Metal deposition of acoustic wave devices for mobile & Internet of Things

Kuohsiung Li PhD of Raisin Technologies and John Hubschmann discuss the applications of SAW and BAW devices in wireless communication and IoT.

The Internet platform and mobile devices have ushered in a new phase in human productivity and social life. This profound transition is manifested by 2.8 billion Internet users and 5.2 billion mobile phone users in 2014 (www.kpcb.com/internet-trends). The next leap in connectivity is anticipated with the evolution in the Internet of Things (IoT). As many as 50 billion connected devices are envisioned for 2020 and consequently an increasingly high premium will be put on the maximization of spectrum utilization. To ensure high-quality communication within each of the booming number of frequency bands, engineers deploy filters to reduce the interference among bands. With high performance, small size and low cost, bulk acoustic wave (BAW) and surface acoustic wave (SAW) filters win over the market from the traditional ceramic and LC filters.

The number of acoustic wave devices utilized in a cellular phone has increased from 2 in a feature phone to about 5 in a low-end smart-phone and more than 15 in a high-end smart-phone. The market size of acoustic wave devices is projected to grow from $1.9bn in 2011 to $4.9bn in 2016, with BAW growing more than twice as fast as SAW (www.bccresearch.com). Although the lower insertion loss, steeper filter skirts and better out-of-band rejection of BAW enable it to perform better at high frequency and for communication bands of close proximity, recent innovation in temperature compensation and circuit design have expanded SAW into previous BAW territory, especially in China's latest-generation TD-LTE (time-division long-term evolution) communication market due to the Asian market's sensitivity to cost. The battle between SAW and BAW manufacturers remains fierce.

In light of the increasing competition from both the well established (i. e. Qualcomm) and a number of startup CMOS companies in the mobile power amplifier (PA) marketplace, which is currently dominated by compound semiconductor (CS) IC companies, the compound semiconductor industry is seeking opportunities to grow their top line (revenue) meaningfully. Acoustic wave devices become the most natural business opportunity for the expansion of compound semiconductor IC companies for the following reasons:

- The total component price of acoustic wave devices for a high-end mobile device now far surpasses that of PA devices. Acoustic wave devices therefore enable a high growth rate in future revenue.
- The similarity in processing technology between the acoustic wave and PA devices is such that the technical barrier of entry into the SAW/BAW business is not high for compound semiconductor RF IC companies.
- Much of the processing equipment used in the compound semiconductor RF IC fab could be used just as well for SAW/BAW processing. This enables flexibility to maximize equipment and facility utilization.

Nonetheless, in order to profitably serve the acoustic devices market, compound semiconductor RF IC companies must still address the problem of many patents being owned by other companies. After a few years of intense consolidation (through merger, acquisition, partnership and alliance), many leading compound semiconductor companies (i.e. Avago, Qorvo, Skyworks etc.) are now in a good position to grow their acoustic wave business aggressively. Since SAW and BAW are fabricated on different substrate materials than compound semiconductor RF IC, the SAW/BAWs are not integrated into the same chip with the PAs. However, acoustic wave devices are incorporated into the same module as PA devices in order to minimize the size and to reduce the cost of mobile devices.

This paper presents the many considerations involved in the metal evaporation process for high-yield acoustic wave devices and the benefit of Ferrotec's UEFC-5700/4900 evaporators for the production of SAW and BAW devices (see Figure 1).

Device characteristics of acoustic wave filters

FBAR (film bulk acoustic resonator) and BAW-SMR (solidly mounted resonator) are popular implementations of BAW devices. FBAR confines the acoustic energy via the large difference in acoustic impedances between the FBAR structure and air on both the top and bottom sides. On the other hand, BAW-SMR has an acoustic reflector at the bottom. There should be a large mismatch in acoustic impedance between the electrode and the reflector to ensure the confinement of acoustic wave. The superior confinement of acoustic energy by FBAR and BAW-SMR makes these filters ideal for communication at higher frequency compared with SAW filters. Consequently they are widely deployed in the new generation (4G) of smart-phones and 5GHz Wi-Fi. AlN is the piezoelectric material of choice for BAW filters due to its higher acoustic velocity (10,400m/s) compared with ZnO (6330m/s) and less acoustic loss (5dB/us versus 8.3dB/us @1GHz). As a rule, the piezoelectric mono-crystal should also have a high degree of crystal orientation and be very smooth (~5Å rms) for the production of filters with high-Q (quality factor).

