AN ULTRA-THIN PACKAGED MEMS OSCILLATOR

Brian H. Stark, Eric Radza, Pavan Gupta, Jason Sharma, Ganesh Peramaih, Sherwin Deng, Sunny Suen, Robbie Sheridan, Aaron Partridge, and Markus Lutz
SiTime Corporation, Sunnyvale, California, USA

ABSTRACT

This paper reports the world's thinnest packaged oscillator, the SiT8002UT (Figure 1). This device is a $370\mu\text{m}$ thick oscillator ($3.0\times 3.5\text{mm}$ lateral dimensions) that can be programmed to a frequency between 1 and 125MHz with a 10ppm initial frequency resolution. The stability of the SiT8002UT over the industrial temperature range is evaluated to be $\pm 20\text{ppm}$. The SiT8002UT is also, to our knowledge, the thinnest packaged MEMS product. In order to realize this device, functional $75\mu\text{m}$ -thick MEMS wafers are also demonstrated.

Figure 1: Images of the SiT8002UT. Nominal thickness is $370\mu\text{m}$ ($\sigma=5\mu\text{m}$).

INTRODUCTION

The quest for thinner oscillators is driven by the continuing decrease in the size of consumer electronics [1]. While many IC and passive components can be shrunk with relative ease, precision timing references heretofore have resisted the trend of extreme dimensional reduction [2]. In many portable applications, thickness is a more critical size metric than lateral dimensions. Comparative commercially viable oscillators (Figure 2) are at least $400\mu\text{m}$ thicker than the SiT8002UT. These oscillators are made from traditional quartz technology, which is limited in its ability to scale to thinner dimensions. As quartz must be vacuum encapsulated, the thickness of the package is fundamentally linked to the lateral dimensions of the part; to withstand the pressure of a vacuum cavity, the quartz package must have a relatively thick metal membrane around the package. As the membrane is thinned (to reduce package height), it must also be shrunk laterally to maintain stiffness. Shrinking lateral dimensions in quartz technology necessitates an increase in device cost, as solder seal rings are

reduced and process yields decrease dramatically. As a result, a further limitation of traditional quartz oscillators is that cost increases as device thickness shrinks. In comparison, semiconductor products evidence no fundamental linkage between device thickness and footprint. Furthermore in modern batch packaging technologies, price decreases with decreasing dimensions, as more units can be encapsulated in a single molding operation.

Figure 2: Size comparison of State-of-the-Art packaged oscillators. This work represents the thinnest device reported. Other oscillators are at least $400\mu\text{m}$ thicker than this work. Thickness is a critical metric for many space constrained consumer applications.

To reduce the height of a standard MEMS oscillator, two basic mechanisms are employed: 1) the stacked die configuration employed in current oscillators is replaced in favor of a side by side configuration and 2) the die are thinned as much as possible. At the onset of this project, it was unclear how much thinning could be reasonably achieved on a MEMS resonator without deleterious performance implications. Previously reported literature [3] has suggested that a thinned MEMS substrate results in an unacceptable deterioration of the Quality factor of the device. As a result (mitigating risk of thinned MEMS), two technologies to build a $370\mu\text{m}$ thick oscillator are explored (Fig. 3). One package is based upon a $240\mu\text{m}$ thick mold cavity (X2 mold thickness) on top of a $125\mu\text{m}$ thick Cu leadframe (X2QFN technology). The other utilizes a $370\mu\text{m}$ thick mold cavity (U mold thickness) on top of an $8\mu\text{m}$ thick Au/Ni/Au galvanically formed leadless land grid array pattern (ULLGA). The X2QFN requires thinner silicon die (reliability risk) and has worse stress behavior over temperature; the ULLGA allows for thicker silicon and exhibits less bimorph-induced stress, but can be more prone to delamination. In one variant of the X2QFN, to accommodate thicker MEMS die (again for risk mitigation if $75\mu\text{m}$ MEMS weren't practical – later shown unnecessary), a half-etched pocket was implemented in the leadframe. Both technologies were fabricated in high volume facilities that have installed manufacturing capacities exceeding one million units per day. Assembly yields are comparable to industry standards

Figure 3: Diagram of the Ultra-Thin MEMS oscillator in different constructions. A X2QFN is made in two variants: 125µm thick MEMS with a half etched pocket (top) and 75µm MEMS in a standard leadframe (middle). The pocket was shown to be unnecessary as 75µm thick MEMS can be utilized without deleterious effects. The ULLGA is made with a center die paddle (bottom). The die in the ULLGA construction are 125µm thick.

FABRICATION

In both package variants, construction begins with a leadframe (ULLGA process depicted in Figures 4a-d). MEMS and CMOS wafers (described in [4]) are ground and polished to either 75µm or 125µm and diced. This extreme height reduction (thinnest MEMS product reported) is possible due to the low-profile thin film encapsulation utilized in the MEMS process (Figure 5). Contrary to previously reported work [5], no decrease in Q is evidenced by thinning the substrate to these dimensions (Figure 6). After dicing, the chips are placed side by side on leadframe strips and wirebonded with 25µm gold wire. The populated leadframes are then transfer molded. Given the thin mold cap and the corresponding high mold pressures, extreme care has to be exercised in the molding process to prevent wire damage and latent

construction defects (Figure 7). The molded devices are then tested in strip and singulated.

