Ultra-Fast Effects in Metal Cathodes (effects we've been ignoring)

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- Introduction and what we assume about photoemission
- Optical properties and electron dynamics
- The role of bulk and surface resonances
- Summary and conclusions

Pump-probe measurements show a time-dependent electron spectrum

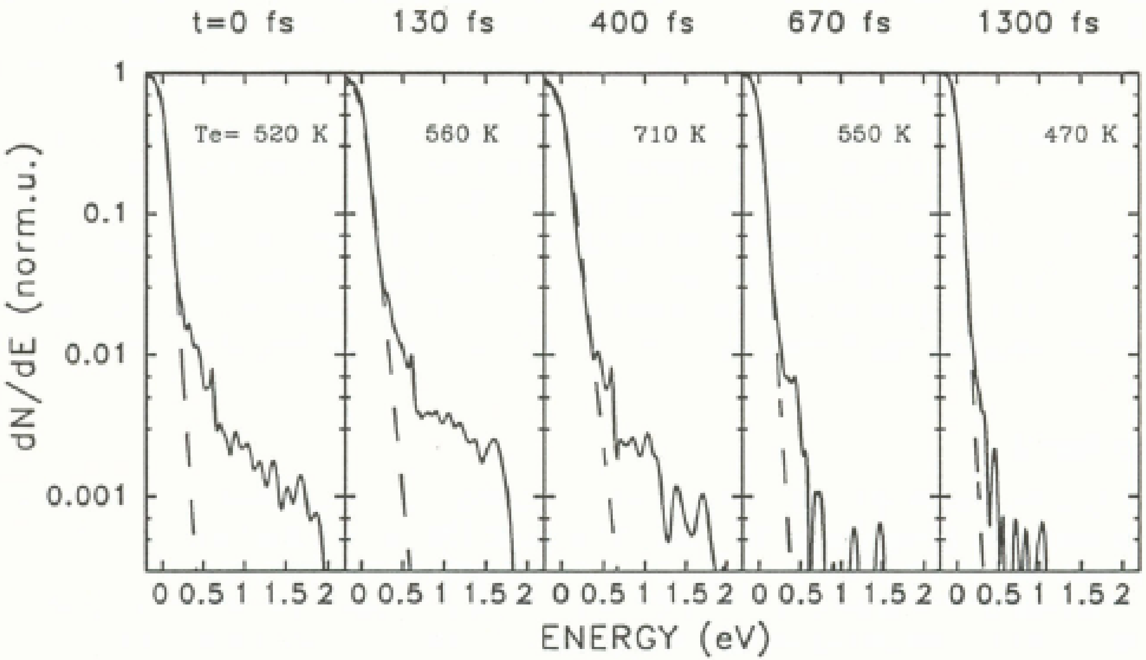
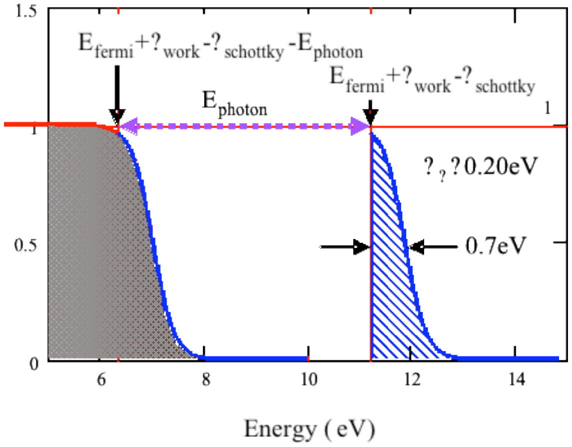


Fig. 1: Electron energy distribution function vs. energy with 120 μJ/cm^2 absorbed laser fluence at 5 time delays. The dashed line is the best Fermi-Dirac fit and the corresponding electron temperature, T_e, is shown. The vertical scale is in units of density of states.

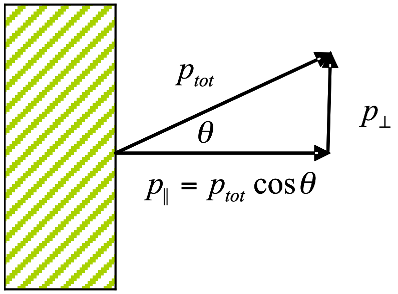
[Fann et al., "Observation of the thermalization of electrons in a metal excited by femtosecond optical pulses," in Ultrafast Phenomenona, ed. J.-L. Martin, A. Meigus, G.A. Mourou and A.H. Zewail, Springer Verlag 1993, p331-334

Photoemission from a simple metal



$$\frac{p_{\parallel}^2}{2m} > E_{fermi} + \phi_{work} - \phi_{schottky}$$

$$\cos\theta_{\max} = \sqrt{\frac{E_{fermi} + \phi_{work} - \phi_{schottky}}{E + \hbar\omega}}$$