Molybdenum (Mo) is a popular electrode material for FBAR with high acoustic impedance and high power handling capability. W, Au, Ti, Al, Pt, V and Cu could also be used as electrodes. BAW is inherently less sensitive to temperature drift than SAW over the typical operating range of –20°C to 85°C experienced by the end users. With boron (B)-doped SiO_2 juxtaposed with one of the electrodes, the temperature coefficient of frequency (TCF) could further be reduced to nearly zero (Avago, 2009, US Patent 7561009). The improvement in TCF enables the deployment of BAW for communication bands of very close proximity (for example, LTE Band 40 has only 1MHz of transition guard band with 2.4GHz Wi-Fi). Furthermore, FBAR and SAW-SMR have the advantage of decreasing size with increasing frequency.

Al (Aluminum) is a popular electrode material for SAW with very low electrical resistance and low density (2.7g/cm^3) which minimizes the mass loading effect. Quartz, $LiTaO_3$ and $LiNbO_3$ are common piezoelectric materials. Typically, 2% Cu (by weight) is added to the Al to serve as 'glue' among Al grains, and hence to inhibit Al electromigration that moves grain boundaries at high temperature or at high power for better device reliability. Although the addition of Cu improves the power handling capability of SAW devices by minimizing hillock and void formation, too much Cu will increase the electrical resistance (see Figure 2). On the other hand, Cu concentration of less than 1% renders the Cu ineffective. There is an optimal range of Cu concentrations that reduces electromigration without unduly increasing electrical resistance.

Although SAW devices typically have a higher TCF of about –45ppm/°C, over-coating of IDT (inter-digital transducer) structures with a dielectric layer (i.e. SiO_2) that increases the acoustic stiffness at high temperature can reduce the TCF to nearly zero. Furthermore, the insertion loss in the pass-band could be reduced as well (TriQuint, 2011, US Patent 8044553).

Fig. 1: Ferrotec UF-5700 electron-beam evaporator for the manufacturing of SAW and BAW devices.

Considerations in metal evaporation process for acoustic wave devices

The most critical processing step for the manufacturing of SAW/BAW devices is the deposition of IDT (inter-digital transducer) metallization, which determines the device performance and reliability under high tempera-

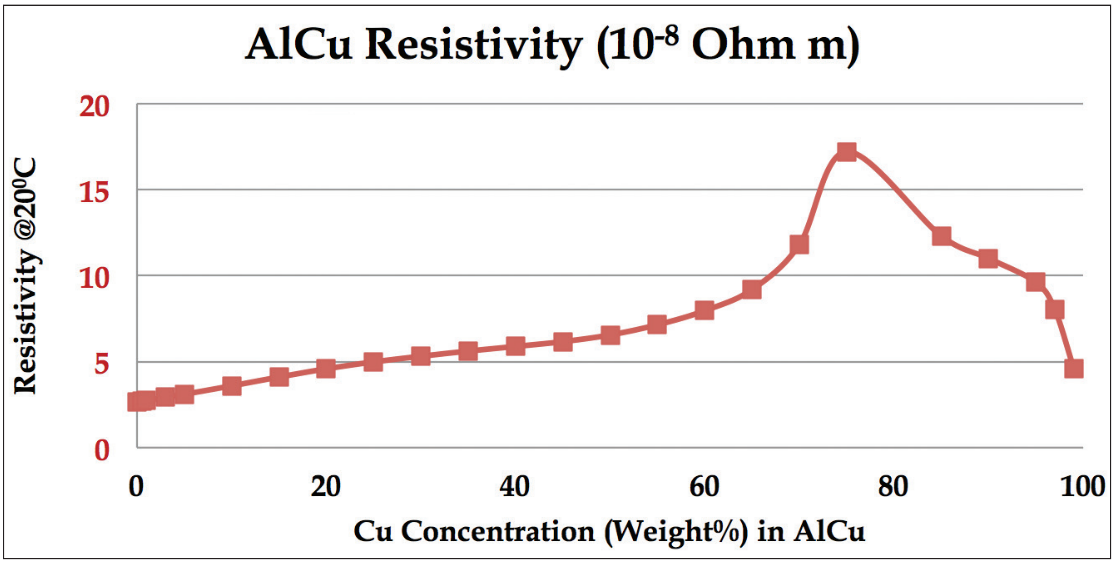

Fig. 2: The resistivity of AlCu as a function of Cu (weight %) concentration (www.nist.gov/data/PDFfiles/jpcrd221.pdf).

