BAW Advantages for Low Power IoT Applications

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***Summary*—All IoT devices require a clock source for computation and communication. Crystal oscillators have been the standard clock source when an accurate, low power reference frequency is needed, but the growing IoT market demands improvements in five areas. These are reduced phase noise for higher data rate communication, faster startup time for duty-cycled systems, smaller physical size for further integration, improved environmental robustness, and resistance to tampering. Reference clocks built from MEMS resonators, including bulk acoustic wave (BAW) resonators, are uniquely suited to meet these requirements.**

Keywords—Bulk acoustic wave; BAW; resonator; clock; oscillator, IoT

I. Introduction

The Internet of Things (IoT) is the concept that things, people and cloud services are connected to the Internet. Despite being more than 20 years old, the market is growing quickly, averaging over 20% yearly since 2015 [1]. In this broad market, there are core requirements that apply to the majority of IoT edge nodes. First, data rates are increasing, which requires the nodes to have frequency references with lower noise. Second, many applications require that the battery last the lifetime of the device, requiring low power devices. Third, these nodes need to be small to enable new applications. Fourth, the edge nodes must be robust so that they can be deployed in harsh environments common in industrial and automotive applications. Finally, security is critical to ensure that the data collected can't be compromised. This article describes the state-of-the-art in BAW resonators and how they can be used to meet these five challenging requirements for the IoT market.

II. Bulk Acoustic Wave Resonators

Crystal oscillators have been the standard clock source when an accurate, low power reference frequency is needed. Another option that can provide similar frequency accuracy is Microelectromechanical Systems (MEMS) resonators. Examples of MEMS in the marketplace are bulk acoustic wave (BAW) resonators. Billions of BAW resonators have been manufactured for use as RF filters. The first BAW oscillator was published in 1976 [2], and over the last few years they have been released in commercial timing and IoT SoCs [3-4].

BAW resonators are passive devices consisting of an aluminum nitride (AlN) piezoelectric material that converts between electrical and mechanical energy, surrounded by electrodes as shown in Fig. 1. The resonant frequency, f_R, is dependent on the thickness of the AlN and the acoustic velocity, usually between 1-3GHz. Bragg reflectors, or acoustic mirrors, have alternating high and low acoustic impedances layers that

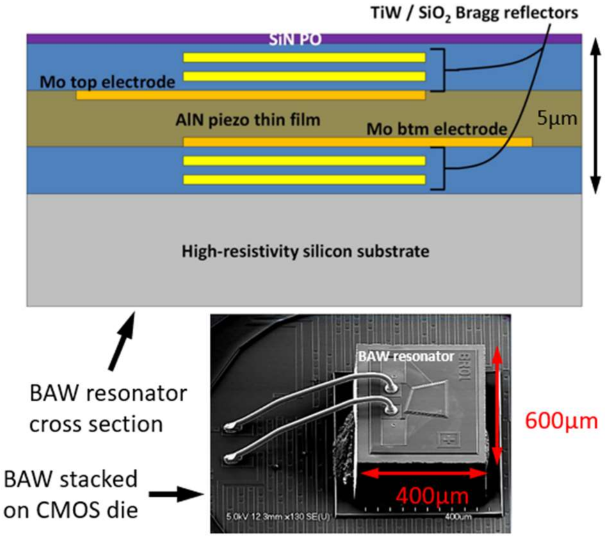

Fig. 1. Cross section of a BAW resonator with dual Bragg acoustic mirrors. Photo BAW resonator stacked and bonded to a CMOS die.

reflect energy back into the AlN, which prevents energy from leaking into the substrate or the package material above improves the quality factor, Q. The dual Bragg structure [5] prevent contamination, so the resonator frequency drift versus time is low and protects the BAW resonator from moisture and helium which makes higher cost vacuum cavities or hermetic packaging unnecessary. Fig 1. shows the BAW resonator wirebonded to a CMOS die.

The uncompensated temperature coefficient of frequency (TCF) of AlN is -25ppm/°C, giving more than 3000ppm frequency shift over the industrial temperature range, which is insufficient for most communications standards. Passive temperature compensation (TC) is implemented by adding a SiO_2 layer, which has a positive TCF, into a BAW resonator to reduce the effective TCF. Manufacturing tolerances are not precise enough to add exactly the right thickness of SiO_2 to make a frequency reference suitable for all communications protocols, many of which needs <±20ppm or <±40ppm. Passive TC is combined active temperature compensation to improve the stability further, from 3000ppm to ±10ppm [6]. A temperature sensor is used to determine the current temperature and a lookup table is used to apply a frequency correction code to the BAW oscillator based on the temperature.

