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# ZINC OXIDE AND ALUMINIUM NITRIDE CMOS-MEMS SURFACE ACOUSTIC WAVE RESONATOR FOR RF APPLICATIONS

BY

ALIZA AINI MD RALIB @ MD RAGHIB

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International Islamic University Malaysia

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# ABSTRACT

The increase in frequency spectrum for wireless communication system has led to the growing interest of thin film electroacoustic technology that scale favourably upon miniaturization. To date, current off chip SAW resonators are made from bulk piezoelectric materials and cannot be easily integrated with silicon substrate. Monolithic CMOS-MEMS integration provides robust platform to realize low power and low cost mass production for a single chip solution. Non-ferroelectric piezoelectric thin films namely Aluminium Nitride and Zinc Oxide are the most promising material for CMOS-MEMS integration due to its silicon compatibility and good piezoelectric properties. This work addresses the implementation of CMOS-MEMS SAW resonators using three different piezoelectric thin film namely Aluminium Nitride (AlN), Zinc Oxide (ZnO) and Al doped Zinc Oxide (AZO). The work begins with finite element modeling using COMSOL Multiphysics to evaluate the performance in terms of resonance frequency, quality factor and electromechanical coupling coefficient. The fabricated devices are based on the optimized simulation results. Post CMOS approach namely piezoelectric thin film deposition, photolithography and wet etching were implemented to fabricate the silicon compatible devices. XRD, AFM and profilometer characterization were conducted to evaluate the quality of piezoelectric thin film. Various issues have been explored such as dependence of RF sputtering power to c-axis orientation and investigation on suitable etchant for AZO thin film. Measurement results revealed AZO thin film enhanced the performance in terms of insertion loss and quality factor compared to ZnO thin film due to improvement in the piezoelectric properties by Al doping. CMOS-MEMS SAW resonator based on AlN thin film demonstrated highest quality factor of 746.8 at 1.040 GHz resonance frequency, giving figure of merit of $Q \times f_S = 7.76 \times 10^{11}$ Hz. Among the three deposited piezoelectric thin films, AlN thin film has the closest to ideal c-axis orientation which leads to highest piezoelectric properties. This result is comparable to current RF MEMS acoustic wave resonators. This work indicates that AlN, ZnO and AZO piezoelectric thin films have high potential to realize single chip transceiver for the next generation of wireless communication system.

# خلاصة البحث

أدت الزيادة في الأطياف الترددية لنظم الاتصالات اللاسلكية إلى زيادة الاهتمام بتقنية شرائح المجسات الصوتية الرقيقة القابلة لتصغير الحجم بشكل إيجابي. حتى الآن، تصنع شرائح التيار الخارج لمرنانات الموجة الصوتية السطحية من مواد كهروضغطية سائبة لا يمكنها الاندماج بسهولة مع رقاقة السيليكون. إن التكامل المتجانس لشبه موصل أكسيد الفلز المكمّل باستخدام نظام الميكانيكية الإلكترونية الميكروية (CMOS-MEMS) يوفر قاعدة صلبة لخفض القدرة وخفض تكلفة الإنتاج الضخم لمعالجة رقاقة واحدة. إن الرقاقات الكهروضغطية السائبة ذات الاستقطاب الإلكتروني العفوي المصنوعة من نتريد الألمنيوم وأوكسيد الخارصين تعد من أفضل المواد لصناعة (CMOS-MEMS) لتوافقها مع السيليكون وخصائصها الكهروضغطية الجيدة. في هذا البحث سيتم عمل مرنانات CMOS-MEMS SAW باستخدام ثلاثة رقاقات مختلفة الخصائص الكهروضغطية وهي مصنوعة من نتريد الألمنيوم (AlN) وأوكسيد الخارصين (ZnO) وأوكسيد الخارصين المطعم بالألمنيوم (AZO). يبدأ العمل مع نماذج العناصر المنتهية باستخدام برنامج COMSOL Multiphysics لتقييم الأداء من حيث تردد الرنين، عامل الجودة ومعامل اقتران الكهروميكانيكية، وتستند الأجهزة المصنعة على نتائج المحاكاة الأمثل. تم تنفيذ نهج CMOS آخر وهو الترسيب والتصوير الضوئي والخدش الرطب للرقاقات الكهرضغطية لعمل أجهزة السيليكون المتوافقة. تم إجراء اختبار حيود الأشعة السينية XRD وقياس القوة الذرية وتوصيف وعورة السطح لقياس جودة الرقاقة الكهروضغطية. وقد تم تقصي قضايا مختلفة مثل اعتماد القوة المضطربة للترددات الراديوية إلى ميل المحور c والتحري عن التنميش المناسب لرقاقة أوكسيد الخارصين المطعم بالألمنيوم (AZO). كشفت نتائج القياس أن رقاقة AZO عززت الأداء من حيث خسائر الإدراج وقياس الجودة مقارنة برقاقة أوكسيد الخارصين ZnO بسبب تحسن الخصائص الكهروضغطية بتطعيم الألمنيوم. مرنانات CMOS-MEMS SAW المعتمدة على نتريد الألمنيوم أظهرت قياس جودة أعلى بمقدار 746.8 في تردد رنين قدره 1.040 غيغا هيرتز، وأعطت نسبة جدارة ($Q \times f_S = 7.76 \times 10^{11}$) هرتز. ومن بين الرقاقات الكهروضغطية الثلاث التي تم اختبارها، تقترب رقاقة نتريد الألمنيوم AlN إلى ميل المحور c المثالي الذي يؤدي إلى خصائص كهروضغطية أعلى. وهذه النتيجة مماثلة للترددات الراديوية MEMS لمرنانات الموجة الصوتية الحالية. يشير هذا العمل إلى أن الرقاقات الكهروضغطية المصنوعة من نيتريد الألمنيوم وأوكسيد الخارصين وأوكسيد الخارصين المطعم بالألمنيوم تتمتع بإمكانيات عالية لتحقيق رقاقة الإرسال والاستقبال الواحدة للجيل القادم من نظام الاتصالات اللاسلكية.

