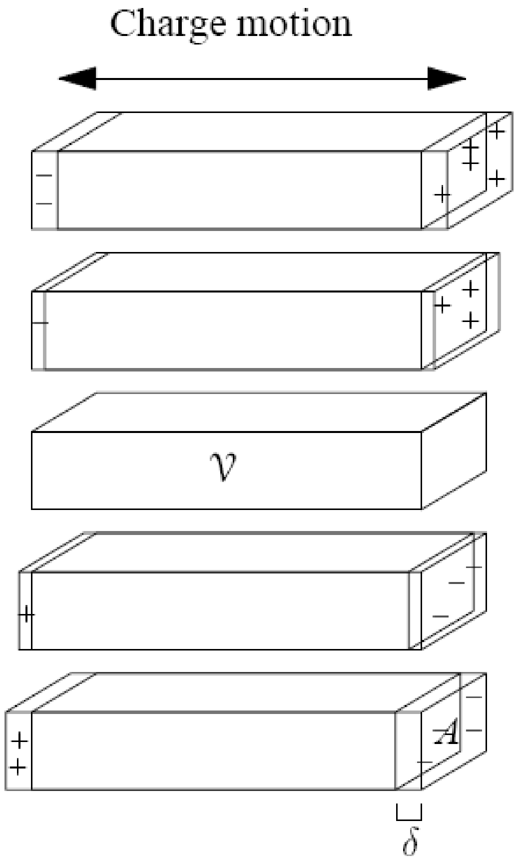
$(D)\ \omega > \omega_p \rightarrow 0 < \varepsilon(\omega) < 1$

EM wave propagates with phase velocity $c/\sqrt{\varepsilon} > c$



Plasma wave

A simple picture of plasma oscillation



$$m\ddot{\delta} = -eE = -(4\pi ne^2)\delta$$

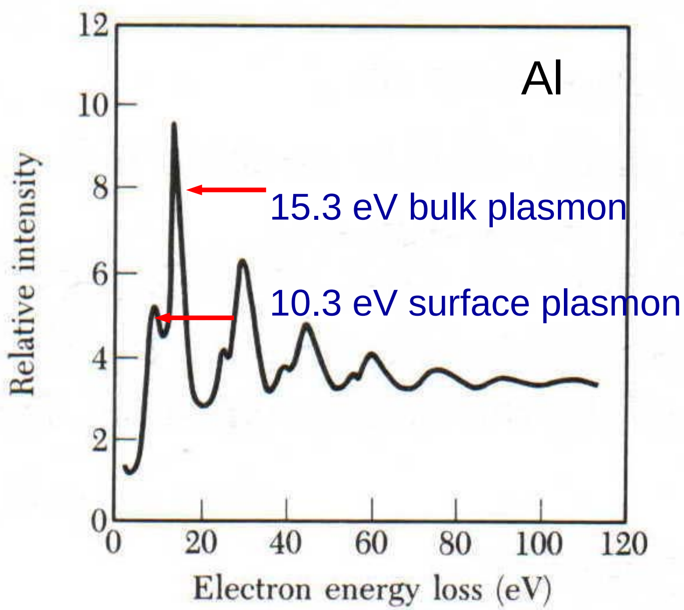
$$\rightarrow \omega_p = \sqrt{4\pi ne^2 / m}$$

For copper, $n = 8\times10^{22}$ /cm^3

$\omega_p = 1.6\times10^{16}$/s, $\lambda_p = 1200$A (ultraviolet)

Material	Observed	Calculated $\hbar\omega_p$	Calculated $\hbar\tilde{\omega}_p$
Metals			
Li	7.12	8.02	7.96
Na	5.71	5.95	5.58
K	3.72	4.29	3.86
Mg	10.6	10.9	
Al	15.3	15.8	
Dielectrics			
Si	16.4–16.9	16.0	
Ge	16.0–16.4	16.0	
InSb	12.0–13.0	12.0	

ε_{core} correction



Dynamic susceptibility in the long wavelength limit (chap 20)

$$\varepsilon(\vec{q},\omega) = 1 - \frac{\omega_p^2}{\omega^2}\left[1 + \frac{3}{5}\left(\frac{\hbar k_F}{m\omega}\right)^2 q^2\right]$$

