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Graphene as an active virtually massless top electrode for RF solidly mounted bulk acoustic wave (SMR-BAW) resonators

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Abstract
Mechanical and electrical losses induced by an electrode material greatly influence the performance of bulk acoustic wave (BAW) resonators. Graphene as a conducting and virtually massless 2D material is a suitable candidate as an alternative electrode material for BAW resonators which reduces electrode induced mechanical losses. In this publication we show that graphene acts as an active top electrode for solidly mounted BAW resonators (BAW-SMR) at 2.1 GHz resonance frequency. Due to a strong decrease of mass loading and its remarkable electronic properties, graphene demonstrates its ability as an ultrathin conductive layer. In our experiments we used an optimized graphene wet transfer on aluminum nitride-based solidly mounted resonator devices. We achieved more than a triplication of the resonator’s quality factor \(Q\) and a resonance frequency close to an ‘unloaded’ resonator without metallization. Our results reveal the direct influence of both, the graphene quality and the graphene contacting via metal structures, on the performance characteristic of a BAW resonator. These findings clearly show the potential of graphene in minimizing mechanical losses due to its virtually massless character. Moreover, they highlight the advantages of graphene and other 2D conductive materials for alternative electrodes in electroacoustic resonators for radio frequency applications.

Keywords: graphene, massless electrode, aluminum nitride, bulk acoustic wave, piezoelectric

(Some figures may appear in colour only in the online journal)

Introduction

Bulk acoustic wave (BAW) resonators have gained more and more attraction as key building blocks for radio frequency (RF) filters as used in wireless communication devices [1]. The rapid increase of data transfer rates requires RF filters to be more and more efficient regarding energy conversion and accurate signal handling.

Generally, a BAW resonator consists of a piezoelectric thin film material. A standing acoustic wave in the bulk of the thin film is exited via an AC input signal from a top and a bottom electrode (BE) [2]. The obtained resonance frequency directly depends on the thickness and sound velocity of the piezoelectric layer. An excellent performance characteristic, which is usually specified by the quality factor \(Q\) and the coupling coefficient \(k_{\text{eff}}\) [3], requires a strong interplay between the device design and the material quality. The main goal in device optimizations concerns the reduction of energy loss mechanisms, mostly regarding the energy dissipation within the active material. Recent research activities have brought into focus the minimization of mechanical losses [4],
spurious mode suppression and the investigation of electrical losses within the active material and the electrodes [5–7].

Losses in the piezoelectric layer and the electrodes significantly influence the conversion of electrical and mechanical energy and act as an additional viscous damping of the device system. In this publication, we focus on the influence of the electrode material on the resonator performance.

As far as mechanical losses are concerned, decreasing the mass-load by making the electrodes thinner is beneficial. According to the Fuchs–Sondheimer model, however, commonly used metal electrode materials show an incremental degradation in conductivity with decreasing thickness due to dominating surface scattering effects [8]. Moreover, a structural integrity is often not preserved in extremely thin films. As a consequence of this, typical electrodes cannot be made arbitrarily thin. The use of light and conductive electrode materials can tackle these challenges. At this point, atomically thin graphene comes into play. With the evolution of large-area chemical vapor deposition (CVD) techniques for graphene deposition [9, 10], Qian et al already showed the possibility of using graphene as a virtually massless passive top electrode for NEMS devices [11, 12]. In their work, graphene acts as a floating potential compensation by confining the RF field of the resonator, due to its passive use electrical properties do not play a decisive role. Additionally, graphene’s massless character and its high mechanical stability [13] lead to promising findings in the field of microtechnologies [14, 15], using graphene as a replacement for metallic membranes.

However, in this work, we also consider the electrical properties of graphene [16]. In extension to previous work [17], we investigated the influence of vanishing electrode mass on the resonator device performance by employing graphene as an active electrode material for resonator devices. This is theoretically already described by Schmidhammer et al [18]. Considering the challenge of reducing the metal/graphene contact resistivity, which was already elaborated on in other publications [19, 20], the focus of this work is the investigation of the impact of the graphene quality and the metallization design on the BAW resonator performance.