# APPROVAL PAGE

The thesis of Aliza Aini Md Ralib @ Md Raghib has been approved by the following:

Anis Nurashikin Nordin
Supervisor

Raihan Othman
Co-Supervisor

Amelia Wong Azman
Internal Examiner

Ibrahim Ahmad
External Examiner

Badariah Bais
External Examiner

Waahabuddin Ra’ees
Chairman

# DECLARATION PAGE

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature　　　　　　　　　　　　　　　　Date

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# LIST OF SYMBOLS

| | |
|---|---|
| $f_r$ | Resonance frequency |
| $v$ | Acoustic wave velocity |
| $\lambda$ | Wavelength |
| $E$ | Electric field |
| $\rho$ | Density |
| $[T]$ | Stress tensor |
| $[S]$ | Strain tensoor |
| $[D]$ | Electric displacement |
| $[c^E]$ | Elastic stiffness tensor at constant electric field |
| $[e]$ | Piezoelectric stress tensor |
| $[\varepsilon^S]$ | Dielectric permitivitty tensor at constant strain |
| $N_t$ | Number of transducer pairs |
| $L_c$ | Distance between input and output electrode |
| $L_g$ | Distance between reflectors |
| $T_c$ | Thickness of piezoelectric thin film |
| $W$ | Width of aperture |
| $L$ | Distance between reflectors |
| $\kappa^2$ | Piezoelectric Coupling Coefficient |
| $t_c$ | Thickness of Piezoelectric Material |
| $V_{in}$ | Input voltage |
| $\phi_1+$ | Transmitter amplitude |
| $\mu_1(f)$ | Transmitter response function |
| $g_{\mu 2(f)}$ | Receiver response function |
| $G_1(f)$ | Radiation conductance |
| $B_1(f)$ | Radiation susceptance |
| $Y_1(f)$ | Acoustic admittance |
| $C_t$ | Electrostatic capacitance |
| $C_{ox}$ | Oxide capacitance |
| $R_m$ | Motional resistance |
| $L_m$ | Motional inductance |
| $C_m$ | Motional capacitance |
| $C_f$ | Feedthrough capacitance |
| $R_f$ | Feedthrough resistance |
| $d_{ij}$ | Piezoelectric stress coefficient |
| $e_{ij}$ | Piezoelectric strain coefficient |
| W | Watt |
| µm | micrometer |
| Ω | ohm |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| RF | Radio Frequency |
| CMOS | Complementary Oxide Semiconductor |
| MEMS | Micro-electromechanical system |
| SAW | Surface Acoustic Wave |
| BAW | Bulk Acoustic Wave |
| FBAR | Thin film bulk acoustic wave resonator |
| LWR | Lamb Wave Resonator |
| IF | Intermediate Frequency |
| UHF | Ultra-High Frequency |
| VHF | Very-High Frequency |
| IDT | Interdigitated Electrodes |
| Al | Aluminium |
| AZO | Aluminium doped Zinc Oxide |
| ZnO | Zinc Oxide |
| AlN | Aluminium Nitride |
| PLD | Pulse Laser Deposition |
| UHV | Ultra High Vacuum |
| Q | Quality factor |
| $HNO_3$ | Nitric Acid |
| $H_3PO_4$ | Phosphoric Acid |
| $CH_3COOH$ | Acetic Acid |
| $H_2O$ | Water |
| FOM | Figure of Merit |
| $SiO_2$ | Silicon dioxide |
| ANOVA | Analysis of Variance |
| FEM | Finite Element Analysis |
| OA | Orthogonal Array |
| S/N | Signal to noise ratio |
| LB | Lower the better |
| HB | Higher the better |
| NB | Nominal is best |
| G-S-G | Ground-signal-ground |
| AFM | Atomic Force Microscopy |
| XRD | X Ray diffraction |
| FWHM | Full width half maximum |

