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INTERNATIONAL STANDARD

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Radio frequency (RF) bulk acoustic wave (BAW) filters of assessed quality – Part 2: Guidelines for the use

Filtres radiofréquences (RF) à ondes acoustiques de volume (OAV) sous assurance de la qualité – Partie 2: Lignes directrices d'emploi

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

RADIO FREQUENCY (RF) BULK ACOUSTIC WAVE (BAW) FILTERS OF ASSESSED QUALITY –

Part 2: Guidelines for the use

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International Standard IEC 62575-2 has been prepared by IEC technical committee 49: Piezoelectric, dielectric and electrostatic devices and associated materials for frequency control, selection and detection.

The text of this standard is based on the following documents:

FDIS	Report on voting
49/994/FDIS	49/999/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 62575 series, published under the general title *Radio frequency (RF) Bulk acoustic wave (BAW) filters of assessed quality*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
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INTRODUCTION

RF BAW filters are now widely used in mobile communications. While the RF BAW filters have various specifications, many of them can be classified within a few fundamental categories.

Standard specifications, given in IEC 62575, and national specifications or detail specifications issued by manufacturers, define the available combinations of nominal frequency, pass bandwidth, ripple, shape factor, terminating impedance, etc. These specifications are compiled to include a wide range of RF BAW filters with standardized performances. It cannot be over-emphasized that the user should, wherever possible, select his RF BAW filters from these specifications, when available, even if it may lead to making small modifications to his circuit to enable standard filters to be used. This applies particularly to the selection of the nominal frequency.

This standard has been compiled in response to a generally expressed desire on the part of both users and manufacturers for guidance on the use of RF BAW filters, so that the filters may be used to their best advantage. To this end, general and fundamental characteristics have been explained in this part of IEC 62575.

It is not the aim of this standard to explain theory, nor to attempt to cover all the eventualities which may arise in practical circumstances. This standard draws attention to some of the more fundamental questions, which should be considered by the user before he places an order for an RF BAW filter for a new application. Such a procedure will be the user's insurance against unsatisfactory performance.

RADIO FREQUENCY (RF) BULK ACOUSTIC WAVE (BAW) FILTERS OF ASSESSED QUALITY –

Part 2: Guidelines for the use

1 Scope

This part of IEC 62575 gives practical guidance on the use of RF BAW filters which are used in telecommunications, measuring equipment, radar systems and consumer products. General information, standard values and test conditions will be provided in a future IEC standard[1].

This part of IEC 62575 includes various kinds of filter configurations, of which the operating frequency range is from approximately 500 MHz to 10 GHz and the relative bandwidth is about 1 % to 5 % of the centre frequency.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

None.

3 Technical considerations

It is of prime interest to a user that the filter characteristics should satisfy a particular specification. The selection of tuning networks and RF BAW filters to meet that specification should be a matter of agreement between user and manufacturer.

Filter characteristics are usually expressed in terms of insertion attenuation as a function of frequency, as shown in Figure 1. A standard method for measuring insertion attenuation is described in IEC 60862-1:2003, 5.5.2. Insertion attenuation characteristics are further specified by nominal frequency, minimum insertion attenuation or maximum insertion attenuation, pass-band ripple and shape factor. The specification is to be satisfied between the lowest and highest temperatures of the specified operating temperature range and before and after environmental tests.

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1 This standard (under consideration) is expected to bear the reference number IEC 62575-1.

