Bisecting Microfluidic Channels with Metallic Nanowires Fabricated by Nanoskiving

Gerard A. Kalkman, Yanxi Zhang, Enrico Monachino, Klaus Mathwig, Machteld E. Kamminga, Pieter E. Oomen, Sarah A. Stratmann, Zhiyuan Zhao, Antoine M. van Oijen, Elisabeth Verpoorte, and Ryan C. Chiechi

ABSTRACT: This paper describes the fabrication of millimeter-long gold nanowires that bisect the center of microfluidic channels. We fabricated the nanowires by nanoskiving and then suspended them over a trench in a glass structure. The channel was sealed by bonding it to a complementary poly(dimethylsiloxane) structure. The resulting structures place the nanowires in the region of highest flow, as opposed to the walls, where it approaches zero, and expose their entire surface area to fluid. We demonstrate active functionality, by constructing a hot-wire anemometer to measure flow through determining the change in resistance of the nanowire as a function of heat dissipation at low voltage (<5 V). Further, passive functionality is demonstrated by visualizing individual, fluorescently labeled DNA molecules attached to the wires. We measure rates of flow and show that, compared to surface-bound DNA strands, elongation saturates at lower rates of flow and background fluorescence from nonspecific binding is reduced.

KEYWORDS: nanoskiving, 3D nanofabrication, nanowires, microfluidics, single-molecule fluorescence imaging

Nanotechnology necessarily involves creating (or co- opting) and manipulating widgets or patterns with dimensions on the nanoscale. Creating nanoscale widgets can be done by constructing them from smaller components, e.g., synthesizing molecules or growing colloids, or by fabricating them from bulk materials, e.g., lithography. The latter approach falls generally within the purview of nanofabrication, which enables three important advantages of nanotechnology: the ability to interact with microscale objects (e.g., cells), the miniaturization of macroscale functionality (e.g., microelectronics), and access to very high surface area to volume ratios (e.g., nanowires). Most nanofabrication is confined to a surface, which acts both as a substrate for lithographic processes and as an interface between the macroscopic world and the nanoscopic world.

Nanoskiving, a form of edge lithography in which planar structures are sectioned into thin slabs, circumvents some of these limitations by forming nanostructures inside a host matrix (usually a cross-linked polymer) that can be manipulated one or several at a time. Compatibility of materials with nanoskiving is defined by mechanical properties, and soft, organic materials that cannot tolerate typical photolithographic processing may be used, such as, molecular and graphene templates to define dimensions with subnanometer precision. While nanoskiving can be used to fabricate arbitrary shapes, it can also be used to form nanowires directly from thin films embedded in polymer matrices and planar crystals. The simplest case, sectioning thin metal films, produces metallic nanowires with control over all three dimensions, that can be millimeters long. These wires can be transported, positioned, and aligned directly under a light microscope via the (sacrificial) host matrix. This combination of properties is unique to nanoskiving, directly coupling macro- and nano-regimes and affording access to the entire surface area of the resulting nanowires.

Although nanowires fabricated by nanoskiving are produced serially, this does not have to be a limitation for applications that exploit the functionality of single nanowires, such as microfluidics. Placing nanowires on the floor of a microchannel, however, confines them to a surface and does not take advantage of their discrete nature; there is little functional

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difference between a thin, photolithographically patterned strip of metal or a nanowire lying flat on a surface. In microfluidic devices viscous forces tend to dominate, leading to laminar flow. The flow profile in this case is zero at the solid/liquid interface and at a maximum in the center of the channel. In sufficiently small channels with large surface-to-volume ratios, this profile is confined such that flow is near zero over a large portion of the channel. Therefore, experiments or measurements that utilize flow, but involve structures anchored to a surface in the channel for flow interaction in regions that are near or at zero flow, will yield results that are not fully representative of the flow profile. A common example of this problem arises in the in situ measurement of rates of flow. Planar lithography confines metallic features to two dimensions and anchors them to a surface, requiring two sensing elements and a heating element to measure flow resistively. Microelectromechanical systems (MEMS) can measure flow mechanically, e.g., using external optics, but at the expense of sensitivity and the simplicity of resistive measurements. Another example of an experiment requiring flow in a passive microfluidic system is the study of flow elongation in which long macromolecules (e.g., DNA molecules) are confined to a microfluidic channel and pulled taut by flow for visualization by single-molecule fluorescence. If macromolecules are attached to the surface of the bottom of a channel, they are placed in a region of near-zero flow and require high flow rates to achieve elongation. Moreover, nonspecific binding of, in particular, biological molecules to surfaces can significantly lower the recorded signal-to-background ratio of the bound macromolecules of interest. Both of these examples—one active and one passive—would benefit from the (nanoscale) objects of interest being elevated from the surface and held in the center of the channel where the flow is the highest. However, to do so requires the ability to place discrete, three-dimensional nano-objects at arbitrary positions inside a microchannel, exposing the entire surface area to the fluid environment.

