SAW Devices
and Their
Wireless
Communications Applications

© DIGITAL VISION/EPCOS AG

Today's second-generation (2G) wireless communications market is very dynamic with high growth rates. Soon, third-generation (3G) systems will start operation. Moreover, wireless local-area network (LAN) systems, such as Bluetooth or IEEE 802.11-based systems, are emerging. The key components in the microwave portion [both in the radio- (RF) and intermediate-frequency (IF) sections] of the mobile terminals of these systems incorporate—apart from active RF integrated circuits (RFICs) and RF modules—a multitude of passive components. The most unique passive components used in the microwave section are surface acoustic wave (SAW) filters. The component count for modern terminals is decreasing due to the progress of integration in the active part of the systems. On the other hand, the number of SAW RF filters is increasing for multiband terminals. As a consequence, passive components outnumber RFICs by far in today's systems. The market is demanding smaller and smaller terminals, thus, the size of all components has to be reduced. The size of typical SAW RF filters shrank significantly over the last couple of years, and, for example, a footprint of 1 mm^2 for an RF filter is feasible in the near future using new packaging techniques. For SAW IF filters (e.g., for IS-95 terminals), the footprint has been reduced by more than 80% over the last four years. Further reduction in component count and, therefore, size has been obtained by adding additional functionality to SAW devices. The integration of passive components and SAW devices using low-temperature cofired ceramic (LTCC) technologies reduces the required printed circuit board (PCB) area further. Today, SAW modules, such as for multiband terminals, are available. Such modules include SAW RF filters for the different frequency bands, p-i-n diodes for switching, and

Clemens C.W. Ruppel,
Leonhard Reindl,
Robert Weigel

C.C.W. Ruppel is with EPCOS AG in Munich, Germany.
L. Reindl is with Clausthal University of Technology, Germany.
R. Weigel is with Johannes Kepler University, Linz, Austria.

inductances and capacitors for matching and building inductance-capacitance (LC) filters. SAW devices can offer balun functionality and perform impedance transformations. In addition, the first examples of tuneable SAW filters (with sufficient tuning range to cancel fabrication tolerances and temperature effects) have been demonstrated. Another prerequisite for the use of SAW filters in the RF front-end is a sufficient high-power durability. SAW front-end filters for GSM-900 can withstand more than 34 dBm. In the 2-GHz range (GSM-1800, GSM-1900, UMTS); new electrode materials will allow power levels up to 30 dBm. This means that SAW RF filters can handle all power levels used in the terminals of today's mobile communications systems. Combining high stability, excellent aging properties, low insertion attenuation, high stopband rejection, and narrow transition width from

Figure 1. *Schematic of an interdigital transducer with pitch* p *and associated P-matrix model with* u_{in} *and* i_{in} *being the electrical voltage and current, and* a *and* b *the incident and outgoing acoustic waves.*

Figure 2. *Schematic layout of a two-port SAW resonator. Two IDTs (input and output) are backed by reflector strips forming a cavity.*

Figure 3. *Basic cells for building a generalized SPUDT.*

passband to the stopband, SAW devices offer superior performance. They are fabricated at high volume, further size reductions are in sight, and innovative concepts for future systems are on the horizon.
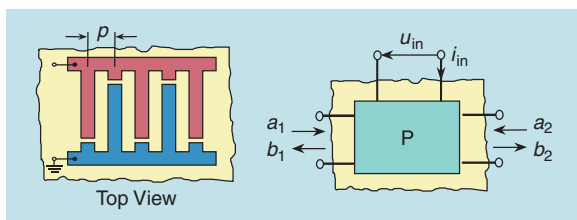
Introduction

A SAW device consists of a piezoelectric substrate with metallic structures, such as interdigital transducers [IDTs (Figure 1)], and reflection or coupling gratings deposited on its plain-polished surface. Triggered by the piezoelectric effect, a microwave input signal at the transmitting IDT stimulates a microacoustic wave that propagates along the surface of the elastic solid [1], [2]. The associated particle displacement of this SAW is bounded in the vicinity of the surface only. Vice versa, a SAW generates an electric charge distribution at the receiving IDT, causing a microwave electrical output signal to occur [1], [2]. During the last decade, driven by booming wireless technology business [3], great and important progress in SAW device performance was made, and a variety of innovative applications were developed. These developments are based on technological improvements (using and linked to the advances made in the field of semiconductor technology in general); fabrication of correlative SAW signal processing subsystems [4], [5]; and the invention and implementation of SAW identification tags and sensor devices [6].

