# A simple, reliable technique for making electrical contact to multiwalled carbon nanotubes

P. J. de Pablo
*Departamento de Fisica de la Materia Condensada, Universidad Autonoma de Madrid, 28049-Madrid, Spain*

E. Graugnard
*Department of Physics, Purdue University, West Lafayette, Indiana 47907*

B. Walsh
*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907*

R. P. Andres
*School of Chemical Engineering, Purdue University, West Lafayette, Indiana 47907*

S. Datta
*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907*

R. Reifenberger[a)]
*Department of Physics, Purdue University, West Lafayette, Indiana 47907*

(Received 7 October 1998; accepted for publication 12 November 1998)

A simple method of making reliable electrical contact to multiwalled carbon nanotubes is described. With these contacts, current in the mA range can be routinely passed through individual multiwalled nanotubes without adverse consequences, thus allowing their resistance to be measured using a common multimeter. The contacts are robust enough to withstand temperature excursions between room temperature and 77 K. $I(V)$ data from different multiwalled nanotubes are presented and analyzed. © *1999 American Institute of Physics.* [S0003-6951(99)04102-9]

The electronic properties of carbon nanotubes are of considerable interest and have received much attention during the past few years.[1–7] A limitation inherent in many of the previous studies is the requirement of a serendipitous deposition of carbon nanotubes across prefabricated electrodes. It would be advantageous to develop simple techniques in which a nanotube is first placed in a controlled way on a substrate and then reliable electrical contacts are made to the ends of the nanotube. In this way, elementary networks might be constructed to further explore the possibility of carbon-based electronics.[8] In this letter, we describe a simple and straightforward technique that allows fabrication of reliable and robust electrical contacts to multiwalled nanotubes (MWNTs).

MWNTs are known to have concentric carbon ''shells'' that traverse the length of the nanotube.[9] The number of such 'shells' which remain intact along the length of the nanotube, along with the diameter of each ''shell'' determines the electronic properties of a single MWNT. In this study, a bundle containing between one and a few MWNTs is transferred with high lateral precision to a transparent substrate and the ends are then covered with a Ti/Au thin film evaporated using a wire shadow mask. We find the electrical contacts to the MWNT are robust and reliable. Using this procedure, we have a success rate of near 80%.

A schematic diagram of the steps in the procedure is given in Fig. 1. A typical high-resolution atomic force microscope (AFM) image of the resulting contact is given in Fig. 2. We find that electrical contacts made to MWNTs in this way withstand repetitive mounting and demounting to a variety of different sample probes. The $I(V)$ data (two-terminal) presented below are found to be very reproducible once the glass substrate is mounted in the probe station. The probe-station contact and lead wire resistance is typically found to be less than a few ohms.

*A priori*, a MWNT might be expected to exhibit two different $I(V)$ characteristics. First, if the MWNT is comprised of concentric ''shells'' which are metallic, these shells will dominate current flow through the MWNT and a linear $I(V)$ characteristic is anticipated. Second, if the MWNT is dominated by semiconducting layers, then the resulting $I(V)$ might be expected to exhibit nonlinear behavior. If a MWNT has both semiconducting and metallic layers intact, then it may be possible for a diode-like $I(V)$ characteristic to result.

Whether the conduction mechanism in any ''shell'' of the MWNT is ballistic or not is also a question of considerable importance. The presence of ballistic transport will be signaled by conductances given by

$$G = N \times M G_0 \times T, \tag{1}$$

where $N$ is the number of intact ''shells'' in the MWNT, $G_0 = 2e^2/h$, $M$ is the number of modes in each ''shell'' and $T$ is the transmission probability for an electron through the tube. Because the MWNT is buried under a Ti/Au contact pad, we assume $T$ is very nearly unity for our contacts. The number of modes in each ''shell'' is still not completely settled. Theoretical considerations predict $M=2$,[10–12] while recent experiments[6] suggest a value of $M=1$.

