GRAPHENE AS VIRTUALLY MASSLESS TOP ELECTRODE FOR RF BULK ACOUSTIC WAVE (BAW) RESONATORS

Marius Knapp\textsuperscript{1}, V. Cimalla\textsuperscript{1}, D. Schwantuschke\textsuperscript{1}, V. Lebedev\textsuperscript{1}, O. Ambacher\textsuperscript{2}, R. Hoffmann\textsuperscript{1}

\textsuperscript{1} Fraunhofer Institute for Applied Solid State Physics IAF, Tullastraße 72, 79106 Freiburg, Germany
\textsuperscript{2} Department of Microsystems Engineering– IMTEK, University of Freiburg, Germany
Motivation

- BAW resonators are key-building blocks for radio frequency (RF) filters used in wireless communication devices (e.g. smartphones)

Source: Oleksiy mark - Fotolia
Bulk acoustic wave (BAW) resonator

- Top electrode
- Piezoelectric material
- Bottom electrode
- Gate electrode
- Source electrode
- Floating potential electrode
- Bragg reflector
- Si substrate
- AIN

Solidly mounted resonator (SMR)
Bulk acoustic wave (BAW) resonator

- Frequency $\omega_s$
- Frequency $\omega_p$
- Floating potential electrode
- Bragg reflector
- AIN
- Si substrate

BAW-SMR

|Y| Frequency

passband

Graphene Flagship
**Bulk acoustic wave (BAW) resonator**

\[
\omega_s = \frac{1}{\sqrt{L_1 C_1}}
\]

\[
\omega_p = \frac{1}{\sqrt{L_1 C_1}} \sqrt{1 + \frac{C_1}{C_0}}
\]

---

**Equivalent circuit (BvD)**

C₀: total plate capacitance  
L₁, C₁: mechanical resonator branch

---

**BAW-SMR**

- **AIN**: Active layer
- **Si substrate**: Silicon substrate
- **Floating potential electrode**: Electrode that is not connected to any terminal
- **Bragg reflector**: Layer that reflects the acoustic wave back into the resonator
Electrode induced electrical and mechanical losses in BAW resonators

- Parallel resistor $R_p$ represents viscous and dielectric losses (non-zero electrode mass)
- Serial resistor $R_s$ represents ohmic losses (non-zero electrode resistance)

**Q factor as main resonator characteristic**

\[
Q_s = \frac{1}{R_s} \sqrt{\frac{L_1}{C_1}}
\]

\[
Q_p = \omega_p R_p \frac{C_1 + C_0}{C_1} C_0
\]
Influence of $R_s$ and $R_p$ on admittance curves

- Resonance peak sharpness indicates Q factor
- Q strongly depends on losses

*Idea:* thin conductive electrodes to reduce viscous losses
Graphene as massless electrode – Fuchs-Sondheimer model

- Fuchs-Sondheimer model

\[ \rho_{ges} = \rho_{bulk} + \rho_{SS}, \quad \rho_{SS} \sim \left( 1 + \frac{1}{d \cdot \ln \frac{1}{d}} \right) \cdot \rho_{bulk} \]
Graphene as massless electrode – Fuchs-Sondheimer model

- Fuchs-Sondheimer model
  \[ \rho_{ges} = \rho_{bulk} + \rho_{SS}, \rho_{SS} \sim \left(1 + \frac{1}{d \cdot \ln\frac{d}{d'}}\right) \cdot \rho_{bulk} \]

- Graphene is virtually massless, still conductive

□ Reduction of viscous losses!

Replacement of conventional metal electrodes (Ti/Au) with graphene
Process development – Graphene growth and transfer

- Cu foil
- Graphene
- Cu foil
- PMMA
- Graphene
- Cu foil
- PMMA
- Graphene
- AlN
- Graphene
- AlN

**Standard CVD process**
- Aixtron BlackMagic CVD reactor
- Methane as precursor, H₂ as carrier gas
- Cu foil as catalytic substrate

Raman spectrum - Graphene on Cu foil
- 2D/G ratio > 2.5
- D/G < 0.15

Intensity (arb. un.)

