A SELF-AMPLIFIED SILICON-GERMANIUM NANOMECHANICAL RESONATOR WITH PIEZORESISTIVE HEAT ENGINES

Faysal Hakim[1], Normarieli M. Passalacqua-Alvarado[2], Keshab R. Sapkota[3], Aleem Siddiqui[3], Xuebin Li[4], Kevin S. Jones[2], George T. Wang[3], and Roozbeh Tabrizian[1]

[1]Department of Electrical & Computer Engineering, University of Florida, Gainesville, Florida, USA
[2]Department of Materials Science & Engineering, University of Florida, Gainesville, Florida, USA
[3]Sandia National Laboratories, Albuquerque, New Mexico, USA
[4]Applied Materials, Santa Clara, California, USA

ABSTRACT

The manuscript presents the first demonstration of self-amplification in integrated $Si_{0.7}Ge_{0.3}$/n-Si superlattice resonator at low frequency flexural modes (376kHz and 878kHz). Piezoelectric $Al_{0.7}Sc_{0.3}N$ thin film is grown atop the superlattice to excite mechanical resonance which is then amplified by application of DC current through n-Si piezoresistive heat engines. Benefiting from large negative piezoresistive coefficient in $Si_{0.7}Ge_{0.3}$/n-Si superlattice, the fabricated test structures show enhancement of vibration amplitude by a factor over 4 upon application of 3mA DC current. Further increase in DC current induced large duffing nonlinearity in the two peaks, with opposite directions. The two modes also showed highly different *TCF*s of -134 ppm/°C and -7.8 ppm/°C, highlighting the potential of self-amplified $Si_{0.7}Ge_{0.3}$/n-Si superlattice resonator to simultaneously serve as an electronic-free temperature sensor or temperature-stable oscillator.

KEYWORDS

Piezoresistive heat engine, self-amplification, silicon germanium, superlattice, oscillator, resonant temperature sensor.

INTRODUCTION

MEMS resonator technologies are capable of generating timing and frequency references with small size, power-consumption, and cost budget. Conventional MEMS resonators, created from piezoelectric thin-films sandwiched between two metal electrodes, can operate at low frequency (LF) spectrum for clock generation, wearable electronics, medical imaging, etc. Often, these low power applications demand high quality factor of resonance (Q) as well as frequency stability across a wide range of temperature. However, piezoelectric MEMS resonators operating in LF spectrum (*i.e.*, in flexural modes) suffers from low Q when operating in atmospheric pressure (due to large air damping). Further, flexural piezoelectric resonators suffer from very large temperature coefficient of frequency that is governed by large residual stress in the metal-piezoelectric-metal stack [1][2]. To obtain high Q, vacuum encapsulation process or external electronic amplifier are needed, adding excessive cost and power consumption, and introducing electrical noise into the system, respectively.

In this paper, for the first time, we demonstrate the use of silicon-germanium/silicon ($Si_{0.7}Ge_{0.3}$/n-Si) superlattice structure below piezoelectric transducer to provide a novel self-amplification physics for enhancement of resonator Q, without the need for external circuity (Fig. 1). Further, the $Si_{0.7}Ge_{0.3}$/n-Si enables realization of resonance modes with highly different temperature coefficient of frequency (*TCF*) over the highly sensitive and temperature-independent extremes.

The large negative piezoresistivity in $Si_{0.7}Ge_{0.3}$/n-Si superlattice enables the use of n-Si layers as embedded heat engines, upon application of a DC current. We show that Q enhancement over 4× can be achieved for two different resonance modes, before entering duffing nonlinearity. The resonator temperature characteristics are also presented highlighting the effect of stress and controlled doping profile in $Si_{0.7}Ge_{0.3}$/n-Si superlattice on achieving highly contrasted *TCF*s that enable the use of resonator in both temperature sensing and stable cock generation modalities.

PIEZORESISTIVE SELF–AMPLIFICATION

The internal piezoresistive amplification in mechanical resonators is governed by thermo-electromechanical dynamics in semiconductor materials present in resonator stack. A mechanical vibration can be created in a piezoresistive substrate (such as heavily n-doped Si) by integrating a piezoelectric transducer (such as $Al_{0.7}Sc_{0.3}N$/Mo) creating a harmonic strain/stress within the semiconductor. Upon application of a DC current through the oscillating piezoresistors, the resistivity of the structure is modulated which translates into proportional temperature fluctuation (*i.e.*, piezoresistors serving as synchronous heat engines). The temperature fluctuation (if in phase with exerted force by piezoelectric film) will create a thermal expansion force which will boost the vibration. The enhanced vibration leading to enhanced stress will further modulate the resistivity/temperature of the engines initiating self-amplification in these resonators up to the point of saturation (set by elastic nonlinearities). A simple one-dimensional analytical model of self-amplification mechanism is developed based on the above-mentioned dynamics (Fig. 2(c)), enabling formulation of amplification rate as a function of material properties and dimension of resonator/heat engines. The intrinsic amplification factor (A_{int}) can be defined as:

$$A_{int} = -\frac{1}{C_{th}}\frac{(\alpha \pi_L E^2 V_{DC}^2)}{(4\pi W f_r^2 R_0)} \quad (1)$$