CVD graphene was transferred with an optimized wet transfer technique [21] onto solidly mounted bulk acoustic wave resonators (BAW-SMR) with aluminum nitride (AlN) as the active piezoelectric layer. The electrode design was specifically developed for an in-depth investigation of the electrode-induced change in the performance characteristic of the resonator devices. By using the modified Butterworth–Van Dyke (mBVD) equivalent circuit model [22], we found that graphene works in principle as an ‘ideal active electrode material’ for BAW-SMR devices in the RF domain (resonance frequency \(f_R \approx 2.1 \text{ GHz}\)) and leads to a significant shift in \(f_R\) compared to Ti/Au metallization, which we used as a reference. Furthermore, we obtained almost tripled quality factors at anti-resonance for graphene as the top electrode, which clearly shows the potential of graphene in minimizing mechanical losses.

**Theoretically expected effect of reduced mechanical losses**

Basically, a thin film bulk acoustic resonator (FBAR) consists of an active, piezoelectric thin film material (AlN or zinc oxide are commonly used), where an acoustic standing wave in the bulk of the thin film is excited electrically via an AC signal, and conducting top and BEs [2]. The resonance frequency \(f_n\) is given as

\[
 f_n = \frac{vn}{2t},
\]

with the thickness of the resonator \(t\), an integer multiple \(n\) of half the acoustic wavelength and the material specific sound velocity \(v\) [22, 23]. Equation (1) describes a standing wave resonance frequency whose acoustic energy is mainly stored in the thickness extensional mode TE1 within the piezoelectric layer. There are two competitive device concept designs to couple the standing wave effectively: FBAR and SMR. Both design concepts take into account the essential acoustic isolation. The SMR approach is considered as being more robust [24] and was first described in 1965 and continuously enhanced [25, 26]. For our work the SMR approach is the more suitable one, since its bottom-up design strongly facilitates the fabrication and characterization methods regarding the graphene wet transfer and subsequent metallization processes. A schematic illustration of the used SMR design is shown in figure 1(a).

The AC signal is applied on top of the device via the ground (G) and signal (S) electrodes. The acoustic wave is...
established with the passive BE via a capacitive coupling. The BE has a floating potential and sustains the electric field. A subjacent BR structure, a stack of several layers with highly different acoustic impedances, ensures the coupling of the wave within the piezo-active layer. The whole layer stack is deposited on a silicon substrate (Si).

Due to different loss mechanisms, the device design, material properties of the piezo layer and the electrodes significantly influence the performance of the resonator regarding the resonance frequency, the quality factor $Q$ and the coupling coefficient $k_{eff}$ as performance indicators [17]. $Q$ is defined as

$$Q = \frac{\text{Energy stored (peak)}}{\text{Energy lost per cycle}} = \frac{\omega}{2} \left| \frac{\text{d} \Phi}{\text{d} \omega} \right|_{\omega_0}. \quad (2)$$

The group delay $|\text{d} \Phi/\text{d} \omega|_{\omega_0}$ describes the rate of the total phase change with respect to the frequency $\omega$. In general, the electrical properties of a BAW resonator can be modeled with the mBVD equivalent circuit model [22, 27–29]. $L_m$, $C_m$ and $R_m$ describe the mechanical branch of the resonator, where $R_m$ is the mechanical loss within the piezoelectric material; $C_0$ is the resonator’s plate capacitance formed by the geometry of the piezo layer between the top and BEs, which is given by

$$C_0 = \frac{A \varepsilon_0 \varepsilon_r}{t}, \quad (3)$$

with the vacuum and relative permittivity $\varepsilon_0$ and $\varepsilon_r$, respectively.