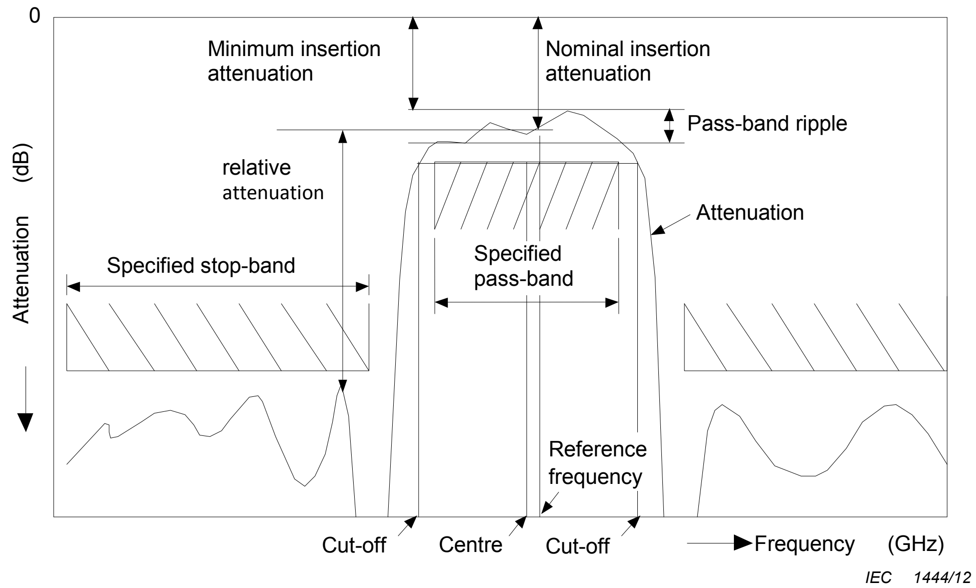


Figure 1 – Frequency response of a RF BAW filter

4 Fundamentals of RF BAW filters

4.1 General

The features of RF BAW filters are their small size, light weight, adjustment-free, high stability and high reliability. RF BAW filters add new features and applications to the field of surface acoustic wave (SAW) filters and dielectric resonator filters. Nowadays, RF BAW filters with low insertion attenuation are widely used in various applications in the gigahertz range.

RF BAW filters are becoming rapidly popular as miniature and low insertion attenuation filters for mobile communication application. RF BAW resonator filters can realize low insertion attenuation easily and of a smaller size than that of the RF SAW filters with the same bandwidth. Their feasible bandwidth is, however, limited by employing piezoelectric materials, design methods and so on. It is desirable for users to understand these factors for RF BAW resonator filters. This standard explains the principles and characteristics of RF BAW resonator filters.

RF BAW filters usually employ a filter configuration called the ladder filter, which is composed of multiple RF BAW resonators. They are classified into two types: film bulk acoustic resonators and solidly mounted resonators. In Figure 2, the applicable frequency range and relative bandwidth of the RF BAW filters are shown in comparison with those of ceramic, crystal, dielectric, helical, SAW and stripline filters.

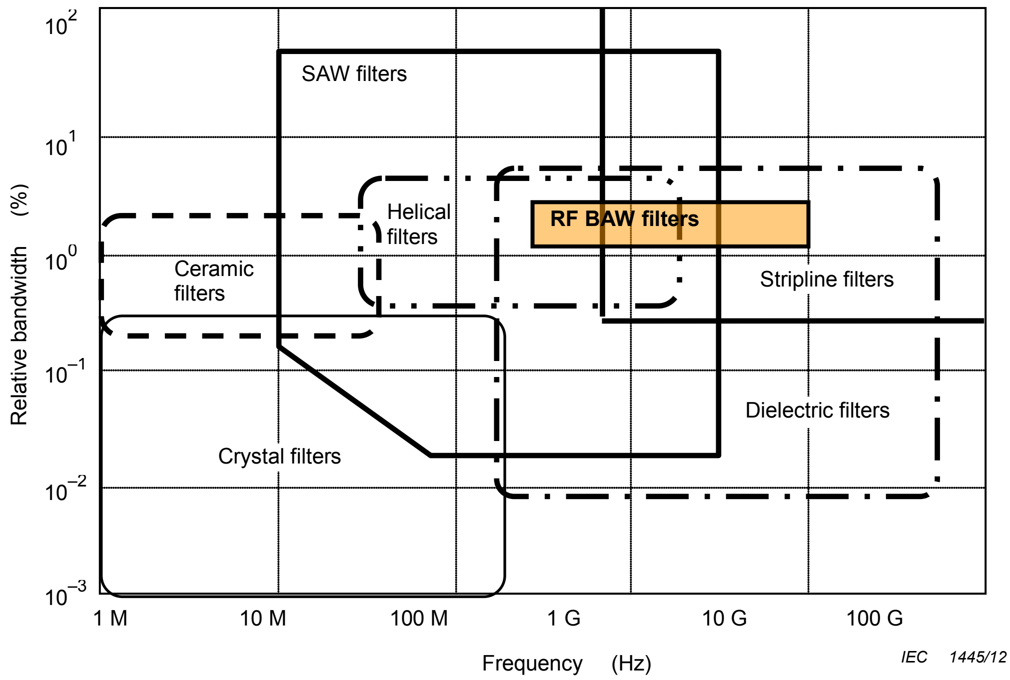


Figure 2 – Applicable range of frequency and relative bandwidth of the RF BAW filter and the other filters