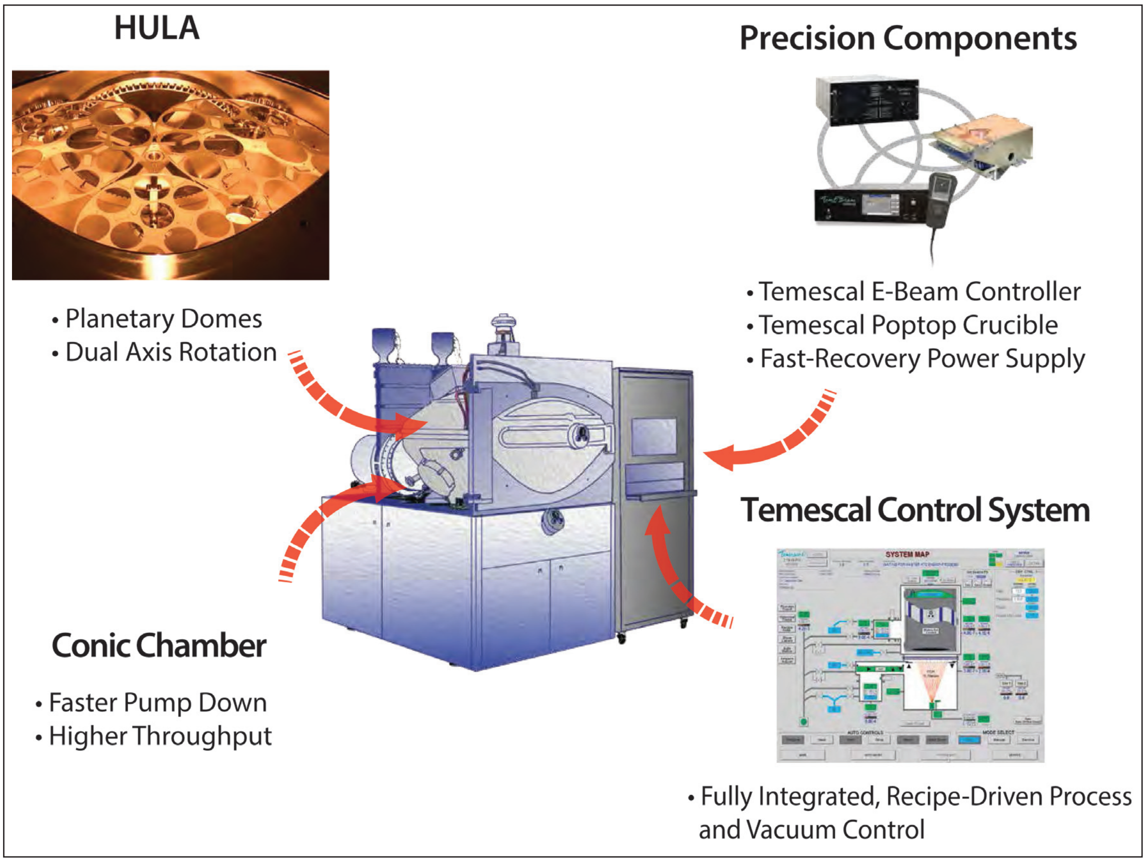

Fig. 3: Ferrotec UF-5700/4900 system control hardware.

ture and high power. Electron-beam evaporation has many advantages for the production of IDT fingers. Chief among them is that the directionality of evaporation facilitates the lift-off process and consequently eliminates the need to selectively etch the blanket metal for the formation of IDT fingers. Additionally, the large batch process reduces the cost of ownership (CoO) and the gentle deposition of evaporants drastically reduces the surface damage on the wafers that would impact acoustic coupling.

