In situ manipulation and electrical characterization of multiwalled carbon nanotubes by using nanomanipulators under scanning electron microscopy

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The results of *in situ* manipulation and electrical transport characterization of individual multiwalled carbon nanotubes (MWCNTs) grown on a nickel tip by using a piezoelectric nanomanipulation system operating in a scanning electron microscope chamber have been reported. The growth of MWCNT directly on nickel wire by chemical vapor deposition technique ensures good electrical contact with the catalyst substrate. Using the electron beam induced welding, a full characterization of electronic properties of several MWCNTs has been explored without the usual postprocessing methods which may alter, in principle, the intrinsic properties of the carbon nanotube (CNT). Thanks to the high mechanical and electrical stability ensured by the electron beam welding procedure, a detailed study of the modification of CNT electrical transport properties under CNT buckling has been performed. The crucial role played by the structural defects in determining an irreversibility of a long MWCNT *I-V* characteristic under mechanical stress has been clearly evidenced. Finally, by a proper sequence of CNT/tip welding and movement, the potential in creating an Ohmic junction between two nanotubes has been demonstrated, opening the route to a systematic investigation of one of the most fundamental aspect of CNT physics.

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I. INTRODUCTION

Since their discovery in 1991,[1] carbon nanotubes (CNTs) have been the focus of considerable research interest due to their peculiar and unsurpassable chemical, mechanical, and electronic properties.[2] Basically, one distinguish between multiwalled carbon nanotubes (MWCNTs), consisting of a series of coaxial graphite cylinders, and single walled carbon nanotubes.[2] Graphite cylinders have been predicted to have metallic or semiconducting electrical transport behavior, depending merely on how the graphite layer is wrapped into a cylinder (chirality) and on its specific diameter.[2] In particular, conduction in defect-free CNTs are predicted to be ballistic, thus involving low energy dissipation within the nanotubes.[2] Furthermore, they present good mechanical strength and thermal conductivity, properties which make CNTs the most promising candidates as building blocks for the development of a new carbon based nanotechnology.[2] Various electronic devices based on individual CNTs have been experimentally realized such as field effect transistor,[3] single electron transistor,[4] and electrical rectifiers.[5] However, in order to truly harness all the technological potentialities of the CNT-based nanostructures, it is essential to develop a detailed understanding of the physics which governs their electrical transport behavior. To this aim, numerous electrical measurements of CNTs have been performed on a large extent of CNTs placed on metallic contacts on a prepatterned surface.[2] The presence of a high energy barrier at the metal/nanotubes contacts has been clearly brought to light,[2,6] which leads to an overall resistance value significantly higher with respect to the theoretically predicted quantum ballistic limit ($h/2e^2=13$ kΩ for metallic MWCNT[2]) and which, in general, masks the intrinsic electrical conduction properties of the individual CNTs. The reported contact resistance ranges from 10^4 to 10^9 Ω,[7,8] deeply affected by the nanotube structure[9] and the chemical composition of the metallic pads.[10] A prolonged exposure of the CNT/metal contact area to a highly focused electron beam appears as an effective technique for reducing the contact resistance by several orders of magnitude.[11] Since the irradiation is capable of breaking the nanotube C-C bonds, it may be possible that the resulting dangling bonds will lead to a stronger nanotube/metal coupling. In this context, the effects of the electron irradiation on the CNT structural properties have been extensively investigated by means of transmission electron microscopy (TEM) technique.[12,13] In particular, the high energy electron bombardment leads to the evaporation of carbon atoms[12] or the formation of defect (vacancy, interstitial), which may support the formation of CNT/CNT junctions.[13] At the same time, it has been supposed that the beam induced decomposition of the residual hydrocarbon present in the measurement ambient creates a carbonaceous deposit over the nanotubes which act as a sort of glue, thus stabilizing the metal/nanotube contact.[14,15] Alternatively, the local current stimulated Joule heating of the metal/nanotubes contact leads to a considerable reduction of the contact resistance as a consequence of the thermally induced carbon-metal bond formation and to the removal of surface contaminants on the metal surface.[16,17] However, the process of preparing and performing such kind of experiments is often elaborate and, at the same time, does not offer any possibility to manipulate the CNTs after their electrical characterization. The related contact preparation method, such as photolithography and electron beam lithography, may also introduce impurities and contaminations of the CNT, which distort the measurement results. Furthermore, the electrical properties of the CNT may be deeply affected by the presence of the surface. Atomic force microscopy experiments[18] and molecular mechanics simulations[19] have shown that the van der Waals forces between the CNT and the substrate on which they are placed lead to a significant deformation of their structure, which may affect, in principle, its intrinsic electrical transport properties.[6] It is, therefore, advantageous to perform electrical measurement on CNTs in the free space, and it is also desirable to have the possibility of manipulating a characterized carbon nanotube into a predetermined position for device construction. To this aim, the use of nanomanipulation systems coupled with scanning electron microscope (SEM) has been suggested and successfully used.[14] A nanomanipulator inside a SEM permits viewing and placing probe contacts at specified locations along a CNT and, with three-dimensional freedom, all the aspects of the investigated CNT can be explored. Because operations can be viewed directly with high resolution under SEM, fewer ambiguities related to the interpretation of the results of electrical and mechanical experiments still remain.

