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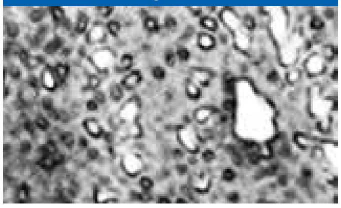
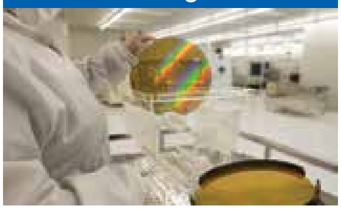
When x-ray and ultrasound join forces

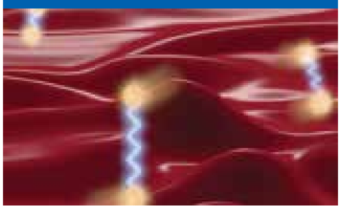


Wafer bonding enables future RF manufacturing

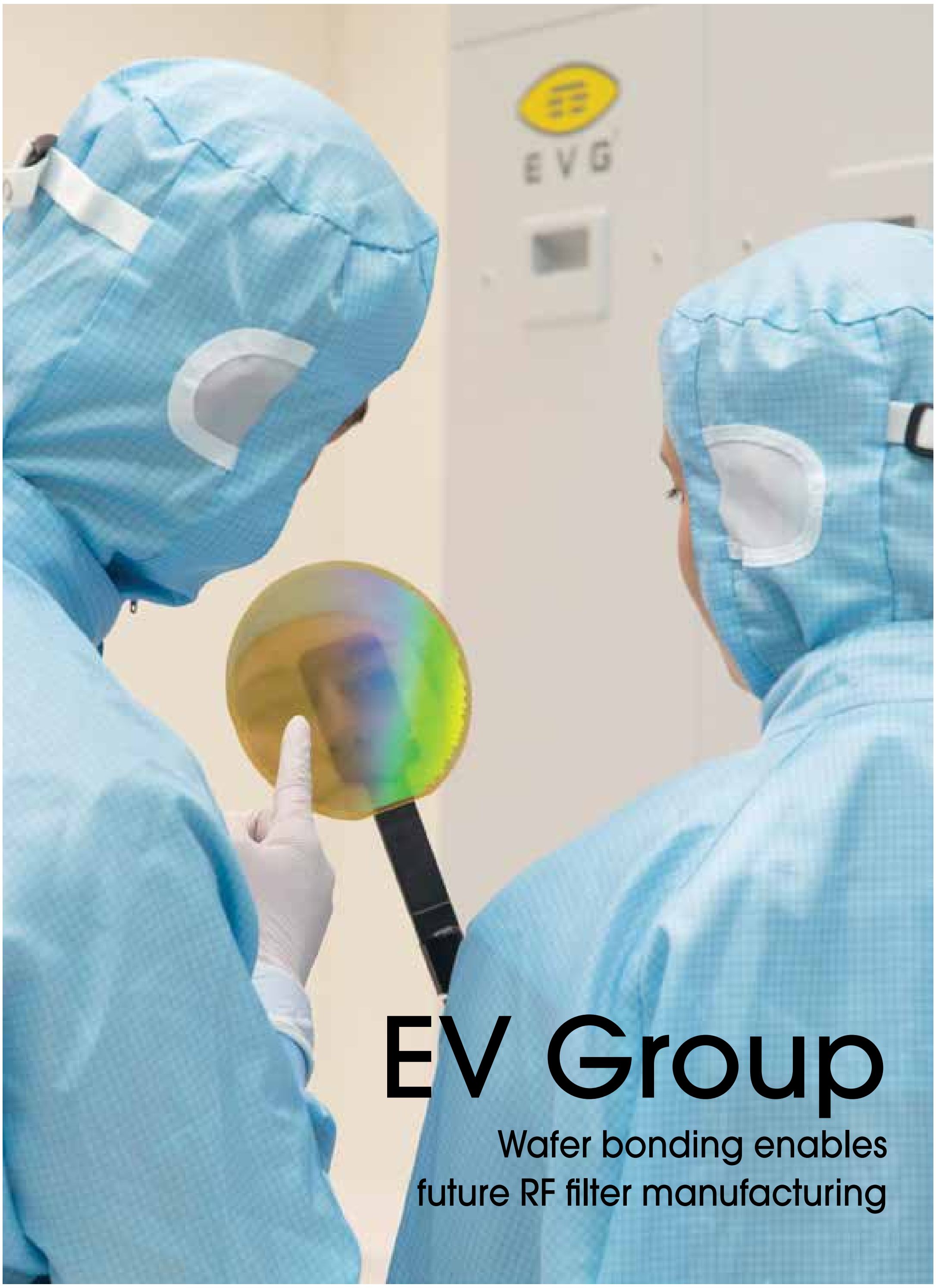
Benefit from customized wafer cleaning



In the search for efficient thermoelectrics



Water creates traps in organic electronics



EV Group

Wafer bonding enables future RF filter manufacturing

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AN ANGEL BUSINESS COMMUNICATIONS PUBLICATION

Wafer bonding enables future RF filter manufacturing

The continually growing demand for faster mobile data access and smart integration strategies is creating new and greater requirements affecting RF filter designers and manufacturers. EV Group examines ways to accelerate the production of SAW-based devices through the use of new materials and packaging methods supported by advanced wafer bonding techniques.

By Dr. Thomas Uhrmann, EV Group

MOBILE TECHNOLOGY has emerged as a primary engine of economic growth and transformed our everyday lives in a profound way. With each passing year, mobile technology's spread throughout the world increases – through new types of electronic devices as well as new applications. Volume shipments of smartphones are expected to reach nearly 1.8 billion annually by 2021 [1]. Not surprisingly, global mobile traffic growth is also rising rapidly, with some estimates of traffic usage at 49 exabytes per month by 2021 [2]. These trends are leading to growing bandwidth demands and more crowded spectrum.

