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COMMENTARY

Aluminum Scandium Nitride based frequency-switchable acoustic devices for next-generation mobile communication

Ji Li,[1,2] Fanping Meng,[2] Sitong Chen,[2] Fang Ye,[2] Qiushuang Chen,[2] Weiping Xie,[2] Li Chen,[2] Jie Lin,[2] Jiayin He,[3] Ziheng Liu,[3] Ju Gao,[3] Wenbo Xia,[1] Jinyan Wang,[3] Jichun Ye,[2] and Wei Guo[2,*]

[1]School of Software & Microelectronics, Peking University, Beijing 102600, China

[2]Ningbo Institute of Materials Technology and Engineering, Chinese Academy of Sciences, Ningbo 315201, China

[3]School of Integrated Circuits, Peking University, Beijing 100871, China

*Correspondence: guowei@nimte.ac.cn

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INTRODUCTION

Given the surge in increasing demand for wide bandwidth and high-speed data transmissions, dynamic spectrum allocation in a wide frequency range is urgently desired for wireless communication systems. Currently, in most radio frequency front end (RFFE) modules, spectrum management is realized using a large set of static RF filters designed for different communication bands, as shown in Figure 1A. These miniaturized filters are primarily based on surface and bulk acoustic wave (SAW and BAW) resonators. Filters with different center frequencies (f_c) are packaged together with other components and RF switches in substrates to form multi-band spectral processors in RFFE circuits. By controlling the switches, signals from different frequency bands can be selected, thereby achieving dynamic spectrum allocation. However, this strategy increases the footprint of the packaging substrates, and the switches introduce unfavorable insertion loss, which degrades the signal quality.

To solve these problems, reconfigurable filtering technologies based on frequency-switchable acoustic devices have emerged and drawn much interest recently. Different from conventional fixed-frequency filters, these tunable components have two or more passbands, and their operating states can be switched via control ports (Figure 1A).

THE WORKING PRINCIPLE OF CONVENTIONAL FBAR FILTERS

Nowadays, ladder-type filters with cascaded multiple stages are the mainstream topology in RFFE. Each stage consists of two acoustic resonators connected in series and parallel (R_s and R_p) as shown in Figure 1B. As a type of BAW device, film bulk acoustic resonators (FBARs) are the most commonly utilized design, especially in the high-frequency range over 2.5 GHz, because of the superior electromechanical coupling coefficient (k_{eff}^2) and quality factor (Q). FBAR is composed of a fundamental sandwich structure (metal/piezoelectric layer/metal) and an air cavity reflector (Figure 1B). Since the piezoelectric polarization direction of AlN is parallel to the c-axis, when alternating current (AC) voltage is applied on the top and bottom electrodes, longitudinal waves are generated, propagating along the c-axis of the AlN film. Due to the reflection at the electrodes and air interfaces, acoustic

