Supplementary Information

Electrical conductivity of a single parallel contact between carbon nanotubes

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Estimation of the size factor of electrical resistance

The interfacial resistance R_{inter} varies with the contact length between two nanotubes. In order to derive the contact-length-independent property, we express R_{inter} by using size-independent part (electrical resistivity of the interface) and size-dependent part (size factors). R_{inter} is then represented as shown in Eq. (2) in the main text:

$$R_{\mathrm{inter}} = \rho_{\mathrm{inter}}\frac{l}{A} = \rho_{\mathrm{inter}}\frac{l}{Cx} = \frac{\alpha}{x}. \quad (2)$$

Here, ρ_{inter} represents the electrical resistivity of the interface, while l and A represent the length and cross-sectional area that contribute to contact transport, respectively. Since cross-sectional area A is proportional to contact length x, A can be written as $A = Cx$. To evaluate the electrical resistivity of the interface ρ_{inter} from the experimentally obtained value $\alpha(= \rho_{\mathrm{inter}} l/C)$, we roughly estimated the size factors l and C related to interfacial conduction. Figure S1(a) presents a schematic model for considering the combined cross-section of two adjacent multiwalled carbon nanotubes (MWCNTs). We first define the minimum and maximum distance between two adjacent MWCNTs, where the outer walls of both MWCNTs contribute to the interfacial conduction, to be l_0 and l_1, respectively. We can then calculate l and C, respectively, as the average distance and the length of the arc over which contact transport takes place, as functions of l_0 and l_1. We approximated $l \approx (l_0 + l_1)/2$ for simplicity. Assuming $l_0 =$ 0.34 nm as the interlayer spacing for the *c*-plane of graphite, the size factor l/C can be written as a function of l_1. Figure S1(b) presents l/C as a function of l_1 as calculated for nanotubes of diameter 15 nm. As shown in Fig. S1(b), the change in the size factor with increasing l_1 is not significant for l_1 values above ~0.5 nm. Indeed, we assume that $l_1 = 0.68$ nm in the calculation in the main text.

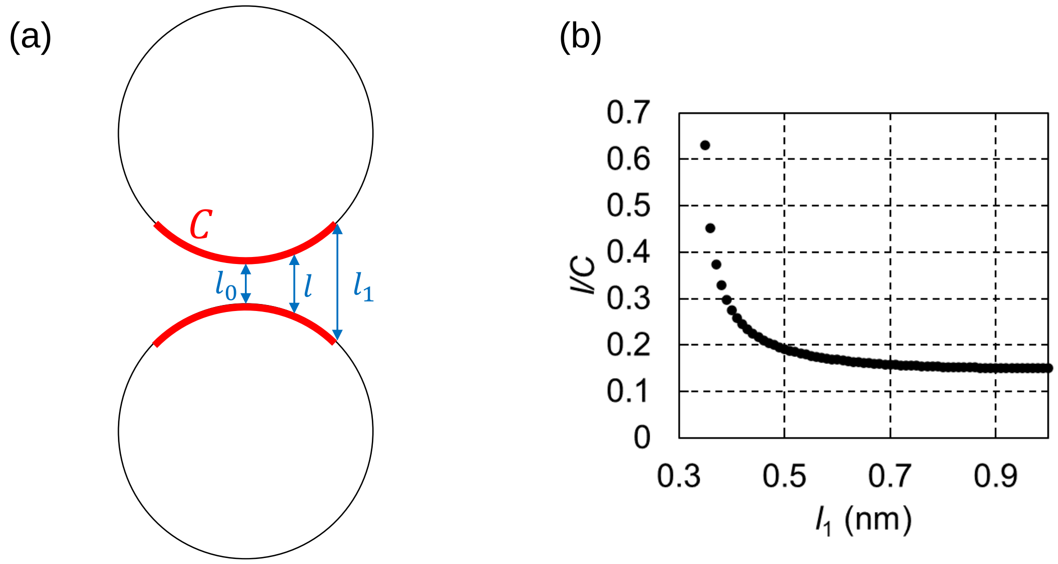

Fig. S1. Estimation of size factor of interfacial electrical resistance. (a) Schematic of the cross-sections of two adjacent multiwalled carbon nanotubes. (b) Size factor l/C as a function of l_1.