The migration from 3G to 4G and 4G LTE broadband wireless technologies has enabled multimegabit bandwidth, more efficient use of the radio network, latency reduction, and improved mobility – ultimately enabling faster download speeds. This in turn is driving a dramatic increase in the need for advanced filtering technologies, with some high-end, feature-rich phones today incorporating over 50 radio frequency (RF) filters [3]. The transition to 5G – driven not only by consumer demand for more graphic-processing-intensive applications such as augmented/virtual reality (AR/VR) but also the Internet of Things (IoT), the Tactile Internet, Industrial 2.0/IIoT, smart grid/energy and autonomous vehicles – will further drive new filter requirements [4]. These include different frequencies (and more of them), as well as steeper skirts in individual filter bands to reduce cross-talk between the bands and improve frequency accuracy.

RF filters need to be simultaneously smaller, cheaper and have increased functionality in order to support these growing requirements for consumer mobile devices. However, surface acoustic wave (SAW) filters are difficult to scale dimensionally due to the physical properties of the substrate material used to fabricate them. Opportunities at both the materials/substrate level as well as in packaging are emerging that can enable RF filter manufacturers to drive down RF filter costs and footprint as well as increase filter functionality. These are:

- The adoption of substrates with improved electrical properties such as lithium tantalate ($LiTaO_3$, also referred to as LTA) and lithium niobate ($LiNbO_3$, also referred to as LN) on silicon
- The adoption of wafer-level packaging to drive down costs, reduce footprint and increase device performance for improved robustness/protection from the elements or even f or hermetic sealing

Wafer bonding plays an important role in enabling the integration of new materials like LTA and LN on silicon in SAW filter manufacturing. This article will explore several wafer bonding technologies that are needed for both substrate processing and packaging of LTA- and LN-on-silicon based SAW filters.