SAW technology has evolved to the GHz range in recent years and now routinely covers the frequency range of up to 3 GHz. This frequency band is used as carrier frequency for many new wireless communication and sensor applications, especially at the industrial, scientific, and medical (ISM) frequency of 2.5 GHz, and also as intermediate frequency for broadband systems operating at higher frequencies [7]. Currently, submicron manufacturing and material techniques are improving greatly and encompassing even higher frequencies of up to 10 GHz.

Technology, Design, and Simulation Techniques

In 1965, the invention of the IDT as a most efficient technique for the generation and detection of SAW waves on a piezoelectric substrate immediately opened up gateways to two major microwave engineering product design directions with quite different thrusts. At one end of the scale, in the high-volume, low-cost component market, the challenge was related to whether or not mass-produced SAW filters and resonators could be competitive in price and performance with established technologies. At the opposite end, the focus was on low-volume, high-cost components for radar signal processing, and maximum emphasis was given to the efficient implementation of SAW pulse compression filters with very large compression gains. Between these two extremes, a wide range of other SAW device configurations and applications started to receive intensive research scrutiny.
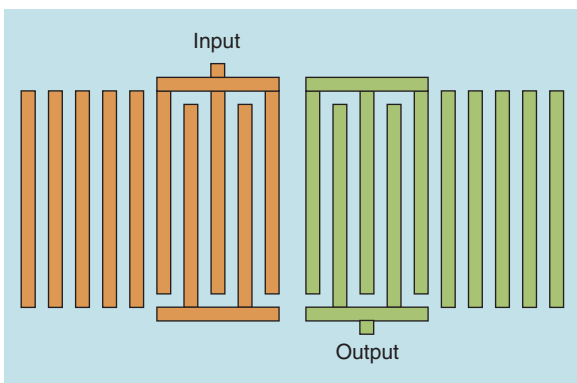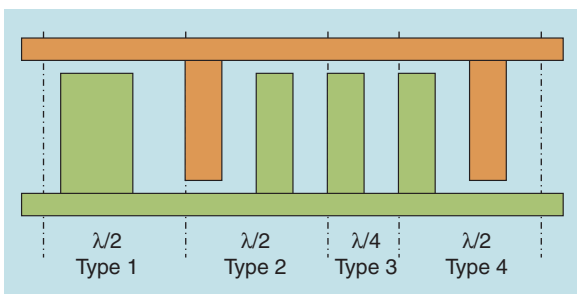
SAW devices are based on propagating and/or standing microacoustic waves. A wide variety of single-crystalline cuts of quartz (SiO_2), lithium tantalate ($LiTaO_3$), and lithium niobate ($LiNbO_3$) are commonly used as SAW substrates. The wave types propagating on these substrate materials show velocities v between 3,000-5,000 m/s that are slower by a factor of 10^5 compared to that of guided electromagnetic waves, e.g., waves guided by microstrip transmission lines. Thus, devices operating in the VHF/UHF frequency region can be fabricated with strip widths in an order of microns or below that can be produced very accurately and reproducibly using optical projection printing techniques. Based on a variety of physical principles, methods and techniques have been developed for microwave-microacoustic transduction, reflecting, guiding, focusing and amplifying waves, and introducing controlled dispersion.

The use of transduction and reflection, which are the basic mechanisms in most SAW devices, is discussed by way of a two-port resonator illustrated in Figure 2. Both the IDTs and the reflectors are distributed elements, i.e., they consist of an array of metallic electrodes or strips. The (active) IDTs exploit piezoelectricity to launch and detect the SAW waves. The (passive) reflector gratings, usually a set of metal strips which can be short- or open-circuited, act within their stopband as a mirror reflecting the incident waves, thus forming a cavity. The widths and spacings of the electrodes and strips, which are $\lambda/4$ or less (λ = SAW wavelength), determine the operating frequency f and the bandwidth B because of the relation $\lambda = v/f$. Thus, the phase velocity v is a fundamental design parameter. Elements combing transduction and reflection with a predefined phase relation (Figure 3) are in use for advanced SAW IF filters. They enable single-phase unidirectional IDTs (SPUDTs) that contribute to the size reduction of IF filters by using resonances within the transducers. The second basic design parameter is the electromechanical coupling coefficient k^2 that is a measure of the efficiency in converting an applied microwave signal into mechanical energy associated with the microacoustic wave and determines the insertion loss of the device for a given relative bandwidth. Both v and k^2 depend on the material tensor elements of elasticity, piezoelectricity, and dielectric permittivity and on the mass density (among others). Aluminum is usually used as metallization layer.