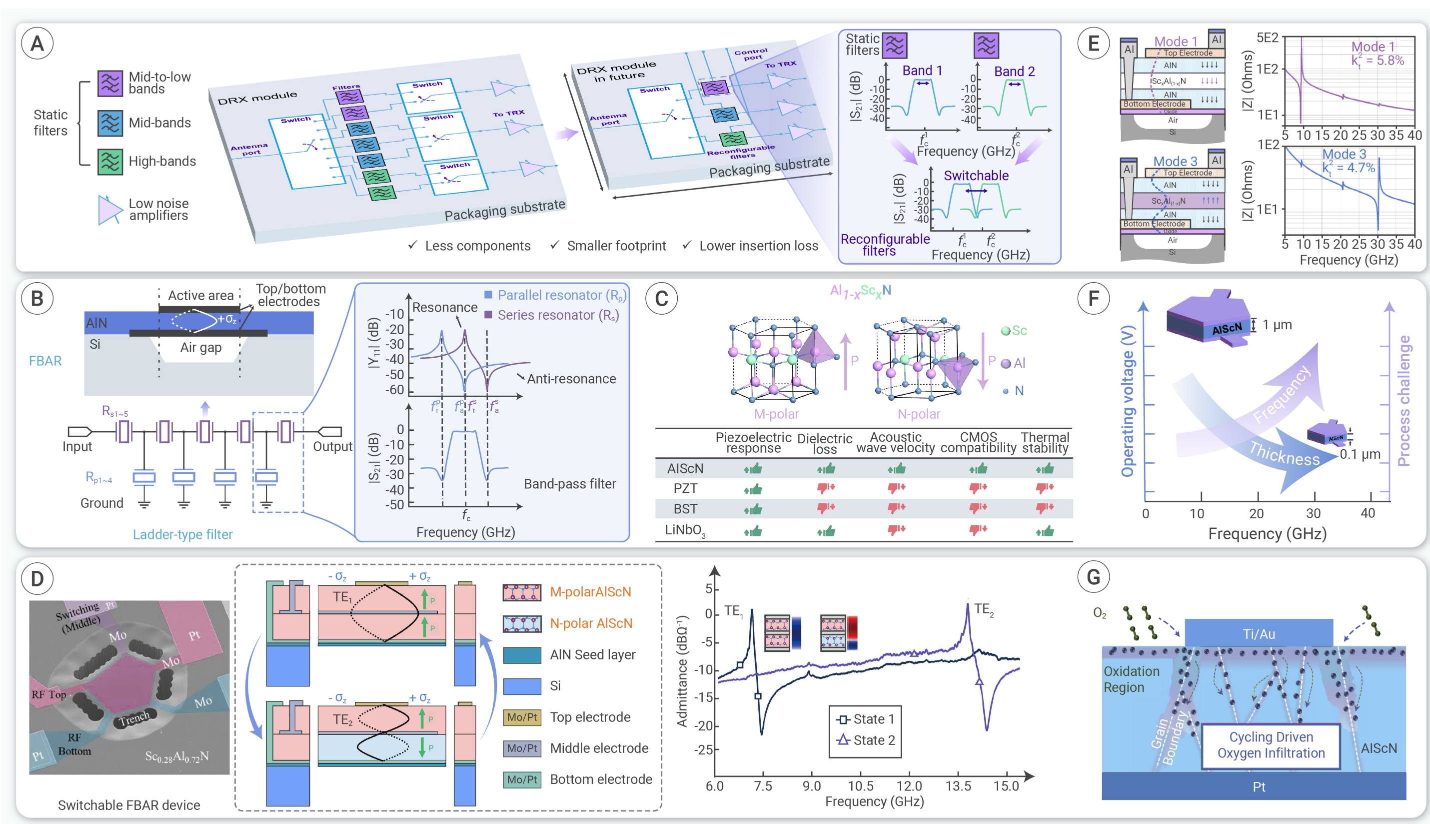

Figure 1. Schematic and working principle of AlScN-based frequency-switchable FBAR (A) Schematic diagram of a Diversity Receive Module (DRX) utilizing reconfigurable filters. (B) Schematic illustration of a ladder-type filter composed of FBARs. (C) Crystal structure of wurtzite Aluminum Scandium Nitride (AlScN) ferroelectric thin film and comparison chart with other ferroelectric materials. (D) Schematic of a frequency-switchable FBAR device and its two operation states. Reproduced with permission.[1] Copyright 2022, IEEE. (E) A simplified frequency-switchable FBAR device and its test results. Reproduced with permission.[2] Copyright 2023, IEEE. (F) Schematic of the benefits and challenges of thickness scaling. (G) Schematic of a fatigue mechanism in AlScN films: cycling driven oxygen infiltration along the grain boundaries. Reproduced with permission.[3] Copyright 2025, IEEE.

waves at specific frequencies resonate within the structure in the form of standing waves. Electrically, this manifests as the resonance frequency corresponding to a maximum in admittance and the anti-resonance frequency corresponding to a minimum in admittance. By matching the design of R_s and R_p, a flat passband of the ladder-type circuit is created in the frequency response of the forward transmission coefficient, as shown in Figure 1B. Only RF signals within this frequency band can pass through the filter network with relatively low insertion loss.

ALUMINUM SCANDIUM NITRIDE(AlScN)-BASED FREQUENCY-SWITCHABLE FBAR DEVICES

Despite AlN being the preferred choice for the piezo-layer in FBAR devices, its piezoelectric coefficient (d_{33}) is still relatively low (5.5 pC/N) compared with other piezoelectric materials such as $Ba_{1-x}Sr_xTiO_3$ (BST) or $Pb(Zr_xTi_{1-x})O_3$ (PZT). In 2009, Akiyama et al. confirmed that doping scandium (Sc) into AlN can significantly enhance the value of d_{33} (24.6 pC/N for $Al_{0.57}Sc_{0.43}N$).[4] However, as the Sc content continues to increase, the non-piezoelectric cubic phase gradually becomes dominant in $Al_{1-x}Sc_xN$ alloys, leading to the loss of piezoelectricity. Similar to other wurtzite III-nitrides, AlScN has two antiparallel polarization directions along the *c*-axis, *i.e.*, metal-polar and nitrogen-polar (Figure 1C). The structural and chemical changes brought about by Sc doping reduce the energy barrier between these two polarization states, enabling ferroelectric switching behavior. As shown in Figure 1C, AlScN possesses a lot of advantages, such as high piezoelectric response, low dielectric loss, high acoustic velocity, good thermal stability, and CMOS compatibility.

For conventional FBAR filters, the passband frequency range is determined by the thickness of the piezo-layer, lacking reconfigurability. In response to the requirement of multi-band frequency switching, FBARs require the capability of multi-mode resonance. Ferroelectric AlScN thin films provide a solid foundation for the development of the frequency-switchable FBARs.

