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Dual High-Frequency Surface Acoustic Wave Resonator for Ultrafine Particle Sensing

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***Abstract*— This paper describes the development of a low-cost robust Surface Acoustic Wave Resonator (SAWR) micro sensor capable of detecting sub-micron size particles below 1 ng. The device comprises two 262 MHz Rayleigh wave SAW resonators fabricated on ST-cut quartz where one is used for particle sensing and the other as a reference channel. Electro-acoustic detection of different particles (including carbon, gold, sucrose, silicon, and PTFE) with different diameters was studied. The mass sensitivity of the SAWR was found to be typically 275 Hz/ng or 4 pg/Hz for the detection of 750 nm diameter gold particles. We believe that the device could be used as a low-cost and low power microsensor for the real-time and ubiquitous monitoring of airborne particulate matter. In particular, our SAWR sensor can be used to detect the typical levels of ultrafine particulate pollutants (PM2.5) found in city air today.**

I. Introduction

Cities play a critical role in the regional and global air pollution due to multiple sources of emission including transportation and various industrial activities. This could bring about several direct and indirect, serious and immediate concerns related to human health and to the environment [1]. As a result, there is a significant need to detect atmospheric particulate matter (PM) (e.g. fine particles such as dust, soot and pollen) related to increasing pollution levels in our city centers. More stringent requirements by legislators for indoor and outdoor air quality monitoring and recent advances in nanoparticle based technologies have generated an increased interest in the precise measurement of ultrafine particles.

Commonly used sensors for monitoring airborne-particle size distribution and concentration are based on optical measurement techniques including nephelometry, polychromatic LED method, Scanning Electron Microscopy or MEMS based resonant mass sensors [2]. Unlike optical methods, SAW devices do not require sophisticated and expensive setups and can be operated with low cost electronic circuitry, providing the desired sensitivity level [3]. High frequency SAW resonators are known to be simple devices that are very sensitive to mass loading, because of the acoustoelectric coupling between the acoustic wave and materials deposited on the device surface.

In this paper, we report the development of a highly sensitive 262 MHz Surface Acoustic Wave (SAW) based sensor capable of detecting sub-micron size particles with masses below 1 ng. The nanoparticle sensor fabricated on a quartz substrate utilizes Rayleigh waves with a penetration depth of around 5 µm, i.e. comparable to the size of the particles being probed as illustrated in Figure 1. The SAWR devices can be integrated with analogue circuitry (e.g. Pierce oscillators) to obtain sensitive, low-power, low-cost particle detectors.

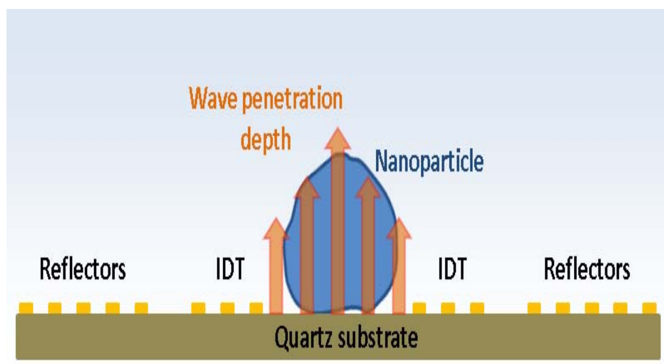

Figure 1. Penetration depths of Rayleigh waves from a SAWR can be tailored to the nanoparticle diameters of interest here.

II. Sensor Design

The acousto-electric transducer used in this work was batch fabricated on a 4" ST-cut quartz substrate wafer using UV lithography (PacTech, Germany). The high temperature stability of ST cut based Rayleigh SAW devices eliminates the need of using temperature control circuitry [4]. These sensors resonates at a frequency of 262 MHz consists of aluminum based inter-digital-transducers (IDT) in order to produce a

Rayleigh wave in the crystallographic X-direction. Each IDT comprises a set of 60.5 finger pairs with a finger width of 3 µm and an acoustic aperture of 720 µm. The distance between the two IDT structures was set at 303 µm, to create a standing wave pattern. The IDTs are surrounded by 600 shorted reflector gratings on each side with a 6 µm pitch.

Since the use of a comparable reference sensor is the most popular method for compensation [5], the designed 2-port SAW sensor operates in a dual configuration with an overall die size of 9.6 × 3.6 mm^2. The dual resonator configuration eliminates common mode interferences on the sensing signal, such as changes in ambient temperature or pressure. One side of each dual device acts as a reference signal, while the other side is used for the detection of the nanoparticles. This differential signal have reduced noise level and improved signal stability by maintaining a high signal to noise ratio. The typical device insertion loss is *ca.* 9 dB which shows that the electrical power dissipation due to acousto-electric conversion at the IDT/substrate interface is very low.