4.2 Fundamentals of RF BAW resonators

a) Acoustic resonance

When a mechanical impact is applied to a solid surface, acoustic waves are generated, and a portion of their energy is transmitted by propagation of the acoustic waves in the bulk. This type of wave is called the bulk acoustic wave (BAW). Remaining energy may be transferred by acoustic waves propagating along the surface. This type of wave is called the surface acoustic wave (SAW).

There are two types of BAWs: the longitudinal or dilatational BAW, with the displacement toward the propagation direction, and the transverse or shear BAW, with the displacement normal to the propagation direction. Acoustic wave velocities in solids are a few hundreds of meters per second to twenty thousands of meters per second. Usually the longitudinal BAW is few times faster than the shear BAW for a given material and orientation.

In the case of acoustic wave propagation in a parallel plate, it is known that the plate causes a mechanical resonance (thickness resonance) when the plate thickness h is half-integer times the wavelength λ of acoustic waves propagating in the plate normal to the plate surface, i.e. $h = n\lambda/2$, where n is an integer and called the order of modes. We obtain mechanical resonance frequencies f_r as

$$f_\mathrm{r} = V/\lambda = nV/(2h) \qquad (1)$$

where V is the acoustic wave velocity. Equation (1) indicates that in addition to a lowest-order resonance (n=1) called the fundamental resonance, a series of higher-order ($n\neq1$) ones might be excited. Since f_r for $n\neq1$ will be integer times f_r for n=1 in this case, higher-order resonances are often called harmonics or harmonic resonances. When the longitudinal BAW is responsible for the thickness resonance, it is called the thickness extensional (TE) resonance but when the shear wave is responsible, it is called the thickness shear (TS) resonance.

There are also acoustic waves propagating along the plate top surface. When wave energy is well confined near the top surface and influence of the back surface is negligible, the waves are called the surface acoustic waves (SAWs). On the other hand, when wave energy penetrates into the plate and influence of the back surface is not negligible, the waves are called plate waves or Lamb waves.

b) Piezoelectric excitation and detection

In the case where a piezoelectric plate is sandwiched between two parallel electrodes (see Figure 3), when an electrical voltage E is applied between two electrodes, mechanical force is generated through the piezoelectricity, and acoustic motion will be induced. On the other hand, electrical charges will be induced to the electrodes by electric fields associated with propagating acoustic waves.

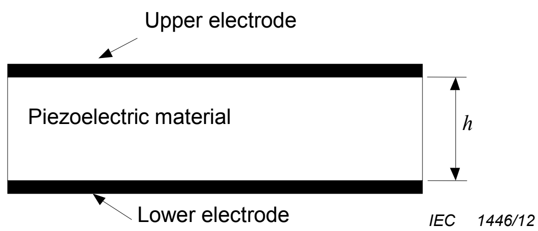


Figure 3 – Basic BAW resonator structure

An electromechanical equivalent circuit shown in Figure 4 may be deduced from these relations. In Figure 4, C_0 is the clumped capacitance originating from the electrostatic coupling between two electrodes, and C_1, L_1 and R_1 are the motional capacitance, inductance and resistance, respectively, originating from mechanical reaction, i.e. elasticity, inertia and damping, respectively. This circuit is called the Butterworth-Van Dyke (BVD) model.

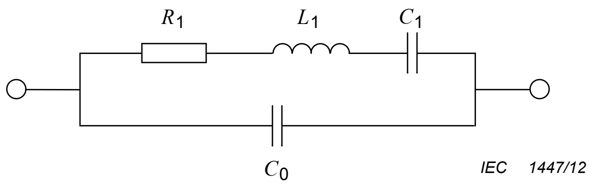


Figure 4 – BVD model

Figure 4 implies that mechanical resonances described above can be excited and detected electrically through the electrodes. Namely, this device serves as an electrical resonator. This type of resonator is called the BAW resonator. Proper choice of the piezoelectric material offers small acoustic attenuation, which results in long duration of the mechanical vibration. This mechanical property influences the electrical one as large quality (Q) factor of the electrical resonance circuit.