Different wave types propagating in different crystalline directions on different substrate materials show varying phase velocities and coupling coefficients. Table 1 gives an overview on the fundamental SAW properties of some of the most frequently used material cuts.

Table 1.
**Properties of some frequently used SAW substrate material cuts.**

Material	Orientation		vph	k2	TCD
	Cut	Prop.			
Quartz	ST	X	3158 m/s	0.1%	0
	37° rotY	90° rotX	5094 m/s	0.1%	0
LiNbO3	Y	Z	3488 m/s	4.1%	94 ppm/°C
	41° rotY	X	4750 m/s	15.8%	69 ppm/°C
	128° rotY	X	3980 m/s	5.5%	75 ppm/°C
LiTaO3	36° rotY	X	4220 m/s	6.6%	30 ppm/°C

Quartz crystal cuts show excellent temperature stability, which is given by the temperature coefficient of delay (TCD). Their coupling coefficient k^2, however, is low, which limits the relative bandwidth that can be electrically matched without losses to a few percent. Therefore, quartz crystal cuts are mainly used for narrowband devices down to 0.1% relative bandwidth and when steep skirts in the transfer function are specified. SAW devices on quartz are used in the IF stages of mobile phones, for resonators or delay lines used in local oscillators, and for dispersive delay lines used in radar applications. The coupling coefficient k^2 of $LiNbO_3$ is much larger than that of quartz, allowing medium-loss devices for wideband applications with relative bandwidths up to some 10%. SAW devices on $LiNbO_3$ are used for IF filtering in TV or satellite receiver sets, for example. Some special cuts, like the 41° rotY cut of $LiNbO_3$ or the 36° rotY cut of $LiTaO_3$ show extreme high coupling coefficients that make these cuts highly suited for low-loss and wideband applications needed in the RF stages of mobile phones.

