2011

MICRORESONATOR FILTERS AND FREQUENCY REFERENCES

Sandia National Laboratories

R&D 100

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Product Information

Microresonator Filters and Frequency References

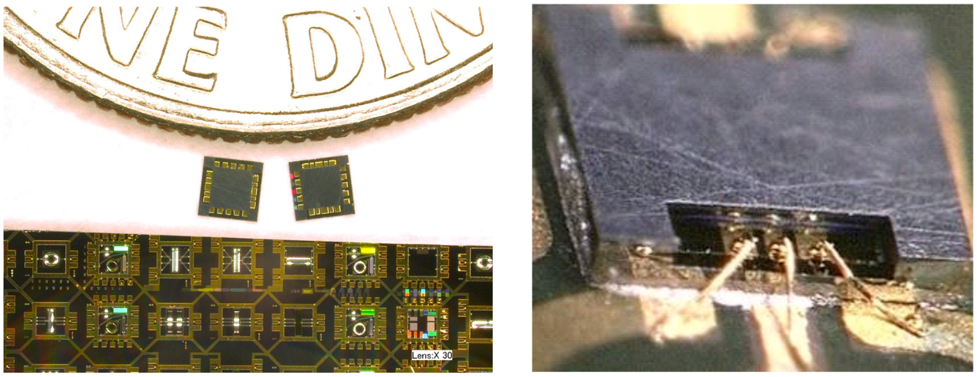

Figure 1. Left: At bottom are microresonators prior to packaging and singulation from the wafer; above them are two packaged microresonator die next to a US dime. Right: Perspective image of a packaged microresonator in next-level assembly.

Brief Description

Our miniature acoustic resonators perform RF filtering and frequency synthesis in next-generation wireless devices—offering higher performance in a smaller package with a lower price.

Product First Marketed

Rockwell Collins, a commercial sponsor of this technology, requested a license for the technology in July of 2010. The technology became fully available for licensing on 17 September 2010.

R&D 100 Awards Entry or Previous Winner

No to both questions.

Principal Investigator

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Product Price

The price of a microresonator filter in low-volume production (<10,000 units) at Sandia National Laboratories' MESA fabrication facility is $7.20 per filter. The price in high-volume production in a commercial facility is expected to be less than $1.00 per filter.

Patents or Patents Pending

J.W. Wittwer and R.H. Olsson III, "Micromechanical resonator and method for fabrication," US Patent Number US 7,616,077 B1, Issued Nov. 10, 2009.

J.W. Wittwer and R.H. Olsson III, "Micromechanical resonator and method for fabrication," US Patent Number US 7,652,547 B1, Issued Jan. 26, 2010.

R.H. Olsson III and Kenneth E. Wojciechowski, "Method for Fabricating a Microelectromechanical Resonator," US Patent Application # 12/884,237, Filed 09/17/2010.

R.H. Olsson III, Kenneth E. Wojciechowski, and Maryam Ziaei-Moayyed, "Microelectromechanical Filter Formed from Parallel-Connected Lattice Networks of Contour-Mode Resonators," US patent Application # 12/884,245, Filed 9/17/10.

Product's Primary Function

Our microresonators are miniature acoustic resonators fabricated using complementary metal-oxide semiconductor (CMOS)-compatible microfabrication techniques. When grouped together, our microresonators operate as filters; they provide frequency selection in radios and other electronic equipment. When connected with transistor electronics, microresonators can provide frequency reference functions (such as clocking) to radios, microprocessors, and other electronic devices.

How It Operates

Microresonators are constructed from a metal/piezoelectric/metal film stack suspended in plate form above a silicon substrate, as shown in Figure 2. When a voltage is applied across the piezoelectric material—for example to the aluminum electrodes that make up Port 1 in the figure—the plate displaces perpendicular to the substrate via the d_{31} piezoelectric coefficient (as opposed to the d_{33} piezoelectric coefficient, which would drive displacements normal to the substrate) and a charge is generated by the strain on the output electrodes (Port 2 in the figure). Thus a microresonator converts RF electrical energy to the acoustic domain for processing before converting it back into the electrical domain. This results in much smaller components at RF frequencies, since the speed of sound is four orders of magnitude slower than the speed of light. When the applied RF voltage is at the frequency of the acoustic resonance in the microresonator plate, the resonator displaces Q times as far (where Q is the resonator quality factor) and produces Q times as much output charge. In this way a microresonator can be used to select or filter an electronic radio frequency. Q is a measure of energy storage and is equal to energy stored divided by energy lost per cycle. The higher the Q, the steeper the filter roll-off will be.

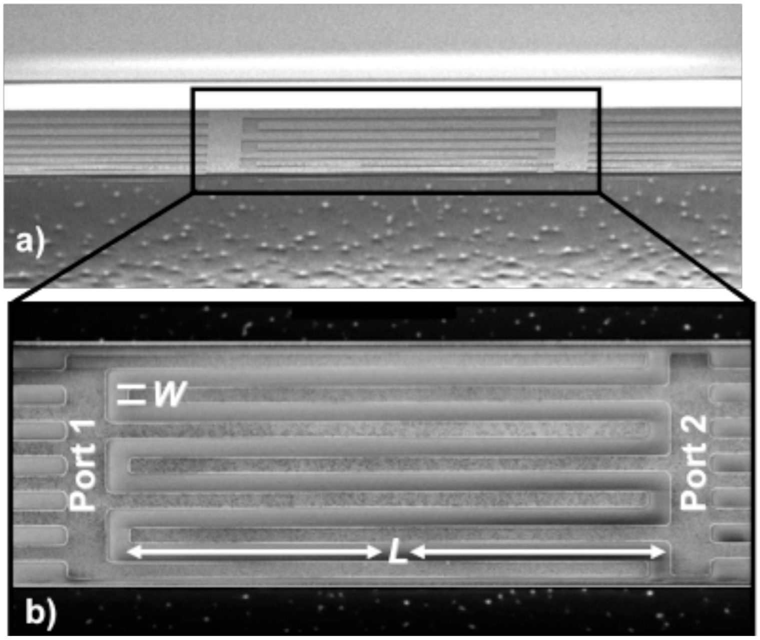

Figure 2. (a) Cross-section scanning electron microscope image of a suspended microresonator plate. (b) Top down view of the plate showing the interdigitated metal electrodes. The electrode width, W, is 4.25 μm and the electrode length, L, is 257 μm.

A cross-sectional image of a typical microresonator vibration mode is shown in Figure 3. The figure shows a finite element analysis of an aluminum nitride microresonator.

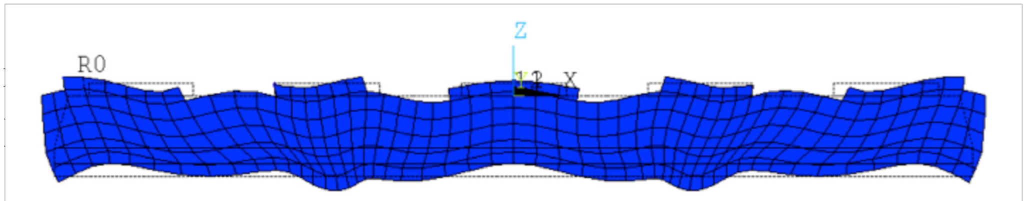

Figure 3. Typical Lame wave vibration mode in a microresonator plate.

