Piezoelectric MEMS: High Performance Oscillators

March 6\textsuperscript{th} 2013

Harmeeet.Bhugra@idt.com
Managing Director
MEMS Division, IDT Inc.
**Overview:** Founded: 1980; NASDAQ: IDTI; Workforce: ~1800 Employees; Headquarter: San Jose, CA; FY12 Revenue: ~$526M, R&D Spending: $150M/yr

**Core Expertise:** World Leader in Timing, Serial Switching and Interfaces

---

**IDT is the #1 silicon Timing supplier in the $1.2 B silicon timing market.**

**Innovation:**
- Over 4,000 unique timing devices
- Best Performance Silicon Timing

**Understanding:**
- Foremost experts in Silicon timing technology

**Unparallel Service and support:**
- Fast-turn model for custom timing devices
- World class applications engineers

Sources: CS&A, IDT
What is an Oscillator or a Timing Reference?

- Oscillator’s, Xtal resonator’s, PLL’s, etc are all called “Clocks or Timing Reference or Frequency Reference”
**Analogy**

The **CPU** is the brains. (does all the calculations / processing)

**Memory** is where all the data is stored for processing.

**Timing Reference** is the heartbeat of the system.
Heartbeat... what does it mean?

Controls the *flow* of data....and it beats on a regular interval
Data Transfer and Processing

Maximum of Four Processors per Memory Controller Hub

Processors Share FSB Bus Bandwidth

I/O & Memory Share FSB Bus Bandwidth

PCI-X Bridge

GBE (x2)

On-MCH Interface Limits PCI Express Expansion

Fibre Channel

IDE, SIO, USB, Etc.

I/O Hub

IOP

PCI Express

PCI-X

http://www.idt.com/go/mems
Data Storage and Transfer

Memory/Storage

0001101001001101
0001101001001010
1101000101001011
1000011010001101
0001101000010110
0001101000101011
0001101000101101
1010101100101010
0110110010101011
0011100010101101
1001110010101010
0010110010101011
0101010101001101
1001101011001010
0101101010101011
1010010110101011

CPU

1 1 0 1 1 0
Data Transfer

With Clock

001101001001101
0011010001001010
1101000101001011
100011010001101
001101000010110
00110100010111
1010101010101010
0110110010101011
0011000010101101
1001110010101010
0011000010101011
0101010101001101
1001101011001010
0101101010101011

Without Clock

001101001001101
0011010001001010
1101000101001011
100011010001101
001101000010110
00110100010111
1010101010101010
0110110010101011
0011000010101101
1001110010101010
0011000010101011
0101010101001101
1001101011001010
0101101010101011

Clock
Examples of Clocks

Crystal Resonators

Ceramic Resonators

Crystal Oscillators

MEMS Oscillators

http://www.idt.com/go/mems
Performance, Reliability, Cost, Package, Size and Power consumption vary significantly for different applications

<table>
<thead>
<tr>
<th>Military &amp; Aerospace</th>
<th>Industrial</th>
<th>Consumer</th>
<th>Automotive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communications</td>
<td>Communications</td>
<td>Watches &amp; clocks</td>
<td>Engine control,</td>
</tr>
<tr>
<td>Navigation</td>
<td>Telecommunications</td>
<td>Cellular &amp; cordless</td>
<td>stereo, clock,</td>
</tr>
<tr>
<td>IFF</td>
<td>Mobile/cellular/</td>
<td>phones, pagers</td>
<td>yaw stability</td>
</tr>
<tr>
<td>Radar</td>
<td>portable radio</td>
<td>Radio &amp; hi-fi equipment</td>
<td>control, trip</td>
</tr>
<tr>
<td>Sensors</td>
<td>, telephone &amp; pager</td>
<td>TV &amp; cable TV</td>
<td>computer, GPS</td>
</tr>
<tr>
<td>Guidance systems</td>
<td>Aviation</td>
<td>Personal computers</td>
<td></td>
</tr>
<tr>
<td>Fuzes</td>
<td>Marine</td>
<td>Digital cameras</td>
<td></td>
</tr>
<tr>
<td>Electronic warfare</td>
<td>Navigation</td>
<td>Video camera/recorder</td>
<td></td>
</tr>
<tr>
<td>Sonobouys</td>
<td>Instrumentation</td>
<td>CB &amp; amateur radio</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Computers</td>
<td>Toys &amp; games</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Digital systems</td>
<td>Pacemakers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CRT displays</td>
<td>Other medical devices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disk drives</td>
<td>Other digital devices</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Modems</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tagging/identification</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Utilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sensors</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

