Directed Assembly of Nanowires in AC Fields: Tuning Wire Design and Electrode Geometry to Observe Ordered Arrays

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Introduction:

Nanowires form a fascinating topic of inquiry in modern research and offer material properties that are advantageous in fields such as next-generation electronics, solar cells, and optics [1]. Dense, ordered arrays of nanowires are needed to investigate potential advantages. In unregulated assembly, however, nanowires tend to become trapped in entropically unfavorable positions and orientations. This project explored the introduction of an applied current (AC) field on gold (Au) nanowires to form assemblies with observable and ultimately reproducible properties. Partially-etched nanowires were synthesized and assembled in lithographically-designed gold electrodes. Field strength was fine-tuned for specific wire designs, and the use of different electrode geometries created unique field conditions that visibly influenced resulting assemblies. Effectiveness of electrode geometries was also studied in experiments.

Wire Synthesis:

It was necessary to fabricate nanowires in large quantities while maintaining a relatively narrow size distribution. This was achieved using a porous alumina membrane that acted as a nanotemplate for the metallic wires. Multicomponent nanowires featuring segments of different metals were able to be prepared via electrodeposition into pores beginning bottom-upwards from a sacrificial silver base. Removal of both the membrane and base yielded approximately a billion monodisperse wires in solution, with a nominal diameter of 300 nm and length determined by deposition time.

The wire design chosen for experiments featured a 2 μm gold (Au) segment and a 3 μm etched segment (2Au-3E) (Figure 1). To achieve partially-etched nanowires, silver (Ag) metal was deposited on top of the gold segment. A thin coating of amorphous silica retained wire shape, and selective etching of the silver segment left a hollow, solvent-filled segment in its place. Assemblies resulting from these wires were more ordered than wires featuring a longer Au segment, so experiments with the 2Au-3E wires were chosen for accurate analysis of lattice structures.

Electrode Synthesis:

Electrodes were designed featuring a central gap, micrometers in diameter, to accommodate the small wire size. Au electrodes were fabricated using standard photolithography techniques. After spinning positive photoresist onto 35 mm circular glass cover slip, projected light through a patterned mask exposed certain regions in the precise shape of electrodes. After removal of the reacted areas in a developing solution, a binding titanium (Ti) layer and a 50 nm Au layer were deposited via electron-beam evaporation. Lift-off in another developing solution removed all remaining photoresist to leave usable Au electrodes behind on the substrate surface. The two extended probes at the electrode base provided an attachment site for an external field generator.

Two types of electrodes were fabricated for assemblies (Figure 2). Bulb-stem electrodes featured alternating circular and

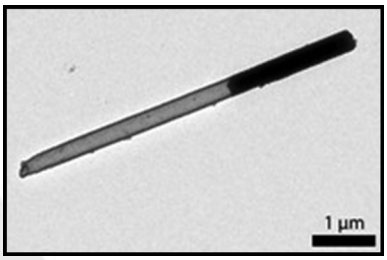

Figure 1: TEM of one of the 2Au-3E nanowires used in experiments.

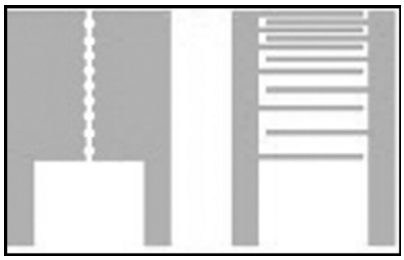
Figure 2: The two electrode designs: bulb-stem (left) and interdigitated (right).

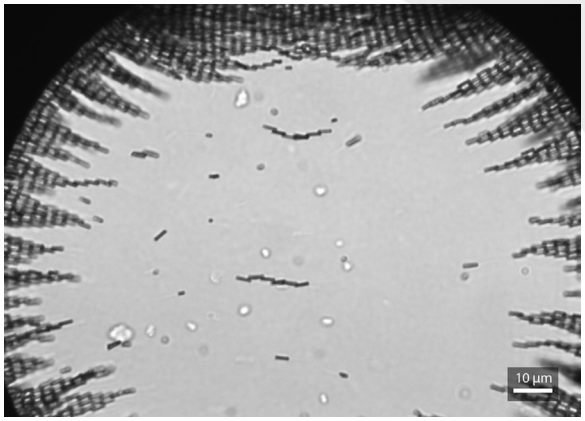

Figure 3: A 100 µm bulb region of the bulb-stem electrode during assembly.

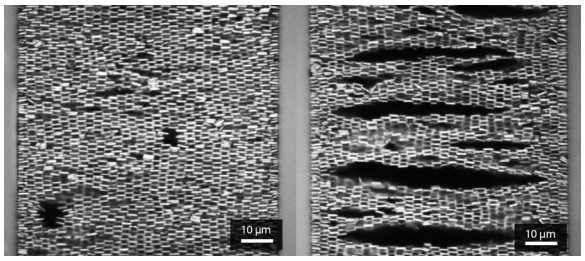

Figure 4: Annealed assemblies in the 50 µm gap of bulb-stem electrodes (left) and interdigitated electrodes (right).

rectangular regions, 100 μm at the widest and 50 μm at the narrowest. Interdigitated electrodes featured gaps of uniform widths ranging from 10 μm to 150 μm. Both electrode geometries produced unique areas of field maxima and minima that influenced final lattice structure.

Experimentation and Results:

Nanowires were appropriately diluted and placed in a silicone spacer on top of the electrode. Electrodes were attached to an external field generator using a thin Au wire and Ag epoxy binding on each probe. The cover slip with the set-up apparatus was then placed on an inverted optical microscope for real-time observation during experiments. Once wires were sedimented to the substrate surface, the field was turned on at low conditions and increased over time (Figure 3).

At low voltage and frequency, wires began to orient preferentially with Au segments in contact with the electrode edge. Particle motion occurred through a process called dielectrophoresis, where field-induced dipoles on polarizable gold segments drew wires towards the stronger field gradient at edges. Increasing voltage and frequency of the field drew in a greater number of wires and eventually allowed wires to completely bridge the electrode gap.

After the field was on for a significant amount of time, assembly structures were "annealed"—we refer to annealing as turning on and off the field to give wires the opportunity to reorient positions. The annealed structures in the 50 μm gaps of both the interdigitated and bulb-stem electrodes were compared (Figure 4). The lattices in the bulb-stem electrodes had significantly less defects, perhaps a result of "funneling" concentrating effect towards stem centers produced by larger bulbs. Since interdigitated electrodes had parallel edges, lattices did not exhibit the same density and uniformity.

A qualitative comparison of the two suggests that electrodes of alternating bulb-stem patterns are more capable of producing ideal nanowire arrangements than isometric gaps. In addition, we observed that spacing between wires was too small to accommodate the longer etched segment, suggesting that some wires had to be positioned out of plane for uniform lattices to form.

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Summary:

Overall, ordered arrays of partially-etched gold nanowires were successfully produced using the 2Au-3E wire design. The bulb-stem electrodes proved to be the most effective at condensing assemblies by comparing final annealed structures to the IDE geometry.

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References:

[1] Triplett, D. A., et al.; "Assembly of Gold Nanowires by Sedimentation from Suspension: Experiments and Simulation"; J. of Phys. Chem. C., 114, 7346 (2010).