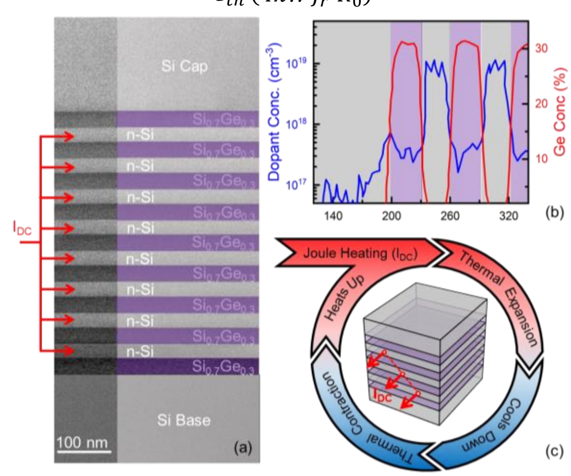

Fig. 1: *(a) Cross section HRTEM image of superlattice highlighting eight pairs of $Si_{0.7}Ge_{0.3}$/n-Si layers sandwiched by Si base and capping layer. (b) Carrier concentration and Ge content in $Si_{0.7}Ge_{0.3}$/n-Si superlattice up to 350nm depth from top. The shaded gray and purple regions indicate Si and $Si_{0.7}Ge_{0.3}$ layers. (c) Schematic illustration of piezoresistive self-amplification concept.*

where, α,π_L, and E are thermal expansion coefficient, piezoresistive coefficient and Youngs' modulus of the medium; C_{th},W, and R_0 are equivalent thermal capacitance, critical dimension, and resistance of the beam; f_r is the resonance frequency, and V_{DC} is applied DC voltage. For, n-type semiconductor, the negative π_L fulfils the in-phase criteria between thermal expansion and mechanical force which eventually results in a positive A_{int} (*i.e.*, self-amplification).

SUPERLATTICE RESONATOR IMPLEMENTATION

Superlattice $Si_{0.7}Ge_{0.3}$/n-Si structure is epitaxially grown atop a 200nm thick SOI substrate. Alternating layers of 31.2nm-thick $Si_{0.7}Ge_{0.3}$ and 28.3nm-thick Si are deposited for a total of eight (8) layers of each resulting in a superlattice with height ~507nm (Fig. 1(a)). During epitaxial growth, the Si interlayers are in-situ doped with phosphorous while the doping in $Si_{0.7}Ge_{0.3}$ (Fig. 1(b)) is minimized. The superlattice is then capped off by a 200nm-thick Si. This is followed by growth of 50nm-thick $Al_{0.7}Sc_{0.3}N$ layer atop superlattice in a pulsed DC sputtering system. Finally, a 30nm thick Molybdenum (Mo) electrode layer is sputtered atop $Al_{0.7}Sc_{0.3}N$ to form the integrated transducer. A simple clamped-clamped membrane is fabricated using a standard five (5) mask process for integrated $Al_{0.7}Sc_{0.3}N$-on-superlattice resonators. Figure 2(a) shows an optical image of 150µm wide and 300µm long membrane in which electrical connection through n-Si multilayers is established by sputtering thick Pt metal on the sidewall.

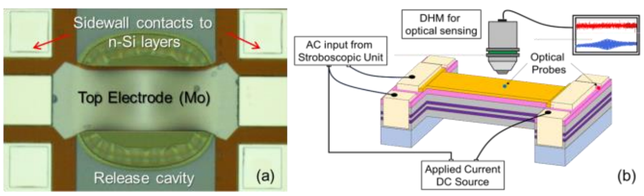

Fig. 2: *(a) Optical image of fabricated clamped-clamped membrane with Mo/$Al_{0.7}Sc_{0.3}N$/Superlattice stack. The top and bottom electrode along with backside cavity are labeled. (b) Schematic diagram of measurement setup for resonator actuation and sensing along with application of self-amplification DC bias.*

EXPERIMENTAL CHARACTERIZATION

Figure 2(b) shows the measurement setup to characterize the proof-of-concept test devices where AC electrical excitation is provided from a stroboscopic unit. The stroboscopic unit is synchronized with a digital holographic microscope (DHM) that can detect out-of-plane vibration at designated points (optical probes in Fig. 2 (b)). The time-domain mechanical vibration dynamics extracted from DHM is transformed into frequency-domain response from which quality-factor (*Q*) of resonance is extracted. The process is carried out for the fabricated resonator shown in Fig. 2(a) at different AC drive / DC bias scenarios, the corresponding frequency responses are compared, and *Q*s are evaluated.