Quantum Efficiency

$$QE = (1-R)\frac{\int\limits_{E_{fermi}+\phi_{work}-\phi_{schottky}-\hbar\omega}^{E_{vac}} dE \int\limits_{\cos\theta_{\max}(E)}^{1} d(\cos\theta) \int\limits_{0}^{2\pi} d\phi \;\; DOS_{F-D}(E_{fermi},E)}{\int\limits_{0}^{E_{vac}} dE \int\limits_{0}^{1} d(\cos\theta) \int\limits_{0}^{2\pi} d\phi \;\; DOS_{F-D}(E_{fermi},E)}$$

Mean-Square Transverse Momentum

$$\left\langle p_{\perp}^2 \right\rangle = \frac{\int\limits_{E_{fermi}+\phi_{work}-\phi_{schottky}-\hbar\omega}^{E_{vac}} dE \int\limits_{\cos\theta_{\max}}^{1} f(\theta)\, d(\cos\theta) \int\limits_{0}^{2\pi} d\phi \;\; p_{\perp}^2 DOS_{F-D}}{\int\limits_{E_{fermi}+\phi_{work}-\phi_{schottky}-\hbar\omega}^{E_{vac}} dE \int\limits_{\cos\theta_{\max}}^{1} d(\cos\theta) \int\limits_{0}^{2\pi} d\phi \;\; DOS_{F-D}}$$

- •QE dependents upon the reflectivity, the density of states and kinematical filtration
- •Resolving the discrepancies between this simple model and observations for both QE and “thermal” emittance allow improved understanding of the emission process

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Validity of the Fermi-Dirac Distribution and Spill-Out Electrons Surface Structure Can Reduce the Work Function

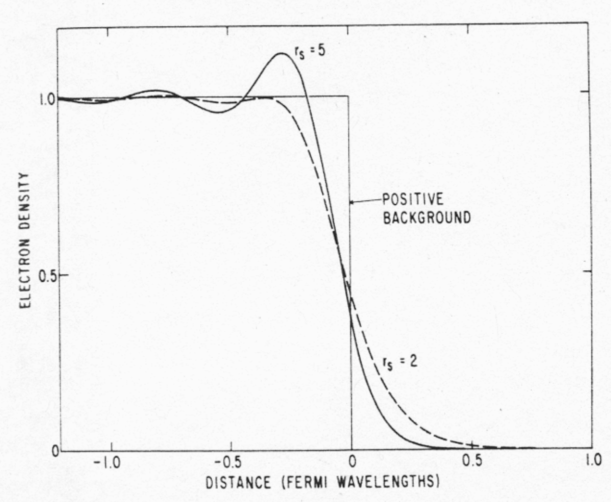
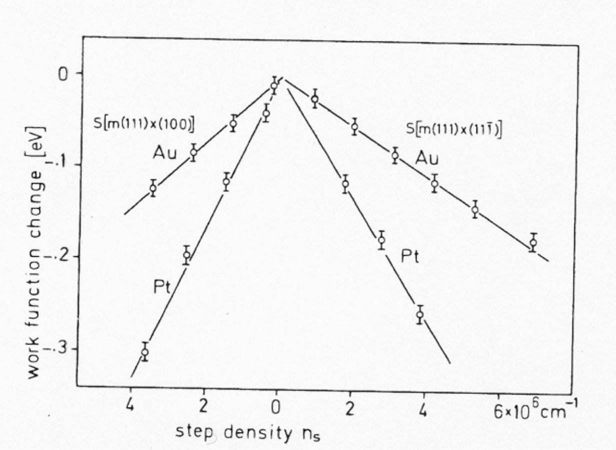


FIG. 2. Self-consistent charge density near metal surface for $r_s = 2$ and $r_s = 5$ (uniform positive background model).