Dielectric losses are represented by a resistor $R_p$. The electrode-induced losses are represented by additional resistivities (figure 1(b)). The resistor $R_e$ stands for ohmic losses due to a certain series resistivity of the electrode, $R_p$ represents the viscous losses due to a non-zero electrode mass which leads to acoustic wave attenuations. The mBVD equivalent circuit describes a series ($\omega_s$) and a parallel resonance ($\omega_p$) behavior, also called a resonance/anti-resonance characteristic. Given these circuit parameters, the corresponding resonance frequencies are approximately (neglecting any losses) obtained by

$$\omega_s = \frac{1}{\sqrt{L_mC_m}}, \quad (4)$$

$$\omega_p = \frac{1}{\sqrt{L_mC_m \left(1 + \frac{C_m}{C_0}\right)}}, \quad (5)$$

In a simplified equivalent circuit, excluding $R_m$ and $R_0$, mechanical damping losses due to the piezoelectric material are included by $R_p$, and the quality factors $Q_s$ (resonance) and $Q_p$ (anti-resonance) directly depend on $R_s$ and $R_p$ and can be approximated by

$$Q_s = \frac{1}{R_s \sqrt{L_mC_m}}, \quad (6)$$

$$Q_p = \omega_p R_p \frac{C_m + C_0}{C_m C_0}. \quad (7)$$

Figure 2 shows simulations of one-port devices employing the mBVD equivalent circuit model and the actual dependence of the theoretical admittance curves on the different resistivity parameters. The figure also illustrates the primary effects on amplitude and width of the resonance peaks. While $R_s$ and $R_p$ just affect the resonance and anti-resonance peak, respectively, the piezo-material induced mechanical attenuation $R_m$ influences both resonances and therefore plays also an eminent role in the resonator’s performance.

$R_m$ affects both $Q_s$ and $Q_p$, which is not described in the strongly simplified equations (6) and (7). Therefore a precise separation of electrode and piezo-material induced loss effects onto the two quality factors is not possible. However, regarding electrode designs providing different combinations of metal/graphene contacts, this separation is particularly important for our work. Therefore, a determination of $Q$ according to equation (2) is preferred for this work, using group delay data obtained from one-port $S_{11}$ measurements.

Following the equations (6) and (7), the quality factors can be increased by a reduction of $R_s$ and an increase of $R_p$ of the electrode material. This can be achieved with thin (high $R_m$) and conducting (low $R_p$) materials. Conventional metals such as titanium (Ti) and gold (Au) show increasing sheet resistivity with decreasing layer thickness (Fuchs–Sondheimer model [8], schematically shown in figure 3(a)), thus the use of these materials cannot tackle these loss problems. In order to get an impression of the thickness dependent resistivity, a thickness variation of aluminum (Al) thin films on Si were fabricated and electrically measured. At a thickness of 100 nm, the Al sheet resistivity is in the range of 0.5–2.0 $\Omega$/sq. and also corresponds with other conventionally used electrode metals, i.e., Ni or Ti/Au. A thickness reduction down to 10 nm results in an increased resistivity >150 $\Omega$/sq. (as marked in blue in figure 3). This finding clearly confirms the Fuchs–Sondheimer model experimentally. Additionally, since a further reduction of the metal thickness is limited from a technological point of view, other materials with the desired properties need to be investigated. As a promising alternative we show that graphene is a suitable candidate as a novel conducting and virtually massless electrode material, which can realize both high $R_p$ and low $R_s$.

**Experimental procedure**

Graphene monolayers were grown by CVD, a mature and commonly applied technique for graphene synthesis [10], on 40 × 40 cm$^2$ copper (Cu) foil (25 µm thickness, 99.8% purity, Alfa Aesar, Haverhill, MA, USA) used as a catalytic metal substrate in a cold wall low-pressure reactor (Black-Magic Pro, Aixtron, Herzogenrath, Germany) using methane and hydrogen as precursor and carrier gas, respectively (flow ratio CH$_4$/H$_2$ = 25%, 1600 Pa, 980 °C, 30 min deposition time). The grown graphene layers were routinely investigated by Raman spectroscopy (InVia Raman microscope, 532 nm excitation laser, grating 1800 lines mm$^{-1}$, Renishaw, Gloucestershire, UK) in order to ensure the existence of monolayers [30]. The graphene monolayers were transferred on 3
inch AlN SMR wafers by applying an optimized wet transfer process developed by our group [21]. The sequence of fabrication steps is summarized in figure 3(c). Transferred graphene was again characterized via Raman spectroscopy (figure 3(b), line scan, 1 μm spacing, 121 measurement points, AlN background correction). The 2D/G peak intensity ratio reproducibly lays around 2.6 and the D peak intensity almost vanishes. This indicates the existence of mostly monolayer graphene on the piezo active AlN layer [31, 32].

