ADVANCES IN PIEZORESISTIVE PENS FOR DIP-PEN NANOLITHOGRAPHY

Albert K. Henning[1], Joseph S. Fragala[1], R. Roger Shile[1], Pam Simao[1], and Sergey Rozhok[2]

NanoINK, Inc.

[1]Campbell, California and [2]Skokie, Illinois

Dip-pen nanolithography (DPN) has found wide-ranging applications, from electronics to materials science to biology, at size scales from at small as 10 nm for dry ink printing, and several um for wet ink printing (for instance, for printing protein biosensor nano-arrays [see Fig. 1]). Typically, DPN requires one pen for writing, and another for reading (x,y) position, and reading what has been written. Also typically, optical lever means have been employed to determine vertical position for the reader pen.

In this work, we present several approaches to an integrated DPN pen. Piezoresistive silicon stress sensors are integrated into a silicon nitride cantilever. Connecting two such sensors on the cantilever, and two reference sensors off the cantilever, into a Wheatstone bridge, provides electrical readout of vertical pen displacement. For some of the pens, thermal actuators are also integrated, allow active pen control plus electrical vertical pen position readout. We will demonstrate the fabrication method for building these sensors, and sensor-actuators.

Our approaches place electrically conductive piezoresistors onto electrically insulating cantilevers, which eliminates the leakage associated with piezoresistors embedded in semiconducting cantilevers, thereby improving the noise figure of the sensors. In addition, silicon nitride cantilevers are less brittle than single crystal silicon cantilevers. Also, silicon nitride tips are much harder, and therefore longer-lasting.

Figure 2 shows a 3D schematic of an integrated DPN piezo-pen. It is a standard silicon nitride AFM-style pen [2], with several enhancements. A previous enhancement addressed the desire for pen actuation, which is realized using a thermal actuator/resistor: changes in the temperature of the thin metal resistor film cause changes in the overall stress in the AFM cantilever, resulting in bending [3]. The enhancement in this work is to add a pair of piezo-resistive stress sensors, not to an electrically-conductive cantilever [4], but to an electrically-insulating cantilever. These sensors replace the standard optical lever approach to vertical position measurement [5]. They are incorporated into a Wheatstone bridge, whose voltage output becomes a function of the cantilever bending.

Figure 3 shows the top-down view of several piezo-pen designs.

Figure 4 shows a schematic of the last step of the process flow to realize the piezo-pens. One innovation in our approach is the attachment of the conductive piezo-resistors to the underside of the cantilever, with electrical vias through the cantilever body to connect to thin metal wires which eventually connect externally to sensing electronics (amplifiers) through conventional wire bonds. The attachment is effected during the early part of the process flow, using high-energy ion implantation and inert atmosphere drive-in/activation, so that a heavily-doped p-type silicon layer is in close proximity to the deposited silicon nitride layer. Use of a process simulator such as FLOOPS [6] is made, in order to quantify the implant energy and dose, and drive-in time and temperature, which assures the boron dopant concentration exceeds roughly 3×10^{20} cm^{-3}: the threshold required to ensure minimal etching in the TMAH solution, used to release the cantilevers mechanically [7].

Conventional surface and bulk micromachining methods were combined to achieve the integrated pen structures. Low-stress silicon nitride (silicon-rich) was deposited using LPCVD to a thickness of about 6000 Å.

Fabrication lithography was effected using a Suss contact printer. Thermo-compression Au-Au bonding was used to bond the device wafer to a silicon handle wafer, using a Suss wafer bonder. After wafer bonding, the cantilevers are released from the device wafer by removal of all the device wafer silicon using TMAH. Figure 5 shows some examples of the finished piezo-pens. The most critical step was the plasma etching of the via holes through the silicon nitride, in order to create an ohmic contact between the TiPtAu metallization, and boron-doped piezoresistors.

Enhanced designs have also been devised (see Fig. 6). These designs concentrate the stress in the cantilever due to deflection, in a pair of hinges at the proximal end of the cantilever. The stress concentration is effected through the use of longitudinal ribs, formed using KOH etching at the same time the pen tips are created. The piezoresistor is also elevated away from the cantilever surface using ion implantation, allowing a lever-arm means to amplify the cantilever stress and transfer it to the piezoresistor through the mechanically stiff plugs.

REFERENCES:

[1] R. R. Harris, *et al.*, "Multiplexed highly sensitive protein nanoarray assays for small volume samples." http://www.nanoink.net/pdf/Posters_ProteinAnalysis/Small%20Sample%20Analysis.pdf

[2] K. Salaita, *et al.*, "Massively parallel dip–pen nanolithography with 55,000-pen two-dimensional arrays." Angewandte Chemie 118 (2006), pp. 7378–7381.

[3] B. Rosner, *et al.*, "Functional extensions of Dip Pen NanolithographyTM: active probes and microfluidic ink delivery." Smart Mater. Struct. 15 (2006), pp. S124–S130.

