Exploring carbon nanotubes as high resolution probes for scanning thermal microscopy

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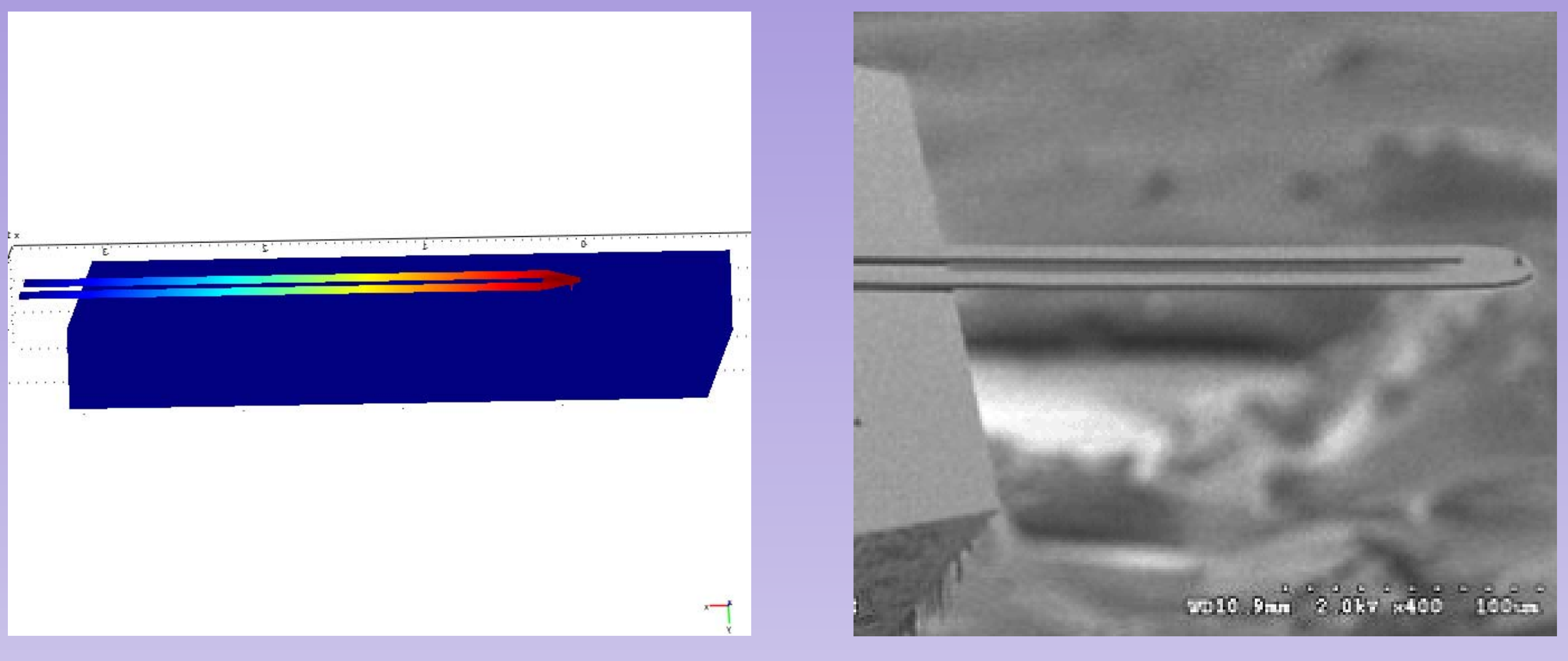
Thermal Microscopy has numerous uses in modern science and Carbon Nanotubes (CNT) have already brought significant potential to SPM as ultimate resolution probes [1]. CNT’s extreme heat conductance as well as their outstanding mechanical properties suggests further exploration of their application in Scanning Thermal Microscopy (SThM). If a fully functional CNT thermal probe could be reliably produced this would greatly increase the thermal and lateral resolution of SThM. Therefore it is important to evaluate the ultimate performance and optimal design for such probes.

To this extent COMSOL Multiphysics was used to create a realistic finite elements model of a thermal probe including both AC/DC and thermal behaviour of the microfabricted probe. This model was then verified by the experimental SThM results and expanded in order to investigate potential advantages and disadvantages of CNT tip as an SThM probe.

At present thermal resolution for SThM is about 100nm but this could be improved to 10nm or less with a CNT tip. CNTs make great tips because; they are strong, hard wearing when in contact and have high thermal conductivity.