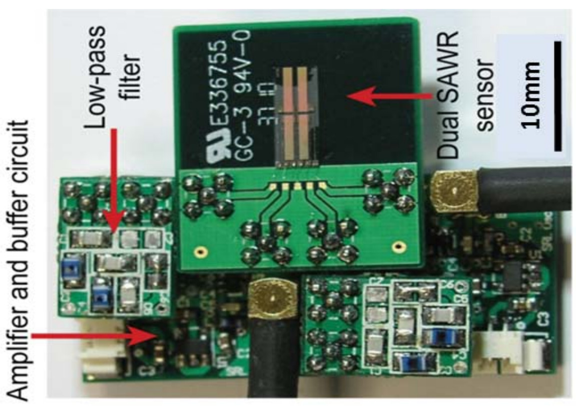

Figure 2. Photograph of a dual 262 MHzSAW sensor and the associated electronics including RF amplifiers, filters and buffer.

The SAW resonators operate in an oscillator configuration (feedback loop based) consisting of RF amplifier, a low pass filter, and the buffer circuitry. In order to avoid the problem of frequency locking of SAW resonators, the oscillator boards are arranged separately for each resonator structure, providing frequency stability. Separation of the power and ground planes on the oscillator board reduces the RF cross talk, thereby improving noise sensitivity. The low pass filter included in the feedback loop suppresses oscillations at spurious frequencies. As the SAW resonators were designed for both input and output impedances of 50Ω, the need of impedance matching circuits were avoided. The dual two-port SAWR sensor (with reference channel) and its associated electronic circuitry for excitation, amplification, buffering and read-out are shown in Figure 2.

III. MASS SENSITIVITY ANALYSIS

The sensitivity of SAW sensors depends on several factors including operating frequency of SAW device, change in the wave velocity due to surface mass loading and density of the substrate material. In general, the mass sensitivity for surface acoustic mode sensors can be defined as [6]

$$S_m = \lim_{m \to 0} \frac{1}{V_o} \frac{\Delta V}{\Delta m} \tag{1}$$

where V_o and V are the wave velocities before and after loading respectively and ΔV is the difference between them produced by adding a mass per unit area, Δm, uniformly on the sensing area of the device. Since a SAW device operates in an oscillator mode, due to negligible oscillator phase shift, and by rearranging equation (1), it can be shown that [4]

$$S_m \Delta m = \Delta V / V_o = \Delta f / f_o \tag{2}$$

where f_o and f are the resonant frequencies before and after mass loading respectively and Δf is the difference between them.

The mass sensitivity of a piezoelectric device could also be expressed as [7]

$$\Delta f = \alpha f_o^2 \Delta m / A \tag{3}$$

where α is a mechanical sensitivity constant and A is the portion of sensing area covered by the mass deposited on the device. This shows that the mass sensitivity is directly proportional to the square of the resonant frequency of the sensor. Additionally, Wenzel et al. [6] utilized Auld's perturbation theory to derive a simple expression for mass sensitivity focusing on resonance wavelength, rather than frequency of operation. Thus,

$$S_m = -K(\sigma) \frac{1}{\rho \lambda} \tag{4}$$

where, ρ is the density of the substrate and λ is the SAW wavelength. $K(\sigma)$ is a parameter that ranges from 1 to 2 for most isotropic solids and is dependent on the rayleigh and shear wave velocities.

Hence, from equations (3) and (4), it can be deduced that, in order to obtain higher sensitivity for SAW devices, the operating wavelength of the sensor must be reduced. In other words, by increasing the resonant frequency of the SAW resonator, a higher sensitivity can be obtained. As a result, we have designed and fabricated a high frequency (262 MHz) SAW resonator for particle detection at ppb level.

IV. EXPERIMENTAL PROCEDURE

The experimental setup for the detection of ultrafine particles have been developed utilizing a dual SAW based sensor as shown in Figure 3. A precision linear translation stage (LS Starrett Co., USA) which incorporates three micrometers with 0.5" travel range along each axis, was placed on top of the sensor system. The deposition of the micro and nano particles on the active area of the SAW sensor was done using a 0.25 µm thick wire attached to the translation stage. The stage allows the micro scale movement of the particles placed on the tip of the wire in all the three axes, prior to their deposition on the SAW sensing area.