SAW device design is based on 1) signal theory, 2) network theory, and 3) field theory [8]. Impulse response modeling allows for a first order design because
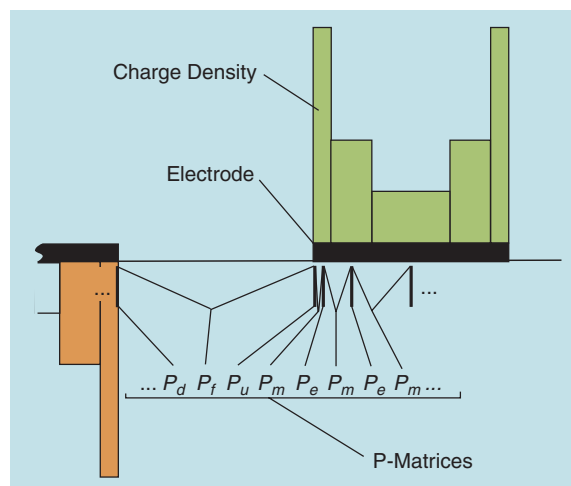
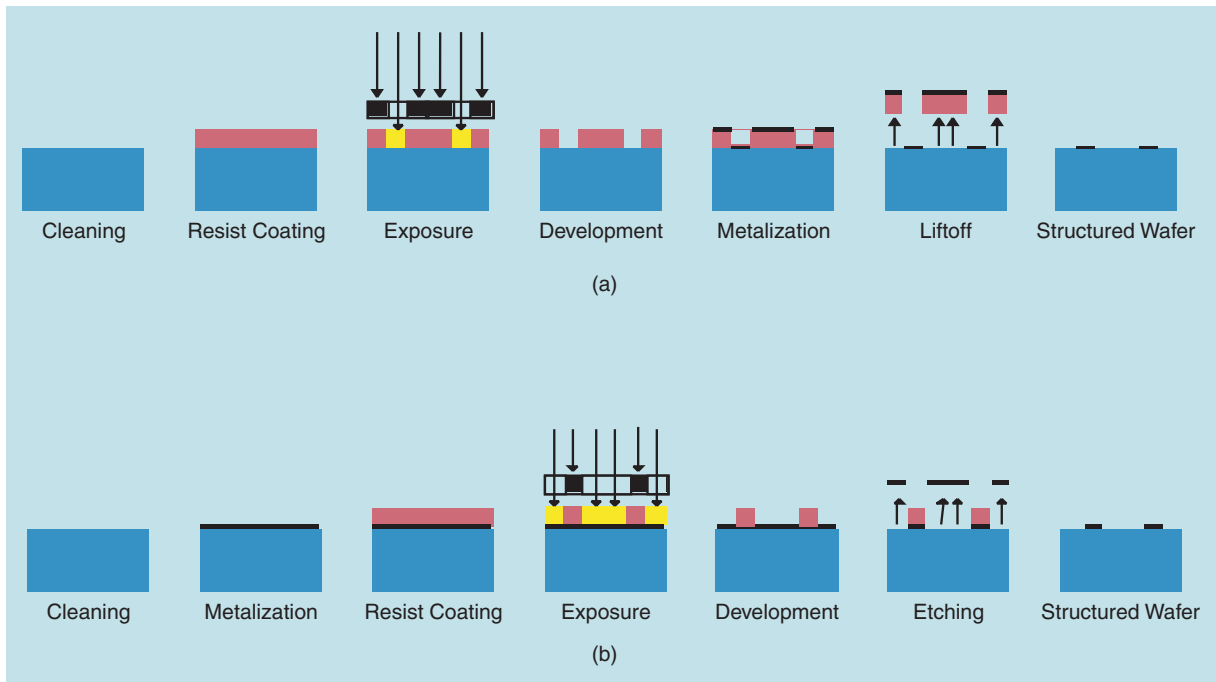**Figure 4.** *Basic cells for the P-matrix model.*
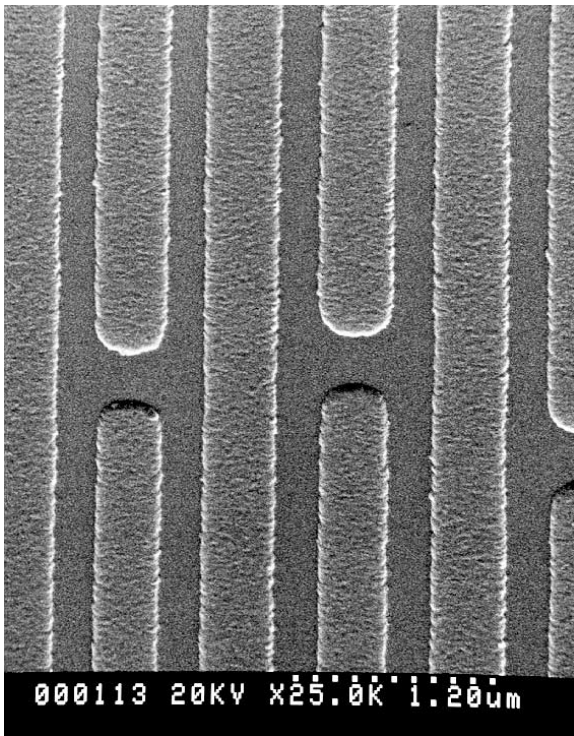
Figure 5. *SEM photograph of part of an IDT.*

the impulse response $h(t)$ of the IDT is—with the help of the SAW velocity v—directly related to the overlap and spacing of the electrodes. Therefore, the frequency response $H(f)$, which is the Fourier transform of $h(t)$, can be computed quite straightforwardly from the electrode pattern. This procedure can also be reversed and used for filter synthesis that usually incorporates some weighting techniques.

Signal-theory guidelines, however, are not capable of accounting for microwave and microacoustic effects. These so-called second-order effects include the acoustic reflections on strips and electrodes; effects due to the charge distribution on electrodes; mechanical loading effects, such as mass loading; stress loading and topographical loading at strip edges; microacoustic attenuation and dispersion; diffraction and refraction of the waves; beam steering due to anisotropy of the substrate; the generation of spurious bulk acoustic waves (BAWs) in the IDTs and/or the conversion of SAWs in BAWs; ohmic losses of the strips; and electromagnetic feedthrough between IDTs. The quantitative characterization of the second-order effects is solved by field theory approaches [9], by test chip measurements, and by a combination of both [10]. In order to store the results in databases, they are fitted to simple, mostly analytic expressions depending on the frequency, geometric parameters, such as metallization height; metallization ratios, etc.; and material parameters, such as coupling coefficient, mass density, and so forth. Bond wires, chip layout effects, and package parasitics are evaluated in a similar manner.