We bisected microfluidic channels with millimeter-long gold nanowires fabricated by nanoskiving. A schematic of the device architecture is shown in Figure 1. We used glass and poly(dimethylsiloxane) (PDMS) for the rigidity and ease of fabrication, respectively. Holes can be made through the top or bottom layers to access the ends of the nanowires. Because the nanowires extend sufficiently far from the channel, these holes can be drilled or punched by hand and filled with conductive paste to connect the wires to macroscopic leads. The fabrication process is extraordinarily simple due to the discrete nature of nanowires formed by nanoskiving; they are not formed in templates, grown from surfaces, or captured from a liquid suspension. They can be placed one-at-a-time or in arrays as part of a convergent fabrication; that is, the channels are fabricated independently and therefore can be combined with wires of arbitrary compositions and dimensions without requiring alteration. This simple, convergent fabrication also enables control over the rotation (about the axis normal to the bottom of the channel), height (relative to the bottom of the channel), spacing (of multiple wires), and position (with respect to the inlet and outlet). To demonstrate the utility of integrating discrete nanowires into microfluidic channels, we designed experiments using two device architectures, one active and one passive. The active device demonstrates a two-terminal, hot-wire anemometer that samples flow in the center of the channel in which the entire surface area of the wire is in contact with the fluid being measured. The passive device uses the nanowires as substrates for the attachment of long DNA molecules for the study of elongation.

**RESULTS AND DISCUSSION**

**Fabrication.** Au nanowires were fabricated by using nanoskiving. A 200 or 400 nm thick gold film was embedded in a block of epoxy from which 200 nm thick slabs were cut and floated onto a water bath using an ultramicrotome. These slabs containing nanowires were transferred from the water and positioned over 30 μm deep trenches etched in glass substrates. The epoxy matrix was then removed by etching with O₂ plasma to yield free-standing nanowire(s) spanning the trench in the etched glass. The yield of the wires (when using a well-maintained knife) was 100%. The devices were completed by sealing a complementary PDMS channel, also 30 μm deep, to the glass to form a closed channel. By stacking Au films, several wires can be installed with arbitrary separation and composition in one channel in a single fabrication step. A detailed description of the entire fabrication procedure is provided in the Supporting Information.

The microfluidic devices were characterized at all stages of fabrication using a combination of optical microscopy, scanning electron microscopy (SEM), and electrical measurement. An image of the finished device is shown in the Supporting Information. To verify that the gold nanowires are suspended...
freely over the channel, SEM images of the etched glass/nanowire assembly were acquired at a 45° angle (after etching the epoxy). An example of a 200 × 200 nm square nanowire spanning the entire width of a 70 μm wide trench etched in glass is shown in Figure 2. The wire is completely suspended and does not contact the surface of the glass inside the trench. The angle of the wire with respect to the channel is controlled by rotating the epoxy section containing the wire while the carrier water from the ultramicrotome boat dries. We found it possible, but difficult, to achieve perfectly parallel wires; however, the angle had a negligible impact on the subsequent experiments.

**Hot-Wire Anemometry.** Sensors that utilize the principle of heat dissipation can be classified as hot-wire, hot-film, or calorimetric. In microfluidics, the rate of flow can be determined by measuring changes in conductivity affected by changes in temperature as the carrier liquid flows past a metallic conductor. To avoid the risk of physically changing flows in microchannels by the insertion of relatively bulky structures to measure flow rates, the heating and sensing elements (e.g., “nanowires” in the form of thin strips of metal) are placed at the bottom of the channel where the flow is near zero. This precludes simple hot-wire anemometry and necessitates more complex, multiwire architectures that include separate heating and sensing elements. Nanowires are small enough that they will not disrupt flow and so can be placed directly in the center of the channel without affecting it. To demonstrate the utility of bisecting microfluidic channels with nanowires fabricated by nanoskiving, we constructed a simple hot-wire anemometer using only a single wire as both the heating and sensing element.

