Fabrication and Measurements Using Ultra-tall Near-field Coaxial Tips

Yaqiang Wang, Charles A. Paulson, Guoqing Ning, and Daniel W. van der Weide

Department of Electrical and Computer Engineering, University of Wisconsin

Madison, WI 53706, USA

***Abstract* — We present a new method for microfabrication of coaxial silicon tips with heights > 50 μm. The coaxial silicon tip acts as an electrically small antenna. Microwave measurements using a microfabricated coaxial tip chip are performed with a network analyzer HP8753D and an atomic force microscope (AFM). Scanning near-field microwave microscopy (SNMM) using the ultra-tall coaxial tip is demonstrated with a commercial AFM silicon probe in noncontact mode as a sample.**

***Index Terms* — scanning near-field microwave microscopy (SNMM), atomic force microscope (AFM), microelectromechanical systems (MEMS), coaxial tip, deep reactive ion etching (DRIE).**

I. INTRODUCTION

Scanning near-field microwave microscopy (SNMM) has gained increasing attention for applications to characterize semiconductor materials and devices and measure biomedical samples, given the subwavelength resolution of near-field techniques and the penetration of electromagnetic fields to image subsurface features [1-3].

Because coaxial waveguides have the advantage of supporting microwave signals with nearly no cut-off limit and producing highly confined electromagnetic fields through the coaxial structure [4], most of the existing SNMM probes use open-ended coaxial cables with a protruding center tapered tip [5] or similar coaxial structures [1]. The widespread use of the atomic force microscope (AFM) has fueled the development of AFM-compatible SNMM probes based on techniques from microelectromechanical systems (MEMS) [2, 6]. These tips have the advantages of miniature size with potential for even finer resolution, batch microfabrication, and compatibility with commercial AFM systems. The key component of a microfabricated SNMM probe is a coaxial tip integrated with an AFM cantilever to conduct simultaneous topographic and microwave imaging. Despite the successful implementation of microfabricated SNMM probes with coaxial tips, parasitic capacitive coupling with the metallization on the cantilever and chip body is still a problem limiting coaxial tip microwave imaging [2]. One solution to address this issue is to increase the tip height (originally around 10 μm in the previous work [2]), thereby decreasing the parasitic capacitance between cantilever and sample.

Here we introduce a new microfabrication method to make ultra-tall silicon coaxial tips with heights > 50 μm. SNMM application using a commercial silicon AFM probe as the sample demonstrates electromagnetic field confinement as well as suppression of the parasitic capacitive effect.

II. MICROFABRICATION

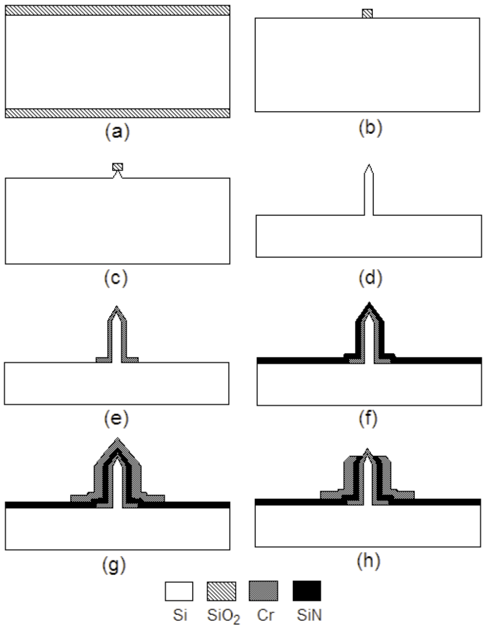

Fig. 1. Fabrication process for an ultra-tall silicon coaxial tip.

The ultra-tall coaxial silicon tip microfabrication process is outlined in Fig. 1. First, a 1-µm-thick thermal oxide is grown on a conductive Si (100) wafer with a resistivity of 0.005 Ω·cm [see Fig. 1(a)]. Then an oxide disk is patterned by standard photolithography and buffered hydrofluoric (BHF) acid etch [see Fig. 1(b)]. The exposed Si is etched by a reactive ion etching (RIE) to form a tip precursor [see Fig. 1(c)]. Next, a deep reactive ion etching (DRIE) process is performed using an STS$^{®}$ Multiplex ICP system to form a tip shaft that determines the ultra-height of the tip. The oxide disc is removed by hydrofluoric (HF) acid after the tip is sharpened using the oxidation-sharpening method [7] [see Fig. 1(d)]. Fig. 2 shows an SEM micrograph of a microfabricated silicon tip with a height of 51µm and apex radius less than 30 nm. This is ultra tall compared with the typical height of 10-20 µm for the commercial AFM tips.