Finite element calculation of the model

We conducted a numerical calculation to verify the validity of the approximation contained in Eq. (4) in the main text:

$$R_{\mathrm{total}} \approx \frac{\alpha}{x} - \beta x + R_0''. \tag{4}$$

In the experiment, two MWCNTs were brought in parallel contact, as shown in the left schematic in Fig. S2(a). The equivalent circuit can be written by using the resistance of CNT and interface of a small area, R_{cnt} and $R_{\mathrm{interface}}$, as shown in the right side in Fig. S2(a). This circuit can be analytically solved, but a numerical calculation is useful because of the calculation amount.

We utilized a finite element method to calculate this model. For simplicity, we derive the partial resistance R_{p} [see Fig. S2(b)] as

$$R_{\mathrm{p}} \approx \frac{\alpha}{x} + \beta' x, \tag{S1}$$

where $\beta' = B/3 = \rho_{\mathrm{bulk}}/2S$. In the model, two rectangular solids are in contact, with high contact resistance. Electric current enters at the right side of the top rectangular solid and exits at the left side of the bottom rectangular solid [see Fig. S2(c)]. The blue circles in Fig. S2(d) and (e) denote the results of finite element analysis (FEA) for α/β' values of 2×10^4 and 2×10^5, respectively. The R_{p} values approximated by Eq. (S1) are also shown as black solid lines. The green and red dashed lines in Fig. S2 (d) denote the first and second terms of Eq. (S1), respectively, thus, the black solid line represents their sum. The FEA results and our approximation show good correspondence, though the resistance is slightly underestimated at high contact lengths. Here, we estimate the values of σ_{inter} and σ_{CNT} from the FEA result shown in Fig. S2(d) by using the approximation in Eq. (S1). The estimated σ_{inter} and σ_{CNT} are 1.02×10^2 for contact length below 50 nm and 1.23×10^5 S/m for contact length above 200 nm, respectively. The original values of σ_{inter} and σ_{CNT} used in the FEA were 1.00×10^2 and 1.00×10^5 S/m, respectively. The estimated values are slight overestimates, which we assume to be due to uncertainty within this analysis.

