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 μm 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 (τ_{EC}), a parameter of Drude model of sputtered tungsten layers, was derived from measurement of electrical conductivity. Electron relaxation times τ_{FF} and τ_{NF} obtained from fitting theoretical model to experimental data on far-field and near-field heat transfer, respectively, are compared mutually and with τ_{EC}.

Theoretical background

Radiative heat flux between plane parallel surfaces

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

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

s-polarized far-field & near-field contribution

$$\mathcal{T}_\perp^{FF} = \frac{\left(1-\left|r_\perp^{(1)}\right|^2\right)\left(1-\left|r_\perp^{(2)}\right|^2\right)}{\left|1-r_\perp^{(1)}\,r_\perp^{(2)}\,\exp(2\,i\gamma_0 d)\right|^2} \quad \mathcal{T}_\perp^{NF} = \frac{4\,\mathrm{Im}(r_\perp^{(1)})\,\mathrm{Im}(r_\perp^{(2)})\exp(-2\gamma_0^{''}d)}{\left|1-r_\perp^{(1)}r_\perp^{(2)}\exp(-2\gamma_0^{''}d)\right|^2}.$$

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

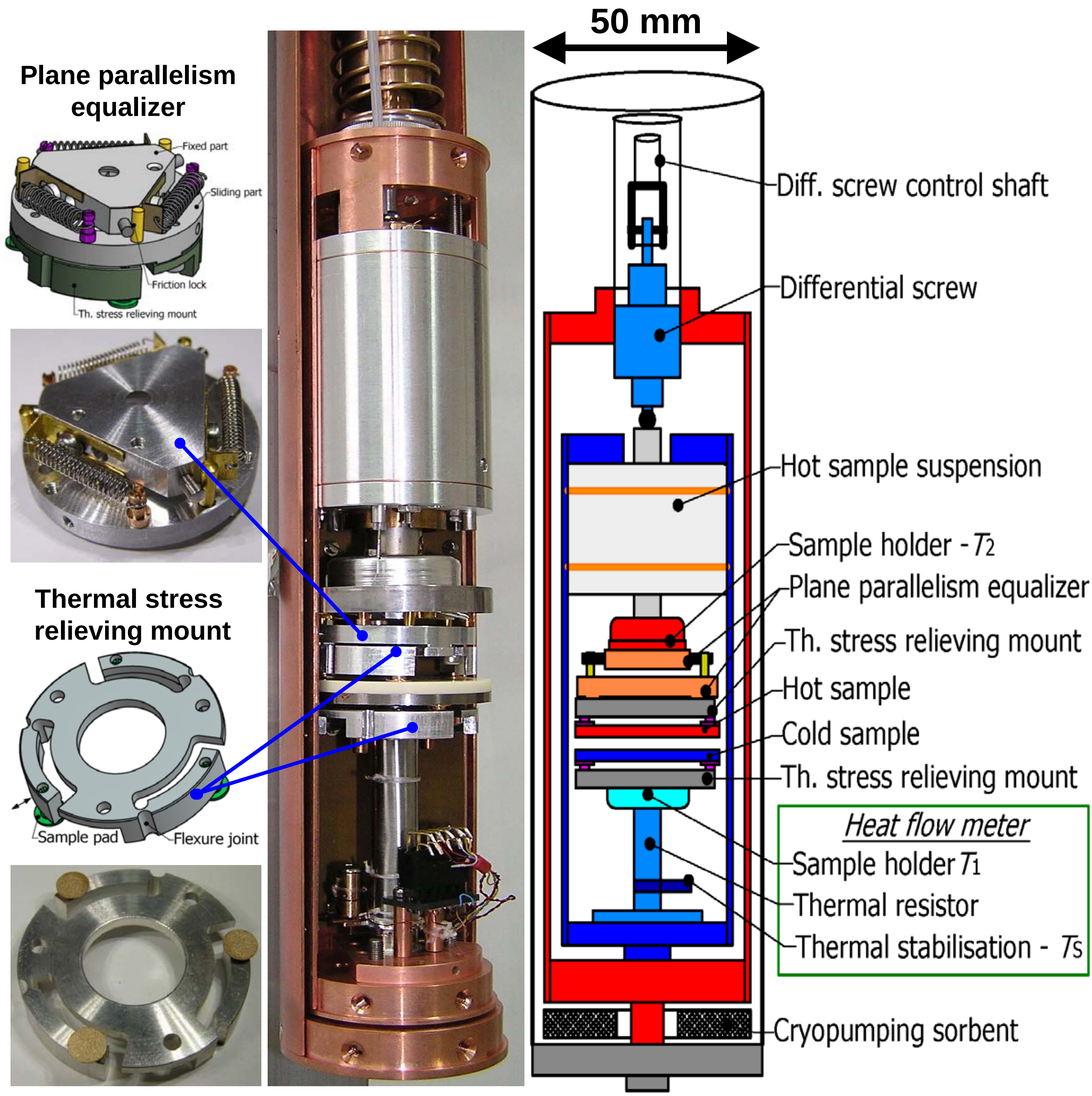
Drude model for tungsten:

$$\varepsilon = \varepsilon_b - \frac{\omega_p^2}{\omega(\omega + i/\tau)} \quad , \omega_p = 9.73\times 10^{15}\,s^{-1}, \; \varepsilon_b = 1.07$$

For substrate room temperature optical constants of sapphire were used.

Apparatus EWA

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:

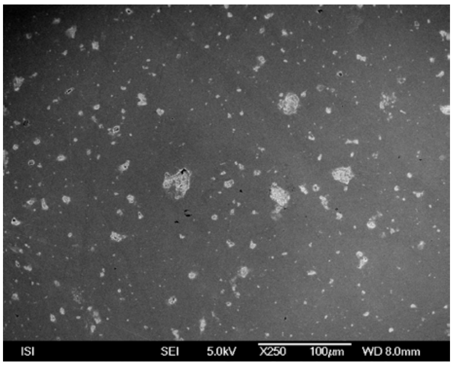
„**W-bulk**": polished pure bulk tungsten.

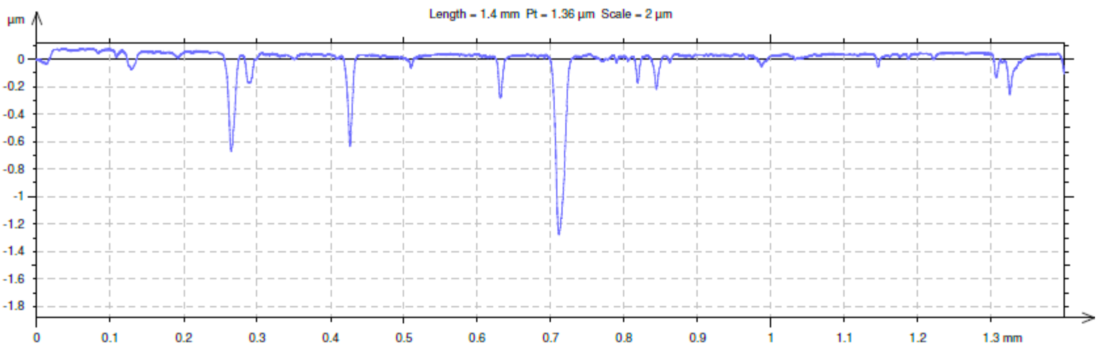
„**W-layer**": 150 nm thick layer sputtered on polished alumina substrates (Al_2O_3 of 99.8% purity, density of 3.87 g/cm^3).

Electron relaxation time of the „W-layer" sample

Derived from measurement of	Value	Relaxation time
electrical resistance	$\rho = 2.82\times10^{-7}$ Ωm (4.2 K–77 K)	$\tau = 6\times10^{-15}$ s
far-field emissivity	$\varepsilon = 3.5–4$ % (10 K–50 K)	$\tau = 3\times10^{-15}$ s

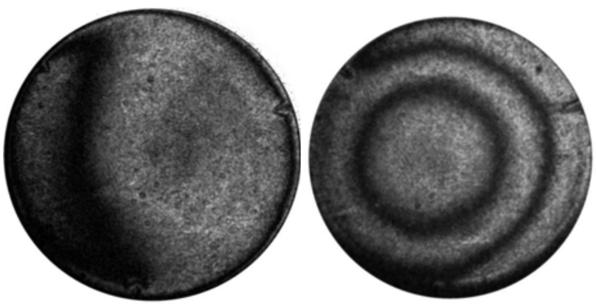
Surface characterisation of the „W-layer" sample





Electron microscope image and surface profile (TalyStep).