In this paper, we present *in situ* electrical characterization of several individual MWCNTs directly grown onto a metallic substrate by using a nanomanipulation system operating inside a SEM. The growth of the CNTs on a metallic substrate ensures a low contact resistance as well as a high mechanical stability which facilitate the electrical characterization of the freestanding nanotubes by putting them in direct contact with a free nanoprobe tip. The effect of the electron beam irradiation of the nanotubes/metallic nanoprobe junction has been extensively investigated. From our study, the electron beam induced irradiation appears as an effective way of reducing the contact resistance and creating stable Ohmic nanotube/metal junction. The high mechanical stability of the metal substrate/nanotube/probe junction has allowed one to investigate the transport characteristic of an individual carbon nanotube in free space as a function of reversible mechanical manipulation. The potential of this method in investigating the physics of the nanotube/nanotube junction has been finally explored.

II. EXPERIMENT

A two (double) MM3A-nanoprobe system manufactured by Kleindeik Co. has been used for the CNT manipulation and electrical transport measurements. The system has been installed inside a SEM (ZEISS, LEO 1430). Multiwalled carbon nanotubes with diameter ranging from 10 to 70 nm have been directly grown onto a nickel wire by means of chemical vapor deposition (CVD) technique.[20,21] The nickel wire has been first polished by a 30 min sonication cycle in acetone in order to remove all the surface contaminants, and inserted in a quartz CVD reactor that has been pumped down to less than 10^{-6} Torr using a turbo molecular pump. The specimen has been annealed at 700 °C for 5 min in NH_3 gas at a flow rate of 100 sccm. The CNTs have been grown on the metallic wire by adding C_2H_2 at a flow rate of 20 sccm for 20 min at the same temperature of the NH_3 annealing treatment. During both annealing and CNT growth, the pressure inside the quartz reactor is kept fixed at 5.5 Torr. According to very recent experimental results,[22] the MWCNT growth is catalyzed by the protrusions and clusters on the nickel surface. The resulting CNTs are distributed quite uniformly on the metallic surface, often organized in bundles from which freestanding nanotube protrudes [see Fig. 1(a)]. The corresponding TEM and high resolution TEM images, reported in Figs. 1(b) and 1(c), respectively, show that the CNT has a multiwalled centrally hollow tube [Fig. 1(b)] with an interlayer spacing of 0.34 nm [Fig. 1(c)] as expected.[2]

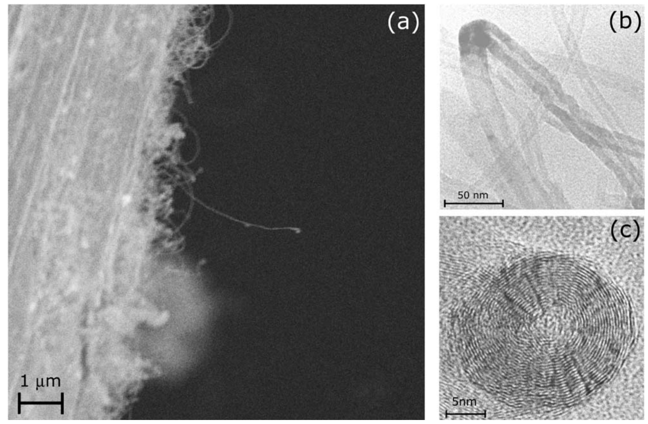

FIG. 1. Typical (a) SEM, (b) TEM, and (c) high resolution TEM images of the CNTs as-grown on nickel substrate.

