Proceedings of 2005 5th IEEE Conference on Nanotechnology
Nagoya, Japan, July 2005

Forming Low Resistance Nano-Scale Contacts Using Solder Reflow

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***Abstract* — We describe the use of solder reflow on the 100 nanometer scale to form electrically conductive contacts. We fabricated nanowires using electrodeposition in nanoporous templates. We investigated the use of directed assembly and nanoscale soldering to integrate the nanowires with microfabricated bond pads, and measured the electrical characteristics of the soldered wires.**

The electrical resistance of a single nanowire on top of two adjacent contact pads dropped by an order of magnitude after solder reflow. The results in this paper demonstrate that it is possible to use solder films as thin as 100 nm to electrically bond nanocomponents to substrates with contact resistances as low as 5 Ω.

***Index Terms* — Nanotechnology, molecular electronics, semiconductor devices, VLSI, Solder, Self-assembly.**

I. Introduction

In order to enable the era of nanoelectronics [1] it is necessary to be able to form low resistance electrical contacts in an easy and parallel manner. Damascene integration [2] that is used extensively in VLSI interconnect integration is an extremely precise layer by layer process; however, damascene integration is expensive and not very versatile. For example, it is extremely difficult to integrate two dissimilar electronic components with each other using a layer by layer approach. Another promising strategy to form nanoscale interconnects involves the use of organic molecules [3]; however, the electrical conductivity of organic molecules is high [4] and molecular interconnects are very sensitive to temperature changes. Hence there is a need to explore new methodologies to form reliable electrical contacts between components on the nanoscale.

In order to facilitate integration of nanoelectronic components, it is also necessary to bridge the gap between the nanoscale to the microscale and beyond. Many devices that contain nanoscale components will need a hierarchy of electrical connections to function effectively on the macroscale. In schemes that involve integration of nanoscale components with microscale contact pads, the contact pads are usually fabricated on top of the component, in order to minimize contact resistance [5]. The contact pads in these systems are patterned using optical or electron beam lithography after the nanoscale components have been deposited. In order to fabricate such contacts, the nanoscale components and the substrate need to be coated with photoresist that is subsequently patterned and lifted off.

In many applications in which the components may be dislodged, contaminated or damaged during subsequent fabrication of the contact pads, it would be nice if it were possible to deposit the components on top of a pattern of pre-fabricated contact pads. Moreover, while it is possible to direct assembly of a large number of components on top of pre-fabricated contact pads, it is virtually impossible to align a large number of contact pads simultaneously on top of dispersed components. However when nanoscale components are deposited on top of contact pads, there is mere physical contact between the components and the pads. Hence in previous examples [6-7] in which wires were deposited on top of contact pads, the resistance of the wires measured was high (175 Ω and up) and was dominated by the resistance of the contact.

In this paper we demonstrate that it is possible to use nanoscale soldering to permanently bond a wire to pre-fabricated contact pads to form low resistance electrical contacts.

II. Experimental Methods and Results

We utilized segmented nanowires as model functional nanoscale electrical components. In order to fabricate nanowires, we electrodeposited [8] metals in structured, porous alumina or polycarbonate templates (Fig. 1). We have fabricated wires as thin as 30 nm (Fig. 1b) using this strategy. A silver (Ag) seed layer was evaporated on one side of the membrane to serve as an electrical contact for electrodeposition. The length of the wires was restricted by controlling the current density and the duration of electrodeposition. Multicomponent nanowires composed of different metals were formed using different electrolytic solutions containing the appropriate metal ions. After electrodeposition, the wires were released into solution by dissolution of the template. The strategy of

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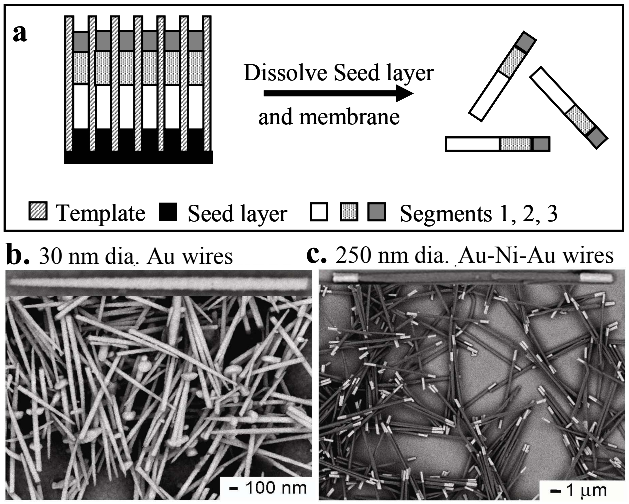

Fig. 1. (a) Schematic diagram of the strategy used to fabricate nanowires using electrodeposition in a nanoporous template. SEM images of (b) 30 nm diameter gold wires, and (c) 200 nm diameter Au-Ni-Au wires. (The back scatter contrast is brightest for metals with higher atomic numbers, Au appears brighter than Ni).

electrodeposition in templates allows the fabrication of metallic and semiconducting particles in a highly parallel and controlled manner. In order to accurately direct the assembly of nanowires on top of pre-fabricated contact pads using magnetic fields, we fabricated nanowires consisting of nickel (Ni: a magnetic material) segments terminated by gold (Au) contacts (Fig. 1c).