For SAW devices, the deposition of alloys such as AlCu presents a challenge in the control of Cu concentration (typically 2% by weight) within the wafer, wafer-to-wafer and run-to-run. When the Cu concentration errs on the low side, the Al migration at subsequent high-temperature process is not arrested and thus results in catastrophic failure. When the Cu concentration errs on the high side, the resistivity of AlCu film and the insertion loss of SAW devices increase. This challenge is due to the difference in vaporization temperature between Al and Cu (2327°C and 2595°C, respectively) which results in a higher evaporation rate of Al than that of Cu. Ferrotec has developed a proprietary procedure that efficiently prepares the AlCu source in the crucible to ensure 2% Cu concentration in the deposited film reliably. This recipe will be provided to Ferrotec's customers to quickly bring the production process on line.

Tight control of the electron-beam evaporation process is required to produce an alloy of precise stoichiometry and thickness. Control of beam sweep and evaporation rate are the most critical. Ferrotec's electron-beam sweep controller allows users virtually infinite control over sweep patterns and beam dwell (sweep speed) time. This — along with the deposition rate controller, featuring programmable temperature ramp rates and dwell (soak) steps — gives users total control over the melt and evaporation conditions (see Figure 3). Patented planetary domes are also incorporated into Ferrotec's UEFC-5700/4900 evaporators to further improve the uniformity control on both the Cu concentration and film thickness.

It is essential to eliminate all surface contamination prior to the evaporation of IDT metal to ensure effective acoustic coupling. A robust multi-stage cleaning process is widely adopted throughout the acoustic wave industry. For example, in a first-stage process to remove chemical residues from the CMP (chemical mechanical planarization) polishing process used by the substrate suppliers, NH_4OH/H_2O_2 solution is heated to 50–60°C to clean the substrates and then followed by a cascade rinse in deionized (DI) water until the DI water reaches 14–16MΩ-cm resistivity.

The second stage of surface cleaning removes hydrocarbon contamination from either the substrate suppliers' process or other natural sources. This requires two heated (50–60°C) ultrasonic tanks. The first tank is filled with acetone to completely immerse the substrates for 10 minutes of ultrasonic agitation. Substrates are then transferred to the second tank for isopropanol alcohol (IPA) immersion with 10 minutes of ultrasonic agitation. The substrates are then immediately dried in a heated 'N_2 only' spin dryer.

The last stage is oxygen plasma cleaning to remove stubborn hydrocarbon residue. The oxygen plasma must be energetic enough to exhibit a glow discharge from the ionization process. Oxygen should also have a high flow rate to maintain a partial pressure of 1 Torr for approximately 10 minutes. In addition, some device manufacturers also use ultraviolet ozone cleaner (UVOC) for 10 minutes to deplete the surface of very aggressive, chemically bonded OH molecules which can cause issues with subsequent processes that are sensitive to OH contamination.

The cleanliness of the surface will need to be verified to ensure the efficacy of the cleaning process. A simple method is commonly employed to measure changes in the surface energy with a goniometer to measure the contact angle. Small angle θ indicates high surface energy exhibits from a clean surface (see Figure 4). Prior to the above-mentioned rigorous surface cleaning procedure, quartz substrates typically have contact angles ranging between 20° to 40°, and 2° to 3° after a multi-stage cleaning.

In SAW/BAW processing, the application of photoresist is necessary to define various layers. Photoresist is a hydrocarbon contaminant and must be completely removed before subsequent processes and before final encapsulation of the acoustic wave devices. The contact angle test can also be used to verify that no photoresist residue (scum) remains; otherwise contact angles of ≥20° are often observed. The presence of any contamination dampens the wave velocity and adversely impacts the coupling of RF electrical energy with the piezoelectric surface and results in an output frequency higher than originally designed. Furthermore, the insertion loss will also be higher. Process engineers may be tempted to increase the IDT metal thickness to bring the frequency back to specification, only to see the next batch of wafers out of specification due to the unpredictability of the photoresist contamination. Therefore emphasis has to be placed on substrate surface cleaning from the start. Proper cleaning ensures any subsequent process steps will only need a short pre-clean via an O_2 plasma de-scum to return the surface to a clean baseline. The UEFC-5700/4900 evaporators also have an option to provide in-situ cleaning with an ion gun. This allows for removal of several atomic surface layers to ensure efficient acoustic coupling to the piezoelectric substrate.