Surface geometry

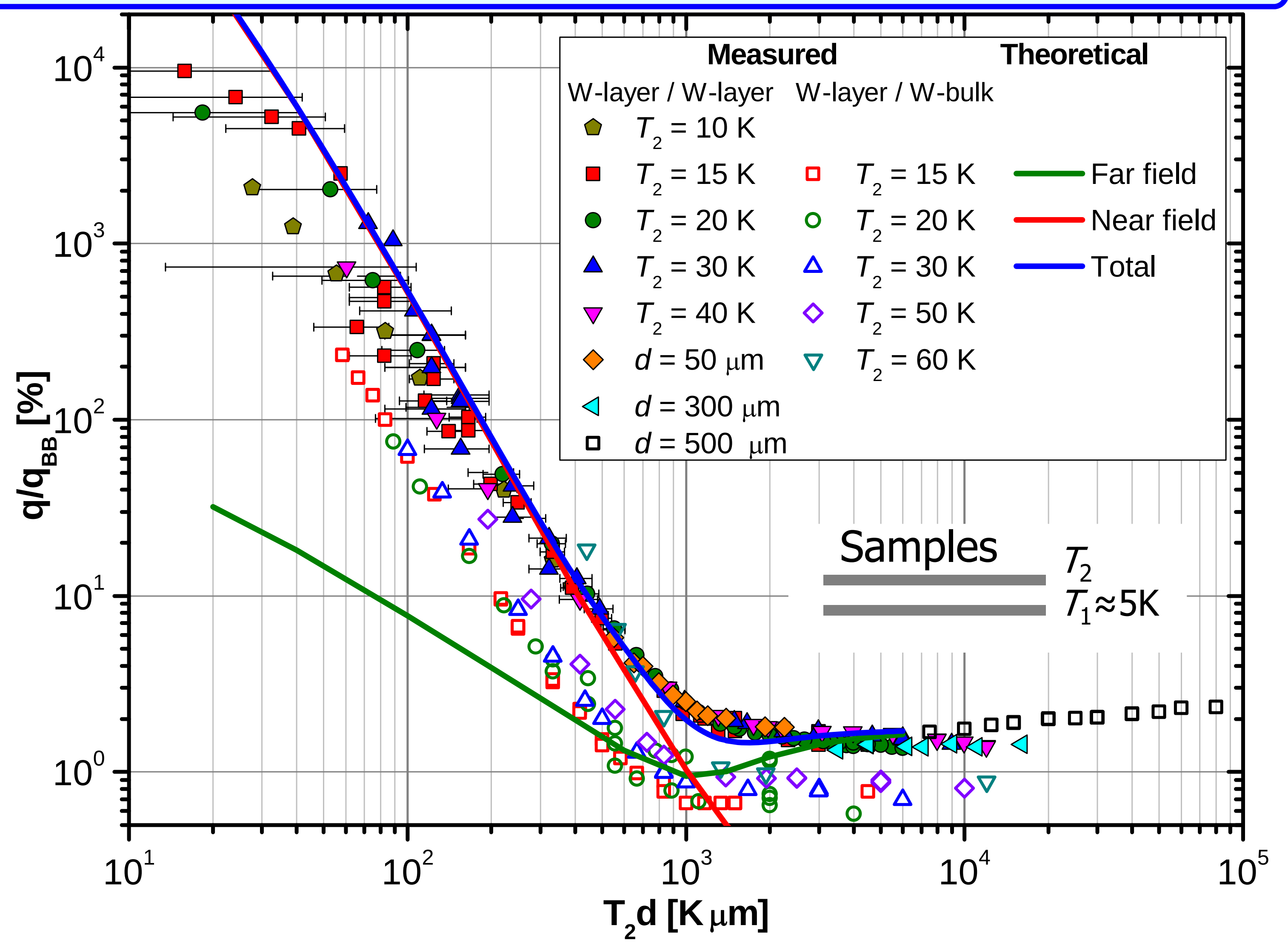


W-layer: planarity of 0.1 µm and 0.6 µm. (concave)

W-bulk: planarity ~7 µm -convex

Images from HeNe laser interferometer (628 nm)

Results



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.

