Langley Research Center
Hampton, Virginia 23665

Technical Support Package

Thermo-Electron Ballistic Coolers or Heaters

NASA Tech Briefs
LAR-16222

National Aeronautics and
Space Administration

Technical Support Package

for

THERMO-ELECTRON BALLISTIC COOLERS OR HEATERS

LAR-16222

NASA Tech Briefs

The information in this Technical Support Package comprises the documentation referenced in **LAR-16222** of *NASA Tech Briefs*. It is provided under the Commercial Technology Program of the National Aeronautics and Space Administration to make available the results of aerospace-related developments considered having wider technological, scientific, or commercial applications. Further assistance is available from sources listed in *NASA Tech Briefs* on the page entitled "NASA Commercial Technology Team."

Additional information regarding research and technology in this general area may be found in a variety of publications available from the NASA Scientific and Technical Information (STI) Program Office. You can access the STI Program Office via **http://www.sti.nasa.gov** or as follows:

NASA STI Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076-1320

Telephone: (301) 621-0390, Fax: (301) 621-0134, E-mail: help@sti.nasa.gov

---

NOTICE: This document was prepared under the sponsorship of the National Aeronautics and Space Administration. Neither the United States Government nor any person acting on behalf of the United States Government assumes any liability resulting from the use of the information contained in this document or warrants that such use will be free from privately owned rights. If trade names or manufacturers' names are used in this report, it is for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

DEVELOPMENT OF A NEW AND NOVEL THERMO-ELECTRON BALLISTIC (TEB) COOLER

By

Sang H. Choi

SUMMARY

The proposed invention, thermo-electron ballistic (TEB) cooler, uses electron ballistic transport property and high current density capacity within single-walled carbon nanotubes ① or within the room-temperature superconducting polymers ②. The TEB cooler is regarded as a new and novel cooler concept that promises high efficiency, high cooling power, high power density and wide range of operational temperature differences as compared to the state-of-the-art cooler concepts and devices. The TEB can be built as a cooler or vice versa a heater in either a fixed or a flexible form and in either micro or macro-scale that are useful for wide cooling applications.

INTRODUCTION:

A recent finding of electron ballistic transport process within single-walled carbon nanotubes [1~5]① or within the room-temperature superconducting polymers (RTSP) [6~16]② gives rise to new opportunities for many applications. So far, there are no known theories that define why single-walled carbon nanotube (SWCNT) structure allows electrons to have a ballistic transport behavior without experiencing any scattering from impurities or phonons as they move from one end of the nanotube to the other. Effectively, the electrons encounter no resistance, and dissipate no energy in the SWCNT. A possible interpretation of the observation is quantum conductance where electron resistance is independent of conductor length or diameter and electrons act more like waves as superelectrons behave in superconductors than particles in structures. In superconductors, electron transport occurs due to an interaction between electrons, which is transmitted by phonons. Electrons travel in pairs, interacting with each other through lattice vibrations, or phonons. The electron motion in pairs is described by the fact that an electron having spin-up and forward momentum (**k**, wave vector) pairs with a spin-down electron traveling in the opposite direction with momentum (-**k**). Likewise happening in superconductors, the usual wave-particle duality normally associated with a single quantum particle can now be applied to the entire ensemble of superelectrons in nanotubes①. This phenomenon occurs because nanotube size approaches that of the wavelengths of electrons. Carbon nanotubes show the pseudo-superconductor characteristics and thus allow electron ballistic motion (or superelectrons). The ballistic transport property of electrons holds only on a condition of very low energy dissipation through the passage. Carbon nanotubes are dissipation free unless electrons are in oscillatory mode coupling with nanotubes' vibrations or geometrical and material defects are present.

Another distinctive nature of CNT① is high current carrying capabilities since CNT has high thermal conductivity and is stable at high temperature. The measured current density capacity® in multi-walled nanotubes appears to well exceed more than 100 MA/cm^2. This current density

---

® cited in [3]

capacity is several orders of magnitude higher than that of superconducting wires. This unique feature of CNT① has been tried out for various applications, such as field-emission displays.