The CNT covered nickel wire has been fixed on one of the manipulators. The contact at the other hand is performed by an electrochemically etched tungsten tip which is connected to the second nanomanipulator, so it can be easily brought into contact with the individual nanotubes of the nickel wire for the electrical measurement. Both manipulators are coupled with a Keithley-236 electrometer, giving the entire system the ability to perform electrical current-voltage (I-V) measurements. The high density of the CNTs and the three-dimensional degrees of freedom of the nanoprobe system allow a systematic characterization of the nanotube electrical transport properties. As already pointed out,[23] such investigation method allows one to perform electrical measurements on the as-grown CNT without involving any postprocessing procedure (dispersion into solution, lift-off, etc.) which may alter, in principle, the intrinsic properties of the investigated nanostructures. To select a nanotube for the investigation, the tungsten movable tip is carefully brought close to a protruding CNT [Fig. 2(a)] and the distance is progressively reduced until the contact is made. Often, due to the electrostatic interaction, the CNT tends to spontaneously lie onto the tip surface, thus relieving the need for an accurate position [Fig. 2(b)]. The contact area between the CNT and the tungsten tip has been focused by SEM and then irradiated with 10 keV electron beam. The effect of such exposure on the overall system electronic transport properties has been systematically investigated by acquiring I-V measurement after each electronic bombardment cycle. Once a strong contact between the tungsten tip and the nanotube has been made, a study of the buckling induced modification of the electronic properties of the CNT is performed. Any further movement of the nanotube and tip has been directly monitored under SEM. Finally, the possibility to widely explore the physics of the CNT/CNT junction by means of the combined use of SEM and nanomanipulation system has been investigated.

III. RESULTS AND DISCUSSIONS

The tungsten tip has been carefully brought into contact with an individual MWCNT protruding from the surface of

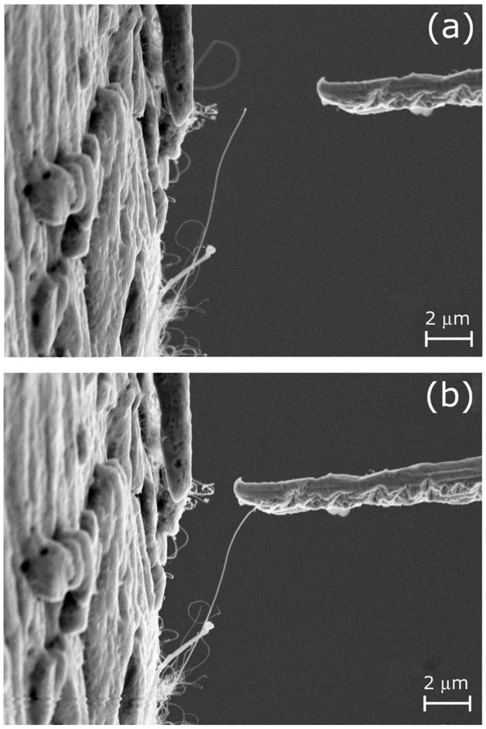

FIG. 2. SEM image of an individual MWCNT protruding from the nickel surface. (b) Spontaneous adhesion of the MWCNT on the tungsten probing tip due to the electrostatic interaction.

the nickel wire as shown in Fig. 3. The CNT measured in this case is 11 μm long with a diameter of 70 nm, as estimated by SEM images. After the contact is made, a limited portion of the CNT/tungsten tip superimposition region ($1.2 \times 0.8\ \mu m^2$), reported as inset in Fig. 3, has been irradiated with a 10 keV electron beam. The evolution of the nickel/CNT/tungsten tip system *I*-*V* characteristics as a function of the exposure time on the nanotube/tungsten tip selected area is reported in Fig. 4. During each electrical measurement, the voltage has been stepped from 0 to 1 V, with a step size of 25 meV and an acquisition time of 0.2 s for each point. As clearly shown in Fig. 4(a), the prolonged electron beam exposure of the CNT/tungsten tip junction results in a strong modification of the *I*-*V* characteristic curve. For each *I*-*V* curve, the overall resistance *R* in the linear regime has also been determined and the corresponding value has been re-

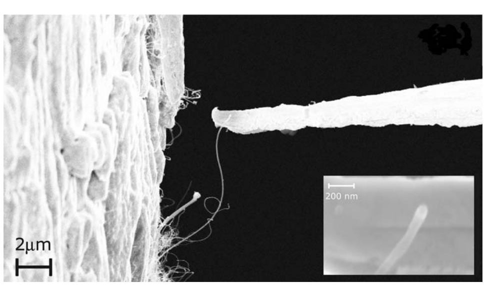

FIG. 3. SEM image of the MWCNT/tungsten tip junction. Inset shows the CNT/tip superimposition region exposed to the 10 keV electron beam during the contact formation.