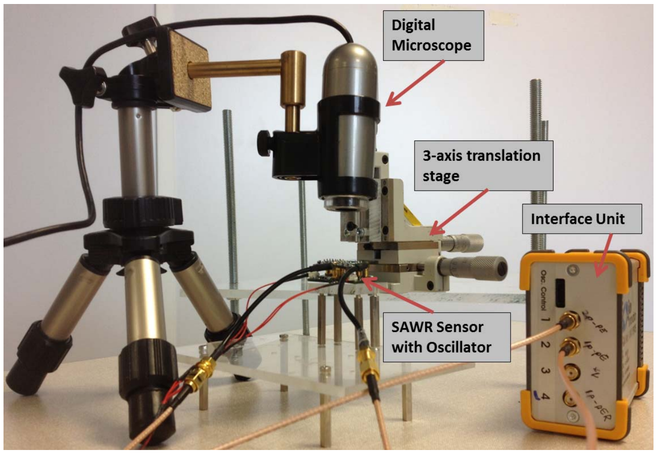

Figure 3. Experimental setup for particle testing consisting of s SAW based sensor system and associated drive and interface circuitries, a digital microscope and a translation stage used for particle deposition.

A digital microscope (Dino-Lite Europe, The Netherlands) enabled the real-time visual monitoring of the particle deposition on the sensor surface. The sensor system was placed inside a housing specifically designed to ensure temperature stability and to eliminate any effects due to environmental variations. It also insured avoidance of deposition of any foreign particulate matter on the sensing area. This in turn ensured a stable SAW baseline signal and reduced noise level. The oscillators are connected to a commercial four channel interface (JLM Innovation, Germany) unit to measure the resonant frequency of the dual SAW device and record it onto a personal computer.

V. PARTICLE DEPOSITION

In order to measure the mass sensitivity of the SAW based resonators, fine particles with known size and composition were deposited and the change in frequencies was monitored. The frequency response of the sensors to particles of different materials and various sizes including 0.75 µm gold powder, 6 µm sugar crystals, 10 µm silicon powder, 20 µm gold and 30 µm PTFE beads was measured. Effects of particle deposition on both the *free* sensing area of the SAWR sensor and between the aluminum inter digital transducers (IDTs) was studied.

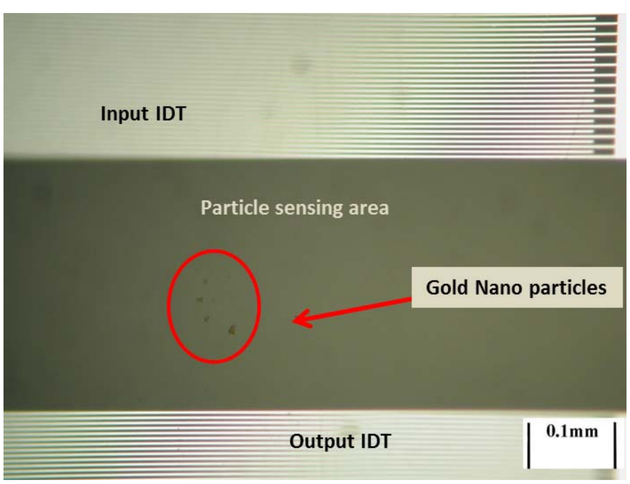

Figure 4. Optical image of gold particles deposited correctly within the free sensing area between the IDTs.

Figure 4 shows the sensor after the deposition of gold particles (diameters less than 1 µm) on the active area of the SAW based particle sensor and Figure 5 shows the SEM image of the gold nanoparticles deposited on the SAW IDT area.

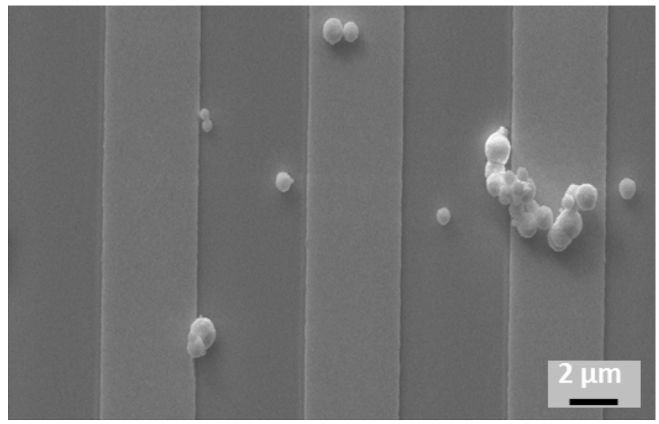

Figure 5. SEM image of gold nanoparticles placed across the 3 µm wide aluminum electrodes of the SAWR IDTs in order to test positional sensitivity.