> “Microresonators offer greater frequency diversity, smaller size, and superior integration when compared to existing technologies.”

When compared to existing acoustic resonator technologies, microresonators offer several advantages, including greater frequency diversity, smaller size, and superior integration with CMOS transistors. Because the size, and thus the resonant frequency, of the plate in Figure 2 is determined lithographically using computer aided design (CAD) layout, any frequency between 32 kHz and 10 GHz can be formed on a single chip using plates and other vibrating structures such as beams. This frequency range is orders of magnitude wider than existing technologies and is wide enough to include time signals, AM radio, FM radio, cellular phone, Wi-Fi, blue tooth, and military radar and satellite communication bands.

Another advantage of the microresonator is that the acoustic wave propagates perpendicular to the applied electric field. This response is a contrast to other acoustic resonator technologies where the acoustic wave propagates in the direction of the applied electric field. The implications of this effect are that the resonator impedance in a microresonator is proportional to the inverse of the operating frequency, whereas in traditional technologies the resonator impedance is proportional to the inverse of the operating frequency squared. The outcome of this difference in physical properties is that microresonators can be made orders of magnitude smaller than the existing state-of-the-art in the lower frequency ranges of RF communications. In the cellular bands, the sizes of the two technologies are comparable. At super-high frequencies, this scaling law prevents microresonators from becoming too small or having too low of an impedance for proper RF matching.

With next-generation, 3G and 4G, mobile handsets predicted to require in excess of 26 discrete filters in order to accommodate all the different frequency bands, microresonators offer the ability to reduce costs and component numbers by realizing many filters on a single chip, even when their operating frequencies are widely different. Furthermore, the integration of microresonators with CMOS circuits enables additional reductions in part count, assembly costs, and tuning to increase production yields.

Building Blocks

The microresonator is constructed from a silicon dioxide (0.9 µm), aluminum (0.17 µm), aluminum nitride (AlN) (0.75 µm) and aluminum (0.2 µm) film stack. Application of an electric field across the piezoelectric AlN layer causes mechanical displacement.

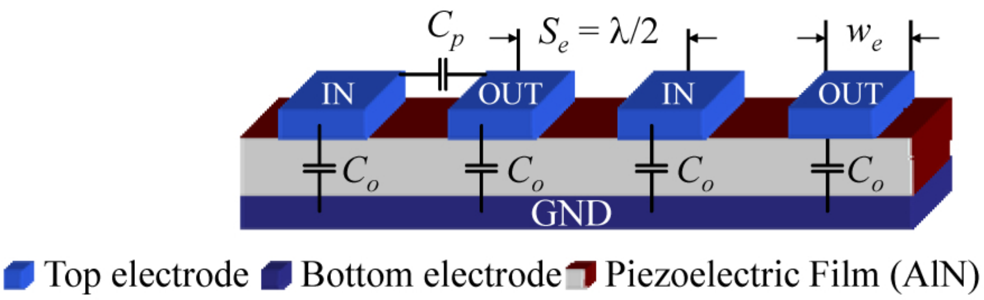

Figure 4: Cross-section of AlN film stack.

Comparison Matrix

There are many competing acoustic filters operating at different frequencies and with varying bandwidths and other performance specifications. Table 1 below lists many of the competing filter models by application and manufacturer. Table 2 directly compares the performance of microresonator filters to existing commercial off the shelf (COTS) filters over a wide range of operating frequencies and applications.

Table 1: Product's Competitors

Manufacturer	Product	Brand name	Model(s)
Triquint	Intermediate Frequency (IF) Surface Acoustic Wave Filter	SAWTECH	854651, 855735, 855736, 855713, 85500, 855659, 854733-1, 855884, 856444, 856691, 856062, 855395, 854833-1, 855049, 855626, 855394, 856706, 856447, 855912, 856234, 855625, 855131, 855780, 855590, 856541, 855068, 855773, 855885, 856445, 856378, 855444, 856151, 855091, 856305, 855377, 855398, 855399, 856464, 856494, 855104, 856534
EPCOS	IF Surface Acoustic Wave Filter	EPCOS	B3891, B4542, B5232, B5014, B3850, B5000, B5045, B3688,
EPCOS	RF 2-in-1 Surface Acoustic Wave Filters	EPCOS	B9200, B9500
Avago	PCS/Cellular/ GPS Quintplexer Bulk Acoustic Wave Filters	Avago	ACFM-7130
Triquint	Bulk Acoustic Wave Filter	Triquint	880369

Table 2: Comparison of microresonator and commercially available filters across the radio frequency communication bands

Product	Company	Center Freq. (MHz)	Bandwidth (MHz)	# of Filters per Chip/ Module	# of Off-Chip Matching Components	Size (mm^2)	Cost
Surface Acoustic Wave (SAW) Filter	Triquint	70	0.31	1/1	6	221.4	$67.95
Microresonator Filter	Sandia	70	0.30	1/1	0	1.7	$7.20
Surface Acoustic Wave (SAW) Filter	RFM	199	0.5	1/1	4	64.6	$8.16
Microresonator Filter	Sandia	199	0.5	1/1	0	1.7	$7.20
Surface Acoustic Wave (SAW) Filter	EPCOS	499.25	2.0	1/1	4	35	$7.15
Microresonator Filter	Sandia	499.25	2	1/1	0	3	$7.20
Surface Acoustic Wave (SAW) Filters	EPCOS	881, 1960	25, 60	2/2	2	5	$1.15
Film Bulk Acoustic Resonator (FBAR/BAW) Filter Module	Avago	837, 882, 1575, 1880, 1960	25, 25, 2, 59, 59	2/5	2	28	$5.64
Microresonator Filter/Oscillator Module	Sandia	0.032, 13, 700 837, 832, 1575, 1880, 1960, 2300, 2500, 3500	3.2x10-6, 1.3x10-3, 20,25, 25, 2, 60, 60, 20, 20, 20	11/11	10	11	$11.00
Bulk Acoustic Wave Filter	Triquint	5775	100	1/1	2	5.2	$192.02
Microresonator Filter	Sandia	5775	100	1/1	2	1.7	$7.20

> “Microresonators will put RF filters on the same track as the other components in the mobile handset industry.”

Improvements over Competitive Products

The mobile handset market is seeing higher levels of electronic integration in components such as power amplifiers, switches, and CMOS electronics. This integration is resulting in additional functionality at lower cost and at smaller size. The only components not following this trend toward higher levels of integration are the RF filters. Meanwhile, filter components are growing in number as consumers desire to have access to more RF bands in a single handset. As a result, RF filters are poised to be both the cost and size driver in next-generation mobile handsets. This is where microresonators will have an impact. Microresonator technology improves on existing RF filtering technologies by allowing for multiple-frequency filters to exist on a single chip that can be integrated directly with CMOS electronics. Such integration will allow additional functionality (i.e., more bands) while reducing part count and cost. Microresonators will put RF filters on the same track as the other components in the fast-growing mobile handset industry.

In addition to application in the RF mobile handset market, microresonator technology offers significant (>100 times) size savings for the intermediate frequency filters used in military applications, which are generally implemented at frequencies below 600 MHz. The reduced size also results in 42 times lower cost as more filters can be fabricated on a wafer.

An example microresonator filter bank design is shown in Figure 5. The 5-channel filter bank exhibits very high performance in terms of insertion loss, and it displays well controlled frequency spacing in an ultra-miniature form factor. Numerous similar filter and filter bank examples demonstrating the advantages of microresonator technology can be found
in our published literature.

