Tunneling Negative Differential Resistance in Flexible Silicone/Graphite Composites

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Developing flexible electronic materials with the ability to amplify signals is a major challenge for bioelectronics. The need for both intelligent sensor arrays that stretch like a skin and implantable control electronics is driving the search for soft conducting materials[1] with active electronic properties. Stretchable interconnects and flexible matrices have been obtained that exhibit pressure-sensing[2], temperature-sensing[3] and electroluminescent properties[4]. The next step in developing an active nervous system calls for a flexible electronic material that produces a signal gain. The ability to tune the electrical conductivity of the graphene bilayer with an electric field provides a route for addressing this challenge through the generation of NDR.

Here we demonstrate a wide NDR region in the current-voltage characteristics of silicone filled with graphitic nanoparticles[5]. At the peak, the conductor breaks up into domains of constant electric field separated by highly resistive domain boundaries. These boundaries are identified as individual graphite nanoparticles whose orientation in the electric field favours conduction across just **two graphene layers** – in such nanoparticles, the tilt angle between the graphite planes and the electric field is 66°-78°. Increasing the electric field opens a partial energy gap at the Fermi level which causes the current carrying bilayer to undergo a **semimetal-to-insulator transition**. The nucleation of highly resistive domain boundaries fragments the composite into electric field domains whose size we measure to be ~0.3mm. This switches off the percolation paths through the composite and gives the observed NDR. This picture explains the dependence of the *I-V* curves on the concentration of graphitic nanoparticles, temperature, channel length, as well as the disappearance of the NDR when the graphitic nanoparticles are replaced with amorphous carbon nanoparticles. We obtain very good agreement with the experimental I-V curves and their dependence on graphite filling fraction by calculating the tunnelling current between two graphite nanoparticles through the silicone potential barrier.

References

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[4] H. Stirringhaus, N. Tessler, R.H. Friend, *Science* **290**, 1741 (1998)
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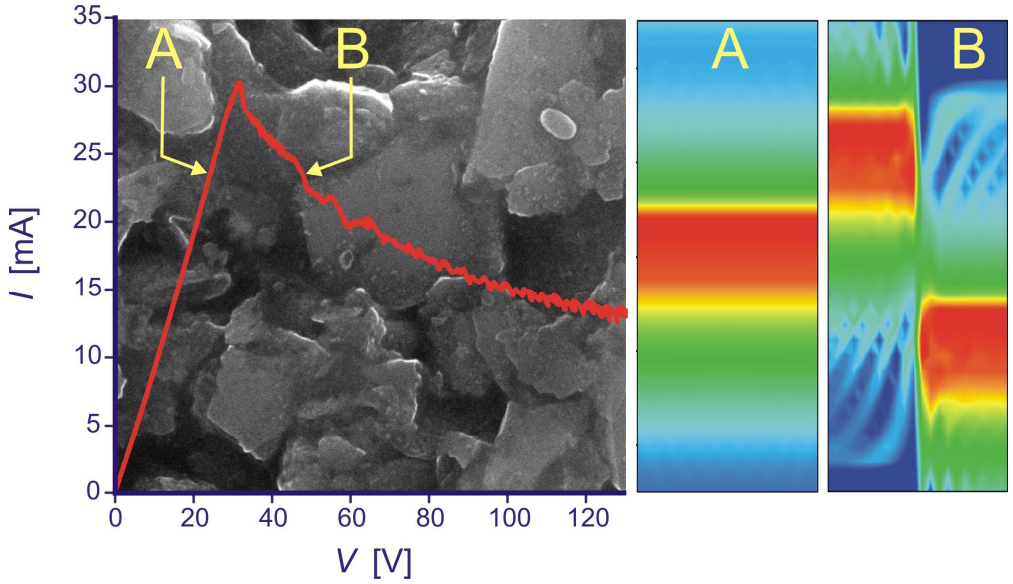

Figure 1:
Current-voltage characteristic of silicone rubber filled with nanoparticles of Highly Oriented Pyrolytic Graphite (HOPG) 450nm in diameter. Nanoparticles whose graphite planes are tilted by 66°-78° from the direction of the electric field conduct across an embedded graphene bilayer (A). Higher electric field breaks the π-band of graphite (B). This semimetal-to-insulator transition is responsible for the NDR.

