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Programs at JIIT

- **PASSIVE COMPONENT COMPACT MODELING**
  - Physical Modeling of Inductor - Inductor as an interconnect
  - SPICE Modeling of MEMS Micromechanical Structures - Cantilevers, Membranes
  - SAW Sensor Modeling
  - High Temperature MOS Modeling
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Agenda

- SAW Basics
- Motivation
- Primitive Structures
- Benchmark Circuits
- Benchmark Tests
- Motivation For SAW SPICE Modeling
- Mason Equivalent Circuit
- SPICE Modeling
- Capacitance Modeling
- Simulation
- Validation
- Model Integration to SPICE Simulator in Verilog-A
- Conclusion
- References
SAW Basics

Monochromatic traveling acoustic wave in z-direction can be described by:

- Particle displacement vector \( u_z(z, t) \)
- Quasistatic electric potential \( \phi(z, t) \)

**Graph:**
- \( u_y \) and \( u_z \) as functions of depth (wavelengths).
- Compression and dilation indicated on the wave graph.
SAW Basics

- Surface Acoustic Wave (Rayleigh Wave) excitation on the surface of a piezoelectric substrate through interdigital transducer was realized by R.M. White \cite{3}, at the University of California, Berkeley in early 70’s by R.M. White.
- The alternating electric field applied between finger pairs of IDT periodic strain field in the piezo-substrate to standing acoustic wave ⇒ Propagating bidirectional wave in the medium.
- The elastic wave generated ⇒ composition of compressional and shear waves in a fixed ratio.
- Typical mechanical wave velocity $3 \times 10^5$ cm/sec. ⇒ Five order smaller than EM Wave Velocity ⇒ Miniaturization of electronic components.
- SAW IDT structures are realized by standard micro lithographic technique.
SAW Basics

- The Wave Energy is confined within wavelength distance/depth of the substrate ⇒ acts as a wave guide.
- Surface confinement of wave energy makes it extremes sensitive to surface perturbation ⇒ sensor application.
- Surface Potential of Wave / Applied voltage to IDT = Transfer Function = $\phi^\pm = \mu_s V_1$, where $\mu_s$ = substrate dependent (Freq. Independent)
- $\phi^+(z) = \mu_s \sum_{n=0}^{n-1} V_n \exp jk(z-z_n)$, $z_n$ : position of nth fingers pair.
Motivation

- Surface Acoustic Waves are sensitive to
  - Ambient Temperature
  - Forces
  - Acceleration
  - Electric Field Strength
  - Dew Point
  - Gas concentration
  - Gas Flow
  - Pathogens, E-coli, virus, bacteria, DNA
  - Gas trace in environment (e-nose)
  - Automobile emission

- A wide range of sensors
  - In Communication:
    - Delay Line, Band pass filters, Dispersive filters, Resonators,
    - Convolvers, Correlators, RF ID...
Primitive IDT Structures - I

- **Finger Width**
- **Finger Spacing**
- **Period (p)**
- **Aperture**
- **Voltage source**
Primitive IDT Structure - II Delay Line

Transmitter

Receiver

Piezoelectric Substrate

$V_1$, $I_2$, $\phi_A^+$, $\phi_B^+$
Double-Electrode IDT Structure \(\implies\) Cancellation of Reflection from Metal Electrodes

\[
\Delta z \approx R_P \cdot \frac{K^2}{2} + R_m \cdot \frac{h}{\lambda} + \left(\frac{h}{\lambda}\right)^2 \quad \text{[For } \frac{h}{\lambda} \ll 0.2\%]\]

\[
\frac{\Delta \nu}{\nu} \approx \frac{K^2}{2}
\]

Mechanical loading

Energy storage
Monolithic SAW Structure: SAW - on - Silicon (S – O – S)\cite{12}

- Absorber
- Metal 2
- Dielectrics (overglass + intermetal + gate oxide)
- Metal 1
- IDT’s (Metal 1)
- Poly
- N-Well Heaters
- Si Substrate
- unexposed oxide
- Delay line (Si exposed)

