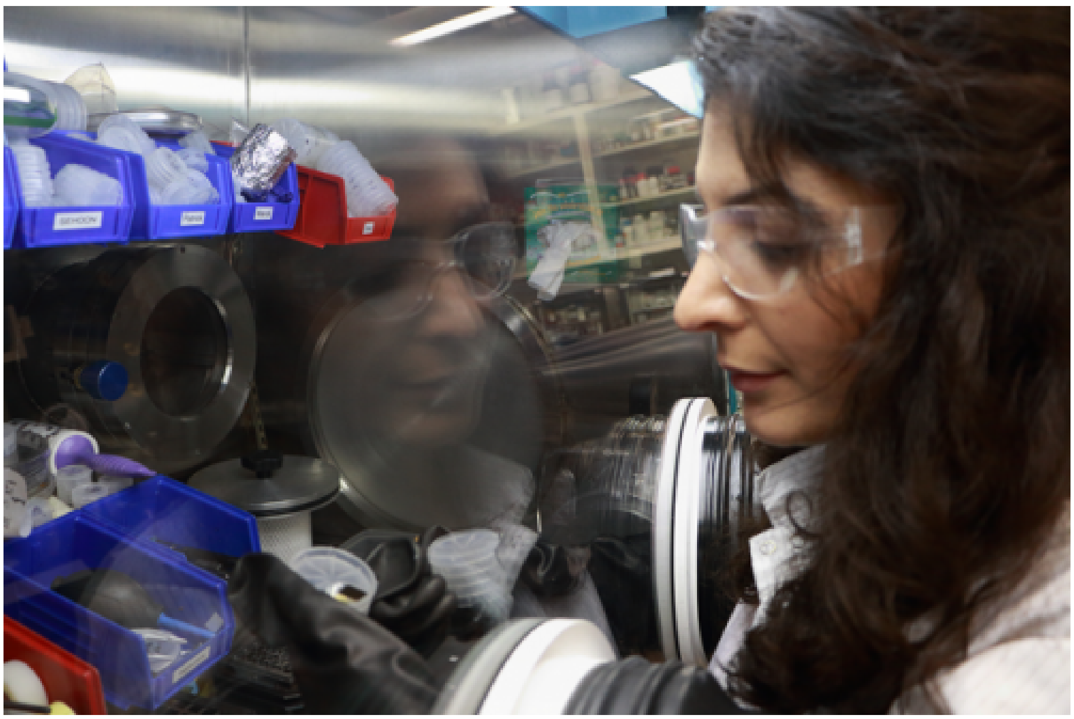
Squeezable nano electromechanical switches with quantum tunneling function

March 5 2015, by Denis Paiste



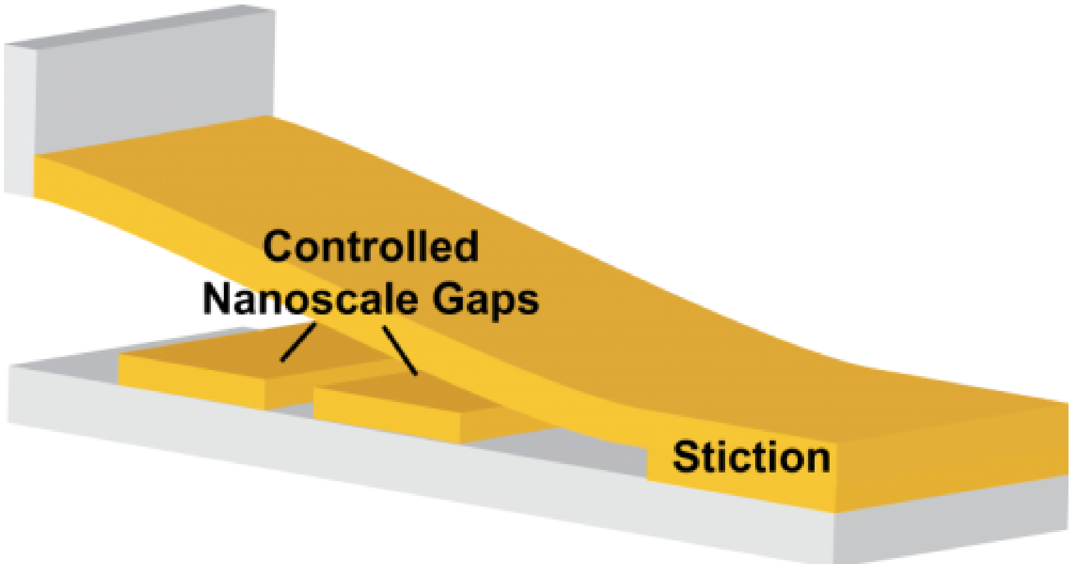
MIT electrical engineering graduate student Farnaz Niroui works in a glovebox, where she prepares a sample for deposition of gold. The glovebox is attached through a transfer line to a thermal evaporator that deposits the gold coating onto squeezable switches, or “squitches,” which Niroui designs, fabricates, and tests in the Organic and Nanostructured Electronics Lab at MIT. Credit: Denis Paiste/Materials Processing Center

