Quantum interference depression in thin metal films with ridged surface

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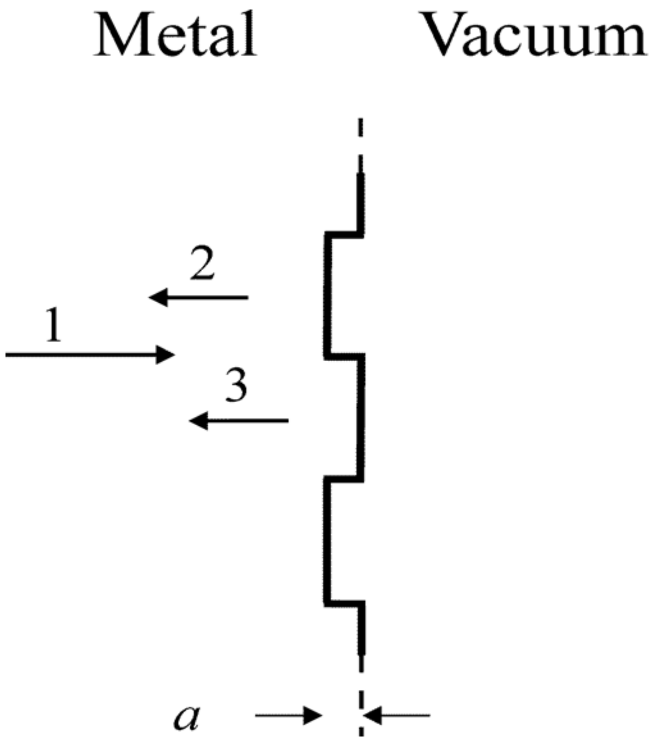
Introduction

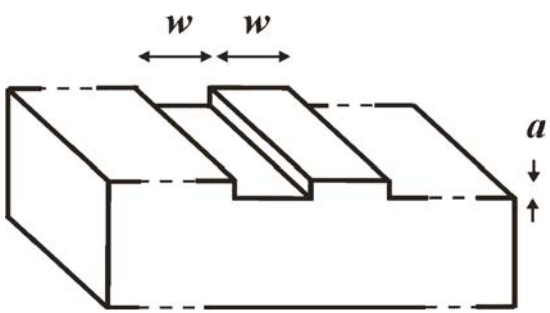


$$a = \lambda / 4$$

Quantum Interference Depression (QID)

Electron in a Ridged Potential Energy Box (RPEB)

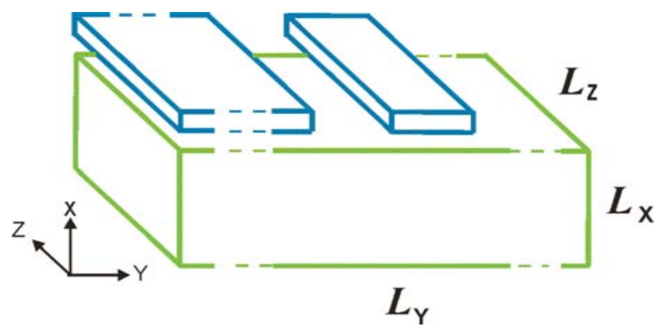
Helmholtz equation



$$\nabla^2\Psi + (2m/\hbar^2)E\Psi = 0$$

$$(\nabla^2 + k^2)\Psi = 0 \qquad k = \sqrt{2mE}/\hbar$$

Volume perturbation method



$$n, j, i, p, q = 1, 2, 3....$$

Matching wave functions in MV and AV

$$\Psi_m(x,y,z), \quad \Psi_a(x,y,z)$$

$$\left.\begin{array}{l}\Psi_m = \Psi_a, \quad \text{and} \\ \dfrac{\partial \Psi_m}{\partial x} = \dfrac{\partial \Psi_a}{\partial x}, \quad \dfrac{\partial \Psi_m}{\partial y} = \dfrac{\partial \Psi_a}{\partial y}, \quad \dfrac{\partial \Psi_m}{\partial z} = \dfrac{\partial \Psi_a}{\partial z}\end{array}\right|_S$$

$$k^{mx} = k^{ax}, \qquad k^{my} = k^{ay}, \qquad k^{mz} = k^{az}$$

Along X direction:

$$k^{cx}{}_{np} = k_n^{mx} \cap k_p^{ax} = (\pi \cdot n / L_x) \cap (\pi \cdot p / a)$$

Matching condition: n $(a/L_x) \in$ N

Spectrum density will be maximum at:

$$(\pi \cdot p / a) \in (\pi \cdot n / L_x) \Rightarrow (L_x/a) \cdot p \in n$$

$L_x/a = o$, where o is natural.