The dimensions of the microfluidic channel test-bed are shown in Figure 1. Ethanol was injected continually into the channel using a syringe pump, and the current response monitored as a function of flow rate at 0.5, 1.0, 1.5, and 2.0 V (the raw data and a calibration curve are shown in the Supporting Information). Joule heating causes the resistance of the nanowire to increase, which is counteracted by the transport of heat away from the wire by the carrier liquid. Higher rates of flow cool the wire more, and higher voltages give higher sensitivity. Thus, the current at a fixed voltage rises to a plateau as the rate of flow is increased. In order to relate the conductance of the nanowire to flow rates, we replotted these plateaus as relative conductance $G/G_0$ versus pump flow rate, where $G$ is the conductance at a plateau and $G_0$ is the conductance at zero flow. These data are shown in the left plot of Figure 3 over a range of 0 to 30 μL/min with increases of 10 μL/min in each step. Data acquired for a nanoskived nanowire placed at the bottom of a channel are shown in red for comparison. These plots clearly show that $G/G_0$ varies with the rate of flow when the nanowire is freely suspended in the channel, but not when it is placed on the floor. Increasing the voltage increases the sensitivity (and the magnitude of $G/G_0$) for the suspended nanowire, but not sufficiently to detect the rate of flow when the nanowire is placed on the bottom of the channel. Ramping the flow rate up and then back down has no effect on the initial value of $G/G_0$, indicating that there is no hysteresis associated with this approach. Although we only report data up to 30 μL/min, the wires are mechanically stable to sufficiently high rates of flow to rupture the devices; we were unable to break the wires from sheer alone.

**Simulations.** To gain further insight into the effect of the position of the wire on the sensitivity of the hot-wire anemometry, we modeled the change in the conductivity of the nanowire numerically using a three-dimensional finite-element simulation (see Supporting Information for details). The right plot of Figure 3 shows simulated data based on the geometry and materials used in the actual device. The simulation agrees qualitatively with the experimental data and is in very close numerical agreement when the wire is bisecting the channel, but overestimates the response when the wire is placed on the floor of the channel. The probable origin of this discrepancy and the dependence of the sensitivity on the position of the nanowire can be seen in the heat map plots shown in Figure 4. The temperature distribution in the center of the microchannel is comparable for both nanowire positions.
and, as predicted, the bisecting wire is in the region of highest flow, while the flow velocity approaches zero at the floor. However, the dominant effect is the proximity of the wire to the glass substrate, which acts as a heat sink, effectively masking the relatively small changes in heat dissipation from the carrier liquid. That is, when the nanowire is suspended freely in the microchannel, the entire surface is in contact with the carrier fluid, and therefore heat dissipation is dominated by the fluid. When the wire is placed on the floor, however, one surface is in contact with the relatively enormous mass of the glass substrate, which dominates heat dissipation; that is, the wire just equilibrates with the glass.

The simulation results confirm that the operation of the hot-wire anemometer is contingent upon the entire surface area of the portion of the wire that spans the channel contacting the carrier fluid. Thus, this method of flow-sensing is nanoscopic in origin and relies on the ability of nanoskiving to produce discrete, three-dimensional nanowires that can be positioned arbitrarily. It is also simple, requiring only the ability to apply voltage and measure current. For potential applications beyond this proof-of-concept, the choice of nanowire dimensions and composition is limited only by the loose constraints of nanoskiving.