Room-Temperature Superconducting Polymers (RTSP)② - Some organic materials exhibit unique characteristic properties, such as conductivity and current carrying capacity equivalent to superconductors, but without the need for cryogenic support.

Electrons in polar crystals, organic or inorganic, interact strongly with the polar mode of vibration (phonon). The phonon-coupled electron that moves along with the induced polarization is called polaron.

In certain polymers, electric dipole groups have large degrees of freedom of movement, and can be oriented easily by moderate electric field. Collectively, they can create itinerant charge-trapping potential wells, capable of capturing (solvating) electrons and ions in the bulk material. Over time they can also become spatially ordered, forming domains with proportionally deeper potentials. These dynamics underlie the electronic separation, and self-organization, of the conducting structures.

Most importantly, when ionizing irradiation creates semi-free electrons at a higher occupied level than Fermi level from molecules in the bulk, these polymer electric dipoles can prevent transition by stably surrounding (solvating) the resulting pseudo-charges (excited to a higher occupied level). This permits the existence of essentially free electrons (or polarons) in the dielectric material. Over time, the electronic and kinetic interactions of the polymer chains results in the self-organization of tubule-like polymer cells – 'superpolarons' - with internally oriented dipoles surrounding an axial electron 'thread' or chain. At sufficient volume concentration, these cells further self-assemble into the larger, contactable features hereafter referred to as "channels". These channels or in other words, "superpolaron" effects allow electrons hopping with fixed quanta under a given potential and consequently result in coherence mode of electron motions without scattering, exactly acting like a superconductor [6].

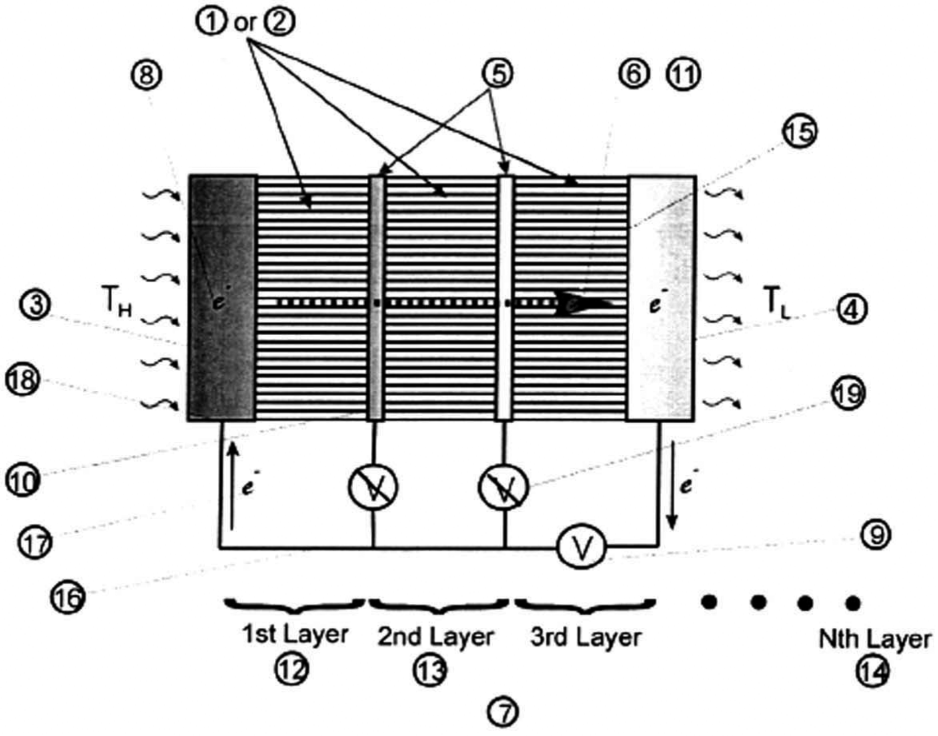
Thermionic behavior of electrons (or electrons in ballistic motion) is well distinguished from thermoelectric (quasi-equilibrium, slow, and diffusive) transport process of electrons. The thermoelectric transport process is dictated by energy transport by an equilibrium parameter, the Seebeck coefficient, or by quasi-equilibrium diffusivity of electrons. Ballistic motion of the most energetic electrons means a fast energy transport process that can be incorporated into either a cooling③ or a heating④ process along with the direction of electron motion since ballistic motion of electrons (or current) is controlled by the differences in voltage (ΔV) and temperature (ΔT). Current density capacity of CNT is also a significant factor in cooling③ or heating④ process to determine the amount of energy transport. High current density flow signifies a large amount of energy transport.