There are many challenges facing creating a CNT probe; attachment to the tip, mechanical stability, heat transfer from sample to tip and the influence of air. A good model will help with over coming these challenges and understand experiments better.

The model was based on the Anasys Instruments ThermaLever probe AN2-300 [2] shown below. All the correct dimensions and properties for this probe were entered into the model. The cantilever was made out of silicon with different doping levels.



Figures 1 and 2: left; Comsol model of thermal cantilever and sample.
Right; scanning electron microscope picture of the Anasys probe that the model is based on.

Our plan was to produce simulations for a simple tip in vacuum and air which were used to test experimental results. The models were then expanded to see the affects of adding a CNT of various dimensions in vacuum and air. As well as dynamic approach such as tapping mode.

The model was first tested by comparing different tip contact diameters as a larger tip contact area should give more heat flow. For a silicon sample the model demonstrated that the larger the thermal contact, the more heat flowed and the lower the temperature of the tip as expected. For both models in vacuum and air showed the same. For models including air a block was added inclosing the entire cantilever with the properties of air. These results are shown in the table below.

	Contact temperature /K	Contact temperature jump /K
0.5 µm	301.315	9.798
100 nm	305.91	5.203

Table 1: results of Comsol models for different contact tip areas. Models were for a Si sample and a non-CNT tip.

A model was created without a CNT so that the results could be compared with experimental data. Models were made for both air and vacuum situations with the contact and non-contact temperatures for different sample recorded. The experimental results were taken by normal scanning mode in an atomic force microscope. These are compared with the model values below.

AIR Sample	Comsol model ΔT	Experiment ΔT
Si	2.25	3.721
Au	2.298	
PMMA	0.003	1.643
Polyimide	0.047	

Vacuum Sample	Comsol model ΔT	Experiment ΔT
Si	5.539	
Au	5.663	1.764
PMMA	0.156	
Polyimide	0.125	1.309

Table 2 and 3: Comparison of temperature jump between contact and non-contact in Comsol models and experimental results.

The experimental temperatures were higher than in the model due to some affect not being taken into account such as; phonon reflections at boundaries and the heating affect of the AFM laser.

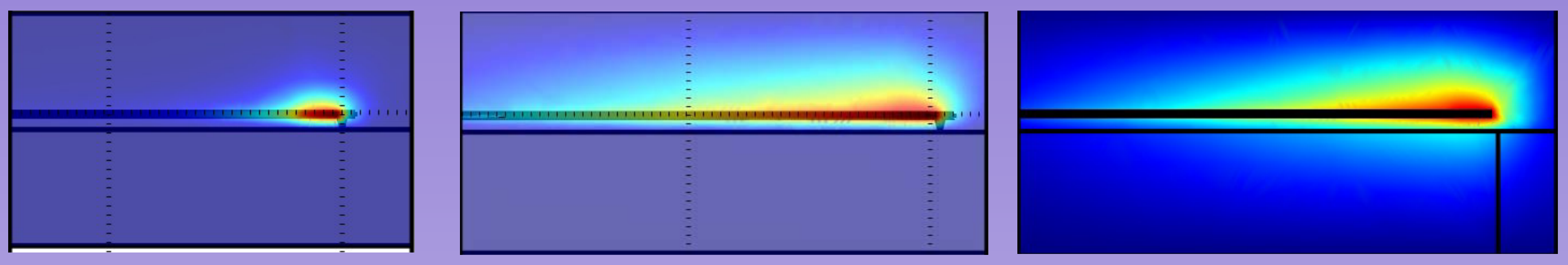


Figure 3, 4 and 5: Comsol side on view of models; 5.7E-6s after heating started, air and non-contact (from left to right)

