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A Bonded-Micro-Platform Technology for Modular Merging of RF MEMS and Transistor Circuits

Ark-Chew Wong, Yuan Xie and Clark T.-C. Nguyen
Center for Wireless Integrated Microsystems
Department of Electrical Engineering and Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

ABSTRACT

A technology has been demonstrated that uses compression bonding to modularly combine platform-supported μmechanical filters with integrated BiCMOS transistor circuits while attempting to preserve the *Q* of mounted resonators. In this process, μmechanical devices are first fabricated onto SOI platforms, which are then released (together with devices) and compression bonded onto a transistor circuit wafer, making electrical connections at the bonds. Prior to bonding, while mounted on unreleased platforms, 6 MHz and 40 MHz clamped-clamped beam μmechanical resonators exhibit *Q*'s of 2,000 and 300, respectively. After release and bonding to the circuit wafer, the *Q*'s are degraded to 520 and 120, respectively. Poor bonding quality is identified as a likely reason for the observed *Q* reductions.

Keywords: resonator, filter, platform, bonding, SOI

I. INTRODUCTION

Micromechanical (μmechanical) resonators and bandpass filters with frequencies in the low-UHF range (e.g., 35-300MHz [1]-[3]) have recently been demonstrated with performances that rival (and even better in some cases) those of bulky, off-chip crystal and SAW filters used in present-day wireless transceivers. By integrating these μmechanical devices together with transistor circuits using a merged MEMS/transistor process technology [4]-[6], single-chip RF MEMS front-ends using high-performance super-heterodyne architectures may eventually become possible. The degree to which MEMS and transistor devices can be *modularly* combined is of utmost importance for RF MEMS applications, since the performance (e.g., *Q*, stability) of resonator devices is especially sensitive to fabrication conditions (e.g., temperatures, materials), which are often compromised in insufficiently modular merging processes.

This work investigates a technology that uses compression bonding to modularly combine platform-supported μmechanical resonators and filters with active transistor electronics. This bonded platform technology allows low-capacitance, "single-chip", merging of MEMS and transistors with several key advantages: (1) It is truly modular, requiring no compromises in either the MEMS or transistor modules; (2) It attempts to minimize *Q*-degrading anchor losses experienced by previous bonding-based methods [7] by bonding *platforms* housing resonators, instead of directly bonding the anchors of resonators; and (3) It constitutes not only a wafer-scale batch approach, but also a repeatable approach, where a step-and-repeat procedure can be used to allow a single MEMS wafer to service several transistor wafers.

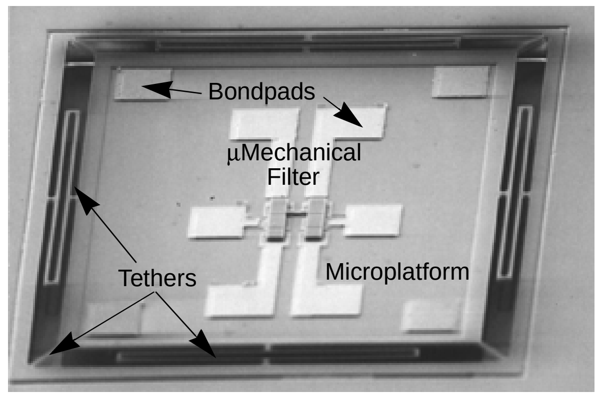

Fig. 1: SEM of a μplatform housing a 40 MHz, two-resonator CC-beam μmechanical filter

Using this process, functional platform-mounted clamped-clamped beam ("CC-beam") μmechanical resonators and bandpass filters with center frequencies up to 40MHz have been demonstrated, but unfortunately with some degree of *Q* degradation. After describing the basic process flow, this paper identifies several deficiencies in the process—particularly ones associated with the bonding process and the specific platform design—that ultimately constrain resonator performance.

II. THE BONDED MICROPLATFORM PROCESS

Figure 1 presents a scanning electron micrograph (SEM) of a completed μplatform housing a two-resonator, 40 MHz μmechanical filter [3], just before bonding to a transistor wafer. In addition to the filter, the platform also includes several 30×30μm^2 gold pads that serve as bonding sites to the transistor wafer. Some of these pads are strategically placed at corners of the platform to enhance stability during and after bonding, while others are located to serve as vertical interconnects between resonator electrodes and transistor electronics.