[redacted]

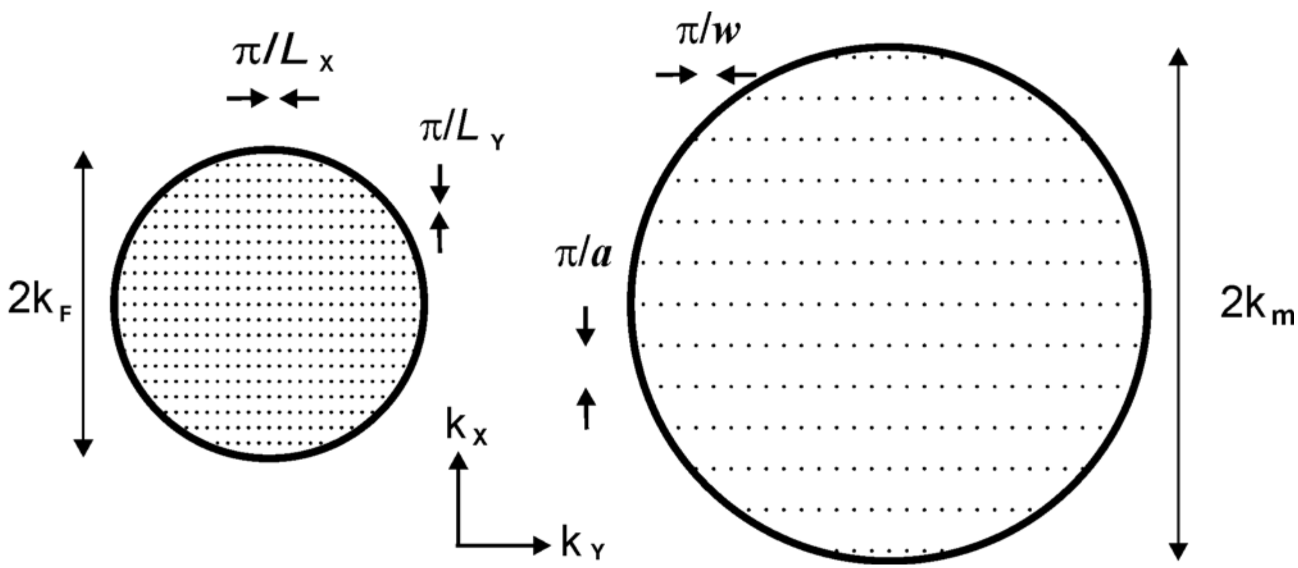
Dramatic increase in Fermi sphere diameter due to QID

Along Y direction $\quad k_{jq}^{\mathrm{cy}} = k_j^{\mathrm{my}} \bigcap k_q^{\mathrm{ay}} = (\pi \cdot j / L_{\mathrm{y}}) \bigcap (\pi \cdot q / w)$ Maximum spectrum density

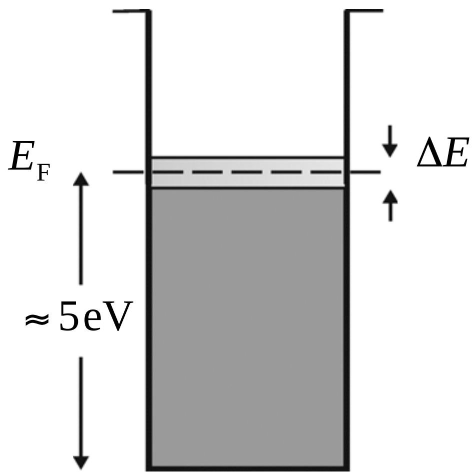
$$\boxed{k_{jq}^{\mathrm{cy}} = (\pi \cdot q / w)} \qquad k_{np}^{\mathrm{cx}} = (\pi \cdot p / a), \quad k_{jq}^{\mathrm{cy}} = (\pi \cdot q / w), \quad k_i^{\mathrm{az}} = \pi \cdot i / L_{\mathrm{z}}$$

[illegible]

$k_n^{\mathrm{x}} = \pi \cdot n / L_{\mathrm{x}}, \quad k_j^{\mathrm{y}} = \pi \cdot j / L_{\mathrm{y}}, \quad k_i^{\mathrm{z}} = \pi \cdot i / L_{\mathrm{z}}$ PEB



