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Flexible thermoelectrics based on 3D interconnected magnetic nanowire networks

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3D networks of ferromagnetic (FM) nanowires fabricated by direct electrodeposition into the crossed nanopores of polymer templates are effective thermoelectric materials. The interconnected nanowire networks are formed from pure metals, alloys, and FM/Cu multilayers. Giant magneto-Seebeck effects in multilayer nanowires allow the determination of key parameters in spin caloritronics such as spin-dependent Seebeck coefficients and can be exploited to design flexible thermoelectric switches with optimal magnetic field-induced control of the sign and magnitude of the thermoelectric power output. Homogeneous nanowire arrays exhibit extremely high thermoelectric power factors that make them effective materials as flexible active Peltier coolers for thermal management of hot spots.

***Index Terms*— active Peltier cooling, magnetic nanowire network, spin-caloritronics, thermoelectric switch**

I. Introduction

Flexible and lightweight thermoelectric (TE) materials and devices based on the Seebeck and/or Peltier effect offer innovative perspectives in a sustainable development context [1]-[2]-[3]. Flexible TE generators should make it possible to respond to the rapid development of miniature, lightweight and functional portable electronic devices for nomadic products (Internet of Things) and medical sensors. On the other hand, spin caloritronics, which exploits the coupling between spin and heat transport in nanostructured materials, offers new perspectives for heat-assisted spin-based logic, thermal energy conversion, and sensors applications [4]-[5]. In this context, template-assisted electrodeposition of crossed nanowire (CNW) networks revealed to be a promising technique to develop flexible macroscopic spin caloritronic devices [6]-[7]. The 3D nanowire networks are fabricated by direct electrodeposition in track-etched polymer templates with crossed nano-channels. This technique allows the fabrication of interconnected NWs consisting of both homogeneous ferromagnetic (FM) metals and FM/Cu multilayer stack with controlled morphology and material composition (see Fig. 1). The 3D NW network allows to apply thermal and electrical currents in the macroscopic in-plane direction, while the current is locally restricted along the NW segments (see Fig. 1c). Homogeneous CNWs have high thermoelectric power factors (PF = S^2/ρ, with S, the Seebeck coefficient and ρ the electrical resistivity), almost as high as their bulk constituents, and allow for positive and negative Seebeck coefficient values [8]. These high PFs are essentially maintained in multilayer CNWs which also exhibit giant magnetoresistance and magneto-thermopower (MTP) effects [6]-[8], displayed in the current perpendicular-to-plane (CPP) configuration that are easily measurable along the macroscopic in-plane dimensions of the network films. The MTP effects result from the very contrasting spin-dependent Seebeck coefficients $S_\uparrow$ and $S_\downarrow$ that have been experimentally extracted for several ferromagnetic metals and alloys [1-3]. At room temperature, typical values for $\Delta S = S_\uparrow - S_\downarrow$ are in the range of -8 to -13 μV/K for Co/Cu, $Co_{50}Ni_{50}$/Cu and $Ni_{80}Fe_{20}$/Cu NWs, although ΔS may exceed -20μV/K in $Ni_{97}Fe_3$/Cu NWs [8]-[9].

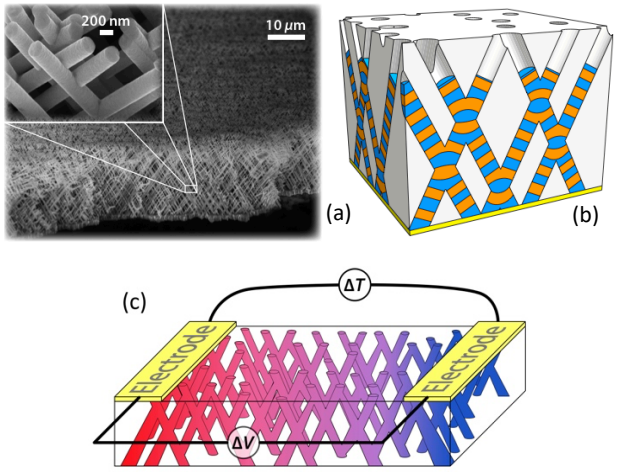


Fig. 1. (a) SEM image of a self-supported interconnected NW network film; (b) Schematic of the multilayered NW network embedded within the 3D nanoporous polymer template; (c) Device configuration for measurement of the Seebeck coefficient of interconnected NW network film.

