

NANOPROBE CONCEPTS FOR FIELD EMISSION NANOMACHINING

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Abstract

Multi-walled carbon nanotubes are excellent conductors and are considered ideal electron emitters since their high aspect ratios ensure concentrated electric fields. Their field emission characteristics and recent developments in growth of aligned nanotubes onto electrically conductive substrates make them promising for use in nano manufacturing. Combining resistive (Coulomb) heating, spot heating with a laser and absorption of electrons emitted from the tips of nanotubes, nanoscale machined features may be produced on conductive substrates. Therefore, we are presently designing Nanoprobes that incorporate nanotubes for their tips to enable experimental tests. This paper presents several concepts for creating nanomachining probes utilizing established microfabrication methods—including discussion on the creation of probes onto which nanotubes can be attached, methods for attaching the nanotubes, and creating 1 and 2D patterns for parallel manufacturing and metrology processes.

Keywords: nanotube arrays, field emission, nanopatterning

Introduction

Carbon nanotubes (CNTs), first discovered in 1991 [1], are self-assembling hexagonal lattices of carbon atoms joined into long narrow tubes. Nanotubes are grown using several techniques including CVD or electric arc discharge in inert atmospheres [2]. Depending on the technique, nanotubes may be comprised of a single layer of graphene sheet (single walled nanotubes or SWNT) or multiple, concentric layers (multi-walled nanotubes, MWNT). Diameters for SWNTs are as small as 2 nm, while MWNTs are typically between a few nm and 100 nm in diameter. MWNTs are excellent conductors and are considered ideal electron emitters since their high aspect ratios ensure concentrated electric fields. Rao et al. [3] developed a CVD technique to grow MWNTs aligned perpendicular to a polished titanium nitride (TiN) substrate, which exhibited superb field emission

properties. The field emission characteristics of these nanotubes encouraged us to investigate their potential application in nano manufacturing.

Fig 1 illustrates a potential nano-machining approach using energy transmitted during field emission from carbon nanotubes. We seek to remove clusters of atoms from workpiece surfaces using multiple energy sources. Bulk heating can be applied to the workpiece using resistive (Coulomb) heating or radiative heating. If necessary, further localization of the energy is achieved with a laser beam focused to a spot-size of a few microns. Finally, high resolution patterning capability might be obtained with the absorption of electrons emitted from the tips of nanotubes.

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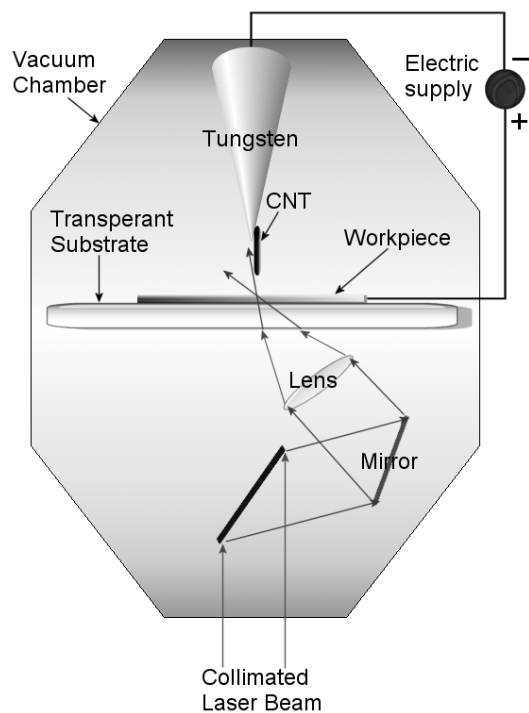


Fig 1: Setup for High-Resolution Nanomachining with Carbon Nanotubes

Recent simulations of the energy transferred during electron and laser absorption by a gold film deposited on quartz suggest the feasibility of this nanomachining approach [4]. Therefore, we are presently designing nanoprobe tips to enable experimental tests. As illustrated in Fig 2, we are interested in designing three categories of field-emission nanoprobe tips: 1) probes with only one NT for serial processing of the workpiece, 2) probes with 1D patterns of emitting NTs, and 3) probes with 2D patterns of emitting NTs. Probes in the first category are most appropriate for scientific investigation, but the second and third categories hold greater promise for manufacturing processes.