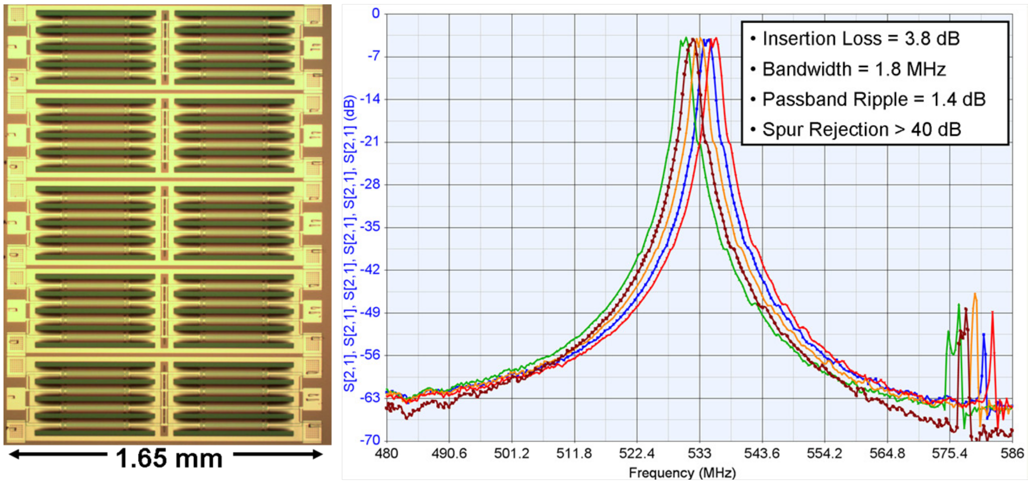

Figure 5. Left: Image of a 5-channel filter array centered at 533 MHz. Right: Measured 5-channel filter bank centered at 533 MHz.

> “Next-generation mobile handsets are expected to require discrete filters. Microresonators will allow many of these filters to be realized on a single chip.”

Product Limitations

The main criticism of microresonator technology is that the maximum bandwidth filters (without inductors) that can be realized are 1.1% of the filter center frequency, compared to competing technologies where the bandwidths as a function of center frequency are typically up to 6%. Although 6% bandwidth is required to select the entire code division multiple access (CDMA) cellular band, no single user occupies this entire bandwidth. Instead, many users occupy this band, and the band is subdivided into channels by lower frequency filters. Microresonators, because they can realize many frequencies on a single chip, provide an opportunity to perform this channel selection at the RF front-end, and they improve overall radio performance by eliminating in-band interferers. If wide bandwidth filters (that is, > 1.1 %) are desired, microresonator technology can realize these filters via the incorporation of inductors, which are readily available in CMOS processes.

Product Use

Principal Applications

The principal application of microresonators is radio frequency filtering. In this application, microresonator technology serves two distinct markets.

1. The first application space is in consumer electronics, namely in mobile communications. With next generation, 3G and 4G, mobile handsets—which are predicted to require in excess of 26 discreet filters in order to accommodate all the different expected frequency bands—microresonators offer the ability to reduce costs and component numbers by realizing many of these filters on a single chip, despite the filters’ widely different operating frequencies.
2. The second application space is in defense or military radios. Military radios require higher performance than consumer wireless handsets. This performance is generally achieved through additional stages of filtering. Many of these additional filters, commonly called intermediate frequency (IF) filters, operate at frequencies where microresonator-based filters are >100 times smaller than the current state-of-the-art. In addition, the microresonator filters often eliminate the need for large external matching networks. The end result is that, when applied to low/moderate volume military applications, microresonator IF filtering reduces part counts from 5 to 1, reduces overall size by >300 times, and reduces costs by a factor of 42.

Other Applications

Microresonator technology is also well suited for realizing oscillators or frequency references. The advantages of microresonator technology when compared to competing oscillator technologies are (1) smaller size, (2) lower power consumption, (3) lower production costs, (4) three orders of magnitude lower power consumption for ovenized oscillators with excellent thermal stability, and (5) lower vibration sensitivity and lower phase noise. AlN microresonator oscillators are poised to replace temperature-compensated quartz crystal oscillators in mobile handsets, defense radios and radars, and digital consumer electronics.

Summary

Microresonators are a miniature acoustic filtering and oscillator technology offering much wider frequency diversity and smaller size when compared to the current state of the art. Microresonators enable many filters in different RF bands to be realized on a single integrated circuit, which can then be integrated with CMOS electronics, overcoming the filter cost and size bottleneck of next-generation mobile handsets. When applied to IF filtering in high performance defense radios and radars, microresonators reduce size and cost compared to current solutions by more than 100 times. Microresonators will enable more functionality at reduced cost and size in consumer wireless products, and they will facilitate miniaturization of radios for US national security.

“Microresonators will enable more functionality at reduced cost and size in consumer wireless products, and they will facilitate miniaturization of radios for US national security.”

Affirmation

By submitting this entry to R&D Magazine you affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

Roy H. Olsson III

Appendix A:

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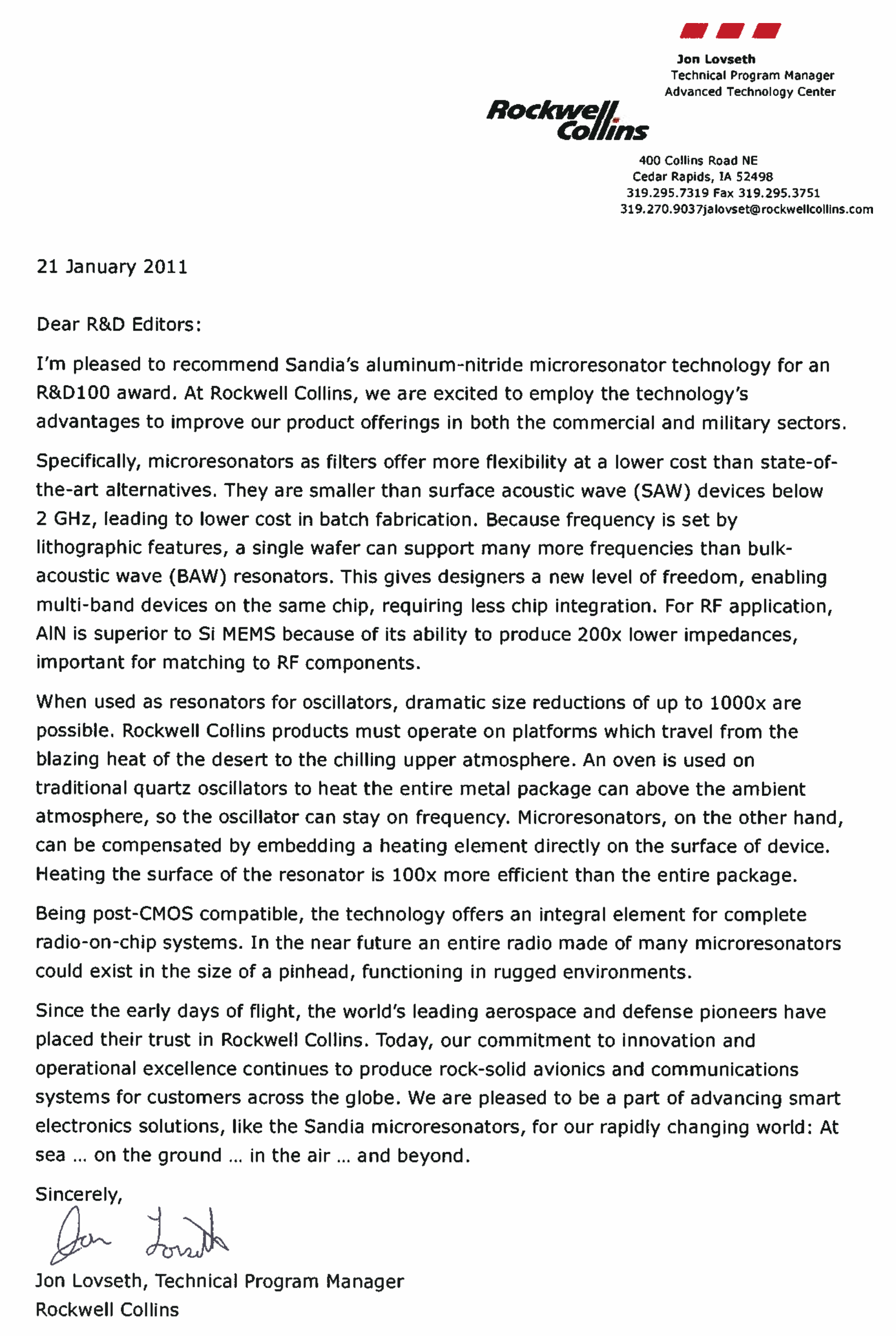
Appendix C: Letter of Support



