STABLE PULL-IN ELECTRODES FOR NARROW GAP ACTUATION

Eldwin J. Ng[1], Yushi Yang[1], Vu A. Hong[1], Chae Hyuck Ahn[1], David L. Christensen[1], Brian A. Gibson[2], Kamala R. Qalandar[2], Kimberly L. Turner[2], Thomas W. Kenny[1]
[1]Stanford University, USA
[2]University of California, Santa Barbara, USA

ABSTRACT

This paper reports the use of movable electrodes that can be electrostatically pulled in to achieve narrow gaps beyond lithography / etch capabilities. Width-extensional resonators with frequencies of 50 MHz and quality factors of 150k are demonstrated with such movable electrodes to have a significantly lower motional impedances when pull-in occurs. Sub-ppm stability over 10^5 pull-in/pull-out cycles is measured using temperature-compensated resonators within the *epi-seal* epitaxial polysilicon encapsulation process. The pull-in phenomena is reversible, but can be made permanent by electrically welding the pulled-in electrode to a stop.

INTRODUCTION

The performance of most capacitive MEMS devices has a significant dependence on the dimensions of the capacitive transduction gap. In particular, the motional impedance of a resonator is lowered by having narrower gaps, contributing to a reduction in the phase noise of resonator-based oscillators. By shrinking the gap size, bias voltages can also be reduced considerably.

A number of methods have been presented to create deep submicron gaps in silicon. Deep reactive ion etching (DRIE) forms the basis for most of these methods, creating trench gap widths with aspect ratios of up to about 100:1 [1, 2]. To further decrease the gap size, one could employ a sacrificial oxide / polysilicon refill process (e.g. the High Aspect-Ratio Combined Poly and Single-Crystal Silicon (HARPSS) [3]). However, in the effort to produce a device compatible with the *epi-seal* epitaxial polysilicon encapsulation process (a high vacuum, ultra-clean, high yield, wafer-scale commercial process that has been used for stable resonators) [4, 5], such a sacrificial oxide / polysilicon refill process cannot be used, as the high temperature (>1000°C) bake step in an epitaxial reactor removes the native oxide and the polysilicon surface roughens due to silicon migration [6]. This roughening of the polysilicon surface on the order of hundreds of nanometers precludes the use of the material for submicron narrow gaps within the *epi-seal* process. Another method of reducing the gap dimension is to use an epitaxial gap tuning process [7] that produces smooth monocrystalline silicon on both sides of the gap. However, the selective epitaxial deposition step is dependent on the crystal growth direction, and could be undesirable for curved structures.

Alternatively, instead of defining the gap dimension during the fabrication process, another possibility is to use a movable electrode, where the gaps are defined with regular DRIE, and the electrode-to-device gap can be narrowed post-process by electrostatically pulling in the electrode. A significant reduction in the motional impedance of a resonator has thus been demonstrated previously [8], but the stability of such a device is in question especially when repeated pull-in cycles are performed. This work reports on a width-extensional mode resonator with pull-in electrodes that is fabricated in the *epi-seal* process. Sub-ppm stability is demonstrated over extended on-off bias voltage cycle testing.

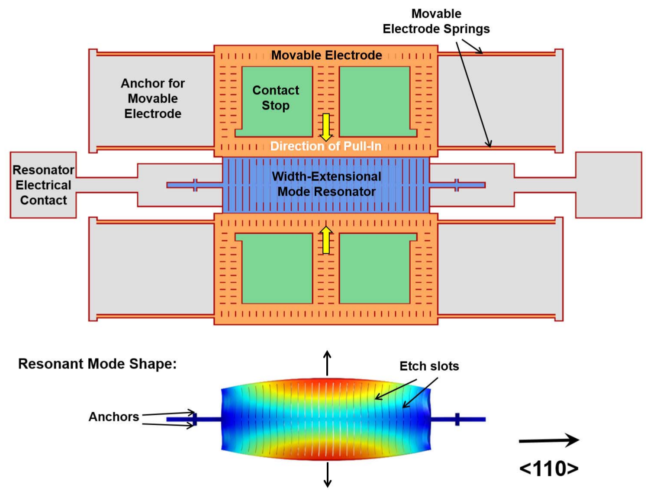

Figure 1: Width-extensional mode resonator with movable electrodes that can be pulled in to a stop.