In order to demonstrate nanoscale soldering of wires, it was necessary to deposit the nanowires on top of pre-fabricated contact pads. We used magnetic fields to control the orientation and position of the nanowires across the contact pads [5-7]. The contact pads were fabricated using photolithography, evaporation, lift-off and electrodeposition on an insulating SiO_2 coated wafer. The contact pads were made of 50 nm of chromium (Cr: an adhesion promoter), 100-200 nm of Ni (the magnetic material), 50-100 nm of copper (Cu: the base metal that is readily wet by solder) and 50-400 nm of tin/lead (Sn/Pb) solder. The thickness of the thin films was important in directing the assembly of the nanowires and the subsequent reflow of solder. The substrate, patterned with the contact pads, was placed at the bottom of a vial containing a suspension of nanowires in ethanol, and the vial was placed in a magnetic field (field strength = 200 gauss) and gently agitated for 30-60 minutes (Fig. 2). The nanowires aligned preferentially at the energy minimum of the magnetic field, in between the nickel contact pads. The relative thickness of Ni, Cu and Sn/Pb was important in determining the outcome of the assembly. If the Ni layer was too thin or the capping Cu-Sn/Pb layer was too thick, there was no preferential alignment of the wires in between the pads and it was virtually impossible to get wires positioned in between the pads.

As a control, in a separate experiment we fabricated contact pads on top of the nanowires, using the conventional process of integrating nanowires with contact pads. Nanowires were deposited (by dip coating) on a 1 μm thick SiO_2 layer grown on a Si wafer using thermal oxidation. A layer of photoresist was spun on the substrate and the contact pad mask was aligned with respect to the ends of the nanowires. Subsequently 50 nm of Cr and 300 nm of Cu were evaporated and the photoresist was dissolved in acetone. Fig. 3a shows the contact pads fabricated on top of a single nanowire using microlithography. The 300 nm thick layer of copper is thick enough to completely cover the nanowire and hold it in place. The nanowires deposited on top of the pre-fabricated contact pads using magnetic assembly are shown in Fig. 3 b and c. By controlling the concentration of the wires in the solution it is possible to get two wires (Fig. 3b) or a single wire (Fig. 3c) positioned in between two adjacent contact pads.

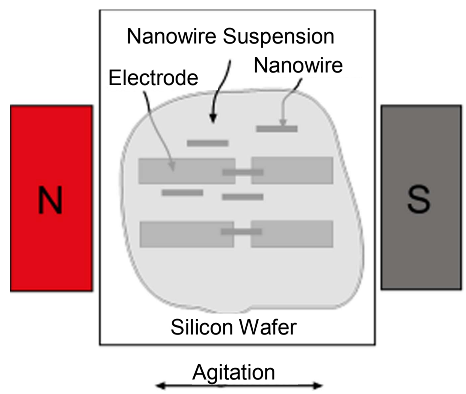

Fig. 2. Schematic diagram of directed assembly using magnetic fields.

All resistances were measured using four probes and two Keithley 2400 source meters. For contact pads fabricated on top of wires (Fig. 3a) we performed 3 experiments and found the wires to have an average resistance of 11 Ω with a range of 3 Ω (Fig. 4c). Although we fabricated nanowires in a membrane with a pore diameter of 200 nm, the actual wires obtained have a range of diameters between 200 nm and 300 nm (median: 250 nm). Theoretically, assuming bulk values of resistivity, we expect the resistance of 250 nm diameter Ni wires to be 0.141 Ω/100 nm and Au wires to be 0.045 Ω/100 nm. Hence, the measured resistance of the nanowires (with approximately 500 nm of Au at each end and 5 μm of Ni in the center) is dominated by the

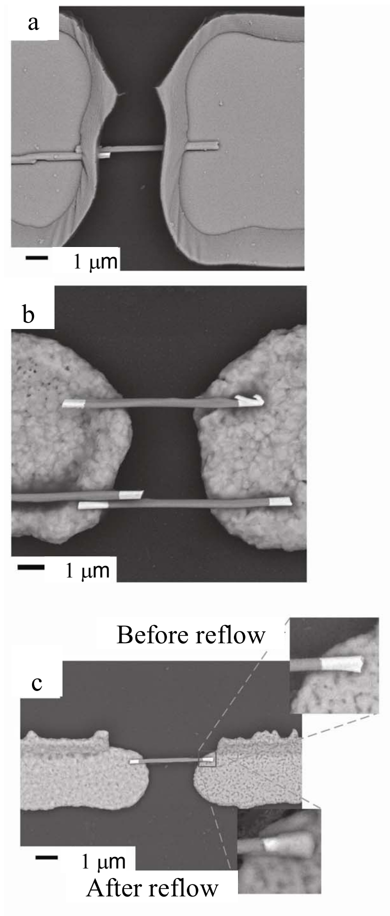

Fig. 3. (a) SEM image of contact pads aligned over the ends of a nanowire using photolithographic patterning. SEM image of (b) two wires, and (c) a single wire deposited on top of pre-fabricated contact pads using magnetic assembly.

resistance of the actual wire with a small contact resistance (< 2 Ω). The resistance of wires magnetically aligned on top of the contact pads was measured in the range of 200 Ω to 1 MΩ (Fig. 4a). The high resistance was a consequence of the high contact resistance at the junction between the nanowire and the contact pad, since the wire was just sitting on top of the contact pad with no robust electrical contact. In some cases, the resistance of the contact was so high that the wire was blown off the pads with a current at mA level.