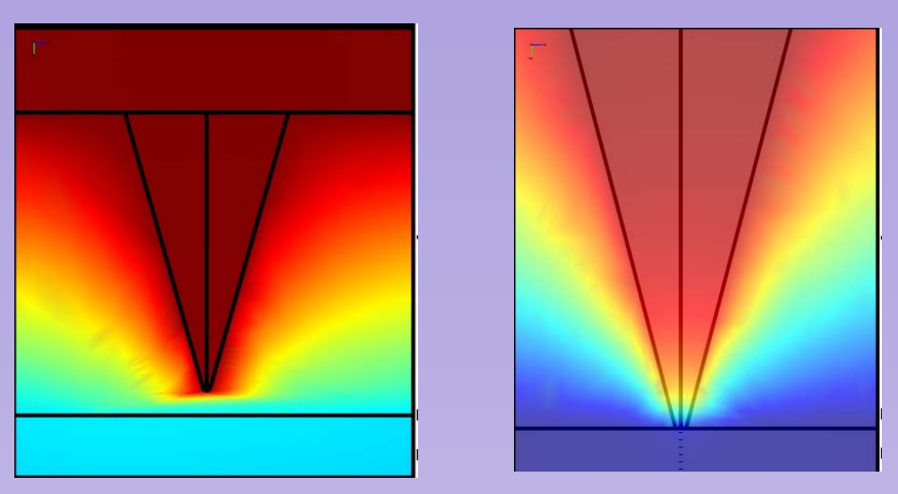


Figure 6 and 7: (left) non-contact air model, (right) contact with Si.
From fig. 6 and 7 its clear that most of the temperature drop