Thermotunnel refrigerator with vacuum/insulator tunnel barrier: A theoretical analysis

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The authors use two insulator layers in thermotunnel refrigerator to modify the shape of the tunneling barrier so that electrons with high kinetic energy pass it with increased probability. Theoretical analysis show that the overall tunneling current between the electrodes contains an increased number of high kinetic energy electrons and a reduced number of low energy ones, leading to high efficiency. The particular case of vacuum gap and solid insulator layer is calculated using digital methods. Efficiency remains high in the wide range of the emitter electric field. The cooling coefficient is found to be as high as 40%−50% in the wide range of the emitter electric field. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2803717]

Thermotunnel refrigeration at room temperature is widely discussed in the literature.[1–5] Analysis of such systems shows that they have advantages over traditional thermoelectric refrigerators. Efficiency could be as high as 20%−30%. A cooling power of 100 W/cm^2 could be achieved at room temperature.[1] Attempts of practical realization of such a system underlined some problems.[2,5,6] A major problem is the short circuit between the electrodes.

Thermotunnel refrigerator contains two conductive electrodes separated by a vacuum gap width of ~ 10 nm. Driven by applied electric field, electrons tunnel from the emitter to the collector carrying heat energy. Mirror forces and external electric field reduce the potential energy barrier. Tunneling electrons are distributed in a wide range of initial kinetic energies. For efficient cooling it is necessary for electrons to tunnel from high energy levels. We offer to coat the collector with a thin 3–5 nm layer of an insulator. The insulator magnifies the electric field inside the vacuum gap. It changes the profile of the potential barrier so that high energy electrons tunnel through a barrier of less height and less width. At the same time low energy electrons tunnel through a barrier of more width.

The potential of the electron between the conductive electrodes, with respect to image forces, has the following form:

$$\begin{aligned}V(x) &= \Phi_1/q - V_1 x\theta(d_1 - x)/d_1 - \theta(x-d_1)[(\Phi_1-\Phi_2)/q \\ &\quad + V_1 + V_2(x-d_1)/d_2] \\ &\quad + (q^2/16\pi\varepsilon_0)\sum_{n=0}^{\infty}\sum_{i=0}^{n}\sum_{j=0}^{i} P_{n,i,j}k^i\{[\theta(x-d_1)/\varepsilon \\ &\quad + \theta(d_1-x)][2(d+\alpha)^{-1} - (x+\alpha)^{-1} - (d-x+\alpha)^{-1}] \\ &\quad + k\theta(d_1-x)[(d_1-x+\alpha)^{-1} - 2(d_1+\alpha)^{-1} \\ &\quad + (x+d_2+\alpha)^{-1}] + k\theta(x-d_1)[2(d_2+\alpha)^{-1} \\ &\quad - (x-d_1+\alpha)^{-1} - (2d-d_2-x+\alpha)^{-1}]/\varepsilon\}, \qquad (1)\end{aligned}$$

where x is the distance from the emitter, d_1 is the thickness of vacuum gap between the emitter and the insulator layer, d_2 is the thickness of the insulator layer, $d=d_1+d_2$, q is the electron charge, Φ_1 is the work function of the emitter, Φ_2 is the work function of the collector, ε is the high frequency dielectric constant of the insulator, $V_1=\varepsilon d_1 V_0/(d_2+\varepsilon d_1)$ is the potential drop inside the vacuum gap, $V_2=d_2V_0/(d_2+\varepsilon d_1)$ is the potential drop inside the dielectric layer, V_0 is the is external voltage applied to the electrodes, $P_{n,i,j}=(-1)^{(i-j)}[n!/i!(n-i)!][i!/j!(i-j)!]$, $k=(1-\varepsilon)/(1+\varepsilon)$, $\alpha=(i-j)d_1+jd_2+(n-i)d$, and $\theta(x)$ is the step-like function. Electron energy is given relative to the Fermi energy of the emitter.

Figure 1 shows potential profiles for the cases $d_2=0$, $d_2=30$ Å, and $d_2=50$ Å. The potential barrier height and width reduce in the presence of an insulator coating the collector. The values of work functions and applied voltage are $\Phi_1=\Phi_2=1$ eV, $V_0=1$ V, and $\varepsilon=10$ for all three profiles.

Integral tunneling current density contains electrons emitted from all energy levels up to the potential barrier height—H,

$$J_{\text{tun}} = \int_{-\infty}^{qH} N(E_x)D_{\text{tun}}(E_x)dE_x, \qquad (2)$$

where $N(E_x)=mk_BT/2\pi^2\hbar^3 \ln[1+\exp(-E_x/k_BT)]$ is the number of electrons emitted from the unit area during the unit time having a kinetic energy in the range of (E_x, E_x+dE_x) and $D_{\text{tun}}(E_x)$ is the probability of tunneling of the electron through the potential barrier.

Figure 1 shows that near the border of the insulator and vacuum potential changes rapidly. Because of it, using the Wentzel–Kramers–Brillouin (WKB) method in that range will reduce the accuracy of the calculation. Actually, there is singularity in the potential profile at the border of the insulator and vacuum. It is due to the zero width of the surface charge region. To avoid singularity we assume that mirror forces act only for distance that is more than some critical value. We chose a critical value of 6 Å because in practice

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