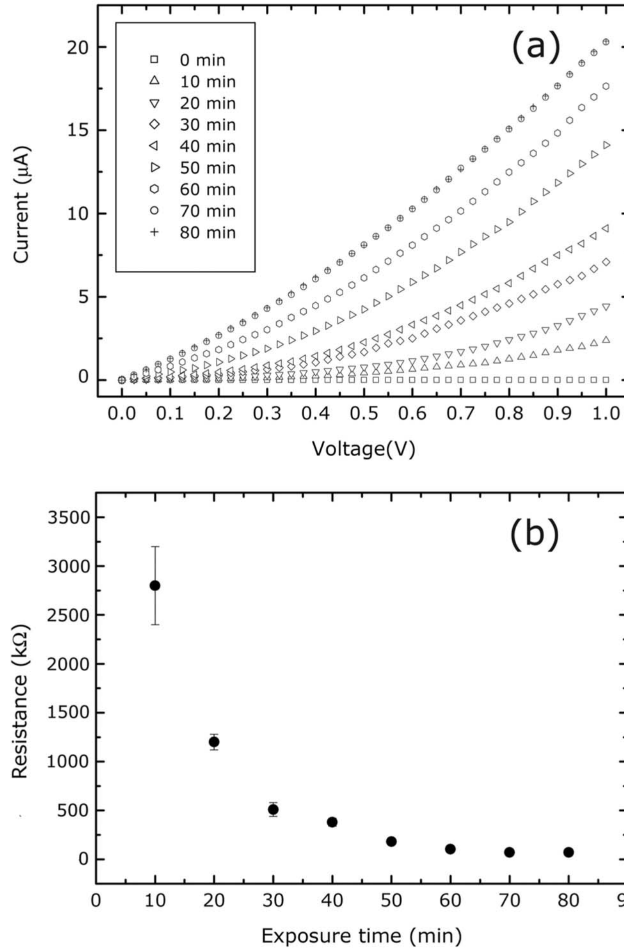

FIG. 4. Evolution of (a) *I*-*V* curve and (b) overall low field resistance as a function of the exposure time to the electron beam onto a selected CNT/tip superimposition area. The initial value of resistance ($\sim 10^9\ \Omega$) has not been reported for scaling reasons.

ported in Fig. 4(b) as a function of the electron beam exposure time.

Once the first contact between the nanotube and the tungsten movable tip is reached, only a very limited current (around 10^{-10} A, $R \sim 10^9\ \Omega$) is detected within the applied voltage range ["0 min" curve in Fig. 4(a)]. After 10 min of electron beam exposure of the CNT/tip junction, a slight increase of the current passing across the whole system is observed, the *I*-*V* curve showing a peculiar nonlinear characteristic. The enhancement of the electron beam exposure time leads to a significant increase of the current, while the *I*-*V* characteristics become progressively more linear [see "70 min" curve in Fig. 4(a)], indicating a progressive reduction of the overall resistance. Finally, above 70 min of exposure time, further electron beam dosing does not lead to any appreciable modifications in the quite linear *I*-*V* characteristic plot, where an overall Ohmic resistance of about 71 ± 1 kΩ is measured [Fig. 4(b)].

In order to understand the effect of the electron beam exposure on the electrical transport properties, it is worthy to note that since the CNT has been directly grown onto a metallic nickel tip, its perfect Ohmic contact with the metal is warranted, thus resulting in a nonappreciable contact barrier across the nickel CNT junction.[6,23] Consequently, the overall electrical resistance can be mainly ascribed to the intrinsic properties of the MWCNT and to the contact effects in correspondence of the tunable nanotube/tungsten tip junction, where a side contact CNT/metal electrode occurs. Furthermore, taking into account the high selectivity of the irradiation process (which is strictly limited to the CNT/metal area), the electron beam dosing results in a significant improvement of the quality of the MWCNT/tip contact, thus reducing the contact contribution to the overall resistance. The band gap value estimated for the 70 nm diameter nanotube is around 5 meV,[23] which is considerably less than the thermal agitation energy at room temperature (25 meV). Therefore, the 70 nm nanotube is expected to be basically metallic.

