Fabrication of thin-film metal nanobridges

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Thin-film fabrication techniques for forming three-dimensional “point contacts” are presented. As-fabricated nanobridges can be modified using electromigration to make the constriction region smaller or dirtier. Scientific applications to quantum transport studies, 1/f noise, and electromigration are discussed.

Three-dimensional point contacts have long been used for a variety of applications, including studies of inelastic electron scattering at low temperatures,1 superconducting Josephson devices,2 and very high frequency nonlinear detectors.3 Conventional techniques for forming point contacts are shockingly a metal-insulator-metal thin-film sandwich to break down a small region of the insulator, and bringing two bulk metal samples together at a point. The former method can yield contacts that are stable in time and under temperature cycling, but the bulk point contacts can be of much higher quality. In both cases the cleanliness of the contact region relative to that of the electrodes, the number of contact regions, and the precise geometry, including both the size and the length of the contact are all uncertain.

Here we present a method of microfabricating point “contacts” which provides good control over the quality of the constriction region, and excellent contact stability. These metal nanobridges, as small as 10–20 atoms across, are stable for weeks at 300 K and also stable under temperature cycling to 4 K. For these nanobridges, the cleanliness of the contact region is the same as that of the electrodes, due to the fabrication technique. Furthermore, devices only occur when they are intentionally patterned, so there are never multiple contacts. Finally, the nanobridges can be studied using scanning transmission electron microscopy, so that at least the approximate sample geometry can be determined. These advantages of nanobridges over conventional point contacts provide much greater confidence as to the true nature of the constriction region.

Nanobridge fabrication starts using standard techniques involving anisotropic etching of (100) silicon4 to form: 50-nm-thick, ~40-μm-wide suspended membranes of the low-pressure chemical vapor deposition Si₃N₄. Membranes are formed on a 3 mm grid in a 9×9 array, which can be separated into individual chips so that there are potentially 81 devices per wafer. Next a single 40–100 nm dot is exposed in poly(methylmethacrylate) in the center of each membrane using a JEOL JBX5D11U electron beam machine, and developed in 1:1 MIBK:isopropyl alcohol. A range of exposures, 30–210 mC/cm², using a 0.1 pA, 50 kV beam ensure that the subsequent marginal etch of the Si₃N₄ will be timed correctly for some of the dots, regardless of the exact nitride thickness.

The electron beam pattern is transferred to the Si₃N₄ using a CHF₃/O₂ reactive ion etch (RIE) at 30/0.7 sccm, 30 mT, 0.25 W/cm² for 2 min, removing the wafer and doing an oxygen clean of the RIE chamber to speed the CHF₃ etch, and then doing another RIE with the above conditions for 2 3/4 min. Although the CHF₃ etch is significantly longer than is required to etch through 50 nm of bulk Si₃N₄, it is marginal, just breaking through the membrane, so that the far side opening is much smaller than that actually patterned. (RIE rates are substantially reduced in constrained geometries.) Finally, the wafer is rotated to expose both sides while metal is evaporated, filling the hole and coating the membrane in a single evaporation. Typically, the evaporated metal is of high enough quality that at low temperatures devices are in the ballistic transport regime. So far copper, silver, aluminum, platinum, and palladium nanobridges have been made. A cross-sectional schematic of a thin-film nanobridge, to scale for a 30 Ω ballistic sample, is shown in Fig. 1(a).

Copper, silver, and aluminum nanobridges are characterized using point contact spectroscopy (PCS), in which the second derivative of the low-temperature I–V characteristic for a ballistic constriction yields the phonon density of states times the electron-phonon coupling strength. Figure 1(b) shows the phonon spectrum for a 35 Ω copper device.

![Fig. 1](image-url)

**Fig. 1.** (a) Cross-sectional schematic, to scale of a 30 Ω nanobridge. (b) Phonon spectrum for a 35 Ω copper nanobridge. Such a high quality phonon spectrum confirms that transport is ballistic at low temperatures in this device.
taken at 4.2 K. These nanobridges have very high quality PCS signals, confirming ballistic transport in these nanobridges, and suggesting that the nanobridge is spanned by a single crystallite. The as-fabricated devices never show any zero bias anomalies (structure at low voltages), and the magnitude of the signal correlates very well with the sample resistance. The size of the PCS signal is actually about three times larger than expected based on electrical conductivity data and an ideal geometry. Because the PCS signal is larger the more time an electron spends in the constriction region (provided that transport is still ballistic), a signal as large as this is most likely the result of each nanobridge having the same length as width.

We can estimate the size of the ballistic samples based on the resistance for a ballistic constriction,\[ R \sim 4\rho \lambda / (3\pi a^2) \], where \( \rho \) is the resistivity, \( \lambda \) is the electron mean free path, and \( a \) is the constriction radius. For ballistic nanobridges typical resistances of 5–200 \( \Omega \) imply dimensions of 12.5–2.5 nm. Our platinum and palladium samples have \( \lambda \sim 20 \) nm, ten times smaller than for our copper samples, and are not fully ballistic at low temperatures. However, they are fabricated the same way as nanobridges of other materials, so we can use the bulk resistivity and a combination of the ballistic resistance and the spreading resistance for a constriction, \( \rho / 2a \), to estimate their size. For these nanobridges, typical resistances range from 30 to 200 \( \Omega \), implying a size range similar to that of the ballistic devices.

