# Comparison of Current-Voltage Characteristics of Nanofibres and Nanotubes

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**Abstract.** The current-voltage characteristics of a number of nanoscale materials show some striking similarities despite the differing conduction mechanisms expected in different materials. We make a comparison of experimental *I-V* characteristics of Ag-$V_2O_5$ nanofibre networks with those of carbon nanotube networks and polyacetylene nanofibres, using as a base the generic expression for the nonlinear conductance given by our numerical calculations for fluctuation-assisted tunnelling and thermal activation. We find a remarkably similar change from linear behaviour at high temperatures to nonlinear conduction at lower temperatures.

## INTRODUCTION

The advent of nanofibres and nanotubes has opened up new possibilities for conducting materials that show novel behaviour due to their limited size and the quasi-one-dimensional nature of conduction [1,2]. For example, polyacetylene nanofibres show temperature-independent Zener-type tunnelling at very low temperatures [3] that we have shown [4] could arise from tunnelling of the conjugated bond pattern along single polyacetylene chains.

In this paper, we compare our new data on the evolution of the current-voltage (*I-V*) characteristics with changing temperature for Ag-$V_2O_5$ nanofibre networks with earlier data for other nanoscale materials: single-wall carbon nanotube (SWCNT) networks and individual polyacetylene nanofibres, as measured by Kim et al. [5] and Park et al. [6], respectively. We also compare the *I-V* characteristics to the generic expression for nonlinear conductance suggested by our numerical calculations for fluctuation-assisted tunnelling and thermal activation.

## Ag-$V_2O_5$ NANOFIBRE NETWORKS

Vanadium pentoxide ($V_2O_5$) can be made in the form of fibres of molecular dimensions (with cross-section approximately 1.5 nm by 10 nm and length several μm) that can (for example) be used as chemiresistors in sensor applications [7]. The structure of the fibres is one-dimensional and conduction is attributed to hopping (thermally activated tunnelling) between $V^{5+}$ and $V^{4+}$ sites.

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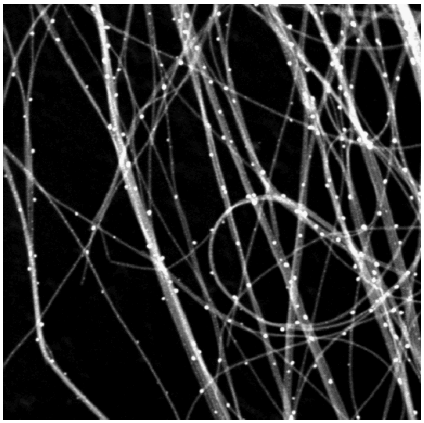

**FIGURE 1.** Image of the network of Ag-$V_2O_5$ nanofibres with attached Ag clusters obtained by scanning transmission electron microscopy (S-TEM) operated in the High-Angle Annular Dark-Field (HAADF) mode; the width of the image is approximately 720 nm.

In the present case, Ag-$V_2O_5$ nanofibres were grown in an aqueous solution via polycondensation of vanadyl acid [8]. Ag ions were added to the solution to speed up the growth of the fibres. Note that Ag cluster are attached to the fibres, as can be seen in the scanning transmission electron microscope image of Figure 1. Transport measurements were made on networks of fibres deposited on an interdigitated electrode array with 10 μm separation between electrodes.

## CURRENT-VOLTAGE CHARACTERISTICS

Figure 2 shows the *I-V* characteristics of an Ag-$V_2O_5$ nanofibre network for a range of temperatures. The *I-V* characteristics were symmetric to within experimental error with respect to reversal of the voltage direction, so only the positive quadrant is shown. Figures 3(a) and 3(b) show the positive quadrant of the *I-V* characteristics of an individual polyacetylene nanofibre [6] and of a SWCNT network [5], that also show symmetric behaviour.