As shown in Fig. 1, the μplatform is suspended by weak low stress nitride tethers to be broken after bonding to a transistor wafer by tearing away the MEMS wafer, leaving bonded μplatforms behind, in a procedure succinctly summarized in Fig. 2. This "tear away" approach borrows from the work of [7], and offers similar advantages in that a single MEMS wafer with platform/device repetitions can be used to service several transistor wafers—as many as there are repetitions. The economy of such an approach is obvious, especially for integrated MEMS/transistor systems where the transistor circuit

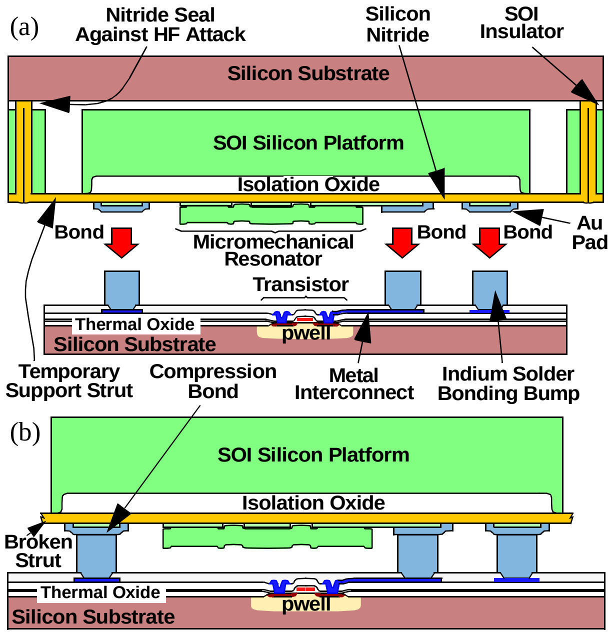

Fig. 2: Illustration of the procedure for achieving a combined MEMS/transsistor chip via the described flip-bond-and-tear process. (a) Bonding. (b) Final cross-section.

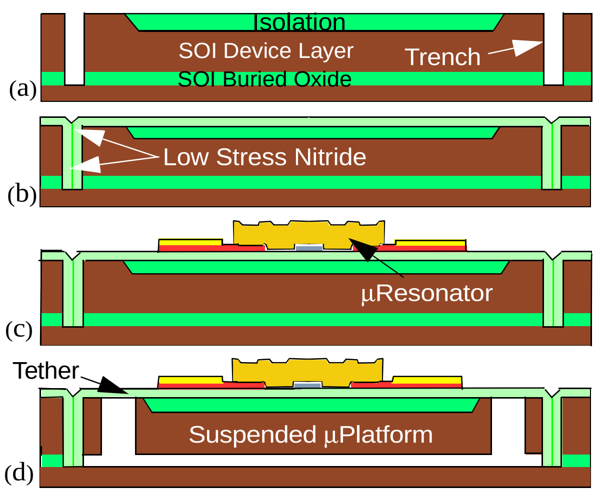

Fig. 3: Schematic showing cross-sections of the µplatform fabrication process flow.

dominates the die area.

III. FABRICATION DETAILS

The µplatform is realized using an SOI approach, where the silicon device layer of an SOI wafer defines the platform structure, and the buried oxide layer serves as a sacrificial layer, which is later removed to suspend the platform before bonding. The device layer in the SOI wafer is chosen to be 10-20µm-thick with the intent of maximizing the acoustic impedance of the eventual platform in order to minimize energy loss through the platform itself, and to minimize microphonic effects.

Figure 3 presents cross sections summarizing the µplatform process sequence. Here, a 5µm wide, 20µm deep trench is first etched around the platform area

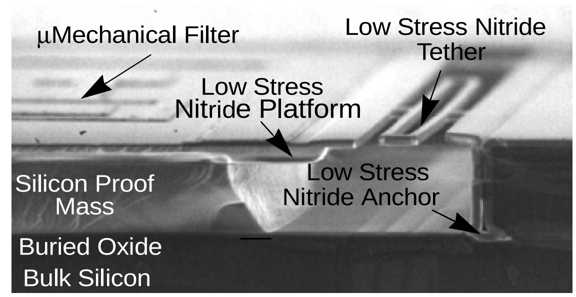

Fig. 4: SEM showing the cross-sectional view of the µplatform.

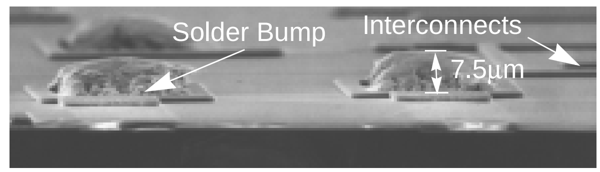

Fig. 5: SEM showing the solder bumps deposited on the BiCMOS wafer.