For longitudinal EM wave $\quad \varepsilon(\vec{q},\omega) = 0$

$\longrightarrow$ Energy dispersion for the plasma wave

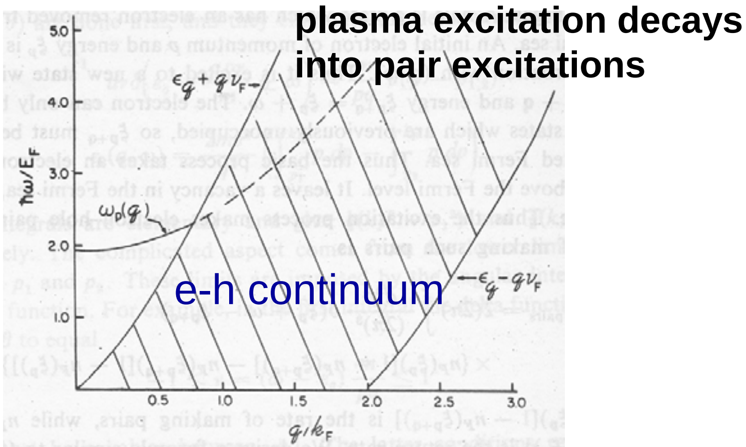
$$\omega^2 = \omega_p^2 + \frac{6}{5}\frac{\varepsilon_F}{m}q^2 + O(q^3)$$

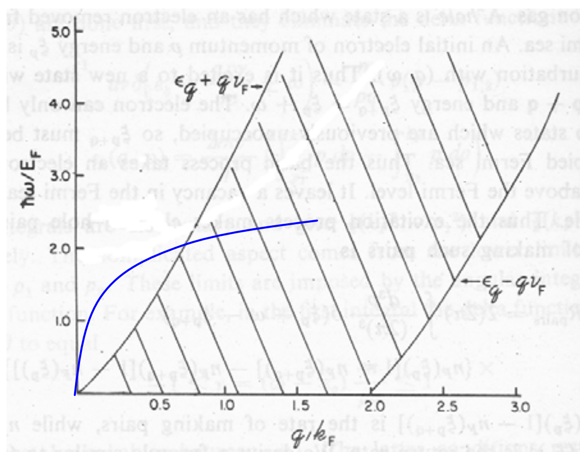
2D: for long wavelength

$$\omega_{\mathrm{p}}^2 = \frac{2\pi n e^2}{m}q + \frac{3}{4}q^2 v_F^2 + O(q^3)$$

There is NO plasma gap

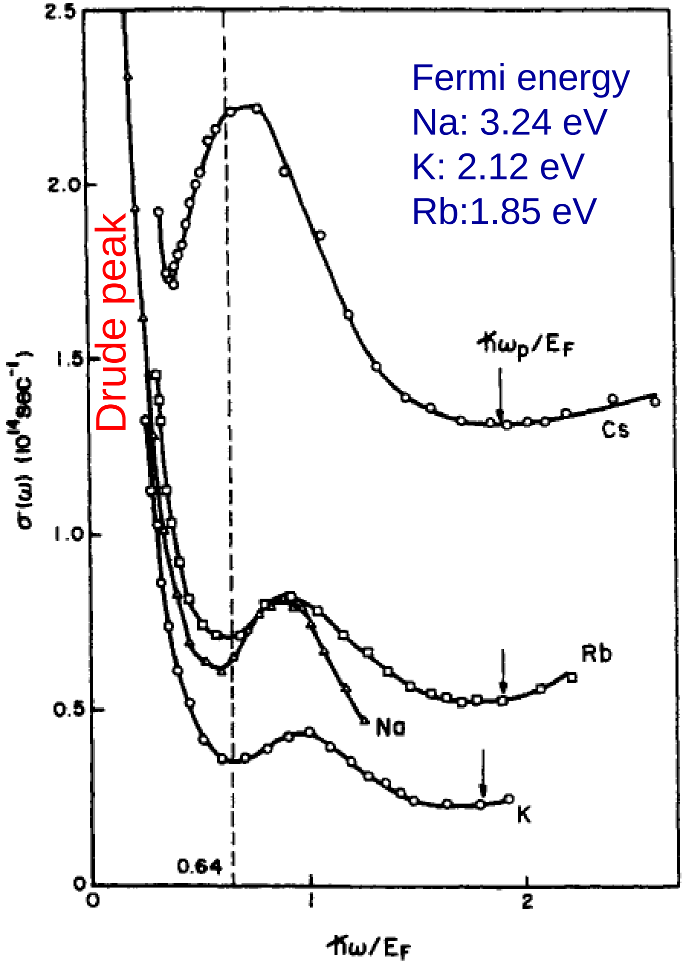
Collective excitation vs quasiparticle (e-h pair) excitation in metal





