DIRECT PICK, BREAK, AND PLACEMENT OF NANOSTRUCTURES 
AND THEIR INTEGRATION WITH MEMS

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ABSTRACT
A direct, simple, and versatile assembly method for the manipulation of one-dimensional nanostructures and their integration with MEMS has been demonstrated. Using common MEMS equipment – an optical microscope and an unbiased tungsten probe – the facile process has been employed to accurately manipulate titanium dioxide nanoswords and zinc oxide nanowires under a room-temperature, dry environment. The surface morphology of the nanostructures, probe tips, and adhesion forces were characterized. Using this process, a nanosword was integrated with a MEMS device to characterize its sensitivity to ultraviolet light. As such, the technique could enable the rapid assembly of individual nanostructures with CMOS-compatible devices.

KEYWORDS
Nanostructure Manipulation, Nanostructure Integration, Pick and Place, TiO₂ Nanoswords, ZnO Nanowires

INTRODUCTION
One of the fundamental challenges in the field of micro and nanotechnology is the ability to manipulate and position one-dimensional (1D) nanostructures. Several diverse manipulation methods have been reported in both wet and dry environments, but the development of promising and versatile, yet simple processes is still in high demand. For example, atomic force microscopy (AFM) [1] and microfabricated MEMS tweezers [2] have been used for the manipulation of individual nanostructures. However, the equipment and fabrication costs of such techniques are high, their operation is complicated, and the available motion is limited. Dielectrophoretic assembly techniques are also very popular for the assembly of nanowires [3] and nanotubes [4], but device architecture is critical and single nanowire integration remains a challenge. Recently, elegant techniques such as the use of optoelectronic tweezers [5] and patterned target substrates [6] have further exemplified the need for manipulation, integration, and assembly control of nanostructures. In this work, we present a direct manipulation and integration technique in which pick, break, and placement of nanostructures is demonstrated using a commercially available tungsten probe tip installed on micromanipulator under a conventional probe station.

The basic principle of the proposed technique depends on the net attractive forces between two objects. Theoretically, two objects may be attracted to one another through a variety of different forces. However, as the separation distance between the two objects is reduced to the nanoscale, surface-based forces like surface tension, van der Waals and electrostatic forces dominate adhesion for nanostructures [7]. Furthermore, the effective contact area is a key factor in determining the degree of adhesion.

Figure 1 illustrates the process to “pick,” “break,” and “place” 1D nanostructures and their possible “integration” with MEMS devices. Titanium dioxide (TiO₂) nanoswords are shown as an example. First, a standard tungsten probe tip contacts a nanosword protruding from a growth substrate as visualized under an optical microscope and starts to bend the 1D nanostructure. When the stress at the base of the nanosword becomes large enough, the nanostructure breaks free from the growth substrate and remains on the probe tip. The nanostructure may be subsequently positioned onto a target substrate, completing the integration process. This technique is versatile, quick, and simple for the assembly of various 1D nanostructures to create nanodevices that would be quite challenging using other assembly methods.

MANIPULATION AND INTEGRATION OF NANOSTRUCTURES
The reason why the nanostructures may be easily acquired from growth substrates and positioned onto...
various target substrates is believed to be due to the difference in the effective contact area of the nanostructure. When held by the probe tip, the effective contact area between the nanostructure and the probe tip is lower than when the nanostructure is adhered to the target substrate. This occurs for two reasons. First, after detachment from the growth chip, only a section of the nanostructure makes contact with the probe tip, whereas a larger area of the nanostructure may make contact when it is placed onto the target substrate. Secondly, the roughness of the probe tip is greater than the roughness of polished substrates resulting in a stronger overall adhesion.

To illustrate the working principle of the technique, one-dimensional TiO$_2$ nanoswords [8, 9] and zinc oxide (ZnO) nanowires were rapidly synthesized using the previously reported induction heating platform [10, 11] for a duration of several minutes. The nanoswords had lengths of 3-10 µm, widths of 200-1000 nm, thicknesses of 50-60 nm, while the [0001]-grown ZnO nanowires were 75-125 nm in diameter with lengths of 9-12 µm. The Cascade Microtech tungsten probe tips used in this work had a specified radius of curvature of 2.4 µm.