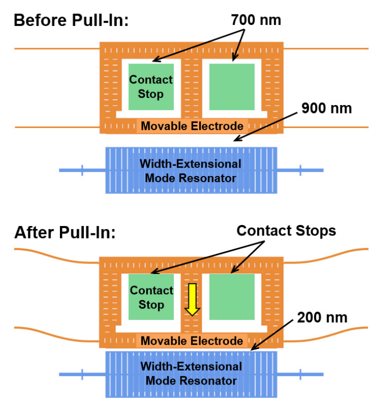

Figure 2: Gap reduction by pulling in a movable electrode.

DEVICE CONCEPT AND DESIGN

To demonstrate the pull-in concept within the *epi-seal* platform, a 50 MHz width-extensional mode resonator [9] is designed with movable electrodes suspended on springs of dimensions 3 μm wide by 160 μm long (Fig. 1).

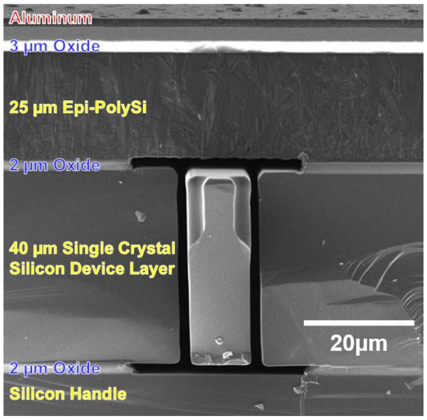

Figure 3: Cross-section SEM of an epi-seal encapsulated beam.

To operate the resonator, a bias voltage is applied to the resonator body to amplify the ac actuation force on the resonator body. In this case, it also serves a second purpose, which is to electrostatically pull in the movable electrodes (Fig. 2). To prevent the movable electrode from physically contacting and shorting to the resonator, a stop is placed to limit further movement of the movable electrode towards the resonator. The designed gap is hence the difference between the resonator-electrode gap and the electrode-stop gap: with a resonator-electrode gap of 900 nm and an electrode-stop gap of 700 nm, the designed gap is 200 nm.

FABRICATION PROCESS

The devices were fabricated in an *epi-seal* fabrication process [4]. *Epi-seal* is a high vacuum (sub-Pa), ultra-clean (high temperature seal, native oxide-free), high yield, wafer-scale process that is similar to the one used commercially at SiTime. For this fabrication run, a 40 µm-thick, highly n-doped (phosphorus doped, 6e19 cm^{-3}) device layer was used. The cross-section of a beam representing a final encapsulated device is shown in Fig. 3. It is useful to note here that although the walls of the trench are smoothed by the hydrogen anneal to the nanometer level, they are not flat, and some residual unevenness is observed. This has a direct impact on the contact, as it means that the contact between two surfaces is likely to be asperity dominated.

RESULTS

Pull-In and Pull-Out

Frequency sweeps were performed using an Agilent 8753ES network analyzer connected to the movable electrodes and a dc bias voltage applied on the resonator. The bias voltage was ramped up in steps, and for each voltage step, a frequency sweep was performed.

The peak magnitude of the frequency response depends on the bias voltage as well as the gap size, with the motional impedance R_m given by [9]:

$$R_m \propto \frac{g^4}{V_{Bias}^2} \qquad (1)$$

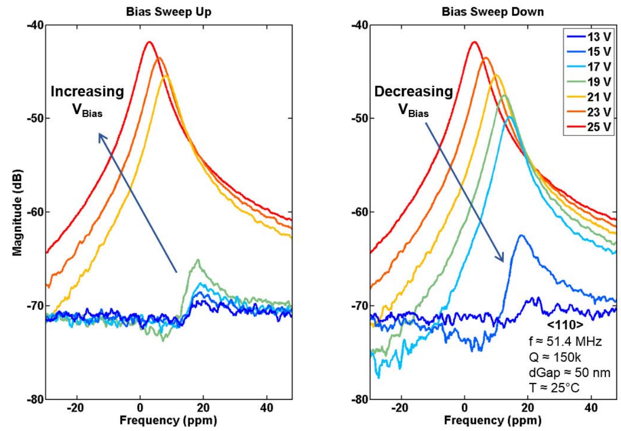

Figure 4: Frequency response of a resonator with pull-in electrodes at various bias voltages.