Figure 2. Simulated admittance curves in dependence of the three resistivities $R_m$, $R_s$ and $R_p$. Resonance and anti-resonance frequencies are depicted in dashed lines.

Figure 3. (a) Schematic comparison of the specific sheet resistivity $\rho$ of graphene (red) with conventional metal electrode materials according to the Fuchs–Sondheimer model. For small film thickness the sheet resistivity of graphene can outperform any metal. Stated resistivity value (blue) corresponds to a 10 nm thick AlN film for comparison. (b) Raman spectroscopy image of graphene on AlN (line scan, average of 121 measurement points with 1 μm spacing). (c) Fabrication procedure from graphene CVD growth to graphene wet transfer onto AlN-SMR devices.

In order to fully understand the effect of graphene, investigations regarding both the graphene quality and the overlying graphene metallization were carried out. Three different metallization structures for the top electrode were investigated for this purpose (figure 5). The reference (state-of-the-art) was formed by a Ti/Au pad (10 nm/100 nm thickness) as depicted in the left picture of figure 5. The Ti/Au pad was also used to contact the pure graphene layer (central picture) and to contact the additional Ti/Au E-shaped bar structure (15 μm bar thickness) in order to improve the contact situation as shown in the right picture. The metal contacts were deposited via electron-beam evaporation (EBPVD, LAB700, Bühler AG, Uzwil, Switzerland) in a
pattern shown in figure 6. With this design setup, 576 resonators could be fabricated on each wafer. The number of relevant graphene based resonators was reduced to approx. 300 working devices due to the limited graphene wet transfer size of $40 \times 40 \text{mm}^2$, which results in nearly 20 devices for each design and quality variation and therefore enables a good statistic evaluation.

In order to investigate the effect of the graphene quality on the resonator performance we synthesized graphene with different sheet resistivities $R_{GR}$. As stated in figure 3(a), our
optimized transfer process offers graphene with $R_{GR}$ down to 350 $\Omega$ sq., due to process stability criteria and statistics we focused on graphene with $R_{GR}$ of 1–4 $k\Omega$ sq. $R_{GR}$ is directly influenced by the quality of the graphene monolayer. Both varying growth conditions and cracks/strain arising during the transfer directly affect the crystalline structure of adjacent graphene flakes in the layer and result in different conductivity values [33]. In order to ensure a clear physical separation between signal (GR) and ground (Ti/Au) electrode, the graphene layer of each device was isolated via laser treatment.

The fabricated one-port devices were electrically measured in a micromanipulator probe station (Summit10000, Cascade Microtech, Beaverton, Oregon, USA) and $S_{11}$ parameters were extracted using GSG measurement probes (Cascade Microtech). The conversion into admittance values was done with a network analyzer (NWA) (Agilent E5061B, Agilent technologies). The obtained admittance curves were fitted with a non-commercial software developed in-house (LARA 10, [34]). For the fitting routine the mentioned mBVD (figure 1(b)) equivalent circuit model was used to determine all relevant fit parameters. Furthermore, two-dimensional finite element method (FEM, COMSOL Multiphysics 5.3, COMSOL AB, Stockholm, Sweden) simulations were performed to obtain the corresponding resonance frequency. The corresponding quality factors were obtained from group delay measurements according to equation (2).

Results and discussion

Figure 7(a) shows an exemplary admittance plot which was obtained via NWA measurements (1.2–2.7 GHz). The Ti/Au reference (red), Ti/Au pad (blue) and a 15 $\mu$m bar structure (black) are shown. A significant frequency shift from 1.74 to 2.12 GHz already reveals a strong decrease of electrode damping due to a mass reduction of 0.037% $m_{Ti/Au}$. Two-dimensional FEM simulations show that the damped SMR Ti/Au top electrode structure and the undamped case with no top electrode exhibit a $\omega_q$–$\omega_p$ resonance behavior at 1.75 GHz and 2.14 GHz, respectively (dashed lines).