**Suspended DNA Curtains.** The observation of protein–DNA interactions at the single-molecule level represents a powerful approach to understand the molecular mechanisms that are responsible for the copying, reading, and repairing of the genetic information stored in DNA. A frequently used method relies on the fluorescence imaging of long, stretched DNA molecules and the proteins interacting with it. A common requirement for such techniques is the coupling of one end of a long linear DNA molecule to a planar surface and its stretching by a laminar flow. However, a major drawback of this approach is that the DNA molecule and proteins bound to it are susceptible to nonspecific interactions with the surface. Further, stretching surface-tethered DNA molecules by flow is challenging because of the low rate of flow close to the surface in a laminar, Poiseuillian flow. By binding DNA molecules to a gold nanowire bisecting a flow cell (microfluidic channel), we anchor DNA molecules far away from the four walls of the channel, thereby preventing any interaction of the DNA with the surface. Furthermore, being attached to an elevated nanowire, the DNA molecules experience a more uniform flow and higher rate of flow than if they were tethered to a surface, allowing a lower overall rate of flow.

The attachment of many linear DNA molecules to a suspended nanowire results in a pattern that is defined as a “DNA curtain.” A curtain of DNA molecules grants the possibility of recording several single-molecule events at the same time and allows the study of DNA–protein interactions at high local DNA concentration. These curtains are usually formed by planar lithography, using e-beam writing and etching to define barriers that interrupt a passivating lipid layer. Defining this passivating layer is a critical step in the formation of the curtains and for imaging the DNA. Bisecting microfluidic channels simplifies the formation of curtains by eliminating the planar lithography steps and obviating the need for passivation of a surface. In principle, these advantages come without any significant loss in the quality of the recorded images as compared to fluorescence imaging approaches visualizing proteins interacting with long DNA molecules.

Using a similar channel geometry as shown in Figure 1, we coupled DNA molecules to the suspended nanowires using standard Au–S chemistry to attach biotin/streptavidin followed by the introduction of biotinylated DNA. By specifically coupling one end of linear lambda-phage DNA (48.5 kilobases of double-stranded DNA; contour length 16.3 μm) to the nanowire, we obtained a curtain of DNA molecules that can be stretched by flow. Stable attachment at only the biotinylated end of the DNA was confirmed by reversing the flow direction. The DNA density on the nanowire was controlled by varying the DNA concentration and the time of incubation. At sufficiently low densities, single molecules could easily be resolved. Figure 5 shows a DNA curtain attached to a nanowire (in the presence of intercalating dye to stain the double-stranded DNA) fluoroescently) alongside an image of surface-bound DNA molecules. Other than the obvious difference between DNA molecules arranged along a nanowire and molecules randomly bound to a surface, the experiment using the nanowire results in fewer image artifacts due to nonspecific binding (visible as diffuse shapes between isolated DNA molecules in the left image). Intensity profiles along the lengths of DNA molecules (Figure 5 top and bottom) show that the signal intensity is indeed slightly higher and more uniform in the curtain than in the randomly bound surface case. We ascribe this difference to the complete lack of background signal from the separation of the curtain from the floor of the channel; that is, nonspecific binding still occurs, but it is far removed from the focal plane.

The ability to image individual, nanowire-coupled and flow-stretched DNA molecules at high signal-to-background ratios allowed the determination of the length of the DNA molecule as a function of rate of flow, ranging between 1 and 40 μL/min (measured at the pump). These flow–extension data are shown in Figure 6. At low rates of flow, large DNA fluctuations orthogonal to the flow direction were visible and the total DNA extension was measured to be significantly less than the contour length. This behavior represents the entropic collapse of the long DNA molecule at low stretching forces. At a high rate of flow, such fluctuations were no longer visible and the hydrodynamic force increased the mean extension of the DNA molecules. The relation between a force applied to the DNA and its extension has been extensively studied and well described by the worm-like chain (WLC) model. In our setup, the tension along the DNA molecules decreases as one moves from the tethered end to the free end, instead of being...
measured, and their average length was normalized by their average length at 40 μL/min (Figure 6). At relatively low rates of flow, 5 μL/min, the DNA reaches 75% of its contour length. By contrast, DNA bound to the floor of the same microchannel did not reach 75% extension until 15 μL/min. The origin of this difference is the higher rate of flow experienced by the nanowire-bound DNA, demonstrating that the presence of the nanowire does not interfere significantly with laminar flow in the center of the channel. Although we do not have experimental evidence that the wires have no effect on laminar flow at all, this observation is important, as the apparent noninterference with the laminar flow is a crucial prerequisite for the further application of these nanowires to flow-based measurements.

