The desire to use molecules as the ultimate building blocks of electronic circuits motivates the quest to understand transport in molecular wires. However, most molecules with delocalized electronic orbitals undergo a structural Peierls transition to an insulating state at low temperature. The resistance per molecule is less than 100 kilohm and varies weakly with temperature. Below the superconducting transition temperature (1 kelvin) of the contacts, proximity-induced superconductivity is observed. These results imply that DNA molecules can be conducting down to millikelvin temperature and that phase coherence is maintained over several hundred nanometers.

**Proximity-Induced Superconductivity in DNA**


Conductivity measurements on double-stranded DNA molecules deposited by a combing process across a submicron slit between rhenium/carbon metallic contacts reveal conduction to be ohmic between room temperature and 1 kelvin. The resistance per molecule is less than 100 kilohm and varies weakly with temperature. Below the superconducting transition temperature (1 kelvin) of the contacts, proximity-induced superconductivity is observed. These results imply that DNA molecules can be conducting down to millikelvin temperature and that phase coherence is maintained over several hundred nanometers.
ture (RT) resistance was 17, 11, and 40 kilohm, respectively. Measurements were made in a dilution refrigerator, at temperatures ranging from RT to 0.05 K, through filtered lines. Magnetic fields up to 5 T could be applied perpendicularly to the contacts and the molecules. The temperature dependence of the resistance of the three samples between RT and 0.05 K (Fig. 2) shows that down to 1 K, all three samples presented a moderate monotonous increase of resistance with decreasing temperature, which can be approximately fitted by a small negative exponent power law. The absolute value of this exponent increases with the resistance of the sample and can be determined within a 10% accuracy to be 0.03, 0.05, and 0.08, respectively, for DNA2, DNA1, and DNA3 (Fig. 2A). Over this temperature range, transport is ohmic.

The resistances $R_m$ of DNA1 and DNA2 are on the order of the resistance quantum $h/2e^2 \sim 13$ kilohm, the maximum resistance of a phase-coherent conducting wire (above this value, strong localization is expected to take place) (15), indicating that the number of DNA molecules $N_c$ participating in transport, with a typical resistance of $N_cR_m$, is on the order of one or two.

The temperature dependence changed dramatically below the superconducting transition of the Re/C contacts, around 1 K. The resistances of DNA1 and DNA2 decreased, by 75% at 0.05 K for DNA1 and by 15% for DNA2. The resistance of DNA2 increased slightly below 0.1 K (Fig. 2B). In contrast, the resistance of DNA3 (the most resistive sample) increased monotonically, with no change at the contact transition temperature. The transition observed on DNA1 and DNA2 was shifted to lower temperature in a magnetic field and disappeared at fields higher than 1 T, where the resistance increased with decreasing temperature, and all curves overlapped (Fig. 2B). We attribute these transitions to a lower resistance state to a proximity effect in the SNS (superconducting-normal-superconducting) systems constituted by DNA1 and DNA2 between the two superconducting electrodes. In contrast to DNA1 and DNA2, which had a positive magnetoresistance because of the PE (a magnetic field weakens the induced superconducting correlations and increases the resistance of the SNS system), DNA3 had a negative magnetoresistance up to 1 T (Fig. 2C). Further investigation with different field orientations with respect to the molecules may help discriminate between an orbital or spin origin of this singular magnetoresistance.

At low temperature, the transport on all samples was nonlinear (Fig. 3). In zero magnetic field, the differential resistance of DNA1 dipped at low voltage, with two sharp peaks at 300 $\mu$V (close to the gap of Re estimated around 200 $\mu$V at zero magnetic field), followed by bumps at higher voltage. The normal state resistance was recovered above 1 mV. This low-bias differential resistance dip became weaker and narrower at higher magnetic field and disappeared around 1 T. Above 1 T, the differential resistance peaked at zero current and was similar to that of DNA3. The behavior of DNA2 was intermediate, with a zero bias peak at all magnetic fields, within a larger dip that disappeared around 1 T. The differential resistance curve of DNA1 is reminiscent of what is observed in carbon nanotubes mounted on superconducting contacts, where the proximity-induced superconductivity is incomplete (16). The broad dip in DNA2 can also be interpreted as residual induced superconductivity. The most reasonable explanation for the different behaviors of the three samples is different transparencies of the contacts between the molecule and the superconducting film. It is also possible that the different base sequences in the different samples play a role.