VI. RESULTS AND DISCUSSION

A typical differential frequency output produced by the deposition of fine gold particles (750 nm) on the sensing side of the dual SAWR sensors is as shown in Figure 6. From this, it can be seen that the SAW sensor has a fast and low noise response. In a similar manner, the frequency response due to other types of particles including carbon, gold, sucrose, silicon, and PTFE were also obtained in an attempt to obtain the mass sensitivity of the SAW particle sensor.

The mass sensitivity of the particle sensor was calculated for each particle type, utilizing the value of the particle density and diameter. The relationship between the mass sensitivity, $\Delta f/\Delta m$, and particle diameter has been established as shown in Figure 7. It can be noted that the SAW sensor displayed the highest mass sensitivity for the particles of less than ca. 5 µm in diameter. For all other particle diameters outside this range, the sensitivity was significantly smaller.

The change in mass sensitivity with particle dimensions could be explained by the knowledge of acoustic penetration depth of the SAW resonator. Rayleigh waves travel along the surface of the substrate with the particle vibration in the vertical plane. This particle motion consists of a combination of P (compressive) and SV (shear vertical) vibrations in the axis normal to the direction of wave. The penetration depth is the depth at which the signal amplitude is degraded to e-1 of its value at its surface [8], and it changes inversely with the frequency of operation of SAW sensor. Thus, in a highly sensitive SAWR particle sensor, surface interactions occur in the close proximity, resulting in increased mass sensitivity [9].

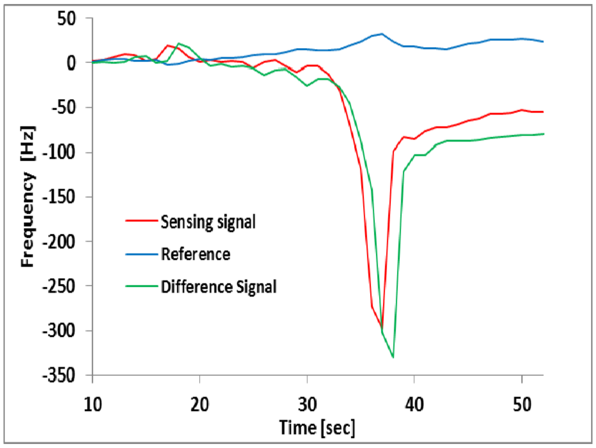

Figure 6. Typical frequency shifts of a dual SAWR sensor after the addition of gold nanoparticles in sensing region.

As the particle diameter decreases, a high frequency Rayleigh based particle sensor allows particle monitoring in the close proximity of sensor surface. Hence the particle size must be less than the acoustic penetration depth to allow acoustic coupling of the entire particle volume. Otherwise, the sensor only probes the part of the particle near its surface.

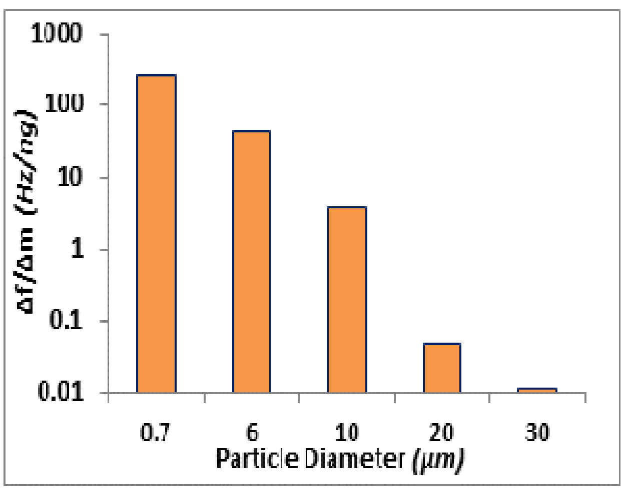

Figure 7. Plot showing the relationship between SAWR sensitivity Δf/Δm and particle diameter for different sized particles.

For a Rayleigh SAW device with a wave length λ, the penetration depth is typically about 0.4λ [8] and therefore a characteristic penetration depth of 262 MHz SAWR sensor is in the range of ca. 5 µm. This phenomenon may be utilized to monitor pollutants with different particle size distribution by employing SAWRs operating at different frequencies.

Ideally, if the size of a gold particle is within the penetration depth range, e.g. 4 µm, then the mass of that particle detected by the sensor is calculated to be *ca.* 0.65 ng. Thus by using sub-micron size particles, masses in the picogram range could be detected by the sensor.

VII. Conclusion

A low cost SAW based particle sensor capable of detecting ultrafine particulate matter with masses below 1 ng has been developed and discussed. A high sensitivity of 275 Hz/ng was measured which shows good close agreement with the theoretically estimated value. Work is under progress to develop a compact and low power particle sensor system by implementing the oscillator circuit in a silicon CMOS process.

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