This paper presents several concepts for creating nanomachining probes utilizing established microfabrication methods. This includes discussion on the creation of probes onto which nanotubes can be attached, methods for attaching the nanotubes, and creating 1 and 2D patterns for parallel manufacturing and metrology processes.

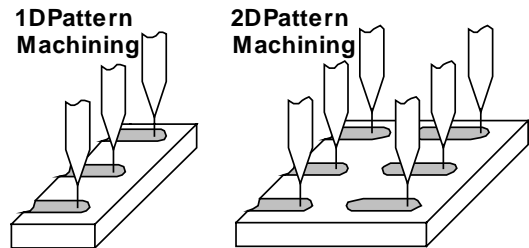
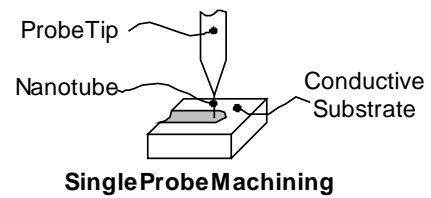


Fig 2: Field Emission Nanoprobes in serial, 1D pattern and 2D pattern configurations

Nanotube Synthesis

The synthesis process for nanotubes uses a chemical vapor deposition chamber to deposit the nanotubes on a suitable substrate, such as TiN, quartz, or nickel. Therefore, a suitable growing site can be created by selectively coating the probes with a thin layer of Ni at the tips using e-beam lithography. The location of the nanotubes is determined by the location of a nucleating catalyst particle—making the number of nanotubes grown on the probe a function of the nickel layer’s surface area.

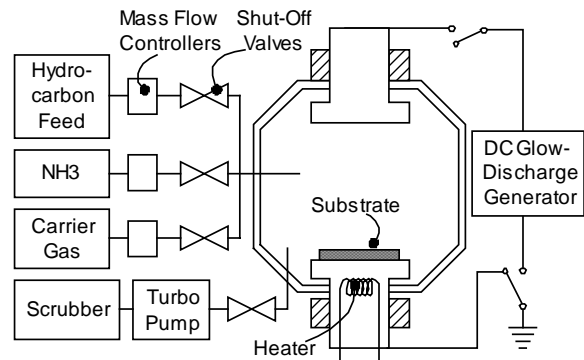


Fig 3: Plasma Enhanced CVD chamber for growth of carbon nanotubes

Growth of nanotubes directly onto an AFM tip has been demonstrated experimentally [5,6]. If repeatable on a larger scale, it would be the preferred method of obtaining nanotubes on the probe tips, as this would eliminate the need for additional equipment and attachment processes.

Another process would involve growing the nanotubes in a pattern directly onto a flat substrate—

eliminating the need for the probe tips entirely. This can be achieved by depositing the nickel catalyst in nano-sized dots using e-beam lithography, and then synthesizing the nanotubes in the PECVD chamber. Staggered heights for the nanotubes might be obtained by etching the substrate prior to the nickel deposition.

Joining Nanotubes to Probes

An alternate approach is necessary if growth of nanotubes directly onto probe tips is not a reliable solution. Nanotube tips can be attached after the growth process by transferring them from the growth substrate onto the tips. This process has been demonstrated using the electron beam from an SEM to weld the nanotube to an AFM tip [7]. Stephens, et al. produced similar results using an electrical arc discharge method in open air [8].

Probe Conceptual Designs

The ideal probe for integrating nanomachining and SPM requires at least two electrically isolated attachment sites for nanotubes. Making these sites close together is also preferable, as this makes it faster to obtain results on recently machined areas. It also facilitates alignment of the tip paths, increasing accuracy of the metrology information. We are also concerned with ease of fabrication; both for the probe tip manufacture and the subsequent attachment of the nanotubes.