Figures 3(a) – (d) show measured vibration amplitude of two flexural resonances at 376.7kHz and 877.9kHz. From fig. 3(a) and 3(c), the resonance *Q* is enhanced for each mode by application of DC current through the piezoresistive n-Si heat-engines. The *Q* amplification is initiated above ~1.5mA current and is maximized at ~3.4mA. Beyond 3.4mA, the resonator enters duffing nonlinearity due to large amplification of vibration amplitude. Figures 3(a) and 3(c) also show gradual increase in resonance frequency indicating reduction in damping in these modes, upon self-amplification. The enhanced amplification in low frequency flexural modes indicates existence of large piezoresistivity in $Si_{0.7}Ge_{0.3}$/n-Si superlattice which is not possible to achieve in standalone n-Si substrate and therefore limiting the amplification to high frequency bulk modes [3]. Figures 3(b) and 3(d) show nonlinear response for large AC excitation in the two modes, indicating opposite trends (*i.e.*, nonlinear stiffening and softening). Figure 4 shows the measured temperature characteristic of the two modes indicating very different TCFs. The low frequency mode at 376kHz is significantly affected by temperature, showing a TCF of -134 ppm/°C. On the other hand, the 878kHz mode shows a low TCF of -7.8 ppm/°C.

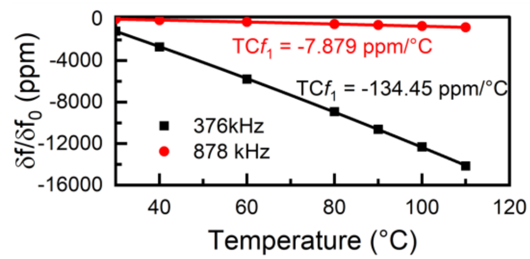

Fig. 4: *Measured temperature characteristics of membrane resonator for different resonance modes.*

ACKNOWLEDGEMENTS

This work is supported by the Sandia National Laboratory under contract DE-NA-0003525.

REFERENCES

[1] V. Thakar, et. al., "Piezoelectrically Transduced Temperature-Compensated Flexural-Mode Silicon Resonators", *JMEMS*, 2013.
[2] A.K. Pandey, and R. Pratap, "Effect of flexural modes on squeeze film damping in MEMS cantilever resonators", *JMEMS*, 2007.
[3] A. Ramezany, et. al., "Nanoelectromechanical resonant narrow-band amplifiers", *Nature Micro Nano*, 2016.

CONTACT

*Faysal Hakim, email; hakimfaysal@ufl.edu.

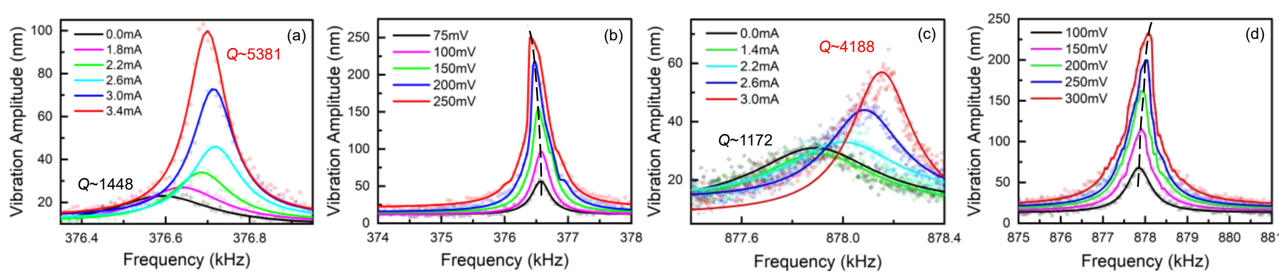

Figure 3: *Measured frequency responses of $Al_{0.7}Sc_{0.3}N$-on-superlattice $Si_{0.7}Ge_{0.3}$/n-Si nanomechanical resonator, operating at two different modes and under different drive / bias. Figures (a) & (c) show the measured displacements of 376kHz and 877kHz modes, respectively, for 100mV AC drive and variable DC currents. Figures (b) and (d) show measured response of 376kHz and 877kHz mode.*