Electronic Supplementary Information (ESI) for:

Highly Stable Copper Wire/Alumina/Polyimide Composite Films for Stretchable and Transparent Heaters

Peng Li, Jangang Ma,* Haiyang Xu, Xiaodan Xue, and Yichun Liu*

Center for Advanced Optoelectronic Functional Materials Research, and

Key Laboratory for UV-Emitting Materials and Technology of Ministry of Education,

Northeast Normal University, 5268 Renmin Street, Changchun 130024, People's Republic of China

* majg@nenu.edu.cn and ycliu@nenu.edu.cn

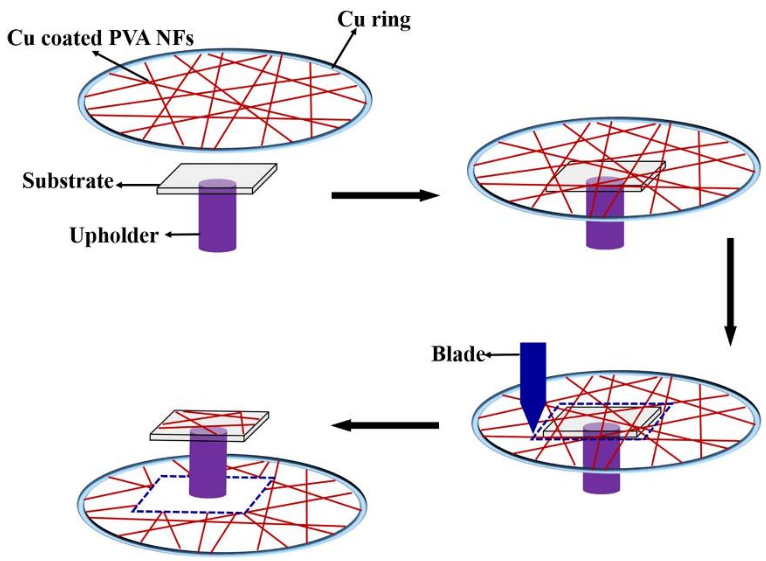

Figure S1. Schematic of the transfer process steps of Cu wire network to its substrate.

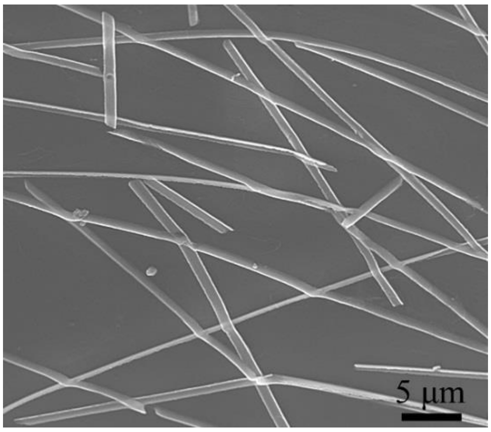

Figure S2. SEM image of Cu coated PVA nanofibers after dissolving PVA with water to show the breakage of Cu nanotrough.

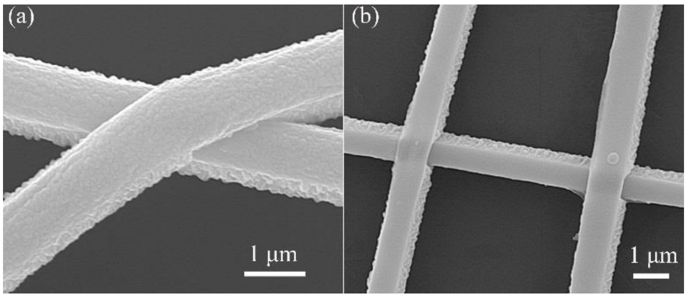

Figure S3. SEM images of Cu wires on the substrates **(a)** with Cu side up; **(b)** with Cu side down.

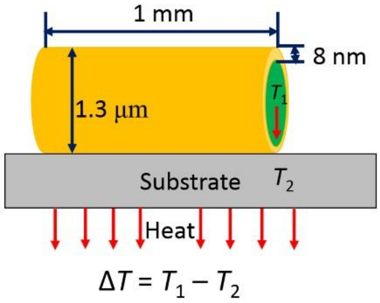

Figure S4. Schematic diagram of heat transfer model for a Al_2O_3 coated Cu wire on the substrate to calculate the temperature drop (ΔT) caused by the Al_2O_3 layer.