http://www.idt.com/go/mems
Today Oscillators are synonymous with Quartz

Frequency selective tank

Resonating Tank

Amp

Sustaining Amplifier

LC tank
MEMS resonator
Quartz Crystal, SAW

The Heartbeat of High-Tech for 75 Years

http://www.idt.com/go/mems

In the Beginning...

Bliley Technologies Inc. was originally founded as the Bliley Pie Dawson Bliley. Initially, we manufactured quartz crystals for the 1930s, our customers and products soon broadened to match the and commercial communications fields and our name was chan 1939 we were the largest Crystal Company wi
What determines the Crystal performance?

- The angle and axis of cut determines the performance and characteristics.

- The rate of vibration (frequency), is determined by the cut, size, and shape of the resonator.

- Crystals have many different modes of vibration. (fundamental, harmonic, overtone, etc)

- Thickness of quartz plate determines frequency of vibration.

  **Thinner plate = Higher frequency**

- Oscillations at odd multiples of the fundamental mode, which include the 3rd, 5th, 7th, 9th, and 11th.
  - Mostly only the 3rd overtone is used.
  - For higher frequencies overtones are more economical.
Resonant Vibration Topographs of a Quartz Plate


Lots of grinding and polishing

Ceramic Substrate
Hermetic Package
Capacitor
Quartz Resonator
ASIC

Manufacturing Process of Crystal Blank

- Synthetic Quartz Crystal
- Lumbered
- Cutting
- Lapping
- Cut to Pieces

Manufacturing Process of Crystal Resonator

1. Etching
2. Cleaning & Drying
3. Base Plating
4. Frequency Adjustment
5. Sealing
6. Printing
7. Mounting & Adhering
8. Final Inspection
9. Product Delivery

Source: KDS

http://www.idt.com/go/mems
Quartz references have a number of issues:

- Difficult to achieve >50MHz without using over-tones & degrading reliability
- Failure rates (zero time failure) vary significantly for quartz oscillators
- Doesn’t remain stable under vibration & shatters with shock
- Limited number of suppliers grow bulk quartz material and develop ceramic packages
- Presence of activity dips
- Requires hermetically sealed packages
PIEZOELECTRIC MEMS TECHNOLOGY
Piezoelectric MEMS Resonators ~10 yrs ago

\[ f_0 = \frac{1}{2 \cdot L} \sqrt{\frac{E_{\text{eff}}}{\rho_{\text{eff}}}} \]

- **\( f_0 \)**: resonant frequency
- **\( L \)**: device’s lateral length
- **\( E_{\text{eff}} \)**: effective elastic constant
- **\( \rho_{\text{eff}} \)**: effective mass density

- pMEMS™ resonator: Single crystal silicon (SCS) with piezoelectric layer (e.g., AlN) on top. Piezoelectric transduction on Silicon.
- Frequency determined by material’s acoustic velocity and device dimension \( L \).
- No DC voltage required, Low motional resistance and large power handling.