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21 January 2011

Dear R&D Editors:

I'm pleased to recommend Sandia's aluminum-nitride microresonator technology for an R&D100 award. At Rockwell Collins, we are excited to employ the technology's advantages to improve our product offerings in both the commercial and military sectors.

Specifically, microresonators as filters offer more flexibility at a lower cost than state-of-the-art alternatives. They are smaller than surface acoustic wave (SAW) devices below 2 GHz, leading to lower cost in batch fabrication. Because frequency is set by lithographic features, a single wafer can support many more frequencies than bulk-acoustic wave (BAW) resonators. This gives designers a new level of freedom, enabling multi-band devices on the same chip, requiring less chip integration. For RF application, AlN is superior to Si MEMS because of its ability to produce 200x lower impedances, important for matching to RF components.

When used as resonators for oscillators, dramatic size reductions of up to 1000x are possible. Rockwell Collins products must operate on platforms which travel from the blazing heat of the desert to the chilling upper atmosphere. An oven is used on traditional quartz oscillators to heat the entire metal package can above the ambient atmosphere, so the oscillator can stay on frequency. Microresonators, on the other hand, can be compensated by embedding a heating element directly on the surface of device. Heating the surface of the resonator is 100x more efficient than the entire package.

Being post-CMOS compatible, the technology offers an integral element for complete radio-on-chip systems. In the near future an entire radio made of many microresonators could exist in the size of a pinhead, functioning in rugged environments.

Since the early days of flight, the world's leading aerospace and defense pioneers have placed their trust in Rockwell Collins. Today, our commitment to innovation and operational excellence continues to produce rock-solid avionics and communications systems for customers across the globe. We are pleased to be a part of advancing smart electronics solutions, like the Sandia microresonators, for our rapidly changing world: At sea … on the ground … in the air … and beyond.

Sincerely,

Jon Lovseth

Jon Lovseth, Technical Program Manager
Rockwell Collins

Appendix D: Patents/Pending Patents

US007616077B1

(12) **United States Patent**
Wittwer et al.

(10) **Patent No.: US 7,616,077 B1**
(45) **Date of Patent: Nov. 10, 2009**

(54) **MICROELECTROMECHANICAL RESONATOR AND METHOD FOR FABRICATION**

(75) Inventors: **Jonathan W. Wittwer**, Albuquerque, NM (US); **Roy H. Olsson**, Albuquerque, NM (US)

(73) Assignee: **Sandia Corporation**, Albuquerque, NM (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 391 days.

(21) Appl. No.: **11/689,567**

(22) Filed: **Mar. 22, 2007**

(51) **Int. Cl.**
H03H 9/02 (2006.01)
H03H 9/46 (2006.01)

(52) **U.S. Cl.** **333/186**

(58) **Field of Classification Search** 333/186, 333/188, 200
See application file for complete search history.

(56) **References Cited**

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(Continued)

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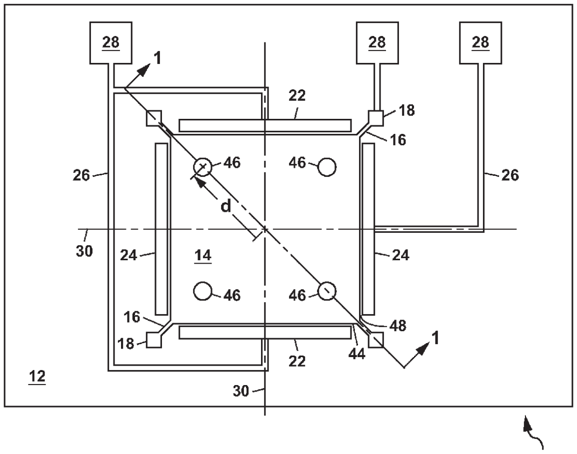
(57) **ABSTRACT**

A method is disclosed for the robust fabrication of a microelectromechanical (MEM) resonator. In this method, a pattern of holes is formed in the resonator mass with the position, size and number of holes in the pattern being optimized to minimize an uncertainty Δf in the resonant frequency f_0 of the MEM resonator due to manufacturing process variations (e.g. edge bias). A number of different types of MEM resonators are disclosed which can be formed using this method, including capacitively transduced Lamé, wineglass and extensional resonators, and piezoelectric length-extensional resonators.

19 Claims, 9 Drawing Sheets



Appendix D: Patents/Pending Patents

US007652547B1

(12) **United States Patent**
Wittwer et al.

(10) **Patent No.: US 7,652,547 B1**
(45) **Date of Patent: Jan. 26, 2010**

(54) **MICROELECTROMECHANICAL RESONATOR AND METHOD FOR FABRICATION**

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(73) Assignee: **Sandia Corporation**, Albuquerque, NM (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **12/269,094**

(22) Filed: **Nov. 12, 2008**

Related U.S. Application Data

(62) Division of application No. 11/689,567, filed on Mar. 22, 2007, now Pat. No. 7,616,077.

(51) **Int. Cl.**
H03H 3/013 (2006.01)

(52) **U.S. Cl.** **333/186**; 333/197

(58) **Field of Classification Search** 333/186, 333/188, 197
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

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(Continued)

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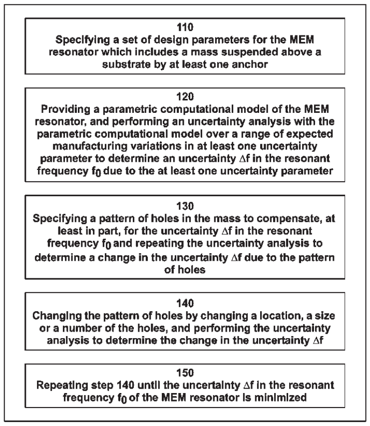
Assistant Examiner—Alan Wong
(74) *Attorney, Agent, or Firm*—John P. Hohimer

(57) **ABSTRACT**

A method is disclosed for the robust fabrication of a microelectromechanical (MEM) resonator. In this method, a pattern of holes is formed in the resonator mass with the position, size and number of holes in the pattern being optimized to minimize an uncertainty Δf in the resonant frequency f_0 of the MEM resonator due to manufacturing process variations (e.g. edge bias). A number of different types of MEM resonators are disclosed which can be formed using this method, including capacitively transduced Lamé, wineglass and extensional resonators, and piezoelectric length-extensional resonators.