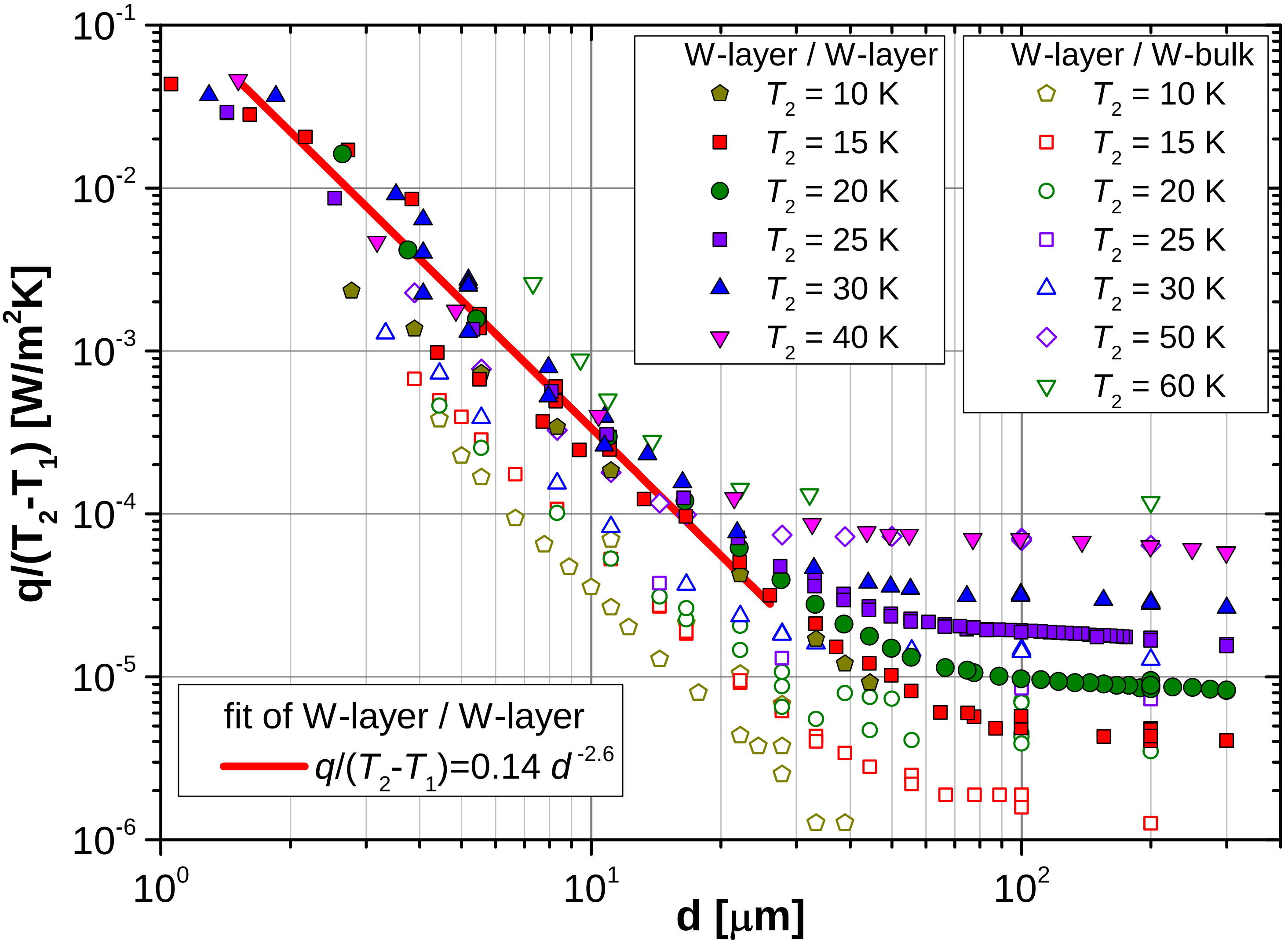
Full coloured symbols : heat flux between samples with 150 nm thick tungsten layers on polished alumina substrates (W-layer/ W-layer). Temperatures T_1≈5 K, T_2=10–40 K.

Open coloured symbols : heat flux between „W-layer" sample at T_2 and „W-bulk" sample at T_1. Temperatures T_1≈5 K, T_2 =15–60 K.

Open black squares : Far-field data (*d*=500 µm, 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 $\tau=8\times10^{-15}$ s.

Results



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.

Summary

- 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 τ_{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 ~1000, which corresponds to $\lambda_m/3$ (one third of Wien’s wavelength $\lambda_m\approx3000/T$ [μm]).

Related papers

- KRALIK, T., et al. Cryogenic apparatus for study of near-field heat transfer. Review of Scientific Instruments, 2011, 82(5), 055106.
- KRALIK, T., et al. Strong Near-Field Enhancement of Radiative Heat Transfer between Metallic Surfaces. Physical Review Letters, 2012, 109(22), 224302.