Figure 5 shows typical resonance characteristics calculated by the BVD model. It is seen that a series resonance occurs at a frequency f_r where the electrical impedance Z between two electrodes becomes pure resistive and very small. From the BVD model, f_r is given by

$$f_r \approx 1/2\pi\sqrt{L_1 C_1} \quad (2)$$

On the other hand, at a frequency f_a slightly above f_r, a parallel resonance occurs where Z becomes pure resistive and very large. From the BVD model, f_a is given by

$$f_a \approx 1\Big/2\pi\sqrt{L_1(C_1^{-1}+C_0^{-1})^{-1}} \qquad (3)$$

These frequencies are called the resonance and the anti-resonance frequencies, respectively[2]

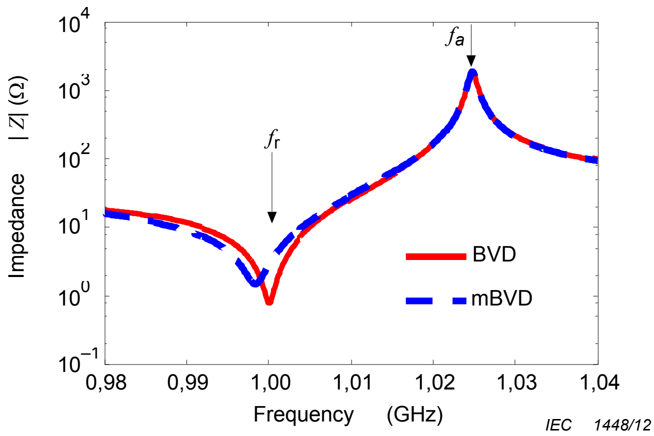


Figure 5 – Typical impedance characteristics

The capacitance ratio r is often used as a measure of the resonator performance, and is defined by

$$r = \left[(f_a/f_r)^2 - 1\right]^{-1} \qquad (4)$$

From the BVD model, and r is given by

$$r = C_0/C_1 \qquad (5)$$

In the filter design discussed later, r limits achievable fractional frequency bandwidth for filter applications.

At frequencies much lower than f_r, the resonator is equivalent to a capacitor with the capacitance of $C_0 + C_1 = C_0(1 + r^{-1})$, which is given by $\varepsilon S/h$, where ε is the dielectric constant and S is the electrode area. Thus C_0 is adjustable only by S because h is mostly determined by the frequency setting.

It is clear from Equation 5 that r indicates weakness of the piezoelectricity. In fact, full wave analysis gives a relation between f_r/f_a and the electromechanical coupling factor k_t^2 for the thickness-longitudinal vibration of the piezoelectric material as

$$k_t^2 = (n\pi f_r / 2f_a)/\tan(n\pi f_r / 2f_a) \qquad (6)$$

When $f_r \cong f_a$, Equations (3) and (5) become

2 Frequencies f_m and f_n giving minimum |Z| and maximum |Z| are the frequencies of maximum and minimum admittance or those of minimum and maximum impedance. When Q is large, f_m and f_n are almost equal to f_r and f_a, respectively.

$$(f_a - f_r)/f_a \cong 1/2\gamma \cong \begin{cases} 4k_t^2/n^2\pi^2 & n:\text{odd} \\ 0 & n:\text{even} \end{cases} \quad (7)$$

This indicates three important facts:

1) achievable r is limited by k_t^2 of employed piezoelectric material;

2) even-order overtones cannot be excited electrically; and

3) γ increases rapidly with an increase in n.