**CONCLUSIONS**

Applications of microfluidic devices that take advantage of flow, but that are constrained to the solid–liquid interface at the walls of the channel, require high rates of flow and must compete with nonspecific binding. Measurements of flow upstream or downstream of an experiment are often limited to sampling the rate of flow at the walls, where it is lowest. Bisecting a microfluidic channel with a gold nanowire allows experiments to be performed in the center of the channel, where the rate of flow is the highest. Measurements of flow can then be conducted at the region of the highest rate of flow and directly at a point of interest. However, forming the discrete, millimeter-long gold nanowires necessary to bisect microfluidic channels is prohibitively complex using standard lithographic techniques. Nanoskiving enables the fabrication of these ultralong nanowires and facilitates the implementation of the wires, which are simply scooped off of the surface of a wafer bath directly onto a channel as they are formed. While it is possible to place very thin (micrometer-sized) wires in a microfluidic channel, true nanoscale wires benefit from a very large surface-to-volume ratio, low drag, and minimized effects on laminar flow.

Methods of flow sensing based on heat dissipation rely on a heating element and a downstream sensor to achieve a temperature gradient sufficient to measure a change in conductivity. However, a single nanowire is sensitive enough to serve both as the heating and sensing element if it is suspended in a microfluidic channel. Finite-element analysis reveals that this sensitivity arises from having the entire surface area of the wire in contact with the carrier liquid, eliminating the mass of the substrate as a heat sink. Binding DNA uniformly applied to the end as assumed in the WLC model. However, even in this case the length will asymptotically approach the contour length (0.34 nm per base pair). The lengths of six DNA molecules at various rates of flow were

![Figure 6](https://example.com/figure6.png)

*Figure 6. Left: Sequential images of the elongation of lambda-phage DNA bound to a Au nanowire bisecting the microfluidic channel at the midpoint. Right: Extension–force curve of lambda-phage DNA showing the normalized length averaged from six DNA molecules bound to nanowires (green squares) and from 12 DNA molecules bound to the surface of the same device (red triangles) versus rate of flow. It shows the influence of the different flow velocities at the nanowire and the surface. The dashed line is an exponential fit to guide the eye.*
molecules to nanowires similarly exposes the entire surface of the nanowire—DNA assembly to the carrier fluid, eliminating background signal from nonspecific binding in fluorescence experiments and forming a curtain of DNA along the length of the nanowire. Flow-elongation measurements reveal that the DNA reaches maximum extension at lower rates of flow (measured at the pump) because the rate of flow within the channel is highest away from the walls of the channel. This fabrication technique provides the ability to place a nanoscale object directly in the center of a microfluidic channel, gaining access to the peak rate of flow. We demonstrate the technique with gold nanowires, but nanoskiving is compatible with virtually any nonbrittle material. Any experiment or measurement that utilizes flow across a stationary widget can therefore potentially benefit from this technique.

METHODS

Au nanowires were fabricated by nanoskiving. First, 200 or 400 nm thick gold films were deposited onto a silicon wafer (used as-received) through a Teflon mask by thermal evaporation. The gold films were then covered with a layer of Epoxi epoxy (Catalog #1232, Electron Microscope Sciences), and after curing, the epoxy was separated from the wafer mechanically. The gold films remained attached to the epoxy. The epoxy was rough cut with a jeweler's saw into small enough pieces to fit into a “coffin mold” used to form standard blocks for ultramicrotomy. The mold was filled with more epoxy and then cured at 60 °C overnight. The result was a 200 or 400 nm thick gold film embedded in a block of epoxy. The 200 nm thick slabs were sectioned and floated onto a water bath using an ultramicrotome (Leica UC-6). These slabs, containing nanowires, were transferred from the water onto the appropriate substrate (e.g., etched glass). Nanowires were liberated from the epoxy matrix by O2 plasma dry etching for 1 h at 100 mTorr, 30 W, using a Harrick plasma cleaner.