Free electrons in low-dimensional metal with ridged wall



$$dV_k = \frac{8\pi^3}{L_x L_y L_z}, \quad dV_m = \frac{8\pi^3}{awL_z}$$

$$\mathbf{k}_m = \mathbf{k}_F \, [L_y (L_x + a/2)/(aw)]^{1/3}$$

[illegible]

$$E_m = E_F + \beta \, E_F \, \{[L_y (L_x + a/2)/(aw)]^{2/3} - 1\}$$

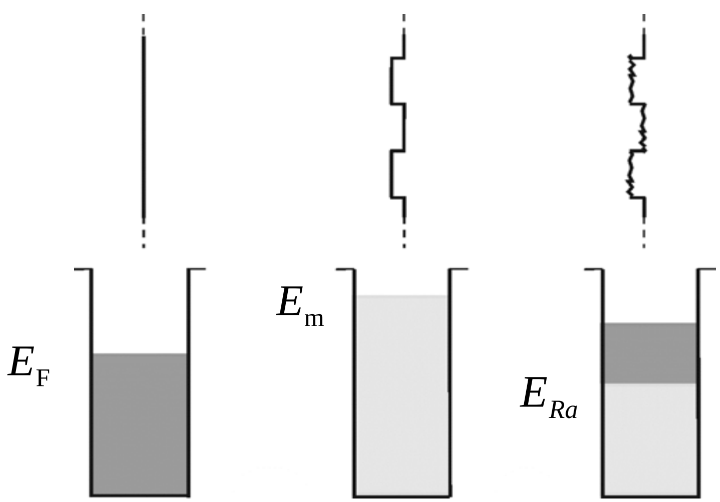
$$0 < \beta < 1$$

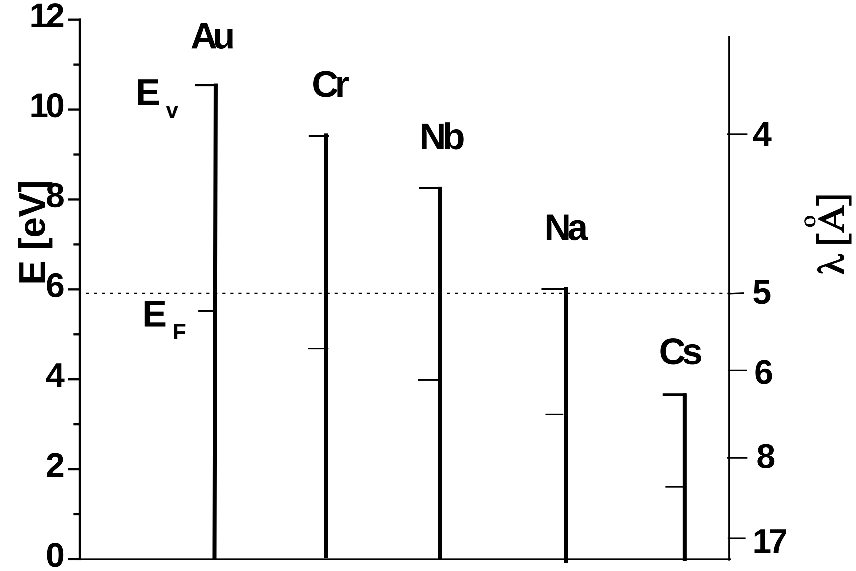
For single crystal with zero surface roughness β=1