It should be noted that Equations (6) and (7) are only valid when a uniform piezoelectric layer is sandwiched between two infinitesimally thin electrodes with infinite conductance. Since influence of electrodes is not negligible as will be discussed later, piezoelectric strength of the resonator structure is often characterized by the effective electromechanical coupling factor defined by

$$k_{\text{teff}}^2 = (\pi f_r/2f_a)/\tan(\pi f_r/2f_a) \quad (8)$$

From the BVD model, the Q factor at f_r is given by

$$Q_r = 2\pi f_r L_1/R_1 \quad (9)$$

and is often referred to as the resonance Q or Q_r. We can also evaluate the Q factor at the anti-resonance frequency, and the value is called the anti-resonance Q or Q_a. In the filter design, Q_r and Q_a determine steepness of the pass-band edges for filter applications.

For resonator characterization, the figure of merit, M is defined as

$$M = Q_r/r \quad (10)$$

In the filter design, M determines achievable minimum insertion attenuation.

It is interesting to note that the BVD model indicates that

$$M \cong 2\pi f_a C_0 Z_{\text{max}} \cong 1/2\pi f_r C_0 Z_{\text{min}} \quad (11)$$

where Z_{max} and Z_{min} are electrical impedances of the resonator at f_n ($\approx f_a$) and f_m ($\approx f_r$), respectively. Thus $Z_{\text{max}}/Z_{\text{min}}$ called the impedance ratio is also used for the resonator characterization.

NOTE 1 This approximated form is valid only when Q_r and r are large.

c) Secondary effects

Basic operation of BAW resonators is simulated fairly well by the use of the BVD model described above. In real devices, however, various secondary effects occur, and their influences shall be well-controlled for device design and production. Significant secondary effects are:

1) Lateral wave propagation

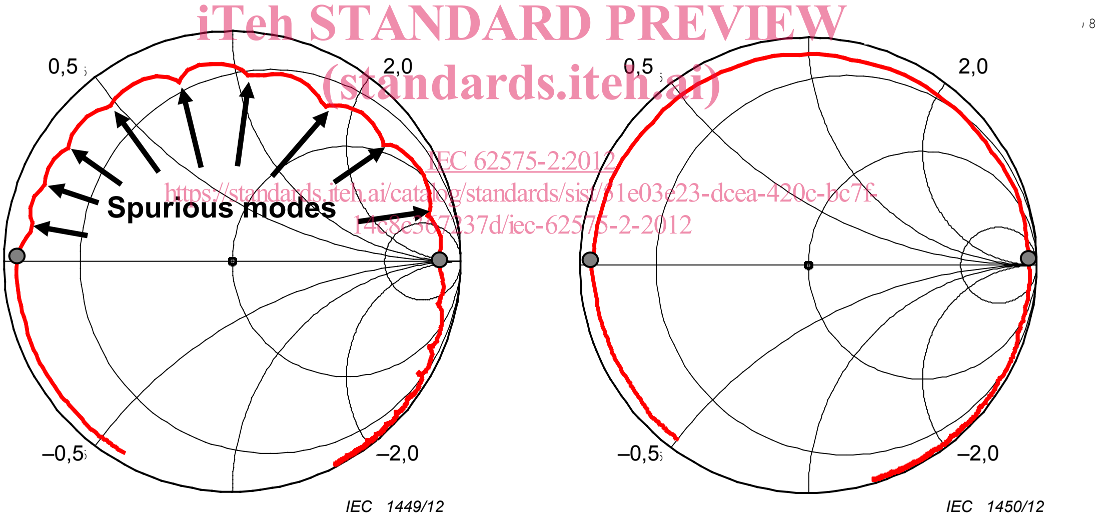
At frequencies close to the resonance, Lamb waves are excited and propagate along the surface. If their wave energy is dissipated, it will cause Q reduction of the main resonance. If the resonator structure is designed to confine the wave energy, the resonance Q might be preserved, while it may cause unwanted resonances often called spurious resonances. Since lateral structural size is significantly larger than the BAW wavelength in general, frequency separation between the resonances is narrow. From this property, these spurious resonances are called inharmonics. The top surface of the resonator is sometimes shaped in an irregular polygon to smear out spurious resonance peaks.

2) Parasitic impedances

Ohmic resistances, parasitic capacitances, and inductances of the electrodes and pads are not negligible in radio frequencies (RF).