In order to decrease the contact resistance and form a robust contact, we soldered the wires in place by reflowing the solder on the contact pads. Reflow was carried out by placing the substrate containing the contact pads with the aligned nanowires at the bottom of a vial. A drop of flux (RMA-5, Indium Corporation) was placed beside the chip and the vial was purged with nitrogen. Fluxes are used in soldering to chemically clean the surfaces to be joined, and to maintain the cleanliness of the surfaces so that a metallic bond can be formed at the interface, resulting in a robust electrical contact [8]. The vial was purged with nitrogen that functions as a protective atmosphere which prevents oxidation of the solder film during reflow. During reflow the wires were first pre-heated to 120 °C for several minutes, and then the vial was heated to 180 °C to activate the flux aned then quickly ramped to the peak reflow temperature ~250 °C. This temperature profile was modeled on the process used in commercial solder reflow in IC packaging [9].

After reflow, the substrates were characterized using SEM and electrical probe testing. From SEM analysis, in some cases no discernible visual difference was observed (top-down), before and after reflow, even though the resistance of the wire dropped substantially. We believe that the relative thickness of the Ni, Au Cu and solder films are important in observing dramatic reflow, since solder wets Cu but does not wet Ni well, and Au and Sn rapidly diffuse into each other. We measured 4 data points and obtained resistances with an average of 30 Ω with a range of 20 Ω. (Fig. 4b) This resistance measured after reflow was an order of magnitude lower than that measured before reflow. We attribute this decrease in measured resistance to a large drop in contact resistance (to approximately 5 Ω per contact). The contacts formed in our experiments were robust and survived currents as high as 500 mA. It should be noted that the role of the flux is crucial in obtaining low resistance contacts. In the absence of flux, the oxide interface formed prior and during reflow precludes the formation of low resistance

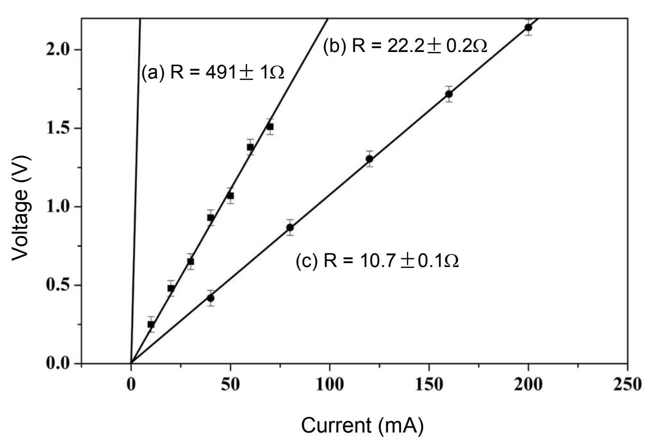

Fig. 4. Typical nanowire resistance curves. (a) A wire on top of contact pads before reflow with a high contact resistance, (b) a wire on top of contact pads after reflow with a small contact resistance, and (c) a wire underneath the contact pads with minimal contact resistance.

electrical contacts. One possible reason for the large range in resistance values measured is due to the variation in the soldered contact area between the wire and the contact pad. There are a lot of factors that affect reflow in solder films as thin as 100 nm. Oxidation of the solder as well as intermetallic formation (that is a result of base metal diffusion into the solder) can seriously impact contact resistance. The effect of thickness of the films, flux, reflow temperature profile and type of nanowires used on the resistance values measured is being investigated further.

III. Conclusion

In conclusion we have demonstrated that solder reflow can be used to form low resistance electrical contacts between nanoparticles and substrates. Although the resistance of the contacts is higher than that obtained by patterning contact pads on top of the wires, it is much lower than that measured with wires deposited on pads without solder reflow. Solder reflow on the nanoscale is especially sensitive to oxidation and intermetallic formation and it is necessary to investigate new strategies to protect the solder during reflow, and develop solders that resist surface degradation. Since the formation of low resistance contacts on the nanoscale is difficult, nanoscale soldering may prove to be a valuable strategy to form such contacts.

Acknowledgement

Acknowledgement is made to the donors of the American Chemical Society Petroleum Research Fund for the partial support of this research. This research was supported in part by an NSF-CAREER award from the Program of Design, Manufacture, & Industrial Innovation (DMII).

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