Modified AFM Probe

One approach is to modify a commercially available SPM cantilevered probe. There have been documented results that demonstrate attaching nanotubes to cobalt coated AFM probes [8]. For our purposes, electroplating the tip with a thin layer of Ni would provide a conductive surface without drastically diminishing the sharpness of the tip—providing a catalytic base onto which nanotubes can be attached or grown.

The staggered tip necessary for integrated manufacture and metrology would be obtained using a lithographic etching process. Once the probe geometry shown in Fig 4 has been obtained, the two plateaus must be electrically isolated. By applying layers of conductive and dielectric materials via electron beam lithography to create the pattern shown in Fig 5, nanotubes on the two plateaus can be activated independently.

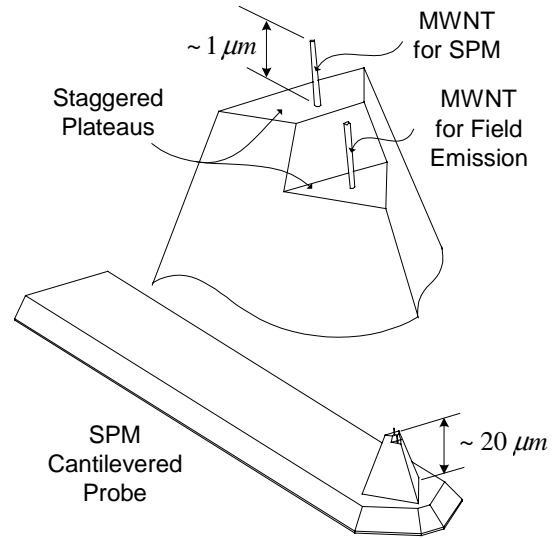


Fig 4: Proposed Staggered Plateau Probe with Two Nanotubes for Field Emission and Scanning Probe Microscopy

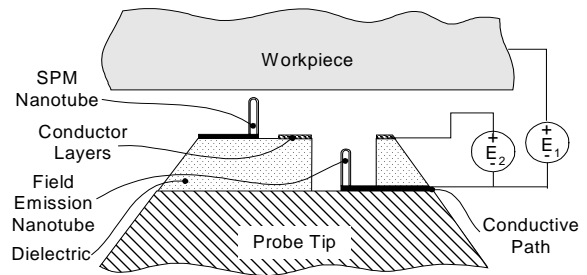


Fig 5: Staggered Probe Tips with Gated Nanotubes for Focusing Field Emitted Electron Beams

While this method has been proven for a single nanotube attachment, the staggered plateau and electrical isolation geometry provide a manufacturing challenge. Also, the commercial availability of the cantilevered probes provides limited control over many of the probe parameters.

Electrochemically Etched Tungsten Wire

Another method for preparing the tips utilizes electrochemical etching of tungsten wire. The etching process, shown schematically in Fig 6 has been well documented [9, 10] and can achieve a tip radius as small as 5 nm [11]. An optical microscope image of tungsten wire etched in this manner is shown in Fig 7.

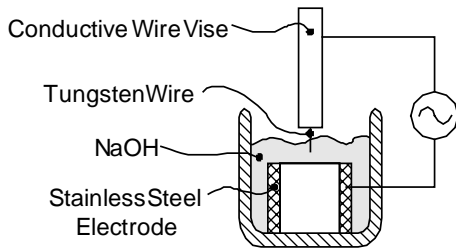


Fig 6: Electrochemical etching process for tungsten probe fabrication

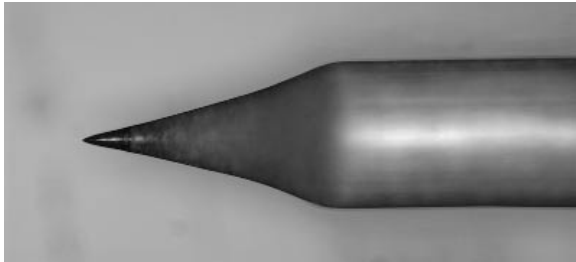


Fig 7: Electrochemically etched 300- μ m diameter tungsten probe

In order to create multiple probe geometry, several of these sharpened wires would be mounted onto a silicon ferrule, illustrated in Fig 8. The ferrule can be created by taking advantage of [100]-oriented silicon's natural tendency to form v-groves with 54.74° inward angles when etched. The non-conductive nature of silicon would provide the necessary electrical isolation for using multiple tips.