Care should further be taken on the accuracy of thickness measurement. The conventional method used for thickness measurements of thin-film metals has been the surface profilometer. This tool has several inherent draw backs for measurement on films below 800Å. First of all, the signal-to-noise ratio is insufficient for ±1% accuracy. Secondly, the stylus contacts the surface and has a downward force as it moves across the measured features and may damage them. The solution is to incorporate numerous design verification structures across each wafer in sacrificial areas for non-contact thickness measurement via white light interferometer (WLI).

In addition, the accurate measurement of the thin-film resistivity of IDT fingers is critically important as a key indicator of film quality and Cu concentration in AlCu.

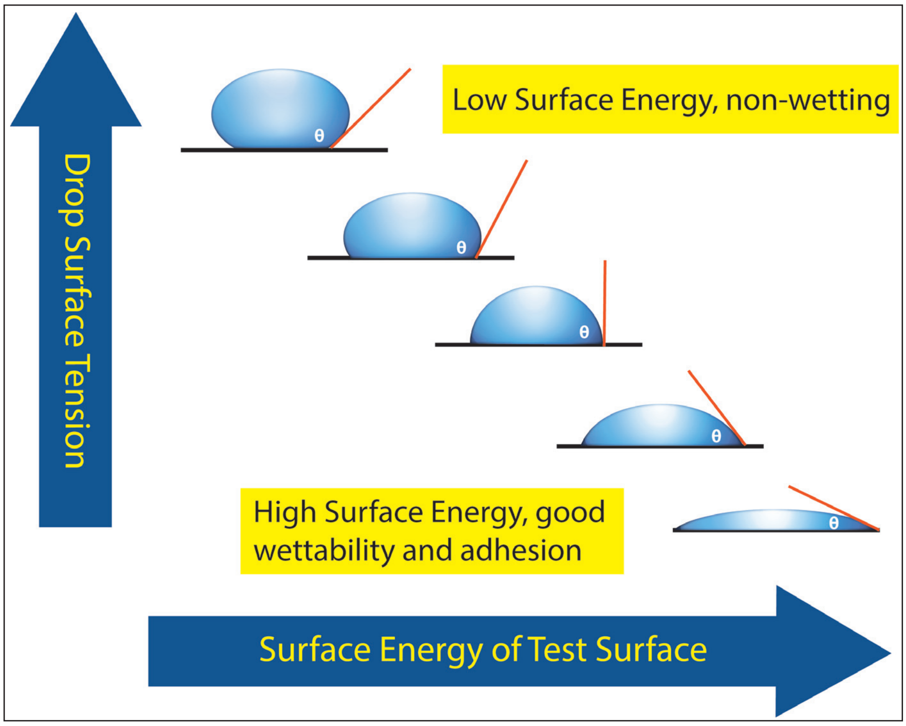

Fig. 4: Deionized water droplets showing contact angle as a function of surface energy.

