Tunneling Accelerometers

Submitted by
Samantha C. Cruz, Kevin P. Lee and Deepak Ponnavolu

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Professor Horacio D. Espinosa

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**Project Summary**

In this paper we will investigate tunneling accelerometers. Accelerometers are widely used in applications for motion sensing in automobiles for airbags and rollover detection, as well as used for vibrational and shock measurements. Advanced accelerometers based on concept of tunneling current are being integrated in inertial navigation systems, microgravity measurements, acoustic measurements, and seismology.

Tunneling accelerometers are distinguished by their method of acceleration detection. This can be seen in the fabrication of tunneling accelerometers. Tunneling accelerometers are based on bulk silicon micromachining, normally incorporating boron etch-stop wafer processes. Some of the main physical components in a tunneling accelerometer include a proof-mass, a tunneling tip and a counter electrode. When the accelerometer experiences acceleration, the distance between the tunneling tip and the counter electrode changes, inducing a change in the tunneling current between the two. The tunneling current between the tip and counter electrode is held constant through a feedback system and the electrical force used to hold the current constant is measured and converted into an acceleration measurement. In comparison, other MEMS-based accelerometers main physical components include a shuttle and many beams, both movable and fixed which comprise multiple capacitors.

The fabrication of tunneling accelerometers will be thoroughly discussed and its advantages and disadvantages will be explored. We will also discuss the sensing technology and analyze a feedback control circuit that is used to control this setup.
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Project Description

Introduction
Accelerometers are mechanical or electromechanical devices used for the measurement of acceleration or deceleration. They can be understood through the concept in which they operate; roughly as a combination of two transducers, one which measures the acceleration and converts it in terms of displacement and the other which converts the results into an electrical signal.

As long ago as 1965, accelerometers have become Micro Electro Mechanical Systems. By the great decrease in size, accelerometers have been widely applied to commercial and industrial products. Accelerometers are created with different characteristics in mind, such as range of acceleration, frequency response and acoustic noise sensitivity. With higher resolution sensitivity, the frequency response becomes slower such as in very high resolution tunneling accelerometers. Hence accelerometers can cover a vast range from $10^{-9}g$ to $10^6g$. However also in relation to higher sensitivity, accelerometers become more susceptible to acoustic noise. These constraints determine the application in which the accelerometer can be bound, for instance low sensitivity accelerometers can be found in braking systems, airbag deployment, and in the extreme cases of impact testing.

High resolution accelerometers have been large and expensive to manufacture, however with the constant developments in MEMS, accelerometers can be bulk micromachined and thus produced at much lower costs. Furthermore, the advancement of using a tunneling tip allows a resolution on the scale of Å displacements. With such high-precision, accelerometers can be found in taking microgravity measurements, acoustic measurements, and seismology.

Tunneling tips have been utilized to increase resolution and sensitivity over the miniaturization of accelerometers based upon piezoresistive, piezoelectric or capacitive transducers. Due to scaling laws, these accelerometers suffer from either poor resolution or very narrow measurement bandwidth. Since electron tunneling can only be observed when the gap between the electrodes is near the order of 10Å, the size constraint of a tunneling accelerometer must be of the same order. By utilizing a feedback control circuit to maintain a constant tunneling gap between tip and counter-electrode, the accelerometer is able to maintain minute displacement readings. With such sensitive readings, tunneling accelerometers are sought to measure very fine perturbations such as detecting and identifying submarines.

Microfabrication
Two methods of fabrication for tunneling accelerometers are bulk-micromachining and surface micromachining. Noise resolution is generally less in bulk-micromachined accelerometers [1] and both methods will be described. Bulk-micromachining consists of only subtractive (etching) methods on a Si wafer, where as surface-micromachining can involve both subtractive and additive (CVD etc.) methods. Both methods result in an accelerometer that has the same two major components, a single proof-mass component and a tunneling tip and electrode.

Surface Micromachining
In surface-micromachining the proof-mass is normally where the tunneling tip is and the cantilever that acts as counter-electrode. There is a tunneling tip that is kept in close proximity.
The steps in surface-micromachining include the fabrication of metal electrodes, a tunneling tip and cantilever. Two simple processes are described. The first process results in the cantilever functioning as the counter electrode with the fabrication process sequence shown in Figure 1. A Ti/Pt/Au layer is used as the tunneling electrode and is deposited on a Si wafer using e-beam evaporation (fig. 1a). A tunneling tip is grown on the metal layer through FIB lithography and ion milling, and then a mask is used with optical lithography as to define the electrodes through ion milling (fig 1b and 1c). Next, a sacrificial layer is deposited and a mask is used to define a Au base for the cantilever (fig. 1d). Another resist layer is deposited, and finally the cantilever beam is electroplated with Au (fig. 1e). The cantilever is then released by the removal of the sacrificial layer (fig. 1f) [2].