The design procedure is based on network theory and these databases. SAW structures are subdivided into substructures that are further subdivided into basic two-port (with two acoustic ports) or three-port cells (with two acoustic and one electric port). A typical basic cell may be a single electrode as well as a detail of an electrode. This may be necessary when the charge distribution on the electrodes or edge effects are modeled. The electrical and acoustical descriptions of the substructures are then recursively combined using network theory algorithms. Popular techniques include

| Cleaning | Resist Coating | Exposure | Development | Metalization | Liftoff | Structured Wafer |

(a)

| Cleaning | Metalization | Resist Coating | Exposure | Development | Etching | Structured Wafer |

(b)

Figure 6. *Process-flows of the SAW device fabrication: (a) lift-off technique and (b) etching technique.*

various lumped-element methods, such as equivalent circuit modeling techniques; matrix manipulation techniques, such as P-matrix formalisms (Figure 4); or coupling-of-modes (COM) techniques [15]. By cascading all the subcells and including the microwave parasitics and electrical matching structures, the electrical terminal behavior of the micro-acoustic design can be analyzed and further optimized.

Manufacturing

SAW manufacturing has been developed from the technology of integrated circuits (ICs) [11]. A major issue is the minimum line width obtainable because this determines the maximum operation frequency. Very fine lines can be obtained by X-ray or electron beam exposure, however, this is not yet a commercially useful variant. SAW companies usually make use of optical exposure by which submicron patterning with very high precision of the line widths is already achievable. Processes based on optical projection printing routinely allow for highly stable line widths of less than 0.3 μm [7]. As is seen from Figure 5, high resolution and good edge quality are achieved. Using this process, the design and fabrication of a SAW ladder-type bandpass filter at 3.15 GHz having a bandwidth of 128 MHz and an insertion attenuation of 1.7 dB has been demonstrated [12]. Wafers with diameters of up to 4 in are processed at a high-volume production level. In contrast to the semiconductor process, only one single metallization layer has to be manufactured, but with a much higher demand on precision of line-width and thickness variations. For the fabrication of the metallization structure, an etching or lift-off technique is used (Figure 6). The required pattern is repeated many times on the mask so that a large number of devices can be exposed simultaneously. For larger SAW devices, such as long delay lines, tapped delay lines, chirp filters, and convolvers, the process is more specialized. Certain crystal substrates are available commercially, with lengths of up to 25 cm, that enable SAW devices to have delays in the order of 50 μs. The processed wafers are sawn into individual chips that are mounted using adhesives and electrically connected with bond wires. The packages are then hermetically sealed in an inert atmosphere or vacuum to exclude moisture and surface contaminants. Standard packages, such as ceramic surface-mount device (SMD) packages, are used for smaller devices used in mobile RF and IF applications (Figure 7) [13], and custom-designed packages are employed for the longer ones, such as SAW convolvers.

From the point of view of packaging, the most pertinent commercial challenge today is the miniaturization of mobile radio RF filters and the integration into modules [14].

SAW devices combine high stability, excellent aging properties, low insertion attenuation, high stopband rejection, and narrow transition width from passband to the stopband.