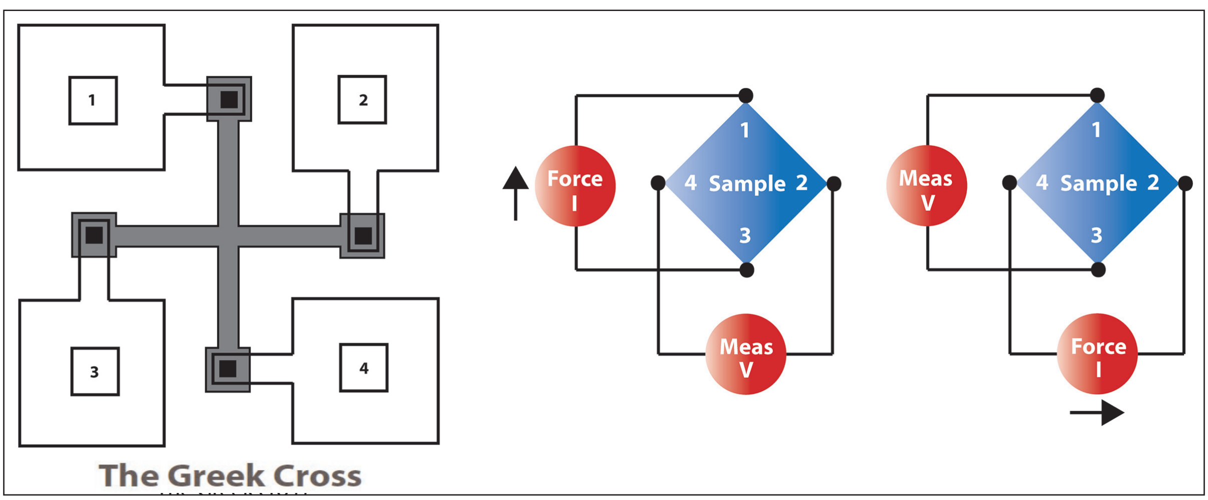

Fig. 5: A Van der Pauw structure, known as a 'Greek cross' for voltage measurement with applied current to extract the sheet resistance.

Fig. 6: Ferrotec's HULA Planetary rotating domes (left) and conic chamber (right).

The resistivity measurement must be sensitive enough to detect minute changes that reflect the variation in copper concentration. A Van der Pauw structure, known as a 'Greek cross' in the semiconductor industry, is commonly used (see Figure 5). Automatic test on the product wafers could thus be performed 'in process' (before bond pad metal). This sensitive 'in process' test allows for early screening of bad wafers to save manufacturing cost.

Advantages of Ferrotec UEFC-5700/4900 for SAW, FBAR & BAW-SMR

Ferrotec's UEFC-5700 and UEFC-4900 incorporate two main features to minimize the CoO of an electron-beam (E-beam) evaporator. The first is the patented magnetic drive HULA (High Uniformity Liftoff Assembly), which is a set of planetary rotating wafer carrier domes that change the location of each wafer relative to the evaporants in the source crucible continuously via a contactless magnetic drive. Each wafer remains orthogonal to the direction of evaporation. This directionality is critical to a high-yield lift-off process. The second is the patented conic shape chamber design that minimizes both the volume and surface area of the product chamber. This leads to much reduced pump-down time and hence better throughput (see Figure 6). The magnetic HULA drive is contactless and therefore generates no particles and thus results in better yield. The planetary domes rotate around the central axis of the product chamber and each dome is also self-rotating to facilitate uniform depositions for all wafers. Furthermore, the design of UEFC-5700 is footprint efficient, such that the batch size is increased by 40% for the same footprint (as Ferrotec's more traditional 'box coater' FC-4400) to allow for better utilization of cleanroom space.

Ferrotec has previously demonstrated the ability of UEFC-5700 and UEFC-4900 for the precise control of eutectic composition (Amirani I., 2015. The Resurgence of Electron Beam Evaporation. Compound Semiconductor magazine). This allows for the control of eutectic melting temperature within a narrow range to ensure the bonding quality. Even without the utilization of a uniformity mask, UEFC-5700/4900 could control the 80%Au/20%Sn eutectic composition to 0.02% standard deviation (see Figure 7) within-wafer, and about 0.3% standard deviation from wafer to wafer. Care should be taken to control the batch-to-batch thickness repeatability as well.