To investigate whether the Al_2O_3 layer will prevent heat dissipation to surrounding, we calculated the temperature drop (ΔT) between two sides (Cu wire and substrate) of the Al_2O_3 layer. ΔT can be calculated from Fourier's Law by this heat conduction equation: $\Delta T = R_{jc} \cdot P$, where P is the Joule heating power of Cu wire; the thermal resistance (R_{jc}) is $L/(kA)$, where L is the thickness, k is the thermal conductivity, A is the cross-sectional area (perpendicular to the path of heat flow) of the Al_2O_3 layer. Take an individual Cu wire which we have measured I-V characteristic in the Figure 5a as an example, the Joule heat that generated by the Cu wire network need to flow through the Al_2O_3 layer to raise the temperature of the substrate (see Figure S4). The Al_2O_3 layer can be seen as a hollow cylinder with 8 nm wall thickness (L), 1 mm $\cdot$ 1300π $\cdot$nm cross-section area (A), $k^* = 1.8$ W K^{-1} m^{-1}, $P = 4$ V $\cdot$42 mA. The calculated ΔT is only 0.36 K. The low ΔT between the two sides of Al_2O_3 layer verifies the fact that the thin Al_2O_3 film will not severely prevent heat dissipation to surrounding. We ascribed these results to the large length to diameter ratio of Cu wire and the low thickness of Al_2O_3 film. Thus, we ruled out the possibility that the thermally insulating layer of Al_2O_3 will prevent heat dissipation to surrounding.

k^* Reference: A. Cappella, et al., Adv. Eng. Mater., 2013, 15, 1045−1050.

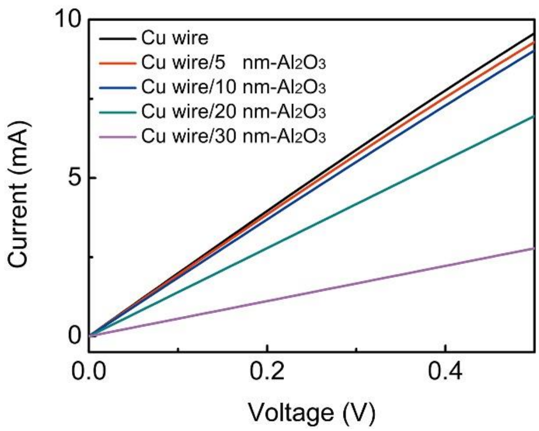

Figure S5. I-V characteristic curves of individual Cu wire/Al_2O_3.

The experiment was conducted as this: a long Cu wire on the slide glass was cut into four parts. Then these identical Cu wires were covered with Al_2O_3 film with thickness of 0, 5, 10, 20, 30 nm, respectively. Two terminals of each Cu wire were fixed with 400 nm-thick Cu contacts, which were separated from each other with a distance of 1 mm. Thus, the same electrodes were deposited on these Cu wires with 0~30 nm Al_2O_3 interlayers between electrodes and Cu wires. We measured I-V characteristic for each Cu wire and the resistance can be calculated from the reciprocal of the slope of I-V curves. I-V curves in Figure S5 show almost the same slope when the thickness of Al_2O_3 film is less than 10 nm. The slope decreases sharply when the thickness is 20 nm. These phenomena mean that thin Al_2O_3 film (less than 10 nm) will not significantly increase the contact resistance of electrodes until the thickness of Al_2O_3 film is larger than 20 nm.

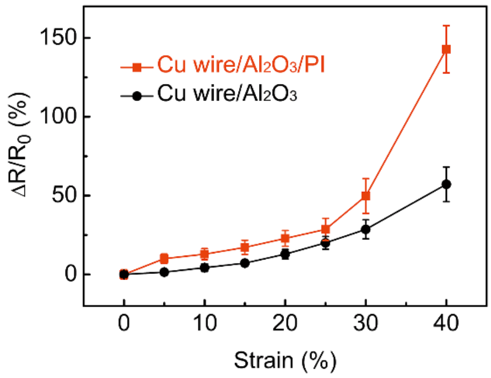

Figure S6. Percentage changes of resistances of Cu wire/Al_2O_3 network and Cu wire/Al_2O_3/PI composite film after stretching and releasing for 10 times at 0~40% strain.

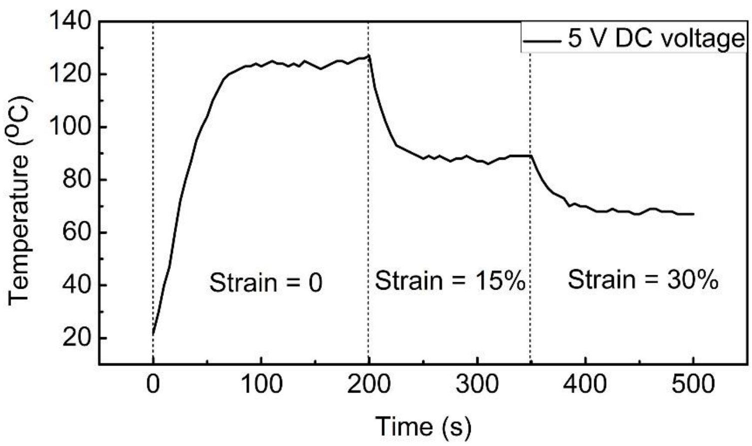

Figure S7. Transient temperature evolution of Cu wire/Al_2O_3/PI composite film heater at 0, 15% and 30% strains under a constant voltage.