II. Magnetically Activated Thermoelectric Switch

A concept of flexible thermoelectric switch triggered by a magnetic field is shown in Fig. 2a [10]. The two legs of the thermocouple, one formed by homogeneous NWs and the other by multilayer NWs, are connected electrically in series and thermally in parallel. The branch formed by $Ni_{80}Fe_{20}$/Cu or $Co_{50}Ni_{50}$/Cu multilayers combines high room-temperature Seebeck coefficients (up to −25 μV/K) and giant magneto-Seebeck effects (up to −34%) [8]. The other branch, consisting of homogeneous NWs (pure metals or alloys), has Seebeck coefficients between −30 μV/K (pure Co) and −20 μV/K (pure Ni) and shows very weak magneto-Seebeck effects. Therefore, by appropriately selecting the magnetic materials and multilayers that make up the two legs of the thermocouple, we achieve high variability in the output power of the nanowire-based thermoelectric generator when the system is exposed to an external magnetic field. Indeed, this thermoelectric device can switch from an “on state” (with output voltage ΔV of several tens of μV for ΔT ~ 10K) to an “off state” (ΔV = 0) at the saturation field of multilayer nanowires (see Fig. 2b), or vice versa at zero

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field. In addition, reversible switching of the thermoelectric voltage sign under an external magnetic field can also be achieved, without any degradation after successive cycles. From a practical point of view, the magnetic control of the magnitude and sign of the thermopower, opens the route toward the development of thermally activated sensors and logic devices exploiting the residual thermal energy. In addition, Onsager reciprocity between Peltier and Seebeck effects implies that a switchable Seebeck voltage results in a switchable Peltier heat flow, so that these NWs based thermoelectric modules can be used as thermal switches, offering prospects for precise thermal management.

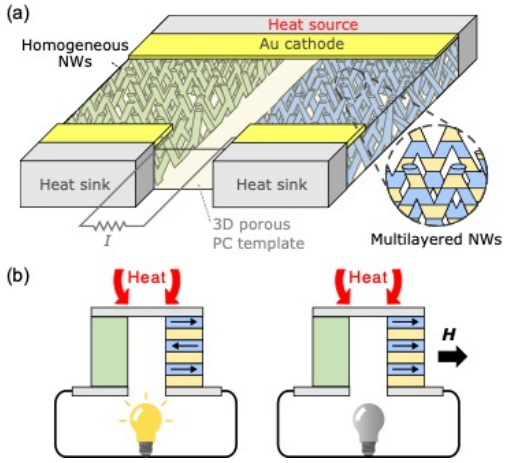


Fig. 2. Magnetically activated thermoelectric switch. (a) The thermocouple consists of two legs made from homogeneous NWs and multilayered NWs connected electrically in series and thermally in parallel. (b) Ideal TE switch where the "on" and "off" state are reached at zero and saturation magnetic field [10].

III. Flexible Active Peltier Cooler

Very recently, we demonstrated that 3D networks of interconnected ferromagnetic nanowires embedded in a polymer film are effective materials as active Peltier coolers [11]. The increasing development of electronic products requires that conventional cooling systems (by conduction) be combined with dynamic thermal management (by thermoelectric cooling) to quickly dissipate heat peaks that disrupt the operation of devices. In this regime, called active cooling, the Peltier heat flow carried by the electric current is added to the natural flow of heat from the hot to the cold side (see inset of Fig.3). As recently demonstrated, suitable materials for thermal management of electronic hot spots must not only have a high thermoelectric PF, but also high thermal conductivity [12]-[13]. Therefore, conventional Peltier TE modules are not suitable for this application due to the low thermal conductivity of their semiconductor components. On the contrary, some transition metals such as Co and Fe, are excellent candidates as thermoelectric material for active cooling. Indeed, cobalt combines the highest room temperature power factor among known materials, with a value around 15 mW/K^{2}m, and a large thermal conductivity. At T = 300K, these two physical characteristics for Co are about a factor of 10 and 100 higher than that of bismuth tellurium, respectively. Besides, thermocouples based on Co-Fe NWs exhibit much higher PF and thermal conductivities than other existing flexible thermoelectric systems (see Fig.3). We recently demonstrated [11] that the effective thermal conductance of our lightweight flexible NW-based device can be strongly and rapidly increased by the Peltier effect, especially for small temperature differences, thus offering great potential for thermal management of hot spots on complex surfaces.

