The 2019 Surface Acoustic Waves Roadmap

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Abstract

Today, Surface Acoustic Waves (SAWs) and Bulk Acoustic Waves (BAW) are already two of the very few phononic technologies of industrial relevance and can been found in a myriad of devices employing these nanoscale earthquakes on a chip. Acoustic radio frequency filters, for instance, are integral parts of wireless devices. SAWs in particular find applications in life sciences and microfluidics for sensing and mixing of tiny amounts of liquids. In addition to these continuously growing number of applications, SAWs are ideally suited to probe and control elementary excitations in condensed matter at the limit of single quantum excitations. Even collective excitations, classical or quantum, or integrated optomechanical are nowadays coherently interfaced by SAWs.

This wide, highly diverse, interdisciplinary and continuously expanding spectrum literally unites advanced sensing and manipulation applications. Remarkably, SAW technology is inherently multiscale and span from single atomic or nanoscopic units up even to the millimeter scale.

The aim of this roadmap article is to present a snapshot of the present state of Surface Acoustic Wave science and technology in 2019 and provide an opinion on the challenges and opportunities that the future holds from a group of renown experts covering the interdisciplinary key areas, ranging from fundamental quantum effects to practical applications of acoustic devices in life science.

Introduction

Phonons represent – in addition to photons or electrons – a fundamental excitation in solid state materials. Over the past decades, innovation for radically new devices has mostly been driven by controlling electrons (electronics) and photons (photonics) or magnetic (magnonics) and spin excitations (spintronics). Recently, phonons shifted back into the focus of both fundamental and applied research, as controlling these similarly to electrons and photons would, for instance, harness sonic energy in novel phononic devices [1].

Many of nowadays ‘acoustic’ devices employ acoustic phonons, which have striking analogies to their electromagnetic counterparts, photons. Both sound in a rigid material and light in a transparent medium share a linear dispersion and are only weakly attenuated. However, for sound waves the propagation velocity amounts to a few thousand meters per second, which is roughly 100 000 times slower than the speed of light. Micro acoustics deliberately takes advantage of these very dissimilar propagation velocities: electromagnetic microwave devices in the technologically highly relevant radio frequency domain, spanning the range from several 10s of megahertz to several gigahertz, are bulky since the corresponding wavelength of light ranges between centimeters and millimeters. Using sound, these dimensions can be elegantly shrunk by a factor of 100 000 to fit on a small chip for signal processing in mobile communications. Thus, several dozen acoustic radio frequency filters are integral parts of nearly every current (LTE) or future (5G) wireless device [2]. SAWs and BAWs also increasingly find numerous applications in the life sciences and microfluidics (acoustofluidics) for sensing or mixing and processing tiny amounts of liquids leading to so called Lab-On-a-Chip (LOC) or micro Total Analysis Systems (µTAS) [3]. Such thumbnail-sized microfluidic devices begin to emerge and revolutionize diagnostic quests in medicine. Remarkably, all the above devices are inexpensive, sometimes they may even be considered as consumables, because they are mass-produced by state-of-the-art cleanroom technologies. In addition to the continuously growing number of already very practical applications, SAWs and BAWs are ideally suited for fundamental research and to probe and control elementary excitations in condensed matter even in the limit of single quanta.

This Roadmap and its 15 contributions are meant to conclude the Special Issue on Surface Acoustic Waves in Semiconductor Nanosystems, which was initiated by the successfully concluded Marie Sklodowska-Curie Innovative Training Network *SAWtrain* with ten beneficiaries in seven European countries. The Special Issue comprises Topical Reviews and Research Articles from leading experts from the entire field on novel sensors [4],[5] waveguide modulators [6], single quantum dot structures [7],[8],[9] two-dimensional materials [10],[11],[12],[13],[14],[15] piezoelectric materials and hybrid devices [16],[17],[18],[19],[20],[21], and even macroscopic quantum systems [22],[23].