Figure 2 shows a scanning transmission electron micrograph of a copper nanobridge, looking through the membrane. The nanobridge is the 7 nm spot, which is bright because it takes a while for the hole to fill with metal during the evaporation, so that the copper is thinner over the nanobridge than over the rest of the electrode. Although the resistance of this device is unknown, an ideal point contact 7 nm across has a resistance of about 25 \( \Omega \), a typical sample resistance. The faint 40 nm halo about the device is probably the edge of the hole patterned by electron beam lithography. We find the typical crystallite size is \( \sim 50 \) nm, much larger than the nanobridge itself. Thus most devices probably consist of a single crystallite threading the nanobridge region, as would be expected based on the quality of the phonon spectra.

After nanobridges have been fabricated, the size and amount of scattering in the device region can be changed by a rather unique fabrication technique, using electromigration. The result of shocking a nanobridge is a discontinuous device, but through careful application of a high sample bias the resistance can change gradually but irreversibly. Typical voltages for sample electromigration range from 30 mV for a 5 \( \Omega \) aluminum nanobridge at 300 K to 500 mV for a 100 \( \Omega \) copper nanobridge at 4 K. An increase in nanobridge resistance is to be expected as material should move out of the constriction where the current density is highest, but a decrease is somewhat surprising. Because these are ballistic devices, a decrease in resistance cannot reflect the disappearance of scatterers. Instead this behavior presumably results when relaxation of strain in the nanobridge region dominates the forces producing atomic motion, resulting in the addition of material to the constriction.

Using PCS to characterize the modified samples we find that if the resistance only goes up during electromigration, the constriction region simply gets smaller. Dimensions as much as five times smaller than the as-fabricated sample size can be attained. Such electrically modified samples are just as stable and reliable as original constrictions of a similar size. Electromigration is thus a useful technique for fabricating the smallest possible nanobridges, albeit with somewhat reduced yields.

If during electromigration the resistance ever decreases, the PCS spectrum indicates that a significant density of scatterers are introduced into the nanobridge region. In Fig. 3 we show the PCS spectrum measured following the decrease of the nanobridge’s resistance from 40 to 30 \( \Omega \) during electromigration. The noticeable decrease in spectrum quality indicates that significant disorder has been introduced into the nanobridge region. This disorder is attributed to the fact that the nanobridge cross-sectional area is increasing rapidly, a process that does not maintain crystalline order. The appearance of random variations of \( dR / df \) with \( V \) at low voltage as seen in Fig. 3 verifies that this decrease in resistance is accompanied by an increased probability of electron scattering in the nanobridge region. These resistance fluctuations, which are currently under detailed investigation, are the re-

FIG. 2. Scanning transmission electron micrograph of a copper nanobridge, looking through the silicon nitride membrane. The nanobridge is the bright spot. The 20 nm marker shows that the nanobridge is \( \sim 7 \) nm across, implying a sample resistance of \( \sim 25 \) \( \Omega \).

FIG. 3. Phonon spectrum of a 30 \( \Omega \) copper nanobridge after the resistance has dropped \( \sim 25\% \) during electromigration. The magnitude of the phonon spectrum is greatly reduced compared to that of the sample before electromigration indicating the addition of scatterers, and time-independent resistance fluctuations appear at low voltages.
suit of quantum coherence effects that require multiple scattering of the electrons traversing the sample. If such a nanobridge is further subjected to high biases, the PCS spectrum does not recover; instead it gradually deteriorates until a single zero-bias anomaly, symptomatic of weak localization and thus diffusive transport, begins to form.  

As discussed elsewhere, these samples are so small that we can actually observe the resistive effect of individual atomic scale defects moving in the nanobridge region. Because these samples are stable, we can study the dynamics of such fluctuations in detail. Thus the origin of the dominant source of $1/f$ noise in metals can be clearly observed. Similarly, the detailed study of the response of such atomic scale defects to high electrical biases has revealed the key role of inelastic electron scattering in determining the dynamics of electromigration in single-crystal samples.  

As fabricated, these nanobridges have a shunt capacitance of $C \approx 1 \mu F$. This is sufficiently small to permit the study of the intrinsic properties of essentially ideal, unshunted, aluminum superconducting-constriction-superconducting Josephson devices. But for superconductors with higher gap frequencies and for far-infrared nonlinear detectors, still smaller values of $C$ are required to avoid capacitive loading. A straightforward lithographic addition to the fabrication process could reduce $C$ to $\sim 1 \mu F$, which for a $50 \Omega$ nanobridge results in a cutoff frequency of $> 3 \text{ THz}$.  

In summary, stable metal nanobridges as small as 20 atoms across can readily be fabricated, using thin-film processing techniques that take advantage of a marginal etch to achieve dimensions much smaller than those actually patterned. By first forming the hole in a suspended insulator and then depositing the metal that defines the device, the quality of the constriction region can be controlled. After the nanobridges have been made using thin-film fabrication techniques, electromigration can be exploited to produce either smaller or dirtier samples. A number of scientific applications of such nanobridges have already been demonstrated, while extensions of the fabrication technique to produce nanobridges from alloy systems and nanobridges with known inclusions or with bimetallic interfaces can readily be envisioned.  

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