OPTICAL PROPERTIES OF INDIUM NANOWIRE ARRAYS

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INTRODUCTION

Advances in nanotechnology have opened up research opportunities on materials with ultrafine microstructures. The design and characterization of nano-composite materials consisting of a mixture of conducting and insulating phases in the nanometer range is now possible. The bulk electronic properties of such nano-composites may be tailored by altering the constituents, their size and shape distributions, or their relative concentrations. Semiconductor-insulator and metal-insulator nanostructures exhibit a modified optical response as a result of size, shape, and surface effects and have applications in optical filters, transparent contacts, and nonlinear optical elements.

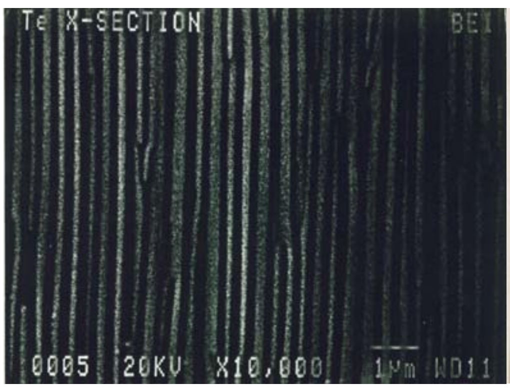
In this study a nanowire array is developed in which the active phase occupies a volume fraction of several tens percent. The synthesis technique is described and samples prepared by this technique have been structurally characterized. The optical properties are investigated and compared to very rudimentary Maxwell-Garnett models.

SAMPLE PREPARATION AND EXPERIMENTAL RESULTS

The samples were prepared by high pressure injection of the conducting indium melt into a nanoporous alumina matrix.[1, 2] The matrix used was a commercially sold matrix for micro-filtration under the trade name Anopore. It consists of an Al_20_3 plate 25 mm in diameter and about 55 μm thick, which supports an array of parallel, non-interconnected, cylindrical channels running perpendicular to the plate surface. An externally applied hydrostatic pressure is needed to overcome surface tension which resists the melt from entering the narrow channels. For a channel diameter of 10 nm, the required injection pressure ranged between 0.5 and 3.5 kbar. The sintering of the nanochannel insulators sets an upper limit on the melting temperature of the impregnant of about 1400 ^{0}C.

To allow for measurement in an optical absorption spectrometer the sample is made into a thin disk with well polished sides. The sample was approximately of 50 μm thickness initially, and brittle, and it was therefore mounted on a rigid substrate. After some experimentation it was found that if the sample is mounted to a sapphire disk using Epoxy adhesive Cyanoacrylate Glue gel it can be handled safely. The sample was abraded and polished using a conventional Alpha-alumina powder to produce a highly polished, scratch-free, and mirror-like surface.

The structures of the samples were analyzed using a scanning electron microscope (SEM). A Digital Instruments NanoScope® scanning force microscope was used both for topographical and electrical field measurements. The sample was mounted with conductive epoxy to a metal holder and held at a few volts relative to a conductive cantilever tip which was grounded. The metal coated, etched single crystal silicon tip had a radius of curvature of about 5 nm. The tip is set to oscillate at a frequency near its resonance frequency (78 KHz). When the cantilever encounters a vertical electric field gradient, the effective spring constant is modified, shifting its resonance frequency. By recording the amplitude of the cantilever oscillations while scanning the sample surface, an image revealing the strength of the electric force gradient is obtained. The image, however, may also contain topographical information, making it difficult to separate the two effects. This is circumvented by taking measurements in two passes over each scan line.[3] On the first pass, a topographical image is taken with the cantilever tapping the surface and the information is stored in memory. On the second pass, the tip is lifted to a selected separation between the tip and local surface topography (typically 20 to 200 nm), such that the tip does not touch the surface. By using the stored topographical data instead of the standard feedback, the separation remains constant. In this second pass, cantilever oscillation amplitudes are sensitive to electric force gradients without being influenced by topographic features. This two-pass measurement process is recorded for every scan line, producing separate topographic and electric force images.



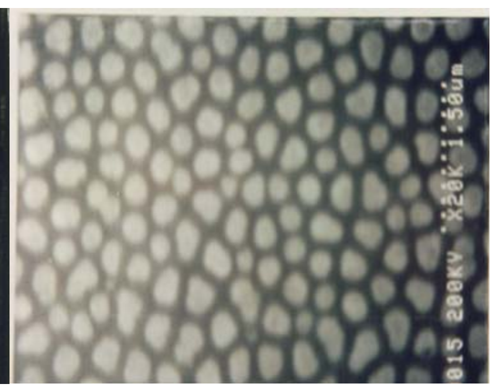


Figure 1. (left) Cross-sectional image.