14 Claims, 9 Drawing Sheets



110
Specifying a set of design parameters for the MEM resonator which includes a mass suspended above a substrate by at least one anchor

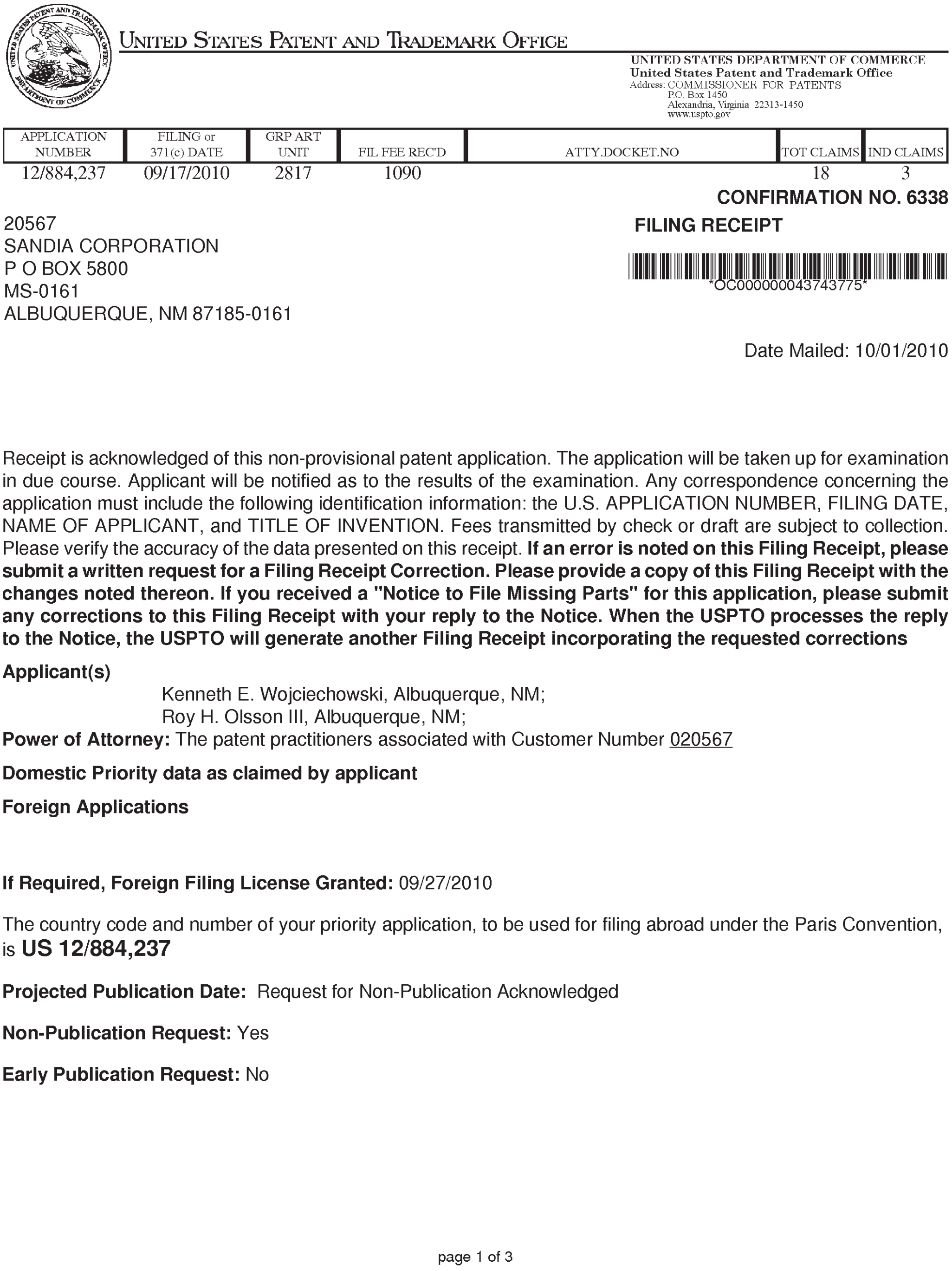
120
Providing a parametric computational model of the MEM resonator, and performing an uncertainty analysis with the parametric computational model over a range of expected manufacturing variations in at least one uncertainty parameter to determine an uncertainty Δf in the resonant frequency f_0 due to the at least one uncertainty parameter

130
Specifying a pattern of holes in the mass to compensate, at least in part, for the uncertainty Δf in the resonant frequency f_0 and repeating the uncertainty analysis to determine a change in the uncertainty Δf due to the pattern of holes

140
Changing the pattern of holes by changing a location, a size or a number of the holes, and performing the uncertainty analysis to determine the change in the uncertainty Δf

150
Repeating step 140 until the uncertainty Δf in the resonant frequency f_0 of the MEM resonator is minimized

Appendix D: Patents/Pending Patents



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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
12/884,237	09/17/2010	2817	1090		18	3

CONFIRMATION NO. 6338

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SANDIA CORPORATION
P O BOX 5800
MS-0161
ALBUQUERQUE, NM 87185-0161

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Date Mailed: 10/01/2010

Receipt is acknowledged of this non-provisional patent application. The application will be taken up for examination in due course. Applicant will be notified as to the results of the examination. Any correspondence concerning the application must include the following identification information: the U.S. APPLICATION NUMBER, FILING DATE, NAME OF APPLICANT, and TITLE OF INVENTION. Fees transmitted by check or draft are subject to collection. Please verify the accuracy of the data presented on this receipt. **If an error is noted on this Filing Receipt, please submit a written request for a Filing Receipt Correction. Please provide a copy of this Filing Receipt with the changes noted thereon. If you received a "Notice to File Missing Parts" for this application, please submit any corrections to this Filing Receipt with your reply to the Notice. When the USPTO processes the reply to the Notice, the USPTO will generate another Filing Receipt incorporating the requested corrections**

Applicant(s)

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Roy H. Olsson III, Albuquerque, NM;

Power of Attorney: The patent practitioners associated with Customer Number 020567