By properly modifying the original Simmons approach[24] developed for a metal-insulator-metal (MIM) system, the electronic transport across the CNT/metal side junction has been theoretically explained[9,25] as tunneling across an energy barrier created by the finite separation between the CNT and the metallic electrode. Such a MIM-based picture allows a direct interpretation of the experimental *I-V* behavior. In particular, the nonlinear (linear) dependence of the current in the high voltage (low voltage) range observed in our experiment is perfectly consistent with the presence of a tunnel barrier in correspondence of the metallic CNT/movable junction.[9,24,25] The progressive linearization of the *I-V* curve with the exposure time, and the corresponding reduction of the overall system resistance, can be similarly explained in terms of an electron beam modification of the barrier parameters, which results in an enhancement of the tunnel probability across the CNT/metal junction. In this context, it is worthy to note that all the proposed theoretical model are convergent as indicated by (i) contact area, (ii) CNT-electrode distance, and (iii) chemical composition of the electrode (the difference between the CNT and metal work function determining the barrier height), the crucial factors which rule the electron tunneling across the CNT/metal junction. In our case, the CNT/tungsten tip contact area remains fixed and can be roughly identified with the portion of the nanotube exposed to the electron beam during the several focalization process (see inset in Fig. 3). Consistently, the electron beam exposure may be supposed to act directly on the nanotube-metal distance. The pressure in the SEM sample chamber is about 6×10^{-6} Torr, so there exist some residual hydrocarbon molecules. The hydrocarbon molecules decompose under the electron beam irradiation, resulting in carbonaceous material across the exposed area. The carbonaceous deposition accumulating across the nanotube may act as a sort of glue and can strengthen the contact between the nanotube and the movable tip. Such an effect of mechanical stabilization is well known in literature[14,15] and has been confirmed, in this work, by several preliminary investigations. However, the carbonaceous deposit is demonstrated to be amorphous and acts as an insulator[15,26] with a resistivity of about 10^{11} Ω cm and cannot be, therefore, associated with the observed reduction of the contact resistance.[15,26] In can be supposed that the electron beam induced mechanical strengthening may lead to a reduction of the CNT-metal distance. Before any exposure, the CNT/tip contact is warranted by the electrostatic van der Waals interaction with a mean bonding distance of tenths of an angstrom.[10] However, such a junction is mechanically unstable and it is subjected to the mechanical vibrations of the whole experimental apparatus which can lead to an increase of the effective CNT-bonding distance. Correspondingly, a very bad and unstable contact between the nanotube and the tip is established, thus resulting in a very low and noisy electrical current [0 min curve in Fig. 4(a)] and in a high overall resistance [around 10^9 Ω, not shown in Fig. 4(b) for scaling reasons]. The deposition of a carbonaceous layer across the junction introduces an additional mechanical stability, which allows a more effective interaction between the CNT and the tip and a consequent reduction of the nanotube-metal distance. Such a stabilization effect (which increases with the amount of deposited amorphous C, i.e., with exposure time) is accompanied by a progressive linearization of the *I-V* curve [70 min curve in Fig. 4(a)] and a reduction of the barrier contribution to the contact resistance [Fig. 4(b)] up to a saturation point. After a certain exposure time (70 min in the case of Fig. 4), in fact, the beam induced deposition is not expected to further contribute to the mechanical stability of the CNT/tip system, leading only to a progressive growth of the carbonaceous deposit. At the same time, the electronic bombardment may cause, via local annealing or mechanical removal, the release of the limited amount of the residual surface adsorbates, such as water, nitrogen, and oxygen adsorbed at the interface region during the previous air exposure, thus enhancing the CNT-metal interaction and, correspondingly, the electrical current across the whole system. Under our experimental condition (electron beam energy $E=10$ keV, exposure time $t=$hour), any electron beam induced damaging effect on the CNT structure is excluded. If present, such structural defects are expected to deeply modify the electrical properties of the CNT. The absence of any structural degradation of the CNT under the electron beam is well demonstrated by the results reported in Fig. 5. At first, a MWCNT [Fig. 5(a)] has been stably welded to the tungsten tip and a quite linear *I-V* curve has been obtained. The middle region of the CNT has then been exposed to the 10 keV electron beam for 30 min [Fig. 5(b)]. No variations of the *I-V* characteristic curve are observed as a consequence of the exposure of the CNT region [Fig. 5(c)], which appears to be covered by a significant carbonaceous deposit as shown in Fig. 5(b). This result clearly indicates a significant CNT structural stability against the prolonged electron bombardment. Therefore, the prolonged exposure of the CNT/metal contact area does not modify the intrinsic electric properties of the nanotubes but acts only on the quality of the CNT/tip junction.

The electron beam induced improvement on the metal/CNT/metal conductance has been confirmed by investigating the CNT/tip welding process and its effect on the electrical transport properties of several other nanotubes. For each case, the low field resistance in the nearly Ohmic *I-V* saturation regime has been measured. The *I-V* saturation curves obtained for several MWCNTs after prolonged exposure to the electron beam are plotted in Fig. 6, while the calculated *R* values are reported in Table I within the diameter and the length of the corresponding nanotubes.

