

Nanopartz has recently released the first commercially available gold nanowires. These gold nanowires are approximately 30nm and up to 20 microns in length exhibit properties that are suitable for many applications including: (1) nanoelectronics; (2) heat pipes for thermal management of advanced electronics; (3) light pipes; (4) optical sensors; and (5) tribology additives .

Gold Nanowires for Nanoelectronics

One of the biggest limitations in nanoelectronics, whether it be a top down or bottom up approach is the method, manipulation and connection of the nanocircuitry. With the development by Nanopartz of gold nanowires in huge quantities and long lengths and more recently the development of cold welding by researchers at Rice University, future opportunities in true nanoelectronics seem possible. ¹

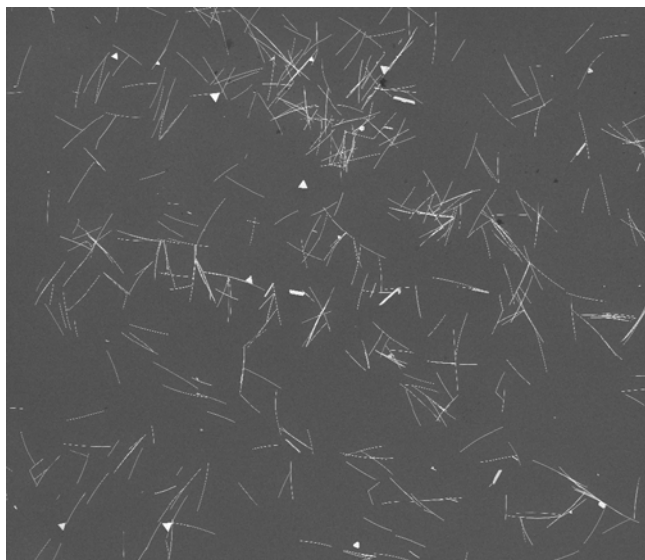


Figure 1 TEM of Nanopartz Gold Nanowires

The conductivity of a nanowire is expected to be much less than that of the corresponding bulk material. This is due to a variety of reasons. First, there is scattering from the wire boundaries, when the wire width is below the free electron mean free path of the bulk material. In copper, for example, the mean free path is 40 nm. Nanowires less than 40 nm wide will shorten the mean free path to the wire width.

Nanowires also show other peculiar electrical properties due to their size. Unlike carbon nanotubes, whose motion of electrons can fall under the regime of ballistic transport (meaning the electrons can travel freely from one electrode to the other), nanowire conductivity is strongly influenced by edge effects. The edge effects come from atoms that lay at the nanowire surface and are not fully bonded to neighboring atoms like the atoms within the bulk of the nanowire. The unbonded atoms are often a source of defects within the nanowire, and may cause the nanowire to conduct electricity more poorly than the bulk material. As a nanowire shrinks in size, the surface atoms become more numerous compared to the atoms within the nanowire, and edge effects become more important.

Furthermore the conductivity can undergo a quantization in energy: i.e. the energy of the electrons going through a nanowire can assume only discrete values, multiple of the Von Klitzing constant $G = 2e^2/h$ (where e is the charge of the electron and h is the Planck constant).

The conductivity is hence described as the sum of the transport by separate *channels* of different quantized energy levels. The thinner the wire is, the smaller the number of channels available to the transport of electrons.

Gold Nanowires for Heat Pipe Operation

Heat pipes are passive, two-phase closed loop systems used for temperature regulation in electronic, power-generation/conversion, and optical systems. Heat pipes are the method of choice for electronic systems thermal management because of the performance advantages they have over conventional aluminum extrusion heat sinks and other solid state cooling technologies. A heat pipe cooler uses the high efficiency evaporation and condensation cycles of a working fluid to transfer heat. Compared to other cooling techniques, such as forced single and two-phase flow cooling and direct immersion cooling, heat pipes do not require mechanical pumps, valves or consume any power. Consequently heat pipes are quiet, more efficient, have no operating cost and are more reliable than other thermal management systems. They require no maintenance, have zero noise and vibration characteristics, and require no power for operation.

