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DOI: 10.1017/S1431927605506548
Microsc Microanal 11(Suppl 2), 2005

In-situ studies of high electrical-current effects in multiwalled carbon nanotubes filled with iron

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As one tries to diminish the size of electrical circuits there is a problem with increasing electrical current densities. Regular wires can withstand current densities of up to approximately 10^4 A/cm^2 where resistive heating becomes a problem and can cause electrical failure. This can be circumvented by using thin metal film conductors on heat sinks, and current densities of up about 10^7 A/cm^2 can then be sustained. At even higher current densities another problem appears; electromigration. Strong electrical fields and high electron currents will cause material to migrate and result in circuit failures. A possible solution to this problem could be the use of carbon nanotubes as these may display ballistic conduction and be able to withstand very high current densities. Detailed studies of electromigration are not easy, as they require imaging with high spatial resolution and an ability to locally apply strong electrical fields and currents.

We have developed an instrument that provides a movable electrical probe inside a side entry holder for a transmission electron microscope (TEM) [1,2], enabling local electrical characterizations and manipulations. Multiwalled carbon nanotubes filled with iron have been produced through pyrolysis of ferrocene and rigidly mounted in one end to serve as one of the electrical contacts. Using our instrument we are able to address individual carbon nanotubes (see fig. 1) and to characterize their electron transport properties and their ability to carry high electrical currents. We have found that the tubes behave as diffusive conductors with a resistivity similar to that of defect-rich graphite. At high current densities we observe electromigration of iron inside the tubes [3]. Figure 2 shows a sequence of TEM-images were an iron filled carbon nanotube is being subjected to a high electrical current. As can be seen the iron contained in the hollow tube-center starts to migrate in the direction of the electron flow (from right to left in the figure). The tubes themselves remain rather intact and can sustain an order of magnitude higher current density before disintegration occurs.

We demonstrate that iron migration is reversible and driven by the electron “wind-force” exerted by the electrons as these travel through the tubes and scatter against defects and interfaces. Such an electron-current driven migration process has previously been discarded by theoretical modeling [4] but is demonstrated here as a way to transport solid material through carbon nanotubes and to enable deposition of iron nanoparticles onto substrates.

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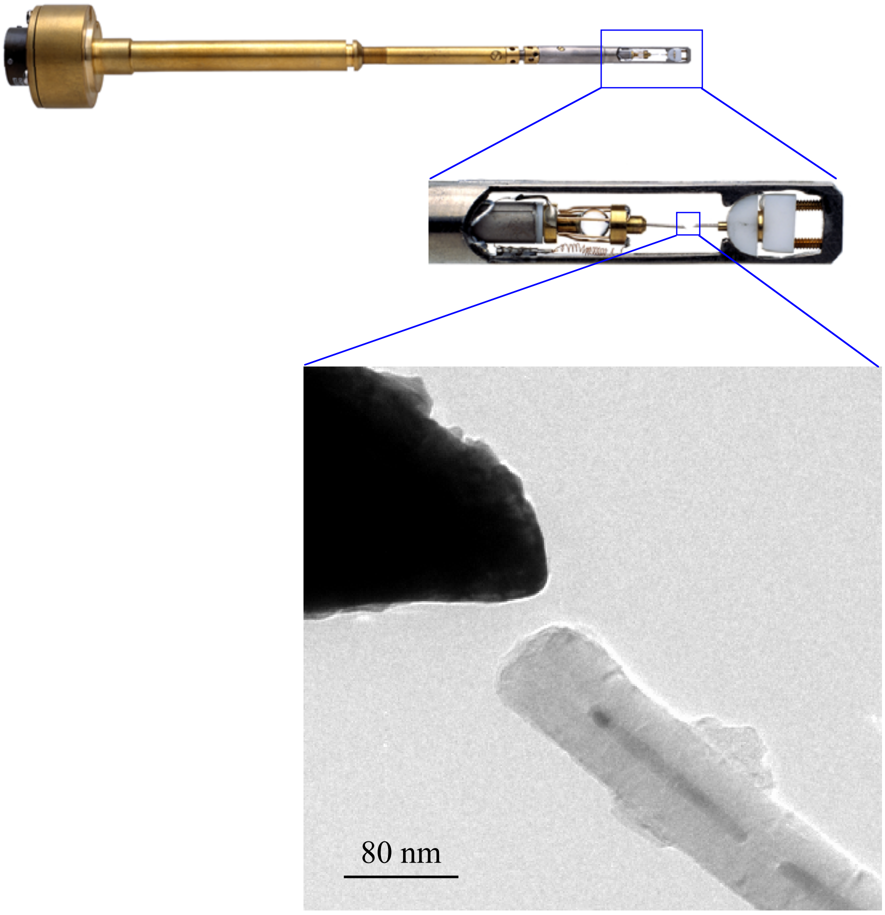

Figure 1. Pictures of the side entry TEM-holder with a close-up of the movable probe mechanism (providing both coarse and fine movements of the tip in three-dimension), together with a TEM-image of the tip apex approaching a carbon nanotube filled with iron.

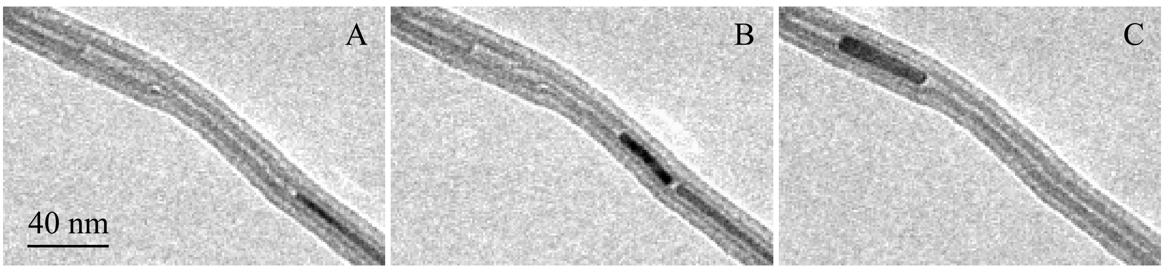

Figure 2. Sequential TEM images of iron electromigrating in the hollow core of a multiwalled carbon nanotube (the migration is in the same direction as the flow of electrons).

https://doi.org/10.1017/S1431927605506548 Published online by Cambridge University Press