[a)]Electronic mail: rr@physics.purdue.edu

 © 1999 American Institute of Physics

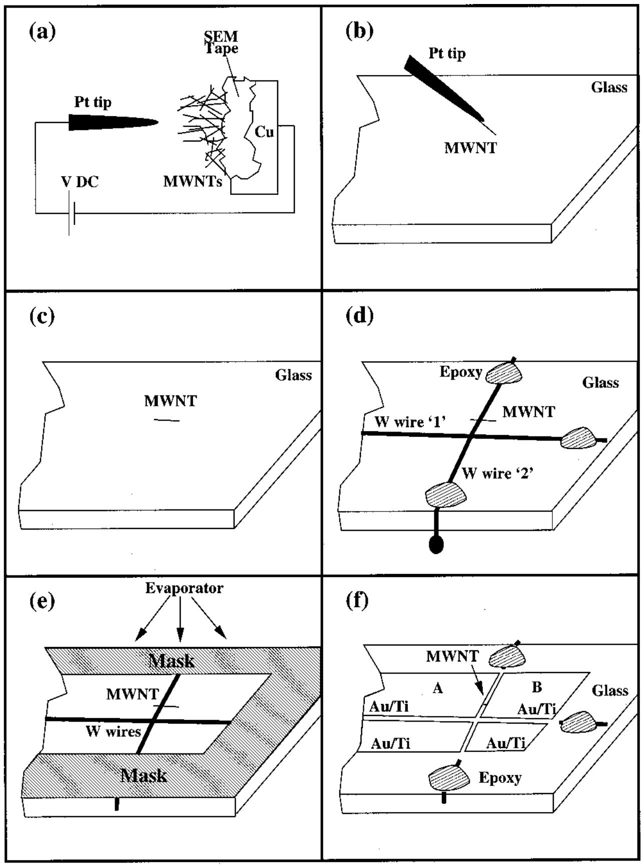


FIG. 1. A schematic diagram of the procedure for making electrical contact to MWNTs. In (a), the selection and capture of a MWNT following the procedure described in Ref. 14. Often, a visible emission of light is observed during this break-off procedure, implying the presence of a localized, intense electrical arc. The spark removal of the MWNT is expected to leave at least one if not both ends of the MWNT open. In (b), a MWNT adhering to the etched Pt tip, followed by (c), the transfer of the MWNT to a glass slide. Surface forces between the MWNT and glass assist in this transfer. In (d), the placement of a 4.3 $\mu$m diam tungsten wire (wire ''1''), roughly parallel to the MWNT and displaced from it by a fraction of a millimeter. This wire serves as a vertical riser to prevent contact between a second W wire (wire ''2'', diameter of 4.3 $\mu$m) and the MWNT. Wire ''2'' serves as a shadow mask. The precise alignment of wire ''2'' is facilitated by first gluing a 5 mm diam solder ball to one end of the wire. The other end of the wire is attached to a micromanipulator. In (e), the sample is covered by a thin, conducting film (100 nm Ti followed by 100 nm Au). The final structure after removal of the tungsten wires is shown in (f). After electrical contact is made to contact pads **A** and **B**, a robust sample results with both ends of the MWNT buried under the Ti/Au film. Steps (a)–(d) are facilitated by viewing with a Nikon Epiphot 200 dark-field microscope equipped with a 50×/0.55 objective having an overall dark-field magnification of 750×.

With a reliable method of making contact to nanotubes, some of these simple expectations can be readily checked. Below, we present some results for two of the more interesting MWNT samples we have studied.

Repeated $I(V)$ data from a MWNT (sample No. 4) having a minimum diameter (as determined from AFM scans) of ~40 nm were found to be highly linear with a resistance of 478 Ω, showing only a fraction of a percent deviation from nonlinear behavior over the ±1.5 V range investigated. Currents up to 3 mA have been passed through this tube without destroying it or changing its resistance due to joule heating. This implies that this MWNT can pass a minimum current density of at least $2.4\times10^{12}$ /m$^2$ without adverse effects.[13]

Because the tube is released from a mat of MWNTs adhering to the scanning electron microscope tape by electrical discharge [see Fig. 1(a)],[14] it is likely that at least one if not both ends of the tube are open. The initial resistance of this MWNT (478 Ω) is considerably smaller than the estimated resistance of ~3 kΩ expected for classical (diffuse) conduction through a high-quality carbon fiber ($\rho\simeq 1\times10^{-6}$ Ωm)[15] of the same dimension. Assuming the initial resistance of 478 Ω is determined by $N$ ''shells'' conducting in parallel and, assuming $N$ must be an integer, leads to a value of $N=27$ and requires $M=1$ in Eq. (1).