After the samples were warmed to RT, microdrops of a saline buffer (1 mM CaCl$_2$)
and 10 mM tris) were continuously deposited on DNA1. The sample resistance remained identical to its initial value for more than half an hour of continuous buffer deposition. But when a deoxyribonuclease (DNase) enzyme was added to this buffer, the resistance rapidly increased to about 1 gigaohm after 30 s, providing additional proof that the transport was taking place through DNA molecules. Similar verifications were performed on the other samples. This test also shows that the conduction of DNA is the same in a dry and a biological environment. A systematic investigation as a function of the buffer’s ionic concentration still remains to be conducted.

These experiments show that ohmic electric conduction can occur through DNA molecules over distances on the order of a few hundred nanometers, even at very low temperature. This result corroborates previous observations by Fink et al. (5), but we found resistance values one order of magnitude lower, for samples with comparable numbers of molecules. This is probably due to better contacts in our case. The power law temperature dependence is in agreement with the Luttinger liquid behavior expected in one-dimensional electronic systems (17). The measured value of the exponent is known to depend on the transparency of the contacts when their transmission is on the order or smaller than the resistance quantum, with no temperature dependence in the case of perfectly transmitting contacts (18). Our results show an increase of the power law exponent with the sample resistance value, in qualitative agreement with this prediction. Finally, observation of proximity-induced superconductivity indicates that electronic quantum phase coherence is achieved (8–10) in DNA molecules at low temperature on a length on the order of few hundred nanometers. The physical mechanism involved in the conduction process remains unclear. The electronic structure of the molecules is not a priori favorable to the existence of chains of delocalized π orbitals along the molecule that would form a half-filled conduction band, as is the case in carbon nanotubes. On the other hand, several authors have suggested (19, 20) that the structure of DNA with a π electron system of four bases stacked on each other can provide a mechanism of electron transfer along the DNA, involving hole hopping from one guanine base to the next. This conduction process is strongly dependent on the base sequence and is thermally activated; it should therefore lead to an exponential increase of resistance at low temperature, which is in strong disagreement with our experimental findings. It could, however, explain the temperature dependence observed in ac absorption experiments on unconnected DNA molecules (21). We should emphasize that the role of the contacts could be crucial in acting as strong electron or hole dopants. They could provide a sufficient number of carriers delocalized along the molecular wire because of the quasi-absence of electrostatic screening in one dimension (22). A systematic investigation of the transport properties of DNA molecules connected to metal contacts with different electronic work functions should be a way to shed light on this issue. The influence of the substrate may also be important. The surface of mica is known to be electrostatically charged because of the existence of uncompensated charges of OH− ions, which also could affect transport through deposited DNA molecules. Finally, it has been shown that DNA molecules present self-assembling properties: They can be cut at precise points with specific enzymes and subsequently hybridized to complementary template (23). In this context, the present demonstration of conducting behavior of DNA molecules, when properly connected to electrodes, could yield interesting applications. For example, the presence of a particular sequence in a connected DNA molecule could be detected by a quick and simple conduction test using restriction enzymes cutting the DNA molecule at this particular sequence. One can also detect the presence of a very small number of molecules having a specific length in a solution (24). The accuracy of these tests requires strict combed molecules, which can be obtained using the method described in (25), where molecules are attached by one end on the substrate before combing. Also, previous experiments on a plastic DNA film (4) have indicated that the conduction of single-strand DNA could be considerably less than the conduction of double-strand DNA. If this property is confirmed at the single molecular level, it could be used as an efficient and cheap hybridization test on DNA chips (26).

References and Notes
14. Two levelled plastic tubes connected to the outlets of a peristatic pump (in order to control the flow rate) were fixed on the sample holder touching the mica surface. The DNA solution [DNA (0.1 ng/μl), 20 mM NH4CH3COOH, and 7 to 9 mM MgCl2] flowed from one tube into the other with a velocity of roughly 1 to 2 cm/s.
24. This can be done using a chip containing various pairs of electrodes characterized by a given spacing between them and subsequently combing DNA molecules across these electrodes. The presence of DNA molecules of length L will be characterized by electric conduction between electrodes separated by a distance smaller than L and the absence of conduction between electrodes separated by a larger distance.
26. It is, however, quite probable that the technique we have used to comb DNA molecules across the metallic contacts will not work for single-strand DNA because of a much lower rigidity of the molecule. This difference could also be used as an alternative hybridization test.
27. We acknowledge fruitful discussions with V. Croquette, B. Sivjak, and F. Livolant, who kindly provided DNase.

Fig. 3. Voltage dependence of the differential resistance measured at 50 mK in magnetic fields of 0, 0.2, 0.4, 0.6, 0.8, and 1 T for all samples. These measurements were done with an ac excitation current of 1 nA at 30 Hz.