Optical properties of alkali metals

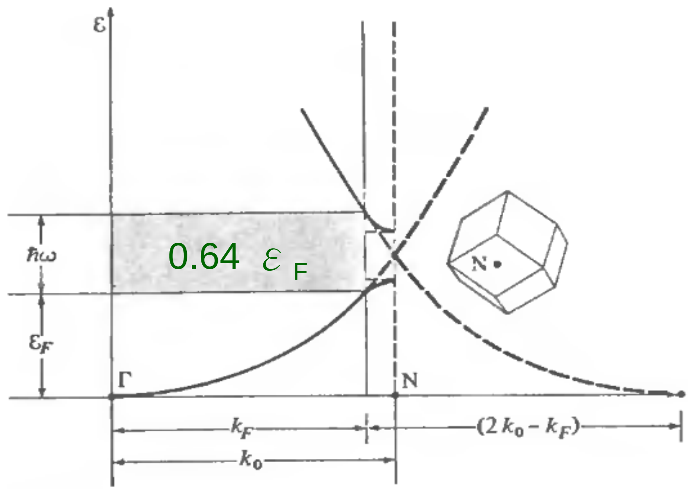
Re σ for Na, K, and Rb

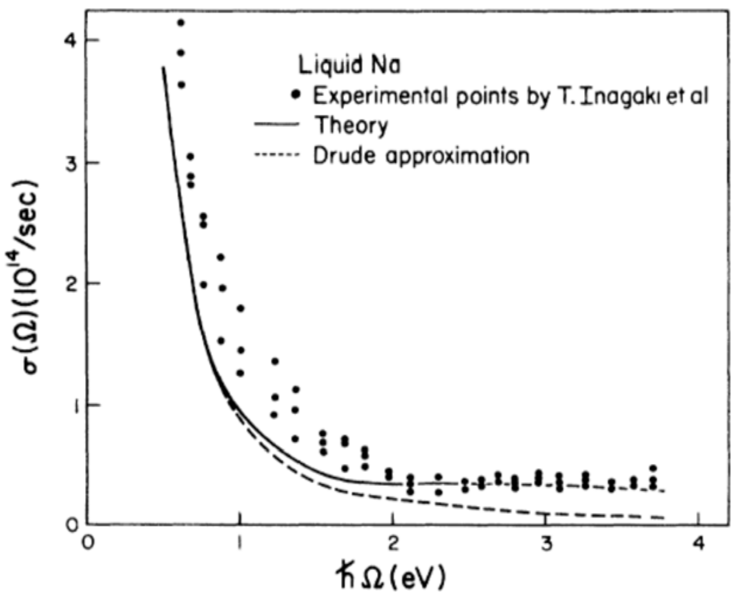


N.V. Smith PRB2 2840 1970

$n = (\varepsilon_0 + 4\pi i \sigma / \omega)^{1/2}$

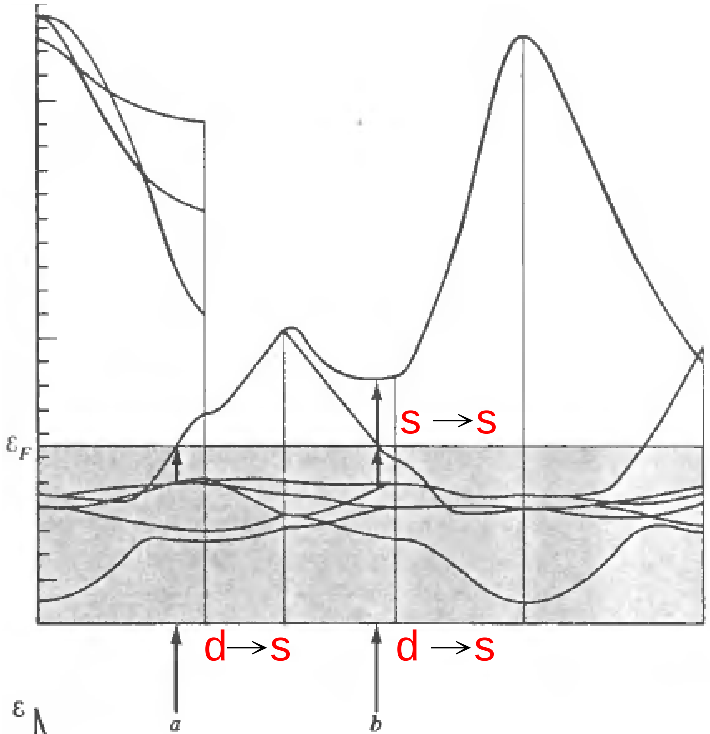
Absorption $\sim$ Im(n) $\sim$ Re(σ)