(defined by the isolation layer) using an STS deep RIE etcher (Fig. 3(a)). The trench is refilled with 2.5µm of low stress nitride to seal off the oxide in field areas from a future HF release step (Fig. 3(b)). The µmechanical filter is then fabricated directly over the platform area using a conventional surface µmachining process [6] (Fig. 3(c)). Upon completion of µmechanical filter processing, and before release, the nitride layer is patterned and dry-etched to delineate the platform and its supporting tethers. The µplatform structure and filters are then released using a combination of dry isotropic and wet etching techniques. The dry isotropic etch step removes the silicon under the nitride tethers, forming a trench opening that exposes the buried oxide. Figure 4 presents a cross-sectional SEM of the µplatform at this juncture. A surfactant-enriched HF solution (for better wetting along the sidewall of the opening) is then used to remove the sacrificial oxide under the platform, resulting in a suspended structure (Fig. 3(d)).

Next, 7.5µm-thick, 30×30µm^2 indium solder bumps are electroplated onto exposed bondpads on the BiCMOS wafer, which are located at sites corresponding to the gold electrode pads of the flipped µmechanical filter. Figure 5 presents an SEM of the deposited solder bump posts, showing some deficiencies in their shapes, and indicating that additional work is needed to fully characterize this step. Bonding of µplatforms to the BiCMOS wafer is then done via an Electronic Visions aligner-bonder using a compressive force of 500N and a temperature of 175^{o}C, which is needed to slightly reflow the solder bumps (Fig. 2(a)). The MEMS wafer is finally torn away from the BiCMOS wafer, breaking the tethers and leaving bonded µplatforms behind (Fig. 2(b)). Figure 6 presents top- and perspective-view SEMs of a µplatform bonded to BiCMOS circuits, with broken tethers clearly visible.

Of all the steps in the above process, the bonding of platforms to transistor circuit wafers proved to be the most difficult. This was due mainly to the poorly formed

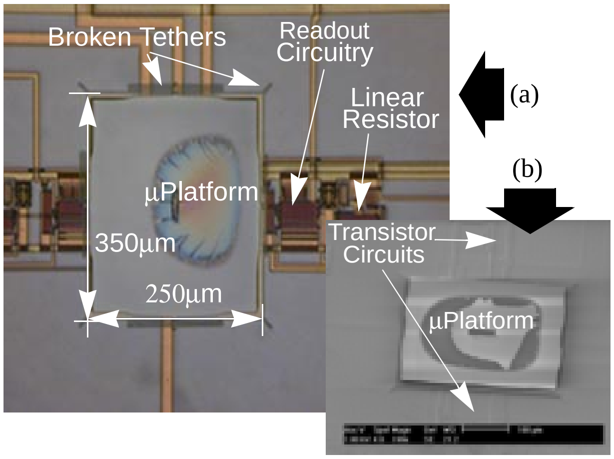

Fig. 6: A μmechanical filter circuit showing both the transistor level electronics and the bonded platform: (a) Top view; (b) Perspective view.

solder bumps (c.f., Fig. 5) mentioned above, but also due to cleanliness problems during bonding. In particular, before bonding, after flipping one wafer above the other, particulates were seen to drop onto the bottom wafer, seriously compromising the quality of the bonds. All tolled, the above problems led to less than 30% yield after bonding. Needless to say, further characterization of the bonding procedure is needed.

IV. EXPERIMENTAL RESULTS

A custom-built vacuum chamber capable of achieving 50μTorr pressure was utilized to test μmechanical resonators and filters housed by bonded platforms. The devices under test included a 40 MHz CC-beam μmechanical resonator and a 38 MHz two-resonator filter, each with electrode-to-resonator gaps d_o of 350Å; and 6 MHz CC-beam resonator with a relatively large gap d_o=1000Å. The 6 MHz device was included in testing, because it suffers less from anchor losses than the others [8], and thus, could better serve as a vehicle for estimating the degree of Q degradation introduced by bonded-platform mounts.

Pursuant to exploring the effect of platform-mounting on device performance (especially, on Q), both bonded-platform-mounted devices and ones on unreleased platforms (still attached to the MEMS carrier wafer; i.e., substrate-mounted) were tested. Figures 7-10 present measured frequency spectra before and after platform-bonding for each of the aforementioned devices.