Raman shift (cm⁻¹)

1200 1600 2000 2400 2800
Process development – Graphene growth and transfer

- Cu foil
- Graphene
- Cu foil
- PMMA
- Graphene
- Cu foil
- PMMA
- Graphene
- PMMA
- AlN
- Graphene
- AlN

Cufoil etching in APS

- Graphene wet transfer process
  - Poly (methyl methacrylate) (PMMA) as protection layer
  - Cu foil etching in Ammonium persulfate (APS)
Process development – Graphene growth and transfer

- Sheet resistance of graphene on AlN via 4-point-measurement:

<table>
<thead>
<tr>
<th>Area</th>
<th>Sheet Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 x 40 mm²</td>
<td>Reproducable $R_S &lt; 2kΩ$</td>
</tr>
<tr>
<td>40 x 40 mm²</td>
<td>Best $R_S \approx 350Ω$</td>
</tr>
<tr>
<td>15 x 10 mm²</td>
<td>Best $R_S \approx 280Ω$</td>
</tr>
</tbody>
</table>
BAW-SMR device design

Mass reduction:

\[ m_{Gr} = 0.00037 \frac{m_{Ti/Au}}{A_{resonator\ area}} \]

resonator area: 200x200µm²

Graphene electrode (Source)

Floating potential electrode

Bragg reflector

Si substrate

BAW-SMR
Electrical characterization – network analyser measurements

Admittance $|Y_{11}|$ (dB)

Frequency (GHz)

-70
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70

1.4
1.6
1.8
2.0
2.2
2.4
2.6

Ti/Au
Graphene
Electrical characterization – network analyser measurements

![Graph showing admittance vs. frequency for Ti/Au and Graphene.](image)

- $f_{\text{Ti/Au}} = 1.75\text{GHz}$
- $f_{\text{Graphene}} = 2.12\text{GHz}$

Admittance $|Y_{11}|$ (dB) vs. Frequency (GHz)

- Ti/Au
- Graphene

Frequency shift

- Frequency shift from 1.75 GHz to 2.12 GHz
Electrical characterization – network analyser measurements

| Admittance \[|Y_{11}|\] (dB) | Frequency (GHz) |
|-----------------------------|-----------------|
| -10                         | 1.4             |
| -20                         | 1.6             |
| -30                         | 1.8             |
| -40                         | 2.0             |
| -50                         | 2.2             |
| -60                         | 2.4             |
| -70                         | 2.6             |

- \[f_{\text{Ti/Au}} = 1.75\text{GHz}\]
- \[f_{\text{Graphene}} = 2.12\text{GHz}\]

Ti/Au
Graphene

Frequency shift
Electrical characterization – network analyser measurements

- Frequency shift: $f_{\text{Ti/Au}} = 1.75\text{GHz}$, $f_{\text{Graphene}} = 2.12\text{GHz}$
- Admittance $|Y_{11}|$ (dB)
- Frequency shift: $f_{\text{AlN}}$
- Base admittance decrease from -35 dB to -53 dB (change in $C_0$)
Determination of quality factor via fitting of equivalent circuit parameters

\[ Q_{p,\text{Graphene}} = 1145 \]
\[ Q_{p,\text{Ti/Au}} = 820 \]

Reduction of viscous losses!
Modifying electrode design

Increase of resonating graphene area

Qm thing

C0 (pF)

Metal pad

Metal bars
Summary

- Graphene avoids electrode induced frequency shift due to its virtually massless character.
- Top electrode metal bar design increases resonating area ($C_0$).
- Viscous losses are strongly reduced resulting in a significantly increased Q factor for parallel resonance ($Q_p$).

Outlook

- Further improvements highly probable for graphene with $R_s << 2k\Omega$ regarding $Q_s$ and $Q_p$.
- Graphene doping, Multilayer graphene.
Thank you for your attention!

Thanks to our colleagues at Fraunhofer IAF.

Thanks as well to our project partners, providing us with SMR samples for our graphene research activities.

Project financed by Graphene Flagship.