ZnO/Si in CMOS Technology
S/i (Smart/Intelligent) SAW

RF Magnetron Sputtered ZnO
Relationship between Transducer Periodicity and Coherently Excited Waves

\[
\begin{align*}
  &+ &- &+ &- &+ \\
  &\downarrow &\downarrow &\downarrow &\downarrow &\downarrow \\
  &n=1 & & & & \\
  \parallel &\parallel &\parallel &\parallel &\parallel &\parallel \\
  &\text{d} & & & & \\
  &n=3 & & & & \\
\end{align*}
\]
Input / Output Equivalent for a SAW Delay Line

\[ V_{\text{in}} \sim \]

\begin{align*}
R_s & \quad C_t \quad G_a(f) \\
V_{\text{in}} & \quad \sim
\end{align*}

\[ I \quad \rightarrow \quad C_t \quad G_a(f) \quad R_L \]

\[ a \quad \text{INPUT IDT} \quad b \quad \text{OUTPUT IDT} \]
Mason Crossed-Field Model [13]

\[ TANEQ = j Z_0 \tan \frac{\theta}{2}, \quad CSCEQ = -j Z_0 \csc \theta, \quad \theta = \pi \frac{f}{f_0}, \quad Z_0 = \frac{1}{k^2 C_s f_0}, \quad f_0 = \frac{\nu_0}{L} \]

- \( k \) : electromechanical coupling constant
- \( C_s \) : electrode capacitance per section
- \( \nu_0 \) = SAW velocity for free region
- \( L \) : the length of one period
Mason Modified Crossed-Field Model \[13\]

\[\begin{align*}
TAN0 &= jZ_0 \tan \frac{\theta_0}{2}, \quad CSC0 = -jZ_0 \csc \theta_0, \quad TANM = jZ_m \tan \frac{\theta_m}{2}, \quad CSCM = -jZ_m \csc \theta_m, \\
\theta_0 &= \frac{\pi}{4} \frac{f}{f_0}, \quad \theta_m = \frac{\pi}{2} \frac{f}{f_m}, \quad Z_0 = \frac{1}{k^2 C_s f_0}, \quad Z_m = \frac{1}{k^2 C_s f_m}, \quad f_0 = \frac{\nu_0}{L}, \quad f_m = \frac{\nu_m}{L}
\end{align*}\]

\(k\) : electromechanical coupling constant ; \(C_s\) : electrode capacitance per section

\(\nu_0\) = SAW velocity for free region ; \(\nu_m\) : SAW velocity for metallized region ; \(L\) : the length of one period
Foster’s Equivalent Network Steps to SPICE Modeling contd...

- T-network elements represent lossless transmission lines. The transformer figures due to electromechanical coupling of the piezoelectric medium.
- The entire transducer is consisting of N periodic section is in cascade acoustically and is parallel electronically.
- Mason’s crossed-field model is believed to produce closer agreement with experimental data.
- The modeling part can be resolved into following components.

1. Transducer modeling (Transmitter and Receiver).
2. Delay path between Transmitter and Receiver ⇒ perturbed/unperturbed.
3. Interface electronics modeling (matching network, layout parasitics, bonding/packaging and pcb integration, signal processing circuits etc.)
Foster’s Equivalent Network

- In Mason’s model, TANEQ, CSCEQ, TAN0, TANM, CSC0, CSCM are frequency dependent.
- **Proposed model** replaces above terms by LC network obtained using Foster’s method yielding a network corresponding to the given functional behavior.
- Foster’s method states that an **input impedance** function can be completed specified by a network
  - through its **poles and zero** locations and
  - its value at some non-zero / non-pole frequency.
- For compact modeling to ensure computational stability a small quantity ($\epsilon > 0$) has been added to pole and zero frequencies without disturbing the function.
Mason’s Circuit Representation of IDTs

\[ A = jR_0 \tan(\psi/2) \]
\[ B = -jR_0 \csc \psi \]

One Periodic Section
SPICE Macro Model for SAW

\[ L_1 \quad C_1 \quad L_2 \quad C_2 \quad L_3 \quad C_3 \quad R_0 \tan \frac{\psi}{2} \]

\[ -L_4 \quad -C_4 \quad -L_5 \quad -C_5 \quad -L_6 \quad -C_6 \quad R_0 \cosec \psi \]

\[ L_9 \quad C_9 \quad L_8 \quad C_8 \quad L_7 \quad C_7 \quad C_0 \quad \text{CSCEQ} \]

\[ \omega_0 \quad 2\omega_0 \quad 3\omega_0 \]

\[ \omega_0 \quad 2\omega_0 \quad 3\omega_0 \]
Benchmark Circuits[9]