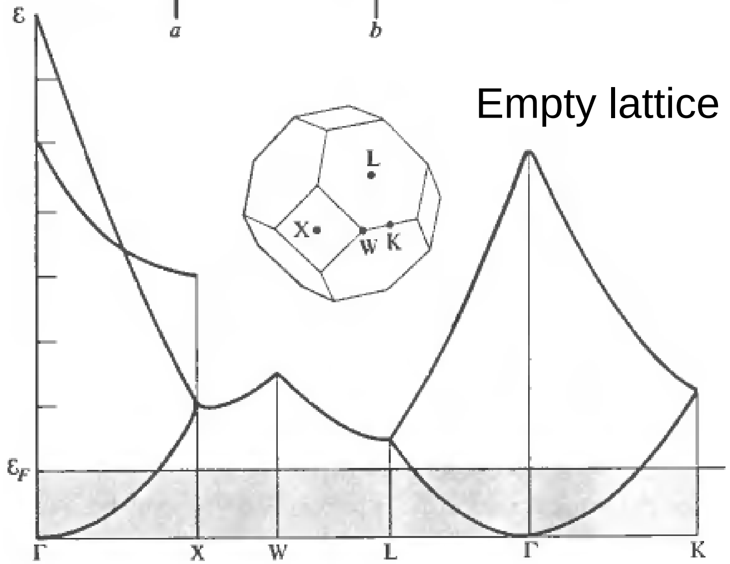




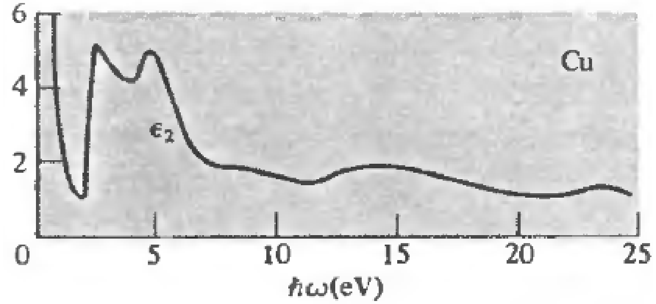
T. Inagaki et al , Phys. Rev. B 13, 5610 (1976).

Optical properties of noble metals

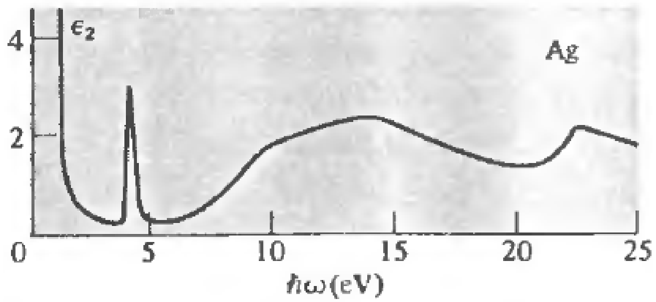


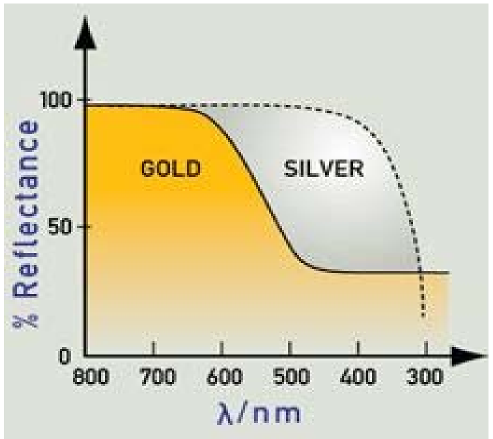


Cu: low threshold (2eV)



Ag: high threshold (4eV)





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