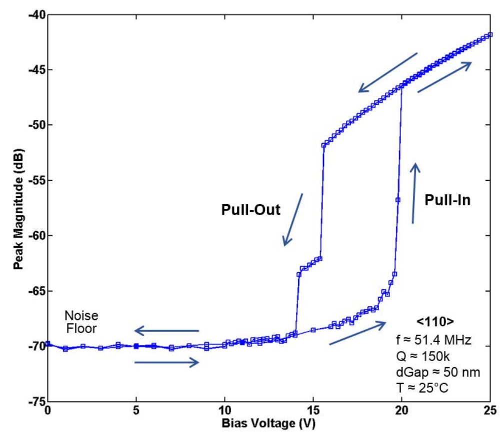

Figure 5: Peak magnitude of the resonator with pull-in electrodes as a function of the bias voltage. Pull-in / pull-out characteristics are observed.

where g is the gap size and V_{Bias} is the bias voltage. With a decrease in gap or an increase in the bias voltage, a motional impedance decreases, or equivalently, the peak magnitude increases. Frequency response plots for a width-extensional resonator with a designed gap of 200 nm are shown for several bias voltages in Fig. 4, while in Fig. 5, the peak value of the frequency response is shown as a function of the bias voltage. A sudden increase in the peak magnitude is seen at the pull-in voltage, corresponding to a sharp decrease in gap size. Further increasing the bias voltage causes the peak magnitude to increase even further as expected from (1). On the other hand, when the bias voltage is swept downwards after pull-in has occurred, a hysteresis curve is observed due to the pull-out voltage being lower than the pull-in voltage.

In addition, a double step is seen in the pull-in and pull-out curves (Fig. 5), because although the two electrodes on either side were designed to have identical pull-in voltages, the actual fabricated parts are not exactly identical, and the observed steps are due to one of the electrodes pulling in / out before the other.

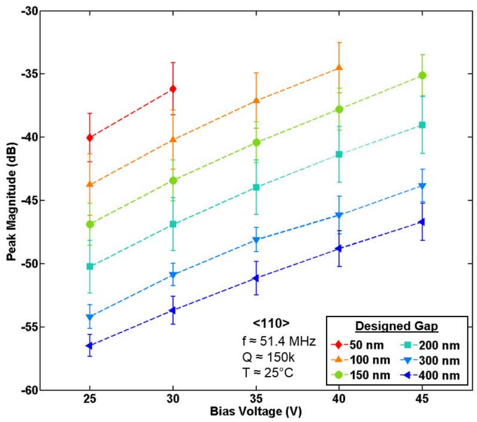

Figure 6: Peak magnitude as a function of bias voltage for various designed gaps.

Various Designed Gap Sizes

Devices with different designed gap sizes were tested, and Fig. 6 shows the variation of the peak magnitude with bias voltage for several designed gaps. About 5 devices of each gap size from around the wafer were tested, and the spread is reflected in the error bars. These devices were tested to the maximum bias voltage until failure (shorting of electrode to resonator), and it is observed that there is a region at the top of the plot beyond which a larger bias voltage is unable to achieve a higher peak magnitude (or a lower motional impedance) without device failure. It is also noted that the peaks are relatively lower than reported in [9]. This could be due to the non-uniform shape of the extensional mode, or the uneven trench profile, causing the average actuation gap to be larger than the designed gap.

Stability

A resonator's frequency stability is crucial for timekeeping applications, and the pull-in electrodes could adversely affect the stability. To investigate the stability at the sub-ppm level, it is important to first remove the effect of temperature fluctuations [10]. Heavily n-type doped silicon is known to change the frequency-temperature dependency [11], and frequency-temperature curves for width-extensional resonators aligned with <110> and <100> direction were measured for a doping level of 6e19 cm^{-3} (Fig. 7). Particularly useful is the frequency-temperature turnover point at 105°C for the <100> orientation, as operating at such a point minimizes the effect of temperature variation on frequency. <100> width-extensional resonators were thus chosen to investigate the stability of the pull-in electrodes. These resonators were placed in a Thermotron S1.2C temperature chamber and maintained at the turnover point of 105°C. Repeated bias voltage on-off cycles (from 0 to 25 V) were performed. The frequency stability and peak magnitude during the cycling is shown in Fig. 8. The first device was operated at an ac drive power of -15 dBm, and the same experiment was repeated on a second device with a higher ac drive power of -5 dBm to reduce noise. Small changes in the peak magnitude over

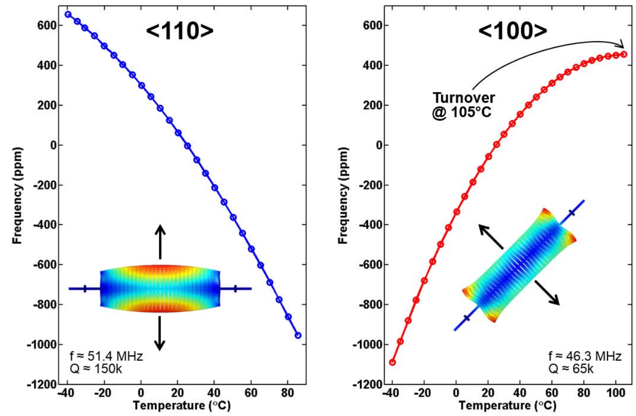

Figure 7: Temperature dependence of the resonant frequency for width-extensional resonators aligned to the <110> and <100> directions for 6e19cm^{-3} phosphorus-doped monocrystalline silicon.