It is clear that there is a remarkable similarity between the *I-V* characteristics for all three materials, which show a similar dependence on applied voltage $V$ as well as a similar qualitative evolution with temperature. As shown by the fitted lines, all the data in these figures are well fitted by the expression:

$$I = G_0 V \exp(V/V_0), \tag{1}$$

i.e. conductance

$$G = I/V = G_0 \exp(V/V_0). \tag{2}$$

The parameter $G_0$ is the low-field conductance, i.e. the ratio $I/V$ as $V \to 0$. $G_0$ shows a strong increase with temperature in each material - approximately activated behaviour in the case of Ag-$V_2O_5$ and the polyacetylene nanofibre, but consistent with fluctuation-induced tunnelling behaviour [10] for the SWCNT network [5,9]. The parameter $V_0$ is the scale parameter for the exponential increase in conductance in Eq. (2). $V_0$ shows only a relatively small increase with temperature for all three materials.

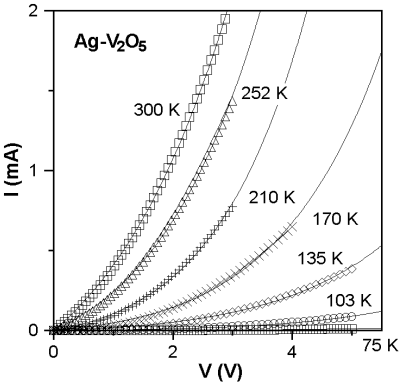


**FIGURE 2.** *I-V* characteristics of a network of Ag-$V_2O_5$ nanofibres at temperatures from 300 K down to 75 K; the lines are fits of the data to Eq. (1).

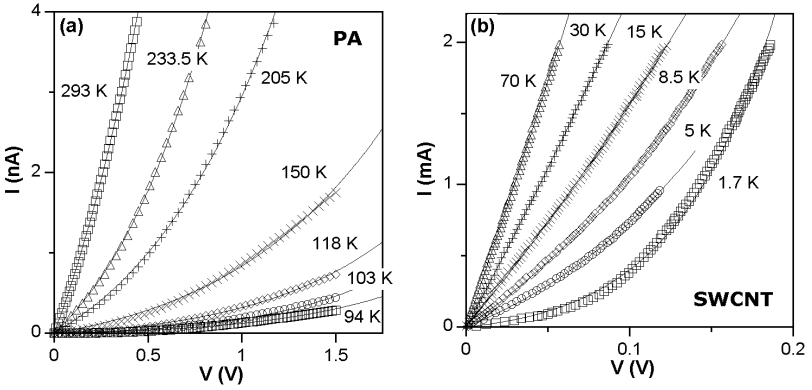


**FIGURE 3.** *I-V* characteristics for a range of temperatures of (a) a polyacetylene nanofibre (PA) of diameter 20 nm doped with iodine as measured by Park et al. [6], and (b) a single-wall carbon nanotube network (SWCNT) measured by Kim et al. [5]. In each case the lines show fits to Eq. (1).

The origin of the fitting expression is our full numerical calculations of fluctuation-induced tunnelling and thermal activation (extending the fluctuation-induced tunnelling model of Sheng [10] to cases of higher conductivity). These calculations give the generic expression [9]:

$$I = G_0 V \frac{\exp(V/V_0)}{1 + h[\exp(V/V_0) - 1]}, \tag{3}$$

of which Eq. (1) is the $h \to 0$ limit.

For $h > 0$, the exponential increase of conductance slows down at higher voltages $V$ (ultimately yielding ohmic behaviour with conductance $G_0/h$ as $V \to \infty$) - there are small indications of such a slowing down in some of the data sets in the figures above.

## CONCLUSIONS

The data shown demonstrate a remarkable similarity in the development of nonlinearities in the *I-V* characteristics as temperature is lowered in Ag-$V_2O_5$ nanofibre networks, SWCNT networks and polyacetylene nanofibres.

The overall shape of these nonlinearities is well described by Eq. (1) given by our numerical calculations for fluctuation-assisted tunnelling and thermal activation. This generic result appears to be applicable more widely for conduction involving tunnelling and thermal activation, not just for the specific model used in the calculations.

## ACKNOWLEDGMENTS

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