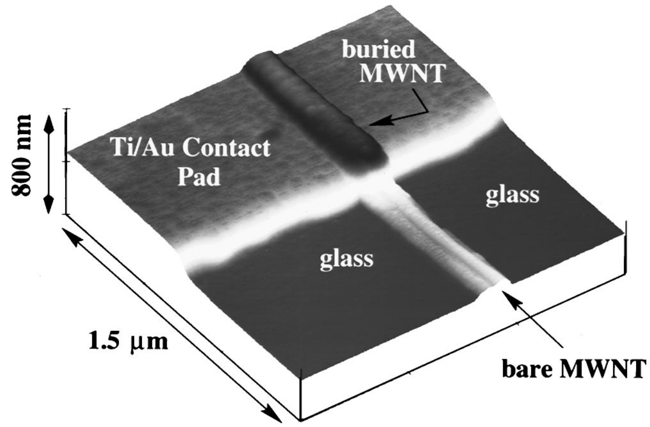


FIG. 2. A 1.5 $\mu$m×1.5 $\mu$m AFM image of a MWNT (sample No. 4) buried under a Ti/Au contact pad. The image shows the substrate comprised of a glass cover slide, one of the two Ti/Au contact pads, a section of the MWNT buried under the Ti/Au film, and a section of the bare MWNT which emerges from under the Ti/Au contact pad.

The resistance of this tube (sample No. 4) has been measured many times. We find the resistance has changed abruptly several times, each time changing resistance by $\Delta R\simeq 21$ Ω. These data are plotted in Fig. 3.

This result can be compared to changes in resistance expected for a ballistic quantum wire that initially conducts through $N$ ''shells,'' but then changes to conduction through $N-1$ ''shells:''

$$\Delta R=\frac{12.9\ k\Omega}{M[N(N-1)]}. \quad (2)$$

The apparent quantized changes of resistance can be under-

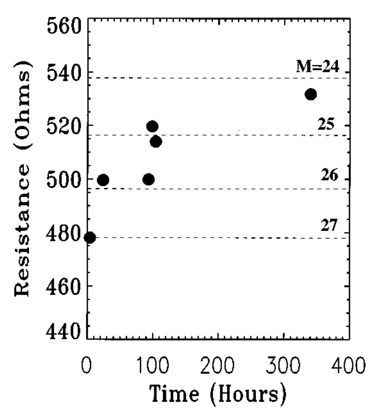


FIG. 3. A plot of resistance vs time (after the initial measurement of resistance) for a highly linear MWNT (sample 4). The tube resistance is found to abruptly change with time. The horizontal dotted lines represent quantized resistance values of $M/G_o$, with $M$=24, 25, 26, and 27. The diameter of this tube as determined from AFM studies is ~40 nm. The length of this tube between the contact pads is ~4 $\mu$m.

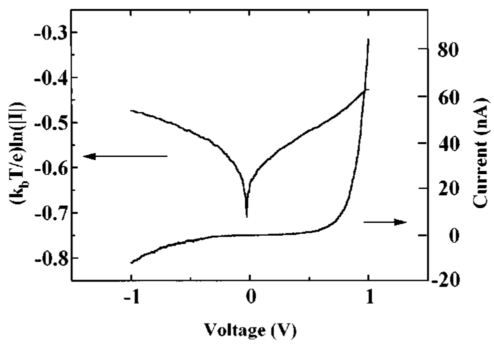


FIG. 4. $I(V)$ data from a MWNT (sample 3) showing diode-like conduction. The minimum diameter of this tube as determined from AFM studies is ~130 nm. The length of this tube between the contact pads is ~4 $\mu$m. The forward bias can be fit to a standard diode equation $I=I_o e^{e\phi/kT} e^{eV/\eta kT}$. A plot of $(kT/e)\ln(|I|)$ vs $V$ is also provided and yields an ideality factor $\eta \simeq 5.6$.

stood if $N\simeq 25$ in Eq. (2), implying that ~25 ''shells'' carry current. Assuming an interplanar separation of 0.3 nm between the walls in each ''shell,'' we estimate that at most, ~65 ''shells'' comprise this particular tube. Again, to avoid values of $N$ that are 1/2 integers, $M$ must be set to equal 1. It follows that contact pads prepared in the way described are capable of making good electrical contact to $(26\pm 1)$ of the possible ~65 ''shells'' in a single MWNT.

The fact that the resistance of the nanotube takes on values that are close to multiples of the fundamental quantum of resistance (12.9 k$\Omega$) leads us to believe that transport might be ballistic as conjectured in some recent experiments.[6] Several theoretical works have recently predicted a suppression of backscattering in metallic nanotubes,[16,17] so it seems plausible for transport to be ballistic over several microns in length. Also, we believe that since the MWNT is buried under a Ti/Au contact pad, we can indeed make good contact at both ends [i.e., $T\simeq 1$ in Eq. (1)], at least to a few shells.