For example, EPCOS has recently demonstrated a highly miniaturized chip-size package technology (Figure 8). The SAW chip is flip-chip mounted onto a chip carrier serving as the bottom of the package. The electrical connections to the chip are realized with solder bumps. An underfiller attaches the SAW chip solidly to the chip carrier. Thus, the backside of the chip can already serve as part of the package. This technology became attainable for SAW filters by utilizing a special chip passivation technique, called PROTEC, that leaves a cavity on the surface of the chip for the
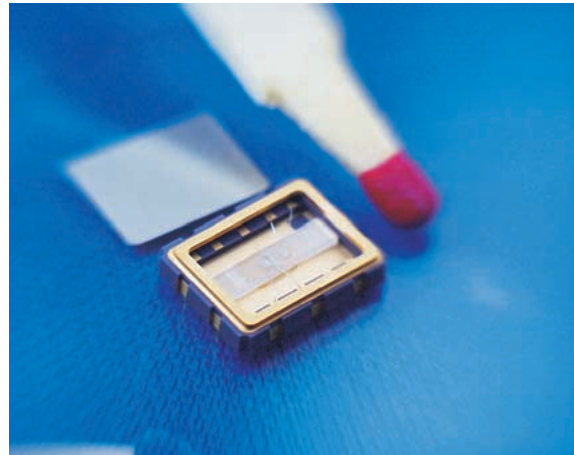
Figure 7. Mounted SAW chip in a dual-chip carrier (DCC)6 housing.
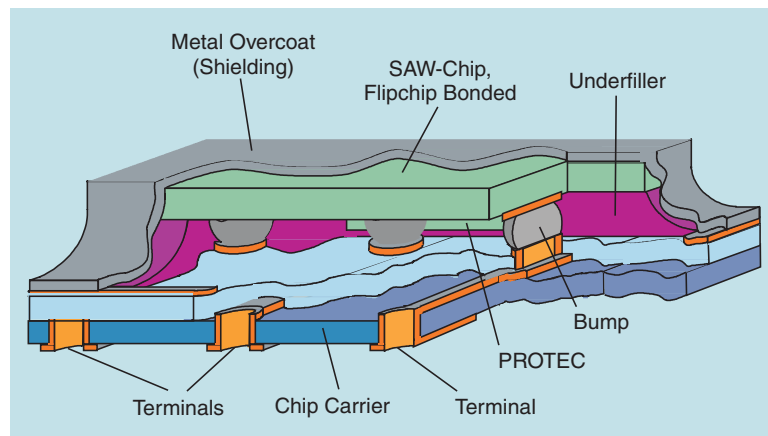
Figure 8. EPCOS chip sized SAW package (CSSP) technology as a key for further miniaturization and integration.
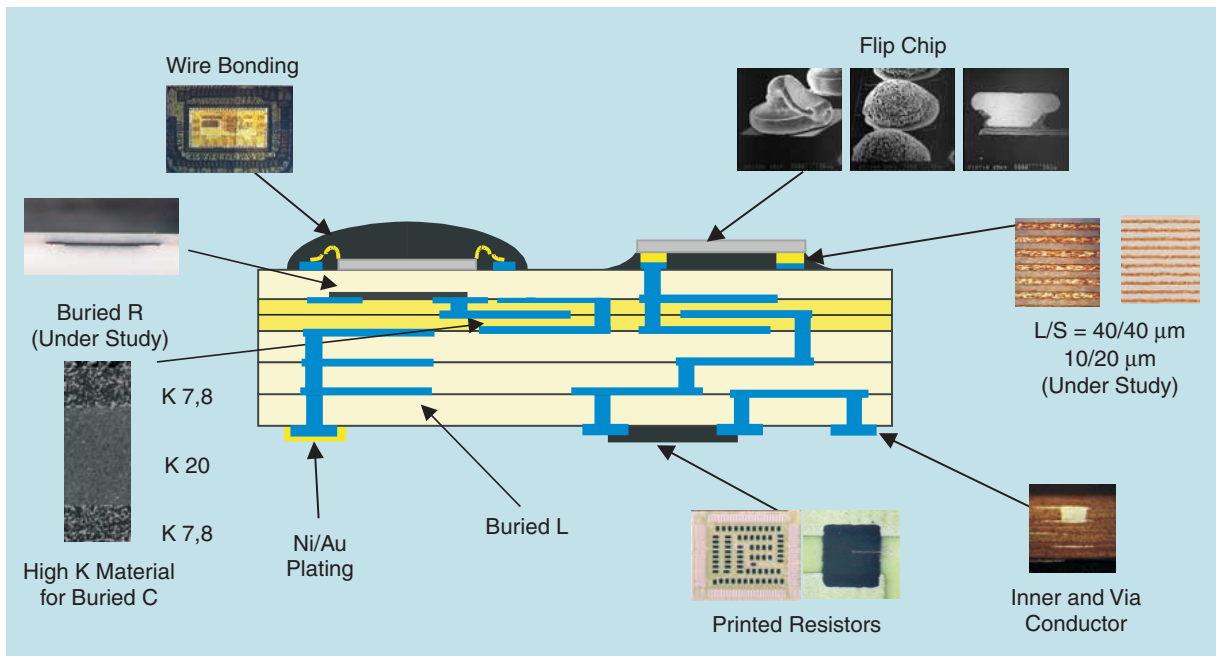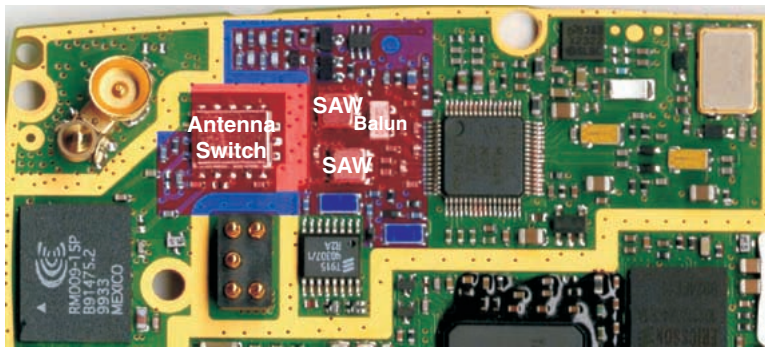
Figure 9. *Schematic representation of a LTCC substrate.*