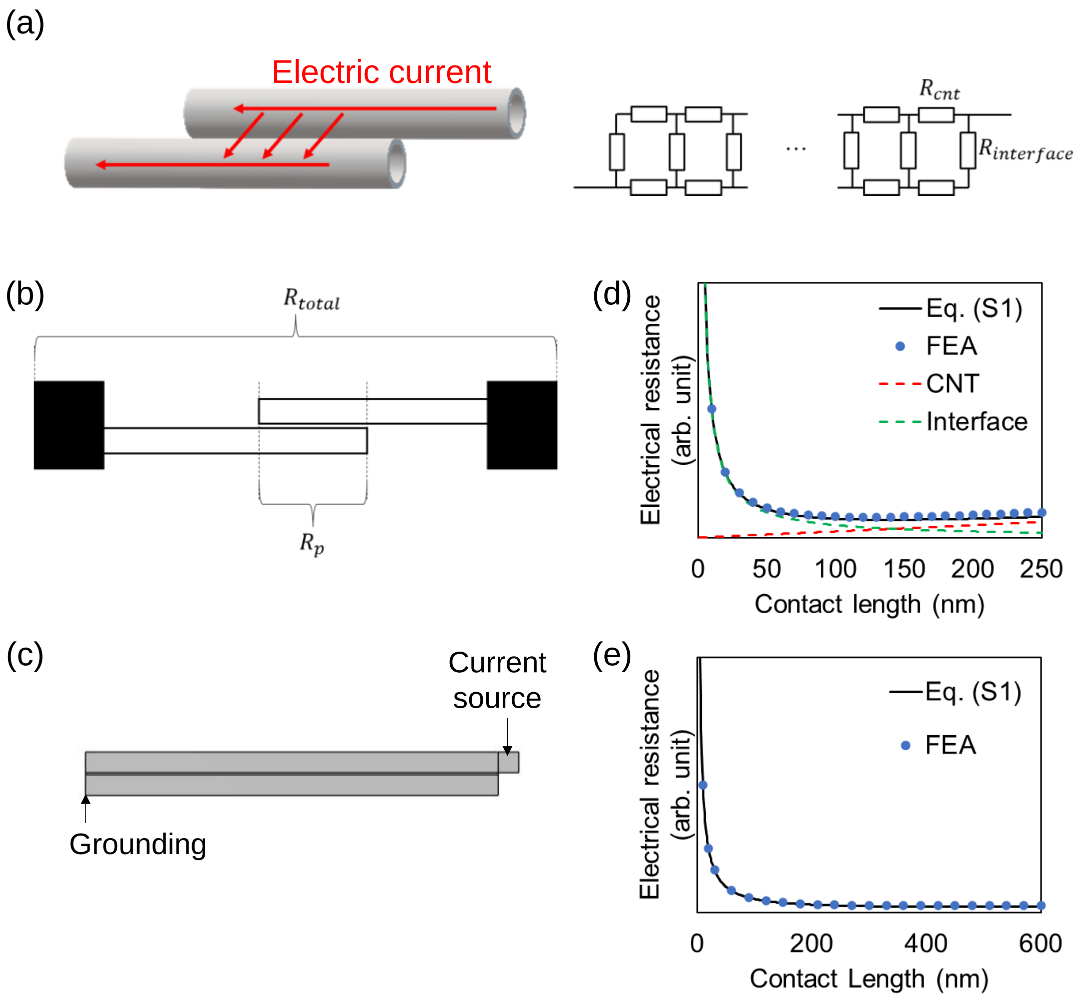

Fig. S2. (a) Schematic of two multiwalled carbon nanotubes connected in a parallel contact (left) and an equivalent circuit of the contact (right). (b) Schematic of two multiwalled carbon nanotubes with a single parallel contact. R_{total} and R_{p} represent the electrical resistance over the entire section in the measurement and over the contact section, respectively. (c) Model for finite element calculation of the electrical resistance of the contact section shown in (b). (d), (e) Comparisons between the finite element calculation results and the approximation given in Eq. (S1) for α/β' values of (d) 2×10^4, (e) 2×10^5.

TEM images of telescoped MWCNT

Fig. S3 presents TEM images and a schematic of a telescoped MWCNT. Outer layers of the MWCNT were partially sublimated by self-Joule heating. Then, the core tube was extracted from the housing tube by using piezo manipulator [Fig. S3(a)–(c)]. The edge of the housing tube is indicated by red arrows in Fig. S3. Fig. S3(e) presents the TEM image of housing tube after extracting the core tube.

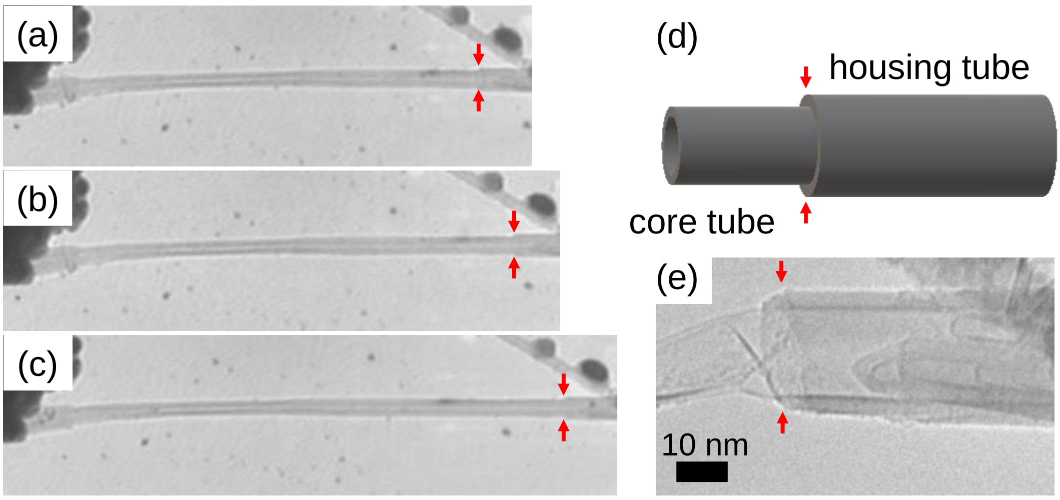

Fig. S3. TEM images and schematic of a telescoped MWCNT. (a, b, c) TEM images of the core tube extraction from the housing tube. (d) Schematic of the telescoped MWCNT. (e) TEM image of the housing tube after core tube extraction. Red arrows indicate the edge of the housing tube.

