Strong Near-Field Enhancement of Radiative Heat Transfer between Metallic Surfaces

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ABSTRACT

We present experimental results on heat transfer between plane parallel metallic (tungsten) surfaces separated by a gap $d = 10^0 - 10^2 \, \mu m$ and kept in vacuo at temperatures below 50 K. Radiative heat flux ranging over six orders of magnitude was measured. Two experiments with two types of samples were done. Comparison with theoretical values of radiative heat transfer is presented. Electron relaxation time ($\tau_{EC}$), a parameter of Drude model of sputtered tungsten layers, was derived from measurement of electrical conductivity. Electron relaxation times $\tau_{FF}$ and $\tau_{NF}$ obtained from fitting theoretical model to experimental data on far-field and near-field heat transfer, respectively, are compared mutually and with $\tau_{EC}$. 
Radiative heat flux between plane parallel surfaces

\[
q(T_1, T_2, d) = \int_0^\infty \omega \, d\omega \, I(T_1, T_2, \omega) \int_0^\infty \frac{2\pi K \, dK}{(\omega/c)^2} \frac{1}{2} \left[ \mathcal{F}_\parallel + \mathcal{F}_\perp \right]
\]

\(I(T_1, T_2, \omega)\) is a difference between spectral intensities of black body radiation at temperatures \(T_1\) and \(T_2\).

s-polarized far-field & near-field contribution

\[
\mathcal{F}_\perp^{FF} = \left( 1 - |r_{\perp}^{(1)}|^2 \right) \left( 1 - |r_{\perp}^{(2)}|^2 \right) \frac{\left| 1 - r_{\perp}^{(1)} r_{\perp}^{(2)} \exp(2i\gamma_0d) \right|^2}{\left| 1 - r_{\perp}^{(1)} r_{\perp}^{(2)} \exp(-2\gamma_0d) \right|^2}
\]

\[
\mathcal{F}_\perp^{NF} = \frac{4 \text{Im}(r_{\perp}^{(1)}) \text{Im}(r_{\perp}^{(2)}) \exp(-2\gamma_0d)}{\left| 1 - r_{\perp}^{(1)} r_{\perp}^{(2)} \exp(-2\gamma_0d) \right|^2}
\]

with reflectivities \(r_{\perp}^{(1)}, r_{\perp}^{(2)}\) of samples and similarly, the transmissivity for p-polarized waves.

Drude model for tungsten:

\[
e = \epsilon_b - \frac{\omega_p^2}{\omega(\omega + i/\tau)} \quad , \quad \omega_p = 9.73 \times 10^{15} \text{ s}^{-1} , \quad \epsilon_b = 1.07
\]

For substrate room temperature optical constants of sapphire were used.
The apparatus is inserted in a wide neck LHe Dewar vessel.
Samples

**Material:** Tungsten - nonmagnetic, mechanically hard, normal skin-effect.

**Shape:** discs 2.5 mm thick and 35 mm in diameter.

**Types of samples:**

"**W-bulk**": polished pure bulk tungsten.

"**W-layer**": 150 nm thick layer sputtered on polished alumina substrates (Al₂O₃ of 99.8% purity, density of 3.87 g/cm³).

**Electron relaxation time of the „W-layer“ sample**

<table>
<thead>
<tr>
<th>Derived from measurement of</th>
<th>Value</th>
<th>Relaxation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrical resistance</td>
<td>$\rho = 2.82 \times 10^{-7}$ Ωm (4.2 K–77 K)</td>
<td>$\tau = 6 \times 10^{-15}$ s</td>
</tr>
<tr>
<td>far-field emissivity</td>
<td>$\varepsilon = 3.5–4$ % (10 K–50 K)</td>
<td>$\tau = 3 \times 10^{-15}$ s</td>
</tr>
</tbody>
</table>

**Surface characterisation of the „W-layer“ sample**

Electron microscope image and surface profile (TalyStep).

**Surface geometry**

**W-layer:** planarity of 0.1 μm and 0.6 μm. (concave)  
**W-bulk:** planarity ~7 μm -convex

Images from HeNe laser interferometer (628 nm)
Heat flux over vacuum gap between samples, normalized to the far-field heat flux $q_{BB} = \sigma_B (T_2^4 - T_1^4)$ transferred between black surfaces, as a function of the gap size $d$ and the temperature $T_2$ product.

**Full coloured symbols**: heat flux between samples with 150 nm thick tungsten layers on polished alumina substrates (W-layer/ W-layer). Temperatures $T_1 \approx 5$ K, $T_2 = 10$–40 K.

**Open coloured symbols**: heat flux between „W-layer“ sample at $T_2$ and „W-bulk“ sample at $T_1$. Temperatures $T_1 \approx 5$ K, $T_2 = 15$–60 K.

**Open black squares**: Far-field data ($d=500 \mu$m, $T_2=15$–160 K) derived from heat transfer measured between „W-layer“ samples and a black surface.

**Full lines**: Theoretical values are calculated for $T_1=5$ K, $T_2=20$ K and $\tau = 8 \times 10^{-15}$ s.
Measured heat flux $q$ divided by the temperature difference $T_2 - T_1$ is plotted as a function of the gap size $d$.

*Full coloured symbols:* heat flux between samples with 150 nm thick tungsten layers on polished alumina substrates (W-layer/W-layer). Temperatures $T_1=5\ K$, $T_2=10–40\ K$.

*Open coloured symbols:* heat flux between „W-layer“ sample at $T_2$ and „W-bulk“ at $T_1$ (W-layer/W-bulk). Temperatures $T_1=5\ K$, $T_2=10–60\ K$.

Fit of W-layer / W-layer: $q/(T_2-T_1)=0.14\ \ d^{-2.6}$
• Results on samples “W-layers” 150 nm thick on polished alumina substrate with high planarity were compared with theory.

• Electrical conductance of W-layers was independent on the temperature below 70 K which means that electron relaxation time in Drude model is constant ($\tau_{EC}=6\times10^{-15}$ s). It means that FIR optical properties of used sputtered tungsten layers do not depend on their temperature.

• Calculations showed weak dependence of theoretical results on the accuracy of substrate optical constants. Reflectivity of polished alumina surfaces was very close to the published values for ordinary ray of sapphire. Optical constants of sapphire were used for calculations.

• Theoretical data in plot $q/q_{BB}$ vs. $T_2d$ reduced to one curve within about ±15 %.

• Near field relaxation time ($\tau_{NF}=8\times10^{-15}$ s) agrees reasonably well with that derived from electrical measurements ($\tau_{EC}=6\times10^{-15}$ s).

• Discrepancy between far-field value ($\tau_{FF}=3\times10^{-15}$ s) and $\tau_{NF}$ we ascribe to the higher sensitivity of far-field emissivity to surface morphology of the layers sputtered on alumina surfaces.

• At the smallest gap sizes the measured heat flux exceeded 100 times the black body limit. FF and NF values became equal at $T_2d' \sim 1000$, which corresponds to $\lambda_m/3$ (one third of Wien’s wavelength $\lambda_m \approx 3000/T$ [µm]).