Figure 6 shows polar plot (Smith chart) of the return coefficient Γ of two RF BAW resonators. Γ is given by $(Z\text{-}R_0)/(Z+R_0)$, where Z is the device impedance and R_0 is the characteristic impedance of the measurement system. The trace rotates clockwise with the frequency, and leftmost and rightmost points of the trace correspond to the resonance and anti-resonance frequencies, respectively. Series of inharmonics are seen in Figure 6 a). It should be noted that the overtones are only seen above the resonance frequency, and this property called the cut-off indicates they are due to lateral wave propagation.

Application of an appropriate technology enables to suppress inharmonics almost completely as shown in Figure 6 b). In addition, it is seen that the trace approaches to the outermost circle, namely $|\Gamma|$ close to unity. This indicates the lateral wave propagation can be one of the most significant loss mechanisms.



a) before suppressing spurious resonances b) after suppressing spurious resonances

Figure 6 – Typical impedance characteristics of RF BAW devices

The BVD model is often modified to take these effects into account. Figure 7 shows an example, where series resistance R_s and shunt resistance R_0 are added to express variation of energy dissipation with frequency, and L_s expresses inductance of the interconnecting electrodes and/or bonding wires.

NOTE 2 A modification of the equivalent circuit is not unique. For example, R_0 in Figure 7 is sometimes placed in parallel with C_0 instead of series.

Even if L_s and/or R_s are small, their impact is significant near the resonance frequency where $|Z|$ becomes extremely small. This modified BVD model gives the resonance frequency f_r and the resonance Q, Q_r, as

$$f_r \approx 1 \big/ 2\pi\sqrt{(L_s + L_1)C_1} \tag{12}$$

and

$$Q_r = 2\pi f_r (L_1 + L_s)/(R_1 + R_s) \tag{13}$$

respectively. On the other hand, impact of R_0 is significant near the anti-resonance frequency where $|Z|$ becomes extremely large. This modified BVD model gives the anti-resonance Q, Q_a, as

$$Q_a = 2\pi f_a L_1/(R_1 + R_0) \tag{14}$$

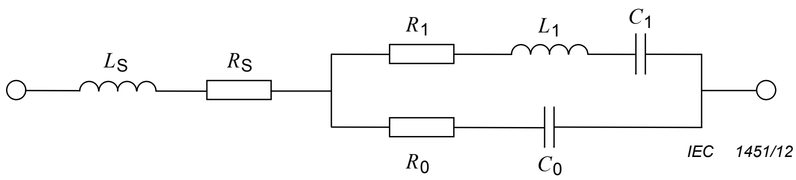


Figure 7 – Modified BVD model

Figure 5 compares the electrical impedance $|Z|$ given by this modified BVD model with that given by the original one. In this calculation, R_0 is set to zero. It is seen that f_r and Q_r are slightly decreased while f_a and Q_a are unchanged. It should be noted that the original BVD model indicates $Q_r \cong Q_a$, but this is not true in general.

Since L_s effectively increases k^2_{teff}, it is often used positively to enhance the filter performance. On the other hand, the parasitic capacitance between terminals effectively increases C_0 and results in decreased k^2_{teff}. Thus the device package shall be co-designed with the BAW device chip itself so as to optimize the total device performance.

4.3 RF resonator structures

For applications lower than a few tens of MHz, BAW resonators can be mass-produced by thinning and polishing piezoelectric materials. For higher frequencies, on the other hand, since required thickness h is reduced to micro metre order, thin film technologies are applicable instead of mechanical processing. Although use of overtones with $n \neq 1$ is another choice, it results in significant increase in r.

Aluminium nitride (AlN) is widely used as a piezoelectric layer for the RF BAW resonator because of its several distinct features: low propagation loss, high electrical resistivity, and possible growth of high quality films on underneath metal electrodes. Although various materials such as zinc oxide (ZnO), lead zirconate titanate (PZT), etc. have been investigated extensively, realized performances are much lower than those attained by AlN and far from practical use.

Lack of material choice limits applicability of RF BAW filters. That is, r limiting the filter bandwidth is mostly determined by the piezoelectric material as indicated in 4.2. Molybdenum, Ruthenium, Tungsten, etc., are used for the electrodes because their large acoustic impedance offers slight decrease in r or increase in $k_t^2{}_{\mathrm{eff}}$ and they act as a good seed layer for the AlN growth.

RF BAW resonators are categorized into two types.