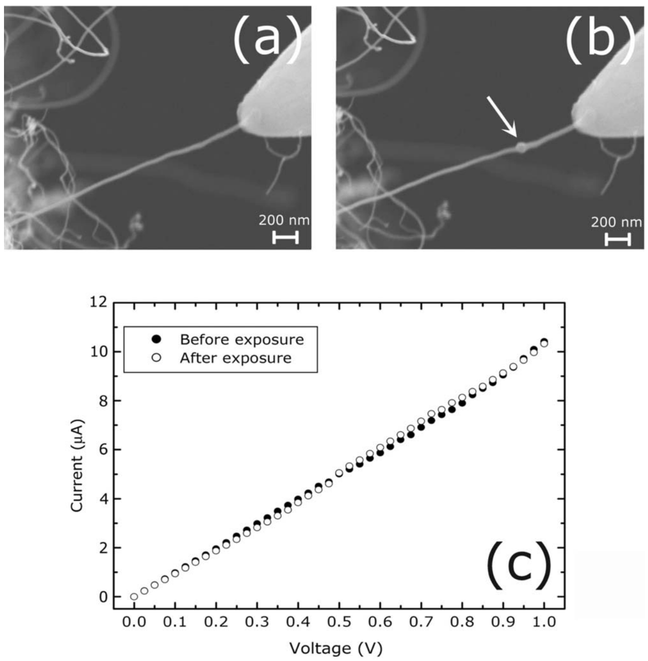

FIG. 5. SEM images of (a) MWCNT connected to the tungsten tip and (b) after electron beam bombardment of the MWCNT middle region has been performed. Note (as indicated by the arrow) the carbonaceous deposit formation corresponding to the electron beam exposed areas (CNT/tip junction and middle region of the CNT).

All the measured overall resistance values are comprised within the 30–220 kΩ range, which is higher with respect to the ballistic limit of 13 kΩ predicted for the metallic MWCNT nanotubes.[2] This is not a surprising result taking into account the presence of a nonideal CNT/metallic electrode junction. Furthermore, the occurrence of several structural defects (vacancy, breaking of internal graphite planes, and C atom rehybridization effects) may deeply affect the electronic transport properties of the CNT, determining, in principle, an increase of the CNT intrinsic resistance with respect to the predicted defect-free ballistic limit.[27] Hence, even if it is not straightforward to quantify the exact contribution of the CNT to the measured resistance, it is worthy to note that our measured values are in agreement with previous observation performed by using scanning probe and nanomanipulation techniques.[15,26]

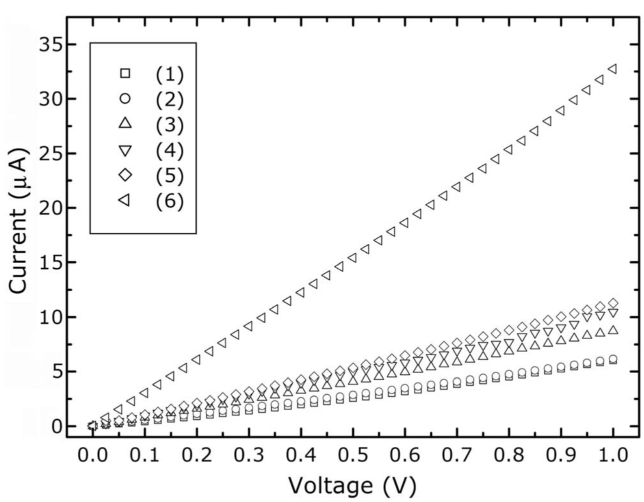

FIG. 6. *I-V* characteristics of various MWCNTs obtained after prolonged and selective exposure of the CNT/tip contact area to 10 keV electron beam. The structural parameter and the corresponding overall resistance value of the various nanotubes, to which the numbers 1–6 are referred, are reported in Table I.

TABLE I. Overall resistance values as measured for several MWCNTs. The structural parameters of the investigated nanotubes (length and diameter) have been explicitly reported, as derived from the corresponding SEM images. The CNT reference numbers are related to the *I-V* curves reported in Fig. 6.

CNT Ref. No.	Diameter (nm)	Length (μm)	$R\pm\Delta R$ ($k\Omega$)
1	40	11	220±20
2	30	3	180±10
3	50	3	120±10
4	50	3	100±10
5	60	8	110±10
6	60	7	32±1

After a stable CNT/tip contact is reached (80 min exposure), the nanotube of Fig. 3 is mechanically deformed by carefully moving the tungsten tip as shown in Fig. 7. The effects of the mechanical stress on the electric transport properties of the CNT have been evaluated by acquiring the *I-V* curve in correspondence of the various CNT positions (indicated by A, B, and C in Fig. 7) and by calculating the corresponding low field overall electrical resistance. In passing from position A to B, only a limited CNT bending is induced, without any appreciable modification of the *I-V* curve and overall resistance value. A further significant mechanical stress results in a dramatic drop of the electrical current [Fig. 8(a)], while the resistance value rises up to 170 kΩ [see Fig. 8(b)]. Interestingly, a careful recovery of the original position (A′ curve) leads to a further reduction of the total current and to a corresponding increase of the resistance value (270 kΩ). Finally, as clearly shown in Figs. 8(a) and 8(b), the *I-V* characteristic curve (curves C′ and A″) and *R* value appear to be quite stable under any further mechanical modification within the A–C position range. Our experimental results clearly indicate that the electrical transport data of the MWCNT have been irreversibly modified through buckling movements. Accordingly, the observed