III. IoT Reference Clock Requirements

A. Improved Phase Noise

Radios used for IoT wireless communication standards such as Wi-Fi and Bluetooth have used crystal oscillators below

60MHz as reference clocks for the RF PLL. However, this is not the optimal frequency for phase noise performance and high data rate communications. The PLL loop bandwidth is limited to about one tenth of the frequency reference, F_{REF}. Increasing F_{REF} allows the loop bandwidth can be pushed out, reducing the in-band noise due to a lower divide ratio N. Using a divider after the BAW resonator to generate F_{REF} allows it to be chosen to optimize performance, enabling higher data rate applications.

B. Fast Startup Time

In many IoT applications, the data throughput requirements are much lower than wireless channel bandwidth, which means duty-cycling can be used to reduce the average current consumption, as shown in Fig 2. The BAW has a Q that is roughly 10x lower than the crystal and it's ~100x higher frequency, giving a ~1000x faster startup time. Because the edge node spends less energy waking up compared to a crystal oscillator, the average system power can be lower due and the battery life is improved. Fast startup-up crystal oscillators have been recent topic of research [7]. BAW resonators however, allow yet further power reduction by replacing the radio PLL completely with careful system planning [8].

C. Integration

Crystals are passives external to a wireless SoC, often 1.6x1.0mm^2 to 3.5x2.5mm^2. When a BAW resonator is used to replace a crystal, it can be packaged with the SoC. The space saved by removing the crystals either reduces the total edge node size, or opens up more room for sensors in the same footprint, increasing the functionality.

D. Environmental Robustness

Crystal oscillators, particularly 32kHz ones, can fail to oscillate due to high humidity causing a low impedance between the pins. The crystals can actually break if subjected to too much shock. Finally, startup problems are quite common as well, and can take a lot of different forms, and sometimes are due to the fast startup features not working as intended. BAW resonators experience less frequency shift when subjected to shock than a crystal oscillator [6], enabling them to continuing operating in the correct frequency band even in harsh environments, factory monitoring, industrial applications, power tools, and automotive.

E. Improved Security

Regardless of other security measures implemented, SoCs can be compromised by glitching the clock [9]. In a CPU during correct operation, at each clock cycle, an instruction is loaded and the previously loaded instruction is executed. However, if the clock comes from a crystal oscillator, it is accessible at a pin. A glitch injected on that pin can cause the CPU clock to be malformed. At the glitch rising edge, an instruction is loaded and the previous one starts to execute. However, it does not finish executing because the real rising clock edge arrives and a new instruction starts to execute. If the skipped instruction was a password check or something similarly critical, the security of the device is compromised. All encryption built into the design is no stronger than the security of the clock system.

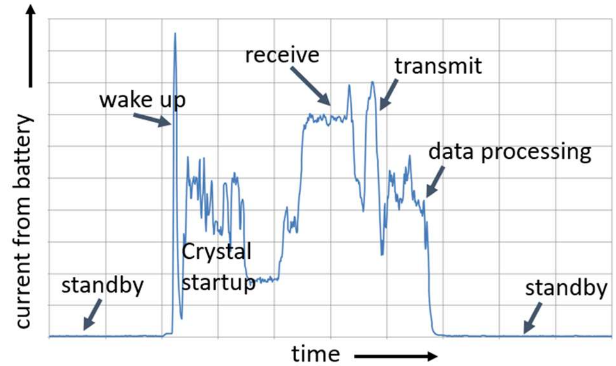

Fig. 2 Duty-cycling is used to reduce IoT power consumption. Crystal oscillator startup energy is a main contributor to power consumption.

BAW oscillators improve security by moving the frequency generation internal to the chip.

IV. CONCLUSIONS

In conclusion, BAW resonators have recently been introduced into commercial IoT SoCs. They are an advancement over 100-year-old crystal technologies. BAW resonators give designers flexibility in choosing PLL frequency reference to achieve best performance for RF PLLs. They provide advantages for systems that are duty-cycled allowing lower average power consumption. They enable reduced size, and they are more robust to shock and vibration due to lower mass which makes this especially interesting for harsh industrial environments. Finally, they provide some protection against security attacks which is becoming ever more important as more and more devices are being connected.

TABLE I. BAW TO CRYSTAL COMPARISON

Parameter	Crystal	BAW
Frequency	<100MHz	1-3GHz
Quality factor	10k – 100k	>1k
Native startup time	~1ms	<1µs
Dimensions, mm^2	2x1.6	0.6x0.4
TCF, ppm, -40 to 125°C	±40ppm	±10ppm
Pins needed	1-2	0
Years in production	~100	4

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