The second type of surface-micromachined tunneling accelerometer has the tunneling tip on the cantilever and has the counter electrode on the surface of the wafer. This particular procedure makes use of a modified SOI assembly which allows for cantilever release without the addition of etch release holes in the structure. The Ti/Pt/Au pads are first defined through masking and e-beam evaporation (fig. 2a). An oxide layer is then deposited on top of the pads, and an oxide cavity is created by a second mask (fig. 2b). Then a second wafer is bonded to the first creating a SOI assembly(fig. 2c). The wafer then etched down to a thin highly doped etch stop. A tip hole is etched through this cantilever assembly and oxide to form a mold for the tunneling tip (fig. 2d). Using another mask, the Au electrode and tip are defined (fig. 2e), and finally the cantilever is fully defined using yet another mask (fig. 2f). The remaining unnecessary SiO₂ is then etched releasing the cantilever without the etch release holes (fig. 2g) [3].
Fig. 2 Surface micromachined accelerometer fabrication process with cantilever as the tunneling electrode. (a) e-beam evaporation with mask, (b) SiO₂ deposition and cavity etching, (c) SOI, (d) removal of back Si to etch stop and tip mold etched, (e) tip and electrode defined through e-beam deposition, (f) cantilever defined through mask and milling, (g) cantilever release.

**Bulk Micromachining**

Bulk-micromachining is a bit different. The two components, the tunneling electrode and the counter electrodes are fabricated in two separate pieces by subtractive methods and then bound together. We will describe the method of fabricating a tunneling accelerometer with the proof mass acting as the counter-electrode [1]. The first piece fabricated would be the tunneling tip and cantilever die. This piece is a Si wafer that is oxidized and by using masks and a KOH underetch, a convex structure results as the tip (fig. 3a). Next low-stress nitride is deposited on the wafer and is metallized, the cantilever holes are defined through plasma etching (fig. 3b). Again a wet etch is used to release the cantilever (fig. 3c). The proof mass section is made from a separate Si wafer that is oxidized and has a low-stress nitride deposited on it (fig. 4a). Using lithography the hinge and proof-mass is defined, and KOH etching defines the hinge thickness (fig. 4b). The mass has a metal layer deposited on it to form the counter-electrode using liftoff techniques (fig. 4c). Finally wet etching is used to release the mass (fig. 4d). The two components are then aligned and bonded with epoxy (fig. 5).
Fig. 3. Bulk-micromachining of tip component in tunneling accelerometer. (a) KOH etch to form tip, (b) nitride deposition to form nitride tip, (c) KOH etch to release cantilever and tip and electrode deposition.

Fig. 4. Bulk micromachining of proof mass and hinge for tunneling accelerometer. (a) coated Si wafer, (b) lithography and KOH etch, (c) lithography and e-beam deposition of Au, (d) KOH release of proof mass.

Fig. 5. Assembled tunneling accelerometer. Two components are bound by epoxy.
Sensing and Control

In order to get any meaningful data from any sensor, we need to be able to get data from it. This sensor however, like most tunneling based sensors needs to be controlled by a feedback loop.

Sensing

![Diagram of tunneling accelerometer]

The current tunneling accelerometer works by measuring the amount of force required to maintain the tunneling tip and the proof mass at a constant distance from each other. When acceleration occurs, the proof mass moves with respect to the tunneling tip thereby changing the tunneling current.

In order for tunneling to occur, the gap must be less 10 Å. The tunneling current between two clean metal electrodes is related to the distance between them by the following expression.

\[ I_t = V_B \exp(\alpha \sqrt{\Phi} x_{tg}) \]

Where

- \( V_B \) = tunneling bias across electrode gap
- \( \alpha_t = 1.025 (\text{Å}^{-1} \text{eV}^{-0.5}) \)
- \( \Phi \) = height of tunneling barrier
- \( x_{tg} \) = minimum tunneling gap
- \( I_t \) = tunneling current

A feedback circuit is used to keep the tip a constant distance from the proof mass by controlling the tunneling current and by measuring the force required to keep the constant distance, we can easily estimate the acceleration.

Feedback Control

A basic example of a feedback circuit used in tunneling sensors is shown below:
A slight biasing voltage (roughly 150 mV) is applied between the proof mass and the tip. Bringing the two together with this potential difference allows tunneling current to flow. The current flow causes a small voltage drop across the 10 M resistor. A roughly 1.5nA current causes the voltage at V- of the Op-Amp to match V+.