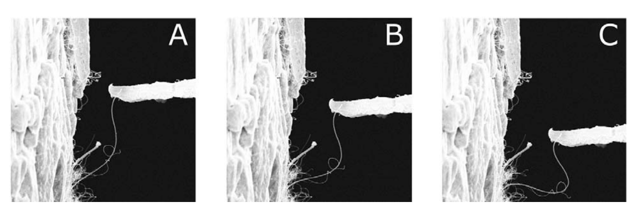

FIG. 7. SEM images of the various CNT/tip positions (A, B, and C) during the nanotube buckling process.

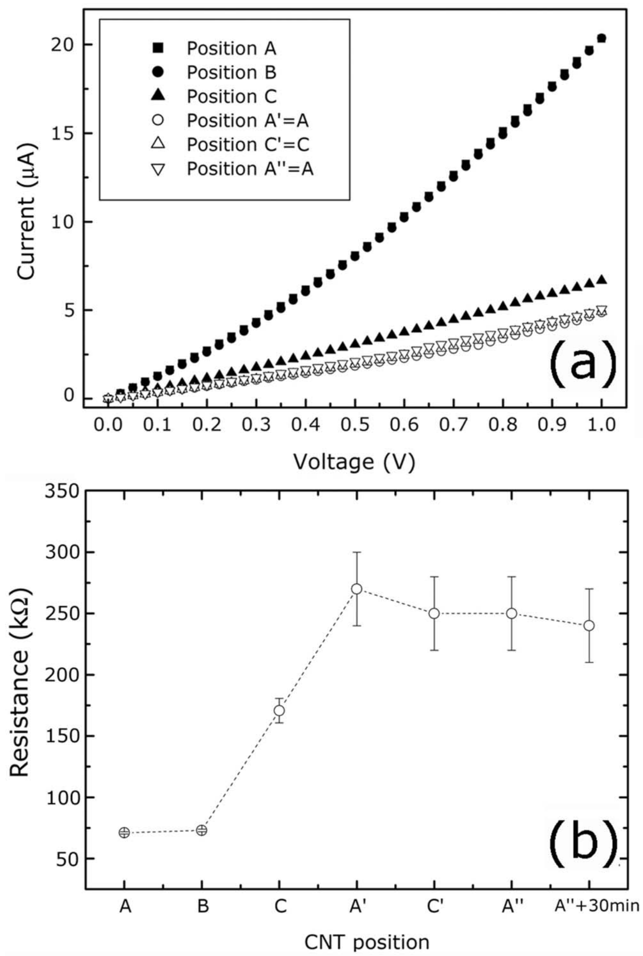

FIG. 8. (a) *I-V* curve and (b) overall resistance values corresponding to the different CNT positions reported in Fig. 7.

variation of the electrical resistance may be completely ascribed, in principle, to a weakening of the CNT/tungsten junction due to the movement of the tip. However, as indicated by the SEM images reported in Fig. 7, during the movement, the tip remains always in good contact with the CNT, thus indicating a strong mechanical adhesion. In addition, after any tip movements, the nickel/CNT/tungsten system retains a nearly Ohmic characteristic, while a bad CNT/tip junction is expected to be associated with a highly nonlinear *I-V* curve [see Fig. 4(a)]. Finally, it is worthy to note that another 30 min electron beam exposure of the CNT/tungsten tip [see $A''+30$ min point in Fig. 8(b)] contact area does not lead to any appreciable modification of the resistance value. Therefore, our experimental results clearly indicate that the intrinsic electrical transport properties of the MWCNT have been irreversibly modified through buckling movements.

As already pointed out, structural defects (atomic vacancies, local amorphization, and internal breaking of the graphite planes) may have a strong influence on the electrical resistance of the MWCNT, presenting additional potential barriers between high conductance regions. By deeply buckling the MWCNT, the position of the defects may be permanently changed and a different structural distortion may be created in correspondence of the predefective region of the CNT. These irreversible structural modifications determine the observed permanent changes of the CNT electrical transport properties. This is in contrast with what was previously observed[28] during similar *I-V* characterization of a MWCNT. According to Ref. 28, the variation of electrical resistance should be attributed to a local band gap opening as a result of the reversible axial stretching of the CNT. However, it is worthy to note that the electrical transport properties reported in Ref. 28 have been obtained for a short CNT (<1 μm length). Therefore, the occurrence of structural defects is expected to be considerably reduced with respect to our measured MWCNT (11 μm length), which is characterized by an irreversible electrical transport behavior against mechanical deformation.