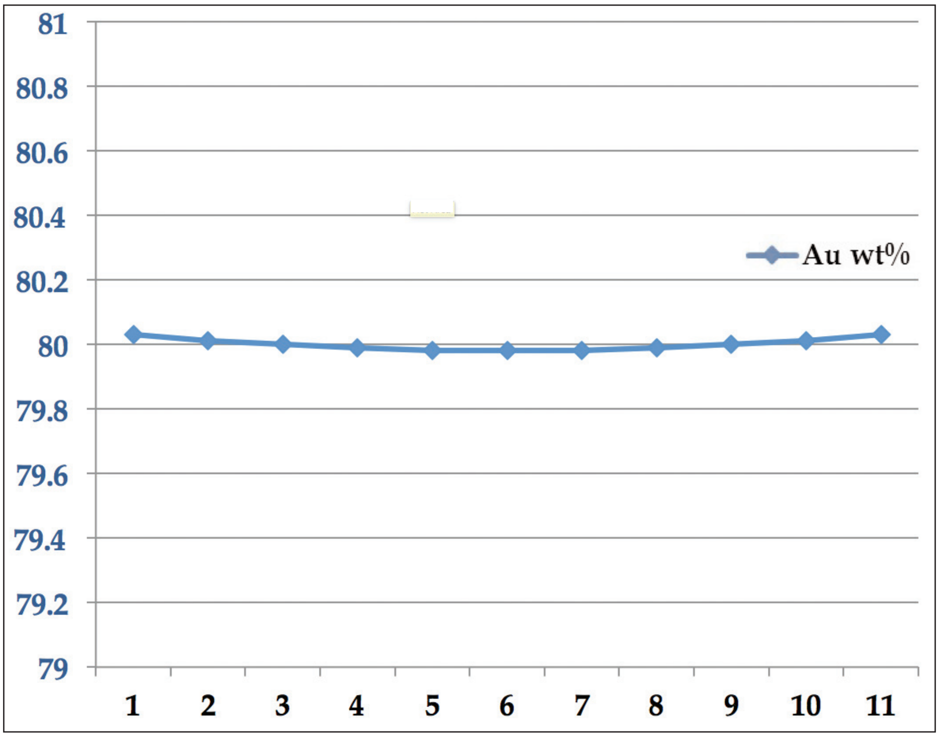

Fig. 7: Precise control of Au/Sn eutectic composition to 0.02% standard deviation within-wafer in a Ferrotec HULA system, without mask.

Ferrotec's UEFC systems have good repeatability on AlCu evaporated from a single-source crucible as well, for the manufacturing of SAW devices. As discussed in the previous section, 2% Cu (by weight) in Al inhibits the electromigration of Al at high temperature and/or at high power. The within-wafer thickness uniformity of AlCu (98%/2% by weight) is about 1% standard deviation and the run-to-run uniformity is also about 1% standard deviation even with a refill of AlCu at the source crucible for run number 8 (see Figure 8). This test is conducted at a relatively high evaporation rate of 10Å/s to simulate high-throughput production.

The control of Cu concentration from run to run is also evaluated in a Ferrotec UEFC-4900 system. The AlCu was evaporated repeatedly from a single-source crucible and a source refill was performed at the 11th run. The Cu concentration could be tightly controlled to 0.2% standard deviation for run-to-run repeatability (see Figure 9).

In addition to electrodes of acoustic wave devices, Ferrotec's evaporators are also ideal for the metal deposition of bond pads, such as NiCr/Au where NiCr serves as a diffusion barrier for Au, or Cr/Al where a very thin layer (<100A) of Cr strengthens the bond pad attachment.

In summary, the applications of acoustic wave devices have exploded with the current wide adoption of mobile devices and the future expansion of IoT. The battles between SAW, FBAR and BAW-SMR are fierce, fueled by innovation in device and circuit design. Mo, AlCu and other electrode materials can be uniformly evaporated by Ferrotec's UEFC-5700 and UEFC-4900 at low cost of ownership. Ferrotec provides customers with guidance on the cleaning of piezoelectric materials, preparation of AlCu source crucible and the high-yield lift-off process of the evaporated metals from a single crucible with precision control on thickness and composition. This is accomplished via the patented HULA planetary domes and conic product chamber. ■

