Over 500% Frequency Tuning Range in Nanoelectromechanical Resonators Based on Ultrasoft Two-Dimensional Semiconductor BiOI

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***Summary*—Nanoelectromechanical systems (NEMS) based on two-dimensional (2D) materials can have motional parts that are atomically thin, and thus can be more sensitive to external tension compared with MEMS resonators based on bulk crystals in terms of frequency tuning by gate. In this work, by using ultrasoft 2D semiconductor bismuth oxyiodide (BiOI), we demonstrate gate tuning of the resonance frequency exceeding 500% in NEMS resonators, the highest value reported to date. Our results can enable ultra-tunable NEMS resonators that can function over a very broad bandwidth.**

***Keywords*—Nanoelectromechanical Resonators; Frequency Tuning; 2D BiOI.**

I. Introduction

NEMS resonators based on 2D materials [1] and their heterostructures [2] have ultralow power consumption, large frequency tuning range, and high sensitivity, making them promising for sensing, signal processing, and computation [3]. In particular, such atomically thin devices can be designed to access different mechanical regimes, allowing frequency tuning efficiencies to be optimized [4]. Among the various frequency tuning mechanisms, electrostatic gating [5] can be easily implemented in device designs and consumes minimal static power, and thus holds promises for future applications of nanoscale resonators with ultrahigh frequency tuning range. Here we demonstrate NEMS resonators based on ultrasoft 2D semiconductor BiOI, and show that with the superb flexibility in the 2D crystal, record-breaking high frequency tuning range exceeding 500% can be achieved with electrostatic gating.

II. Methods

The BiOI NEMS resonators, which are first characterized with Raman spectroscopy to ensure crystal quality (Fig. 1), are fabricated using a previously established routine (Fig. 2) [4]. Through theoretical analysis, we find that 2D BiOI crystal has a Young's modulus much lower than all 2D crystals studied to date (theoretically 1-2 orders of magnitude smaller) that have been explored for NEMS resonators. This suggests that these devices could have ultrahigh frequency tuning ranges.

We study the frequency tuning using a custom-built 2D NEMS resonator measurement system, including optical components for laser interferometry [6], a vacuum chamber to keep the device in ~1×10^{-6} Torr environment, and electrical connections for gate tuning and driving.

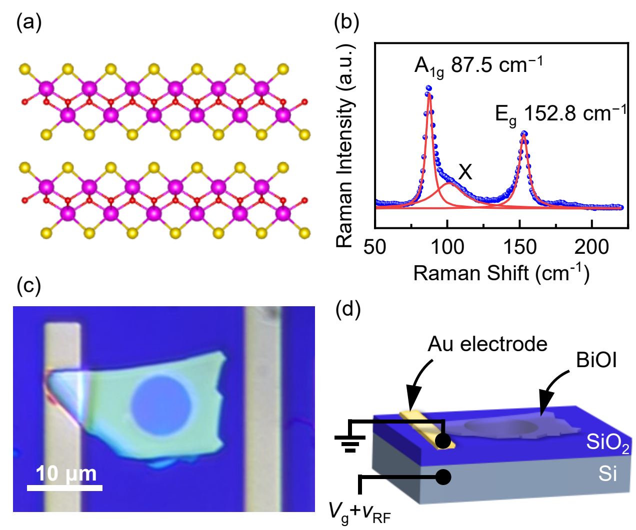

Fig. 1. BiOI resonator. (a). Schematic of BiOI crystal. (b) Raman spectrum of a device. (c) Optical Image. (d) Device schematic and electrical connection.

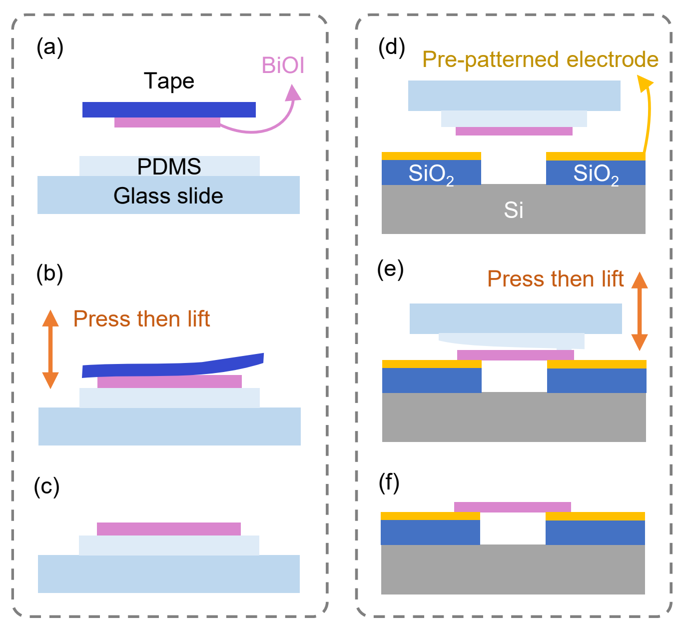

Fig. 2. Device fabrication. (a-c) Exfoliation and deposition to PDMS stamp. (d-f) Transfer of BiOI flake onto prefabricated trench with electrical contacts.

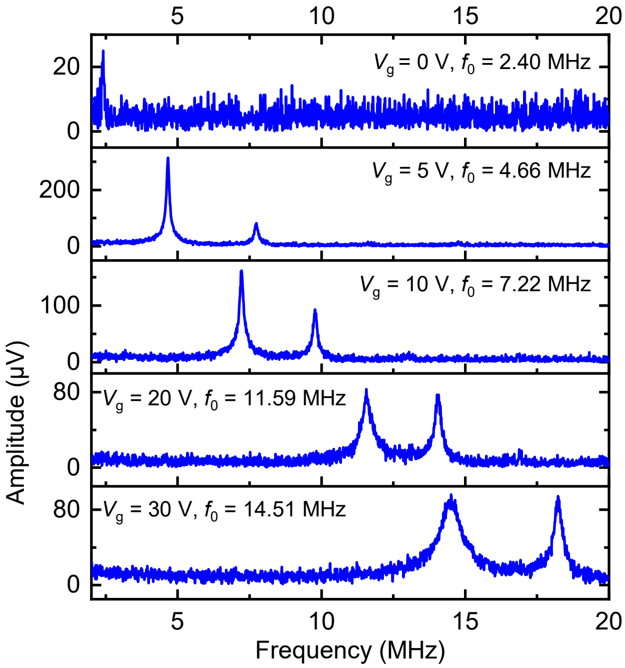

Fig. 3. Resonance spectra under some selected different gate voltages for a BiOI resonator.

III. Results

We vary the gate voltage with a small fixed voltage step between ±30V, and carefully measure the first two resonance modes. The measured resonance spectra under selected different gate voltages are shown in Fig. 3. The resonance frequency of the fundamental mode is tuned from 2.40 MHz to 14.51 MHz, achieving a record-breaking tuning range of 504%. This is the highest among all 2D NEMS resonators tuned by electrostatic gate reported to date. The ultra-tunable characteristic we show here is promising for resonance frequency shift-based NEMS functional devices.

IV. Conclusions

Our work clearly demonstrates that ultrasoft 2D crystal BiOI can enable NEMS resonators with record-high frequency tuning range. Our results hold promises for building ultra-tunable NEMS resonators that can function over a very broad bandwidth.

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