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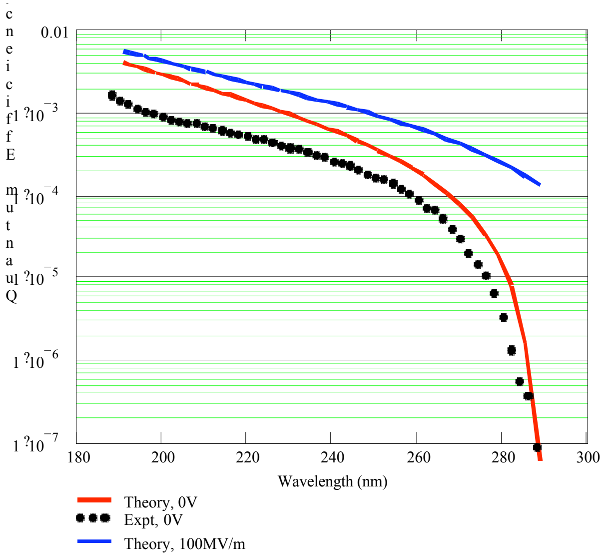
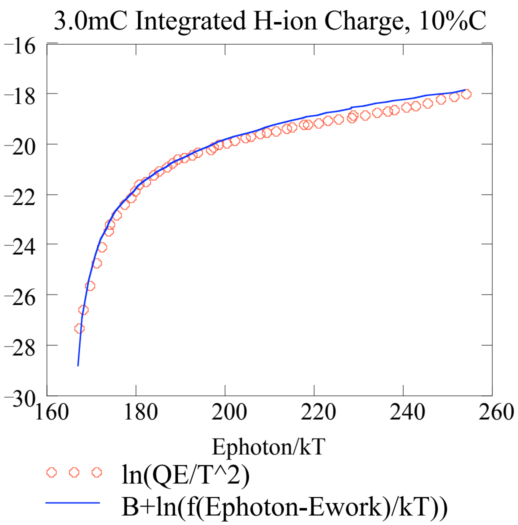
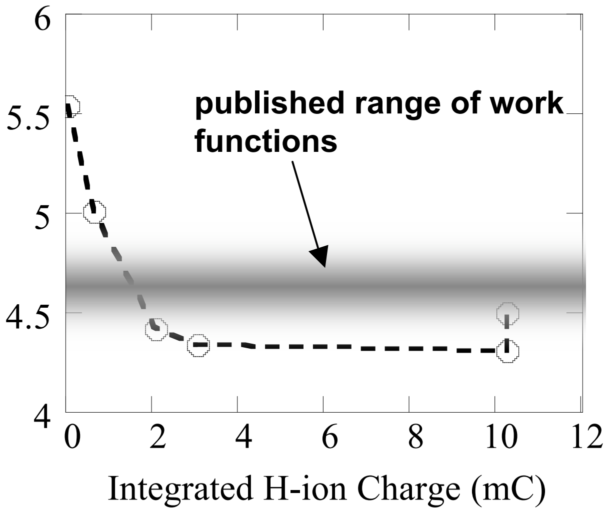
QE Model vs. Experimental Discrepancies, The work function of Cu



Fowler plot





published range of work functions

Theoretical Work Function:
3.9 eV: Hodges & Scott, Phys. Rev B7,73(1972)
4.1 eV: Lang & Kohn, Phys. Rev. B1,4555 (1970)

For a truly clean surface, the measured work function is in reasonable agreement with theory (~10-15% higher than theory)

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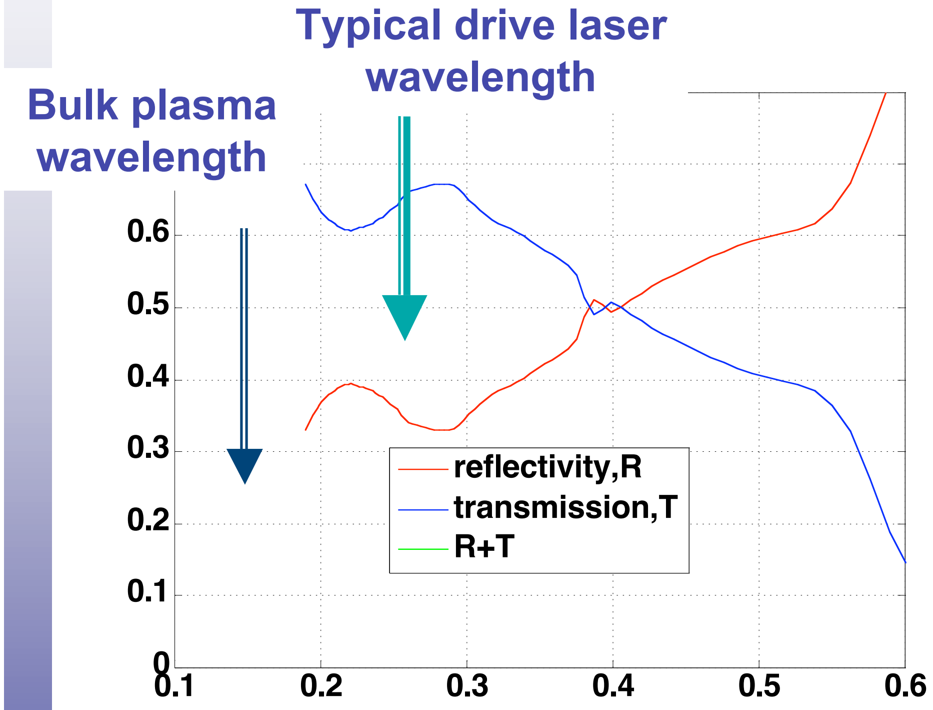
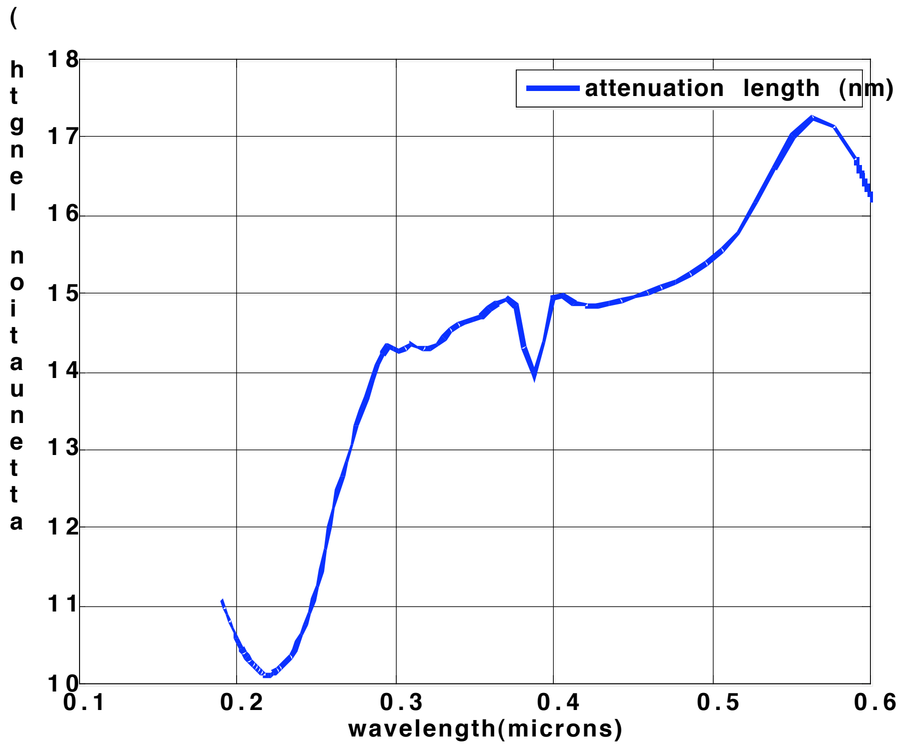
Consider the reflectivity in the wavelength region of tripled TiS and quadrupled Nd:Glass lasers