AlScN-based frequency-switchable FBARs were firstly demonstrated by Mo et al.[1] They achieved the stacking of two sandwich structures of the same size ($Mo/Al_{0.72}Sc_{0.28}N/Mo$) through successive deposition and patterning of $Al_{0.72}Sc_{0.28}N$ and molybdenum (Mo) layers on silicon substrates. The top and cross-sectional views of the device are shown in Figure 1D. In the initial state, both sub-layers were M-polar, and the polarization directions were continuous regardless of the existing middle electrode. Similar to a typical FBAR, under the constructive interference condition, resonance occurred when half of the acoustic wavelength was equal to the thickness of the entire stacked structure. When applying RF voltage on top and bottom electrodes, the first thickness extensional mode (TE_1) was obtained at 7.04 GHz, with a Q of 115 and a k_{eff}^2 of 10.1%. By applying a set of low-frequency switching pulses (80 V) to the middle and bottom electrodes, the polarity of the lower $Al_{0.72}Sc_{0.28}N$ layer was reversed to N-polar, resulting in opposite polarization directions in the two ferroelectric layers. The opposite polarization directions of the two sub-layers resulted in the equivalent thickness of the stacked structure that is half of the original value, doubling the device's operating frequency to 13.4 GHz (TE_2). Large Q and k_{eff}^2 values of 151 and 10.7% were obtained, respectively.

PERSPECTIVE OF FREQUENCY-SWITCHABLE FBARs

In the future, reconfigurable filters with adjustable passbands across a wide frequency range are expected to achieve monolithic integration, which will make the RFFE more compact while reducing costs. For applications that require both lightweight and compact designs, such as drones and wearable electronics, the proposed frequency-switchable acoustic devices offer huge advantages over other counterparts. However, there are still several hurdles that need to be overcome.

A. Structure simplification

To enhance the number of switching modes, it is necessary to prepare a multiple-stacked layer. The repeated deposition and patterning not only increase the complexity but also degrade the crystalline quality of AlScN. The accumulation of more defects leads to a decrease in device reliability during cyclic switching. To tackle this issue, recently, Nam *et al.* further simplified the stacking structure by continually depositing $AlN/Al_{0.7}Sc_{0.3}N/AlN$ using molecular beam epitaxy, as shown in Figure 1E.[2] This design has no intermediate electrodes, avoiding successive deposition and patterning steps, diminishing the parasitic effect introduced by metal layers. The polarization direction of the AlScN layer can be controlled by applying low-frequency DC bias on the top and bottom electrodes, while the polarity of the AlN layers remains unaffected. The test results showed that the operating frequency of Mode 1 was 9 GHz with a Q of 395 and a k_{eff}^2 of 5.1%, while the operating frequency of Mode 3 was 31 GHz with a Q of 61 and a k_{eff}^2 of 5.5%.

B. Thickness scaling

Similar to conventional FBARs, reducing the thickness of the piezoelectric layer can increase the operating frequency of frequency-switchable FBARs, thereby avoiding some crowded frequency bands (Figure 1F). Moreover, thickness scaling can reduce the required DC voltage during ferroelectric switching, enabling lower power consumption. However, ultrathin AlScN films are often accompanied by deteriorated crystal quality and significant leakage current, both of which pose great challenges to the deposition process. Recent work utilizing a hafnium nitride ($HfN_{0.4}$) bottom electrode has successfully minimized lattice mismatch and achieved ultrathin (3 nm) $Al_{0.7}Sc_{0.3}N$ films with low leakage currents, reducing the coercive voltage to 4.35 V.[5] This advances the development of low-voltage AlScN devices that are compatible with CMOS technology.

C. Endurance improvement

The long-term stability of AlScN ferroelectric thin film under repeated polarization switching is important in the evaluation of device performance. For conventional ferroelectric thin films, obtaining remanent polarization (P_r) through P-V loop characterization under stress cycling can effectively reflect ferroelectric fatigue characteristics. In AlScN, the migration and aggregation of nitrogen vacancy, and ferroelectric domain pinning are important factors that affect the endurance property of the AlScN ferroelectric thin film. Furthermore, Wang et al. have recently identified a novel fatigue mechanism in AlScN, where prolonged stress cycling promotes the penetration of oxygen impurities along grain boundaries into the AlScN bulk (Figure 1G), directly contributing to the degradation of ferroelectric properties.[3] The combined effects of multiple mechanisms on ferroelectric fatigue still require further investigation.

CONCLUSION

In conclusion, the recent development on the emerging piezoelectric and ferroelectric material AlScN and its application on frequency-switchable acoustic devices for next-generation mobile communication have been reviewed. The working principles of conventional FBARs and AlScN-based frequency-switchable FBARs were elaborated in detail. The optimization of the overall RFFE system enabled by these novel architectures was demonstrated. Furthermore, the challenges hindering the development of such devices have been summarized. We believe that through material and design optimization, the paradigm of mobile communication systems will be significantly overturned in the near future.

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DECLARATION OF INTERESTS

The authors declare no competing interests.