For the glass substrates, a prefabricated 4 ft square Borofloat wafer coated with chromium and photoresist (Telic, USA, MED027021P) was exposed to a UV light source through a semitransparent mask. Developer (AZ 351 B developer, AZ Electronic Materials, Germany) was used to remove the exposed photoresist. Chrome etch (chrome etch 18, OSC-OrganoSpezialChemie, Germany) was used to remove the chrome layer beneath. The exposed glass was etched using HF. After etching, the unexposed photoresist and chrome were removed using acetone and chrome etch.

Soft lithography was performed using a 40 μm high SU-8 master fabricated on a glass Borofloat wafer (10 cm diameter, 0.7 mm thick). The wafer was cleaned following standard wet cleaning protocols and dried on a hot-plate. A spin coater was used to coat the wafer with a 40 μm thick layer of SU-8 50 (Microchem). After a baking step to evaporate the solvent in the SU-8, the wafer was exposed to UV light through a semitransparent mask. After exposure a baking step was preformed to cross-link the exposed SU-8. Developer (nd-Dev 600, Micro Resist Technology, Germany) was used to remove the unexposed SU-8. PDMS monomer (Sylgard 184, Dow Corning) was mixed with PDMS curing agent in a 10:1 (w/w) ratio, and the mixture was placed under a vacuum for 30 min to remove any bubbles. The uncured PDMS was poured over the wafer and cured on a hot-plate for 3 h at 60 °C. After curing, the desired pattern was cut from the PDMS slab using a sharp razor blade. To create fluid inlets and outlets, a biopsy puncher with a diameter of 1.2 mm was used.

For flow-sensing measurements the nanowire was connected with a Keithley 2400 SourceMeter. The I–V plots of the nanowire suspended in the microfluidic channel before and after the injection of ethanol were recorded before the flow measurements. The current through the nanowire at different voltages was recorded with a step size of 0.1 V. After that, a series of voltages (0.5, 1.0, 1.5, 2 V) was applied to the nanowire, and the resulting current was measured over time at different rates of fluid flow. The fluid inlet of the nanowire device was connected to a 10 mL syringe (Terumo Syringe) with a diameter of 15.8 mm, and the fluid outlet was coupled to a waste beaker.
flowed into the chamber in 20 mM Tris (pH = 7.5), 2 mM EDTA, 50 mM NaCl, 1 mg/mL bovine serum albumin, and 0.025% Tween20. Excess DNA was removed by washing with the same buffer. SYTOX Orange (100 nM, Invitrogen) was used to stain the DNA molecules. The Sytox-stained DNA molecules were excited with a 532 nm solid-state laser (Coherent Sapphire 532-200 CW) at 25 Wcm⁻² in epifluorescence mode. The resulting fluorescent signal was collected through a 100× oil-immersion TIRF objective (Olympus, 1.49 NA) and recorded on an EM-CCD camera (Hamamatsu).

ASSOCIATED CONTENT

 Supporting Information

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Device assembly and additional data; micrographs and photographs of flow-sensing and DNA-stretching experiments (PDF)

AUTHOR INFORMATION

Corresponding Authors

*E-mail: vanoijen@uow.edu.au.
*E-mail: e.m.j-verpoorte@rug.nl.
*E-mail: r.c.chiechi@rug.nl.

Author Contributions

1G. A. Kalkman Y. Zhang, and E. Monachino contributed equally to this work.

Notes

The authors declare no competing financial interest.

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Supporting information for:

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Gerard A. Kalkman,†,‡ Yanxi Zhang,†,¶,§ Enrico Monachino,†,¶ Klaus Mathwig,‡
Machteld E. Kamminga,¶ Parisa Pourhossein,¶,§ Pieter E. Oomen,‡ Sarah A.
Stratmann,¶ Zhiyuan Zhao,¶,§ Antoine M. van Oijen,*,¶ Elisabeth Verpoorte,*,†
and Ryan C. Chiechi*,¶,§

†These authors contributed equally to this work.
‡Groningen Research Institute of Pharmancy, Antonius Deusinglaan 1, 9713 AV
Groningen The Netherlands.
¶Zernike Institute for Advanced Materials, Nijenborgh 4, 9747 AG Groningen, The
Netherlands
§Stratingh Institute for Chemistry, University of Groningen, Nijenborgh 4, 9747 AG
Groningen, The Netherlands

E-mail: vanoijen@uow.edu.au; e.m.j.verpoorte@rug.nl; r.c.chiechi@rug.nl

S1
1 General

1.1 SEM

Scanning electron microscope images of the single Au nanowires were acquired using a field emission SEM (Jeol JSM 7000F) operating at 5 kV. SEM analysis was undertaken for visual characterization of nanowires and determination of the dimensions of the wires. A nanowire (or array of nanowires) was placed on the etched glass substrate and a thin layer of gold was sputtered on the top to avoid charging artifacts. An SEM image of a 200 nm x 200 nm Au nanowire is shown in Figure S1. A top-down image of a 200 x 200 nm Au nanowire suspended over a trench etched into glass is shown in Figure S2.