Figure 2. (right) Top image.

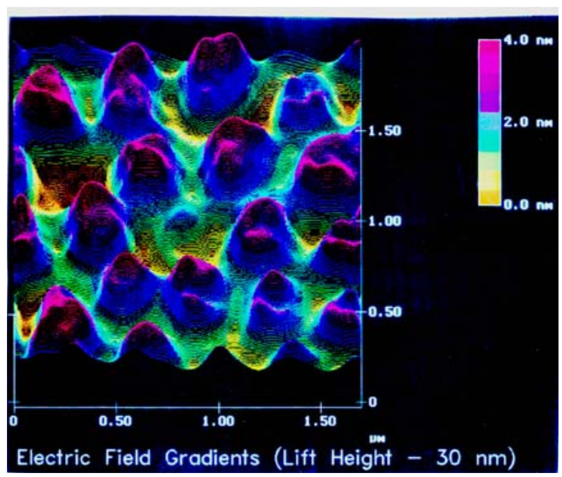


Figure 3. (bottom) Electric Field.

Figure 1 shows the image of a slice of a nanowire composite where the Al_2O_3 has been etched so that the wires protrude slightly. Higher topography features appear as lighter areas and are the Indium nanowires. Figure 2 shows the topographical image where the lighter areas are the wire cross-sections. The corresponding image of the electric force gradient contours taken with a lift height of 30 nm is shown in Figure 3. In the electric field images the amplitude of the cantilever oscillations is found to be very large for small lift heights, and the images fade at separations larger than 80 nm. This is consistent with previous reports of a strong dependence of the tip-surface force on the vertical separation.[4] Note that some of the nanowires that appear in the topographic image are missing from the electric field image. This is because either electrical contact to these nanowires has failed or electrical conduction along the wire length has been interrupted.

MAXWELL GARNET MODEL AND CONCLUSIONS

In Figure 4 the infrared absorption coefficient of an array of indium wires 200 nm in diameter and 8 mm long (metal volume fraction close to 50%) for unpolarized light propagating along the wire length (top solid line) is shown. For comparison, the absorbance coefficient of bulk indium in this spectral region is about 1.3×10^6 cm^{-1}. Infrared-absorption spectra were measured with a single-beam dispersive spectrometer based on a 0.50 m monochromator (5 cm^{-1} resolution), f-number of 8, and a PbS thermo-electrically cooled detector. The signal is detected with a very sensitive lock-in amplifier. The bottom line shows a rudimentary Maxwell Garnet model of dielectric function. The results clearly demonstrate that a more sophisticated explanation is needed for the transmission properties.

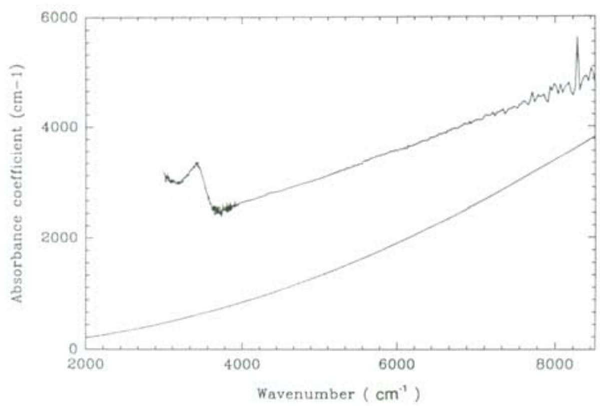


Figure 4. Infrared Transmission.

We are interested to show that the nanowire arrays can be microengineered to become optically transmissive. Good optical transparency and electrical conductivity could be simultaneously achieved in a metal microstructure where there is electrical isolation along the photon electric field (i.e., the photon and current-driving electric fields are perpendicular).[5] It is interesting that there appears to be no effective-medium theory that can be applied to our system. We hope that our experimental measurements will interest other physicists and engineers to the theoretical aspects of this problem. Also, by applying the injection technique to ultrasmall channel insulators (channel diameter less than 50 nm)[6] nanowire arrays can be made for fundamental studies of a variety of phenomena such as quantum confinement of charge carriers and mesoscopic transport.

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