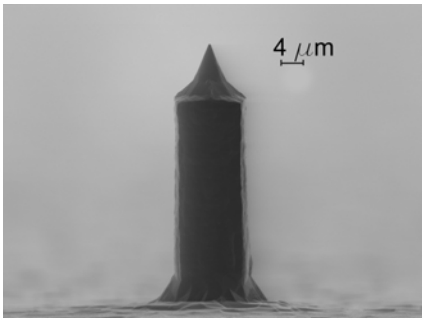

Fig. 2. SEM micrograph of a microfabricated ultra-tall silicon tip.

To form the inner conductor of the coaxial tip structure [see Fig. 1(e)], 300-nm-thick Cr film is then deposited on the wafer. This film is patterned by photolithography using negative-tone SU-8 resist to cover the ultra-tall tip feature. This Cr pattern. The insulation layer of the coaxial tip is a 1-μm-thick SiN layer deposited by plasma enhanced chemical vapor deposition (PECVD) [see Fig. 1(f)]. The outer shield metal layer is a 1-μm-thick Cr film deposited by sputtering. It is patterned by another SU-8 photolithography and etched to form the shield pattern [see Fig. 1(g)]. The key step to fabricate the coaxial tip is a tip-exposure process that consists of a thick resist coating by AZ 4620 and an oxygen plasma etch to expose a portion of the Cr-coated tip with a controlled manner. The final coaxial tip structure is formed by a Cr wet etch and a SiN RIE. Fig. 2 is an SEM micrograph of a coaxial ultra-tall tip based on the silicon tip of Fig. 1 with an opening aperture radius of 3 μm.

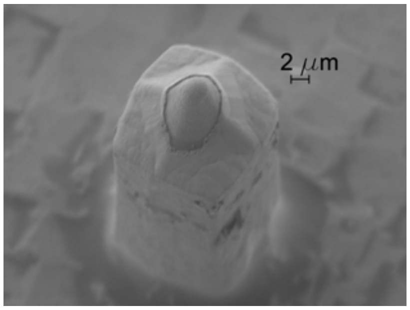

Fig. 3. SEM micrograph of an ultra-tall silicon tip showing coaxial opening.

The microfabricated coaxial tip is assembled with a 50 Ω microstrip line using conductive epoxy to facilitate the following measurement steps. We call this package a “tip-chip”, as shown in Fig. 4.

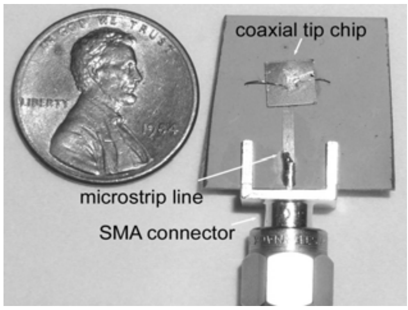

Fig. 4. Assembly of the coaxial tip with a microstrip line.

III. AFM AND MICROWAVE CHARACTERIZATION

The tip-chip was mounted on a specially machined stage to make it mechanically and electrically stable for both AFM and microwave measurements. We use a commercial AFM probe with a tip height of 10 μm (see Fig. 5) to scan the tip-chip and to locate the coaxial tip. The piezoceramic of our Topometrix AFM system has a limit of 10-μm-movement in the z-direction; we thus carefully place glue around the vicinity of the coaxial tip to partly fill the topography gap and enable scanning the tall tip.

A schematic of the AFM system is illustrated in Fig. 6. We conducted a noncontact scan at 140 KHz, and special care has been taken to set the scan parameters to prevent the AFM tip from breaking during the transition from the substrate to the coaxial tip. Fig. 7 shows an AFM topography image of the coaxial tip, with the bright circle clearly indicating the dimension of its base. The coaxial structure details do not show up in this scan, probably because the glue is insufficient bring the topography difference into the z-direction movement limit of 10 μm.

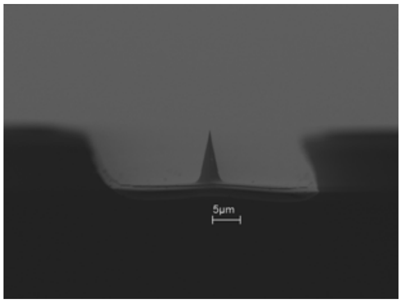

Fig. 5. A commercial AFM tip is used for AFM scan of the coaxial tip and acts as a sample for SNMM scan.