The electronics industry is facing ever increasing power densities as device sizes shrink and the performance of devices such as processors continues to increase. The associated heat load is a critical issue as chip manufacturers, trying to perpetuate Moore's law, find themselves outpacing the capabilities of existing thermal solutions. Power and heat have become the biggest issues for chip manufacturers and companies integrating these chips in everyday

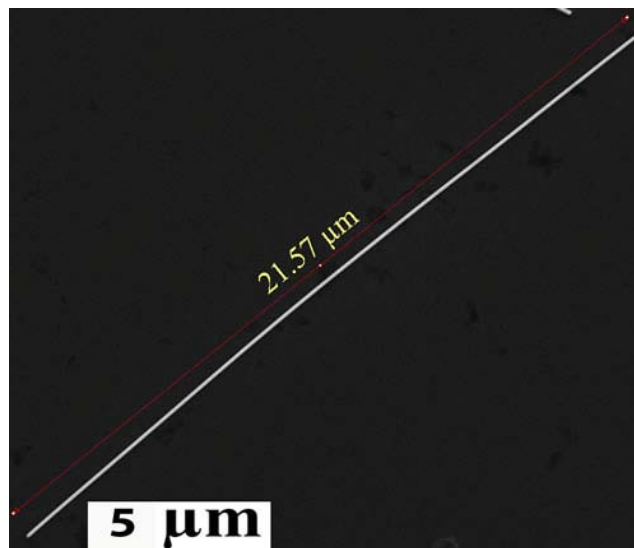


Figure 2 TEM of Nanopartz 30nm x 22um gold nanowire

devices such as cell phones and laptops. The computing power of today's computer chips is provided mostly by operations switching at ever higher frequency. This physically induced power dissipation represents the limiting factor to a further increase of the capability of integrated circuits. Heat dissipation of the latest Intel processors has become a prominent issue. If the trends continue, future chips could approach the temperatures of a nuclear reactor or even a rocket nozzle. As the electronics industry continues to produce smaller and slimmer portable devices, manufacturers are challenged to find new ways to combat the persistent problem of thermal management.

Nanowire arrays have significant attributes that make them advantageous as the wick material in heat pipes. The tight packing of the wires in the array provides a high capillary pressure to promote fluid flow through the wick while the array configuration of the wires provides a clear path for vapor to escape. ⁱⁱ

Photon Ballistic Waveguides

Nanowires are being studied for use as photon ballistic waveguides as interconnects in quantum dot/quantum effect well photon logic arrays. Photons travel inside the tube, electrons travel on the outside shell. ⁱⁱⁱ

Sensors

Gold nanowire sensors have been found to be useful for detecting airborne elemental mercury at concentrations on the order of parts per billion (ppb). ^{iv} Gold nanowire sensors can be regenerated under conditions much milder than those necessary for regeneration of gold films that have been used as airborne-Hg sensors. The interest in nanowire sensors in general is prompted by the expectation that nanowires of a given material covering a given surface may exhibit greater sensitivity than does a film of the same material because nanowires have a greater surface area.

Gold nanowire sensors may also be used in chemisorption mode since chemisorptions from the gas or liquid phase can result in a measurable resistance change in a metallic material when at least one dimension is smaller than the mean free path for electrons. ^v

Tribology

Because of their high Young's moduli, their use in mechanically enhancing composites is being investigated. Because nanowires appear in bundles, they may be used as tribological additives to improve friction characteristics and reliability of electronic transducers and actuators. ^{vi}

Dielectrophoresis

Gold Nanowires exhibit dielectrophoresis (or DEP) is a phenomenon in which a force is exerted on a dielectric particle when it is subjected to a non-uniform electric field. ^{vii} This force does not require the particle to be charged. All particles exhibit dielectrophoretic activity in the presence of electric fields. However, the strength of the force depends strongly on the medium and particles' electrical properties, on the particles' shape and size, as well as on the frequency of the electric field. Consequently, fields of a particular frequency can manipulate particles with great selectivity. This has allowed, for example, the separation of cells or the orientation and manipulation of nanoparticles and nanowires.

ⁱ *Nature Nanotechnology* 5, 218 - 224 (2010)

ⁱⁱ Proceedings of ITP2009 Interdisciplinary Transport Phenomena VI: Fluid, Thermal, Biological, Materials and Space Sciences October 4-9, 2009, Volterra, Italy

ⁱⁱⁱ Simulation of a plasmonic tip-terminated scanning nanowire waveguide for molecular imaging
Appl. Phys. Lett. 93, 193101 (2008); doi:10.1063/1.3013816

^{iv} Detecting Airborne Mercury by Use of Gold Nanowires NASA's Jet Propulsion Laboratory Wednesday, July 01 2009

^v Single Porous Gold Nanowire Sensors *J. Phys. Chem. B*, 2006, 110 (9), pp 4318-4322

^{vi} Liquid-like tribology of gold studied by *in situ* TEM, *Wear*, [Volume 265, Issues 11-12](#), 26 November 2008, Pages 1864-1869

^{vii} "Nanowires get reconfigured". Oct 19, 2006