Before commenting on the observed “before and after” Q changes, some justification for the difference in Q between the various substrate-mounted test resonators is in order. Specifically, from the curves of Figs. 7 and 8, the Q of the substrate-mounted 6 MHz resonator is clearly much higher than that of its substrate-mounted 40 MHz counterpart. Although anchor losses, which are higher for the stiffer 40 MHz resonator, are partly responsible for this [8], it is actually Q-loading by parasitic interconnect series resistance R_s that dominates the difference in Q. In particular, although both devices “see” approximately the same load resistance R_s ~150Ω,

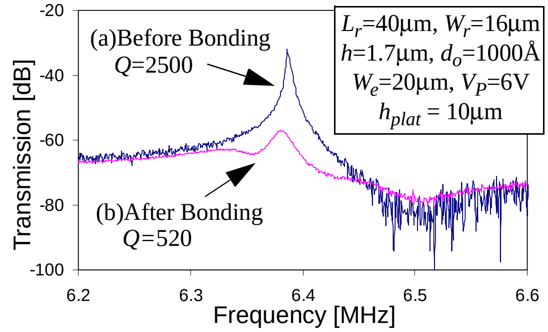

Fig. 7: Frequency response of a 6MHz μresonator (a) before bonding and (b) after bonding.

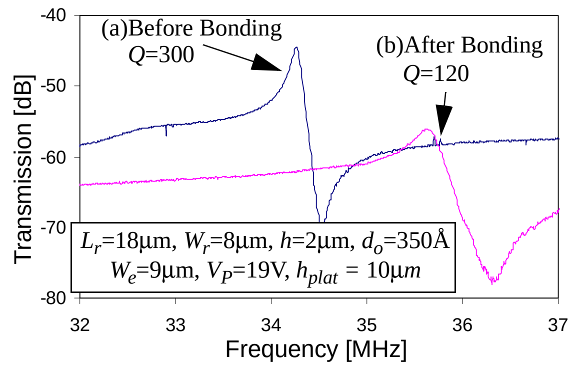

Fig. 8: Frequency response of a 40MHz μresonator (a) before bonding and (b) after bonding.

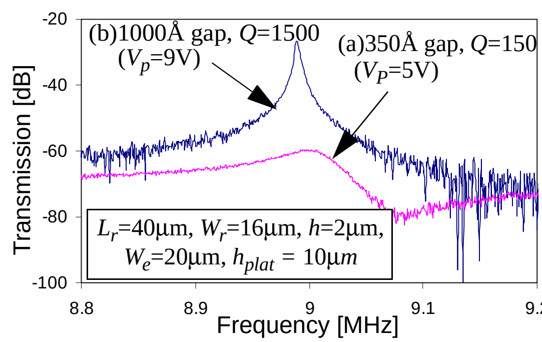

Fig. 9: Frequency response of a 9MHz μresonator with (a) 350Å gap (b) 1000Å gap.

the 40 MHz device has a much smaller series motional resistance R_x ~25Ω than its 6 MHz counterpart (R_x~2.75kΩ), since its electrode-to-resonator gap spacing d_o is much smaller. (As detailed in [8], R_x goes as d_o^4, so its value rolls off very quickly as d_o gets smaller.) Thus, the Q of the 40 MHz resonator is loaded more heavily by R_s, as predicted by expression for loaded Q

$$Q_L = Q\left[\frac{R_x}{R_x + R_s}\right] \qquad (1)$$

where Q and Q_L are the intrinsic and loaded Q’s, respectively. As further testament to this loading-dominated Q-degradation mechanism, Fig. 9 presents measured spectra for two 9 MHz CC-beam resonators—one with d_o=300Å, the other with d_o=1000Å—where the Q =1,500 for the larger-gapped device is clearly much higher than the Q=150 of its smaller-gapped counterpart.

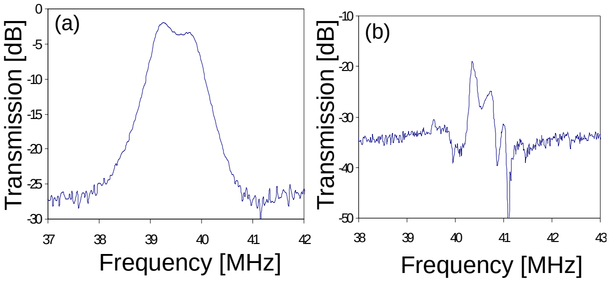

Fig. 10: Frequency response of a 40MHz filter (a) before bonding and (b) after bonding.