Wafer bonding considerations for new substrate combinations

Bulk LTA and LN substrates possess unique optical, piezoelectric and pyroelectric properties that make them valuable for SAW applications such as RF filters. However, LTA and LN are very expensive as well as brittle materials, which make them prone to breakage and yield loss. In addition, LTA and LN are anisotropic materials, which have different linear expansion coefficients in different directions. RF filters built with these materials have a temperature yield drift, which makes it very challenging for the filter to stay on the designated band. As a consequence, the filter chip has to be physically broad – with relatively wide spacing of the interdigitated finger structures deposited on the filter – in order to compensate for the temperature-related shift and remain on the designated band while maintaining good filtering properties with little to no signal degradation.

To address this thermal expansion and band drift problem, a thin layer of LTA or LN can be bonded onto a bulk silicon substrate, with the subsequent wafer stack processed, diced and packaged versus manufacturing RF filters on bulk LTA or LN substrates. Unlike LTA and LN, silicon is isotropic, whereby the substrate expands at the same rate in every direction. In a typical LTA-on-silicon stack, the LTA layer may be as thin as one micron or even less, while the silicon layer is 100 times thicker in the final filter. Representing the bigger component in the thermal expansion equation by far, the silicon stabilizes the thermal properties of the filter. This makes the filter less prone to reacting to temperature changes and parasitic effects. This allows the thickness of the filter and band selection to be made much narrower and more finely tuned, keeping the frequencies

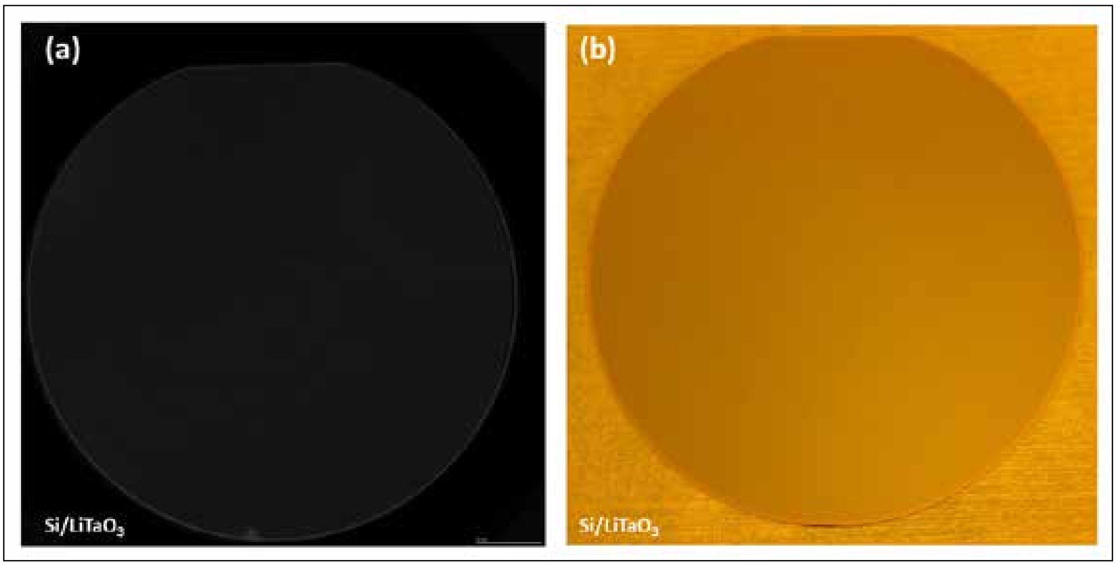

Figure 1. Lithium tantalate (LTA) bonded on silicon using LowTemp plasma activation (a) scanning acoustic image, and (b) photography of the bonded wafer pair.

locked to a tighter band. This approach has additional cost and yield benefits. For example, since silicon is a much less expensive material compared to LTA and LN, the overall cost of the filter can be reduced. At the same time, silicon is a material that is already well understood in the wafer fab and easy to incorporate into a volume production environment.