Electrical resistance before and after cutting MWCNT

We conducted the electrical resistance measurement before and after cutting the MWCNT. Figure S4(a) and (b) present the transmission electron microscopy (TEM) images of the MWCNT before cutting [i.e., single MWCNT] and after cutting [i.e., two MWCNTs connected by an interface], respectively. Since the electrodes were attached to the outermost layer of MWCNT, the electric current preferentially flows via outer layers, and the outer layers preferentially sublimated by Joule heat. Then, it resulted in the sharpened tips of broken MWCNT as shown in Fig. S4(b). The tips of broken MWCNTs were connected by a single interface whose length is ~100 nm. Fig. S4(c) presents the current–voltage relationships for the specimens shown in Fig. S4(a) and (b). The electrical resistance increased from 15 kΩ to 18 kΩ by the presence of the interface, indicating that the interfacial resistance was not dominant.

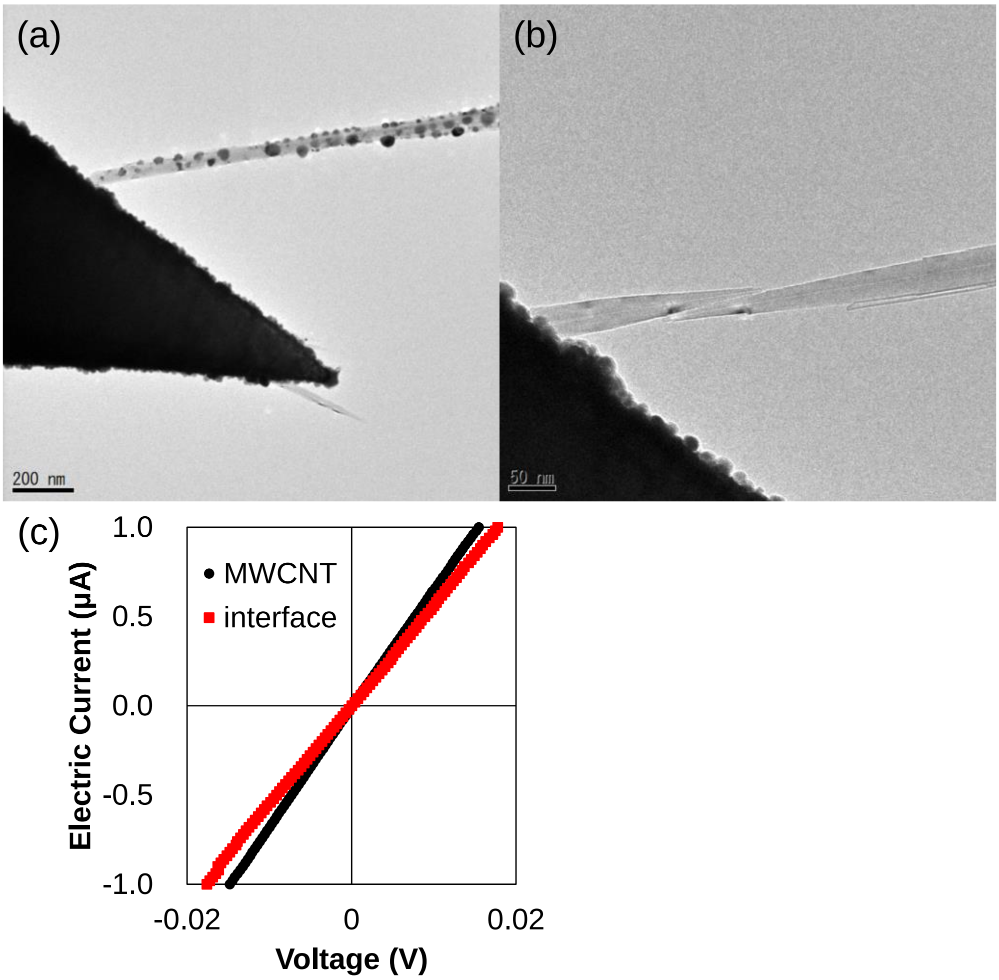

Fig. S4. Electrical resistance before and after cutting the multiwalled carbon nanotube (MWCNT). (a, b) Transmission electron microscopy images of (a) single MWCNT and (b) two MWCNTs connected by an interface. (c) Current–voltage relationships for the MWCNT without and with an interface, corresponding to the images shown in (a) and (b), respectively.