Thermal conductivity mapping on embedded carbon fibers

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Scanning thermal microscopy (SThM) allows measurement of local temperature or thermal conductivity with nanometer resolution, e.g. in semiconductor devices or polymer science. Thereto, a small temperature sensor, e.g. a thermocouple, is placed at the apex of an AFM cantilever tip. The tip is raster scanned across the surface to record the sample topography and simultaneously the temperature-related material properties.

For many applications, polymers provide advantages over metallic materials due to lower weight, high corrosion resistance and often easier processability allowing more design freedom. However, polymers are commonly poorly thermally conductive. Additives, such as carbon fibers, are widely used to provide such polymers with thermal conductivity. Depending on the additive and manufacturing process, heat transport within such compounds can be directional, e.g. in plane rather than through plane, which can help optimizing the thermal management in different environments and applications. Thermally conductive compounds are typically found in LED luminaires, temperature sensors, aerospace and automotive cooling systems as well as consumer electronics.

Here, we used a *Flex-Axiom* system extended with an *AppNano VertiSense Thermal Microscopy Module* to map the thermal conductivity of carbon fibers embedded in a polymer resin. Figure 1 (top) shows carbon fibers embedded into a polymer matrix. After polishing, the carbon fibers slightly protrude the polymer matrix. Thermal conductivity

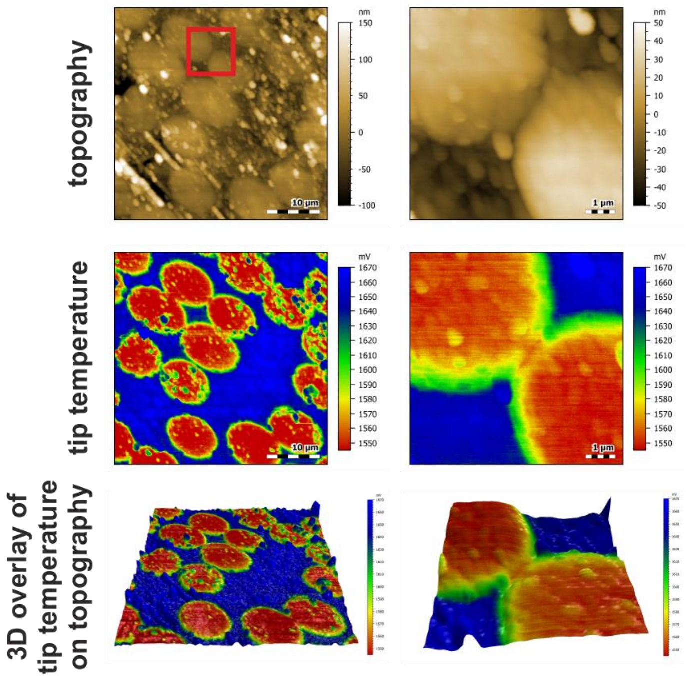

Figure 1. AFM imaging and thermal analysis of polymer-embedded carbon fibers. AFM topography (top), tip temperature (uncalibrated Imaging Amplifier output, middle) and tip temperature mapping to the 3D sample topography representation (bottom). Images in the left column show a 40 µm sample area, while the images in the right column were recorded inside the area indicated by the red square shown on the topography image in the left column.
Top: AFM topography of carbon fibers embedded into a polymer. Fibers were cut nearly perpendicular to the fiber axis and polished. Middle: In the thermal conductivity mapping mode, the cantilever tip is heated by the laser and its temperature reflects the thermal conductivity of the underlying substrate: the higher the thermal conductivity of the material the lower the cantilever tip temperature due to heat dissipation from the tip into the sample. A higher tip temperature is here reported by a higher output value of the Imaging Amplifier. Bottom: Thermal conductivity mapping to the 3D topography representation.
An AppNano VTP500 cantilever was used in static mode for simultaneous AFM imaging and thermal conductivity measurements.
Sample courtesy Dr. Wölling, Fraunhofer ICT, Augsburg

mapping (Figure 1, middle) revealed that the carbon fibers exhibit a higher thermal conductivity (i.e. lower tip temperature) compared to the surrounding polymer matrix. Some areas on the carbon fibers show a reduced thermal conductivity pointing towards polymeric debris on top of the fiber surface. Such debris could be remainder material from the cutting/polishing process. Superimposing the thermal conductivity map on a 3D representation of the sample topography allows clear correlation of the thermal conductivity properties with sample topography.

