

ABSTRACT

Nanoelectromechanical systems (NEMS) are microelectromechanical devices (MEMS) scaled down to nanometer range. NEMS resonators can be fabricated to achieve high natural resonance frequencies, exceeding 1 GHz with quality factors in excess of 10^4 . These resonators are candidates for ultrasensitive mass sensors and frequency determining elements of precision on-chip clocks. As the size of the NEMS resonators is scaled downward, some fundamental and nonfundamental noise processes will impose sensitivity limits to their performance. In this work, we examine both fundamental and nonfundamental noise processes to obtain the corresponding expressions for phase noise density, Allan deviation, and mass sensitivity. Fundamental noise processes considered here include thermomechanical noise, momentum-exchange noise, adsorption-desorption noise, diffusion noise, and temperature-fluctuation noise. For nonfundamental noise processes, we develop a formalism to consider the Nyquist-Johnson noise from transducer-amplifier implementations.

As an initial step to experimental exploration of these noise processes, we demonstrate the phase noise measurement of NEMS using the phase-locked loop scheme. We analyze control servo behavior of the phase-locked loop and describe several implementation schemes at very high frequency and ultra high frequency bands. By incorporating the ~ 190 MHz NEMS resonator into the frequency modulation phase-locked loop, we investigate the diffusion noise arising from xenon atoms adsorbed on the device surface. Our experimental results can be explained with the diffusion noise theory. The measured spectra of fractional frequency noise confirm the predicted functional form from the diffusion noise theory and are fitted to extract the diffusion coefficients of adsorbed xenon atoms. Moreover, the observed Allan deviation is consistent with the theoretical

estimates from diffusion noise theory, using the total number of adsorbed atoms and extracted diffusion times.

Finally, very high frequency NEMS devices provide unprecedented potential for mass sensing into the zeptogram level due to their minuscule mass and high quality factor. We demonstrate *in situ* measurements in real time with mass noise floor ~ 20 zeptogram. Our best mass sensitivity corresponds to ~ 7 zeptograms, equivalent to ~ 30 xenon atoms or the mass of an individual 4 kDa molecule. Detailed analysis of the ultimate sensitivity of such devices based on these experimental results indicates that NEMS can ultimately provide inertial mass sensing of individual intact, electrically neutral macromolecules with single-Dalton (1 amu) sensitivity. This is an exciting prospect—when realized it will blur the traditional distinction between inertial mass sensing and mass spectrometry. We anticipate that it will also open intriguing possibilities in atomic physics and life science.