ARRAYS OF COUPLED NANOMECHANICAL RESONATORS

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ABSTRACT

Arrays of coupled radio-frequency (RF) nanomechanical resonators were fabricated using ultra-thin SOI wafers, e-beam lithography and a combination of a dry and wet etch. Wide-scale propagation of the collective modes of the elastic excitations through the arrays has been demonstrated experimentally by utilizing an optical setup with a laser-driven thermoelastic excitation and an interferometry-based detection of the mechanical motion. We show the acoustic band formation in our arrays and provide an estimate of the density of states as well as the localization length of the extended modes. We envision applications in sensing and RF signal processing that would employ arrays of coupled resonators operated as delay lines, which motivates our ongoing study of the propagation of the elastic waves through the resonator arrays. The presence of a third, independently positioned laser beam in our setup allows us to simulate the loading of the array, by introducing a heat-induced stress, and thus detuning the resonators at chosen locations. We present experimental data regarding group velocity, phase shift relations, dispersion, and a brief discussion of practical implementations of devices based on such arrays.

INTRODUCTION

The collective behavior of coupled nanoelectromechanical resonators can be seen as a tool for breaking scaling laws that limit the performance of microminiaturized high frequency devices [1,2,3,4]. By expanding the number of high frequency, high quality factor resonators that are coupled into arrays, one can create a new media - an artificial crystal with extended acoustic bands formed by splitting and overlapping of the mechanical resonances of the individual devices. Direct control over the geometry of the resonators and coupling strength provides the ability to engineer the frequency response of the arrays (including some nonlinearities). Numerous wave-based phenomena from crystalline solids, microwaves, and optics can be simulated in realm of the elastic waves in nanoresonator array (NRA). For example, the presence of the bandgaps in the acoustic spectra of NRA opens an opportunity to operate with acoustic excitations in terms of defect-induced impurity levels, borrowing the ideology from doped semiconductors and photonic crystals. Controlled dispersion and nonlinear effects may allow the acoustic waves to exhibit solitons, intrinsic localized modes (ILM), waves scattering, *etc.*

For sensing applications (*i.e.* added mass sensing, vapor sensing, *etc.*) the resonator array can be considered as an ultimate flexural plate wave (FPW) device [5]. For a NRA the extra sensitivity to mass-loading is gained by decreasing the mass of the resonators, increasing the frequency of operation, and lowering phase velocity (*i.e.* shrinking the wavelength) of the elastic waves

that are used to probe the loading. The NRA features well-controlled acoustic bands in the radio frequency range that can be used to design a variety of novel RF devices dedicated for frequency domain signal processing. Broadband filters, traveling wave amplifiers, dispersion-based spectrum analyzer, *etc.* can be designed to operate with broadband excitations implemented as elastic waves propagating through the array.

In this paper we present results of the fabrication and experimental study of 2D arrays of coupled plate-type nanomechanical resonators (Fig. 1). Each resonator is comprised of a silicon square plate supported by a square SiO₂ pillar at the center. Coupling between neighbors is provided by narrow beams connecting the centers of the square sides (Fig. 1).

Figure 1. SEM image showing part of the paddle resonator array. The dimensions of the silicon square paddles are $2 \times 2 \mu\text{m}$, thickness 45nm . The SiO₂ pillar supporting the center of the paddle has a cross section $0.54 \times 0.54 \mu\text{m}$ and is 150nm tall. The connecting bars are $2 \mu\text{m}$ long and 200nm wide. Inset shows the results of finite element analysis for the density of states in the 10×10 paddle array. DOS was calculated by direct counting of the number of modes (deduced from FEM modal analysis) per frequency interval.