Efficient cooling devices are in great demand for many applications, such as microelectronics, sensors, and electro-optronic devices, power chips, satellites, "hot" laser-diodes etc.

PROPOSED INVENTION:

Basic principle of the proposed devices can be shown by a pair embodiment of a layer of aligned carbon nanotube (a-CNT) bundle① with a semiconductor material layer⑤ (Fig. 1) to form a

Schottky barrier as a P-N junction that controls electron flow rate and maintains electrons in a uni-direction⑥. The multilayer formation⑦ is possible by serial placement of pairs as shown in Fig.1. In this concept, the thermally agitated electrons⑧ at the hot plate are adiabatically swept away and channeled through nanotubes (SWCNT)① or RTSP② by an applied voltage differential⑨. These hot electrons⑧ undergo ballistic motion through aligned SWCNT① or RTSP② and reach the interface between layers ⑩ of aligned SWCNT① and semiconductor



⑤ where a barrier structure imposes the work function that energetic electrons⑧ have to overcome. In other words, the hot electrons⑧ gain momentum and become energetic by the applied voltage to run ballistically through aligned SWCNT① or RTSP②. Then these energetic electrons⑧ overcome the work function at the interface ⑩ and traverse the barrier ⑤. The interface, Schottky barrier diode, ⑤, ⑩ acts like a one-way electron valve ⑪ that allows one way run of energetic electrons⑧. The energetic electrons⑧ that were successfully tunneled out through the first layer ⑫ repeat the same routine through the second layer ⑬ and successive layers ⑭. Finally, the energetic electrons⑧ that arrived at the cold side④ are removed through an ohmic contact electrode ⑮ at the cold side. Through a closed circuit ⑯, charge neutrality is maintained at the hot side③ by adding electrons ⑰ adiabatically through ohmic contact electrode ⑱ at the hot side. The bias voltage ⑲ applied at the interfaces ⑩ controls the tunneling effect of energetic electrons⑧ through barriers ⑤.

Contact resistance at the Ohmic contact electrodes⑩,⑮, ⑱ is typically high and poses a serious obstacle to ballistic motion of energetic electrons⑧ [17]. However, the contact resistance can be reduced or alleviated by using a metal with a sufficiently large Fermi wave vector such as aluminum whose Fermi surface extends all the way to the SWCNT Fermi point [17].

A large number of energetic electrons⑧ are in ballistic motion through aligned-SWCNT (e.g. 100 MA/cm^2) as reported by P. Avouris [3] or through RTSP [6]. This feature may offer advantages of a low driving voltage for operation, a very high power density [W/kg], a very high cooling power [W/cm^2], and a very high efficiency to the Carnot cycle efficiency limit.

Usually, the material configuration/impurity-associated impedance of SWCNT and RTSP dictates the overall efficiency and cooling or heating capacity. Thus, fabrication of clean and pure, highly aligned SWCNT (a-SWCNT) sheet or of RTSP with interfaces is also a major part of the challenges.

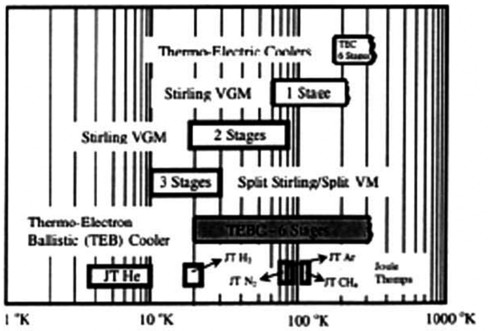


Fig. 2 Capability of various cryo-coolers

The substrate where a-SWCNT is grown or RTSP is laid out can be selected as the hot③ or cold plate④ of TEB cooler. A clean-cut formation of the sheet plane of a-SWCNT by either growing or cutting is a key for the interfacial material coating. Thin-film interface of semiconductor materials on the a-SWCNT sheet plane fabrication requires a clean and flat a-SWCNT plane. The overall thickness of TEB cooler is determined by SWCNT length (~ 5 μm) and layer thickness of semiconductor material. The TEB cooler would be very thin that a film-like formation is possible and applicable to flexible structures.