For thermal conductivity mapping the AppNano VertiSense system extended the Nanosurf Flex-Axiom system. The Verstisense system consists of an Imaging Amplifier and special cantilevers:

- The Imaging Amplifier (Figure 2) is compatible with the Nanosurf C3000 controller (Signal I/O option required) and the Nanosurf EasyScan2 controller (signal module required)
- The Imaging Amplifier output can be directly converted into tip temperature using the configurable Nanosurf controller user input and recorded alongside with sample topography.
- The thermocouple sensor is located at the apex of the cantilever tip (Figure 3) allowing precise temperature measurements. The material surrounding tip sensor is thermally insulating to prevent heat loss from the tip to the cantilever.
- The system can be operated in two different modes. Here, the conductivity mapping mode (CMM) was used.

Figure 2. The VertiSense Imaging Amplifier. It connects to the VertiSense cantilever and the Nanosurf AFM controller. The Imaging amplifier is controlled via a tablet or smartphone application.

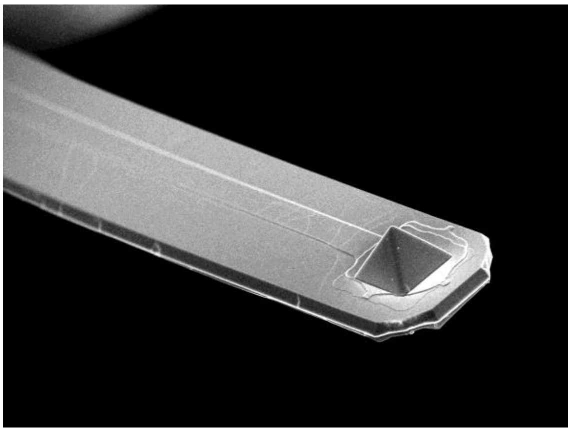

Figure 3. Scanning electron micrograph of a VertiSense AFM cantilever. The cantilever bears a tiny thermocouple element at the apex of the AFM cantilever tip. The material around the thermocouple is thoroughly chosen to prevent heat loss from the thermocouple into the cantilever material. Thus, precise temperature

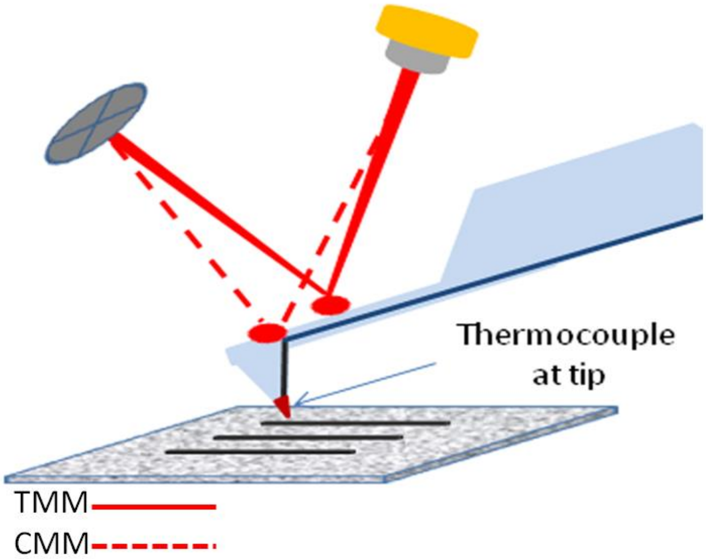

Figure 4. Different operating modes of the VertiSense system. In the thermal conductivity mapping mode (CMM), the laser is focused right above the tip of the cantilever (dashed line). The laser thus heats the cantilever tip containing the thermocouple at its apex. Passing over a thermally conductive area of the sample, heat from the tip will be dissipated more efficiently into the sample and thus the temperature of the tip is lowered. On thermally less conductive areas, the heat dissipation is less efficient and the tip temperature is lowered to a smaller degree.

In the temperature mapping mode (TMM), the laser is focused behind the tip of the cantilever (solid line) and thus does not heat the tip. The thermocouple at the tip can thus measure the sample temperature.

Qualitatively, the VertiSense Imaging Amplifier reports the temperature as an output voltage where a higher voltage corresponds to a higher temperature of the tip. Using a special temperature-controlled reference sample, the thermocouple can be calibrated to facilitate absolute temperature measurements.