We use modal analysis based on numerical simulations that employ finite elements methods (FEM) to predict the response of our arrays. Shell-type elements were used to model the resonators as plates, free on outside and clamped on the pillars' edges. Direct counting of the number of the normal modes of the array per frequency interval provides us with the density of states (DOS) for our "artificial crystals". The inset of Fig. 1 demonstrates the DOS for a 10×10 array of the plate resonators shown in the SEM image. The DOS plot shows the presence of two distinct acoustic bands ($45\text{-}50\text{ MHz}$ and $65\text{-}95\text{ MHz}$) separated by a pronounced bandgap. Inspection of the mode shapes of the array and cross-referencing

with the modes of a single paddle resonator indicate that the low frequency band of the array's DOS is being populated by the "bridge-type" modes produced by the motion of the connecting arms, while the upper band is filled with a variety of modes stemming from the square plate itself. Experimental observation of the predicted band structure in our microfabricated resonator arrays, estimation of the localization range for the collective modes, and evaluation of the disorder effects were the initial research goals. We present our recent results and discuss the broader topic related to propagation of the broadband elastic excitation through the resonator arrays.

FABRICATION

Commercially available SOI wafers with the silicon layer thickness 45nm and buffered oxide (BOx) 150nm were used in the fabrication. Direct e-beam writing in 50nm-thick hydrogen silsesquioxane resist (HSQ, Dow Corning) spun over SOI wafer was used to create a mask for subsequent dry etch through the Si layer. We utilized a cryogenic plasma etch ($T=100$ K) in a SF_6 and O_2 gas mix (SF_6 serves as a source of fluorine radicals for the etching and oxygen provides passivation of the sidewalls) [6]. This process, implemented in an inductively coupled plasma (ICP) chamber, is known to provide very high selectivity towards the etching of Si with respect to a SiO_2 mask. Ion-induced damage is also minimized in the ICP process. This prevents additional ion implantation, and thus does not adversely affect the internal friction for these resonators. A subsequent wet etch in concentrated HF (48%) is timed to partially undercut the BOx layer, releasing the periphery of the Si square plates, while leaving a SiO_2 supporting pillar at the center of the resonator.

EXPERIMENTAL DETAILS

Optical transduction was used to study the vibratory response of the array. A long working distance glass corrected objective lens was used to focus three laser beams each into micron-sized spots on the NRA located in a vacuum chamber ($P \sim 10^{-8}$ Torr). The optical path of one of the lasers (blue, wavelength 412nm) was fixed and its focused spot was positioned within the NRA using a microstep stage moving the entire vacuum chamber. The other two laser beams (red HeNe 633nm and green YAG 512nm) were equipped with steering mirrors, which allowed us to position their spots independently within $60 \times 60 \mu\text{m}^2$ image area provided by CCD camera (Fig. 2). A point-type thermoelastic excitation was provided by modulating the intensity of the blue diode laser (412 nm) focused on a single paddle resonator within the array. The amplitude of the laser power modulation delivered to the sample was adjusted to ~ 50 microWatts. The time-variable local heating induced by the focused laser beam in our structures generated a modulated stress due to thermal expansion and thus provided the driving force. The resulting motion of the suspended structures was detected interferometrically, by focusing another laser (red CW HeNe, 633 nm) at a different point in the array and measuring the modulation of the reflectivity [7]. This modulation originates in the motion-induced variation of the gap in a Fabry-Perot interferometer created by the resonator plate (acting as a semitransparent mirror) and the underlying substrate.

Independent positioning of the blue (drive) and red (detect) lasers provides the flexibility that is necessary to detect propagation of the elastic waves through the array "from point A to point B". However, the response at "point B" is a result of the interference of numerous elastic waves taking different paths through the array. In order to study the propagation pattern we

have introduced a third laser (green YAG, 512nm) in our setup. This laser delivers up to 2mW of CW power to a chosen resonator "C" located somewhere in between "A" and "B" and causes significant detuning of that resonator "C" due to heat-induced stress. The presence of the green laser upgrades our NRA to a "three-port" device allowing us to introduce well-controlled local perturbations into the dynamics of the array.