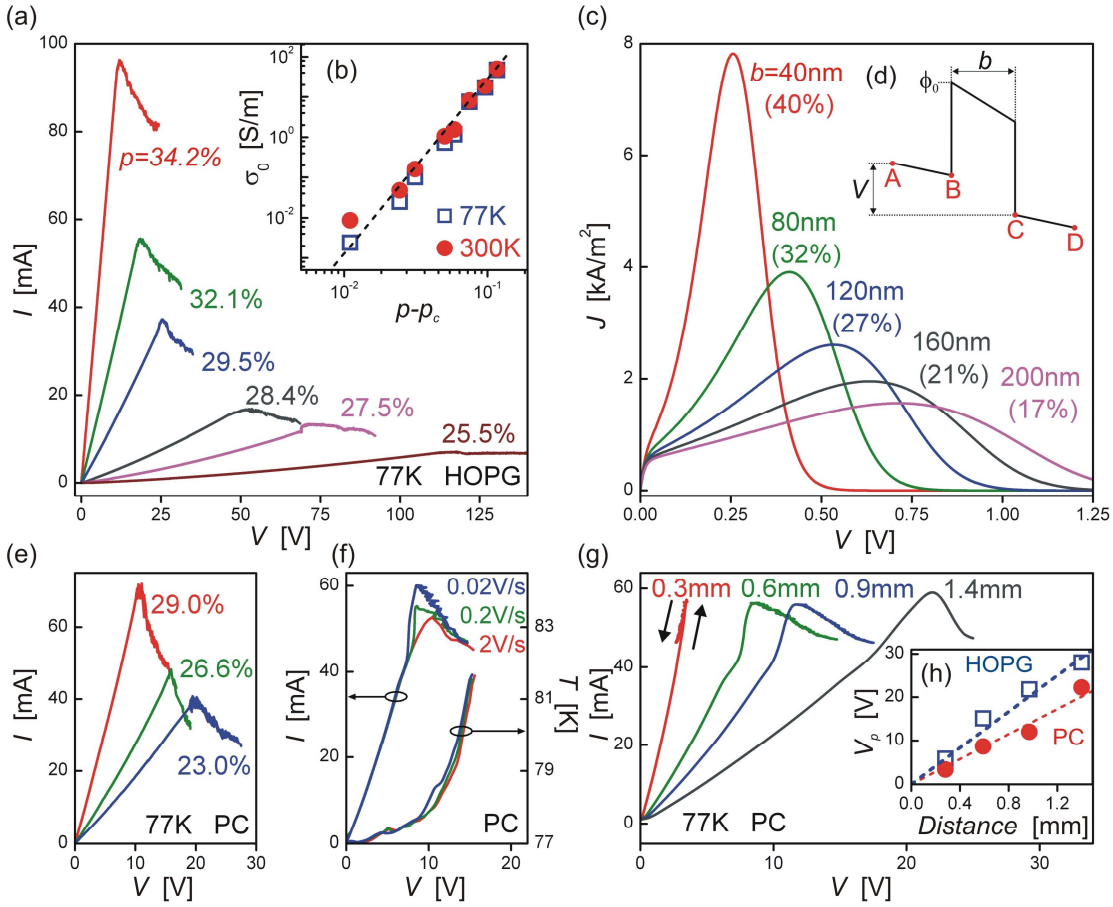

Figure 2:
(a) Dependence of the NDR on the HOPG graphite filling fraction; (b) percolation plot $\sigma \propto (p - p_c)^4$ (c) calculated tunneling current and its dependence on filling fraction; (d) composite made of pyrolytic carbon nanoparticles; (f) Joule heating; (g) The NDR vanishes when it is measured across smaller lengths of composite. The onset of the transition gives the size of the electric field domains ~0.3mm.