[4] B. W. Chui, "Low-stiffness silicon cantilevers with integrated heaters and piezoresistive sensors for high-density AFM thermomechanical data storage." J. MEMS 7 (1998), pp. 69-78. Also: M. Tortonese, R. Barrett, and C. Quate, "Atomic resolution with an atomic force microscope using piezoresistive detection." Appl. Phys. Lett. 62 (1993), pp. 834–836. Also: F. Goericke, J. Lee, and W. P. King, "Microcantilever hotplates with temperature-compensated piezoresistive strain sensors." Sensors and Actuators A143 (2008), pp. 181–190. Also: S.-J. Park, J. C. Doll, A. J. Rastegar, and B. L. Pruitt, "Piezoresistive Cantilever Performance—Part II: Optimization," J. MEMS 19 (2010), pp.149-161.

[5] S. Alexander, *et al.*, "An atomic-resolution atomic-force microscope implemented using an optical lever." J. Appl. Phys. 65 (1989), pp. 164-167.

[6] M. Law, http://www.swamp.tec.ufl.edu/floops.html. Link verified 24 August 2012.

[7] E. Steinsland, *et al.*, "Boron etch-stop in TMAH solutions." Sensors and Actuators A54 (1996), pp. 728-732.

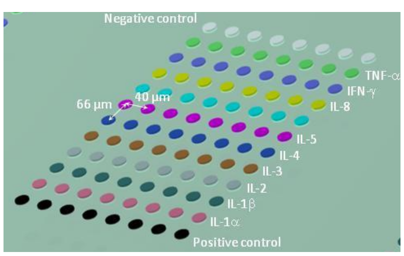

Figure 1: Protein biosensor nano-array, fabricated using silicon nitride cantilever pen array [1].

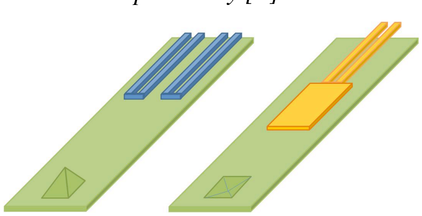

Figure 2: 3D schematic of standard AFM pen, with integrated thermal actuator, and piezo-resistor for either vertical or torsional position sensing.

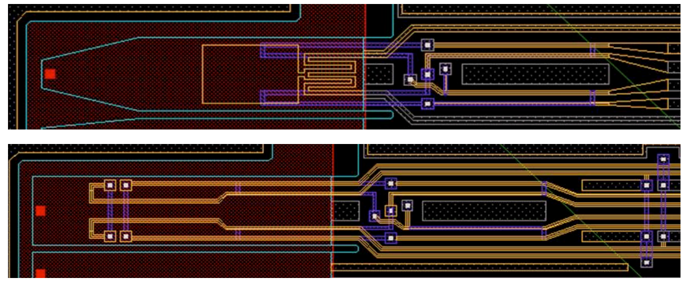

Figure 3: Design of integrated piezoresistors on silicon nitride cantilevers. Upper: longitudinal sensor, combined with thermal actuator. Lower: torsional sensor.

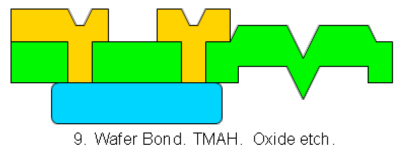

Figure 4: Schematic cross-section of heavily-doped piezoresistor integrated onto silicon nitride cantilever.

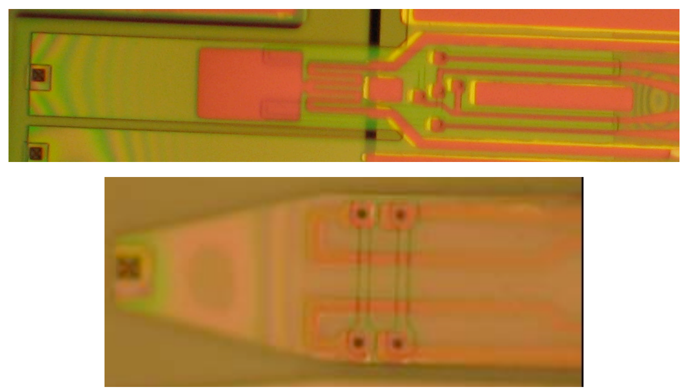

Figure 5: Fabricated, integrated piezoresistors on silicon nitride cantilevers. Upper: longitudinal sensor, combined with thermal actuator. Lower: torsional sensor.

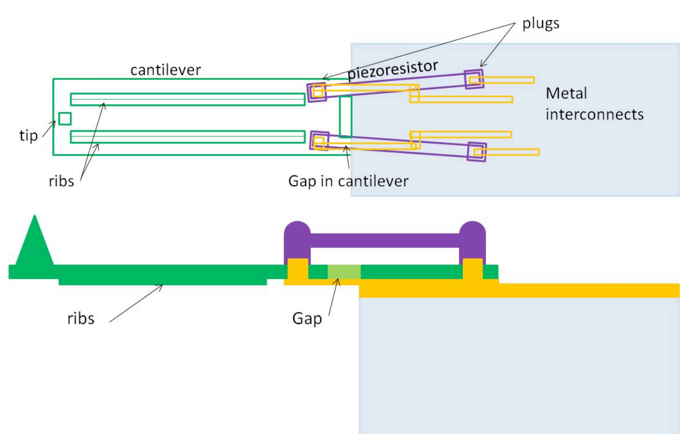

Figure 6: Elevated piezoresistive sensor on stiffened, hinged silicon nitride cantilever.