Nanopore-Integrated Microwave Sensors for Capacitive Detection of Single Nanoparticles inside Liquid

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Characterization of individual nanoparticles in a liquid constitutes a critical challenge for environmental, material, and biological sciences. To detect nanoparticles, electronic approaches are especially desirable owing to their compactness and lower costs. Indeed, for single-molecule and single-nanoparticle detection, resistive pulse sensing has advanced significantly during the last two decades. While such resistance-based measurements providing geometric size information have become the focus of many studies, capacitive measurements to obtain dielectric signatures of nanoparticles have scarcely been reported.

To explore this orthogonal sensing modality, we developed a capacitive sensor based on a microwave resonator with nanoscale features (Figure 1 a) . Microwave resonators can be viewed as the electromagnetic counterparts of micro/nanomechanical resonators. Microwave resonators are sensitive to changes in the dielectric permittivity of the surrounding medium, for instance by the sudden introduction of a micro/nanoparticle. Typically, microwave resonators are centimeter-scale structures with millimeter-scale features: therefore, they have limited performance in sensing small-scale analytes. To convert them into sensors with single micro/nanoparticle detection capability, a sensing region should be introduced by the use of micro/nanofabrication techniques.

In this work, we fabricated a microwave resonator with a nanoscale sensing gap (defined by electron-beam lithography), surrounding a nanopore drilled using focused ion beam on a Silicon Nitride membrane. The migration of single nanoparticles near the sensing region and their translocation through the nanopore induced sudden changes in the capacitance of the structure. The capacitive changes in turn were translated into changes in the phase response of the microwave resonator which were detected by a custom electronic circuitry.

We worked with 100 nm polystyrene nanoparticles to observe single particle events and related them to capacitive size information. The work provides an orthogonal sensing modality for nanoparticle characterization to open the door for permittivity-based material classification of nanoparticles.

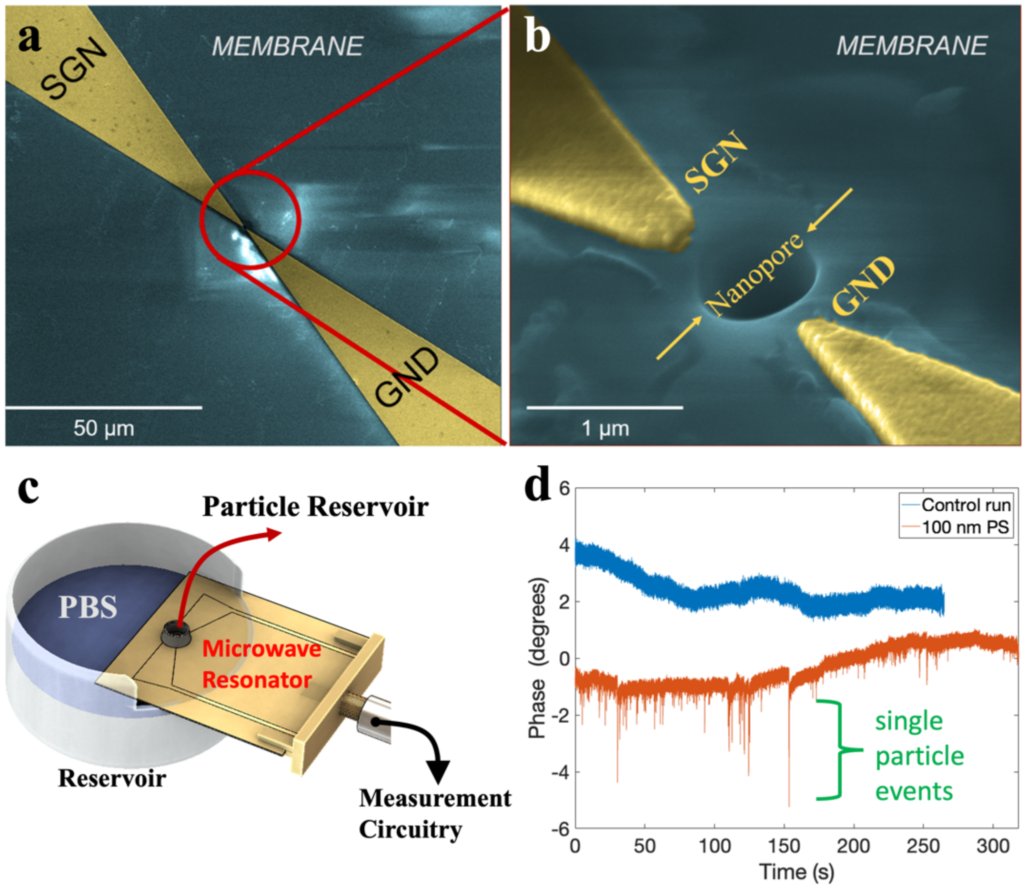

Figure 1: Nanopore Integrated Microwave Sensing: (a,b) are the colorized SEM images of the sensing region where two electrodes (SGN: signal, GND: ground) of the microwave resonator converges within a sub-micron gap around a nanopore. (c) the sensing region shown in (a,b) are sandwiched between two liquid reservoirs, the particle reservoir at the top containing nanoparticles and a reference reservoir at the bottom. The nanoscale sensing region of the microwave sensor shown in (a,b) extends to larger dimensions to form a microwave resonator which is probed by a custom-built measurement circuitry which tracks capacitive changes in the sensing region. (d) Experimental data shows spike-shaped events arising from single nanoparticles passing through the nanopore and detected capacitively (orange). Negative control experiments under the same conditions (but without the presence of nanoparticles) do not exhibit any spike-shaped events (blue trace, which is shown with a +4 degrees phase shift for clarity).