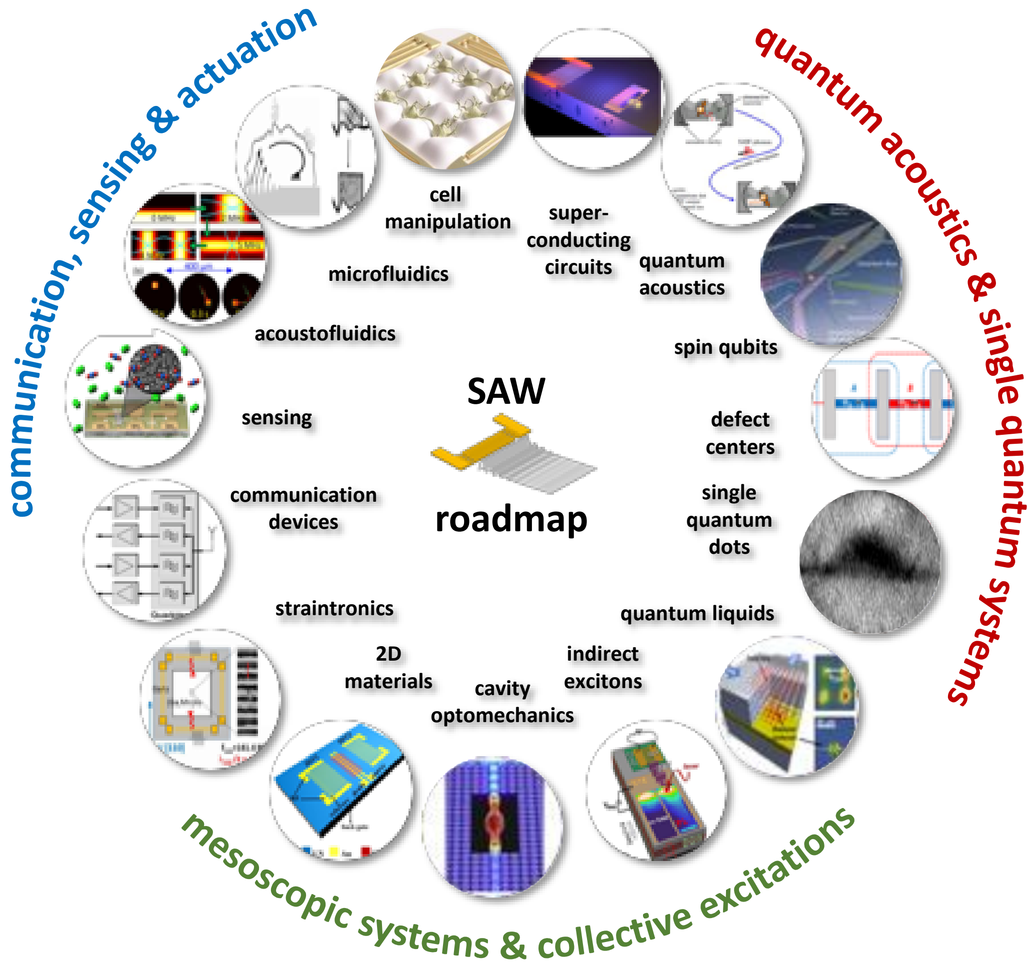

Figure 1 – Areas of SAW research covered in this Roadmap.

In the present Roadmap we pick up several of these and other topics and present a snapshot of the present state of Surface Acoustic Wave science and technology in 2019 and provide an opinion on the challenges and opportunities that the future hold. The topics addressed in this Roadmap are illustrated in Figure 1. These span from the exploitation of phonons in emerging hybrid quantum technologies, the manipulation and spectroscopy of collective excitations, signal processing to advanced sensing an actuation schemes in life science.