Figure 2. a) SEM image of a probe tip with an attached nanosword. AFM roughness of the tip (b) and nanosword (c).

Figure 2a shows an image of the tungsten probe tip with a nanosword attached to the visibly roughened tip. Tapping mode atomic force microscopy was used to visualize the surface morphology of the probe tip. The three-dimensional rendering of the surface roughness at a location approximately 3 µm from the probe tip is shown in Figure 2b. At this location, the RMS roughness was measured to be 11 nm. A scan was also taken along the surface of the nanosword on a silicon substrate shown in Figure 2c. The RMS roughness of the surface of the nanosword was measured to be <1 nm, similar to the roughness of the silicon surface. Though a precise quantification of the nanosword roughness necessitates a different technique, it suffices to say that the nanosword surface is very smooth.

Figure 3. Sequence of nanostructure “pick and place.” Probe tip is used to acquire 1D nanostructures and precisely position them.

Figure 4. Several key demonstrations of the technique. a) ‘NANO’ was written by the positioning of nanoswords b) ZnO nanowire is cantilevered on a silicon MEMS bridge. c) A single nanosword at the tip of MEMS actuator/probe.

The nanoswords for this work were grown in bulk on copper TEM grids. When observed with an optical microscope at 1000x magnification, the protruding nanostructures are clearly visible. The nanostructure encircled in Figure 3a was acquired by the probe tip (Figure 3b), and positioned (Figure 3c) on a target substrate, an AFM calibration grid. An oblique angle SEM image shows the positioned nanosword in Figure 3d. It should be mentioned that the overall process could be accomplished in as little as 30 seconds.
Figure 4 shows several key examples demonstrating the versatility of this technique including the assembly of the word ‘NANO’ on oxidized silicon using twelve nanoswords, the placement of a ZnO nanowire on the edge of a silicon-on-insulator (SOI) fabricated MEMS bridge, and positioning of a nanosword at the end of an SOI MEMS actuator/probe.

ADHESION FORCE TESTING

To quantify the adhesive forces of the nanosword to the surface materials, contact-mode atomic force microscopy was used to apply a moment to a fixed-free cantilevered nanosword on various different substrates as shown in the inset of Figure 5. The moment was incrementally increased and eventually overcame the moment from adhesion, at which point the nanostructure fell off of the substrate.

Test specimens were first prepared on the following three substrates: 1) piranha-cleaned, p-type (B), 10-50 Ω-cm, <100> silicon, 2) piranha-cleaned, c-plane sapphire, and 3) silicon with a 5 nm / 20 nm Cr/Au evaporated thin film. All substrates were cleaved or broken to create a sharp, well defined edge from which the nanoswords were cantilevered. The specimens were SEM imaged to measure the effective nanosword-substrate contact area. Subsequently, the specimens were hotplate heated to 120 °C and oxygen-plasma cleaned. The specimens were then loaded into the AFM and the spring constants of the rectangular cross-section AFM tips were calibrated using the method by Sader et al [12]. The AFM tips were brought into contact with the nanosword and nanosword profile was measured at several locations to verify thickness uniformity. The moment was then applied to the cantilevered section, and when failure occurred, the moment data were recorded. It was assumed that the adhesion force was constant across the entire effective contact area, and a no slip condition was considered. The moment data was applied to equation (1) to quantify the adhesive force per area, f_{adh}.

\[
f_{adh} = \frac{F_{AFM}a}{bA_{adh}}
\]

In equation (1), \(F_{AFM}\) is the applied force, \(a\) is the moment arm, \(A_{adh}\) is the estimated nanosword-substrate contact area, and \(b\) is the edge-to-centroid distance as calculated using the SEM image. Table 1 shows selected parameters for four of the samples used in the adhesive force testing, while Figure 5 illustrates the complete set of data. The data show a linear dependence of the adhesive force with respect to the nanosword contact area, as expected. Silicon showed the greatest adhesion, followed by sapphire and gold, which is believed to be due to the surface roughness (the grains of the deposited gold layer, for example, increased the surface roughness). The linear slope of the data reflects a constant adhesion force per area. If the intercept is set to zero, the linear slope values for silicon, sapphire, and gold substrates are 658, 417, and 287 nN/µm², respectively.