A longstanding problem in designing nanoscale electromechanical switches is the tendency for metal-to-metal contacts to stick together, locking the switch in an "on" position. MIT electrical engineering graduate student Farnaz Niroui has found a way to exploit that tendency to create electrodes with nanometer-thin separations. By designing a cantilever that can collapse and permanently adhere onto a support structure during the fabrication process, Niroui's process leaves a controllable nanoscale gap between the cantilever and electrodes neighboring the point of adhesion.

Niroui, who works in Professor Vladimir Bulović's Organic and Nanostructured Electronics Laboratory (ONE Lab), presented her most recent findings Jan. 20 at the IEEE Micro Electro Mechanical Systems (MEMS) Conference in Portugal. MIT collaborators include professors Jeffrey Lang in electrical engineering and Timothy M. Swager in chemistry. Their paper is titled "Controlled Fabrication of Nanoscale Gaps Using Stiction."

Stiction, as permanent adhesion is called, is a very important challenge in electromechanical systems and often results in device failure. Niroui turned stiction to her advantage by using a support structure to make nanoscale gaps. "Initially the cantilever is fabricated with a relatively larger gap which is easier to fabricate, but then we modulate the surface adhesion forces to be able to cause a collapse between the cantilever and the support. As the cantilever collapses, this gap reduces to width much smaller than patterned," she explains.

"We can get sub-10-nanometer gaps," she says. "It's controllable because by choosing the design of the cantilever, controlling its mechanical properties and the placement of the other electrodes, we can get gaps that are different in size. This is useful not only for our application, which is in tunneling electromechanical switches, but as well for molecular electronics and contact-based electromechanical switches. It's a general approach to develop nanoscale gaps."



MIT electrical engineering graduate student Farnaz Niroui has designed a fabrication process for nanoscale electromechanical switches in which a cantilever can collapse and permanently adhere onto a support structure, leaving a controllable nanoscale gap between the cantilever and electrodes neighboring the point of adhesion, which is called stiction. Credit: Farnaz Niroui

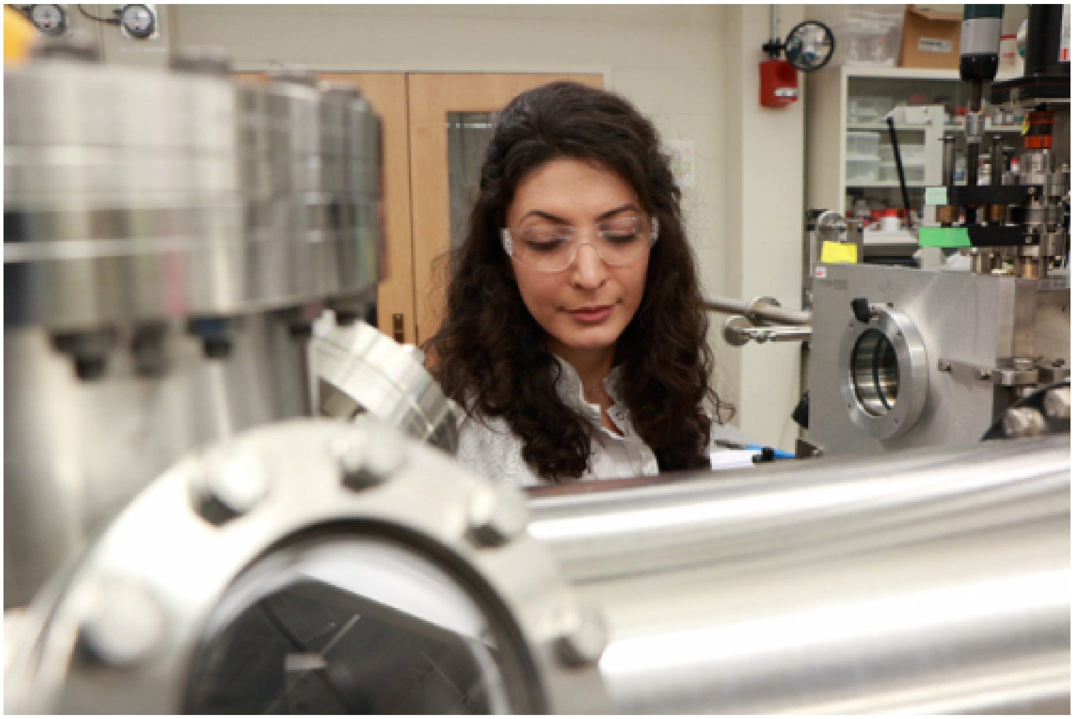
Niroui's latest work builds on her earlier work showing a design for a squeezable switch—or "squitch"—which fills the narrow gap between contacts with an organic molecular layer that can be compressed tightly enough to allow current to tunnel, or flow, from one electrode to another without direct contact—the "on" position—but that will spring back to open a gap wide enough that current cannot flow between electrodes—the "off" position. The softer the filler material is, the less voltage is needed to compress it. The goal is a low-power switch with repeatable abrupt switching behavior that can complement or replace conventional transistors.