undisturbed propagation of acoustic waves. The cavity is built on the wafer with a photolithographic process in two steps. First, a closed polymeric wall is placed around the active filter structure. Using the same process, this wall is then covered with a roof. With this technology, EPCOS could introduce SAW filters for 2-GHz applications, like personal communications networks (PCNs), personal communications services (PCSs), and universal mobile telecommunications standards (UMTSs) coming in a $2 \times 2 \times 0.8$-mm^3 chip-sized SAW package (CSSP) package. Moreover, the technology allows for a further miniaturization of SAW filters beyond a 1-mm^2 footprint area.

Integration

Even more important than pure miniaturization is the fact that CSSP technology permits passive integration to attain significantly higher levels of complexity. Thus, several chips can be accommodated on a single substrate, and not all of them need to be SAW components. The substrate can also perform additional functions; planar integration allows diplexers, low-pass filters, matching elements, delay lines, and other functions to be implemented. This quantum leap in passive integration is set to revolutionize the design of mobile phones. Virtually unlimited possibilities open up for products, such as antenna switches with integrated SAW filters, single or multiband SAW duplexers with integrated branching elements, and other components. Even active functional units, such as low-noise amplifiers, can be integrated into these SAW modules manufactured using multi-layer LTCC technology (Figure 9). The great potential of passive integration that can be exploited in a state-of-the-art dual-band mobile phone is illustrated in Figure 10. Although the design shown is already highly integrated, its RF stage still contains numerous active and passive components. Components close to the antenna like switches, filters, and baluns (highlighted in red) could be easily integrated in a SAW module. Components in the region highlighted in blue can then follow in a second step.

Soon, manufacturing of what is currently the smallest front-end module (FEM) for Groupe Spécial Mobile (GSM) triple-band mobile phones based on LTCCs will start. The module has dimensions of only $6.7 \times 5.5 \times 1.8$-mm^3 and integrates more than 50 components (Figure 11). Compared with conventional solutions with discrete components, this reduces the required space by 95%. About 40

Figure 10. *There are no limits for integration: the red shaded area of this GSM dual band receiver section can easily be merged into one SAW module, but there is no reason why the remaining components should not be integrated into the same module in the long run.*

Figure 11. *Front-end modules for GSM triple-band terminals.*

components—capacitors and inductors—are embedded in the 14-layer LTCC structure. The remaining components are mounted onto the substrate as SMD devices. In addition to p-i-n diodes, ceramic capacitors, and resistors, they include the world's smallest SAW filter with an integrated balun from EPCOS featuring a footprint of only 1.4×2-mm^2. This new development has made it possible for the first time to implement the complete range of functions of an FEM for triple-band mobiles into a single module. It consists of a diplexer and a Tx/Rx switch as well as low-pass and SAW filters. In addition to the enormous space savings achieved, which permit further miniaturization and a simultaneous increase of functionality, placement costs are reduced. Development times and costs can also be dramatically cut. Another advantage of LTCC technology is the significant increase in reliability achieved, as these modules have a much higher mean time between failures (MTBF) than discrete solutions.