is at the very tip in the space of about 40nm.

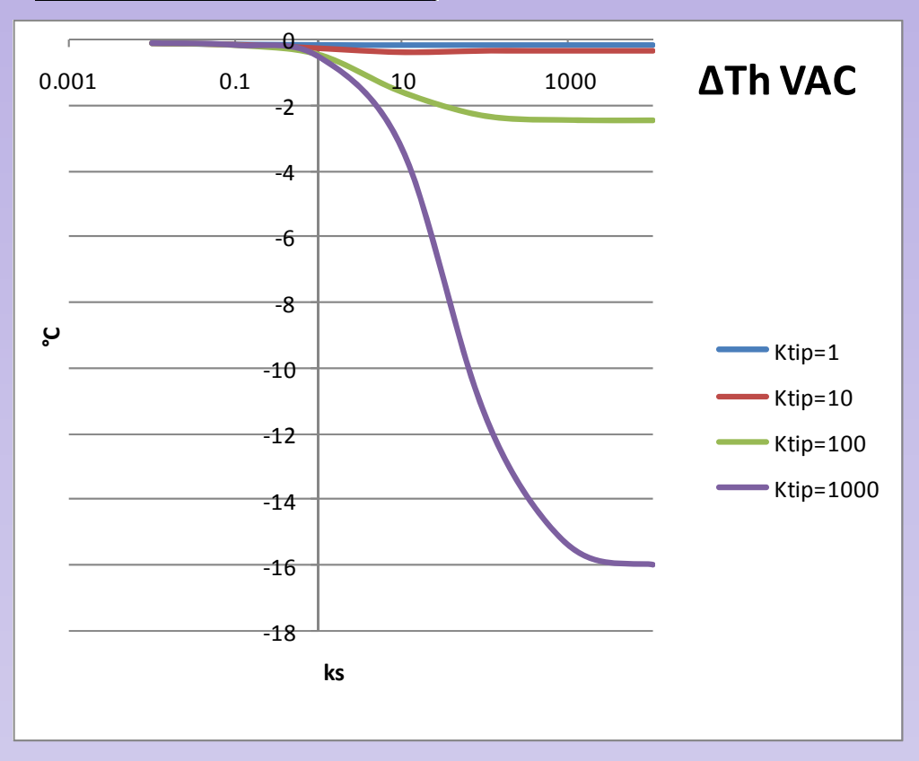
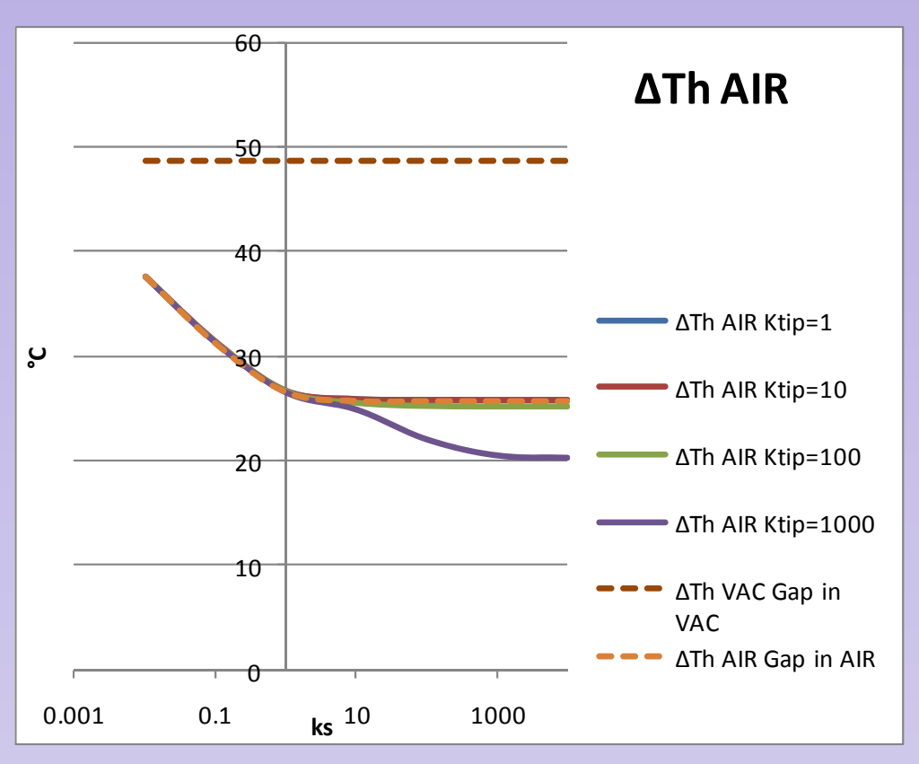
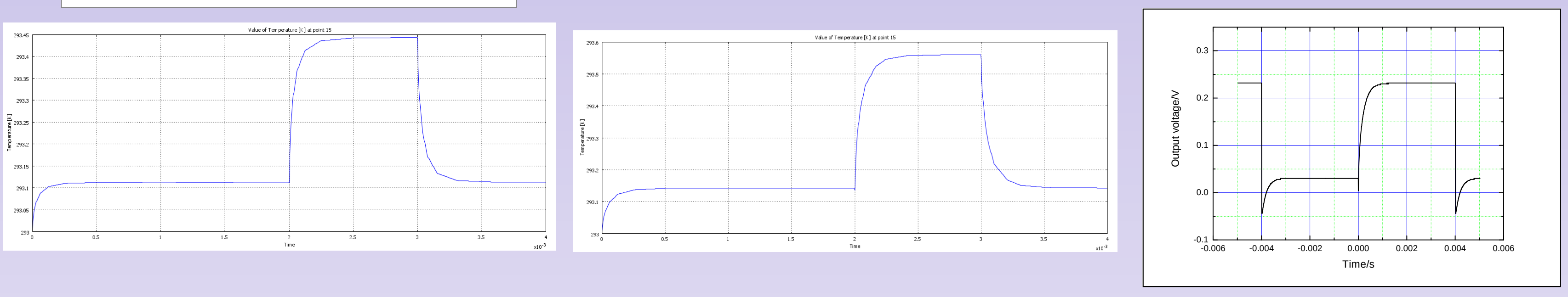