Figure 2. Schematic diagram of the experimental setup. RF modulated blue diode laser (412nm wavelength) was used to excite the NRA. The red laser (HeNe 633nm) provides interferometric detection of the mechanical motion. An independently positioned green laser was employed to introduce local perturbations in the array.

RESULTS AND DISCUSSION

Fig. 3 shows the frequency response of a 20×20 NRA with $2 \mu\text{m}$ -long connecting arms. Instead of a few distinct peaks corresponding to normal modes of a single resonator, the system exhibits hundreds of peaks arranged in two wide-spread bands: the low-frequency band (45-55MHz) and upper band (70-105MHz). The positions of the bands are in very good agreement with the results of the numerical calculations shown in Fig. 1. The direct counting of the number of peaks in the lower band (Fig. 3) provides an estimation of 12 MHz^{-1} for the DOS. This number is almost an order of magnitude lower than the value expected from FEM analysis. We attribute this discrepancy to the fact that only a limited number of resonators surrounding the driving point is participating in the collective modes. We suggest that the propagation of the elastic waves over the array is limited by the Anderson's localization [8] and is determined by "disorder," *i.e.* mistune of the resonators forming our "artificial crystal" [9]. Inset in Fig. 4 shows the spatial decay of the band-averaged elastic energy (calculated by integrating the square of the amplitude of the motion over the frequency band). By moving the detecting red

laser away from the driving point we observe that the amplitude of the motion is nearly vanished at a distance of 5 unit cells. We conclude that the array has an effective size of approximately 10×10 which leads to a theoretical prediction of the DOS that is in good agreement with the experimental value.

Figure 3. Frequency response of 20×20 paddle array with $2 \mu\text{m}$ -long connecting arm. Data acquired by driving a paddle at the center of the array and detecting the vibrations at the next paddle.

Lines 1-5 in Fig. 4 show unwrapped phase-frequency dependences acquired for separations from 1 to 5 unit cells between the driving and detecting beams. The slope $d\phi/d\omega$ of these curves provides an estimate for a group delay for the elastic waves propagating through the array. Given the separation distance, the group velocity $v_{gr} \sim 3$ m/s can be calculated. This number is few orders of magnitude slower than typical value for group velocity used in FPW devices.

Figure 4. Phase delay for the low-frequency band of 20×20 paddle array with $2 \mu\text{m}$ -long connecting arm. Numbers 1-5 next to curves correspond to separation (in unit cells) between driving and detecting beams. Inset shows spatial decay of the acoustic energy averaged over the low band (squares) and upper band (circles).

In order to demonstrate control over the band diagram of our array we increase the coupling between paddle resonators by reducing the length of the connecting arms down to $1 \mu\text{m}$ without modifying the size of the paddles or the width of the undercut (Fig. 5). This modification shifts the lower band in Fig. 3 up in frequency and makes it merge with the upper band, eliminating the bandgap. Numerical simulations based on a model of an ideal 10×10 paddle array (no disorder) confirm the presence of a single band comprised of a few merging sub-bands that originate from different modes of vibrations (inset in Fig. 5). After introducing disorder, implemented in our model as random mistune of the

resonators, ($df/f \sim 3\%$ according to experimental data) the FEM calculations predict much more “homogenized” DOS within the band, due to the spread and interpenetration of different sub-bands and the creation of somewhat exotic collective modes that exhibit different types of normal modes at different nodes of the array.

Figure 5. Resonator array with stronger coupling (i.e. $1 \mu\text{m}$ connecting arms). Part of the frame is shown. The inset shows the results of FEM simulations for the density of states of 10×10 array.

Figure 6 shows the vibrational spectrum of a 40×40 NRA with $1 \mu\text{m}$ arms. The single band is observed in accordance with FEM calculations. Peak counting provides an estimated 12 MHz^{-1} for the density of states and the phase slope corresponds to the group velocity $v_{gr} \sim 4$ m/s. By stepping the red laser and measuring the amplitudes of vibrations at different separations from the driving point we demonstrate that at least a 20×20 area of our 40×40 paddle array is participating in the collective modes.

