Two-Dimensional Diffusion and Longitudinal Rotation of Silicon Nanowires

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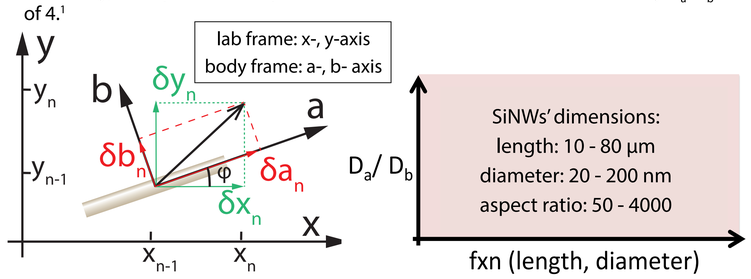
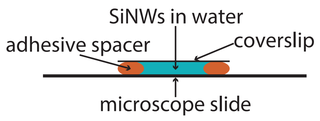
Anisotropic Brownian motion in two-dimensions

$\langle[\Delta r(t)]\rangle = 4Dt$ two-dimensional mean square displacement

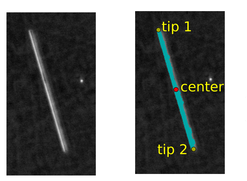
- High Aspect Ratio Nanoparticles (HARN) are abundant in nature and often exhibit Brownian motion (BM). Some HARN (e.g. asbestos, bacteria, virus) can cause serious health problems. However, study of the diffusion of highly anisotropic particles has been limited.
- Here, we study two-dimensional BM of individual silicon nanowires (SiNWs) in water near a flat surface.
- Unlike spherical particles, BM of SiNWs show directionality: diffusivity along the long axis (D_a) is greater than the diffusivity perpendicular to the long axis (D_b).
- Previously, 1:8 aspect ratio ellipsoids showed directional BM characterized by D_a/D_b of 4.[1]

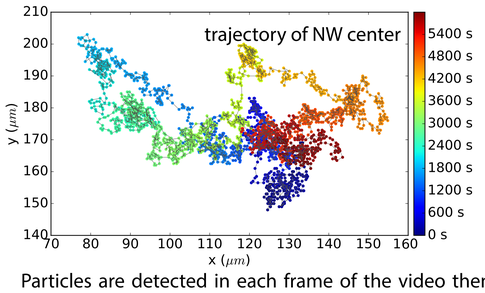


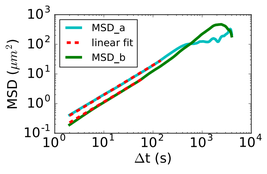
1. Brownian motion video acquisition and data processing



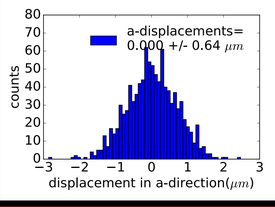
SiNWs, sonicated in water, are enclosed in a 120 μm-thick glass chamber. We take BM videos of SiNWs near the microscope slide with an inverted optical microscope in darkfield mode.







Particles are detected in each frame of the video then connected to form a trajectory. Displacements of the NW tip 1, 2, and center are calculated. Displacements in the a and b directions are calculated by projecting the displacements of the NW center on the body frame. Diffusivities can be obtained from the slope of the MSD vs. t plot or from the standard deviation of the distribution of displacements: $\sigma_x^2 = 2Dt$.

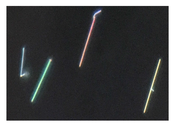


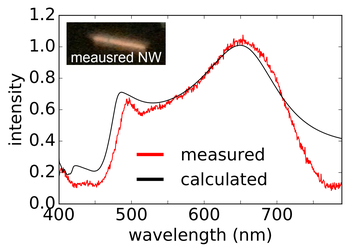
$$P(x)dx = \frac{1}{\sqrt{4\pi Dt}} e^{-x^2/4Dt} dx$$

one-dimensional displacement PDF

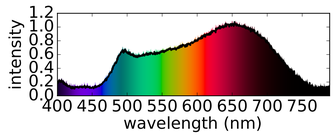
2. SiNW diameter measurement

SiNWs' scattered colors are unique to their diameter. Based on the Mie approximation, scattered spectra of SiNWs can be calculated.[2] We take SiNWs' spectra in darkfield with a spectrometer coupled to the microscope. By finding the best match between the obtained and calculated spectra, we can determine the NWs' diameters.