Augsburg, March 31st 2019

Hubert Krenner Achim Wixforth Christoph Westerhausen

14. Acoustofluidics in microfluidics

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Status

The use of Surface Acoustic Wave (SAW) has become key in the toolbox of different methods available to manipulate fluids, opening up a range of microfluidic applications in medical diagnostics, drug delivery, cell sorting, tissue engineering and life science research. Despite the novelty of many of the methods being proposed, it is perhaps surprising that the first practical demonstration of interaction of SAWs with fluids, was made nearly 30 years ago by Shiokawa et al. [1] in Japan, and involved demonstrating the liquid actuation functions of pumping and nebulisation by a Rayleigh wave, on a piezoelectric lithium niobate ($LiNbO_3$) wafer (Figure 1a). White et al. [2], working in the USA, also showed that piezoelectric ZnO thin films on a silicon nitride membrane (or plate) could also be used to create a liquid pump, this time showing the application of Lamb waves to actuate the fluid.
More recently, work by Wixforth's group [3] showed that Rayleigh SAWs can play a particularly powerful role when manipulating very small (nl-µl) microfluidic volumes of liquid - as the majority of the energy associated with the SAW is confined at the piezoelectric surface, and can be efficiently dissipated into the liquid. The smaller the volume, the greater the proportion of its volume that "feels" this dissipated energy, and thus the more efficient the actuation process (whether this be movement or heating). One further advantage of using SAWs in such systems results from mechanical forces which cause convective streaming within the liquid, and also, depending upon the nature of the induced flow, may enhance mass transfer for the rapid mixing of reagents [3,4]. This latter phenomenon saw the first commercial applications of SAWs in life-science instrumentation.
Extensive studies have now also demonstrated that SAW-based acoustofluidics provides the unique ability to manipulate liquids (and particles/cells within them) without contact (offering a contamination-free solution) and in a biocompatible and programmable way [5] (see also section 13). Such capabilities place SAW as a technique of choice to overcome many challenges in fluid handling within microfluidic systems and deliver its long-standing promises. Further advances, which may lead to new applications in wearable diagnostics and ubiquitous sensors and actuators, include decreasing the cost of materials used (by using thin piezoelectric films) [6], or increasing functionality (by creating bendable/flexible functions and new flow profiles).

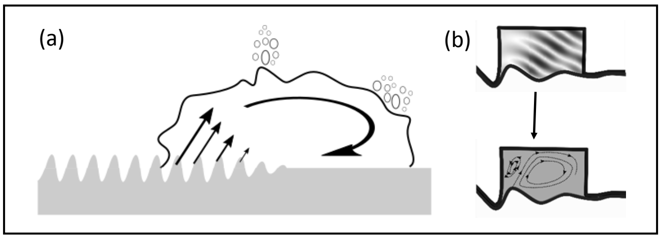

Figure 1. Schematic cross-sectional representation of the different fluidic actuations emerging from interactions between a SAW and a volume of liquid in a droplet (a), leading to deformations on the surface (and ultimately movement, jetting or nebulisation), as well as streaming and recirculatory flows, or within a microchannel (b).

Current and Future Challenges

This section discusses the big research issues and challenges. (350 words max)

For many applications, $LiNbO_3$ has been the piezoelectric material of choice, because it is very consistent in its behaviour and response (e.g. its piezoelectric coefficient is large and predictable for different crystal orientations, despite being relatively expensive, difficult to process and fragile). This has allowed the creation of very complex field structures [7], translating approaches from optical wave shaping (also termed wavefront engineering) into acoustofluidics. To realise new opportunities of SAW-based acoustofluidics, there is a need for new strategies to further integrate the piezoelectric actuator with other sensing and microfluidic functions to enable new low-cost and low power solutions – opening up new challenges in fluid mechanics and acoustics.

Over the last few decades, the liquid has often been processed as a 'wall-less' droplet placed directly onto the piezoelectric surface to maximise the energy transfer (Figure 1a). The fluid may also be contained within an elastomeric microchannel with a defined geometry (figure 1b), with the possibility of allowing the reuse of the actuator [8]. However, the manufacturing and assembly of such devices are complex, limiting their practical applications. As an alternative, SAW manipulations can be produced on a thin disposable chip placed on the surface of the piezoelectric SAW substrate which can act as a disposable biochip [9]. Such chips have come to be known as superstrates as they sit in contact with the piezoelectric substrate. Their design can be further modified through the introduction of arrays of microstructured features in order to create phononic crystals [10], producing new complex acoustic fields, which can also be used to control liquid flows and interfaces [11]. However, the physics of the complex interactions between the liquids, the newly shaped acoustic field and the different interfaces of the system can be challenging to model, predict and control.

