PhD Thesis Defense PETER WEBER 'Graphene Mechanical Resonators Coupled to Superconducting Microwave Cavities'

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Quantum NanoMechanics

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In recent years, mechanical resonators based on graphene have attracted considerable interest as nanoelectromechanical systems (NEMS). Graphene NEMSs allow for exceptional properties such as high mechanical strength, high frequencies and quality factors, tunable mechanical properties, and ultra-low mass. As a consequence, these systems are promising to investigate motion in the quantum regime, probe rich nonlinear phenomena, sense minuscule masses and forces, and study surface science. However, a central challenge in graphene NEMS research is the coupling of the mechanical vibrations to external systems for efficient read out and manipulation. In this dissertation, we report on a novel approach, in which we harness the optomechanical radiation pressure interaction to investigate few-layer and multilayer graphene mechanical resonators at cryogenic temperatures (T = 15 mK). The capacitive coupling between graphene mechanical systems and the microwave photons of a superconducting microwave cavity allows for investigation of the mechanical properties with unprecedented accuracy and control. In a first experiment, the coupling of circular, high-Q graphene mechanical resonators (Qm _ 105) to a nearby cavity counter electrode results in a large single-photon optomechanical coupling of _ 10 Hz. The initial devices exhibit electrostatic tunability of the graphene equilibrium position, strong tunability of the mechanical resonance frequency, and the possibility to control the sign and magnitude of the observed During nonlinearity. Compared to optomechanical systems fabricated from bulk materials, the strong tunability of the mechanical properties of graphene NEMS is unique.

In a second experiment, we quantitatively investigate the sideband cooling and force sensing performance of multilayer graphene optomechanical systems. The strong coupling to the microwave photons allows to achieve a mechanical displacement sensitivity of 1:3 fm Hz¿¿1=2 and to cool the mechanical motion to an average phonon occupation of 7:2. In ter s of force sensing performance, we find that the force sensitivity is limited by the imprecisi n in the measurement of the vibrations, the fluctuations of the mechanical resonant frequenc , and the heating induced by the measurement. Our best force sensitivity, 390 zN Hz¿¿1=2 is achieved by balancing measurement imprecision, optomechanical damping, and J ule heating. These results hold promise for studying the quantum capacitance of graphene, its magnetization, and the electron and nuclear spins of molecules adsorbed on its surface. n a third experiment, we implement energy decay measurements to study mechan cal dissipation processes in multilayer graphene mechanical resonators. We study the en rgy decay in two regimes. In the low-amplitude regime, the mechanical quality factor surpa ses Qm = 106. This quality factor is larger than that obtained with spectral measureme ts, because energy decay measurements are immune from dephasing. In the high-ampli ude regime, the motion of atomically-thin mechanical resonators is radically different from hat has been observed in other resonators thus far. Instead of a smooth exponential de ay, energy decays discontinuously, that is, the dissipation rate increases step like above a cer ain threshold amplitude. We attribute these phenomena to nonlinear decay processes. T ese findings offer new opportunities for manipulating vibrational states..

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