Wafer bonding challenges

Direct wafer bonding is a bonding approach that enables the combining of two different materials with different lattices and coefficients of thermal expansion (CTEs) without any additional intermediate layers. The bonding process, which is based on chemical bonds between two surfaces that are established by elevating the temperature of the surfaces and applying pressure, can be used to enable LTA/LN on silicon. However, there are several key considerations with direct wafer bonding:

- **Surface roughness:** excessive roughness inhibits sufficient contact of the wafers, which leads to low bond strength or no bonding at all
- **Cleanliness:** particles on the wafer surface result in voids due to lack of surface contact in that region of the wafer
- **CTE Mismatch:** at high bonding temperatures, CTE mismatch introduces stress that results in wafer bow and can even lead to cracks

Current methods of manufacturing LTA and LN wafers are generally less sophisticated compared to silicon wafer manufacturing. For example, bright polishing is often used instead of chemical mechanical polishing (CMP), which is insufficient for properly conditioning the wafer's surface prior to bonding. In addition, the CTE of the two materials differs significantly from silicon (by a factor of 3 in the case of LN, and by a factor of 4-6 depending upon direction in the case of LTA) [5]. As a result, even bonding at temperatures lower than 200°C results in cracks, which cause massive yield loss. However, treating the surface of the silicon substrate with plasma prior to bonding the LN/LTA layer allows the annealing temperature to be reduced to 100°C, which in turn eliminates voids and cracking (Figure 1). In addition, a pre-cleaning step prior to plasma activation can eliminate surface roughness and particles to ensure maximum bonding yield [6]. Plasma-activated wafer bonding thus provides an ideal process for manufacturing temperature-compensated SAW filters. Figure 2 illustrates a typical plasma-activated wafer bonding process flow.

Modularization drives new RF packaging requirements

Packaging has a very high impact on the size of RF filters. To support filter scaling, future packaging needs for RF filters (including those based on LTA and LN-on-silicon) are being driven by the industry trend toward "modularization", where individual RF filter components are being bundled into filter bank modules rather than integrated individually. Whereas with the earliest cell phones, individual band filters would be used for different area codes and packaged separately, more recent models are incorporating modules that may encompass all area codes in a country or region. The resulting module is a discrete device, yet ends up being extremely bulky to cover all the functionality within.

Modularization is occurring as a result of a combination of factors, including industry consolidation and customer segmentation, which is driving wireless chipmakers to acquire component manufacturers as a means of gaining competitive

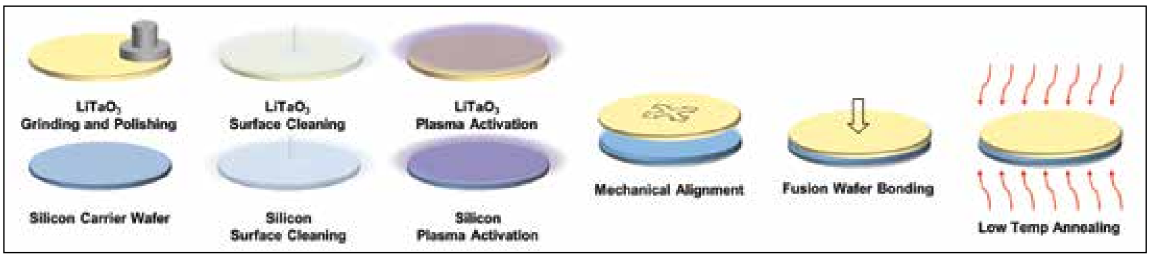

Figure 2. Example of a plasma-activated wafer bonding process flow.