Finally, in order to fully demonstrate the huge potential of the combined use of the nanomanipulation inside a SEM system and the electron beam induced welding for the investigation of the physical properties of CNT, in an additional experiment, the transport properties across a nanotube/nanotube junction have been investigated. At first, a mechanical and electrical contact between a CNT and the tip has been produced by prolonged electron beam exposure of the CNT/tip contact area. After this, the nanotube can be removed from the nickel wire by simply pushing back the tungsten movable tip [Fig. 9(a)]. The probes, now with the nanotubes attached, have been then repositioned, thus creating a nanotube/nanotube junction [Fig. 9(b)]. The superimposition area between the two nanotube has then been irradiated with 10 keV electron beam [Fig. 9(c)]. The resulting *I-V* curve (obtained after 30 min of exposure) shows a quite linear characteristic, indicating Ohmic contacts between the CNT and the movable tungsten tip. The corresponding value

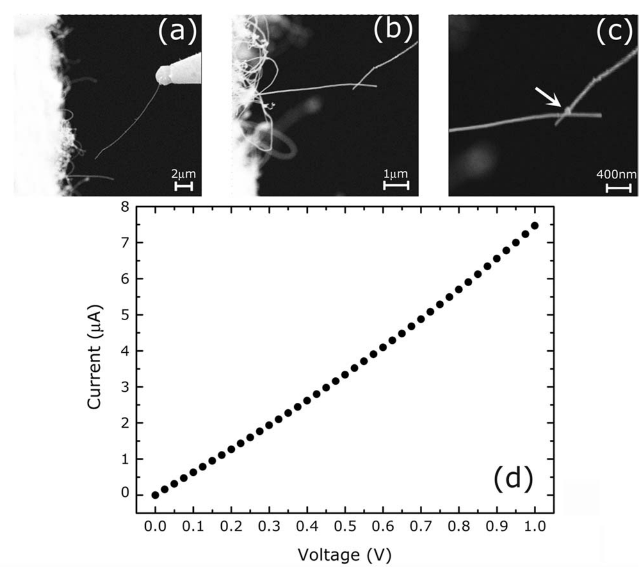

FIG. 9. SEM images showing the steps for the CNT/CNT junction formation: (a) CNT/tip welding and mechanical removal of the MWCNT. (b) Selection of the CNT/CNT contact area. (c) Selective irradiation of the CNT/CNT contact area with final formation of carbonaceous deposit (indicated by the white arrow) (d) *I-V* characteristic of the junction between two MWCNTs.

of overall resistance is 100±10 kΩ, in good agreement with what was previously reported.[28] Such an Ohmic electrical transport regime across the CNT/CNT junction has been proposed by Rueckes *et al.* for the development of molecular computing based on electrostatic switching of nanotubes.[29]

However, as already pointed out, the overall resistance value is not truly representative of the intrinsic resistance of the CNTs and of the CNT/CNT junction due to the presence of a CNT/metal junction effect. A possible solution to this problem lies in the growth of the CNT directly on a nickel movable tip and then putting it in contact with another CNT on the nickel wire. In this way, the contact resistance at the metal/CNT junction should be minimized and the final conductance should be quite entirely ascribed to the intrinsic value of the nanotube and to the effect of the nanotube/nanotube junction. In this way, thanks to the three-dimensional manipulation under SEM, various contact geometries may be explored and the corresponding results may be more directly compared with the prediction of theoretical calculations. Some preliminary results which are currently under analysis seem to confirm the validity of such approach in investigating the electronic properties of the CNT/CNT junction.

IV. CONCLUSIONS

In conclusion, it has been extensively illustrated the possibility of *in situ* manipulation and electrical transport characterization of individual MWCNT grown on nickel templates by using a nanomanipulation *I-V* probing system operating in a SEM chamber. The growth of MWCNT directly on a nickel template ensures good electrical contact with the catalyst substrate. The electron beam induced welding (via carbonaceous deposition on the CNT/tip contact area) represents an effective low damaging method for building up a CNT Ohmic junction with a movable metallic tip. In this way, the electronic properties of several MWCNTs may be fully explored without the usual postprocessing methods which may alter, in principle, the intrinsic properties of the CNT. Thanks to the high mechanical and electrical stability ensured by the electron beam welding procedure, a detailed study of the modification of CNT electrical transport properties under CNT buckling has been performed. The use of SEM allows a reproducible and precise CNT positioning. The crucial role played by the structural defect of long nanotubes in determining an irreversibility of a long MWCNT *I-V* characteristic under limited mechanical stress has been clearly brought to light.

Finally, by a proper sequence of CNT/tip welding and movement, the possibility to create a CNT/CNT Ohmic junction has been demonstrated, opening the route for a systematic investigation of one of the most fundamental aspect of CNT physics.

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