Conclusion

Due to the superior performance of SAW filters, combined with additional features, e.g., impedance transformation, balun functionality, and integration of two or even three filter functions into one package, SAW filters have become the key components in mobile communication and multimedia applications. More cost-effective and miniaturized designs are effectively supported by reducing overall component count and PCB space used.

References

[1] S.V. Biryukov, Y.V. Gulaev, V.V. Krylov, and V.P. Plessky, "Surface acoustic waves in inhomogeneous media," in *Springer Series on Wave Phenomena 20*. Berlin, Germany: Springer-Verlag, 1995.

[2] D.P. Morgan, *Surface-Wave Devices for Signal Processing*. Amsterdam, The Netherlands: Elsevier, 1991.

[3] C.C.W. Ruppel, R. Dill, A. Fischerauer, G. Fischerauer, W. Gawlik, J. Machui, F. Müller, L. Reindl, W. Ruile, G. Scholl, I. Schropp, and K.C. Wagner, "SAW devices for consumer communication applications," *IEEE Trans. Ultrason., Ferroelelect., Freq. Contr.*, vol. 40, pp. 438-452, Sept. 1993.

[4] M. Hikita, C. Takubo, and K. Asai, "High performance SAW convolvers used in high bit rate and wideband spread spectrum CDMA communication systems," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 47, pp. 233-241, Jan. 2000.

[5] A. Springer, M. Huemer, L. Reindl, C.C.W. Ruppel, A. Pohl, F. Seifert, W. Gugler, and R. Weigel, "A robust ultra-broad-band wireless communication system using SAW chirped delay lines," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 2213-2219, Dec. 1998.

[6] L. Reindl, A. Pohl, G. Scholl, and R. Weigel, "SAW-based radio sensor systems," *IEEE Sensors J.*, vol. 1, pp. 69-78, June 2001.

[7] L. Reindl, C.C.W. Ruppel, S. Berek, U. Knauer, M. Vossiek, P. Heide, and L. Oréans, "Design, fabrication, and application of precise SAW delay lines used in a FMCW radar system," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 787-794, Apr. 2001.

[8] F. Seifert and R. Weigel, "SAW-based wireless sensor and communication techniques," in *Proc. European Microwave Conf.*, Jerusalem, Israel, 1997, pp. 1323-1346.

[9] R. Weigel, "Efficient modeling of microacoustic structures in terms of electromagnetic field concepts," in *Proc. Int. Symp. Antennas and Propagation*, Chiba, Japan, 1996, pp. 897-900.

[10] R. Thomas, T.W. Johannes, W. Ruile, and R. Weigel, "Determination of phase velocity and attenuation of surface acoustic waves with improved accuracy," in *Proc. IEEE Int. Ultrasonics Symp.*, Sendai, Japan, 1998, pp. 277-300.

[11] U. Knauer, J. Machui, and C.C.W. Ruppel, "Design, fabrication, and application of GHz SAW devices," in *Proc. IEEE Int. Microwave Symp.*, Denver, CO, 1997, pp. 1821-1824.

[12] A. Springer, F. Hollerweger, R. Weigel, S. Berek, R. Thomas, W. Ruile, C.C.W. Ruppel, and M. Guglielmi, "Design and performance of a SAW ladder-type filter at 3.15 GHz using SAW mass-production technology," *IEEE Trans. Microwave Theory and Tech.*, vol. 47, pp. 2312-2316, Dec. 1999.

[13] Y. Yamamoto, H. Kawahara, N. Sakairi, Y. Takahashi, R. Kajihara, T. Tsuda, and S. Yoshimoto, "Intermediate frequency SAW filters for mobile phone application in Japanese markets," in *Proc. IEEE Int. Ultrasonics Symp.*, Lake Tahoe, NV, 1999, pp. 333-340.

[14] H. Meier, T. Baier, and G. Riha, "Miniaturization and advanced functionalities of SAW devices," *IEEE Trans. Microwave Theory Tech.*, vol. 49, pp. 743-748, Apr. 2001.

[15] C.C.W. Ruppel, W. Ruile, G. Scholl, K.C. Wagner, and O. Männer, "Review of models for low-loss filter design and applications," in *Proc. IEEE Int. Ultrasonics Symp.*, 1994, pp. 313-324.