1.2 Choice of fluid

All of the flow sensing data are from channels filled with ethanol. We chose ethanol for experimental convenience because the surface tension of water is sufficient to break the nanowires upon introduction to the channel. However, we were able to use pure water by
Figure S1: SEM image of a gold nanowire with the width of 200 nm

Figure S2: An SEM image of a nanoskived nanowire suspended over a trench with the width of 70 μm on glass substrate
first filling the channels with ethanol and then introducing water as long as no bubbles were introduced. The DNA stretching experiments described below were performed in PBS and Tris buffer using this method.

2 Flow Sensor

2.1 Device fabrication

Figure S3 shows a schematic overview of the steps in the device fabrication. The device consists of a glass bottom part and a PDMS top part, each containing a channel structure. Both parts are bonded together with the structures facing each other and the nanowire positioned in between. The bottom part was first etched in glass as described above (Figure S3A). A sand blaster (Sandmaster FG 2-94) was used to create holes for contacting wires. The holes were positioned approximately 2 mm from the center of the channel. Next, two contact wires were added (0.1 mm tin wires) through the holes and the glass was mounted on a microscope slide using epoxy glue for easy handling and mechanical stability (Figure S3B and C). A nanoskived epoxy section containing a 200 x 200 nm Au nanowire (or an array of wires) was transferred to the glass bottom of the device, over the center of the channel (Figure S3D and E). The top PDMS part was then fabricated as described above. A 3 mm-diameter biopsy puncher was used to create two holes in the PDMS top part, one on either side of the center of the channel, approximately 0.5 mm from the sides of the channel. These holes are later filled with silver paste to connect each end of the nanowire electrically with a contact wire. The epoxy matrix was then removed using oxygen plasma etching (Figure S3F). The glass and PDMS parts of the device were then irreversibly bonded. This was done by briefly exposing both parts to oxygen plasma and then bringing both surfaces in contact with each other. A custom-built aligner (Figure S4) was used to align both parts prior to bonding. The aligner consists of a bottom and top stage that can be moved independently. The bottom stage has a trench in which a standard microscope slide (∼2.6 cm width) can be
placed. The top stage consists of an 8 x 8 cm glass plate that can be moved vertically. The bottom stage can be rotated and moved parallel to the top stage. To align two parts, one part is placed on the bottom stage and the second part is attached to the top stage. The top stage is then lowered until both parts are in close proximity. Alignment can be accurately performed by manipulating the bottom stage. Since the top part and the top stage are both transparent, the alignment can be done while observing both parts simultaneously from the top using a microscope. When the parts are properly aligned, we lowered the top stage further until both parts were in contact with each other. In the last step the nanowire was electrically connected to the contact wires by adding a drop of silver paste into the two contact holes. The total dimensions of the top and bottom parts of the device are roughly 2 x 1 cm, which was mounted on a microscope slide with dimensions of approximately 2.5 x 2.5 cm. The length of the channel was 1.0 cm. Devices with glass and PDMS channels of respectively 60 µm and 80 µm in width were designed. The PDMS channels have a depth of 20-40 µm (defined by the spin speed during SU-8 film formation). The width of the channels in the mask used for HF etching were 20 µm wide. This should yield glass channels with a depth of 20 µm. The resulting width of a glass channel is around 70 µm measured by SEM.

Figure S6 is an optical micrograph showing two Au nanowires before the epoxy is etched, placed over a trench etched into glass. It shows how far the wires extend past the trench on both sides. The nanowires are labeled in red and are only visible as thin lines from the index mismatch between epoxy and Au (they are too small to visualize at that magnification). The colorful lines are the result of interference from wrinkles in the epoxy. The dimensions of these devices is such that several wires can bisect a single channel allowing for multiple experiments in a single channel and fabrication procedure.