Figure 6. Part of the vibration spectrum for the 40×40 paddle array with $1 \mu\text{m}$ -long connecting arm. Data acquired by driving a paddle at the center of the array and detecting the vibrations $24 \mu\text{m}$ (8 unit cells) away. The inset shows the full band of the array.

The effective size of the 40×40 array is large enough to start pursuing the major questions of interest: the pattern of the energy flow through the array and the contribution of a particular resonator to the extended modes of the array. In order to evaluate the involvement of a single resonator in the collective modes of vibrations we focus our third, green laser (512nm, 2mW CW power) on that chosen resonator. The resulting local heat-induced stress is sufficient to provide frequency shifts for the fundamental

modes an isolated resonator far in excess of their half-widths. When the affected resonator is a part of the array, the entire band can be modified. To highlight such alterations of the array's response we modulate the intensity of the green laser at a very low frequency (mechanical chopper with $f_{mod} \sim 10$ Hz is utilized in our setup) while acquiring the vibrational spectrum with our usual blue laser drive and red laser pickup. The resulting "telegraphic noise" due to bouncing between the non-perturbed spectrum and the one modified by the green laser is illustrated in Fig. 7.

The fact that the influence of the green laser can be detected at a remote location, and is well-pronounced over a wide spectral range, confirms the extended nature of elastic excitations in our arrays. In sensing applications, for example, a similar local perturbation can be caused by a modified mass loading due to absorption of some analyte to one of the resonators. For RF signal processing the NRA can be considered as a multiport device where each port (*i.e.* node of the array) can control delay and dispersion in a wide frequency range or can also be used to alter the flow pattern of the signal through the array.

Figure 7. *Vibration spectrum of the 40x40 array (1 μ m connecting arms) modulated by the chopped green laser. Blue laser (drive) is positioned at the center (origin), red laser (pickup) is shifted 5 unit cells North and the coordinates for the green laser spot are 2 North, 2 West. The inset is a Nyquist plot of this data.*

Practical implementations of the NRA-based devices may include a thermal actuator fabricated as resistive heater (similar to one described in [10]) located on the frame of the array. An optical setup with micro-packaged VCSEL lasers and integrated photo detectors could be used for the pick-up. One can also envision a magnetomotive detection system with the conducting wire running over series of resonators. Other transduction methods based on ferroelectricity, piezoresistivity, *etc.* can be considered but would probably be limited to the cases when the detection is implemented on a resonator next to the frame. External perturbations for the three-port devices could be introduced either thermally or by applying mechanical stress (with low frequency electrostatic comb-type actuators for example).

CONCLUSIONS

The presence of extended modes of vibrations in microfabricated 2D arrays of coupled nanomechanical plate-type RF resonators has been demonstrated. The vibrational spectra of the array exhibit wide acoustic bands separated by bandgaps that can be tuned by tailoring the geometry of the array. We show that the number of the resonators involved in the collective modes in our arrays can exceed 400 (20x20 effective size) and give an estimate of 12 MHz^{-1} for the density of states. By operating the

array as a delay line an estimate has been obtained of group velocity $V_{gr} \sim 4 \text{ m/s}$ for the elastic excitations propagating through the array. We demonstrate that a local perturbation introduced at a given point in the array can cause alterations to the response of the array that are extended both in space and frequency. We anticipate that nano-resonator arrays may ultimately have a range of applications in sensing and RF signal processing.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Dr. J. Vignola and Dr. D. M. Photiadis for helpful discussions. The authors would also like to thank the member of technical staff of the Institute for Nanoscience at NRL, D. R. King for assistance. This work was supported by the Office of Naval Research and Cornell Center for Material Research (CCMR, NSF IDMR-0079992).

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