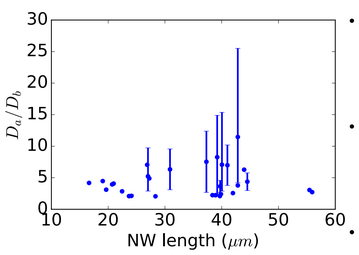




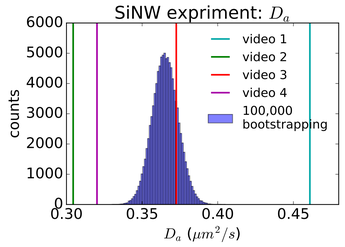
color generated from calculated spectrum
fitted diameter: 169 nm

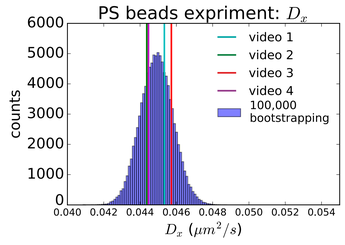


3. High directionality in Brownian motion and challenge in reproducibility



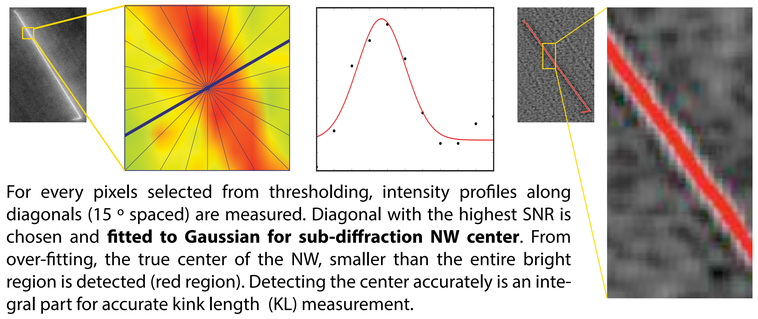
- BM of 17 different SiNWs show directionality much higher than thoses observed in smaller aspect ratio particles. The NWs' BM ranges between D_a/D_b of 2 and 25.
- However, the D_a/D_b ratios of the same NWs measured from different BM videos vary greatly: the percent relative standard deviation (%RSD) ranges from 5 to 100 %.
- Inhomogeneous interactions between the NWs and the substrate is thought to be the most probable cause of the inconsistency.





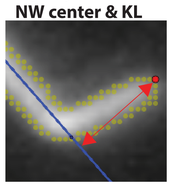
- Control BM experiment with 6 μm diameter polystyrene (PS) beads show definite consistency: % RSD of D_x/D_y ranges from 1 to 15%.
- To evaluate the consistency among different videos of the same particles, displacement data from all the videos were combined and sampled to generate 100,000 bootstrapped trajectories. Whereas most $D_{x \text{ and } y}$ from individual videos for PS bead fall in the bootstrapped $D_{x \text{ and } y}$ region, $D_{a \text{ and } b}$ from individual videos for SiNW mostly do not fall in the bootstrapped region.

1. Kink-length detection with Gaussian particle detection algorithm

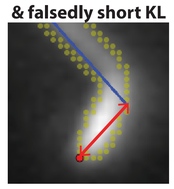


For every pixels selected from thresholding, intensity profiles along diagonals (15 ° spaced) are measured. Diagonal with the highest SNR is chosen and **fitted to Gaussian for sub-diffraction NW center**. From over-fitting, the true center of the NW, smaller than the entire bright region is detected (red region). Detecting the center accurately is an integral part for accurate kink length (KL) measurement.