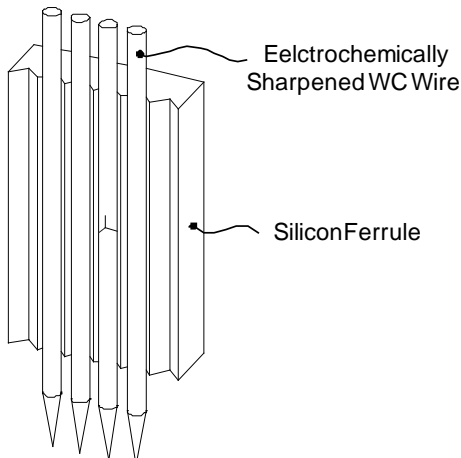


Fig 8: Multiple-tip probe comprised of etched WC wires in a silicon ferrule

This probe configuration is easy to manufacture and provides a convenient solution to the electrical isolation. Also, since the wires would be etched and assembled into the ferrules individually, it would offer a great deal of control over tip parameters—

such as height, tip radius and slope. Also, as can be seen in Fig 8, it allows for more than two tips to be assembled into a single probe. This provides opportunities for two or more independent parallel processes in a single probe.

The wire and ferrule configuration has a few inherent drawbacks. First, it can only easily handle a linear pattern, not 2-D. Also, the distance between tips is severely limited by the diameter of the wire. It would be difficult to get closer than 20-30 μ m between wire tips, compared to 5-10 μ m that would be feasible with the cantilevered AFM probe.

Electrodeposited Patterned Tips

Another manufacturing process considered here is the use of x-ray lithography and electrodeposition to create a patterned probe. This process can produce patterns of nickel towers with diameters up to 500 μ m in height as little as $\sim 2 \mu$ m in diameter [12]. The towers can be electrochemically sharpened to produce a patterned probe, similar to that in Fig 9.

While this process does not inherently produce tips that are electrically isolated, it may be possible to achieve this by modifying the base structure. Our process would involve filling part of the gaps in the pattern with an electrically non-conductive material and then removing the nickel base, shown in Fig 9.

Towers of various heights can be created in the electroplating step, but it would be difficult to retain the exact height differences during the etching process. This procedure does have an advantage in its ability to easily produce 2-D patterned probe tips.

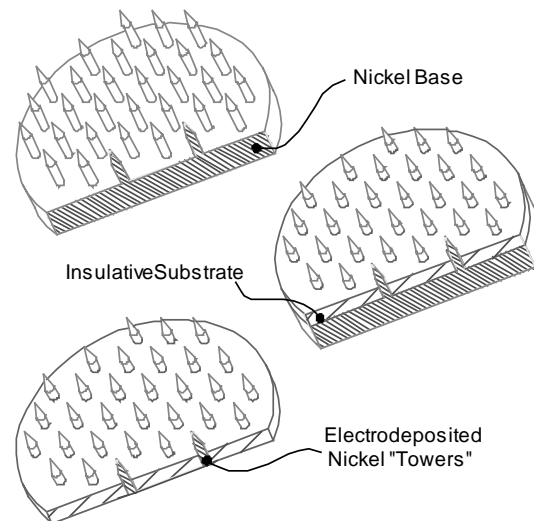


Fig 9: Patterned probe tips manufactured using x-ray lithography and electrodeposition

Conclusions

The field emission properties of carbon nanotubes may be useful in achieving nanoscale machining of conductive workpieces. This paper presents a variety of alternative approaches for fabricating probes for experimentally demonstrating such a process. The fabrication methods considered here incorporate conventional microfabrication methods. They provide varying degrees of difficulty with respect to fabrication, but all show promise for use in either experimental or bulk machining processes.

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