Domestic Priority data as claimed by applicant

Foreign Applications

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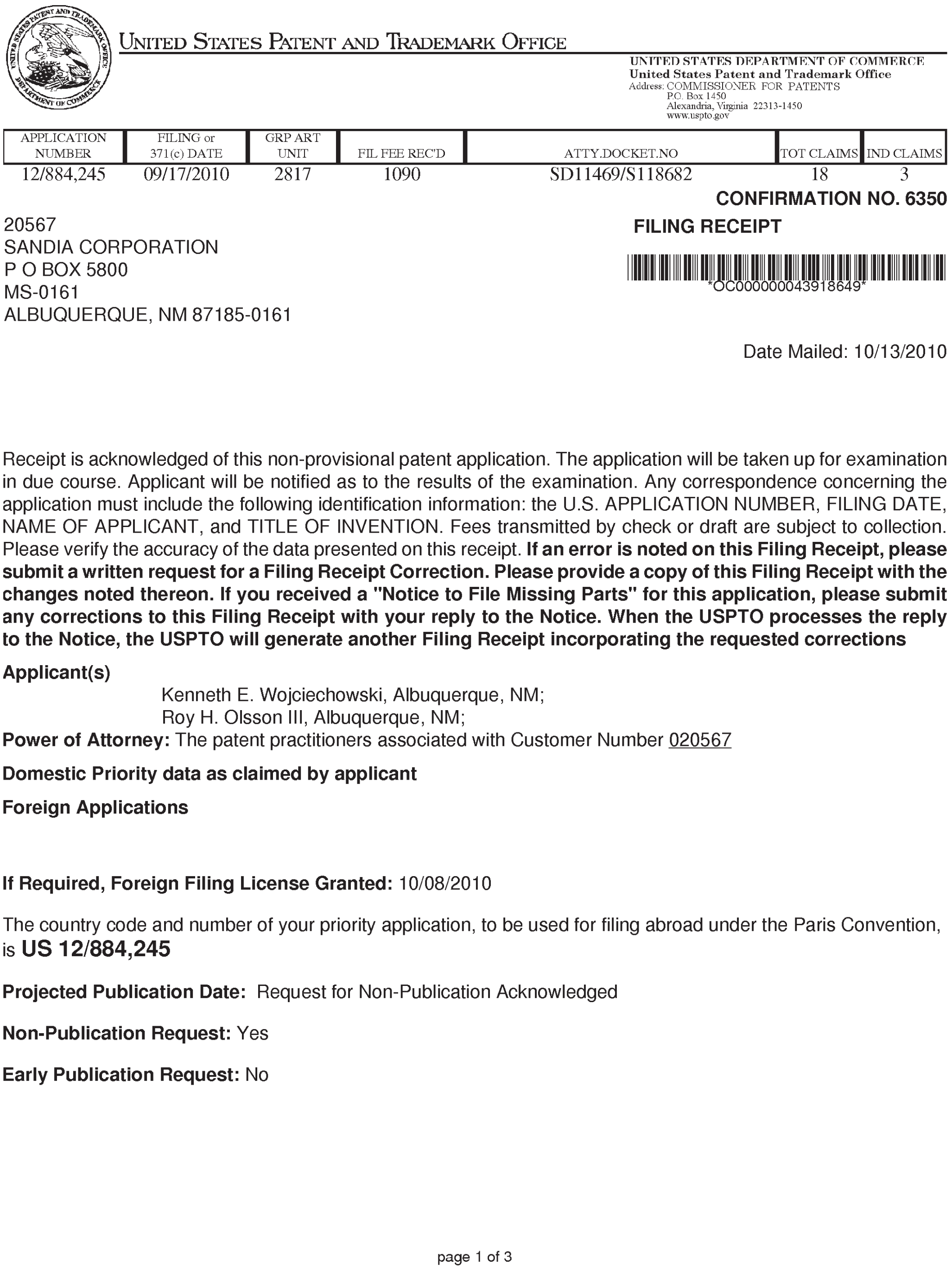
Projected Publication Date: Request for Non-Publication Acknowledged

Non-Publication Request: Yes

Early Publication Request: No

page 1 of 3

Appendix D: Patents/Pending Patents



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APPLICATION NUMBER	FILING or 371(c) DATE	GRP ART UNIT	FIL FEE REC'D	ATTY.DOCKET.NO	TOT CLAIMS	IND CLAIMS
12/884,245	09/17/2010	2817	1090	SD11469/S118682	18	3

CONFIRMATION NO. 6350

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ALBUQUERQUE, NM 87185-0161

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Roy H. Olsson III, Albuquerque, NM;

Power of Attorney: The patent practitioners associated with Customer Number 020567

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page 1 of 3

Appendix E: Articles

Multi-Frequency Aluminum Nitride Micro-Filters for Advanced RF Communications

Roy H. Olsson III, Kenneth E. Wojciechowski, Melanie R. Tuck, James E. Stevens and Christopher D. Nordquist
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Abstract: *An Aluminum Nitride (AlN) MEMS resonator technology has been developed, enabling massively parallel filter and oscillator arrays on a single chip. Low loss filter banks and resonator arrays covering the 10MHz-10GHz frequency range have been demonstrated, as has monolithic integration with inductors and CMOS circuitry. The high level of integration enables miniature multi-band, spectrally-aware and cognitive radios.*

Keywords: cognitive radio; filter; microresonator; oscillator; RF MEMS; real time spectrum analyzer;

Introduction

Aluminum Nitride (AlN) microresonators [1-5] have recently become of great research interest due to their small size, high quality factor (Q), CAD defined low to moderate impedance, potential monolithic integration with RF circuitry [2], and ability to realize multiple frequency filters/resonators operating from 10 MHz to 10 GHz on a single chip. Microresonators have also demonstrated the ability to simultaneously combine high selectivity filtering along with additional RF functionality such as single-ended-to-differential conversion and impedance matching. This paper presents recent advances in AlN microresonator technology at Sandia National Laboratories including state-of-the-art filter, filter array and oscillator demonstrations. Also presented will be a comparison of AlN microresonator technology to competing technologies such as bulk acoustic wave (BAW or FBAR) and surface acoustic wave (SAW) resonators, where microresonators generally have the greatest advantages in terms of size and filter performance below a few hundred MHz and above a few GHz. Finally, the key technological hurdles that must be overcome for microresonator technology to be widely deployed in military systems are presented.

Microresonator Operation

Shown in Fig. 1 is the cross section of an overtone AlN microresonator fabricated using the processes presented in [1], along with the acoustic displacement profile of the excited wave. The resonator consists of a piezoelectric AlN layer sandwiched between two metal electrodes with an underlying oxide layer for passive temperature compensation [4]. As AlN microresonators are transduced via the d_{31} piezoelectric coefficient, the acoustic wave propagates perpendicular to the applied electric field which is across the AlN thin film. This results in a resonator motional impedance per unit area that is independent of operating frequency. Thus, to achieve a given insertion loss, the area occupied by an AlN microresonator changes minimally from 10 MHz to 10 GHz. When combined with lithographically defined microresonator operating frequencies and high sound velocity (reduced lithography requirements), this makes microresonator technology a more frequency diverse technology than SAW or BAW devices. This form of transduction results in much smaller resonators and filters at lower frequencies below several hundred MHz where the motional impedance of SAW and BAW resonators per unit area becomes large due to the increased separation between the actuation electrodes (the acoustic wave propagation is in the direction of the applied electric field for SAW and BAW technologies). The major disadvantage of using the d_{31} piezoelectric coefficient for AlN resonator transduction is that it is lower than the d_{33} piezoelectric coefficient used to transduce AlN BAW resonators. This results in a lower coupling coefficient, k_t^2, than what can be obtained in AlN BAW resonators. The typical coupling coefficients now achieved for AlN microresonators with the temperature compensating SiO_2 layer are 2-2.4% compared to >6% for AlN BAW resonators. SAW resonators fabricated in high piezoelectric coupling coefficient materials such as lithium niobate can achieve k_t^2 >10%, while temperature compensated SAW resonators fabricated on quartz substrates have k_t^2 <1%. The maximum filter bandwidth achievable using traditional filter architectures is approximately $0.5k_t^2$. Given the typical quality factors (Q) of AlN microresonators of 1500-2000, this makes the range