Figure: Complete model of a SAW device

\[ Y(A), Y(x) = \text{Acoustic Input Admittance} \]

\[ Y(e) = \text{Primary - Input Admittance} \]

\[ A_{3G} = \frac{E_3}{E_G}; \quad A_{23} = \frac{E_2}{E_3}; \quad A_{21} = \frac{E_1'}{E_2}; \quad A_{31} = \frac{E_3'}{E_1'}; \quad \text{Voltage ratio} \]
Benchmark Tests IDT Frequency Response - Solid Structure

**Figure:** IDT Frequency Response - Solid Structure Load Characteristics

- **Solid-IDT Load Frequency**
- **YZ Lithium Niobate**
- **N=20, W= 50\(\lambda\)**
- **Central Frequency = 45 MHz**
- **Delay = 10\(\lambda\)**

**Y-Axis:** V(Load) in Volts

**X-Axis:** Frequency in MHz

**Frequency (MHz) --->**
SAW Amplitude for 1V on IDT Terminal for $LiNbO_3$

**Figure:** Overall SAW Impulse Response

- **Solid-IDT Impulse Response**
- YZ lithium Niobate
- $N=20$ $W = 50\lambda$
- Central Frequency = 45 MHZ
- Metallization Ratio = 0.5η

**Y-Axis:** V(Load) in Volts
**X-Axis:** Time in Microseconds
Insertion Loss: Tuned SAW Insertion Loss ($R_a G_a = 1$) \[1\]

**Solid IDT Insertion Loss**
YZ Lithium Niobate
N=20, W= 50\(\lambda\)
Central Frequency = 45 MHz
RaGa=1

**Y-Axis**: Insertion Loss in dB  
**X-Axis**: Frequency in MHz

**Figure**: Tuned SAW Insertion Loss Plot - 1
SAW Device Design - Flow Chart

Start

Choose Material
1. Lithium Niobate (LiNbO₃)
2. ST-Quartz
3. Zinc Oxide

Choose model
1. Solid IDT
2. Split IDT

Enter Syn. freq. \((f_0\) in MHz)

Enter 3 dB BW \((f_{3\text{dB}}\) in MHz)

Enter I/P Resistance, \((R\) in Ω)

Calc no. of finger pairs, \(N\)
\[ N = 0.9 \left( \frac{f_0}{f_{3\text{dB}}} \right) \]

Calc Aperture

if model = solid

NO

Calc Capacitance \(C_s\)
\[ C_s = C_0 W \]

YES

Calc Capacitance \(C_s\)
\[ C_s = 1.4 C_0 W \]

Calc Radiation Conductance
\[ G_a(f_0) = 8 N^2 f_0 C_s K^2 \]

Calc Characteristic Impedance
\[ Z_0 = \frac{1}{K^2 C_s f_0} \]

Stop
SPICE SAW Model Parameter - Foster’s Network Model

Start

Parameters Already in Memory
$Z_0, f_0, C_s$

Calculate foster’s model parameters
$x = Z_0(2\pi f_0); y = \frac{Z_0}{2\pi f_0}$

TANEQ Parameters
- $\text{taneq}(1) = \frac{0.77578}{x}$
- $\text{taneq}(2) = 1.28906y$
- $\text{taneq}(3) = \frac{0.664935}{x}$
- $\text{taneq}(4) = 0.167101y$
- $\text{taneq}(5) = \frac{0.369408}{x}$
- $\text{taneq}(6) = 0.108281y$

int $i = 1$

while $i < 6$

if $(i\%2) == 0$

YES

Print $\text{taneq}(i) \times 10^{12}$
// for Capacitance in pF

Print $\text{taneq}(i) \times 10^{6}$
// for Inductance in $\mu$H

i = i + 1

YES

NO

$\text{taneq}(1)$

contd.
SPICE SAW Model Parameter - Foster’s Network Model

C0SECEQ Parameters

\[ csceq(1) = -\frac{1.551516}{x} \]
\[ csceq(2) = -0.64453y \]
\[ csceq(3) = -\frac{1.39257}{x} \]
\[ \ldots \]
\[ csceq(13) = 0.0407308y \]

int \( i = 1 \)

while \( i < 6 \)

if \((i\%2)\neq 0\)