On some nanotubes we measure very low values of current (nA as opposed to mA). However, the stability and repeatability of our measurements suggest that this can not be attributed to bad contacts. Instead, we believe it is related to internal breaks in the nanotube or perhaps, because we are not making contact to the same shell at either end, the current is required to transmit from one shell to another within the tube. This would explain the $10^6$ reduction in current since the intralayer resistivity of graphite is known to be $\sim 10^6$ times larger than the in-plane resistivity.

The $I(V)$ characteristics for these low current nanotubes look very diode-like (see Fig. 4) and can be fit quite well by a standard diode equation. Previous theoretical works have suggested the possibility of diodelike behavior at junctions between metallic and semiconducting nanotubes,[18] but it is not yet clear whether our observation is related to this effect.

In summary, we have developed a simple method for attaching robust, metallic contact pads to both ends of an individual MWNT. While only a few of the samples studied have been described here, we find that MWNTs prepared in this way routinely withstand currents up to a few mA. $I(V)$ data at room temperature indicate a rich behavior which can be qualitatively understood by considering the electronic properties of individual ''shells'' within the MWNT. We have also conducted preliminary experiments and have established that MWNT samples prepared in this way can withstand cooling to temperatures of 77 K.

An advantage of the technique is its simplicity, thereby opening up the investigation of the electronic properties of individual MWNTs to individuals not currently possessing high-resolution lithographic capabilities. Although we are currently fabricating very rudimentary structures, it is easy to envision the construction of more complicated prototypes using elaborations of the simple technique described above.

The authors would like to thank D. B. Janes, T. Lee, and T. Toepker for helpful discussions during the course of this work. The authors also thank Professor R. Smalley for providing the MWNTs.

[1] T. W. Ebbesen, H. J. Lezec, H. Hiura, J. W. Bennett, H. F. Ghaemi, and T. Thio, Nature (London) **382**, 54 (1996).
[2] S. J. Tans, M. H. Devoret, H. Dai, A. Thess, R. E. Smalley, L. J. Geerligs, and C. Dekker, Nature (London) **386**, 474 (1997).
[3] D. H. Cobden, M. Bockrath, P. L. McEuen, A. G. Rinzler, and R. E. Smalley, Phys. Rev. Lett. **81**, 681 (1998).
[4] S. J. Tans, A. R. M. Verschueren, and C. Dekker, Nature (London) **393**, 49 (1998).
[5] A. Bezryadin, R. M. Verschueren, S. J. Tans, and C. Dekker, Phys. Rev. Lett. **80**, 4036 (1998).
[6] S. Frank, P. Poncharel, Z. L. Wang, and W. A. de Heer, Science **20**, 1744 (1998).
[7] A. Bachtold, M. Henny, C. Terrier, C. Strunk, C. Schönenberger, J.-P. Salvetat, J.-M. Bonard, and L. Forró, Appl. Phys. Lett. **73**, 274 (1998).
[8] P. L. McEuen, Nature (London) **393**, 16 (1998).
[9] S. Iijima, Nature (London) **354**, 56 (1991).
[10] L. Chico, L. X. Benedict, S. G. Louie, and M. L. Cohen, Phys. Rev. B **54**, 2600 (1996).
[11] W. Tian and S. Datta, Phys. Rev. B **49**, 5097 (1994).
[12] M. F. Lin and K.W.-K. Shung, Phys. Rev. B **51**, 7592 (1995).
[13] For simplicity, this current density was estimated by assuming the current to flow uniformly through the entire cross-sectional area of this MWNT.
[14] H. Dai, J. H. Hafner, A. G. Rinzler, D. T. Colbert, and R. E. Smalley, Nature (London) **384**, 147 (1996).
[15] M. S. Dresselhaus, G. Dresselhaus, K. Sugihara, I. L. Spain, and H. A. Goldberg, in *Graphite Fibers and Filaments*, edited by M. Cardona, Springer Series in Materials Science, Vol. 5 (New York, 1988), p. 188–202.
[16] M. P. Anantram and T. R. Govindan, Phys. Rev. B **58**, 4882 (1998).
[17] T. Ando and T. Nakanishi, J. Phys. Soc. Jpn. **67**, 1704 (1998).
[18] L. Chico, V. H. Crespi, L. X. Benedict, S. G. Louie, and M. L. Cohen, Phys. Rev. Lett. **76**, 971 (1996).