Comparing the resonance peaks for Ti/Au (red curve) and the Ti/Au E-shaped bar structure (black), the peak height is slightly reduced due to higher $R_{GR}$ compared to $R_{Ti/Au}$. However, the peak width and amplitude at anti-resonance is observably sharper for the Ti/Au bar structure electrode. These findings directly reinforce the virtually massless character of graphene and indicate its influence on the electric characteristic of the resonator device (compare to figure 2). Using the equivalent circuit as shown in figure 1(b) the equivalent circuit parameters of each electrode configuration can be estimated. An exemplary fit is shown in figure 7(b) and reveals the aforementioned high accuracy of the simulation model with a fit divergence of only 1%–3%. For the SMR devices with Ti/Au pad contacting the graphene based electrode (blue curve) as the top electrode, a strong admittance shift is observable. According to the mBVD model and the applied fits this originates from a significantly lower plate capacitance $C_0$, which indicates a significant reduction of the total resonating area. Furthermore, it is noteworthy that for both the Ti/Au pad (blue line) and the Ti/Au bar structure (red) a small resonance curve at 1.74 GHz coexists, as in the case of full Ti/Au metallization. Our experiments show how this additional resonance can be influenced and minimized.

Influence of graphene quality

In a first examination the changed resonance performance for differently synthesized CVD graphene, which was transferred onto SMR devices, having sheet resistivities $R_{GR}$ of 1 ($\pm$0.2), 1.8 and 4 $k\Omega$ sq., was investigated. In figures 8(a) and (b) the fitted resistivity values $R_p$, $R_s$ and $R_m$ are depicted ($R_0 = 0$). Two explicit trends are directly visible. The parallel resistivity $R_p$ (black square, figure 8(a)) continuously increases for decreasing sheet resistivity, whereas $R_s$ (figure 8(b), blue squares) and $R_m$ (figure 8(b), red circles) decrease from 13.5 $\Omega$ to 4.4 $\Omega$ and from 8.7 $\Omega$ to 0.4 $\Omega$, respectively. These
effects directly support our theoretical assumptions. $R_s$ represents the ohmic losses of the electrodes, which will be reduced with decreasing graphene sheet resistivity. Keeping in mind that the AC signal is applied on the metal bar structure, which contacts the graphene electrode, $R_{GR}$ directly determines the voltage drop along the graphene layer. Lower $R_s$ results in a more shallow voltage drop and therefore in a larger resonating area. This theoretical principle can directly be verified by comparing the obtained plate capacitance $C_0$ (table 1), which corresponds to the actual resonating area (equation (3)). $C_0$ strongly increases from 18.2 ± 2.2 nF (for $R_{GR} = 4$ kΩ/sq) to 41.3 ± 1.3 nF ($R_{GR} = 1$ kΩ/sq) for the bar structure electrode design. With the assumption of $\varepsilon_r \approx 9.8$, valid at TE1 mode [35], this results in an increase of the resonating area from approximately 3.4 × 107–7.8 × 108 μm². Thus, the metal/graphene coverage ratio decreases, resulting in a lower piezoelectric damping in the 1.7 GHz region. This explains the rapid drop in $R_m$ since the mechanical damping of the Ti/Au-AlN resonating system loses ground for higher graphene conductivity. Concurrently, a better graphene quality even raises $R_p$ from 2856 to 3216 Ω. This might result from the fact that the fit divergence is reduced for lower graphene sheet resistivity due to a more homogeneous crack-free graphene layer and therefore a more accurate admittance slope. Compared to conventional Ti/Au top electrodes these values are already located at a high level, indicating a reduction of electrode induced damping (see reference values for full Ti/Au metallization in table 2).

With the obtained group delay data the corresponding quality factors $Q_s$ and $Q_p$ were calculated (figure 8c). The slight increase in $Q_s$ (167–234) arises from decreasing $R_m$ and $R_s$, whereas the almost doubled $Q_p$ (236–449) for graphene with Ti/Au bar structure is mainly caused by the strong reduction in $R_m$.

