Nanofabricated tips for device-based scanning tunneling microscopy

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Abstract
We report on the fabrication and performance of a new kind of tip for scanning tunneling microscopy. By fully incorporating a metallic tip on a silicon chip using modern micromachining and nanofabrication techniques, we realize so-called smart tips and show the possibility of device-based STM tips. Contrary to conventional etched metal wire tips, these can be integrated into lithographically defined electrical circuits. We describe a new fabrication method to create a defined apex on a silicon chip and experimentally demonstrate the high performance of the smart tips, both in stability and resolution. In situ tip preparation methods are possible and we verify that they can resolve the herringbone reconstruction and Friedel oscillations on Au(111) surfaces. We further present an overview of possible applications.

Keywords: scanning tunneling microscopy, nanofabrication, device physics

Scanning tunneling microscopy (STM) is a leading tools for probing electronic and topographic information at the atomic scale [1]. Since its inception a few decades ago, data quality has dramatically improved by focusing on mechanical stability, tip preparation and lower temperatures [2–4]. New possibilities have emerged and greatly extended the range of STM, including quasiparticle interference studies with density of states mapping [5–9], spin-polarized STM [10, 11], and ultra-low temperature operation [2, 12, 13].

Here, we introduce a platform for bringing device-based functionality to STM, with the aim to utilize decades of progress in device engineering for the field of scanning probe. We replace the conventional electrochemically etched, pointy metal wire with an integrated metal tip on a silicon chip. This new platform, which we call smart tip, allows in principle to directly add additional capabilities to a STM tip, including novel spin-sensitivity, local heating, local magnetic fields, local gating, high-frequency compatible coplanar waveguides, qubits, and double-tips. However, it is a priori unclear whether a nanofabricated tip will function for STM measurements, as several challenges arise:

- the stability needs to be below the picometer scale,
- stringent requirements exist on the shape and sharpness of the freestanding tip,
- and contamination from fabrication residues need to be absent.

In this paper, we demonstrate the feasibility of nanofabricated tips and the novel smart tip platform. We first discuss our newly developed fabrication procedure and then experimentally show the functionality of these tips in standard STM measurements.

The challenge in realizing smart tips is to make devices that are fully compatible with conventional STM, yet allow for compatibility with standard nano- and microfabrication processes. Specifically we need: (i) a clear protrusion of the tip relative to the underlying chip, (ii) precise control of the tip shape, and (iii) reliable, reproducible fabrication recipes.
To meet these requirements, we developed a new fabrication method using suspended silicon nitride (SiN) tips covered with gold to create on-chip STM smart tips, described below and shown in figure 1.

Using SiN as a base for our suspended STM tips has a number of key advantages. First, it has a large selectivity to the Si etch we use to suspend the tip, allowing for clear protrusions. Making the tips solely out of metal without the Si etch we use to suspend the tip, allowing for clear protrusions. The shields are now unsuspended and will fall off leaving only the freestanding tip. (d) As a last step, the full chip is covered with a metal, e.g. gold, avoiding residues from the processes before.

Our microfabricated tips rely on and are compatible with existing STM systems and only requires the modification of the tip holder. In this study, we loaded the tips into a modified commercial Unisoku 1500 ultra-high vacuum STM with an operating temperature down to 2.3 K. We customized the BeCu holder for the smart tips, as shown in figure 2(d). The metal covered top side of the chip is placed against the body of the holder and thereby creates a large metal to metal surface to ensure good electrical contact (few Ohms) and a clamp pushes against the bottom of the chip. The chip is placed under an angle of 10° to avoid contact between the Si sidewall of the chip and the sample. As the metal tip is electrically isolated from the Si by the SiN layer and because Si is highly resistive at low temperatures, tunneling can only originate from the metal tip itself.

Next, we demonstrate the performance of the nanofabricated tips, and show that they are fully compatible with STM. For this, we use a single smart tip made from gold. After having verified that such tips routinely achieve atomic resolution without any tip preparation in ambient conditions on freshly cleaved graphite, we move to atomically flat Au(111) for more reliable tests. We use a Au(111) film on mica at 5.8 K under UHV conditions. The gold surface is prepared by cycles of Ar ion sputtering (1 kV at 5 × 10⁻⁵ mbar) and subsequent annealing at 600 °C for 1 min. We use standard tip cleaning procedures, such as voltage pulsing up to −3 V and mechanical annealing [14, 15]. The latter procedure consists of repeated and controlled indentation of the tip into the surface up to several conductance quanta and leads to a crystalline, atomically sharp tip apex [15]. All these procedures worked repeatedly with our microfabricated tips.
Figure 2. (a)–(c) Scanning electron microscope (SEM) images of a smart tip from the side (a) and the top (b), (c). The freestanding tip made of Au (colored in yellow) covered SiN has a length of 10 μm and a tip radius of approximately 20 nm. The light yellow area is suspended, while the dark yellow parts are still attached to the underlying Si. (c) The tip radius of this particular device is approximately 20 nm. (d) Photograph of a smart tip mounted in our custom BeCu holder. (e) Topograph of Au(111) surface taken with a fabricated tip at 5.8 K ($V_s = 100$ mV, $I = 300$ pA). We observe the herringbone surface reconstruction as well as single adatoms (bright dots). In the center a cluster of three adatoms is surrounded by Friedel oscillations. (f)Dispersion of the surface state measured by quasiparticle interference.

Figure 3. Examples of functionalized smart tips. (a), (b) SEM images of a prototype double-tips to measure the Green’s functions. The arrow in (a) indicates a spacing of approx. 45 nm. The two tips (colored in yellow) are electrically completely separated as shown in (b). (c) Conceptual design of a smart tip with a high-frequency compatible coplanar waveguide, which should be easily adaptable from the double-tip design in (b).
in figure 3(c). This opens a way for improved spin resonance experiments. A possible application in condensed matter physics is to measure Green’s functions, as suggested previously for experiments with two separate tips [24–30]. Such experiments necessitate very short tip-to-tip distances. Recently, much progress has been made with arrangements that rely on multiple conventional tips being brought into close proximity, where the distance between tips are limited by the radii of the tips [31–36], but no Green’s function measurement has been possible thus far. Using microfabricated tips has different strengths and weaknesses compared to these approaches. The smart tips can be implemented in compact, ultrastable STM’s and are brought into tunneling simultaneously. Microfabrication allows to lithographically define both the distance, as well as the shape of the tips. We realize a first proof-of-principle demonstration of this new technique by adapting our single-tip into a two-tip pattern, where the trenches between the tips ensure electrical isolation (see figure 3). This demonstrates that that we can fabricate tip distances smaller than 50 nm. Further work will concentrate on bringing both tips in tunneling simultaneously, e.g. by mounting them on a piezo to allow for a slight tilt. Mechanical annealing [14, 15, 37, 38] can then be used to obtain tips with equal length. The tips then need to be tested on Au(111) samples to ensure that they have the same properties.

Further, one could fabricate a gate that is only nanometers away from the probing tip, using a geometry similar to the one shown in figure 3(b) [18]. Bringing this to the atomic scale allows to image individual donors and their environment in semiconductors and quantum materials. Importantly, there is a large set of quantum materials that are challenging to gate, including high-temperature superconductors. While back- and liquid ion gating had some impact of design guidelines, construction and performance of an ultra-stable scanning tunneling microscope for spectroscopic imaging [Rev. Sci. Instrum. 89 123705] orcid.org/0000-0002-5437-1945

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