Monolithic Integration of Piezoelectric Cantilever in Tunable VCSEL

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Abstract—We have designed, fabricated and characterized the monolithic integrated piezoelectric actuated cantilever beam in tunable short-wavelength VCSEL. Single mode emission with continuously tuning range of 3nm and low power consumption was experimentally obtained.

I. INTRODUCTION

A novel actuation mechanism utilizing the inherent piezoelectric properties of the Al xGa1-xAs compounds is presented for short-wavelength MEMS tunable VCSEL (centered at 850nm). Piezoelectric actuation can provide precise displacements in bi-directions and linear tuning characteristics with respect to the applied voltage, does not suffer from travel limitations and catastrophic damages, consumes very low power (~1µW), and has a fast response compared to the thermal actuation. In addition, piezoelectric actuation based on Al xGa1-xAs films offers a high piezoelectric coupling coefficient comparable to those of zinc oxide and quartz, and can be integrated with high-speed electronic and optoelectronic devices. Furthermore, this novel actuation mechanism allows for improved wavelength control, reduces external and tilt losses and can be easily scaled to long-wavelength VCSEL [1]. Previous work has demonstrated the successful integration in tunable VCSEL [2] and this paper shows further characterization and improvement of the piezoelectric cantilever design.

II. DEVICE STRUCTURE

Fig. 1 shows the SEM image of the device consisting of the integration a MEMS piezoelectric cantilever with VCSEL. The VCSEL comprises a bottom n-DBR, a cavity layer with the active region, and a movable suspended top p-DBR mirror. The suspended DBR is supported by a cantilever that consists of an unevenly distributed p-i-n structure: a thick p-DBR, a thin i-DBR, and a thin n-DBR, where such configuration the neutral axis of the beam is offset from the center. Piezoelectric tuning is accomplished by applying a reverse voltage bias across the top n-DBR and the middle p-contact, as shown in Fig 2. The applied voltage results in an electric field across the undoped piezoelectric layers in the suspended cantilever beam. Such a vertical electric field produces a longitudinal strain (∆L) in the intrinsic DBR layers via the converse piezoelectric effect. The thin piezoelectric layer is rigidly connected to the cantilever beam, which constrains the longitudinal motion of the piezoelectric layer and results in an equivalent bending moment (Mp) applied to the beam. The bending moment produces a deflection (δ) at the tip of the cantilever beam that changes the airgap size, which then varies the emission wavelength of the VCSEL.

III. RESULTS

The piezoelectric actuation was experimentally demonstrated using white light interferometry and atomic force microscopy (AFM) measurement. Fig. 3 shows the resonance frequency measurement using AFM for two lengths of the piezoelectric cantilever beam, showing the fundamental and higher vibration modes. The beams were driven to resonance in air and the resonant frequency is ~100 kHz for a beam length of 120µm and ~23 kHz for 240µm.

To optimize the piezoelectric tuning performance, preliminary experimental study of the piezoelectric...
effect with different cantilever orientations and beam dimensions has been performed and compared with the theoretical calculations. Fig. 4a shows the vertical displacement for different cantilever beam orientation with same length of 240µm. Because of crystal asymmetry of Al$_x$Ga$_{1-x}$As compound, the piezoelectric coefficient ($d_{31}$) governing the piezoelectric actuation varies with crystal orientation [1], which results in decreasing magnitude of piezoelectric actuation towards the <100> direction. Fig. 4b shows the vertical displacement for different cantilever beam length along <110> direction, where a maximum deflection of 130nm and 270nm was obtained for beam length of 240µm and 360µm, respectively.

Fig 5a shows the CW emission spectra of the device with the piezoelectric actuation tuning, where a single mode emission (40dB) is obtained throughout the entire range. Fig 5b shows the emission wavelength as a function of the applied voltage across the top tuning electrodes and the IV-characteristic of the p-i-n structure in the cantilever beam. Within the voltage range from -1V to 8V, ~3nm of continuous and linear wavelength tuning is obtained with very small leakage current (<10nA). The device requires very low power for piezoelectric actuation (<1µW). In addition, the linear wavelength tuning characteristic with respect to the applied voltage shown in piezoelectric actuation may simplify and improve the wavelength control, comparing to the conventional electrostatic actuation. With further optimization of the optical and mechanical designs, it is anticipated that the wavelength tuning range can be easily increased for a wide range of applications including biomolecular sensing, signal routing and switching, and spectroscopy.

REFERENCES