# CHAPTER ONE

# INTRODUCTION

## 1.1 BACKGROUND

The Internet has evolved from the former Internet of Data that traditionally shared computers and documents to the Internet of Things (IoT). These have enabled computing to be truly ubiquitous in offering advanced connectivity of devices, system and services (Sheng, Zeadally, Luo, Chung, & Maamar, 2009) (Mattern & Floerkemeier, 2010). To achieve this, a variety of objects have to communicate wirelessly anywhere and with anything. A wireless transceiver system consists of RF integrated circuits and passive devices such as surface acoustic wave (SAW) devices that are needed to realize wireless connectivity.

Among the advantages of SAW devices include excellent aging properties besides being small, lightweight and are easily reproducible (Weigel, Morgan, Owens, Ballato, Lakin, Hashimoto, & Ruppel, 2002a) (Springer et al., 1998) (C. W. Ruppel et al., 1993) (Morgan, 2003). Therefore, SAW devices are widely used in RF communication systems as surface acoustic wave (SAW) filter and resonator (Le Brizoual et al., 2008; Nordin & Zaghloul, 2007) (Weigel, Morgan, Owens, Ballato, Lakin, Hashimoto, & Ruppel, 2002). Some specific examples of communications systems are mobile cell phones (C. C. Ruppel, Reindl, & Weigel, 2002), global positioning systems (GPS) (De Escobar & McGinnis, 2002) as well as radars and satellite receivers (Campbell, 1998) . In recent years, there has been a rising demand for high data rate in mobile communication. This has led to the need for RF modules to use high frequency bands of up to the GHz range. In recent years, surface acoustic wave (SAW) technology has a lot of progress in the GHz range frequencies (Le Brizoual et al., 2008) (Udo Ch Kaletta et al., 2013) (Hashimoto et al., 2012).

In addition to that, the application for SAW devices are not limited to communication system only, but have also been extended to biosensing and microfluidic applications to be SAW biosensor and droplet ejector (Fu et al., 2010; Tigli, 2007) (Johnston, Kymissis, & Shepard, 2010), automotive electronics (Jakoby, Eisenschmid, & Herrmann, 2002) and industrial applications as gas sensors (Ahmadi, Korman, Zaghloul, & Huang, 2003). All of this serves as clear evidence testifying the importance of SAW devices in the wireless communication system and biosensing applications.

To date, passive devices such as SAW resonators cannot be easily miniaturized and integrated. It is because they have to be implemented on bulk piezoelectric materials such as quartz (Habti, Bastien, Bigler, & Thorvaldsson, 1995) and Lithium Niobate (Naumenko & Abbott, 2003). Therefore, the potential to integrate the passive devices with circuitry for wireless transceiver system can be realised with Radio Frequency Micro Electromechanical Systems (RF-MEMS) (Varadan, Vinoy, & Jose, 2003). RF-MEMS are believed to respond to the challenges of Moore's Law by bridging the gap between mature RF circuitry with emerging MEMS devices that crosses the borders between the electrical and mechanical world. RF-MEMS acoustic wave resonators play a significant role in replacing bulky and off-chip resonators.

Furthermore, the innovation of Complementary Metal Oxide Semiconductor (CMOS) as the predominant IC technology allows the RF-MEMS acoustic wave resonator to integrate with the circuitry parts in order to realize single-chip transceiver system. A complete integration into a single chip offers i) low manufacturing cost due to a single-chip integration at large volume production ii) reducing the parasitic effects