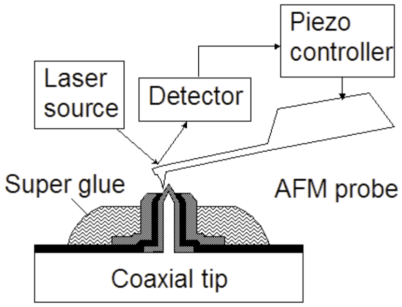

Fig. 6. Schematic of AFM scan for the coaxial tip.

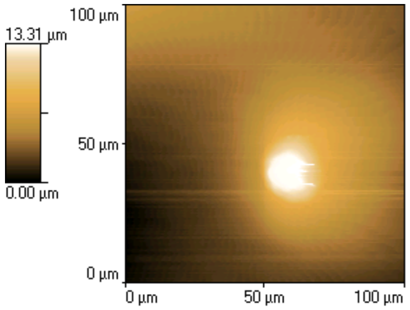

Fig. 7. AFM image of the coaxial tip using the setup in Fig. 6.

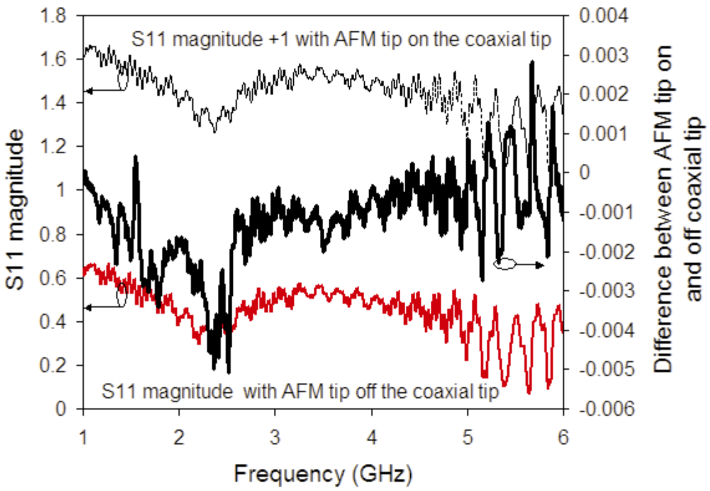

Fig. 8. Microwave reflection for the coaxial tip while it is interrogated by an AFM tip, the S_{11} magnitude with the AFM tip on the coaxial tip was shifted up by 1 for clarity.

After locating the position of the coaxial tip position in the AFM scan, microwave reflection measurements were made with a network analyzer (HP 8735D) using a power level of 0 dBm. By locating the AFM tip on the protruding coaxial tip and on the shield region of the coaxial tip, we obtained two curves of the magnitudes of the input reflection coefficient (S_{11}) in the frequency range of 1 GHz - 6 GHz, which are shown in Fig. 8. These S_{11} values are reasonable in view of the lossy substrate and mismatch from the coaxial tip. The difference between the two measurements is also shown in the same figure by subtracting the S_{11} magnitude with AFM tip on the shield region from the S_{11} magnitude with the AFM tip on the coaxial tip. The peaks at 2.3 GHz, 2.5 GHz, and 5.7 GHz display strong microwave contrast suitable for SNMM scans. This also implies that the parasitic capacitive coupling contributed from the unshielded substrate is not strong enough to interfere with the guided electromagnetic fields at the protruding tip due to the height of the coaxial tip.

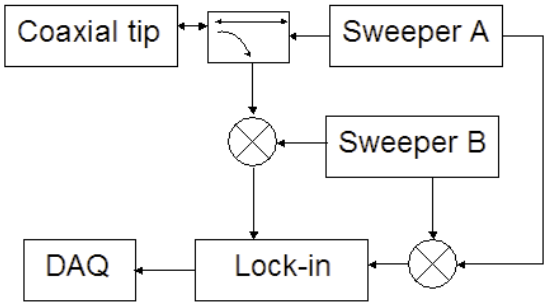

Fig. 9. Circuit schematic for SNMM scan.

IV. SNMM APPLICATION

The SNMM scan schematic is illustrated in Fig. 9. The frequency of sweeper A was 2.36 GHz based on the network analyzer measurement in Fig. 8. Sweeper B was set at 2.36 GHz + 90 KHz. Two mixers were used to translate 2.36 GHz to 90 KHz, which lies in the working frequency range of a lock-in amplifier. A directional coupler was used to guide the microwave source from sweeper A to the coaxial tip, and it coupled the reflected signal from the coaxial tip to one mixer. The output of this mixer contained the information from the sample, which is an AFM probe in this SNMM experiment. The other mixer mixed direct signals from both sweepers as the reference signal for the lock-in amplifier. The lock-in amplifier output was delivered to the data acquisition (DAQ) channel of the AFM system to build up the microwave image of the sample.