Georgia Tech Paper - S. Humad et al, IEDM 2003
- Piezoelectric resonators: electrode directly on piezoelectric layer. No DC bias.
Why is Wafer Level Packaging (WLP) important?
- All resonators are subject to environmental factors such as Moisture, mechanical stress, contamination etc.
- The idea is to micro-encapsulate the resonator at wafer level using semiconductor processes.
- **Eliminate quality/reliability issues faced during crystal oscillator assembly process.**
- WLP is specific to the type of resonator that needs to be encapsulated i.e. is custom designed. It has a direct impact on the die size -&gt; Cost for MEMS die

Benefit: Easier to package in a plastic package since this is like package inside a package
Wafer Level Packaged Resonator

- Silicon device layer with piezoelectric and electrode layer on top
- Wafer level packaging (WLP) provides hermetic solution
• World’s smallest WLP resonator (better reliability and cost)
• No power source needed (passive i.e. mimics quartz)
• Higher native frequency (up to ~1GHz)
• Lower Insertion Loss (IL ~10dB) – Better Noise performance
• Reliable Manufacturing (no ~100nm electrode gaps)
• No Stiction issues (cause reliability failures)
pMEMS™ Oscillator Teardown
First IDT MEMS Products Introduced in 2012


- Goal to replace crystal oscillators with pMEMS™ based oscillators that:
  - Have comparable or better performance than XOs.
  - Have higher native Frequencies with good phase jitter.
  - Smaller packaging.
  - Better Reliability - Highly shock and vibration resistant.
  - Cost effective.

- 40+ MEMS patents have been granted and or pending to IDT for pMEMS™ technology.
BENEFITS / FEATURES

- Get any frequency you want (50 MHz to 625 MHz)
- Phase Jitter less than 1 ps
- Short lead times
- 40X Better Reliability
  No Zero Time Failures, No activity dips, Better shock and vibration resistance
- Save money compared to traditional XO’s
- Industry Standard Footprint

<table>
<thead>
<tr>
<th></th>
<th>LVDS / LVPECL</th>
<th>5032</th>
<th>7050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package Size</td>
<td>5.0 x 3.2 mm</td>
<td>7.0 x 5.0 mm</td>
<td></td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>2.5 or 3.3V</td>
<td>2.5 or 3.3V</td>
<td></td>
</tr>
<tr>
<td>Frequency Range</td>
<td>50 MHz ~ 625 MHz</td>
<td>50 MHz ~ 625 MHz</td>
<td></td>
</tr>
<tr>
<td>Frequency Stability</td>
<td>± 50 ppm</td>
<td>± 50 ppm</td>
<td></td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-40 to +85°C</td>
<td>-40 to +85°C</td>
<td></td>
</tr>
</tbody>
</table>

Standard Frequencies (MHz):

<table>
<thead>
<tr>
<th>Frequency</th>
<th>100</th>
<th>106.25</th>
<th>125</th>
<th>133.33</th>
<th>148.5</th>
<th>150</th>
<th>155.52</th>
<th>156.25</th>
<th>159.375</th>
<th>160</th>
<th>161.133</th>
<th>187.5</th>
<th>200</th>
<th>212.5</th>
<th>250</th>
<th>312.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Additional Custom Frequencies Available Upon Request
4E Enhanced MEMS Oscillators

- **Selectable Frequencies**
  - Up to 4 Frequencies
  - Replaces up to 4 individual oscillators
  - Consolidates Inventory

- **Synchronous CMOS Output**
  - No Asynchronous Timing Concerns
  - Eliminate external XTAL or XO
  - Reduces cost
  - Improves PCB Layout Flexibility

- **Superset to Standard 7050 Package**
  - Provides 2\textsuperscript{nd} source to standard XO (w/ appropriate PCB layout)

- **High reliability**
  - No activity dip concerns
  - No zero time failures

- **Cost Savings**
  - Reduces Component count (eliminates one Oscillator or XTAL)
  - Eliminates margin testing requirement (due to Asynchronous clocks)
  - Reduces Layout Time (allows for PCB layout flexibility)

---

**Frequency Table**

<table>
<thead>
<tr>
<th>Input</th>
<th>LVPECL</th>
<th>CMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS[1,0]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,1</td>
<td>125.00</td>
<td></td>
</tr>
<tr>
<td>1,0</td>
<td>150.00</td>
<td></td>
</tr>
<tr>
<td>0,1</td>
<td>200.00</td>
<td></td>
</tr>
<tr>
<td>0,0</td>
<td>250.00</td>
<td></td>
</tr>
</tbody>
</table>