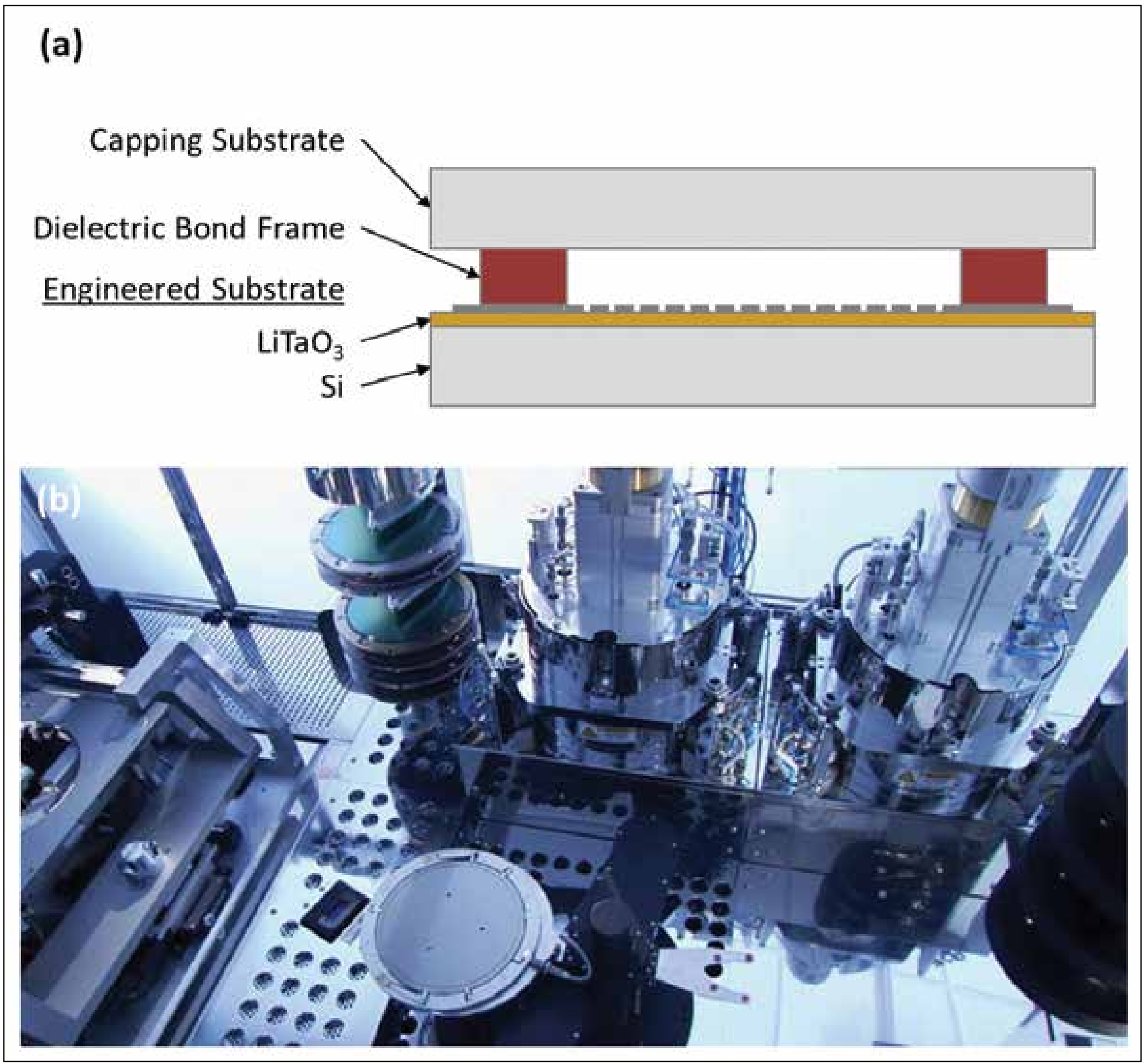

Figure 3a: Example of a SAW filter;

Figure 3b: Internal view of an adhesive wafer bonding chamber.

advantage and greater market share. Recent examples include the formation of the Qualcomm-TDK joint-venture RF360, Avago's acquisition of Broadcom, and the merger of RFMD and TriQuint resulting in the formation of Qorvo. This has led to the creation of the front-end module market with a few key players and preferred customers (handset device makers). For smart phone manufacturers, a major benefit of modularization is the fact that they can manage a single supplier. For the RF/wireless device manufacturer, the greatest benefit for the design winner is gaining a larger piece of the business. However, the reverse is true for the companies that lose out on the design win, as they are at risk of losing a greater share of the overall RF market.

