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Inverse heat flux in double layer thermal metamaterial

M Keidar\textsuperscript{1}, A Shashurin\textsuperscript{1} S Delaire\textsuperscript{1}, X Fang\textsuperscript{1} and I I Beilis\textsuperscript{2}

\textsuperscript{1} George Washington University, 20052, Washington, DC, USA
\textsuperscript{2} Tel Aviv University, Tel Aviv, Israel

E-mail: keidar@gwu.edu

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Abstract
An approach to controlling heat flux based on electron emission in the double layer assembly of two materials with different work functions has been developed. It is shown that this two-electrode assembly promotes the inverse heat flux exhibiting a thermal metamaterial property in a wide range of temperatures. The proposed thermal metamaterial can be used as an active element of a thermal diode, ensuring heat flux in one direction regardless of temperature difference.

Keywords: thermal metamaterials, double layer, electron emission

1. Introduction
Metamaterials are man-made materials engineered with properties that have not yet been found in nature. One of the recent developments in metamaterial techniques is the sound manipulation and management of heat conduction leading to the development of thermal analogs of electronic transistors, rectifiers, and diodes [1]. To achieve this the metamaterial methods that are used for sound manipulation were adapted to heat conduction control [2, 3].

Employing isotropic elements with prescribed particular spatial patterns, it was shown that anisotropy is required for thermal guiding [4]. To this end, various concepts were recently proposed based on cloaks designed using graded materials [1, 2, 5–7]. By changing the geometrical shape of the cloak an inverse thermal flow has been demonstrated [8]. Several ideas based on thermal metamaterials were proposed recently for thermal rectifiers that were followed by experimental demonstration [1, 3, 4]. A solid-state thermal diode formed by non-uniform mass distribution in nanotubes has been shown [9]. Thermal metamaterials can be employed for controlling heat fluxes and thermoelectricity in molecular junctions [10]. It was found that an extremely large gradient ($>10^9$ K m$^{-1}$) can be reached in a nanoscale gap bridged by molecules, thus paving the way for extremely efficient thermoelectric energy conversion devices [5]. Layered thermal metamaterials are shown to be able to direct and harvest conductive heat [11].

The technological transformation of our society has been chiefly based on advances in our ability to manipulate electrons and photons. Another particle of interest is the phonon, which is responsible for heat and sound transfer. Achieving a high level of control of phonons matching that of electrons and would revolutionize devices utilizing heat transfer processes. Nowadays, however, despite the demonstrated localized inverse thermal flow the ability to manage overall heat flux remains elusive. A fundamentally different approach can be proposed to control the reverse heat flux, namely the electron emission effect between two different materials controlled by a weak externally applied voltage.

This paper explores and demonstrates the possibility of creating a material with an inverse thermal flow based on the electron emission effect. As such, we will call this double electrode assembly a thermal metamaterial. An assembly of a two-electrode system with a micron-size gap and low applied voltage is considered allowing the manipulation of the electron energy flux.

2. Model formulation
We will start by considering 1D heat transfer, which can be described by Fourier’s law as:
\[ Q = -k_{\text{eff}} \frac{dT}{dz} = -k_{\text{eff}} \frac{T_H - T_L}{L} \]  
(1)

where \( k_{\text{eff}} \) is the ‘effective’ thermal conductivity coefficient, \( T_H \) is the temperature at the hot end, \( T_L \) is the temperature at the cold end, and \( L \) is the length of the thermal conductor. Naturally the thermal conductivity coefficient is characteristic of a conductive material and it is of positive value. For a metamaterial the coefficient \( k_{\text{eff}} \) might be negative to support the inverse heat flux. In this case the positive heat flux \( Q \) in equation (1) means that the heat is conducted from the low-temperature end to the high-temperature end, i.e. the heat flux is inverse.

Let us consider an inverse heat flux formation in an assembly of layered material shown in figure 1(a). A heat flux exchange within a layered material is maintained by the transfer of electron emission energy and radiation from the material surfaces with significantly different work functions and surface temperature. It should be pointed out that the double electrode assembly has to be in an enclosure to maintain vacuum conditions.