Problems of practical realization –surface roughness

λ < Ra

$$E_{Ra} = 2\pi^2\hbar^2 / m \cdot Ra^2$$



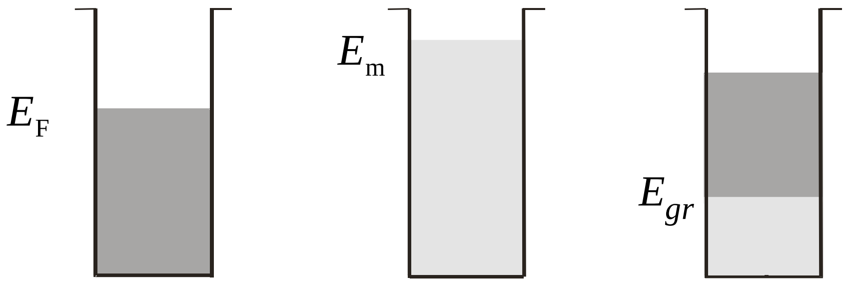


Problems of practical realization – granularity

$\lambda < d$ - electron belongs to the particular grain

$\lambda > d$ - electron belongs to the whole film

$$E_{gr} = 2\pi^2\hbar^2 / md^2$$

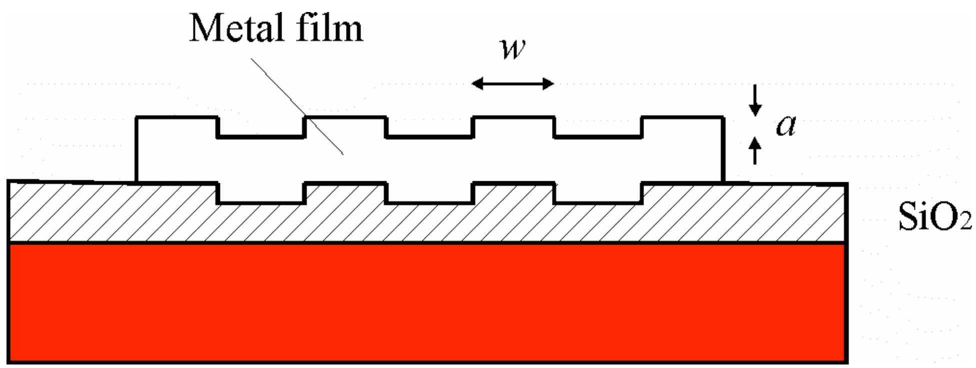


Single crystal film with plane surface

Single crystal film with ridged surface

Granular film with ridged surface

Experiment



a=5-20 nm, w=0.2-3 μm, metal film thickness 30-80 nm.

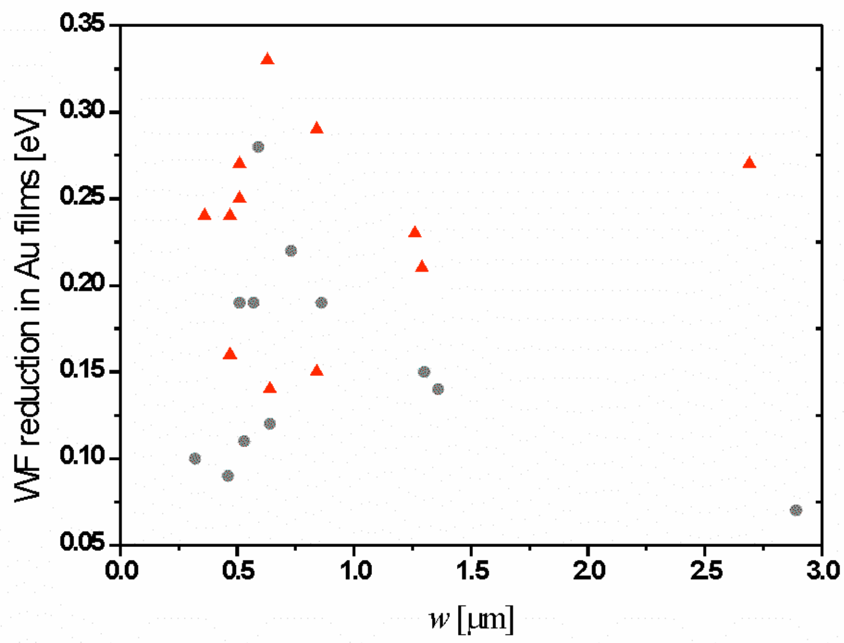
1. Metal films deposited at low temperature substrate always show more $\Delta\phi$.

2. $\Delta\phi$ depends on a in agreement with theory.

a [nm]	50	20	10	5
$\Delta\phi$ [eV]	0.16	0.25	0.56	0.23

Experiment

3. $\Delta\phi$ depends on w in agreement with theory.



Work function reduction dependence on indent width. Circles – room temperature substrate, triangles – cooled substrate..

Conclusions

1. Quantum interference depression effected was predicted theoretically and observed experimentally in thin metal films (Au, Cr, Nb).

2. Theory based on volume perturbation method of solving of Helmholtz equation was developed.

3. Dependences of work function reduction on indent depth and width were recorded. Dependences show qualitative agreement with the theory.

4. Influence of irregularities such as surface roughness and grain boundaries was analyzed and fitting coefficient was introduced in expression for Fermi level.

Acknowledgments

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