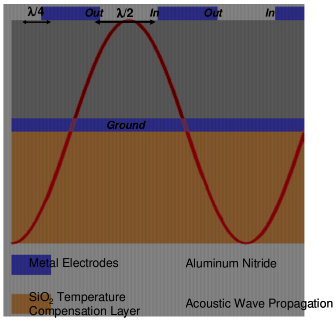

Figure 1. AlN Microresonator Cross-Section and Displacement Profile of the Excited Wave

SINGLE-CHIP PRECISION OSCILLATORS BASED ON MULTI-FREQUENCY, HIGH-Q ALUMINUM NITRIDE MEMS RESONATORS

K. E. Wojciechowski, R. H. Olsson III, M. R. Tuck, E. Roherty-Osmun and T. A. Hill*
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ABSTRACT

Aluminum nitride (AlN) contour mode resonators have been of interest because of their high quality factor, low impedance, large number of frequencies on a single chip and compatibility with CMOS processes [1-3]. While AlN low insertion loss filters [1-3] and oscillators [4-7] have been demonstrated, CMOS integration has yet to be accomplished. This work represents the first time fully-released contour mode AlN microresonators have been integrated with CMOS circuitry to obtain completely monolithic frequency references.

KEYWORDS

Aluminum Nitride, CMOS, Integrated, MEMS, Oscillator, Monolithic, Pierce Oscillator, Resonator,

INTRODUCTION

Recently, Sandia National Laboratories (SNL) has developed an AlN MEMS process and has demonstrated low insertion loss RF filters/resonators at frequencies up to 7 GHz. In addition we have developed an AlN based resonant accelerometer with $0.9 mG/\sqrt{Hz}$ resolution [2]. One of the most promising aspects of this technology is that it can be integrated directly over foundry CMOS circuitry. While single frequency FBAR technology has been demonstrated on BiCMOS [8], integration of contour mode devices allow for multiple frequency filters and frequency references on a single chip. In addition, AlN based sensors could also be integrated on the same substrate. Hence, it enables complete system integration of high-Q, multi-frequency mechanical resonators/filters and sensors, with BiCMOS/CMOS signal processing/RF circuitry on a single miniature IC chip.

Using the process outlined in the following section multiple resonators were deposited on top of oscillator circuitry designed in SNL's 0.35 µm, 3.3V, radiation hardened CMOS on SOI process. Figure 1 shows a 1.1 x 1.2 mm die containing two independent oscillators. A 20/80 MHz length/width extensional oscillator (Figure 1a) and a 100 MHz overtone length extensional oscillator (Figure 1b) were developed. These designs were intended to demonstrate the ability to fabricate multiple frequency devices on a single CMOS die. The oscillator topology used in this work is a Pierce oscillator with a differential output. Finally, the measured oscillator phase noise performance is commensurate with results reported in [4] where the oscillator circuitry and resonators were on separate substrates.

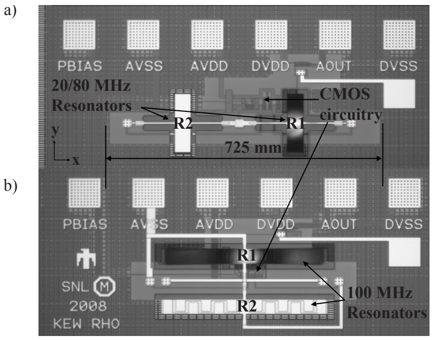

Figure 1: Die photo of integrated AlN resonator with 0.35 µm CMOS on SOI process. a) 20/80 MHz oscillator. b) 100 MHz oscillator. The active oscillator area for both oscillators is approximately 725 µm × 322 µm or 0.23 mm^2.

AlN CMOS COMPATABLE PROCESS

In order to make the resonator release process post-CMOS compatible an amorphous Si release layer had to be added to a previously reported non-CMOS compatible process flow [2]. The CMOS in-compatible flow starts with silicon wafer substrates: First, SiO_2, AlN and electrodes are deposited (Figure 2, step b) on the silicon substrate. Then the resonator size and hence frequency are lithographically defined by etching trenches in the AlN and SiO_2 to bulk Si (step c). Finally the devices are released via removal of the Si substrate using an isotropic etch in dry SF_6 (step d). A similar release process can be implemented directly over CMOS by adding a 400 nm thick sacrificial silicon release layer deposited at 400°C under the resonator (Figure 2, step b1). Subsequent steps (c and d) are identical for the CMOS compatible and previously reported processes [2].

RESONATOR DESIGNS

Two different resonator designs were implemented to provide 20 MHz, 80 MHz and 100 MHz frequency references (Figure 1). The 100 MHz length extensional resonator is 50 µm by 520 µm long. It has a fundamental frequency of 7.7 MHz and operates at its 13th harmonic. The harmonic is driven by interdigitated electrodes spaced at a 40 µm pitch. There are two advantages to operating at a harmonic (overtone) of the device fundamental frequency. First spurious modes are filtered by the

Origins and Mitigation of Spurious Modes in Aluminum Nitride Microresonators

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Abstract—Recently reported narrow bandwidth, < 2%, aluminum nitride microresonator filters in the 100-500 MHz range offer lower insertion loss, 100x smaller size, and elimination of large external matching networks, when compared to similar surface acoustic wave filters. While the initial results are promising, many microresonators exhibit spurious responses both close and far from the pass band which degrade the out of band rejection and prevent the synthesis of useful filters. This paper identifies the origins of several unwanted modes in overtone width extensional aluminum nitride microresonators and presents techniques for mitigating the spurious responses.

Keywords-component; Aluminum Nitride, Microresonator, RF MEMS, Spurious Mode

I. INTRODUCTION

Aluminum Nitride (AlN) microresonators [1,2] have recently become of great research interest due to their small size, high quality factor (Q), CAD defined low to moderate impedance, potential monolithic integration with RF circuitry [3], and ability to realize multiple frequency filters operating from 10 MHz to 10 GHz on a single chip [4,5]. The realization of numerous (10's to 100's) multi-frequency filters on a single substrate promises to reduce component count in next generation wireless handsets and enable frequency, bandwidth and waveform diverse cognitive radios. While the impedance and frequency of the desired extensional modes in AlN microresonators can be accurately adjusted using equations and reduced order finite element models to synthesize a variety of different filter architectures [1, 4, 6-7], spurious modes arising from multiple sources often degrade the ultimate filter performance. Before microresonator filters can be deployed as replacements for surface acoustic wave (SAW), thin film bulk acoustic wave (BAW) and quartz crystal filters, where significant improvements in size, performance and cost are readily achievable at frequencies below several hundred MHz, the origins of spurious modes in AlN microresonators must be well understood and their responses mitigated to acceptable levels.

In this paper three sources of spurious modes in AlN width extensional (WE) microresonators are identified: flexural modes, modes resulting from interactions of the acoustic wave with the interconnect busing, and modes resulting from interactions of the acoustic wave with the anchoring. Spurious flexural modes are studied both using quasi two-dimensional (2D) finite element modeling (FEM) and experimentally. The frequency and relative strength of the spurious flexural modes were found to be dependent on the number of resonator overtones, the thicknesses of the layers in the composite resonator and the electrode configuration. The spurious flexural modes can be found both close and far in frequency from the desired extensional modes. Through proper design of the number of electrodes and resonator overtone, mitigation of spurious flexural modes is demonstrated to realize spurious free filters.