When the tunneling current decreases, V- goes closer ground. Since V+ is greater than V-, the output of the Op-Amp goes towards the positive rail. As a result, the voltage at the Deflection Electrode increases. Larger Deflection Voltages pull the proof mass closer to the tip, which allows more tunneling current to flow. If tunneling current increases, V- is larger than V+, the output of the Op-Amp goes to its negative rail, lowering the Deflection Voltage, which allows the proof mass to move away from the tip. And this helps achieve a constant tunneling current and hence a common distance.

The high voltage supply is used to correct for the error due to fact that deflection voltage for proper separation of the proof mass and tip drifts slowly over time.
Conclusion

Tunneling accelerometers represent a giant leap in technology over conventional accelerometers. The ability of tunneling accelerometers to detect nano-g magnitude accelerations while maintaining a bandwidth between 5 Hz and 1.5 kHz is a fact that makes them critical in high precision applications like microgravity measurements, acoustic measurements, and seismology.

Another huge advantage of this is that it can be fabricated using bulk micromachining as well as surface micromachining. Both these methods have been discussed in this paper.

Using the potential difference between the V+ and the V- described in the feedback circuit, it is possible to figure out the acceleration. However, one must also keep in mind the thermomechanical noise.

\[
\text{Equivalent acceleration error} = \sqrt{(4k_BT\omega_o)/(m_pQ)}
\]

Where,
- \(k_B\) = Boltzmann constant
- \(T\) = Temperature
- \(\omega_o\) = Resonant frequency of proof mass
- \(m_p\) = mass of proof mass
- \(Q\) = Mechanical quality factor

While it does not make sense to use accelerometer for applications where this level of sensitivity and bandwidth is not required, this technology opens the doors for us to further explore the areas where it could be.
References


**Biographical Sketches**

SAMANTHA C. CRUZ was born in Chicago, IL in 1983 and grew up in metropolitan Oklahoma City where she graduated from the Oklahoma School of Science and Mathematics in 2002. She is currently a third year undergraduate at Northwestern University pursuing a B.S. in Materials Science and Engineering. Samantha is a former Ford Undergraduate Research Grant recipient and her research interests focus on nanomaterials. She is currently studying carbon nanotubes under an Academic Year REU from the Institute of Nanotechnology.

KEVIN PUI-KEI LEE-fondly referred to as Pooky- was born in Monterey Park, CA in 1984 grew up 20 minutes away from Cal Tech. He grew up aspiring to attend such a prestigious university…yet as he approached the time for applying to college, he realized he wasn’t strange enough for a technical school. Instead he now is pursuing a B.S in Materials Science and Engineering at Northwestern University with a concentration in nanomaterials and enjoys Ho-Down Hootenannies.

DEEPAK PONNAVOLU was born in Nizamabad, India and grew up in the city of Madras (now called Chennai). After attending DAV Sr. Sec. School for his primary, secondary & high school, he came to Northwestern University as an undergraduate international student to pursue a BS in Materials Science and Engineering with a concentration in nanomaterials. He worked in the Civil Engineering department to do research on Safetycrete (Like safety glass except with concrete). He enjoys design and has worked on many design projects through EDC, IDEA, Design Competition & Solar Car. He is also currently the President of Technical operations of the Northwestern University Solar Car Team.
**Attachments**

**Figure List**

Fig. 1. Surface micromachined accelerometer fabrication process with cantilever as the counter-electrode. (a) e-beam evaporation, (b) tunneling tip is formed through lithography and ion milling, (c) electrode definition through milling, (d) sacrificial layer and cantilever base mold, (e) cantilever masking and metal evaporation, (f) sacrificial layer removal and cantilever release.

Fig. 2. Surface micromachined accelerometer fabrication process with cantilever as the tunneling electrode. (a) e-beam evaporation with mask, (b) SiO2 deposition and cavity etching, (c) SOI, (d) removal of back Si to etch stop and tip mold etched, (e) tip and electrode defined through e-beam deposition, (f) cantilever defined through mask and milling, (g) cantilever release.

Fig. 3. Bulk-micromachining of tip component in tunneling accelerometer. (a) KOH etch to form tip, (b) nitride deposition to form nitride tip, (c) KOH etch to release cantilever and tip and electrode deposition.

Fig. 4. Bulk micromaching of proof mass and hinge for tunneling accelerometer. (a) coated Si wafer, (b) lithography and KOH etch, (c) lithography and e-beam deposition of Au, (d) KOH release of proof mass.

Fig. 5. Assembled tunneling accelerometer. Two components are bound by epoxy.

Fig. 6. Profile of a current tunneling accelerometer

Fig. 7. Schematic diagram of a feedback control circuit used for tunneling applications.