Tunnel junction based displacement sensing for nanoelectromechanical systems

P J Koppinen, J T Lievonen, M E Ahlskog and I J Maasilta
Nanoscience Center, Department of Physics, University of Jyväskylä, P. O. Box 35, FIN–40014 University of Jyväskylä, Finland.
E-mail: panu.koppinen@jyu.fi

Abstract. We demonstrate the feasibility of using normal state Al–AlO_x–Al tunnel junctions for displacement sensing. The experimental setup consisted of tunnel junctions fabricated on a thin silicon nitride membrane, which was actuated with an AFM tip. Advantages of tunnel junction detectors are their small size, relatively high gauge factor, existing high frequency read–out schemes, and ease of integration with the mechanical system. In addition, Al–AlO_x–Al junctions can be used for displacement sensing in zero magnetic field, unlike sensors based on magnetic tunnel junctions.

1. Introduction
Displacement sensing is a difficult task, when the dimensions of the mechanical transducer approach the nanoscale. Sensitive displacement measurements at such scale are becoming more important for performing e.g. mass measurements at atto- or even zeptogram resolution [1]. In addition, sensitive detectors are required for achieving quantum limited motion [2, 3]. Displacement detection at nanoscale dimensions is clearly more challenging than microscale sensing, which already has a wide range of commercial applications.

Typical microscale displacement detection is usually based either on capacitive sensing or on optical transducers. Methods based on capacitive sensing are compromised when dimensions approach nanometer size, since parasitic capacitances will be overwhelmingly large compared to the capacitance of the system under study. Optical transducers will not work well with small dimensions because of the diffraction limit. In addition, displacement detection with optical sub–wavelength read–out requires sophisticated off–chip equipment with photodetectors etc. However, there are several other methods for displacement detection in nanoelectromechanical systems (NEMS): Typically semiconducting or simple metal film transducers based on piezoresistive effect are used [4].

In this article we demonstrate displacement sensing for NEMS using normal state Al–AlO_x–Al tunnel junctions. Tunnel junction detectors have many advantages, such as their small size, relatively high gauge factor, and existing high frequency read–out schemes [5, 6]. They can also be easily integrated with the mechanical system. The measuring scheme is very simple, since displacement is detected by measuring the change in the tunneling resistance of the detector.
Figure 1. (a) SEM image of a sample fabricated on a 30 nm thick SiN membrane. (b) Zoom into the junction region. The dark area is the SiN membrane, lighter lines are Al leads. 4 tunnel junctions of area $0.1 \mu m^2$ are located at the intersection of the horizontal and vertical Al leads in (b).

2. Experimental techniques
Samples containing Al–AlO$_x$–Al tunnel junctions with junction area $\sim 0.1 \mu m^2$ were fabricated with electron beam lithography (EBL) and vacuum evaporation techniques on a thin (30 nm thick) silicon nitride (SiN) membrane, with lateral dimensions $122 \mu m \times 150 \mu m$. Double layer e–beam resist with a top layer of poly(methyl methacrylate) PMMA and bottom layer of copolymer P(MMA–MAA), containing PMMA and methacrylic acid (MAA) was used as evaporation mask. Before metal deposition, the substrate was cleaned with O$_2$ plasma to reduce the amount of organic impurities, such as resist residues in the junction area. Two Al layers, with thickness of 20 nm and 35 nm, were deposited with a rate 0.2 nm/s in an ultra high vacuum (UHV) chamber equipped with an electron gun. After deposition of the first Al layer, oxide barrier was grown in situ in the loading chamber of the UHV system by exposing the sample to pure oxygen pressure of 40 mbar for 4 minutes. Figure 1 shows a SEM image of a typical sample containing four tunnel junctions in parallel, all contacted with a one common electrode.

In the experimental setup the SiN membrane was actuated with an AFM tip attached to a stiff Si cantilever with a spring constant $k = 42$ N/m. Actuation was performed by pressing the membrane with a linearly increasing force sweep of duration 100 seconds, reaching a maximum vertical displacement of $4.5 \mu m$, holding tip at maximum displacement for 60 sec and then releasing back to its original shape in another 100 seconds (Inset of figure 3). A stiff cantilever was used to reduce the bending of the cantilever itself, while applying the force to the membrane. Simultaneously with the actuation, the zero bias differential tunneling resistance $R_T \equiv dV/dI$ of a junction was measured with a standard lock–in technique, at frequency 17 Hz. Typical values for $R_T$ were $\sim 10-20$ kΩ. In addition to $R_T$, the photodetector and $z$–piezo movement signals of the AFM were also recorded. All experiments were performed in room air and at room temperature.

3. Results and discussion
Figure 2 demonstrates the resistance modulation vs. time, while the membrane is being actuated. The solid (black) line represents the measured $R_T$, and the dashed (red) line the AFM photodetector signal vs. time. The photodetector signal measures the bending of the cantilever, which can be converted into the displacement of the membrane with a simple calibration once the $z$–piezo movement is known. As we see, the resistance response to the displacement is

2
Figure 2. (Color online) Zero bias differential tunneling resistance $R_T \equiv dV/dI$ (solid, black) and displacement (dashed, red) vs. time.