Figure 8 and 9: Temperature jump of the heater with thermal conductivity of the sample; in vacuum (left) and (right) air for different tip thermal conductivities.

CNT has thermal conductivity of about 3500Wm^{-1}K^{-1}.





Figures 10, 11 and12: (from left to right) variation of tip temperature in contact and air, tip temperature in contact and vacuum, and experimental results of Si in contact in air.

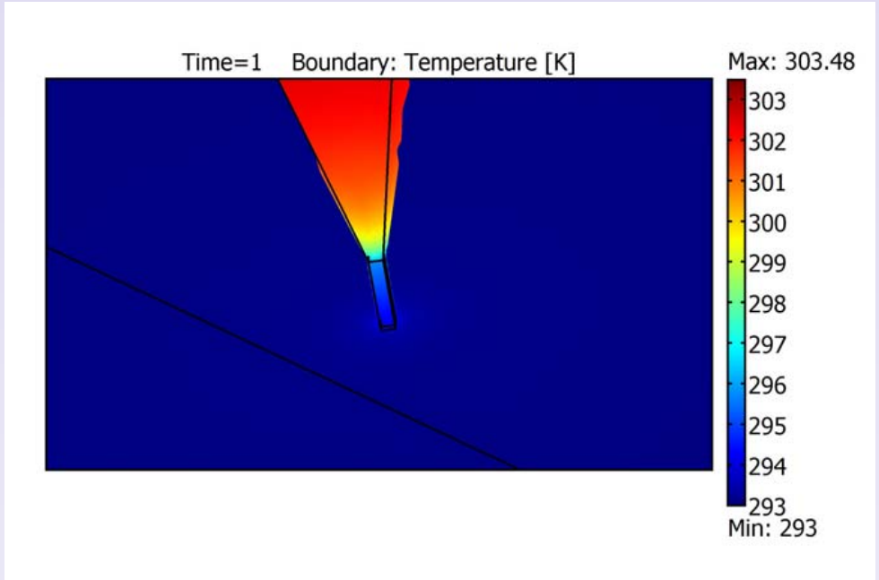
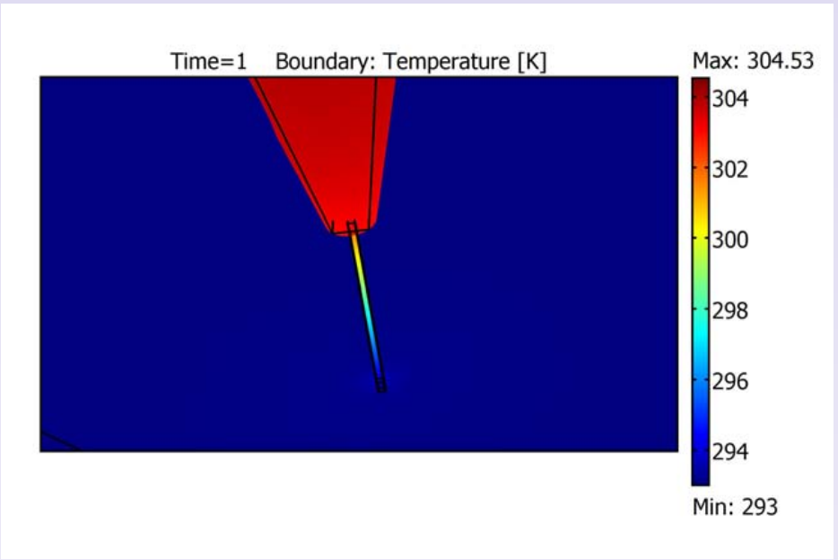


Figure 13 and 14: (left) A 100nm, (right) 20nm diameter CNT tip in contact with Si in vacuum.

For the narrow CNT the temperature drop is in the CNT itself. Where as the thicker CNT has the drop in the sample making it better at measuring the sample thermal conductivity.



Conclusions: An affective model was produced and demonstrated accurate results with experiment. The larger the contact area the more heat transferred to the sample as expected. Generally the temperature of the cantilever was high in experiments due to the heating affect of the AFM laser. Polymers in the model have a much lower temperature jump than the experiments. This was because the polymer had such a lower thermal conductivity it was like non-contact and the model does not take into account the water miscues that covers surfaces in air dominating thermal conductance. In vacuum the temperature jump is bigger because the only heat transfer is by solid-solid contact which when in non-contact is totally removed.

From the models its clear that most of the heat drop happens at the very tip which is a long way from the heat sensor. A better design would be to have the heater senor in the tip.

The temperature drop in vacuum is great than in air for all tip conductivities as demonstrated in figures 8 and 9. The larger the tips conductivity the larger the temperature drop and easier to detect. CNTs have high conductivities making them perfect for thermal tips. It also can be seen that for very low conductive sample there is a very small temperature jump making it difficult to distinguish between different polymers.

Figures 10 to 12 show that Comsol gives the same pattern of heating and cooling as the experiment for a time pulse only in a shorter time scale. The initial conditions were the same so Comsol must not take something into account that is responsible for slowing the heat propagation.

For the CNT tip a larger diameter is better so that most of the heat drop is in the sample and not the CNT itself.

In the future we plan to carry out vacuum scanning and compare this with the model. Also to produce a CNT tip that can be used for thermal scanning and these models will aid with that.

REFERENCES:
[1] Wilson, Neil R; Macpherson, Julie V; *Carbon nanotube tips for atomic force microscopy*, Nature nanotechnology **Vol 4,** 2009 page 483-491.
[2] Anasys Instruments, ThermaLever probes, AN2-300, http://www.anasysinstruments.com/nano-TAprobes.pdf,

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