* FS0, FS1 includes weak pull-up resistor

---

http://www.idt.com/go/mems
Typical Reference Design

Integrated Solution

Two XO's: LVPECL & CMOS

Integrated Solution

LVPECL XO

http://www.idt.com/go/mems
MEMS Oscillator Application Demos

Networking Application: SRI0 PCIe Bridge (4x5Gbps)
- MEMS Oscillator:
  156.250 MHz, LVPECL, 7050 Package

FPGA Application: Xilinx Virtex 6
- MEMS Oscillator:
  200.000 MHz, LVDS, 5032 Package

Storage Application: SAS Controller for SSD
- MEMS Oscillator:
  150.000 MHz, LVPECL, 7050 Package
4M / 4E MEMS Oscillator Applications

- High Frequency Applications
  - Servers
  - Networking
  - Industrial
  - High Performance Consumer

- 6-pin LVDS / LVPECL type XO’s
- 7050 and 5032 Packages
## Why do system designers prefer MEMS?

<table>
<thead>
<tr>
<th>Feature</th>
<th>Want?</th>
<th>MEMS Oscillators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency</strong></td>
<td>Higher</td>
<td>pMEMSTM resonators can cost effectively provide higher native frequencies that enable lower jitter (sub-ps).</td>
</tr>
<tr>
<td><strong>Size</strong></td>
<td>Smaller</td>
<td>MEMS enables sizes smaller than traditional XOs</td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>Better</td>
<td>MEMS demonstrates either comparable or better stability</td>
</tr>
<tr>
<td><strong>Functions</strong></td>
<td>More</td>
<td>Configurable PLL, multipliers, dividers, programmable, multiple Outputs</td>
</tr>
<tr>
<td><strong>Power Supply</strong></td>
<td>Lower</td>
<td>LVPECL, LVDS, 3.3V, 2.5V and lower...</td>
</tr>
<tr>
<td><strong>Activity Dip</strong></td>
<td>Absence</td>
<td>None</td>
</tr>
<tr>
<td><strong>Lead Times</strong></td>
<td>Short</td>
<td>Very short lead times, Immediate sampling</td>
</tr>
<tr>
<td><strong>Inventory</strong></td>
<td>Small</td>
<td>No Shortages&lt;br&gt;- Semiconductor Level Availability</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Better</td>
<td>Higher Reliability&lt;br&gt;- Silicon Level Reliability, Production Cost Savings</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>Lower</td>
<td>Lower costs due to semiconductor scaling and plastic packages</td>
</tr>
<tr>
<td><strong>Operating Temperature ranges</strong></td>
<td>Wider</td>
<td>Wide temperature ranges commercial/industrial</td>
</tr>
</tbody>
</table>
MEMS Oscillators just coming out of Development phase into the growth phase.
Summary

- Quartz Frequency References have been around for decades
  - Technology Disruption is underway
    - MEMS is taking advantage of silicon level reliability, manufacturability and miniaturization to push frequency references into a new era.
    - pMEMS oscillators demonstrate improved reliability over existing solutions (semiconductor WLP reliability and vibration resistance). Excellent long term stability
  - Barriers to entry are high for MEMS products
    - Look at the whole picture (MEMS + IC + Packaging + Final Test + Form Factor). MEMS die drives product differentiation but is only 30% of the overall effort.
    - Actively manage Performance/Cost tradeoffs without giving up on Quality and Reliability

- MEMS adoption for frequency reference applications is increasing.
  - Today MEMS frequency reference solutions offered only by small startups with some technical and commercial barriers yet to be overcome.
  - Established timing companies such as IDT are helping bringing these technologies to market.

- The future for MEMS frequency references is bright...
  - .... and pMEMS™ technology offers a compelling solution for high performance oscillators.
Thank You

http://www.idt.com/go/MEMS