Figure 3. (Color online) Tunneling resistance $R_T$ vs. displacement. Solid line represent pressing and red open circles releasing the membrane, respectively. Straight solid line is a guide for eye.

reproduced in each force sweep.

Figure 3 shows the tunneling resistance vs. displacement curve for pressing (black solid line) and releasing (red open circles) the membrane with the AFM tip. Curves are averaged over all the sweeps shown in Fig. 2. The change in the tunneling resistance is from 9.12 kΩ down to 8.90 kΩ, i.e. relative change of 2.4 % for a 4.5 µm displacement. With small displacements the response of the tunnel junction is linear, but with larger displacements there is a clear deviation from linear behavior. The non–linear behavior is probably caused by the non–linearity of the mechanical response of the cantilever with large displacements. There is a clear hysteresis observed in the resistance curve, this is most likely caused by the difference of the interaction between the AFM tip and the membrane in push and pull phases.

The gauge factor of a detector that measures the magnitude of resistance response relative to applied strain (displacement) is defined as [7]

$$\gamma = \frac{\Delta R}{R_0 \epsilon},$$

where $\epsilon$ is the applied strain, $R_0$ is the resistance of the unstrained detector and $\Delta R$ is the difference in the resistance between strained and unstrained configuration. A larger gauge factor corresponds to a larger response of a detector to a smaller relative displacement. A typical gauge factor for metal film detectors is of order 2–4 [8], and in doped semiconductors gauge factor can be increased by few orders of magnitude [9]. Gauge factor for a tunnel junction detector can be estimated from the dimensions of the membrane and the data presented in Fig. 3. Strain $\epsilon$ can be defined as the relative change of the membrane length $\Delta L/L$, which can be estimated to be $\epsilon \equiv \Delta L/L = 0.27\%$ from geometrical considerations. By substituting the corresponding change in the tunneling resistance with strain into equation (1), the resulting gauge factor is $\gamma \geq 9$. Finite element (FEM) simulation shows that the compressive strain component is dominant for the membrane at the location of the tunnel junctions. Hence, we obtain that the simple area variation of the junction results in $\gamma = 2$, since tunneling resistance is proportional to the junction area. The rest of the gauge factor is then probably related to changes in the barrier height and thickness. For magnetic tunnel junction detectors gauge factors as high as 600 are reported [10], but the disadvantage of these detectors is that an external magnetic field must be applied.
We have shown that tunnel junction displacement detector shows a competitive gauge factor compared to thin film detectors, but is smaller than for doped semiconductors. However, $\gamma$ is only one of the parameters for optimizing the performance of the displacement detector. For semiconductors high $\gamma$ is usually achieved with low carrier densities and disordered samples with high resistivity [4]. With thin metal film detectors the high gauge factors are obtained with relatively high resistivity materials. This can lead to difficulties for high frequency read–out.

The most probable explanation for the resistance response to the displacement in non–magnetic tunnel junctions is barrier deformation due to the applied strain. Even a small deformation in the barrier can lead to a large change in the resistance. This implies that it may be possible to improve the gauge factor of the detector by adjusting the junction parameters, such as the thickness or the height of the potential barrier. Adjustment of the barrier parameters could be done e.g. by thermal annealing of the junctions [11].

Acknowledgments
This work has been supported by the Academy of Finland Projects No. 118665 and 118231. P.J.K. and J.T.L. acknowledges the National Graduate School in Materials Physics, Ellen and Artturi Nyyssönen foundation and Finnish Cultural Foundation for partial financial support.

References
[1] Yang Y T, Callegari C, Feng X L, Ekinci K L and Roukes M L 2006 Nano Lett. 6 583
[2] LaHaye M D, Buu O, Camarota B and Schwab K C 2004 Science 304 74
[3] Knobel R G and Cleland A N 2003 Nature 424 291
[4] Li M, Tang X and Roukes M L 2007 Nature Nanotechnology 2 114
[5] Schmidt D R, Yung C S and Cleland A N 2003 Appl. Phys. Lett. 83 1002
[6] Shoelkopf R J, Wahlgren P, Kozhevnikov A A, Delsing P and Prober D E 1998 Science 280 1238
[7] Parker R L and Krinsky A 1963 J. Appl. Phys. 34 2700
[8] Jen S U, Yu C C, Liu C H and Lee G Y 2003 Thin Solid Films 434 316
[9] Smith C S 1954 Phys. Rev. 94 42
[10] Löhndorf M, Duenas R, Tewes M, Quandt E, Rührig M and Wecker J 2002 Appl. Phys. Lett. 81 313
[11] Koppinen P J, Väisä L M and Maasilta I J 2007 Appl. Phys. Lett. 90 053503