Table S1: Literature comparison of transparent heaters.

Ref.	Material	Typical T_R (%), R_S (Ω/sq), and $\sigma_{dc,B}/\sigma_{Op}$	Typical V (V/cm), T(°C) Substrate	Max, T (°C)	Thermal resistance (°C cm^2 W^{-1})	Response time (s)
1	CNT	76%, 356, 3.6	3, 80, PET	200	54	60
2	CNT	97%, 23k, 0.53	6, 47, glass	47	140	60
3	Graphene oxide/Ag NW	91%, 11, 355	1.2, 59, glass	100	---	300
4	Ag NW /PDMS	85%, 30, 74	6, 110, PDMS	150	---	10
5	Ag NW	90%, 20, 300	7, 105, glass	105	---	60
6	Ag NW /PEDOT:PSS	70%, 4, 241	1.2, 90, glass	120	179	200
7	Graphene	89%, 43, 73	3, 100, PET	100	409	75
8	Graphene	90%, 68, 51	6, 120, glass	120	660	200
9	Au wire	87%, 3.2, 858	6, 600, glass	600	189	30
10	Ag wire	84%, 0.9, 2445	1.5, 95, PET	100	515	20
11	CuNi	85.6%, 16.2, 145	3.6, 230, glass	225	---	60
12	CuZr	90%, 3.8, 917	3.5, 180, PDMS	180	---	90
This work	Cu wire /Al_2O_3/PI	91.4%, 8, 512	4, 288, glass	288	197	55

Ref.=reference; T=temperature; T_R=transmittance; R_S=sheet resistance; T_{Max}= maximum temperature

References

1. Y.-H. Yoon, J.-W. Song, D. Kim, J. Kim, J.-K. Park, S.-K. Oh and C.-S. Han, *Adv. Mater.*, 2007, **19**, 4284−4287.
2. T. J. Kang, T. Kim, S. M. Seo, Y. J. Park and Y. H. Kim, *Carbon*, 2011, **49**, 1087–1093.
3. D. Kim, L. Zhu, D.-J. Jeong, K. Chun, Y.-Y. Ban, S.-R. Ki, J.-H. Ki and Oh, S.-K. *Carbon*, 2013, **63**, 530−536.
4. S. M. Lee, J. H. Lee, S. Bak, K. Lee, Y. Li and H. Lee, *Nano Res.*, 2015, **8**, 1882–1892.
5. S. Hong, H. Lee, J. Lee, J. Kwon, S. Han, Y. D. Suh, H. Cho, J. Shin, J. Yeo and S. H. Ko, *Adv. Mater.*, 2015, **27**, 4744–4751.
6. T. Y. Kim, Y. W. Kim, H. S. Lee, H. Kim, W. S. Yang and K. S. Suh, *Adv. Funct. Mater.*, 2013, **23**, 1250−1255.
7. S. Ji, W. He, K. Wang, Y. Ran and C. Ye, *Small*, 2014, **10**, 4951−4960.
8. J. Kang, H. Kim, K. S. Kim, S.-K. Lee, S. Bae, J.-H. Ahn, Y.-J. Kim, J.-B. Choi and B. H. Hong, *Nano Lett.*, 2011, **11**, 5154−5158.
9. J. J. Bae, S. C. Lim, G. H. Han, Y. W. Jo, D. L. Doung, E. S. Kim, S. J. Chae, T. Q. Huy, N. V. Luan and Y. H. Lee, *Adv. Funct. Mater.*, 2012, **22**, 4819−4826.
10. K. D. M. Rao and G. U. Kulkarni, *Nanoscale*, 2014, **6**, 5645−5650.
11. H.-J. Kim, Y. Kim, J.-H. Jeong, J.-H. Choi, J. Lee and D.-G. Choi, *J. Mater. Chem. A*, 2015, **3**, 16621−16626.
12. B. W. An, E.-J. Gwak, K. Kim, Y.-C. Kim, J. Jang, J.-Y. Kim and J.-U. Park, *Nano Lett.*, 2016, **6**, 471–478.