Returning to our comparison of substrate- versus platform-mounted resonator performance, Fig. 7 reveals that the Q of the 6 MHz resonator drops from 2,500 for the substrate-mounted device, to only 520 after its platform is released and bonded to the transistor wafer. Figure 8 shows a similar effect for the 40 MHz resonator, where the Q drops from 300 to 120 after release and bonding of the platform mount. Needless to say, the observed Q loss is disappointing, and can tentatively be attributed to either or all of the following mechanisms:

(1) Poor mechanical quality of the compression bonds (c.f., Section III). If these bonds are not perfectly rigid, they can be a source of losses in cases where energy is transferred from the resonator device, to the platform, to the substrate.

(2) Insufficient platform rigidity. The 10 μm-thick platform may in fact not be thick enough to present an infinite acoustic impedance to a resonator. The farther from infinity the impedance, the greater the losses, and the lower the system Q.

(3) Poor electrical quality of the compression bonds. In particular, bond deficiencies described in Section II can raise the R_s by up to 5X, making Q-loading an issue for even medium-gapped resonators.

(4) Insufficient cleanliness in the process. After bonding, the yield of working devices was substantially lower than before bonding. Given the well-known susceptibility of μmechanical devices to contamination [3], this could easily be a source of Q degradation.

Design and fabrication adjustments are presently underway to remedy or investigate the above phenomena.

In the meantime, Fig. 10 presents measured frequency characteristics for the 38 MHz two-resonator μmechanical filter, before and after platform release and bonding. Again, significant performance degradation is observed after platform bonding, and not all of it can be attributed solely to Q-degradation. In particular, if Q-reduction were the only deficiency, then the same frequency characteristics would be expected in (a) and (b), with only an insertion loss difference between the two. Instead, distortion is seen in (b), possibly caused by a variety of phenomena, including platform-based capacitive/charging effects, or even contamination.

The on-chip circuit in Fig. 6 (detailed schematic shown in Fig. 11(a)), comprises a test-bed for evaluating passband termination properties for μmechanical filters. In this circuit, a capacitive feedback op amp circuit is

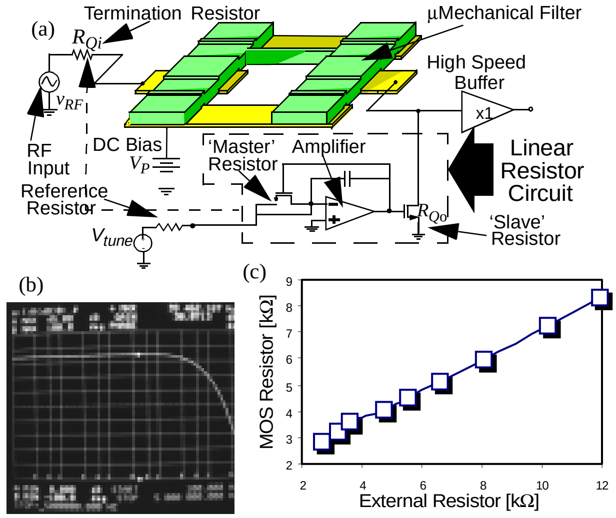

Fig. 11: (a)A μmechanical filter with Q-control resistor circuit. (b)Transfer function of the amplifier used in the resistor. (c) Response of the on-chip MOS resistor.

used to force an on-chip MOS "master" resistor to match an external reference resistor, which then forces a "slave" resistor to also take on this value. The slave resistor then serves as a settable termination resistor for the μmechanical filter. Figure 11(b) presents the open loop transfer function of the amplifier, showing a measured dc gain of 38dB and a 3dB roll-off frequency at 1MHz. The response of the MOS resistor to different external reference resistors is presented in Fig. 11(c).

V. CONCLUSIONS

A bonded-microplatform technology for modular, wafer-level merging of RF MEMS and transistor circuits has been demonstrated. Although device functionality has been achieved, a number of deficiencies still remain in the process flow that hinder the Q of merged MEMS/transistor systems. Among the several possible contributors to Q-reduction in mounted devices, poor bonding quality, brought about mainly by poorly formed bond pads, is the most likely suspect. To alleviate this deficiency, further characterization of the bonding process and a redesign to increase the size of bond pads (to allow a more even distribution of forces during bonding) are in progress. Once (and if) the above problems are solved, this technology has good potential for use in mixed RF MEMS/transistor communication architectures.

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