reflectivity and attenuation length for normal incidence



Typical drive laser wavelength

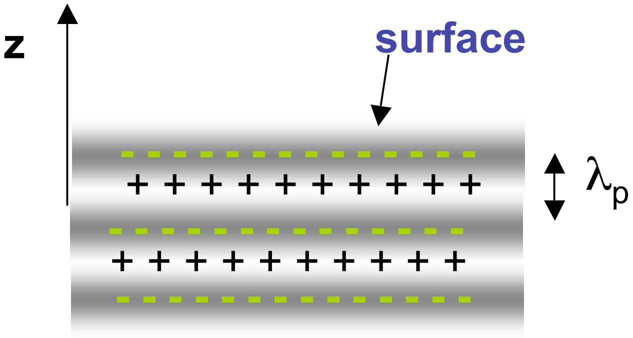
Bulk plasma wavelength



Bulk plasma frequency for copper is 1.66×10^{16} rad/s or λ_{plasma}=0.113 microns

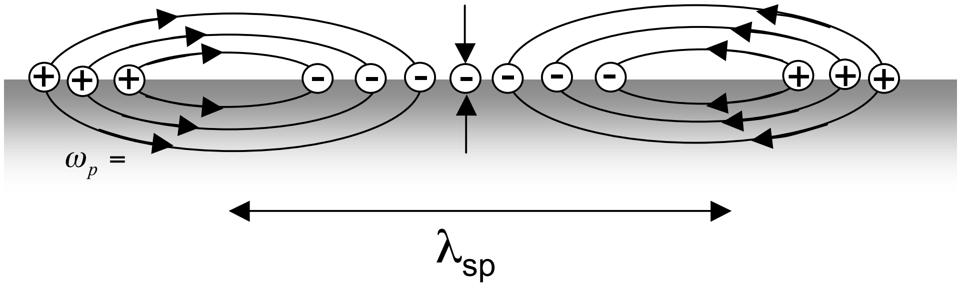
Bulk and Surface Plasmon States Determine the High-Frequency Behavior of the Dielectric Constant and Reflectivity

Bulk Plasmon State: Collective Longitudinal Excitation



$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m}}$$

Surface Plasmon State: Collective Oscillations of the Surface Charge



$$\omega_{sp} = \sqrt{\frac{ne^2}{2\varepsilon_0 m}}$$

Frequency dependent dielectric constant

$$\frac{\varepsilon(\omega)}{\varepsilon_0} = 1 + \frac{Ne^2}{\varepsilon_0 m}\sum_j \frac{f_j}{\omega_j^2 - \omega^2 - i\omega\gamma_j} = 1 + \chi_e$$

Sum of oscillator strengths

$$\sum_j f_j = Z$$

See Kittel, “Introduction to Solid State Physics”, p 274-277; Zangwill, “Physics at Surfaces”, p139-144

