Surface heterostructure nanomechanical actuators with atomic resolution

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A continuously tunable vertical actuator with subnanometer resolution is presented. It consists of a heterostructure cantilever which has collapsed over a 125 nm thick nanogap. Its operating principle relies on the temperature dependence of the adhesion energy between two InGaAs surface quantum wells. Deflections from −17 to 5 nm with a precision better than three atomic layers have been measured. © 2007 American Institute of Physics. [DOI: 10.1063/1.2735675]

In micro-optics, electrostatic actuators can readily change the spacing between mirrors to control the resonance of a micro-optical cavity. Since both photons and electrons have wave characteristics, one should be able to manipulate the quantum states of electrons in a similar manner. However, actuators that tune electron states must have extremely high resolution across much smaller gaps than existing actuators. They must also be immune to “snap-in” effects where the surfaces collapse into contact due to capillary, van der Waals, and related forces. This problem is particularly severe, since the forces across nanoscale gaps have a much stronger force law than is seen in common micromechanical actuators. This letter presents an actuator concept based on capillary forces, which provide vertical deflections of −17–5 nm with a resolution of 0.7 nm between surface quantum wells and which is easily compatible with quantum-coupled devices.

The term “friction” refers to a condition where surface forces cause an otherwise freestanding structure to permanently adhere to the surface. The adhesion energy—the energy to separate two parallel surfaces—quantifies the combined strength of the adhesion forces. For most conditions capillary forces dominate the surface interaction. The gap between two surfaces may fill with water in a process called condensation, where the surfaces collapse into contact due to capillary, van der Waals, and related forces. This is particularly severe, since the forces across nanoscale gaps have a much stronger force law than is seen in common micromechanical actuators. This letter presents an actuator concept based on capillary forces, which provide vertical deflections of −17–5 nm with a resolution of 0.7 nm between surface quantum wells and which is easily compatible with quantum-coupled devices.

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In this equation, \( n \) is the molar volume, \( \gamma \) the surface tension of water, and \( \cos \theta \) the contact angle between the water and the semiconductor surface. \( R \) stands for the universal gas constant, \( T \) for the temperature, and \( RH \) for the relative humidity. In practice, the roughness of the two surfaces affects the condensation distance \( d_{in} \) and capillary condensation occurs first between asperities. As the temperature decreases, the relative humidity increases and the “threshold” condensation distance \( d_{th} \) increases. The radii of the already existing water menisci increase and new menisci form in places previously void of water. As a consequence of the increasing amount of water in the gap between the surfaces, the adhesion energy increases. A similar argument holds for increasing temperatures. Therefore adjusting the local temperature provides an effective means to change the adhesion energy of the surface.

Several authors analyzed the shape of a cantilever under the influence of surface forces. Sufficiently long cantilevers attain an \( s \) shape after collapsing due to surface attraction,

\[
u(x) = \begin{cases} h(-2(x^3/s^3) + 3(x^2/s^2)) & \text{for } x \leq s \\ h & \text{for } x < s, \end{cases}
\]

where \( \nu(x) \) is the vertical deflection, \( h \) is the initial step height, and \( s \) is the unadhered length of the cantilever given by

\[
s = \frac{3Et^2h^2}{2\Gamma}.
\]

Here \( E \) is the elastic modulus, \( t \) the thickness of the cantilever, and \( \Gamma \) the adhesion energy. Previous research has shown that van der Waals forces across the nanogap do not contribute significantly to the deformation.8 Thus Eq. (2) also applies to cantilevers collapsed across a nanogap.

An increase in the adhesion energy from \( \Gamma_0 \) to \( \Gamma_1 \) decreases the unadhered length of the cantilever from \( s_0 \) to \( s_1 \). The vertical deflection of the cantilever \( \nu(x) \) depends on the unadhered length, as evident from Eq. (2). Therefore, an increase of the adhesion energy yields a change of deflection of \( \Delta \nu(x) = \nu_0(x) - \nu_1(x) \). As a result, every point of the cantilever undergoes a vertical deflection of

\[
\frac{\Delta \nu(x)}{h} = \begin{cases} 2x^3K_1 - 3x^2K_2 & \text{for } 0 \leq x \leq s_1 \\ -2(x^3/s_1^3) + 3(x^2/s_1^2) - 1 & \text{for } s_1 < x \leq s_0 \\ 0 & \text{for } x > s_0, \end{cases}
\]

with \( K_1 = 1/s_1^3 - 1/s_0^3 \) and \( K_2 = 1/s_1^2 - 1/s_0^2 \). The displacement ranges from zero at the end points to its maximum value \( \Delta_{\text{max}} \) of

\[
\Delta_{\text{max}} = -h \frac{K_2^3}{K_1^2} \text{ at } x_{\text{max}} = \frac{K_2}{K_1},
\]

with \( s_0 \) the adhesion energy before and \( s_1 \) after the change in temperature. As a consequence, changing the adhesion energy allows for the possibility to control the distance between the cantilever and the surface with great precision, as Fig. 2 illustrates.