Print \( csceq(i) \times 10^6 \)  
// for Capacitance in µF

Print \( csceq(i) \times 10^{12} \)  
// for Inductance in pH

\( i = i + 1 \)

while \( i < 13 \)

if \((i\%2)\neq 0\)

Print \( csc(i) \times 10^6 \)  
// for Capacitance in µF

Print \( csc(i) \times 10^{12} \)  
// for Inductance in pH

\( i = i + 1 \)

STOP
Capacitance Modeling

At $\eta = 0.5,$

$$C_n = \frac{4}{\pi} C_s W \cdot \frac{1}{4n^2 - 1}$$
Variation of $C_n$ with Metallization Ratio, $\eta$

At $\eta = 0.5$, 

$$C_n = \frac{4}{\pi} C_s W \cdot \frac{1}{4n^2 - 1}$$
For $\eta < 0.75$

$C_1 = C_1(\eta = 0.5) \exp[1.75(\eta - 0.5)]$

$C_2 = C_2(\eta = 0.5)(\eta/0.5)(0.18)$

Total Capacitance $C_T = \sum_{odd} n 2C_n = NC_s W$

For Split electrode $C_T = 1.4NC_s W$
Driving Pt Impedance vs Frequency

Split-IDT Metal Driving Point Impedance
N=20, W = 80λ
Central Frequency = 45 MHz

Y-Axis: Impedance in Ohms
X-Axis: Frequency in MHz

Figure: Z0 vs Freq
Conductance vs Frequency: $G_0$ vs frequency

Figure: Go vs Freq

- SOLID IDT Radiation
- Conductance
- YZ Lithium Niobate
- $N=20$, $W=50\lambda$
- Central Frequency = 45 MHz

Y-Axis: Radiation Conductance in MHo
X-Axis: Frequency in MHz
Susceptance vs Frequency : $B_a$ vs frequency

Figure: $B_a$ vs Freq

Solid-IDT Transducer
Susceptance
YZ Lithium Niobate
N=20, W= 50$\lambda$
Central Frequency = 45 MHz

Y-Axis : Susceptance in MHo
X-Axis : Frequency in MHz
Simulation: SAW Solid Electrode Frequency Response

Solid-IDT Magnitude
YZ Lithium Niobate
N=20, W=50\(\lambda\)
Central Frequency = 45 MHz

Y-Axis: V(Transmitter) in Volts
X-Axis: Frequency in MHz

Figure: SAW Solid Electrode Frequency Response
Simulation: SAW modified crossed-field model frequency response

Figure: SAW modified crossed-field model frequency response

Solid-IDT Metal Magnitude
YZ Lithium Niobate
N=20, W=50\lambda
Central Frequency = 45 MHz

Y-Axis: V(Transmitter) in Volts
X-Axis: Frequency in MHz
Simulation: SAW split electrode modified crossed-field frequency response

Figure: SAW Split electrode modified crossed-field frequency response

Split-IDT Metal Magnitude
YZ Lithium Niobate
N=20, W=50λ
Central Frequency = 45 MHz
Delay line = 10λ

Y-Axis: V(Load) in Volts
X-Axis: Frequency in MHz
Validation: SAW metallization ratio-effect impulse response ($\eta=0.25$)\[9\]

**Figure:** SAW Metallization ratio - effect impulse response plot - I

- **Solid IDT Impulse Response**
  - YZ-Lithium Niobate
  - N=20 W=50\(\lambda\)
  - Central Frequency = 45MHz
  - Metallization Ratio = 0.25

**Y-axis:** \(V\)(transmitter) in Volts
**X-axis:** Time (in nanoseconds)
Validation: SAW metallization ratio-effect impulse response ($\eta=0.5$)[9]

**Figure:** SAW Metallization ratio - effect impulse response plot - II

- **Solid IDT Impulse Response**
- **YZ-Lithium Niobate**
- **N=20 W=50\(\lambda\)**
- **Central Frequency = 45MHz**
- **Metallization Ratio, \(\eta=0.5\)**