Fig. 2 shows the capability of various cryo-coolers, including the projection of multi-stage TEB cooler. In comparison with the thermo-electric (TE) coolers, the proposed TEB cooler has the electron mobility (e.g. ballistic in TEB vs. diffusive in TE) and number density (e.g. 100 MA/cm^2 in TEB vs. a few tens of A/cm^2 in TE) by at least several orders of magnitudes higher than those of TE coolers. Also, unlike other coolers, the range of TEB cooling capability could be wide from thousands of degree Kelvin to cryogenic temperatures since the energetic electrons could run through the cycle adiabatically without dissipation (due to quantum conduction).

The TEB cooler (or may be called "thermionic" cooler) concept is a new and novel because it is based on the newly found quantum-wire-like property of carbon nanotubes. So far, not a single attempt has been made to realize such a cooler. Therefore, it is expected that many scientific questions and technological issues must be answered and resolved before setting the engineering layout of the concept.

ADVANTAGES:

Numerous advantages are foreseen once successfully developed. The most notable advantage is the anticipated high efficiency to the Carnot efficiency limit, high power density, and high cooling power due to a thermionic process resulted in electron ballistics and high current density capacity within carbon nanotubes. Other advantages are the flexible thin-film structure allows shaping, patterning, and reconfiguring capabilities, miniaturization for microelectronics and sensor applications, and small package volume and small interface.

UNIQUENESS OF THE PROPOSED IDEA

A similar concept was proposed by G. D. Mahan, et al. [22] but is based on many semiconductor superlattices within which electrons might move ballistically under a low work function ($\phi \sim 0.3$ eV). It is no doubt that such small barriers (e.g. $\phi \sim 0.3$ eV) are easily attainable in semiconductor materials. However, the intrinsic resistivity against electron mean-free path (λ), even within p-n junctions, causes thermal effects. Otherwise, the mean-free path ($\lambda \approx 50 \sim 100$ nm) of electron must be longer than the barrier thickness (L_b). Another constraint is the barrier thickness (L_b) that must be greater than the minimum thickness ($L_t \approx 5 \sim 10$ nm) to prevent the electrons from tunneling through the barrier. Knowing all these 4 parameters a priori and ensuring a multilayered superlattice structure that performs as desired are the most grueling tasks. The proposed idea of using carbon nanotubes, on the other hand, does not impose a limit to the barrier thickness due to the mean-free path and tunneling behaviors of electrons. As mentioned earlier, the ballistic motion of electrons within carbon nanotubes is related to the quantum conductance where electron resistance is independent of conductor length or diameter and, therefore, electrons act more like waves than particles in structures as in superconductors. The usual wave-particle duality normally associated with a single quantum particle can now be applied to the entire ensemble of superelectrons. This phenomenon occurs because nanotube size approaches that of the wavelengths of electrons.

REFERENCES

1. --, "Simple Method Helps Test Nanotube Theories," R&D Magazine, page 9, April 1999.
2. Heiblum, M. and L. F. Eastman, "Ballistic Electrons in Semiconductors," Scientific American, Vol. 256, No. 2, p65, 1987.
3. Lerner, E. J., "Putting Nanotubes to Work," The Industrial Physicist, Vol. 5, No. 6, p22, Dec. 1999.
4. --, "Ballistic Conductance Observed in Carbon Nanotubes," Solid State Technology, page 34, September 1998.
5. Frank, S., P. Poncharel, Z. L. Wang, and W. A. de Heer, Science, Vol. 20, p1744, 1998.
6. Grigorov, L.N., **Proc.** ***9th*** *Cimtec World Forum on New Materials,* ***1999, vol. 23,*** Symp. VI Science and Engineering of HTC Superconductivity, p 675
7. Kivelson, S.A., et al., Nature, 1998, 393, p 550
8. Shen, Z., Science, 1999.