The molecular beam epitaxially (MBE) grown InP/InGaAs heterostructure consists of the three lattice-matched layers: a 5 nm InGaAs etch stop layer on top of the...
InP substrate, a 125 nm InP sacrificial layer, and a 5 nm InGaAs layer at the top. A 3.2 μm layer of plasma-enhanced chemical-vapor deposited silicon nitride deposited on the top InGaAs layer serves as the structural layer. A plasma etch transfers the cantilever pattern onto the nitride. Then the top InGaAs layer is etched for 120 s in a H₂SO₄:H₂O₂:H₂O 1:8:100 wet etch. The cantilevers are etched for 40 min in a stirred HCl:CH₃COOH 1:2 release etch which was heated to 40 °C. The etch preferentially undercuts along the (100) directions which assured a clean edge perpendicular to the cantilever. An oxygen plasma cleans the surface of organic residue. Figure 1 shows a set of 40 μm wide cantilevers after this process step. Finally, 25 nm of aluminum are evaporated onto the sample to enhance the contrast during the optical measurements.

An interferometric microscope analyzes the deflections of the cantilever. In order to obtain measurements at different temperatures, the samples are placed on top of a thermoelectric (TE) element. A closed loop configuration of the heater assures precise control of the sample temperature. Within seconds after changing the temperature, stationary fringes indicate that the sample has attained thermal stability. This large thermal time constant results mainly from the heat capacity of TE element and is not intrinsic to the actuation physics. A next generation of devices could easily include a microfabricated resistor on the cantilever, decreasing the thermal time constant to less than 1 ms. After a measurement at room temperature, the samples undergo a heating and cooling sequence. During our experiments, 4 min are allowed between temperature adjustment and sample measurement to allow any possible transient effects to dissipate. Subtracting two shape measurements taken at different temperatures then reveals the deformation as a result of the altered adhesion energy. From the data the maximum vertical deflection Δₘₐₓ and the adhesion energy before, Γ₀, and after, Γ₁, the temperature change are extracted. The value of the adhesion energy at room temperature is similar to previous measurements. Note that the influence of the relative humidity on the adhesion energy can be largely excluded because the experiments were conducted within such a short time interval that the relative humidity is almost certainly constant. Later measurement found the relative humidity to be 37%. Further, the surface tension of water changes by less than 10% over the operational temperature range (5–60 °C).

Figure 2 shows the shape change as the cantilever is cooled from 25 to 5 °C. The deflection closely matches the expected shape. The relationship between the maximum vertical deflection along the beam versus temperature in Fig. 3 shows that a disproportionate amount of tuning occurs close to the dew point. A least square approximation indicates a dependence on the square root of the change in temperature, Δₘₐₓ ∝ √ΔT. When the sample is heated above room temperature, the deflection quickly reaches a maximum value of approximately 5 nm and no measurements at higher temperatures were conducted. In the temperature range of operation, the measurements do not detect a hysteresis in the deflection of the cantilever. However, at excessively high temperatures, annealing and chemical bonding impact...
the reproducibility.\textsuperscript{11} At low temperatures (at or near the dew point), water condensing within the gap also caused hysteresis.

Every single data point is compiled from four cantilevers with five measurements on each one. Statistical analysis of the profile data then yields the error range. The surface roughness of the nitride and the vertical resolution of the interferometer are the main contributors to the error range of approximately ±0.7 nm with a confidence interval of 95%. The larger error ranges for the measurements at 5 and 15 °C result from the same cantilever the shape change of which slightly deviated at those two temperatures. Roughness measurements of the InGaAs layer on top of the substrate show a surface roughness of about 3 Å. Hence the epitaxially grown InGaAs layer on the underside of the beam is expected to have an atomically smooth surface as well.

In summary, this letter presents a vertical actuator which can achieve downward deflections of 17 nm and upward deflections of 5 nm. The deflection is approximately proportional to the square root of the temperature. The precision of the actuator is better than 0.7 nm which corresponds to three atomic layers of the semiconductor. This device allows for controlling the gap spacing with a resolution sufficient to investigate quantum-coupled devices.

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