Another integration strategy is to deposit piezoelectric films such as ZnO, AlN, and PZT onto a variety of substrates including silicon, metals, glass and plastics. This will provide new opportunities for integration whilst bringing about a dramatic decrease in material costs, and opening the way for implementing integrated, disposable, or bendable/flexible lab-on-a-chip devices [6]. However, there remain issues including their performance and reliability as well as the development of low-cost manufacturing methods.

Advances in Science and Technology to Meet Challenges

Acoustic waves generally manifest on timescales of microseconds and produce surface deformations on the piezoelectric wafer that may be below a few tens of nanometers. In contrast, the deformations on fluid surfaces are generally responding on the order of milliseconds with displacements that may be a few microns in size. The subsequent flows within the bulk of the liquids provide functionalities in seconds and with distances on the order of the millimetre and beyond. All commonly-used approaches to simulate these phenomena, from finite-element, finite-volume to finite-difference time-domain methods, have imposed constraining boundary conditions to reach practical computational capabilities, that limit precise predictions. To advance the boundaries of our understanding of acoustofluidics beyond currently well-established wave and flow profiles, new analytical and modelling approaches will be required to bridge these spatio-temporal scales. As an example, new approaches that combine analysis in the frequency domain and time-domain [12] may reveal new behaviours, especially where complex rheological and surface properties are available.

In the field of advanced materials, the recent demonstration of deposition of thin piezoelectric films onto a great variety of solid surfaces has opened up new avenues of development to enable us to implement acoustofluidics functionalities into deformable components (figure 2) [6]. These, in turn, could realise wearable lab-on-chips, able to process liquid samples close to or inside the human body. To date, this capability has been hindered by the high energy loss encountered in these flexible, 'soft' systems, limiting the physical reach of the waves to only a few wavelengths. New opportunities in thin plates (below the wavelength) and new modes of propagation and their combinations [13] may provide a promising avenue to overcome this limitation. In particular, controlling different (crystal) structure orientations by controlling deposition parameters [6], or integrating acoustic metamaterials with anomalous material properties, will provide the capability to generate complex wave patterns on a single substrate, while to enable the integration of actuation (e.g. for both medical diagnostics and therapy) and molecular sensing on a single, deformable and disposable substrate. In this context, novel materials, such as piezoelectric doped graphene may play a future role in such new lab-on-a-chip systems (see also section 9).

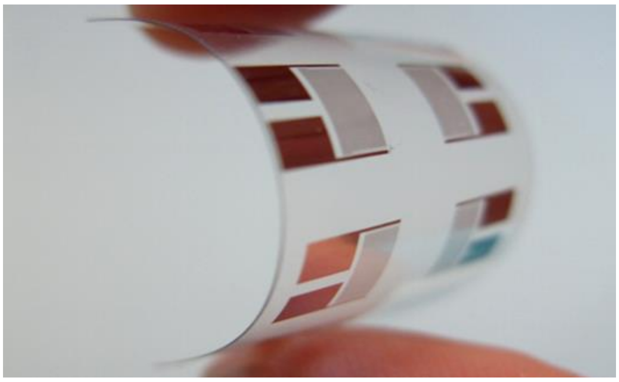

Figure 2. Flexible ZnO/PET SAW device in bending (2 micron thick ZnO film deposited onto 120 micron PET foil which also hosts metal IDTs)

Concluding Remarks

The field of SAW-based acoustofluidics has begun to reach maturity after an initial exponential growth that has spanned the last three decades. The topic is now generating new practical applications in medical diagnostics and drug delivery applications whilst providing biologists with new tools for life-science research based upon cell manipulations and sorting. A new impetus in the fundamental understanding of the physical processes across spatio-temporal ranges that span many orders of magnitude is still required to enable the techniques to be fully realised, enabling translation of capabilities demonstrated in laboratory settings, into real-world settings. This process is likely to require the bridging of different communities and disciplines, a challenge which is not unique to this field, but nevertheless needs to build upon existing knowledge with a shared vocabulary and cross-disciplinary collegiality.

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