Modes resulting from interactions of the acoustic wave with both the interconnect busing and the anchoring require full three-dimensional (3D) FEM to predict. As full 3D FEM of overtone WE resonators is beyond our current capabilities, these modes are studied experimentally. Multiple modes resulting from interactions of the acoustic wave with the interconnect busing are found close in frequency to the desired extensional response. These modes are shown to inhibit the realization of useful filters. Careful design of the busing eliminates or reduces the response of these modes allowing the demonstration of filters. Modes resulting from interactions of the acoustic wave with the anchoring appear far in frequency from the desired extensional response. Adding additional fabrication processing steps to precisely define the anchors and the sacrificial material area, as opposed to using timed releases of the Si substrate material [1-2,4], is shown to reduce these modes by > 20 dB.

II. WIDTH EXTENSIONAL AlN MICRORESONATORS

Shown in Figure 1 is a 7th overtone, 490 MHz WE AlN microresonator. The resonator is comprised of a stack of oxide, Ti/TiN/Al bottom electrode, AlN and Al top electrodes [1,3]. The resonator is transduced via the d_{31} piezoelectric coefficient of the AlN thin film using the input and output top electrodes and the grounded bottom electrode [7]. The devices studied in this paper are all WE AlN microresonators, operating at 320, 516, 533 and 3215 MHz, with corresponding electrode widths, *W*, of 7.08, 4.21, 4.00, and 0.72 µm. All the devices studied had an electrode length, *L*, of 300 µm.

III. SPURIOUS FLEXURAL MODES

AlN micromechanical plates, such as that shown in Figure 1, can be efficiently transduced in either the desired (in this

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This work was partially supported by the Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories. Sandia National Laboratories is a multiprogram laboratory operated by the Sandia Corporation, Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Appendix E: Articles

Sandia proprietary

PARALLEL LATTICE FILTERS UTILIZING ALUMINUM NITRIDE CONTOUR MODE RESONATORS

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ABSTRACT

In this work we describe a new parallel lattice (PL) filter topology for electrically coupled AlN microresonator based filters. While 4th order, narrow percent bandwidth (0.03%) parallel filters based on high impedance (11 kΩ) resonators have been previously demonstrated at 20 MHz [1], in this work we realize low insertion loss PL filters at 400-500 MHz with termination impedances from 50 to 150 Ω and much wider percent bandwidths, up to 5.3%. Obtaining high percent bandwidth is a major challenge in microresonator based filters given the relatively low piezoelectric coupling coefficients, k_t^2, when compared to bulk (BAW) and surface (SAW) acoustic wave filter materials.

INTRODUCTION

Wide percent (> 1 %) bandwidth filters are needed to achieve the high data rates in applications ranging from CDMA base station transceivers to WiMAX and GSM. These require large percent bandwidth at intermediate frequencies or IF frequencies (~70-900 MHz). Typically wide bandwidths are achieved at low IF frequencies with SAW devices using Lithium Niobate, $LiNbO_3$, or Lithium Tantalate, $LiTaO_3$ as the filter material. These materials are used because of their high k_t^2 allowing for low insertion loss (IL). Unfortunately they are not easily integrated with CMOS or other semiconductor technologies. In addition, SAW and BAW technologies result in large devices at these frequencies for a low motional impedance. The motional impedance per unit area, of a SAW/BAW device, is dependent on frequency due to the direct relationship between wavelength, λ, of the acoustic wave and electrode spacing. As a result transduction efficiency is dependent on the wavelength, and as λ increases the effective transduction coefficient decreases for SAW and BAW devices. This results in large devices at IF frequencies which have significant insertion loss (-20 dB) in the pass band [2]. It should be noted that BAW or film bulk acoustic wave devices (FBARs) at low IF frequencies are difficult to manufacture and have high insertion loss because they require film thickness that are on the order of 10's of microns (wavelength/2 or λ/2).

Aluminum Nitride (AlN) contour mode resonators transduced with the d_{31} piezoelectric coefficient have a motional impedance (per unit area) that is independent of device frequency as the acoustic wave in the material is orthogonal to the electric field used to induce it [3]. Hence this form of transduction (dependent on AlN film thickness not wavelength) can result in much smaller filters with similar or lower insertion loss (across a wide range of IF frequencies) than can be achieved with SAW and BAW resonators of equal size.

While SAW filters can create high order filter responses with a single device (advantage SAW), multiple AlN resonators (similar to BAW) must be employed to achieve similar performance. For instance high order ladder or lattice filters can be implemented using multiple resonators. For filter topologies consisting of individual resonators (ladder, lattice) the achievable percent bandwidth of the filter is directly proportional to the separation of the series, f_s, and parallel resonances, f_p, of the resonators used in the filter [4]. For BAW resonators this is directly related to the k_t^2 of the material. This is a direct consequence of the transduction mechanism used in these devices. i.e. the resulting capacitance, C_o, of the piezoelectric transducer is in parallel with the mechanical resonance. For these devices k_t^2 is proportional to the ratio of C_x, the resonator motional capacitance to C_o. Or equivalently it is proportional to the ratio (at resonance $\omega = \omega_s = 2\pi f_s$), of the impedance $Z_o = 1/(\omega C_o)$, to the motional resistance of the resonator, R_x.

$$k_t^2 \approx \frac{d_{ij}^{\,2}}{\varepsilon_i S_{jj}} \propto \frac{C_x}{C_o} \propto \frac{Z_o}{R_x} \tag{1}$$

$$f_p = f_s\sqrt{1+\frac{C_x}{C_{ft}}},\ for\ BAW\ C_{ft} = C_o \tag{2}$$

Where d_{ij} is the piezoelectric coefficient, ε_i is the effective permittivity of the piezoelectric material in the i direction and S_{jj} is the mechanical compliance. It is well known, *(2)*, that the separation of the f_p and f_s is related to the ratio of C_x/C_o in BAW devices. This is because the feed through or the capacitance in parallel with the mechanical resonator, C_{ft}, is equal to C_o. Hence material properties dictate this separation.

In AlN contour mode resonators use of the d_{31} coefficient enables the decoupling of the relationship between material property k_t^2 and the separation between the series and parallel resonance.

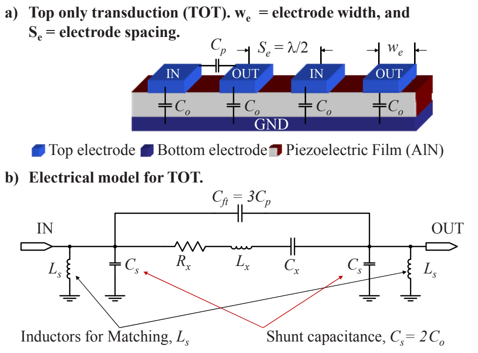

Figure 1: a) Cross section of a TOT AlN overtone resonator. b) electrical equivalent model.

This is achieved by: 1) Using top only transduction (TOT) by arranging the drive and sense electrodes such that the resulting transduction capacitance, C_o, is a shunt capacitance to ground at the inputs and outputs of the resonator (figure 1a). Therefore reducing the capacitance, C_{ft}, which is in parallel with the mechanical resonance. This increases the separation of the series and parallel resonance. 2) The shunt capacitance, C_s, can be resonated out with matching networks consisting of integrated or off-chip inductors (figure 1b). This recovers insertion loss resulting from this configuration. Conversely, capacitance in

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