With this setup, we obtained simultaneous AFM-microwave images of the AFM probe (see Fig. 10) to demonstrate the SNMM capability of the coaxial tip. The AFM scan rate is 2 µm/s with a scan range of 100 µm. The coaxial tip base and the cantilever of the AFM probe can be clearly seen from both AFM and microwave images. The AFM cantilever was imaged because the z-direction movement limit of AFM system made the AFM cantilever contact the coaxial tip during the scan. The coaxial tip outline is evident in the AFM image with the largest topography value, and in the microwave amplitude image with the smallest absolute voltage value. The cantilever width is correctly resolved in both AFM and microwave images, around 38 μm as shown in the SEM micrograph in Fig. 11.

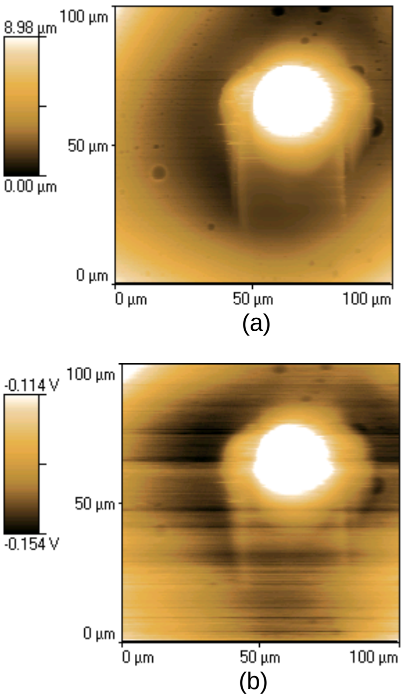

Fig. 10. Simultaneous SNMM images by the coaxial tip. (a) AFM internal sensor image; (b) Microwave amplitude image.

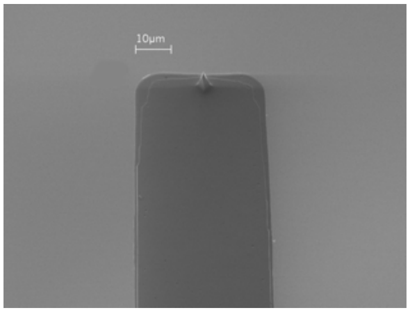

Fig. 11. SEM micrograph showing the cantilever edge step of the AFM probe used to generate images in Fig. 10.

V. CONCLUSION AND FUTURE WORK

We have described the microfabrication of an ultra-tall silicon coaxial tip with a height > 50 μm using combination of RIE and DRIE techniques. The ultra-tall coaxial tip demonstrated good electromagnetic field confinement and immunity to parasitic capacitive coupling from a conductive silicon substrate. A preliminary SNMM application using a commercial AFM system has achieved successful simultaneous AFM-microwave imaging at frequency of 2.36 GHz. Currently AFM-compatible SNMM cantilevers integrated with ultra-tall coaxial tips are under development, which will provide advanced flexibility for detecting varied samples with subsurface features and super resolutions.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance from Hongjoon Kim. This work has been supported by AFOSR MURI03 with Grant No. F49620-03-1-0420.

REFERENCES

[1] J. Park, S. Hyun, A. Kim, T. Kim, and K. Char, “Observation of biological samples using a scanning microwave microscope,” *Ultramicroscopy*, in press, 2004.

[2] M. Tabib-Azar and Y. Wang, “Design and fabrication of scanning near-field microwave probes compatible with atomic force microscopy to image embedded nanostructures,” *IEEE Trans. Microwave Theory & Tech.*, vol. 52, no. 3, pp. 971-979, March 2004.

[3] B. T. Rosner and D. W. van der Weide, “High-frequency near-field microscopy,”*Rev. Sci. Instrum.*, vol. 73, pp. 2505–2525, 2002.

[4] A. Kramer, F. Keilmann, B. Knoll and R. Guckenberger, “The coaxial tip as a nano-antenna for scanning near-field microwave transmission microscopy,” *Micron*, vol. 27, pp. 413-417, December 1996.

[5] A. Imtiaz, S. M. Anlage, “A novel STM-assisted microwave microscope with capacitance and loss imaging capability,” *Ultramicroscopy*, vol. 94, pp. 209-216, 2003.

[6] B. T. Rosner, T. Bork, V. Agrawal and D. W. van der Weide, “Microfabricated silicon coaxial field sensors for near-field scanning optical and microwave microscopy,” *Sens. Actuators. A Phys.*, vol. 102, pp. 185-194, December 2002.

[7] T. S. Ravi, B. Marcus, and D. Liu, “Oxidation sharpening of silicon tips,” *J. Vac. Sci. Technol. B, Microelectron. Process. Phenom.*, vol. 9, pp. 2733–2737, 1991.