Figure 4a: ULLGA process. Fabrication begins with a galvanically formed lead pattern on a sacrificial copper substrate.

Figure 4b: ULLGA process. Thinned die are mounted and wirebonded.

Figure 4c: ULLGA process. The part is molded. The copper substrate is removed after molding via a wet process.

Figure 4d: ULLGA process. The parts are flipped upside down (dead bugged) and strip tested using a probe card.

Figure 5: Cross section of the X2QFN showing manufacturing tolerances. In order to fit into the requirements of this package, 75μm-thick MEMS die are used. At this thickness, the substrate is thinned to ~39μm. As such, there is roughly an equal amount of silicon below the buried oxide as above it. This is the first MEMS resonator reported that achieves this thickness without deleterious performance implications. This extreme thinning is only possible with thin film encapsulation.

Figure 6: MEMS probe map of the center of the wafer showing resonator metrics at full thickness (top) and after thinning (bottom). Contrary to the results in [5], no significant decrease in Q (change from green at $>80k$ to red at $<80k$) is evident due to extreme thinning. Some change in insertion loss (change in shade of green) is observed; this is inaccuracy in the insertion loss measurement. This change does not materially impinge device performance.

Figure 7: X-ray showing wirebond damage caused by poor molding conditions (top) and optimized construction (bottom).

RESULTS

The packaged devices were measured to ensure compliance with thickness specifications. A Mitutoyo disk micrometer (accuracy 1μm) was used to measure the thickness of the entire package (including warpage) on 33 parts. The results are presented in Figure 8. As can be seen, the package is 370μm thick with a standard deviation of 5μm. This gives the package a 6σ confidence interval against a specification of 400μm thick.

Figure 8: Histogram showing thickness measurements on the SiT8002UT.

The devices were extensively characterized. A key component of designing a thin oscillator is maintaining frequency stability of the part over temperature. Furthermore, the product must withstand the rigorous moisture requirements specified in JEDEC STD-020D. After assembly, 50 parts were randomly removed from carrier tape. The parts were placed into an oven and operated continuously from -40°C to 85°C (Industrial Temperature Range) for 5 cycles. Figure 9 shows the performance of these 50 SiT8002UT parts versus temperature (blue curve); these parts demonstrate ± 20 ppm frequency stability. After the initial temperature screen, the parts were subjected to the JEDEC Moisture Sensitivity Level 1 (MSL 1) screen. The parts were then dried at 125°C for 24 hours, and then subjected to 168 hours at 85°C/85%RH and 3 260°C solder reflow cycles. As can be seen, performance is not noticeably impacted (red curve in Figure 9). The parts were also inspected with Scanning Acoustic Microscopy (C-SAM) to probe for delamination (Figure 10). As evidenced, there is no indication of delamination in these packages after MSL 1 exposure. These parts have been subsequently subjected to a full product qualification (HTOL, Biased Hast, Temp Shock, and Temp Cycle) and all units have passed the tests.

Figure 9: Frequency versus temperature (5 cycles) of the SiT8002UT (50 samples) after assembly (blue) and after MSL 1 exposure (168 hours at 85°C/85%RH, 3 cycles to 260°C). The frequency stability is ± 20 ppm.

Figure 10: Scanning Acoustic Microscopy Photo of 22 SiT8002UT packages after MSL 1 exposure. No obvious package delamination can be observed. A delamination would evidence itself as a large red region within the package (this can be especially prevalent in the die attach epoxy)

CONCLUSION

A 370μm thick, packaged MEMS oscillator has been demonstrated in multiple packaging technologies. In the course of developing this product, we have shown that it is possible to build 75μm thick MEMS resonators without noticeable deleterious performance implications. The parts were measured after fabrication and shown to have ± 20 ppm frequency stability, which compares favorably with state of the art timing devices in this thickness range.

REFERENCES

- [1] C. Beelen-Hendrikx and M. Verguld, "Trends in electronic packaging and assembly for portable consumer products," *Proceedings of EPTC 2000*, pp. 24-32, 2000.
- [2] Y. Nagaura and S. Yokomizo, "The machining and characteristics of an ultra-thin, plano-convex-type quartz oscillator," *Proceedings of the 1998 IEEE Frequency Control Symposium*, pp 844-7, 1998.
- [3] Y-H Park and K. C. Park, "High-Fidelity Modeling of MEMS Resonators – Part II: Coupled Beam-Substrate Dynamics and Validation," *IEEE Journal of Microelectromechanical Systems*, Vol. 13, No. 2, pp. 248-57, 2004.
- [4] M. Lutz, A. Partridge, P. Gupta, N. Buchan, E. Klaassen, J. McDonald, K. Petersen, "MEMS Oscillators For High Volume Commercial Applications," *Proceedings of Transducers '07*, Lyon, France, pp. 49-52, 2007.
- [5] A.-C. Wong, Y. Xie, and C. Nguyen, "A Bonded-Micro-Platform Technology for Modular Merging of RF MEMS and Transistor Circuits," *Proceedings of Transducers '01*, Munich, Germany, pp. 992-95, 2001.