There is also an observable change in the coupling coefficient $k_{eff}^2$, which is a measure of the conversion efficiency between the electrical and mechanical energy [36]. $k_{eff}^2$ slightly rises from 2.43% for graphene with 4 kΩ/sq. sheet resistivity to 3.02% for graphene with 1 kΩ/sq. sheet resistivity, as expected due to better energy conversion and less heating losses (compare to $k_{eff}^2$, Ti/Au = 5.14%).

In summary, these results show the influence of the graphene quality regarding its electrical characteristics. A higher conductivity of graphene leads to a reduction of electrode induced ohmic losses, which directly affect $Q_s$ and $k_{eff}^2$.

In a next step a direct comparison with conventional top electrodes was performed.

**Influence of metallization design**

In our main experiment, a graphene based top electrode is directly compared to a conventionally used Ti/Au metallization. In order to obtain a more in-depth evaluation, the metal electrode design is contrasted with a Ti/Au pad on

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**Table 1.** Comparison of extracted fit parameters for resonators with the bar structure electrode design (figure 5, right picture) extracted and calculated from an equivalent circuit (mBVD) fit for different graphene quality regarding the sheet resistivity $R_{GR}$. The quality factors are calculated from obtained group delay data. Ti/Au is the reference sample with full metallization.

| $R_{GR}$ (kΩ/sq.) | $f_r$ (GHz) | $f_p$ (GHz) | $C_0$ ($\times 10^{-9}$ nF) | $R_m$ (Ω) | $R_s$ (Ω) | $R_p$ (Ω) | $k_{eff}^2$ (%) | $Q_s$ | $Q_p$ |
|------------------|-----------|-----------|-----------------------------|----------|----------|----------|---------------|------|------|
| 4                | 2.11      | 2.13      | 18.2 ± 2.2                  | 8.70 ± 4.75 | 13.54 ± 3.01 | 2856 ± 195 | 2.43 ± 0.23 | 167 ± 10 | 236 ± 37 |
| 1.8              | 2.09      | 2.13      | 39.7 ± 1.9                  | 1.28 ± 0.37 | 5.18 ± 0.34 | 2942 ± 161 | 2.87 ± 0.13 | 181 ± 11 | 334 ± 40 |
| 1                | 2.10      | 2.13      | 41.3 ± 1.3                  | 0.42 ± 0.21 | 4.43 ± 0.44 | 3216 ± 366 | 3.02 ± 0.11 | 234 ± 9 | 449 ± 18 |
graphene, a Ti/Au bar structure on graphene and a graphene contacting without any additional metallization. Pristine graphene as a top electrode serves as a reference regarding mechanical damping mechanisms, which is visible in the obtained fit parameters in figure 9 (pure GR). In this case, the highest $R_p = 3387 \pm 542 \Omega$, e.g. the lowest top electrode induced damping, is achieved. The corresponding $Q_p$ reaches 761 ± 55, which represents an almost undamped system, ignoring the slight damping caused by the measuring probe. Certainly, the associated $R_s$ exhibits its maximum at 142.67 ± 57.92 Ω. This results from poor graphene contacting if no additional metal contact is applied [15, 16]. A metal pad contacting of graphene reduces $R_s$ to 21.64 Ω, whereas electrode induced ($R_m$) and piezoelectric damping ($R_m$) increases. While the metal pad design ensures proper contacting of the graphene, the effect of an additional resonance at 1.74 GHz strongly affects the resonator performance. It is obvious from our results that a metal bar structure (15 μm bar thickness) improves both the top electrode and the piezoelectric damping significantly, as shown in table 2. Furthermore, a bar structure is able to increase the total resonance area, which cannot be obtained by a metal pad, as shown by the extracted capacitance values $C_0$. Again, the metallization design primarily bears on the coupling coefficient. The bar structure design ensures a comparably high resonating area where no additional damping inhibits the energy conversion. $k_{eff}$ is therefore increased from 2.24% (pure graphene) to 3.02% (Ti/Au bars). These values are still lower than in the case of conventional Ti/Au metallization (5.14%), which arises from the still high graphene sheet resistivity of 1 kΩ/sq.