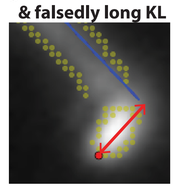
Properly detected NW center & KL



Left-biased NW center & falsedly short KL



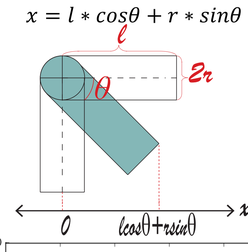
Right-biased NW center & falsedly long KL

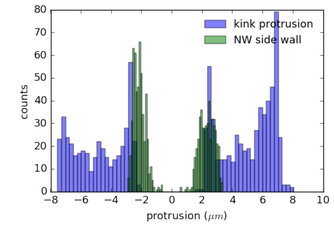


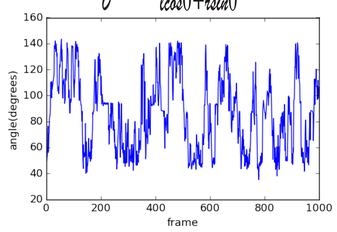
2. Kink-length to axial rotation conversion

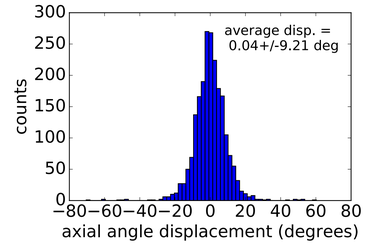
With the measured KL's, we solve for axial orientation (θ) using a simple trigonometry equation. By calculating the axial angle displacements from consecutive frames, we can obtain axial angular diffusivity of the NW.

$$x = l * cos\theta + r * sin\theta$$



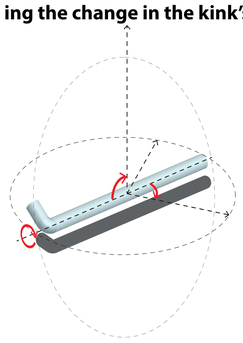


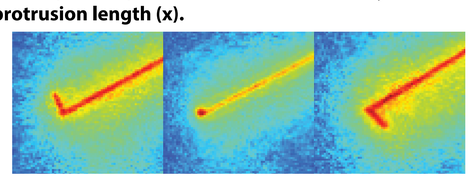


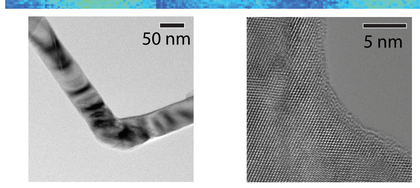


Axial rotation measurement with kinked-SiNW

Tracking particles' axial rotation – rotation around particle's major axis – can reveal interesting physics. For example, bacteria flagella and cargo being transported along axons undergo axial rotation. However, there are a limited number of methods for such a study. We used **kinked-SiNW (k-SiNW) to track its axial rotation by measuring the change in the kink's protrusion length (x).**



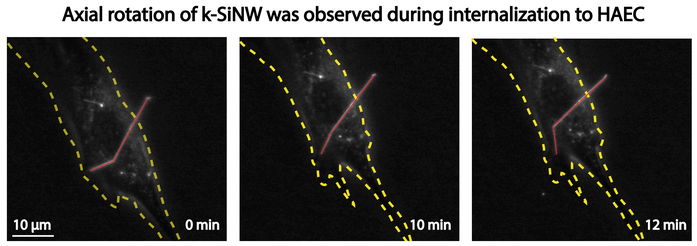




Future directions: axial rotation in biological cells

- Previously, it was shown that SiNWs get internalized by some cell lines such as human aortic endothelial cells (HAEC).[3] We have observed k-SiNW axially rotating during the internalization process. We plan to study the difference in translational and rotational diffusivity based on the NW's placement in the cell culture: extracellular matrix, on the cell membrane, and inside a cell.

Axial rotation of k-SiNW was observed during internalization to HAEC



- To distinguish the rotation caused by the kink and that by NW interacting with the environment, we plan to experiment with k-SiNWs of various kink length and angles. Simulation results showed minimal effect of kink on the NW's axial rotational BM given a small kink length to NW length ratio.

Acknowledgements

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References

1. Han, Y. et al. Brownian Motion of an Ellipsoid. Science 314, 626–630 (2006).
2. Brönstrup, G. et al. Optical Properties of Individual Silicon Nanowires for Photonic Devices. ACS Nano 4, 7113–7122 (2010).
3. Zimmerman, J. F. et al. Cellular uptake and dynamics of unlabeled freestanding silicon nanowires. Science Advances 2, e1601039 (2016).