To this end we are accounting for the thermionic emission. The current density in the case of electron emission depends on the work function and surface temperature. The current density \( J_{\text{eml}} \) emitted from electrode with low temperature and lower work function \( \phi_{\text{el,low}} \) is calculated as:

\[ J_{\text{eml}} = AT_L^2 \exp \left( -\frac{\phi_{\text{el,low}} + U_{\text{gap}}}{k_B T_L} \right) \]  
(2)

where \( T_L \) is the surface temperature and \( A \) is the Richardson constant. On the other hand, current density due to electron emission from the high-temperature electrode with a larger work function \( \phi_{\text{el,high}} \) is calculated as:

\[ J_{\text{emH}} = AT_H^2 \exp \left( -\frac{\phi_{\text{el,high}} + U_{\text{gap}}}{k_B T_H} \right) \]  
(3)

where \( U_{\text{gap}} = U_H - U_L \) is the potential drop across the gap and \( k_B \) is the Boltzmann constant. In the vacuum gap between two layers (shown in figure 1(a)) electron current density obeys Child-Langmuir’s law:

\[ J_{\text{eml}} = J_0 = \frac{4e_0}{9} \frac{2e}{m_e} \frac{3}{L^2} U_{\text{gap}}^\frac{3}{2} \]  
(4)

where \( \varepsilon_0 \) is the permittivity of the vacuum, \( e \) is the electron charge, and \( m_e \) is the electron mass. This equation can be used to determine the required voltage to sustain the emission current. Power density \( Q_{\text{el,low}} \) carried by electrons emitted from the low-temperature electrode is calculated as

\[ Q_{\text{el,low}} = J_{\text{eml}} \frac{2k_B T_L}{e} \]  
(5)

Electrons will gain energy from the electric field in the gap and the resulting power density transferred by the electrons to the hot electrode will be:

\[ Q_{\text{el}} = J_{\text{emH}} \left( \frac{\phi_{\text{el,high}}}{e} + \frac{2k_B T_L}{e} + U_{\text{gap}} \right) \]  
(6)

Power density \( Q_{\text{elH}} \) carried by the electrons emitted by the high-temperature electrode with a higher temperature is calculated as

\[ Q_{\text{elH}} = J_{\text{emH}} \left( \frac{\phi_{\text{el,low}}}{e} + \frac{2k_B T_H}{e} + U_{\text{gap}} \right) \]  
(7)

Additional heat transfer is supported by radiation, i.e. \( \epsilon \sigma T^4 \). It should be pointed out that the thermal radiation wavelength is around 0.5–1 μm, which is smaller that the gap considered here (larger than 5 μm). As such, Stefan-Boltzmann’s law is applicable for this case.

Thus, the heat flux density across the double layer in inverse direction \( Q_{L,H} \) (i.e. from the cold to hot end) can be calculated as

\[ Q_{L,H} = Q_{\text{elH}} + Q_{\text{radl}} - Q_{\text{radH}} - Q_{\text{elH}} \]  
(8)

3. Results and discussions

The calculated power density associated with electron emission as a function of surface temperature is shown in figure 1(b) with the surface work function as a parameter. For comparison the radiative heat flux is also shown. It is important to note that in the considered range of temperatures (as shown in figure 1(b)) the heat flux transferred by the electron emission is larger than that of the radiation. The voltage \( U_{\text{gap}} \) required to sustain the electron flow from the low-temperature to high-temperature electrode (according to equation (4)) depends on the interelectrode gap length \( L \) and the surface temperature of the cold electrode, as shown in figure 1(c) One can see that for cold electrode temperatures lower than 1600K the required voltage is very small (a fraction of a volt), i.e. \( U_{\text{gap}}/\phi_{\text{el}} \ll 1 \). As such, external work by applied voltage is negligibly smaller than the power transferred by heat from the cold electrode to the hot electrode (as can be seen in equations (6), (7)).

The calculated heat flux from the low-temperature end to the high-temperature end and the heat flux in the opposite direction are shown in figure 1(d). One can see that the expected heat flux from the low-temperature to high-temperature end of the assembly is high, i.e. the overall heat flux is in the inverse direction.