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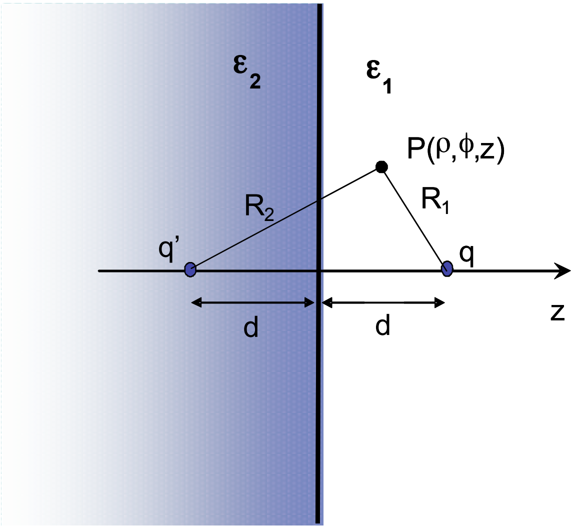
Electron dynamics at the cathode surface



$$\Phi_{>} = \frac{1}{4\pi\varepsilon_1}\left(\frac{q}{R_1} + \frac{q'}{R_2}\right) \qquad z > 0$$

$$q' = -\left(\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1}\right) q$$

For a perfect conductor:

$\varepsilon_2 >> \varepsilon_1$ **and** $q' = -q$

inserting the expression for the dielectric constant gives:

$$q' = \frac{\frac{Ne^2}{\varepsilon_0 m}\sum_j f_j(\omega_p^2 - \omega^2 - i\omega\gamma_j)^{-1}}{2 + \frac{Ne^2}{\varepsilon_0 m}\sum_j f_j(\omega_p^2 - \omega^2 - i\omega\gamma_j)^{-1}}$$

But at high-frequencies for an isolated, undamped resonance at ω_p:

$$\varepsilon_2(\omega) \approx 1 - \frac{\omega_p^2}{\omega^2} \quad \textbf{and} \quad q' = \frac{1}{1 - 2\frac{\omega^2}{\omega_p^2}}$$

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In general the dielectric constant and the image charge should include damping

The damping parameter, γ, for copper is given by the Drude conductivity model:

$\gamma = 4\times 10^{13}/s$ **or a 25fs damping time.**

For an isolated, damped resonance, the complex frequency-dependent dielectric constant and image charge are given by

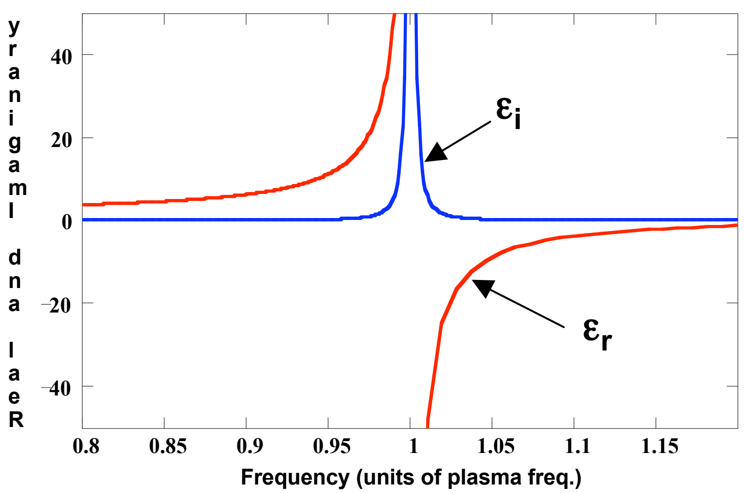
$$\varepsilon = \varepsilon_r + i\varepsilon_i$$

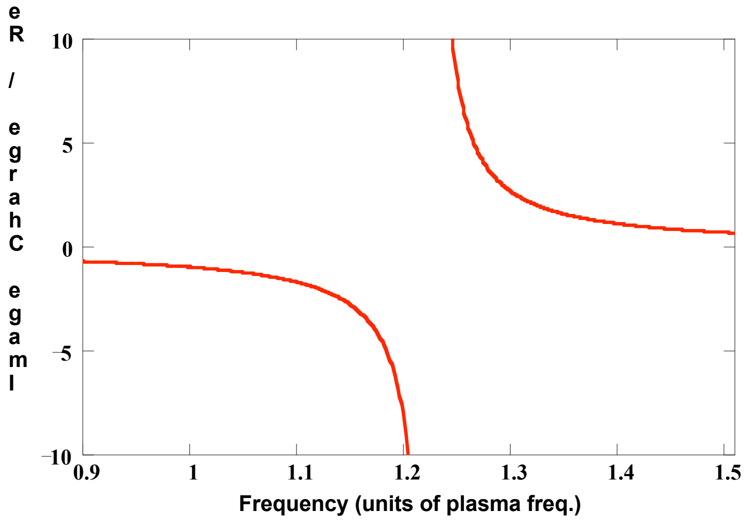
$$\varepsilon_r(\omega) = 1 + \frac{\omega_p^2(\omega_0^2 - \omega^2)}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}$$

$$\varepsilon_i(\omega) = \frac{\omega_p \omega \gamma}{(\omega_0^2 - \omega^2)^2 + \omega^2\gamma^2}$$