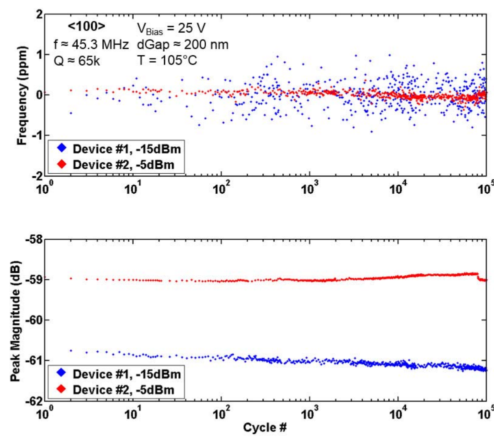

Figure 8: Frequency and peak magnitude stability of temperature-compensated width-extensional resonators with pull-in electrodes for 10^5 bias voltage on-off cycles.

10^5 cycles were observed for both devices, but the frequency remains largely stable at well below ±1 ppm.

Frequency sweeps were also performed periodically during the bias voltage cycling to investigate the contact and the variation of the pull-in and pull-out voltages (Fig. 9). Some variation in the pull-out voltage is observed (between 16 and 19 V), but the pull-in voltage remains stable, varying by no more than 0.2 V (the voltage sweep step size) throughout the 10^5 cycles.

Welded Electrodes

Furthermore, the electrodes can be welded to the stop to eliminate the pull-in / pull-out effect entirely. When the electrode is pulled into in contact with the stop, a current (of about 10mA) can be used to heat and permanently fuse the contacting silicon surfaces together, resulting in permanently pulled-in electrodes that behave like regularly anchored electrodes. Fig. 10 shows a peak magnitude vs. bias voltage plot of a device with welded pull-in electrodes.

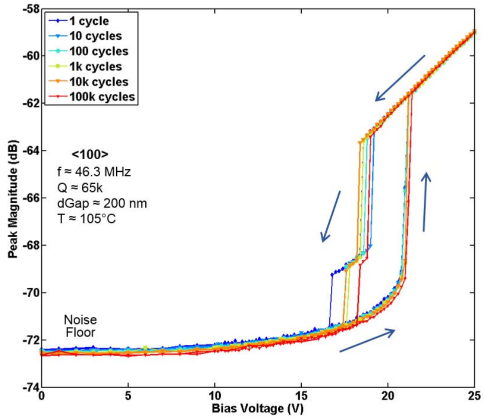

Figure 9: Peak magnitude as a function of the bias voltage as measured over 10^5 bias voltage on-off cycles.

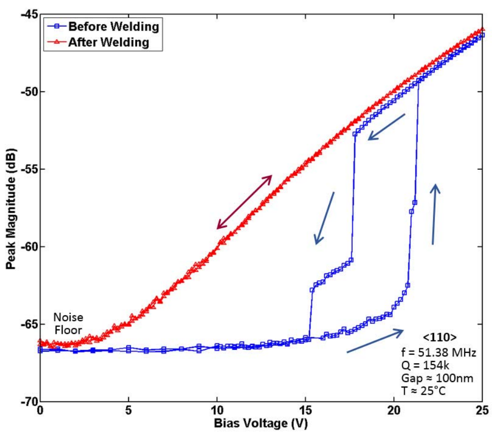

Figure 10: Comparison of a resonator before and after permanently welding the pull-in electrodes to the stop.

CONCLUSION

Demonstrated in this paper is a technique for achieving narrower gaps than lithography / etch capabilities allow within the *epi-seal* process. Lower motional impedances are observed for resonators when the electrodes are pulled in, and sub-ppm stability over 10^5 pull-in / pull-out cycles is achieved. In addition, the movable electrodes can be electrically welded to a stop to eliminate the pull-in / pull-out characteristics.

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CONTACT

*E.J. Ng, email: eldwin@mems.stanford.edu