The ratio of the heat fluxes in both directions is plotted in figure 2. It can be seen that the heat flux from the low-temperature electrode \( Q_{L,H} \) is higher than that from the high-temperature one \( Q_{H,L} \). It is predicted that the heat flux ratio depends on the surface temperature \( T_L \) and the temperature drop across the gap, i.e. on \( T_H - T_L \). For instance, heat flux ratio \( Q_{H,L}/Q_{L,H} > 1 \) if the temperature drop \( T_H - T_L \) is 500K and the surface temperature is higher than about 1550K.

Numerical simulations of the considered double layer assembly were performed using COMSOL multiphysics. Figure 3 illustrates the heat flux and temperature distribution between the two-electrode gap. In figure 3(a) both electrodes are tungsten (W) and have high work functions (5.4 eV), making the thermionic effect negligible. There is only a small radiative flux of 11 W, which corresponds to a \( 1.1 \times 10^5 \) W m\(^{-2}\) heat flux density. In figure 1(b) it corresponds to the difference
between the values at abscises 1400 K and 1800 K on the dotted curve. In this case the heat flux is directed from the high-temperature electrode to the low-temperature electrode as expected. However, in figure 3(b) since BaO has a much lower work function (1.4 eV), it emits energetic electrons to the hot tungsten electrode, which is heated by a 210 W heat flux in the considered example, which corresponds to a $2.1 \times 10^6$ W m$^{-2}$ heat flux density in the tungsten electrode. This is in agreement with the analytical prediction shown in figure 1(d). In this case the heat flux is inverse, i.e. directed from the low-temperature electrode to the high-temperature electrode. Thus, one can see that selection of material with a low work function leads to inverse heat flux.

Note that in figure 3(b), even if the heat flux density is much larger in tungsten than in barium oxide, the temperature variation is larger in barium oxide because it is a good thermal insulator: The thermal conductivity values are 3 and 173 W m K$^{-1}$, respectively, for BaO and W.

4. Concluding remarks

One can see that a two-electrode assembly with electrode materials with a distinct work function produces inverse heat flux. The mechanism that supports inverse heat flux is based on a difference in electron emission current densities from electrodes with different work functions. This thermal metamaterial assembly was characterized by a negative ‘effective’ thermal coefficient in a wide range of temperatures. This electrode assembly allows the heat flux flow from one end to

Figure 1. (A) Schematics of the two-electrode system with distinct material properties with different work functions. (B) Calculated power density as a function of surface temperature. Comparison of the electron emission heat flux (marked as ‘emission’) and radiative heat flux (marked as ‘radiation’), (an emissivity of about 0.3 is considered). The work function is taken into account as a parameter. (C) Calculated voltage across the gap ($U_{gap}$) as a function of surface temperature of the cold electrode with the gap length as a parameter. (D) Comparison of the heat flux from the cold to hot electrode and the heat flux from the hot to cold electrode as a function of surface temperature. The cold electrode has a work function of 1.7 eV (BaO) while the hot electrode has a work function of 5.4 eV (tungsten). The work functions and Richardson’s constant are taken from [12].

Figure 2. Ratio of heat fluxes as a function of surface temperature.
another while prohibiting the heat flux flow in the opposite
direction. A system of this kind can be used as an active ele-
ment of a thermal diode, ensuring heat flux in one direction
regardless of temperature difference.

References

Nature 503 209
electromagnetic fields Science 312 1780–2
312 1777–80
engineered thermal materials Phys. Rev. Lett. 108 214303
anisotropic media in conduction Appl. Phys. Lett. 93 114103
110 195901
thermodynamics: cloaking and concentrating heat flux Opt. Express 20 8207–18
with an apparent negative thermal conductivity Appl. Phys. Lett. 92 251907
Solid-state thermal rectifier Science 314 1121–4
Electrostatic control of thermoelectricity in molecular
junctions Nat. Nanotechnol. 9 881
the directing and harvesting of conductive heat AIP Adv.
5 053403
[12] Wolf B 1995 Handbook of Ion Sources (Boca Raton,
FL: CRC)