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Cooling by resonant Fowler–Nordheim emission

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Abstract

A new method of electronic refrigeration based on resonant Fowler–Nordheim emission is proposed and analyzed. Calculations show that cooling power of at least 30 W/cm^2, as well as temperatures down to 10 K, may be achieved using this effect. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Refrigeration; Resonant tunneling

The idea of cooling by thermionic emission of electrons over an energy barrier has been repeatedly discussed in the literature – see, e.g., Refs. [1,2]. A barrier of the necessary height (a few times $k_B T$) may be readily implemented in solid-state structures, however, the back flow of heat to the cooled conductor presents a very difficult problem. Even a very narrow (submicron) vacuum gap can effectively quench the back heat flow. Unfortunately, in this case the energy barrier height is determined by the conductor workfunction which is too high for most materials. A natural way to enforce electron transfer is to apply a strong electric field (~ 10 MV/cm), inducing Fowler–Nordheim tunneling. However, the tunneling typically pulls out electrons within a relatively broad energy range that results in heating rather than in cooling.

We propose to limit the energy range of transferred electrons using resonant tunneling in a simple structure (Fig. 1) where the bulk emitter (a metal or a heavily doped semiconductor) is covered with a thin layer of a widegap semiconductor. While at zero voltage the electron potential energy profile of this structure has two steps (Fig. 1a), its tilting by the applied electric field creates a triangular-shape potential well (Fig. 1b) and, hence, the discrete levels (subbands for the full energy) localized at the semiconductor film surface. If the lowest subband is aligned with the hot electrons in the emitter (a few $k_B T$ above the Fermi level), their resonant tunneling to vacuum may lead to the efficient heat removal, and hence to emitter cooling. (This cooling mechanism was discussed earlier [3,4], but for non-planar structures in which it is much less effective.)

We have analyzed the cooling effect in the system shown in Fig. 1 assuming perfectly plane interfaces, using WKB approximation, and neglecting band banding and finite level line width. Fig. 2 shows a typical result of the calculations. The cooling power q first increases exponentially with the electric field E (together with electric current density j), because the lowest subband is aligned with more and more populated hot electron levels, and then drops sharply when the subband crosses the Fermi level (at larger fields q becomes negative, indicating emitter heating). The contributions to the current (j') and the emitter heating ($-q'$) due to nonresonant ("direct") tunneling are relatively small compared to j and q in the range of interest. Our model indicates that the net heat flow ($q + q'$) may be positive (i.e., cooling is still possible) for temperatures as low as 10 K.

The largest problem we see with the experimental implementation of resonant emission cooling is the fluctuations of film thickness. Because of that, the electric field should be decreased below the optimal value in order to be sure that we have not stepped into the heating region on any considerable fraction of the emitter area. As a consequence, despite the cooling power up to 10^4 W/cm^2 is possible theoretically, we believe that the practical value can be on the order of 30 W/cm^2 at $T \sim 100$ K while $j \sim 1$ kA/cm^2.[1]

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[1] This structure may be also used as a very effective field emitter of current.

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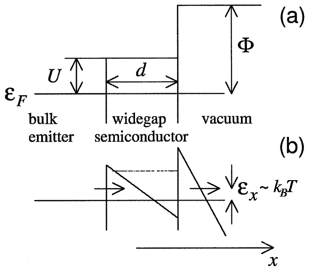

Fig. 1. The energy band edge diagram of the proposed device: (a) in the absence of applied voltage and (b) in a proper electric field. Resonant tunneling via the lower subband removes hot electrons above the Fermi surface, thus cooling the emitter.

Another limitation of cooling power may come from unacceptably large power release density q_a on the anode due to relatively low efficiency of the proposed device. To improve the efficiency, the electric field may be provided by a micromachined "grid" electrode at a small distance d_0 from the cathode, followed by another, much more distant grid at approximately the same electric potential, and a collector at a lower potential, so that electrons are decelerated before the "soft landing". Such systems allow to recover more than 90% of the electron energy. For $q = 30$ W/cm^2 and a feasible value $d_0 = 30$ nm, q_a is reduced below 10 kW/cm^2, and with a good radiator the anode temperature raise may be kept within 300 K. This may be acceptable in practice while giving negligible radiation backflow below 1 W/cm^2.

A preliminary literature search has yielded three candidate material pairs (with acceptable potential step height, good lattice match, and technological compatibility) for the emitter and covering thin film: ZnS on arsenic-passivated Si (0 0 1), AlN on 6H-SiC, and p$^+$ Si layer on an n-Si substrate. For the first pair (which is the most promising) the reported band offset $U = 1.0$ eV and electron affinity $\Phi - U = 2.7$ eV are quite close to the parameters used in Fig. 2.

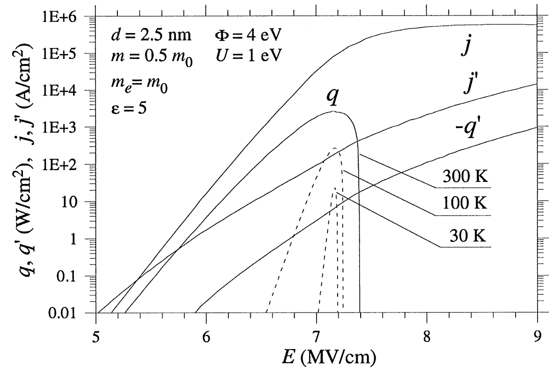

Fig. 2. The resonant current density j, the corresponding cooling power density q, non-resonant tunneling current j', and the corresponding heating $-q'$ as functions of the applied electric field, for several emitter temperatures.

Acknowledgements

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