**Y-Axis:** V(Transmission) in Volts

**X-Axis:** Time (in nanoseconds)
Validation: SAW metallization ratio-effect impulse response ($\eta = 0.75$)[9]

**Figure:** SAW Metallization ratio - effect impulse response plot -III

- **Solid IDT Impulse Response**
  - YZ-Lithium Niobate
  - N=20 W=50\(\lambda\)
  - Central Frequency = 45MHz
  - Metallization Ratio, $\eta = 0.75$

- **Y-Axis:** V(Transmission) in Volts
- **X-Axis:** Time (in nanoseconds)
Validation: Lithium Niobate Re(input admittance) \cite{5}

Figure: Lithium niobate Re(input admittance)
Validation: Lithium Niobate Imag(input admittance) [5]

Figure: Lithium niobate Imag(input admittance)
Validation: Zinc oxide frequency response[12]

Zinc Oxide
Rs=1k
R(load)=1k
N=16
v=3954m/s for h/λ=0.0625
λ=9.6um
W=100um
fo = 411.875 MHz

Y-axis: V(Load) in Volts
X-Axis: Frequency in MHz

Figure: Zinc oxide frequency response
Phase Modulation by selective film affecting elastic wave velocity

- **Delay Line**
  - Passive device
  - Measure I.L. Phase shift

- **Delay + Amplitude**
  - Measure oscillation frequency

- **Resonator/Transducer**
  - Oscillator
  - Passive device
  - Measure $f_{res}$, $Q$, $Z_{in}$

- Insertion loss (dB) $\Delta f$
SAW Delay Line with Selective Film in Wave Propagation Path - Sensor Application

Acoustic Absorber

IDT1

Transmitter Input

n ≈ 0.01 λₚ, ε₀ - vacuum
ρ, σ, λₗ, μₗ
+ Overlay Film

PIEZOELECTRIC SUBSTRATE

(Delay Path Model)

Acoustic Absorber

IDT2

Receiver Output

z

y
Surface Acoustic Wave Sensor Application - Principles

- The change in velocity of the wave in the SAW delay line varies as

\[
\frac{\Delta f}{f} = \frac{\Delta V}{V} = k_1 f h p' - k_2 f h \left( \frac{4\mu'}{V_R^2} \frac{\lambda' + \mu'}{\lambda' + 2\mu'} \right)
\]

- This change in velocity causes a change in the phase of the wave, when the delay line length is changed or a film of different material is deposited on the delay line. This phase change indicates the physical change in parameters such as temperature, concentration of gases etc.
Frequency selection plot

Figure: frequency selection plot
Verilog-A SAW Model Implementation in SPICE

Figure: verilog-A SAW model implementation in SPICE
Verilog-A : SAW Solid Electrode Frequency Response

Figure: SAW Solid Electrode Frequency Response

Solid-IDT Magnitude
YZ Lithium Niobate
N=20, W= 50\lambda
Central Frequency = 45 MHz

Y-Axis : V(Transmitter) in Volts
X-Axis : Frequency in MHz
Conclusion

- **A Compact** SPICE compatible macromodel for SAW has been developed suitable for SAW sensor system development which, presently is an early version undergoing benchmarking.
- SAW IDT integrated with extrinsic interface matching circuits has been validated.
- Validation of SAW SPICE Model Parameters has been made on ST-Quatrz, LiNbO$_3$, ZnO/Si in the range of 40 MHz - 450 MHz.
- Mason’s improved model can be SPICED to capture more accurate reflection from metal electrodes.
- Presently, only primitive structures, have been investigated. withdrawal weighting, floating electrodes, unidirectional IDTs are eminent candidates for inclusion in SPICE model.
Conclusion contd...

- Applicability of SPICE Model for modes such as Love Wave, Shear Horizontal Surface Acoustic Wave (SH-SAW), Shear Transverse Wave (STW), Flexural Plate Wave (FPW), Shear Horizontal Acoustic Plate Mode (SH-APM), Layered Guided Acoustic Plate Mode (LG-APM) that is currently used for high sensitive bio and gas sensor developments to be extended.

- SAW SPICE Model is integrated in CAD-package that where design inputs are material, process and layout.

- **Ricco Criteria**
  - Oscillator $\Delta f$ for bio/gas: wide range of sensing option
  - Model Challenge: Mass loading, shiftness, dielectric constant, temperature, pressure changes in overlay film interacting with SAW.
References


References


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