Modularization is not simply packing more filters into a device, however. The filters themselves are also becoming more complex. For example, several different frequency bands are being manufactured on the same area on the same chip. Advanced wearables such as smartwatches with wireless connectivity have stringent footprint requirements and cannot afford to incorporate bulky filter modules. Smart phones also have stringent requirements when it comes to product thickness as well as improving energy efficiency.
Scaling down the size of these packages through wafer-level chip-scale packaging (WLCSP) is critical to supporting these applications. WLCSP provides many benefits to RF filters:

- **Smaller packaging -** WLCSP requires no bond wires or interposers, which makes ultra-compact packaging possible
- **Increased functional density -** the smaller packaging compared to direct mounting on a printed circuit board enables smaller filter banks as well as filter stacking, which increases functional density
- **Improved performance -** Compensation for RF noise and temperature induced drift effects can be done in the package via dielectric strain buffers, which provides better signal quality for RF filters specifically
- **Lower cost -** WLCSP is a batch fabrication packaging process, which enables higher-volume manufacturing, which ultimately drives down per unit cost
- **Hermetic packaging -** WLCSP can cap the device wafer to protect the active area of the filter using a capping wafer, or by sealing a plane wafer with an additive structure on the capping wafer

Wafer bonding for RF WLCSP

In the case of SAW filters, a polymer frame surrounding the outside of the device is needed in order to create a cavity between the interdigital transducers (IDTs) that are fabricated on the surface of the LTA/LN substrate and the cap wafer. This allows for free movement of the acoustic waves across the top surface of the device wafer. The IDTs are simple lithographic

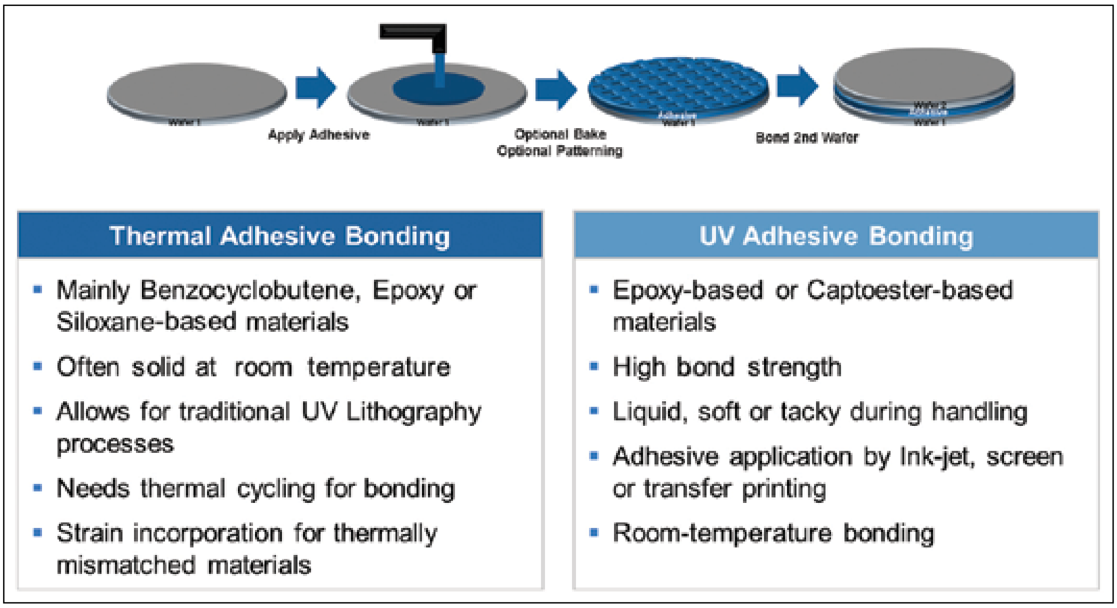

Figure 4. Adhesive wafer bonding process flow and comparison for thermal and UV bonding