Niroui designed, fabricated, tested, and characterized the cantilevered switch in which one electrode is fixed and the other moveable with the switching gap filled with a molecular layer. She presented her initial findings at the IEEE MEMS Conference in San Francisco last year in a paper titled, "Nanoelectromechanical Tunneling Switches Based on Self-Assembled Molecular Layers." "We're working right now on alternative designs to achieve an optimized switching performance," Niroui says.

"For me, one of the interesting aspects of the project is the fact that devices are designed in very small dimensions," Niroui adds, noting that the tunneling gap between the electrodes is only a few nanometers. She uses scanning electron microscopy at the MIT Center for Materials Science and Engineering to image the gold-coated electrode structures and the nanogaps, while using electrical measurements to verify the effect of the presence of the molecules in the switching gap.

Building her switch on a silicon/silcon-oxide base, Niroui added a top layer of PMMA, a polymer that is sensitive to electron beams. She then used electron beam lithography to pattern the device structure and wash away the excess PMMA. She used a thermal evaporator to coat the switch structure with gold. Gold was the material of choice because it enables the thiolated molecules to self-assemble in the gap, the final assembly step.

For the initial tunneling current demonstration, Niroui used an off-the-shelf molecule in the gap between electrodes. Work is continuing with collaborators in Swager's chemistry lab to synthesize new molecules with optimal mechanical properties to optimize the switching performance.



Farnaz Niroui works at a thermal evaporator, which she uses to deposit a gold coating on squeezable switches, or “squitches,” which she designed, fabricated and tested. It is part of a vacuum-sealed transfer line for making nanoscale electronic devices. Credit: Denis Paiste/Materials Processing Center

"Our project uses this design to have two metal electrodes with a single layer of molecules in the middle," Niroui explains. "We use self-assembly of molecules that allows the gap to be fabricated very small. By choosing the molecule and its properties such as the molecular length, we can control the gap thickness very precisely in the few-nanometer regime. The reason we want the gap small is that it allows us to reduce the switching voltage. The smaller the gap, the smaller the switching voltage and the less energy you are going to consume to switch on and off your device, which is very desirable."

The molecules filling the gap act as tiny springs. When an electrostatic force is applied, the electrodes compress the filler, squishing all the molecules. "These molecules are going to prevent the two metals coming into contact. At the same time the compressed layer is going to provide a restoring force, so it's going to avoid the typical sticking problem, permanent adhesion between the two electrodes, that is otherwise very common in electromechanical systems," she says.

Tunneling electromechanical switches work by controlling the gap between two metal electrodes that never come into direct contact. "You always will have a gap between the two electrodes. Because of the gap, the current that you modulate is the tunneling current," Niroui says.

Niroui tested a version of her original device without a molecular gap filler and the two electrodes immediately stuck together. By filling the gap, current-voltage tests showed characteristics that were reproducible and repeatable, so the devices didn't short. "By comparing to theoretical models, we observe that we get some compression of the molecules, and we extract mechanical properties of molecules that match what is reported experimentally in the literature," she says. While the device established proof of concept, improvements are needed in the filler material for practical use.

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