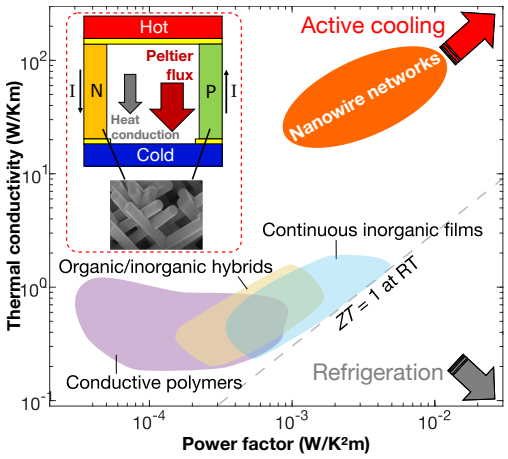


Fig. 3. Power factor vs. thermal conductivity for flexible thermoelectric systems made of magnetic NW networks, conductive polymers, organic/inorganic hybrids and continuous inorganic films. The inset shows that in the active cooling mode, Peltier heat flows from the hot side to the cold side, increasing Fourier heat conduction (contrary to the usual Peltier refrigeration mode) [11].

References

[1] Z. Fan, Y. Zhang, L. Pan, J. Ouyang, and Q. Zhang, "Recent developments in flexible thermoelectrics: From materials to devices", Renewable and Sustainable Energy Reviews, 137 110448, 2021.

[2] L. Zhang, X.-L. Shi, Y.-L. Yang, and Z.-G. Chen, "Flexible thermoelectric materials and devices: From materials to applications", Materials Today 46, 62, 2021.

[3] S. Hong, Y. Gu, J. K. Seo, J. Wang, P. Liu, Y. S. Meng, S. Xu, and R. Chen, "Wearable thermoelectrics for personalized thermoregulation", Science Advances 5, eaaw0536, 2019

[4] G.E.W. Bauer, E. Saitoh, and B. J. van Wees, "Spin caloritronics", Nat. Mater. 11, 391, 2012.

[5] S.R. Boona, R. C. Myers, and J. P. Heremans, "Spin caloritronics", Energy Environ. Sci. 7, 885–910, 2014.

[6] T. da Câmara Santa Clara Gomes, F. Abreu Araujo, and L. Piraux, "Making flexible spin caloritronic devices with interconnected nanowire networks" Sci. Adv. 5, eaav2782, 2019.

[7] F. Abreu Araujo, T. da Câmara Santa Clara Gomes, and L. Piraux, "Magnetic control of flexible thermoelectric devices based on macroscopic 3D interconnected nanowire networks" Adv. Electron. Mater. 5, 1800819, 2019.

[8] T. da Câmara Santa Clara Gomes, N. Marchal, F. Abreu Araujo, and L. Piraux, "Spin caloritronics in 3D interconnected nanowire networks" Nanomaterials 10, 2092, 2020.

[9] N. Marchal, T. da Câmara Santa Clara Gomes, F. Abreu Araujo, and L. Piraux, "Large spin-dependent thermoelectric effects in NiFe-based interconnected nanowire networks" Nanoscale Res. Lett., 15, 137, 2020.

[10] T. da Câmara Santa Clara Gomes, N. Marchal, F. Abreu Araujo, and L. Piraux, "Magnetically activated flexible thermoelectric switches based on interconnected nanowire networks" Adv. Mater. Technol. 7, 2101043, 2022.

[11] T. da Câmara Santa Clara Gomes, F. Abreu Araujo, and L. Piraux, "Flexible active Peltier coolers based on interconnected magnetic nanowire networks", Adv. Electron. Mater., submitted for publication.

[12] M. Zebarjadi, "Electronic cooling using thermoelectric devices", Applied Physics Letters 106, 203506, 2015.

[13] M. Adams, M. Verosky, M. Zebarjadi, and J. P. Heremans, "Active Peltier coolers based on correlated and magnon-drag metals", Phys. Rev. Applied 11, 054008, 2019.

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