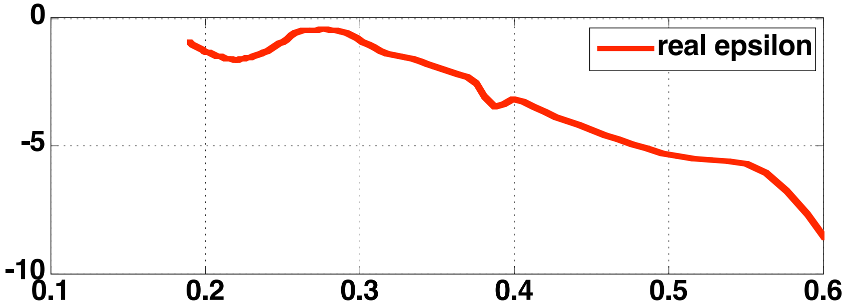
$$\frac{q'}{q} = -\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + \varepsilon_1}$$

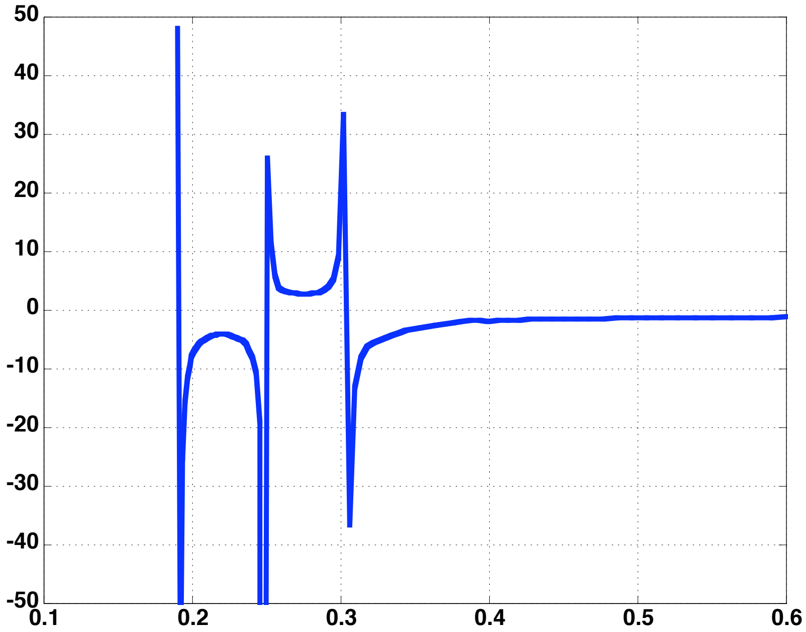
Image charge compute with only the real dielectric constant





The real and imaginary dielectric constants and the image charge for the measured optical properties of copper





As expected the troublesome resonances are all at very short wavelengths (high-frequencies) and there should be no disruption of the electron bunch for longitudinal modulations greater than ~0.4microns or ~1fs.

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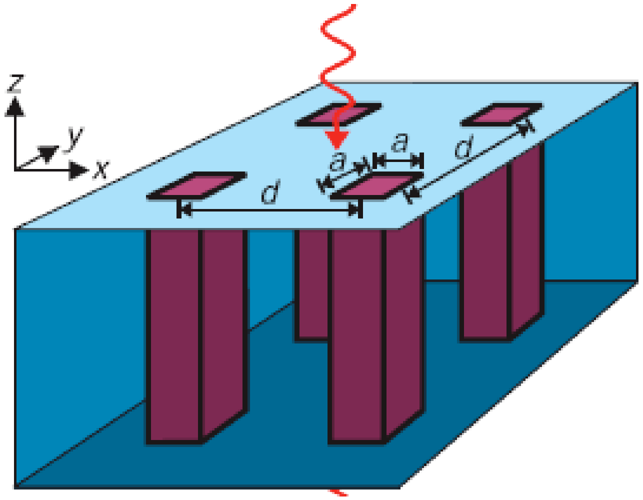
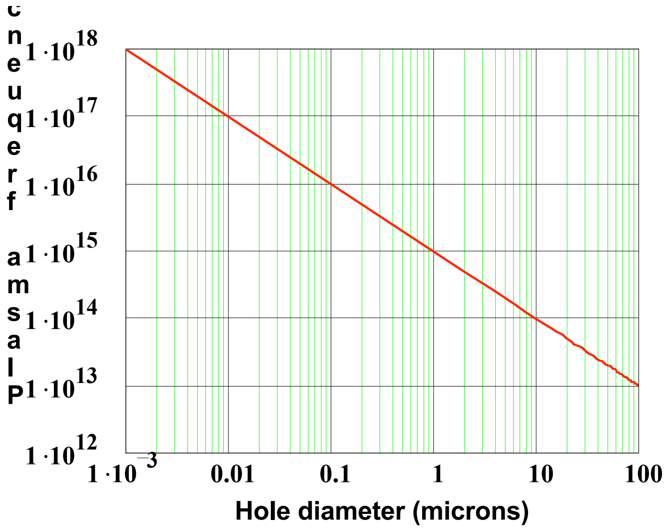
The effect of patterned surfaces on surface states