### Table 2. Comparison of resonator parameters extracted and calculated from an equivalent circuit (mBVD) fit for different top electrode structures.

|        | $f_1$ (GHz) | $f_0$ (GHz) | $C_0$ ($\times 10^{-4}$ nF) | $R_m$ (Ω) | $R_s$ (Ω) | $R_p$ (Ω) | $k_{eff}^2$ (%) | $Q_s$ | $Q_p$ |
|--------|-------------|-------------|-----------------------------|------------|------------|------------|----------------|--------|--------|
| Ti/Au  | 1.71        | 1.76        | 23.9 ± 0.7                  | 1.75 ± 0.22| 1.34 ± 0.34| 1108 ± 244 | 5.14 ± 0.08    | 450 ± 9 | 248 ± 83|
| Ti/Au pad | 2.10        | 2.13        | 3.4 ± 0.1                   | 25.09 ± 4.77| 21.64 ± 4.36| 1431 ± 292 | 2.55 ± 0.15    | 353 ± 23| 154 ± 5 |
| Ti/Au bars | 2.10        | 2.13        | 41.3 ± 1.3                  | 0.42 ± 0.21| 4.43 ± 0.44| 3217 ± 367 | 3.02 ± 0.11    | 234 ± 9 | 449 ± 18|
| Pure GR | 2.12        | 2.14        | 2.3 ± 0.5                   | 21.2 ± 0.87| 142.67 ± 5.79| 3387 ± 352 | 2.24 ± 0.40    | 185 ± 19| 761 ± 55|

**Figure 9.** (a), (b) Comparison of the fitted parameters $R_m$, $R_s$ and $R_m$ according to the equivalent circuit model (mBVD) for different metal/graphene structures. Graphene sheet resistivity is uniformly constant for each measured resonator at 1 kΩ/sq. (c) Corresponding quality factor calculated with equation (2) from obtained group delay data.

### Conclusion and outlook

In summary, our experiments show the successful functioning of graphene as a top electrode for SMR-BAW devices in the 2 GHz region and our obtained data confirm the theoretical hypothesis that monolayer graphene electrodes can reduce mechanical losses in electroacoustic resonators. An almost tripling of the $Q$ factor of the anti-resonance was reached for a graphene top electrode compared to a conventional Ti/Au metallization.

We obtained a clear shift in resonance frequency from 1.74 to 2.12 GHz and distinct improvements in both resistivity parameters and quality factors, as expected from a reduction in mass loading. Furthermore, we have found that the metal contact design directly influences the ratio of the metal free graphene contact area and the metallized area. Keeping the metallized area as small as possible, the damping effects from metal contacts can considerably be reduced. Additionally, this reduction can be obtained by an improved metallization design. Therefore, we investigated an E-shaped bar structure design. The electrical measurements distinctly revealed a performance improvement. The bar structure design, which increases the total metal edge length to the graphene layer, is able to contact a larger area of the graphene, resulting in lower contact resistivity and an increasing $Q$ factor at anti-resonance.

Generally, the combination of graphene quality and an improved metal bar structure design is a key for the design of high performance SMR-BAW devices in the RF domain.
These findings are the main results for future investigations about graphene as an electrode material.

Further improvements can be achieved in two core areas. On the one hand, further progress in the field of optimizing the graphene quality, regarding synthesis and transfer onto the target substrate, is inevitable. In this regard, promising research topics are to be found in doping and chemical functionalization of graphene, since there is still a wide gap to the achieved conductivity of graphene so far compared to conventional metal contacts with sheet resistivities around $1–2 \Omega/\text{sq}$. Further graphene quality investigations can also overcome the issue with the still too low coupling coefficient. On the other hand, continuous optimization of the contacting design for graphene electrodes needs to be carried out. Further decrease in the metal/graphene area ratio with a concurrent increase of metallized graphene edges might be a promising answer to these problems.

In this work we showed that this field of research covers both the basics in graphene growth and the following engineering process. Our results reveal the potential of graphene as an alternative material for electrodes of resonator devices, whenever mechanical losses play a critical role and should be reduced to a minimum.

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