Large Signal RF Applications of BST Varactors

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Outline

- Introduction
  - Applications
  - Device requirements
  - MOCVD deposition method
- Small Signal Measurements
  - Equivalent circuit, loss tangent
  - Tunability
  - Frequency dependent permittivity
- Large Signal Characterization
  - Large signal measurement setup
  - Tunability as a function of RF voltage
- IP3 measurement of a tunable low pass filter
- Nonlinear device modeling issues
Basic Applications

- Varactor for impedance matching network
  - DC/DC power converter
  - Replaces semiconductor varactor
- Voltage Controlled Crystal Oscillator (VCXO)
  - Improves phase noise in tuning circuit
  - Replaces semiconductor varactor diode
- Tunable bandpass filter
  - Replaces switched banks of discrete filters
- Advantages include ease of integration with active devices such as MMICs, low cost and low losses
# Device Requirements

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Impedance matching network</th>
<th>VCXO varactor</th>
<th>Tunable bandpass filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q values</td>
<td>$&gt; 200 \ @ \ 100 \ MHz$</td>
<td>$&gt; 1000 \ @ \ 100 \ MHz$</td>
<td>$&gt; 200 \ @ \ 2GHz$</td>
</tr>
<tr>
<td>Capacitance values</td>
<td>$\sim 600 \ pF$</td>
<td>$\sim 1 - 50 \ pF$</td>
<td>$0.5 \ to \ 10 \ pF$</td>
</tr>
<tr>
<td>Tunability</td>
<td>2:1</td>
<td>2:1</td>
<td>2:1</td>
</tr>
<tr>
<td>Voltage tuning range</td>
<td>28 Volt</td>
<td>$\sim 1 - 10 \ Volt$</td>
<td>1 - 10 volt</td>
</tr>
<tr>
<td>Frequency range</td>
<td>30 - 100 MHz</td>
<td>$\sim 100 \ MHz$</td>
<td>$\sim &gt; 5 \ GHz$</td>
</tr>
<tr>
<td>Self resonant frequency</td>
<td>$&gt; 500 \ MHz$</td>
<td>$&gt; 1 \ GHz$</td>
<td>$&gt; 5 \ GHz$</td>
</tr>
<tr>
<td>Permittivity drift over -55 to +125 °C</td>
<td>$\sim &lt; 10 %$</td>
<td>$\sim &lt; 10 %$</td>
<td>$\sim &lt; 10 %$</td>
</tr>
</tbody>
</table>

- High Field
- High Power
- Moderate Frequency
- Low Field
- Low power
- High Frequency
- Low Field
- Low Power
- Very High Frequency
**BST High Frequency Applications: Considerations**

### Project Goals

- **Low loss @ 30 MHz - 2 GHz**
  - \( \tan \delta \leq 0.002 \) @ 100 MHz
  - \( \tan \delta \leq 0.01 \) @ 2 GHz
- **High tunability**
  - \( \Delta C/C \geq 50\% \)
- **Thick films**
  - \( t \geq 300 \text{ nm} \)

### Approach

- **MOCVD of BST**
  - composition control
  - dopants
  - microstructure control
  - large area
- **Si substrates**
  - large area
  - standard processing
- **Parallel plate capacitors**
- **Pt electrodes**
Liquid Delivery MOCVD of BST Thin Films

Process Conditions

- Substrate temperature 640-680 °C
- Pressure : 0.7 torr
- Ar, O₂ and N₂O total flow : 0.5 - 2.0 SLM
- CVD precursors :
  - Ba(thd)₂ --polyamine, tetraglyme
  - Sr (thd)₂ --polyamine, tetraglyme
  - Ti(OPr-i)₂ (thd)₂
- Precursor flow (liquid) : 4 - 10 ml./hr.
- Deposition rate 40 - 100Å/min.

- Polyamine Ba, Sr adducts used for this work (low and high frequency)
- Tetrasylyme adducts used in previous work (low frequency - DRAMs)
**BST Capacitor Measurements**

- Physical structure and equivalent circuit model used for high frequency measurements
- 50 x 50 µm etched capacitors
Thin BST: Tunability and Tanδ @ 10 kHz

Tunability > 50%, dissipation ~0.003

t = 71 nm
54.2% Ti
Ba/Sr = 70/30
T_{dep} = 640°C
Tunability and Tanδ in Thick BST @ 10kHz

Tunability > 70%, dissipation ~0.005

Dielectric Constant

DC Bias (V)

Dissipation Factor

t = 301 nm
52.8% Ti
Ba/Sr = 70/30
T_{dep} = 640°C

Tunability > 70%, dissipation ~0.005

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Tunability at 50 MHz

- The capacitor was measured with HP8510C VNA
- Tunability > 50% @ 50 MHz with tanδ = 0.004

- $t = 71$ nm
- 54.2% Ti
- Ba/Sr = 70/30
- $T_{\text{dep}} = 640^\circ$C
**Frequency Dependent Permittivity**

- Very little measurable dispersion between 1 GHz and 10 GHz

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t = 71 nm
54.2% Ti
Ba/Sr = 70/30
T_{dep} = 640°C
Large Signal Measurement Setup

- BST capacitors have been measured by using the set-up above.
- The data taken from transition analyzer was then optimized based on the equivalent circuit model and permittivity values were obtained.
**Measured and Simulated Tunability vs. RF Voltage Amplitude**

Measured tunability compression

Simulated tunability compression

- Small signal tunability curve was fitted to a 13\(^{th}\) order polynomial, the nonlinear capacitor associated with this polynomial was simulated in HP-ADS
- Good agreement between measured and simulated tunability is obtained
IP3 Measurement of a Tunable Lowpass Filter

- The low pass filter was designed based on the 5th order Chebychev coefficients for 0.5 dB ripple
- BST capacitors were connected by means of bond wires to the inductors
Measured Insertion & Return Loss

- Increasing voltage improves insertion loss since impedance matching gets better.
- Most of the insertion loss is due to conductor losses
Measured and Simulated IP3 for the Filter

- For frequencies near the cut-off, output intercept point drops
Nonlinear Device Modeling Issues

- Generally assume device nonlinearities dominated by the nonlinear, field-dependent permittivity

- Could there be other contributing factors?

- For example: the dielectric dispersion and corresponding relaxation currents
Nonlinear Device Modeling (contd.)

- Dielectric displacement current corresponding to $\varepsilon_\infty$
- Relaxation Current $\alpha \ t^{-n}$
- Leakage current
- Dielectric permittivity, $\varepsilon$
  - $\varepsilon(f) \propto \omega^{n-1}$
- Loss tangent (frequency independent) up to optical frequencies
- Phonon losses

Log time

Log frequency
**Implications**

- The lower $\tan\delta$, the smaller is the frequency dependency of the device capacitance

- The field dependence of the high frequency permittivity is different to that of the long range polarization. The polarization currents have a weak field dependence

- Where loss tangents are relatively high (e.g. $> 0.005$), these effects may need to be considered for a non-linear device