finger structures that do not oxidize, and thus hermetic sealing is not needed. From this perspective, the design requirements of SAW filters are quite relaxed compared to Bulk Acoustic Wave (BAW) filters and many MEMS devices. As such, adhesive/polymer wafer bonding is an ideal bonding approach for SAW filters both from a technical and cost perspective. Figure 3a shows a typical SAW filter, while Figure 3b provides an overhead view of the inside of an adhesive wafer bonding chamber.

Adhesive bonding is a very simple process compared to other bonding approaches with fewer required wafer preparation steps, as shown in Figure 4. It is a low-temperature process (typically 200-300˚C), which requires less time to ramp up the temperature within the bond chamber. This results in higher bond chamber utilization and a faster bonding process. At the same time, the lower-temperature bond process allows for a wider variety of bonding materials to be used. Adhesive bonding also has a high tolerance for the underlying topography of the wafer, as well as relaxed requirements for overall surface quality and particle contamination.

When using a bulk LTA or LN substrate for SAW manufacturing, the cap wafer is composed of the same material to ensure CTE matching. With LTA- or LN-on-silicon substrates, however, the composition of the cap wafer is no longer limited to these more expensive substrates. Manufacturers have the freedom to use silicon or even glass substrates for the cap layer, which can significantly drive down the cost of manufacturing. Glass can also be bonded as a cap wafer at room temperature using ultraviolet (UV) wavelength.

Areas for future development

As we have discussed in this article, substrate property engineering is vitally important for temperature compensated SAW filters. In addition to low-temperature, thermally-activated adhesive bonding, adhesive research is also focusing more on photonic crosslinked adhesives due to the growing demand for photonic wafer bonding to enable the production of liquid crystal on silicon (LCOS) displays, photonic sensors and wafer-level optics (WLO). UV-based wafer bonding enables room-temperature bonding without any strain incorporation, as well as enables high-throughput processing and the possibility of encapsulating different materials and gases with accurate environmental control.

Summary

The growth in mobile data traffic as well as the growing trend of smart integration in mobile devices is driving greater demands in RF filter technology. SAW filters are both increasing in quantity as well as complexity in smart devices, resulting in modularization and consolidation, which is fundamentally changing the RF mobile communication market. New materials and packaging methods supported by wafer bonding in SAW filter manufacturing are needed to support these trends.

Plasma-activated wafer bonding is an enabling technology for manufacturing SAW filters on new material combinations offering higher performance and lower cost such as lithium tantalate- and lithium niobite-on-silicon. When considering new packaging approaches such as WLCSP that offer greater density, improved performance, scalability and lower cost, adhesive bonding is the wafer bonding method of choice.

Further reading

[1] IDC Worldwide Quarterly Mobile Phone Tracker, March 1, 2017
[2] Cisco® Visual Networking Index (VNI) Global Mobile Data Traffic Forecast Update, 2016-2021 White Paper, March 28, 2017
[3] ibid
[4] J. Kimery, "Is 5 G for Real?", EDN, November 2, 2017
[5] CCW Ruppel, "Acoustic Wave Filter Technology-A Review", IEEE Trans Ultrason Ferroelectr Freq Control. 2017 Sep;64(9):1390-1400
[6] N. Razek and V. Dragoi, "New developments in plasma activated bonding for various materials combinations", Proc. Wafer Bond Conference 2015