THERMAL INSTABILITY OF METAL NANOWIRES

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The technological implementation of nanowires in fields such as nanoelectronics, optoelectronics, and sensorics requires the capability of these extremely thin wires to withstand damage during processing at elevated temperatures. However, due to their reduced size and high surface-to-volume ratio, nanowires are expected to display structural and morphological instabilities during heating. The Rayleigh instability concept, introduced to describe the instability of liquid jets [1], is now being applied to model the fragmentation of metal nanowires during heating [2]. Driven by atomic diffusion [3], a solid cylinder with initial radius r should break up, under given annealing conditions, into a row of spheres with an average spacing = 8.89 r and diameter $d = 3.78\ r$.

In the work presented here, copper and gold nanowires with diameters between 30 and 100 nm are fabricated by electrochemical deposition in etched ion-track membranes [4]. After dissolution of the polymer membrane, the wires are put on a SiO_2 substrate, and heated under vacuum conditions to temperatures between 300 and 600°C.

For copper wires with diameter below 50 nm, different stages of the fragmentation process are identified by high-resolution scanning electron microscopy (HRSEM). A clear dependence of the decay process on temperature is observed [5]: The wires start to fragment at 400°C, form shorter segments with an increase to 500°C, and decay into chains of nanospheres at 600°C (Fig. 1). In the case of Au nanowires, we have observed by HRSEM that fragmentation occurs similarly after annealing at 400°C. For nanowires with larger diameter, other morphology changes as e.g. bending and faceting are perceived. We want to emphasize that all these processes occur at temperatures far below the melting point of bulk copper and gold ($T_{m,\,\mathrm{Cu}}$ = 1084°C, $T_{m,\,\mathrm{Au}}$ = 1064°C).

A more stable layer (e.g. copper oxide) surrounding the nanowire in the form of a tube and prohibiting the diffusion of copper atoms to its outer surface, would confine the atoms inside. By transmission electron microscopy (TEM), copper nanowires surrounded by a Cu_2O tube were heated, and the diffusion of the copper atoms inside the tube was recorded in-situ by a video camera. We observed that the existence of the surface layer impedes the occurrence of the Rayleigh instability. Instead, at ~ 600°C, the copper atoms (while remaining in the solid state) diffuse very fast along the wire axis (Fig. 2), finally exiting the oxide tube on one of its edges forming a big single-crystal

References:

[1] Lord Rayleigh, Proc. London Math. Soc. 10 (1878) 4.
[2] T. Müller, K.-H. Heinig, B. Schmidt, Mater. Sci. Eng. C 19 (2002) 209.
[3] F.A. Nichols and W.W. Mullins, Trans. Metall. Soc. AIME 233 (1965) 1840.
[4] M.E. Toimil Molares, V. Buschmann, D. Dobrev, R. Neumann, R. Scholz, I.U. Schuchert, J. Vetter, Adv. Mater. 13 (2001) 62.
[5] M.E. Toimil Molares, A.G. Balogh, T.W. Cornelius, R. Neumann, C. Trautmann, Appl. Phys. Lett. 85 (2004) 5337.

Figures:

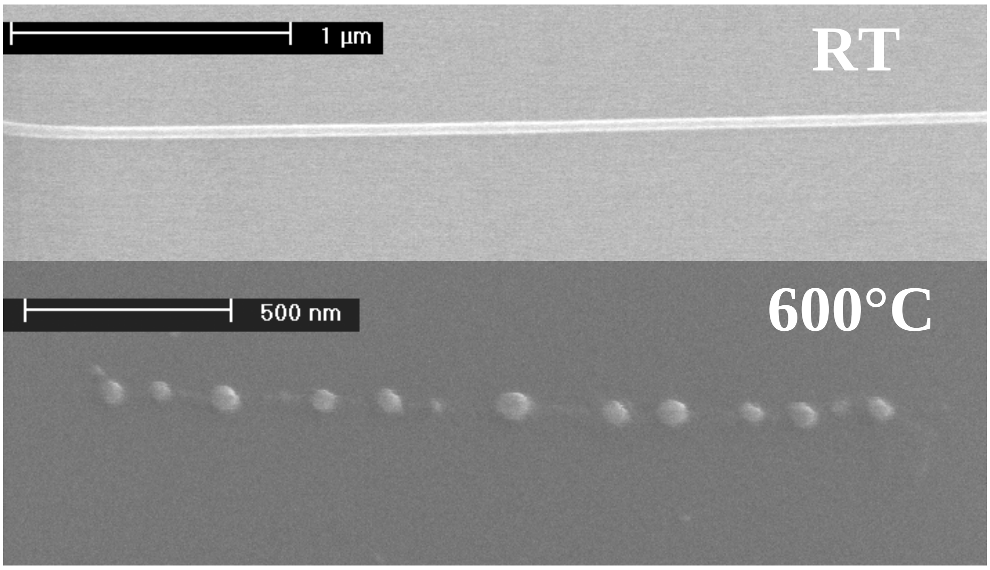

Figure 1 HRSEM images of (top) Copper nanowire of 40 nm diameter displaying a smooth and homogeneous contour, (bottom) Copper nanowire fragmented into a chain of nanospheres after annealing at 600°C. The distance between adjacent spheres and the medium sphere diameter are in very good agreement with the Rayleigh instability predictions.

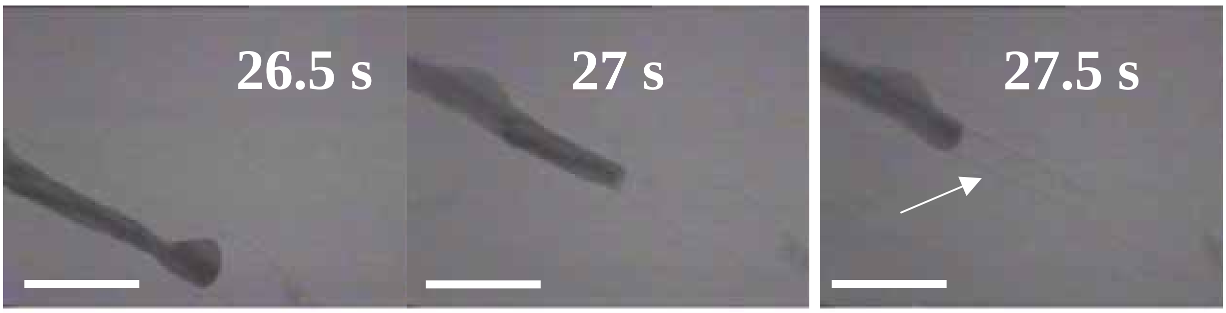

Figure 2 Sequence of TEM images recorded by video during in-situ annealing of copper nanowires at 620°C. As illustrated from left to right, the copper atoms diffuse within one second over a distance > 100 nm along the wire axis. The atomic movement is confined inside the copper oxide tube (see arrow in Fig. 2 (right). Scale bar: 100 nm.