2.2 Resistance versus temperature measurements

The influence of a change in temperature on the resistance of a gold nanowire was measured. A nanoskived gold nanowire (200 x 200 nm) was placed on a piece of glass and connected to
Figure S3: A schematic overview of the device fabrication. A) The bottom half of the channel is etched in glass. B) Contact holes are created using a sand blaster. C) Metal contact wires are added. D) A nanoskived section containing a gold nanowire is added. E) The epoxy from the section is removed using an oxygen plasma, leaving the nanowire behind. F) The PDMS top is bonded to the glass bottom, sealing the channel. The PDMS top contains two holes that each overlap with a contact wire and one end of the nanowire.

two metal contact wires (0.1 mm diameter, tin) using silver paste. The wires were connected to a multimeter (Fluke 10). The nanowire was placed on a hot plate with a digital temperature display. The temperature was set to different values and the resistance was recorded when the temperature stabilized. The resistance of a nanowire as a function of temperature is shown in Figure S7. The resistance of Gold Nanowires shows linear relationship with the temperature. The relation between temperature and resistivity is described by the Temperature Coefficient of Resistivity (TCR) equation (1). In this equation $\rho(T)$ is the resistivity in $\Omega$ at temperature $T$ in °C, $\rho_0$ is the resistivity in $\Omega m$ at reference temperature $T_0$ in °C and $\alpha_0$ is the TCR in °C$^{-1}$. The electrical characterization using standard I-V plots was
Figure S4: An image of the custom-built aligner used to accurately align both parts of the device. The image shows the aligner positioned on the base plate of a microscope. The gray arrows indicate the different ways in which the stages can be manipulated. The top stage contains a transparent piece of glass so that both parts of the device can be viewed simultaneously through the microscope.

Figure S5: An image of fabricated microfluidic channel device for flow sensing
Figure S6: An optical image of a nanoskived section containing two gold nanowires performed in the voltage range of 0 to +1 V. The I-V measurement displayed Ohmic linear responses and exhibited low resistance 400-500 Ω (Shown in Figure S8). This temperature is probably an over estimation of the real temperature of the nanowire since the temperature sensor in the hot place is located closer to the heat element than the nanowire. For control purpose, further, we plotted the I-V curve before and after the injection of ethanol in the channel. However, there is no significant difference, also shown in SI Figure S8.

The TCR can be explained as the change in resistivity per unit of temperature, expressed as a fraction of the resistivity at a reference temperature. The reference temperature is usually 0 °C. The TCR at 0 °C from Figure 2 is $2.60 \times 10^{-3} \, ^\circ\text{C}^{-1}$ and was calculated by dividing the slope of the trend line by the (extrapolated) resistance at 0 °C. This value is roughly in agreement with a value found for 145 nm gold nanowires ($1.34 \times 10^{-3} \, ^\circ\text{C}^{-1}$) and the value for bulk gold ($3.9 \times 10^{-3} \, ^\circ\text{C}^{-1}$).

$$R(T) = R(T_0)[1 + \alpha(T - T_0)]$$  \hspace{1cm} (1)
2.3 Resistance versus flow measurements

The raw $I/V$ data are shown in Figures S9 and S10.
3 Simulations

To further illustrate the applicability of the bisecting nanowire as a flow sensor and to test the validity of the experimental results, we numerically modeled the nanowire conductivity as a function of flow rate and applied potential.

We determined the change in nanowire resistance by sampling the temperature in the wire and then multiplying it by the experimentally determined resistance–temperature dependence (see Figure S7).

The corresponding numerical relative conductances are shown in Figure 3 (right) in the main text as a function of flow rate and potential for a bisecting nanowire as well as a wire positioned at the microchannel floor.

In Figure 4 in the Main Text, the temperature distribution is shown for a flow rate of 30 $\mu$L/min and a potential drop of 0.25 V over 75 $\mu$m for both wires.
Figure S10: The current passed the nanowire placed at the floor of microfluidic channel response to the different rates of flow over time at different voltages: 0.5V, 1V, 1.5V, 2.0V, 3.0V