a pattern of holes with diameter a and lattice spacing d modifies the surface impedance to give the following dielectric constant:



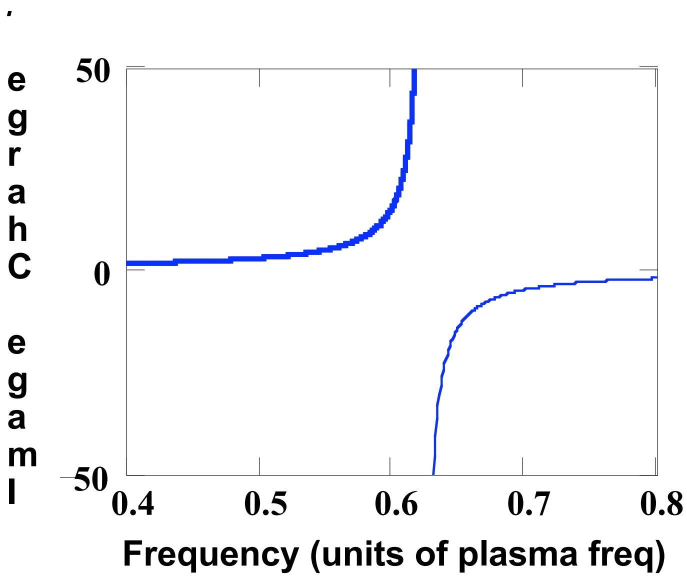
$$\varepsilon_t(\omega) = \frac{\pi^2 d^2 \varepsilon_h}{8\,a^2}\left(1 - \frac{\pi^2 c^2}{a^2\omega^2\varepsilon_h\mu_h}\right) = \frac{\pi^2 d^2 \varepsilon_h}{8\,a^2}\left(1 - \frac{\omega_p^2}{\omega^2}\right)$$

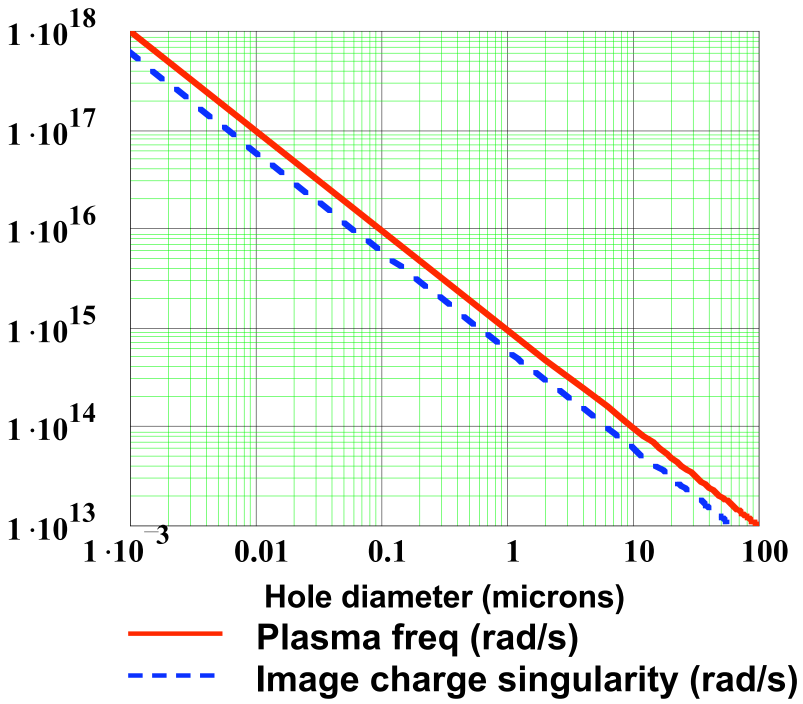
$$\omega_p = \frac{\pi\,c}{a\sqrt{\varepsilon_h\mu_h}}$$



J.B. Pendry et al., “Mimicking surface plasmons with structured surfaces”, Science, Vol 305,p847

The presence of a regular pattern of holes lowers the surface plasmon frequency





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Surface plasmon decay by photoemission