Table 1. Selected parameters for adhesive force testing

<table>
<thead>
<tr>
<th>Test Substrate</th>
<th>Spring Constant (N/m)</th>
<th>Applied Force (nN)</th>
<th>Moment Arm (µm)</th>
<th>Contact Area (µm²)</th>
<th>Adhesion Force (nN/µm²)</th>
</tr>
</thead>
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<tr>
<td>1 Silicon</td>
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<td>0.54</td>
<td>1.37</td>
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</tr>
<tr>
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<td>582</td>
<td>0.62</td>
<td>1.00</td>
<td>274</td>
</tr>
<tr>
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<td>1270</td>
<td>0.56</td>
<td>1.08</td>
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</tr>
</tbody>
</table>

DISCUSSION

The work presented herein represents a simple and practical approach for the manipulation and integration of 1D nanostructures with MEMS. The technique is versatile, as demonstrated by the manipulation of TiO₂ nanowires and ZnO nanowires, and is believed to be adaptable to other 1D nanostructures. It can be accomplished in a room-temperature, dry environment with common MEMS equipment. The positioning accuracy is estimated to be ~1 µm, and with subsequent axial alignment of opposing nanowords having been demonstrated down to 70 nm [13]. The process is also relatively fast, with the entire process taking as little as 30 seconds under manual assembly. Also, it is believed that if an automated pick-and-place platform could be established similar to that for chip-based integration, such a technique could enable a rapid means to assemble individual nanostructures into CMOS-compatible MEMS devices.

To show a device demonstration of the pick, break, and place technique, an ultraviolet (UV) light sensor was characterized by positioning an individual TiO₂ nanosword and fabricating Cr/Au evaporated electrodes. The device was packaged and positioned 10 mm below a 6W UV lamp in ambient conditions, and the output current was
monitored under a 1 V bias as the lamp was power cycled. The results of the UV detection are shown in Figure 6. The response is repeatable, and shows a 25% increase in the output current for a nanosword with an exposed area of approximately 1.25x0.23 µm². A second device demonstration of this technique was used in the fabrication of MEMS-integrated, variable-gap, TiO₂ nanosword plasmonic antennas for SERS detection, recently presented at MEMS 2009 [13].

![UV Sensitivity: Nanosword Output](image)

**Figure 6.** Sensitivity of a single nanosword to ultraviolet light. Output current was monitored under 1V bias as the lamp was power cycled. A repeatable increase of 25% was observed under UV illumination.

This work represents a proof-of-concept demonstration and initial investigation into the direct pick, break, and placement of nanostructures with MEMS using a standard tungsten probe and optical microscope. Extending this, future work will focus on addressing several fundamental areas, including the measurement of the adhesion force of other 1D nanostructure specimens, the development of a theoretical model validating the force of adhesion, and the in-situ SEM observation of the nanostructure-probe interaction during the acquisition process. Each of these research efforts should help further explain the technique and provide insight into its advantages and limitations.

**CONCLUSION**

In summary, we have demonstrated a simple, versatile, and quick assembly process for the manipulation and integration of 1D nanostructures with MEMS. The three step process to pick, break, and place both TiO₂ nanoswords and ZnO nanowires has been demonstrated. It is believed that the difference in the effective nanostructure contact area between the probe tip and the target substrate helped to enable this technique. The nanostructure adhesion force with various substrates was measured using AFM and the estimated adhesion force per unit area between TiO₂ nanoswords and silicon, sapphire, gold substrates were 658, 417, and 287 nN/µm², respectively. Two device examples based on nanoswords, including UV sensor and tunable plasmonic antenna were successfully demonstrated.

**ACKNOWLEDGEMENTS**

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**REFERENCES**


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