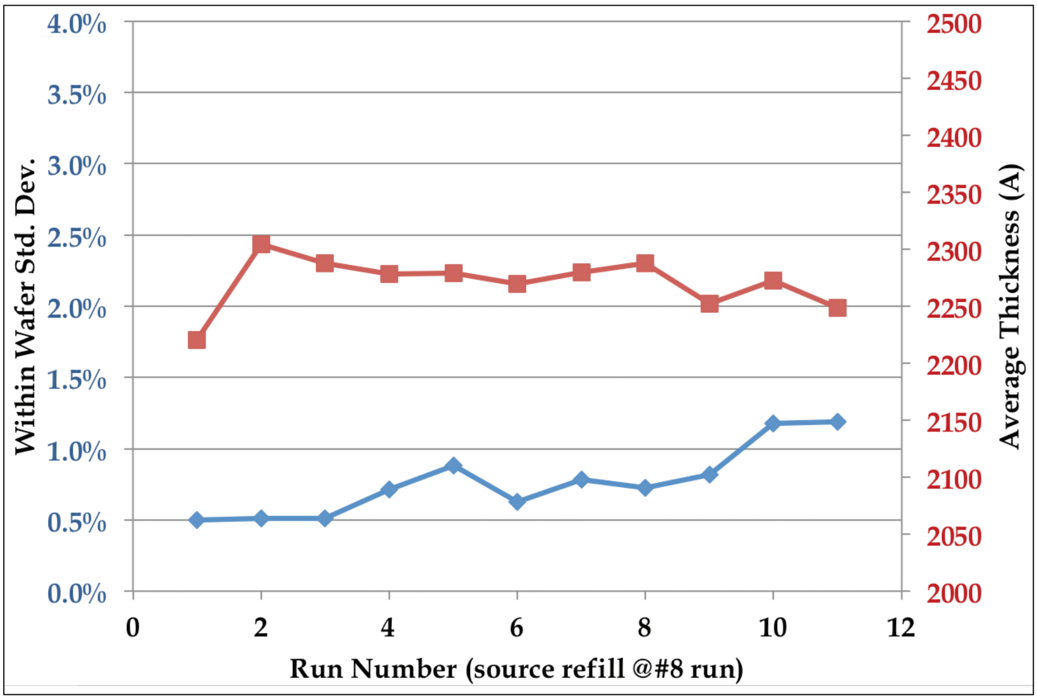

Fig. 8: Within-wafer and run-to-run thickness uniformity of AlCu (98%/2% by weight) evaporated at 10Å/s in a Ferrotec UF-4900 with source refill at run #8.

Authors:
Kuohsiung Li PhD, Raisin Technologies, and
John Hubschmann
J. Hubschmann was with Raytheon for 13 years and is a SAW process specialist.

For more information about the Ferrotec products cited, visit **www.temescal.net**

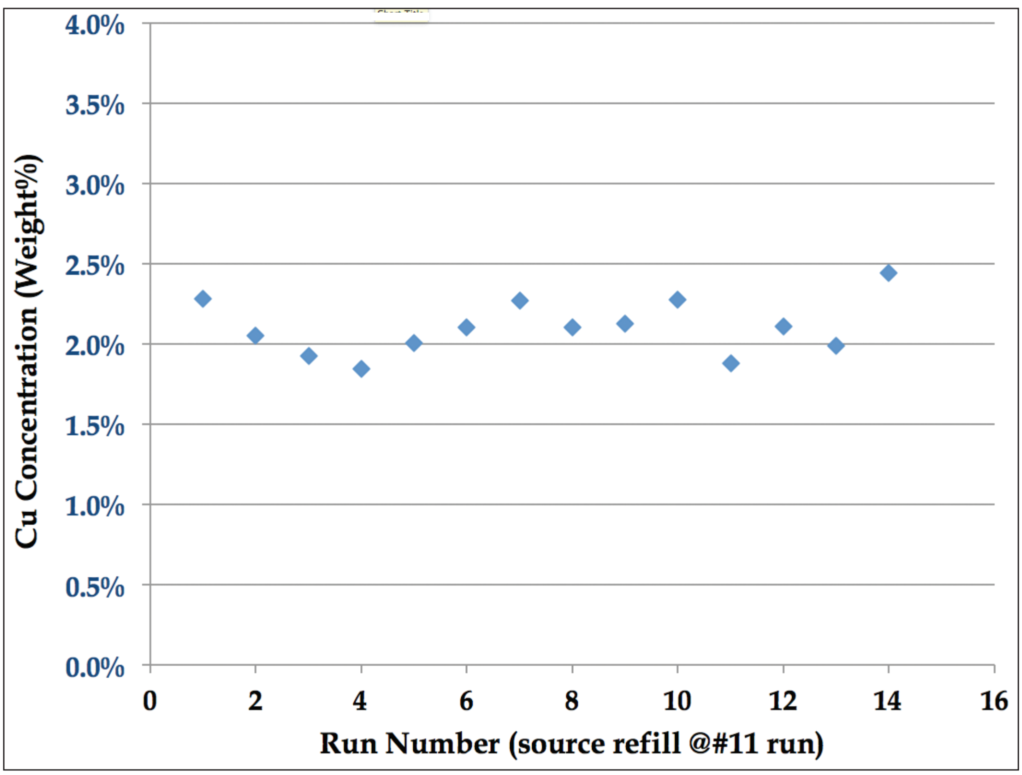

Fig. 9: Run-to-run repeatability of Cu concentration in AlCu targeting 2% Cu with source refill at run #11 in a Ferrotec UF-4900 evaporator.