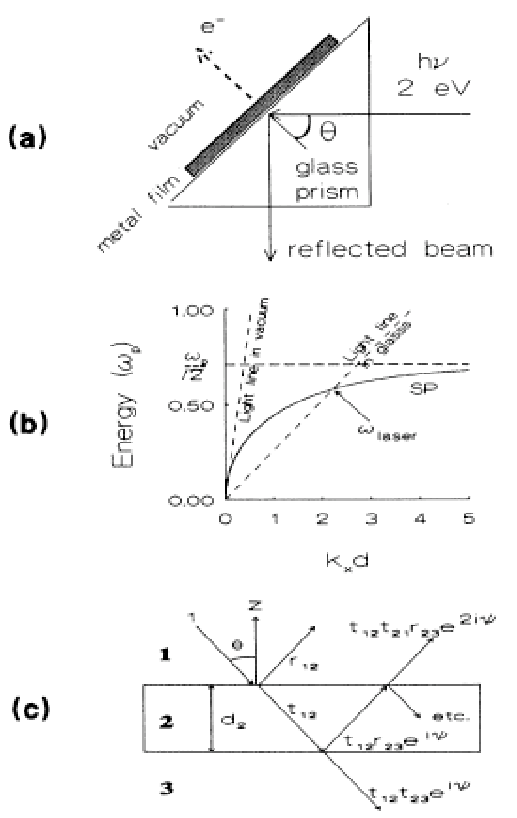

FIG. 1. (a) Kretchmann ATR geometry. (b) SP dispersion curve. (c) Three-layered dielectric structure.

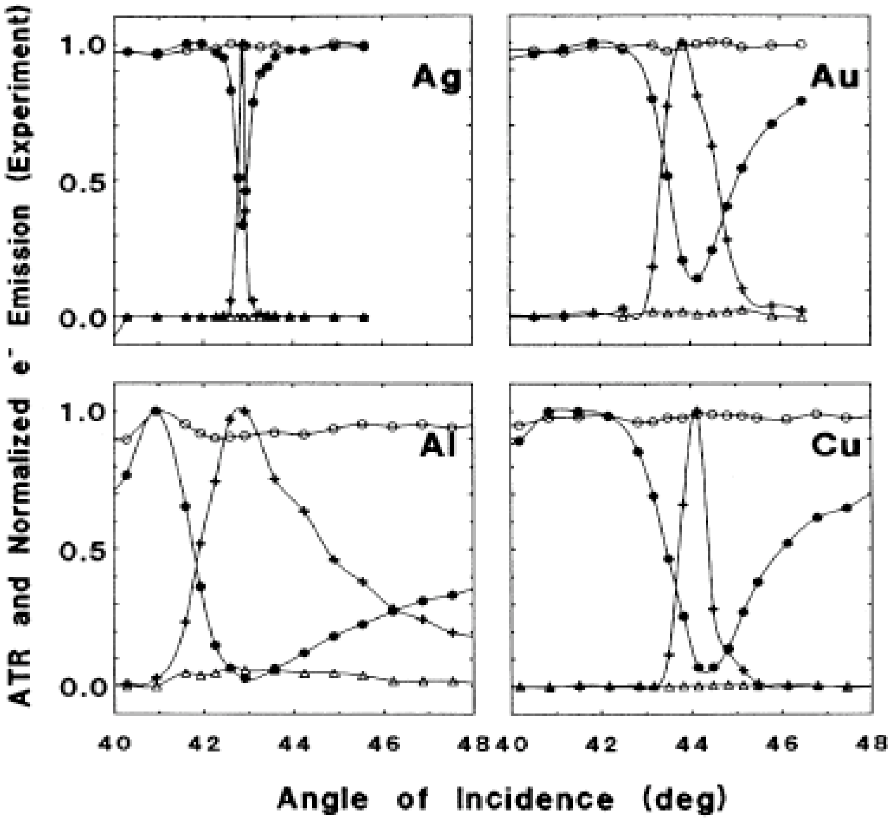

FIG. 4. Experimental values of the p (●) and the s (○) polarized ATR spectra using a femtosecond CPM laser. The corresponding normalized p (+) and s (△) polarized electron emissions are also presented.

Surface-plasmon field-enhanced multiphoton photoelectric emission from metal films, T. Tsang, T. Srinivasan-Rao and J. Fisher, Phys. Rev. B43, 1991, p8870

Summary and Conclusions

- **The optical characteristics determines the cathode’s temporal response**
- **Bulk and surface plasmon excitations determine many of the optical properties**
- **The time-dependent dielectric constant affects the beam dynamics via. the image charge**
- **Beam-shearing is possible near plasmon resonance**
  - **Reversal of the image charge (q_{image}=>-q_{image})**
- **For smooth surfaces, the plasmon frequency effects are in the fs time domain**
- **Surface structures and imperfections can lower the surface plasmon frequency**
- **Surface states can have strong effects on fast electron emission**

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